Proceedings of the 9th U.S.-Japan Natural Resources Panel for Earthquake Research

Edited By Shane T. Detweiler and William Ellsworth

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TABLE OF CONTENTS

Introduction

The UJNR Panel on Earthquake Research promotes advanced study toward a more fundamental understanding of the earthquake process and hazard estimation. The Ninth Joint meeting was extremely beneficial in furthering cooperation and deepening understanding of problems common to both the U.S. and Japan.

The meeting included productive exchanges of information on approaches to systematic observation and modeling of earthquake processes. Regarding the earthquake and tsunami of March 2011 off the Pacific coast of Tohoku, the Panel recognizes that further efforts are necessary to achieve our common goal of reducing earthquake risk through close collaboration and focused discussions at the 10th UJNR meeting. We look forward to continued cooperation on issues involving the densification of observation networks and the open exchange of data among scientific communities. We recognize the importance of making information publicly available in a timely manner. We also recognize the importance of information exchange on research policy and strategies, including the frameworks of research organizations.

Areas of Cooperation

Specific areas of earthquake research where cooperative research between the U.S. and Japan may lead to significant advancement include, but are not limited to:

- Probabilistic earthquake and tsunami hazard estimation, including extraordinarily large earthquakes, both in our respective countries and worldwide, incorporating knowledge of current and past behavior, and physics based computational models;
- Real-time information from seismic, geodetic and strain measurements, including borehole strainmeters and seafloor observations using offshore cabled networks;
- Technologies for measuring crustal deformation;
- Early warning technologies for earthquakes and tsunamis;
- Studies of recurrence of large and extraordinary large earthquakes using paleoseismic, paleotsunami, geodetic and seismic methods;
- Laboratory, theoretical and in situ studies of fault-zone processes;
- Studies of episodic tremor and slow slip events using seismic, geodetic, and borehole strain measurements, and simulation techniques;
- Systematic studies of earthquake predictability through rigorously evaluated scientific prediction experiments and robust databases;
- Studies of near-source ground motions, geological effects and the response of engineered structures.

The Panel strongly urges that the appropriate agencies in the U.S. and Japan that are represented on this panel work together with the academic sector to support and coordinate scientific work in these areas of cooperation. The Panel recognizes the importance of promoting the exchange of scientific personnel, exchange of data, and fundamental studies to advance progress in earthquake research. The U.S. and Japan should promote these exchanges throughout the world. The Panel endorses continuation of these activities.

9th UJNR Panel on Earthquake Research
Denver, CO
October 9-12, 2012

Meeting Agenda

Tuesday, Oct. 9

0800 Registration
0830 Welcoming Remarks by Panel Co-Chairs **David Applegate** and **Kazuo Inaba**

0900 Opening Session- Session Chairs **Toshiya Fujiwara** and **Shuo Ma**
The 2011 off the Pacific Coast of Tohoku Earthquake and lessons learned

Yuki Hatanaka "Interplate coupling on and around the focal area of the 2011 off the Pacific Coast of Tohoku Earthquake, Japan"

0920 **Fred Chester** "Location and structure of the subduction thrust in the region of maximum slip during the 2011 MW 9.0 Tohoku-Oki earthquake"

0940 **Toshiya Fujiwara** "Coseismic fault rupture reaching the trench axis during the 2011 Tohoku-Oki earthquake"

1000 Break

1020 Session 1 (cont.)

Mark Simons "The 2011 Tohoku-Oki earthquake and the Advanced Rapid Imaging and Analysis (ARIA) Project for Natural Hazard Monitoring and Response"

1040 **Makoto Matsubara** "The 2011 Tohoku-oki Earthquake related to a strong velocity gradient within the Pacific plate"

1100 **Shuo Ma** "Uncovering the Mysteries of Tsunami Generation and Anomalous Seismic Radiation in the Shallow Subduction Zone"

1120 **Yasuto Kuwahara** "Stress states before and after the 2011 Great Tohoku earthquake in and around the focal region"

1140 **Brendan Meade** "Geodetic imaging of coseismic slip and postseismic afterslip: Sparsity promoting methods applied to the great Tohoku Earthquake"

1200 **Takashi Saito** "GSI activities in response to the 2011 off the Pacific coast of Tohoku Earthquake"

1220 Break for lunch set-up

1250 Lunch
Keynote Address:
David Wald "Earthquake loss modeling on a global scale: balancing empirical & physics-based approaches"

1420 Break for lunch take-down

1450 Session 2: Session Chairs **Koshun Yamaoka** and **Art Frankel**
Earthquake Hazard Studies, Recurrence, and Map Updates

Art Frankel "USGS Seismic Hazard Mapping Efforts: U.S. National Seismic Hazard Maps and Urban Seismic Hazard Maps Based on 3D Simulations"

1510 **Koshun Yamaoka** "National Policy and Project on the Earthquake Research after the 2011 Off the Pacific Coast of Tohoku Earthquake"

1530 **Margaret Glasscoe** "E-DECIDER: Experiences Developing Earthquake Disaster Decision Support and Response Tools"

1550 **Hiroyuki Fujiwara** "Some considerations for improvement of the National Seismic Hazard Maps for Japan"

1610 **Morgan Moschetti** "Time-independent earthquake forecasts for the Intermountain West, United States"

1630 Break

1650 Session 3: Session Chair **Takeshi Koizumi**
Probabilistic Earthquake and Tsunami Hazard Estimation, Paleoseismology and Paleotsunamis

Bruce Jaffe "Assessing Tsunami Hazard from Paleotsunami Deposits"

1730 **Masanobu Shishikura** "Strategy for evaluating giant earthquake and tsunami by coastal paleoseismology"

1750 **Takeshi Koizumi** "JMA's response to the 2011 off the Pacific coast of Tohoku Earthquake and planned Improvements of Tsunami Warning"

1810 **Discussion**

1830 **Adjourn/Reception Banquet**

Wednesday, Oct. 10

0900 Opening Comments
0910 Session 4: Session Chairs **Dominic Asimaki** and **David Wald**
Studies of Near-Source Ground Motions

Dominic Asimaki “Nonlinear site and topography effects in ground motion predictions: Observations, Hypotheses and Lessons to be learned”

0930 **Shin Aoi** “Strong motion characteristics of the 2011 Tohoku-Oki earthquake observed by K-NET and KiK-net”

0950 **Lisa Grant-Ludwig** “Reconciling precariously balanced rocks with large earthquakes on the San Andreas fault system”

1010 Break

1030 Session 5: Session Chairs **John Vidale** and **Kohei Nagata**
Operational Earthquake Forecasting and Earthquake Early Warning System Development

Jeremy Zechar “Betting against the house and peer-to-peer gambling: a Monte Carlo view of earthquake forecasting”

1050 **Kohei Nagata** “Information services on earthquake prediction and forecast of JMA”

1110 **Yasuyuki Yamada** “Earthquake Early Warning of JMA- The 2011 off the Pacific coast of Tohoku Earthquake and its aftershocks”

1130 **John Vidale** “Early Warning on the US West Coast”

1150 Break for lunch set-up

1220 Lunch
Keynote Address:
Meghan Miller “UNAVCO: Recent Earthquake Responses, Multi-hazard Networks, and Technology Development”

1350 Break for lunch take-down

1420 Session 6: Session Chairs **Ken Xiaosheng Hao** and **Sarah Minson**
Real-time Monitoring of seismic, geodetic and strain measurements, Seafloor GPS

David Chadwell “Potential contributions of Seafloor Geodesy to understanding slip behavior along the Cascadia Subduction Zone”

1500 **Sarah Minson** “Performance Tests of Real-Time Permanent Displacement Estimates and Rapid Rupture Characterization From Real-Time High-Rate GPS”

1520 **Andrea Donnellan** “Integrating GPS and Radar Geodetic Imaging Observations with Models for Earthquake Response and Planning Additional data Collection”

1540 Break

1600 **Ken Xiaosheng Hao** “Rapid assessment of high seismic intensity areas for mega-earthquake using satellite SAR data”

1620 **Gavin Hayes** “Real-Time Monitoring at the USGS National Earthquake Information Center: Past, Present, Future”

1640 **Charles Estabrook** “NSF's EarthScope Program – Introduction and Updates”

1700 **Discussion**

1720 Session 7: **Poster Session**

Shin Aoi
“Ocean bottom seismic and tsunami network along the Japan Trench”

Satoshi Kawamoto (presented by Dr. Yuki Hatanaka)
“Developing a GEONET Real-time Processing System for Rapid Earthquake Modeling

Yasuto Kuwahara
“Asia-Pacific Region Global Earthquake and Volcanic Eruption Risk Management (G-EVER) project”

1800 **Adjourn/Meet for informal dinner**

<u>Thursday, Oct. 11</u>

0900 Opening Comments
0910 Session 8: Session Chairs **Justin Rubinstein** and **Takuya Nishimura**
Episodic Tremor and Slow Slip, in situ Studies of fault-zone Physics

David Shelly “Dynamics of Migrating Earthquake Swarms at Yellowstone and Mount Rainier Volcanic Areas: Evidence for Fluid Triggering?”

0930 **Takuya Nishimura** “Detection of short-term slow slip events along the Nankai trough, southwest Japan using GNSS data”

0950 **Diego Melgar** “Mitigation of Earthquake Hazards with a Seismogeodetic Model as Demonstrated for the 2011 Mw 9.0 Tohoku-oki Earthquake”

1010 **Norio Matsumoto** “Short-term slow slip events in the Kii peninsula by joint analysis of the AIST borehole strainmeter array and the NIED Hi-net tiltmeter array”

1030 Break

1050 Session 8: (cont.)

Bunichiro Shibazaki “3D quasi-dynamic modeling of cycles of megathrust earthquakes along the Japan Trench subduction zone considering high-speed friction”

1110 **Wayne Thatcher** “Advantages and Limitations of Cluster Analysis in Interpreting Regional GPS Velocity Fields in California and Elsewhere”

1130 **Kazushige Obara** “Characteristic activity of tremor as proxy for slow slip in the transition zone along the subducting plate interface”

1150 **Justin Rubinstein** “Repeating Earthquakes on the Parkfield Segment of the San Andreas: Do They Reload Themselves?”

1210 **Discussion**

1230 Closing remarks and Presentation of Meeting Resolution by Panel Co-Chairs **David Applegate** and **Kazuo Inaba**

1240 Group photo

1310 Lunch

1410 Depart for field trip to Golden, CO

1430 Arrive Golden, CO, Tour USGS- National Earthquake Information Center

1700 Free time in Golden, CO. Dinner on own.

2000 Return to hotel

2030 Arrive Hotel

<u>Friday, Oct. 12</u>

0900 Board bus- Depart for field trip

1015 Arrive Boulder, CO, Tour UNAVCO Facility

1230 Box Lunch in Boulder

1330 Depart for Denver, CO

1430 Arrive Country Inn Hotel, Free time

1500 Arrive Sheraton Hotel, Free time

Session I

Abstracts

Interplate coupling on and around the focal area of the 2011 off the Pacific Coast of Tohoku Earthquake, Japan

Yuki Hatanaka, Shinzaburo Ozawa, Takuya Nishimura, and Hisashi Suito
Geography and Crustal Dynamics Research Center, Geospatial Information Authority of Japan

Interplate coupling and coseismic slip of the 2011 off the Pacific Coast of Tohoku Earthquake were estimated based on nearly 18-years-long data of the GEONET, a continuous GNSS network of Japan.

In the period before the 2011 off the Pacific Coast of Tohoku Earthquake, Japan, shortening in east-west direction due to the push by the subducting Pacific plate was main characteristics of the crustal deformation in northeastern Japan. The analysis of GEONET data from 1997 to 1999 shows a large slip-deficit rate off Miyagi prefecture. The EW shortening rate became slower in Fukushima prefecture after 2000, suggesting partial weakening of interplate coupling in progress.

The 2011 off the Pacific Coast of Tohoku Earthquake ruptured the large area from the off Iwate prefecture to off-Chiba prefecture. An extremely large slip is found at a shallow portion of the plate boundary off Miyagi prefecture. The rupture extends to a deeper potion near Miyagi prefecture than off Fukushima prefecture. The north end of the rupture area is close to the rupture area of the 1994 far off Sanriku earthquake. The slip is relatively small off Fukushima where the partial unlocking was inferred before the main-shock. These facts suggest the effect of the preceding aseismic slip on the rupture process of the main-shock.

The main-shock was followed by large postseismic deformation. We assume an afterslip was a main mechanism of the observed deformation and estimated a distribution of the afterslip. The slip areas of the main shock and the afterslip tend to avoid overlapping. The afterslip is taking place mainly at a deeper portion of the plate boundary than the main rupture. The afterslip in off-Miyagi prefecture, where the coseismic slip was very large, is smaller than that of the northern and southern areas. The moment magnitude (Mw) of the afterslip is nearly 8.6 as of September, 2012.

Continuous monitoring of the after-slip is important to understand the cycle of the huge earthquakes since it is revealing the rebuilding process of interplate coupling for the next earthquake. Since the main rupture took place at the offshore area near the trench, where resolving power of GEONET data is low, collaboration with an offshore crustal deformation observation is especially important.

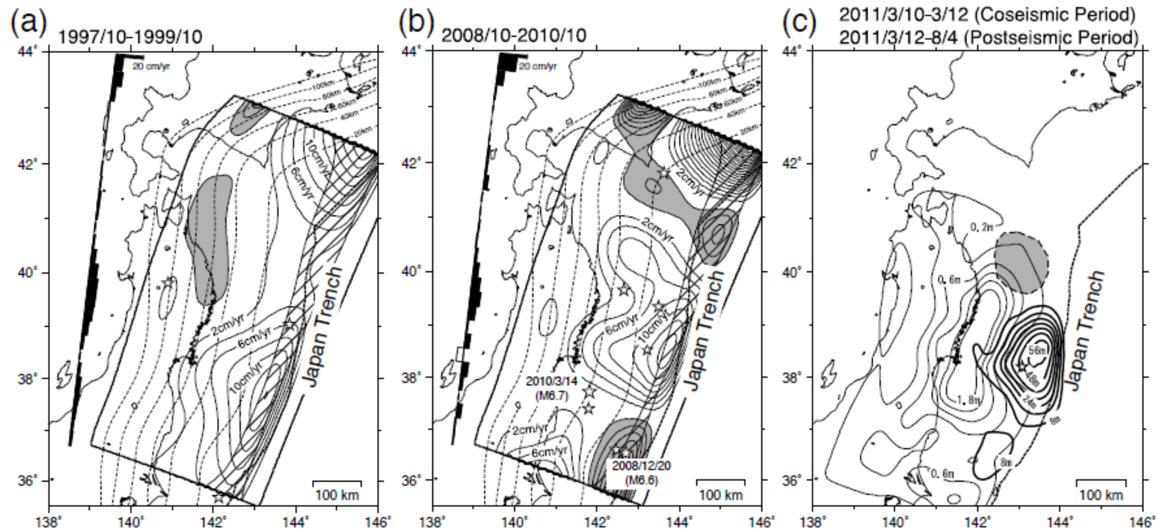

Figure 1. (a) Distributions of slip-deficit rates on the two plate boundaries for Period 1 (October 1997 to October 1999). The thick rectangle on the Pacific side is the fault model region of the subducting Pacific plate. The contour interval is 2 cm/yr. Gray areas represent regions of forward-slip. The heights of bars in the Japan Sea reflect the rate of collision at the plate boundary modeled by the virtual tensile fault. Stars are the epicenters of large earthquakes with magnitudes of ≥6. The broken lines are isodepth contours of the plate interface. (b) Same as (a) but for Period 2 (October 2008 to October 2010). (c) Slip distribution of the 2011 Tohoku-Oki earthquake, from the Geospatial Information Authority of Japan (2011). Thick and thin lines represent coseismic slip distributions estimated from land and offshore GPS data and postseismic slip distributions, respectively, for ~4 months. The gray region with the broken line represents the source area to the 1994 Far east off Sanriku Earthquake (Nishimura et al., 2000) (after Nishimura, 2012).

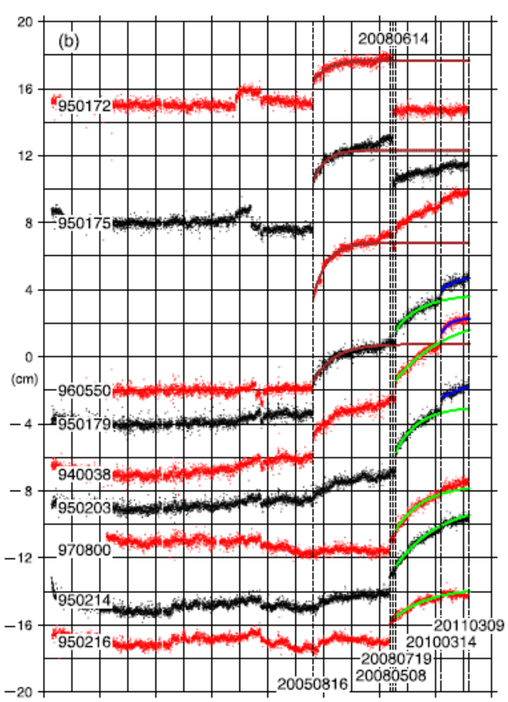

Figure 2. Transient time series of E-W component at selected stations along the Pacific coast of northeastern Japan. Exponential functions are also indicated in brown, green, and blue lines, which correspond to the 2005 Miyagi, 2008 Fukushima, and 2010 Fukushima earthquakes, respectively, at the stations mentioned in the text. Vertical broken lines indicate the date of the earthquakes whose epicenters are shown in (a) as red stars (after Suito et al., 2012).

Location and structure of the subduction thrust in the region of maximum slip during the 2011 M_W 9.0 Tohoku-Oki earthquake

Frederick M. Chester (Texas A&M University, USA), James J. Mori (Kyoto University, Japan)
Nobu Eguchi (CDEX / JAMSTEC, Japan), Sean Toczko (CDEX / JAMSTEC, Japan)
and Expedition 343 and 343T Scientists*

The fault slip during the 11 March 2011 Tohoku-Oki earthquake, which reached a maximum of >50 m near the Japan Trench, was the largest ever observed for an earthquake and was responsible for the peak tsunami heights of 20 to 40 meters that struck the coast of northeast Honshu (Figure 1). Although the cause of such large seismic slip at shallow depths is not entirely understood, a number of possible contributing factors have been identified. These include heterogeneous coupling up dip of the hypocenter or other factors that generate an energetic rupture to drive shallow slip, a compliant wedge and the free surface above a shallow thrust fault that magnifies overshoot, widespread poroplastic failure of the wedge that produces uplift and diminishing slip towards the trench, and friction behavior of the shallow subduction thrust that promotes earthquake rupture propagation even though inhibiting rupture nucleation. Outstanding questions include how displacement was accommodated near the trench, and whether coseismic weakening of the shallow megathrust had a role in the mechanics of such large displacement. These and other questions are being addressed with data from the recently completed rapid-response expedition (Expedition 343 and 343T) undertaken by the Integrated Ocean Drilling Program (IODP).

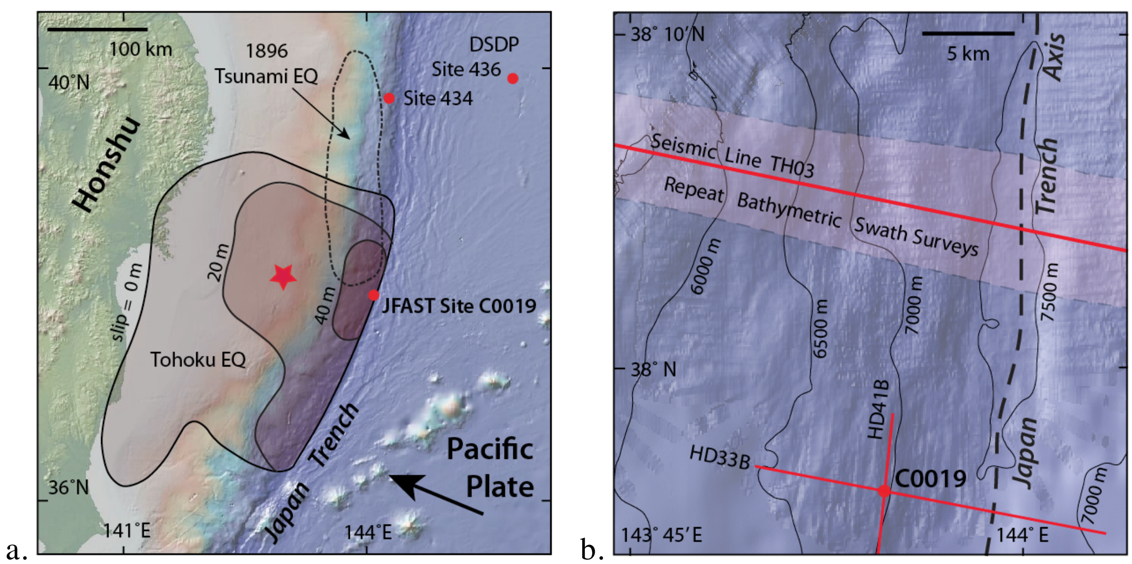

Figure 1. Maps of the location of the JFAST drill site C0019 off of the eastern coast of northern Japan and in the vicinity of the 2011 Tohoku earthquake rupture area. Filled red circles indicate ocean drilling sites, filled red star is the epicenter of the Tohoku earthquake, and the red lines show the location of key geophysical surveys. a) The drill site C0019 is located at the inner slope of the Japan Trench. Contours show a schematic representation of the coseismic slip inferred from various data sets. Dashed line shows the approximate rupture area of the 1896 Meiji-Sanriku tsunami earthquake. b) Detail map shows the proximity of site C0019 to the repeat seismic and swath-bathymetry surveys that document large slip occurred up to the axis of the trench. Line HD33B shows the location of the in-line seismic profile through the drill site.

Drilling the plate boundary interface was technically challenging because of the 6.9 km water depth and the need to penetrate > 800 m through the prism to reach the subducting plate. Nonetheless, three successful holes were drilled to the target depth at Site C0019 (Figure 1), and borehole and core data define the location and structure of the plate-boundary décollement within the area that displayed large, shallow slip during the Tohoku-Oki event. Data from the logging-while-drilling and coring boreholes completed during the first leg of the expedition (343) indicate that the location of the décollement is tens of meters above bedded chert and basalt of the subducting plate and, similar to other subduction thrusts, may be controlled by the lithostratigraphy of the incoming plate. Interpretations of a seismic lines through the drill site suggest a total displacement of more than 3 km has occurred on the décollement at the borehole. Notably, coring shows the décollement zone is less than 5 m thick, which is considerably thinner than subduction thrusts drilled elsewhere. Distinguishing characteristics of the décollement that could favor coseismic weakening mechanisms include the pronounced localization of shear to a meters-thick layer of scaly clay, mesoscale slip surfaces within the layer, and narrow zones of fault-related damage in sediment bounding the layer. A one meter section of the scaly clay was retrieved, which provides ample material for characterization of structural, physical, chemical and mechanical properties of the plate interface, and post-cruise analyses of samples are already producing new results. The third hole was completed during the second leg of the expedition (343T), and a temperature measurement string was successfully installed across the plate boundary to quantify heat generated in this shallow region of the fault zone and allow determination of the fault shear strength during the earthquake. The décollement is not only the likely site of recent seismic slip, but also a type example of the shallow rupture zones that produce tsunami earthquakes along the Japan Trench.

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Coseismic fault rupture reaching the trench axis during the 2011 Tohoku-Oki earthquake

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Fault rupture during the 2011 Tohoku-Oki earthquake (M_W 9.0), which generated huge tsunamis, is thought to have propagated to a shallow part of the subduction zone. This observation calls into question conceptual models that assume that the shallow part of the plate boundary interface in a seismogenic subduction zone slips aseismically. However, the available observations of the earthquake and tsunami do not have sufficient resolution near to the subduction trench to determine whether coseismic fault slip extended all the way to the trench axis. Here we use bathymetric and seismic reflection data to image the seawards of the Tohoku-Oki earthquake epicentre, off the coast of Miyagi in the Tohoku district.

We compared bathymetric profiles taken in 1999 and 2004 with one acquired along the same profile 11 days after the earthquake. The relative differences among these bathymetric data are minimal on the seaward side of the trench despite potential errors of several meters in vertical displacement and ~20 m in horizontal displacement. There were, however, large relative differences landward extended up to the trench axis, suggesting the earthquake fault rupture reached the trench axis. Comparison of the bathymetry before and after the earthquake shows a sharp contrast in seafloor elevation at the trench axis, and the seafloor is shallower throughout the landward side.

Notably, on the outermost landward slope, the 40 km wide area between the slope break and the trench axis, the observed large seafloor elevation change corresponds to a sum of vertical displacement and additional uplift for the sloping seafloor due to horizontal displacement. We estimated the horizontal displacement by calculating the offset distance to maximize the cross-correlation of bathymetry. The estimated displacement is 56 m relative to the 1999 data, and 50 m relative to the 2004 data, toward the east-southeast. After restoring the horizontal displacement, the average elevation change became 10±7 m in comparison between the 1999 and 2011 data (7±7 m between 2004 and 2011). We interpret these to represent vertical displacement, from the fault motion along the subducting plate and uplift from other unknown processes such as inelastic deformation. Overall, the seafloor on the outermost landward slope moved ~50 m in the east-southeast toward the trench and ~7-10 m upward between 1999 and 2011. Furthermore, upward and downward changes in seafloor elevation of ±50 m are evident at the axial seafloor.

We also compared an image of a seismic profile taken in 1999 with one acquired in 2011. Subsurface of the landward slope, above the subducting oceanic crust, is characterized by a highly reflective zone. The highly reflective zone, which is about 2 km thick and seems to thin towards the land, consists of a series of reflectors that are subparallel to the subducting oceanic basement. Before the earthquake, we observed a triangular wedge of sediments at the trench axis. After the earthquake, we observed a deformed upheaval structure in the sedimentary layer that was 3 km long and 350 m thick. This structure is interpreted as compressional (that is, a thrust-up structure) with reverse faults branching from an interface in the subducting sedimentary layer, which is interpreted as the coseismic master fault. The seismic image beneath the landward slope of the trench axis, where 50 m of subsidence was observed in the differential bathymetric data, was imaged after the earthquake as a seismically scattered structure. This structure is interpreted to have formed by slumping. As the overriding block extended over the edge of the horst on the seaward slope, the ~50 m of horizontal movement of the block towards the trench brought the sedimentary block at the edge of the horst over the graben, which may have caused gravitational instability, triggering slumping on the seaward slope.

Our examination of the observed structure leads us to propose the following scenario for the rupture propagation to the trench. Coseismic slip of the Tohoku-Oki earthquake starting from the epicentre at around 20 km depth propagated up-dip along the reflective zone. The slip continued to propagate along the interface beneath the frontal prism and slightly above the oceanic crust. The slip did reach and finally broke the sea floor at the trench axis. We conclude that the shallow plate interface at the subduction trench axis can slip seismically.

The 2011 Tohoku-Oki earthquake and the Advanced Rapid Imaging and Analysis (ARIA) Project for Natural Hazard Monitoring and Response

Mark Simons[1], Sarah Minson[2], Susan Owen[3], Francisco Ortega[1], Frank Webb[3], Paul Rosen[3], Jennifer Cruz[3], Sang-Ho Yun[3], Eric Fielding[3], Angelyn Moore[3], Hook Hua[3], Paul Lundgren[3] and Piyush Agram[1]

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[2] *United States Geological Survey, Department of Earth and Space Sciences, University of Washington, Seattle WA 98195*

[3] *Jet Propulsion Laboratory, California Institute of Technology, Pasadena CA 91109*

The 2011 Tohoku-Oki earthquake represents a watershed moment in both our understanding of giant megathrust earthquakes and the approaches used to describe, assess, and respond to such devastating events. The relatively unexpected nature of this event motivates the need for geophysicists to spend more time describing the inherent ambiguities of their models, in essence quantifying both what is known *and* what is not known. From the perspective of rapid assessment and response, this event also prompts us to consider different ways in which our geophysical tools and models can be exploited to fully benefit society.

In the specific case of estimating fault slip during the different phases of the seismic cycle, we must try to (1) limit the use of *a priori* regularization, (2) understand the impact of both errors in our observations and inadequacies of our models, and (3) look for ways to describe the limited resolution of our inferred models. We will briefly outline how we are addressing these issues using a fully Bayesian methodology. While the computational challenges of this approach require both algorithmic advances and large computer resources, they allow us to hone our understanding of the extent to which our observations place constraints on the mechanical character of large faults.

In order to enable the next leap in event assessment and response, we have initiated the Advanced Rapid Imaging and Analysis (ARIA) project - an effort to automate geodetic imaging capabilities for hazard response and societal benefit. Over the past decade, space-geodesy (e.g., InSAR and GPS) has provided new assessment capabilities and situational awareness on the size, location, and character of earthquakes as well as on volcanic eruptions following magmatic events. Geodetic imaging's unique ability to capture surface deformation with high spatial and temporal resolution allow us to resolve the properties of the earthquake in correspondingly high spatial and temporal detail. In addition, remote sensing with radar provides change detection and damage assessment capabilities for earthquakes, floods and other disasters that can image even at night or through clouds. However, since these data sets are still essentially hand-crafted, they are not generated rapidly and reliably enough to be useful for informing decision-making agencies and the public following an earthquake. The ARIA project is building an end-to-end prototype geodetic imaging system as the foundation for an operational hazard response facility integrating InSAR, GPS, seismology and modeling to deliver monitoring, actionable science and situational awareness products. For the 2011 Tohoku-Oki earthquake, the ARIA project provided processed GPS time series to the international community within days of the event allowing any interested group to model the data. This availability of this derived data product provided the foundation for a community assessment of what had just occurred. This effort was only possible due to GEONET's laudable open data policy.

We describe examples of the ARIA project data products for the 2011 Tohoku-Oki and the M6.3 Christchurch earthquakes. ARIA is now collaborating with USGS scientists in both the earthquake and volcano science program for our initial data product infusion. Perhaps the greatest hurdle for this endeavor is the free, open, and low latency access to relevant data streams for events distributed around the globe. Such access is critical to both advance our science and serve societal needs.

The 2011 Tohoku-oki Earthquake related to a strong velocity gradient within the Pacific plate

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We conduct seismic tomography using arrival time data picked by NIED Hi-net, including earthquakes off the coast, outside the seismic network around the source region of the 2011 Tohoku-oki Earthquake. For these offshore events, we use the centroid depth estimated from moment tensor inversion by NIED F-net. After the Tohoku-oki Earthquake we also used the centroid depth estimated from seismograms of high-sensitivity accelerometers operated by NIED with moment tensor inversion (Asano et al., 2011).

The target region, 20-48°N and 120-148°E, covers the Japanese Islands from Hokkaido to Okinawa. A total of manually picked 4,622,346 P-wave and 3,062,846 S-wave arrival times for 100,733 earthquakes recorded at 1,212 stations from October 2000 to August 2009 is available for use in the tomographic method. In the final iteration, we estimate the P-wave slowness at 458,234 nodes and the S-wave slowness at 347,037 nodes. The inversion reduces the root mean square of the P-wave traveltime residual from 0.455 s to 0.187 s and that of the S-wave data from 0.692 s to 0.228 s after eight iterations (Matsubara and Obara, 2011). After the Tohoku-oki earthquake, we also used arrival time data from many aftershocks determined by moment tensor inversion (Asano et al., 2011) composed of 1,089,228 P- and 593,191 S-wave arrival times from 4,384 events outside of the seismic network.

Centroid depths are determined using a Green's function approach (Okada et al., 2004) such as in NIED F-net. For the events distant from the seismic network, the centroid depth is more reliable than that determined by NIED Hi-net, since there are no stations above the hypocenter.

We determine the upper boundary of the Pacific plate based on the velocity structure and earthquake hypocentral distribution (Fig. 1). The upper boundary of the low-V oceanic crust corresponds to the plate boundary where thrust earthquakes are expected to occur. Where we do not observe low-V oceanic crust, we determine the upper boundary of the upper layer of the double seismic zone within high-V Pacific plate. We assume the depth at the Japan trench as 7 km.

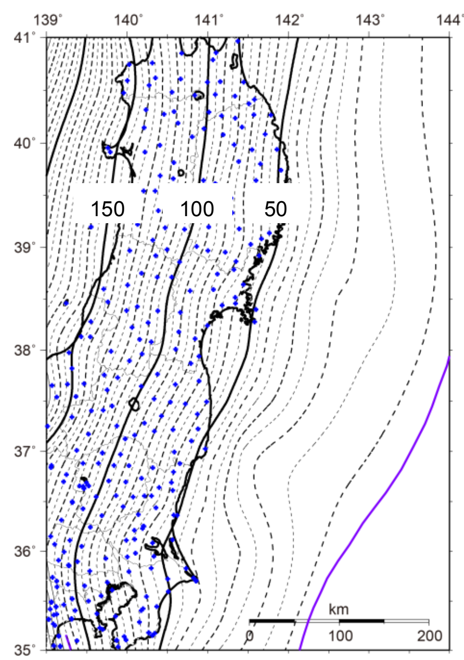

Fig. 1 Depth contour of the upper boundary of the subducting Pacific plate

We can investigate the velocity structure within the Pacific plate such as 10 km beneath the plate boundary. The landward low-V zone with a large anomaly corresponds to the western edge of the coseismic slip zone of the 2011 Tohoku-oki earthquake estimated with waveform analysis (e.g. Suzuki et al., 2011; Yagi and Fukahata, 2011). The initial break point (hypocenter) is associated with the edge of a slightly low-V and low-Vp/Vs zone corresponding to the boundary of the low- and high-V zone. The trenchward low-V and low-Vp/Vs zone extending southwestward from the hypocenter may indicate the existence of a subducted seamount. The high-V zone and low-Vp/Vs zone might have accumulated the strain and resulted in the huge coseismic slip zone of the 2011 Tohoku earthquake. The low-V and low-Vp/Vs zone is a slight fluctuation within the high-V zone and might have acted as the initial break point of the 2011

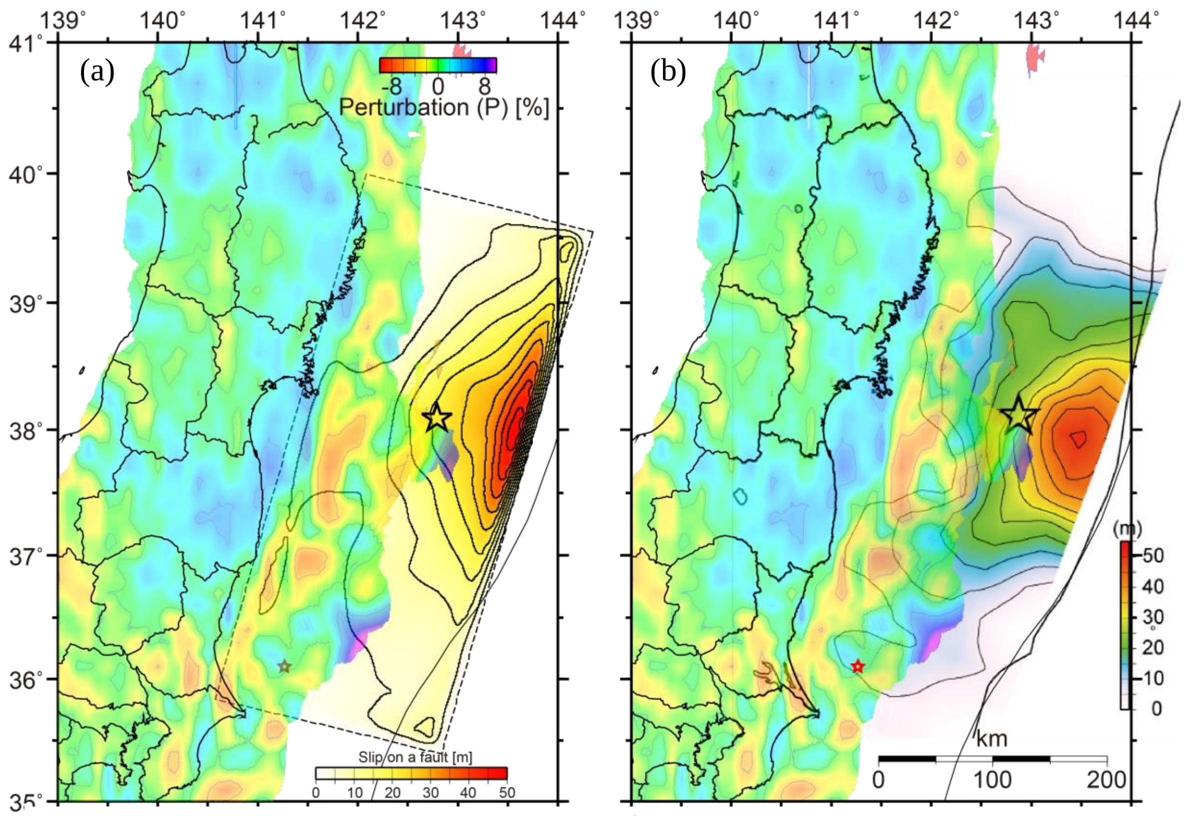

Figure 2 P-wave velocity perturbation within the Pacific plate 10 km below the boundary (Matsubara and Obara, 2011) and the coseismic slip region of the Tohoku-oki earthquake. Coseismic slip is estimated by (a) Suzuki et al. (2011) and (b) Yagi and Fukahata (2011).

Tohoku earthquake.

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Dynamic Wedge Failure Reveals Anomalous Characteristics of Shallow Subduction Earthquakes

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The deficiency of high-frequency seismic radiation from shallow subduction zone earthquakes was first recognized in tsunami earthquakes (Kanamori, 1972), which produce larger tsunamis than expected from short-period (20 s) surface wave excitation. Shallow subduction zone earthquakes were also observed to have unusually low moment-scaled radiated energy compared to regular subduction zone earthquakes (e.g., Newman and Okal, 1998; Venkataraman and Kanamori, 2004; Lay et al., 2012). What causes this anomalous radiation and how it relates to large tsunami generation has remained unclear. Here we show that these anomalous observations can be due to extensive poroplastic deformation in the overriding wedge, which provides a unifying interpretation.

Ma (2012) showed that the pore pressure increase in the wedge due to up-dip rupture propagation significantly weakens the wedge, leading to widespread Coulomb failure in the wedge. Widespread failure gives rise to slow rupture velocity and large seafloor uplift (landward from the trench) in the case of a shallow fault dip. Here we extend this work and demonstrate that the large seafloor uplift due to the poroplastic deformation significantly dilates the fault behind the rupture front, which reduces the normal stress on the fault and increases the stress drop, slip, and rupture duration. The spectral amplitudes of the moment-rate time function is significantly less at high frequencies than those from elastic simulations. Large tsunami generation and deficiency of high-frequency radiation are thus two consistent manifestations of the same mechanism (dynamic wedge failure). Although extensive poroplastic deformation in the wedge represents a significant portion of total seismic moment release, the plastic deformation acts as a large energy sink, absorbing nearly 50% of the total radiated energy from the fault, which leaves much less energy to be radiated and leads to low moment-scaled radiated energy as observed for shallow subduction zone earthquakes.

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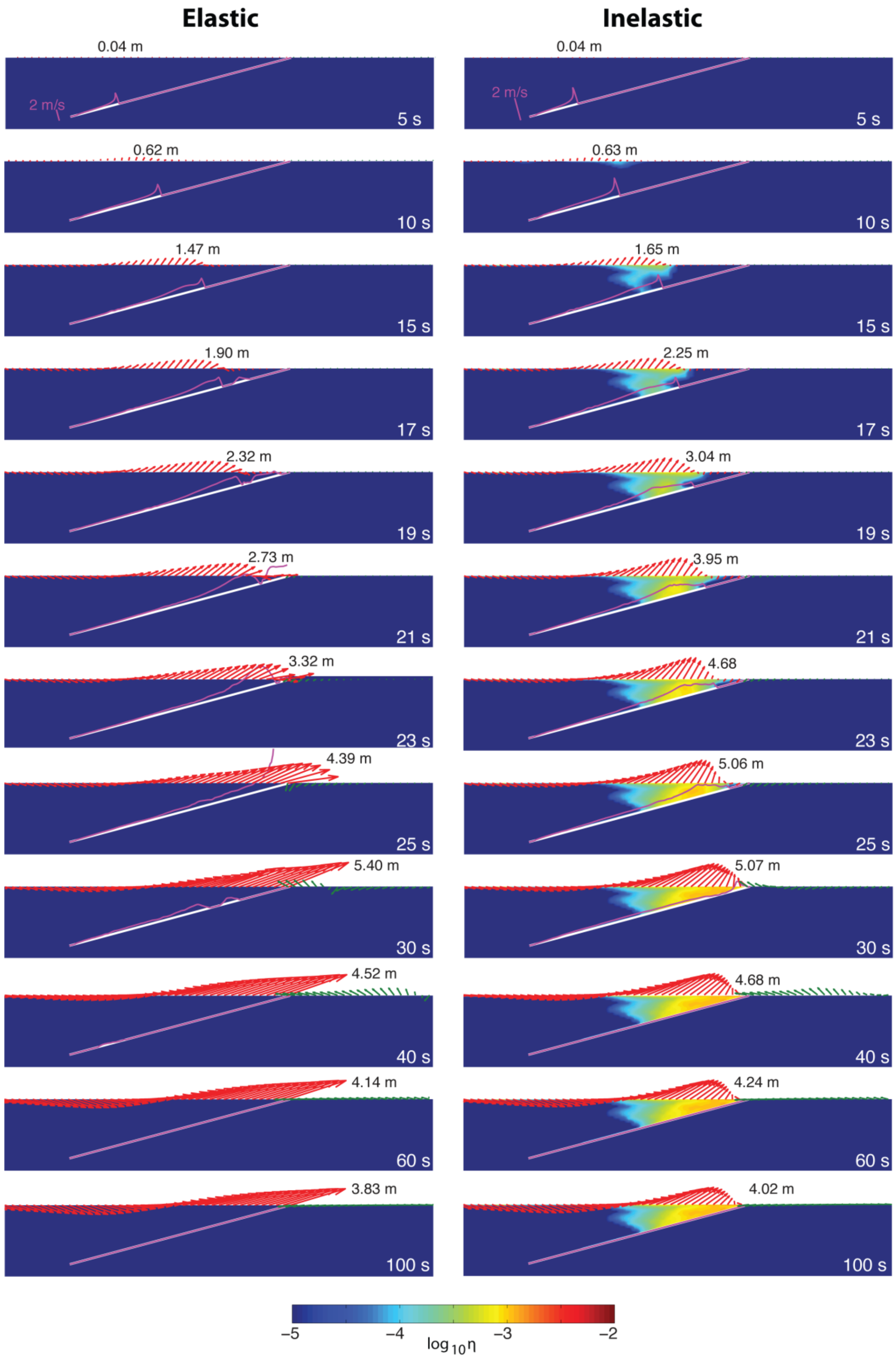
Elastic
Inelastic
0.04 m
2 m/s
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1.65 m
15 s
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17 s
2.32 m
3.04 m
19 s
2.73 m
3.95 m
21 s
3.32 m
4.68
23 s
4.39 m
5.06 m
25 s
5.40 m
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−5
−4
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Stress states before and after the 2011 Great Tohoku earthquake in and around the focal region

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The M_w9.0 Tohoku earthquake causes large changes in seismicity in and around the focal region, suggesting large crustal stress changes in these areas. This change can be qualitatively explained by large slip on a broad fault area of the main shock along the subducting plate interface. Several attempts in research papers quantitatively described how the seismicity changed and suggested the causes of changes, for instance, DCFF calculations etc. Among a lot of regions with large change in seismicity, a normal fault stress regime (NFSR) after the main shock are limited in two inland regions and in the large area of the main shock focal region, where the preshock stress states were considered to be a reverse fault stress regime (RFSR). One of the two inland areas is Iwaki region where an M_j 7.0 normal fault earthquake occurred a month after the main shock. While the deviatoric stress change caused by the main shock is calculated at a few tens MPa in the source region and a few MPa in the inland area at most. This suggests a

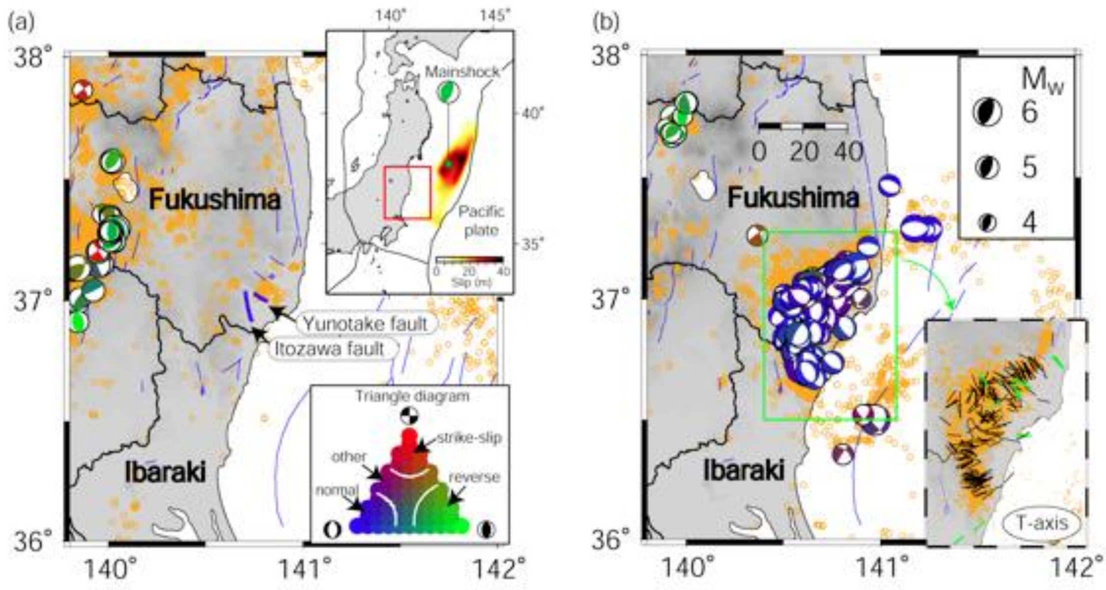

Fig.1 Focal mechanism solutions and epicenter distributions. (a) January 1, 2000 -March 10, 2011 before the 20011 Tohoku earthquake. (b) March 11-December 31, 2011 after the 2011 main earthquake. (From Imanishi et al.(2012))

few candidates of reasons why the normal fault earthquake occurred: one is that the fracture strength of normal faulting is especially small in these areas, or the other is that NFSR existed locally even before the main shock.

We, thus, examined closely the stress state before the main shock in those areas. The preshock stress in Iwaki region, where the focal mechanisms of earthquakes were rarely found in the JMA routine catalogue, was investigated by determining 26 focal mechanisms of microearthquake using absolute body wave amplitudes as well as P-wave polarities. The result shows that the preshock stress state in the Iwaki limited region is the NFSR in contrast to the overall RFSR in the wide area (Imanishi et al., 2012).

As for the main shock source region, Imanishi and Kuwahara (2012) examined the preshock stress field in the overriding plate by using the F-net moment tensor solutions. It is noted that we carefully deselected the earthquakes which occurred along the plated boundary, since they cause a bias in estimation of a stress tensor inversion. The result indicates that the stress fieldd in the northern part of the main shock source region is noticeably different from that in the southern part: the northern part is under the strike slip stress regime with the maximum compressional stress axis (MCSA) trending to the largest slip area in the main shock fault, while the southern part is under the NFSR with the MCSA trending perpendicular to the plate boundary.

Thus, the regions where the normal fault earthquakes occurring after the main shock were found to be under the NFSR even before the 2011 main shock at least in the Iwaki region and in the southern part of the main shock source region.

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Geodetic imaging of coseismic slip and postseismic afterslip: Sparsity promoting methods applied to the great Tohoku earthquake

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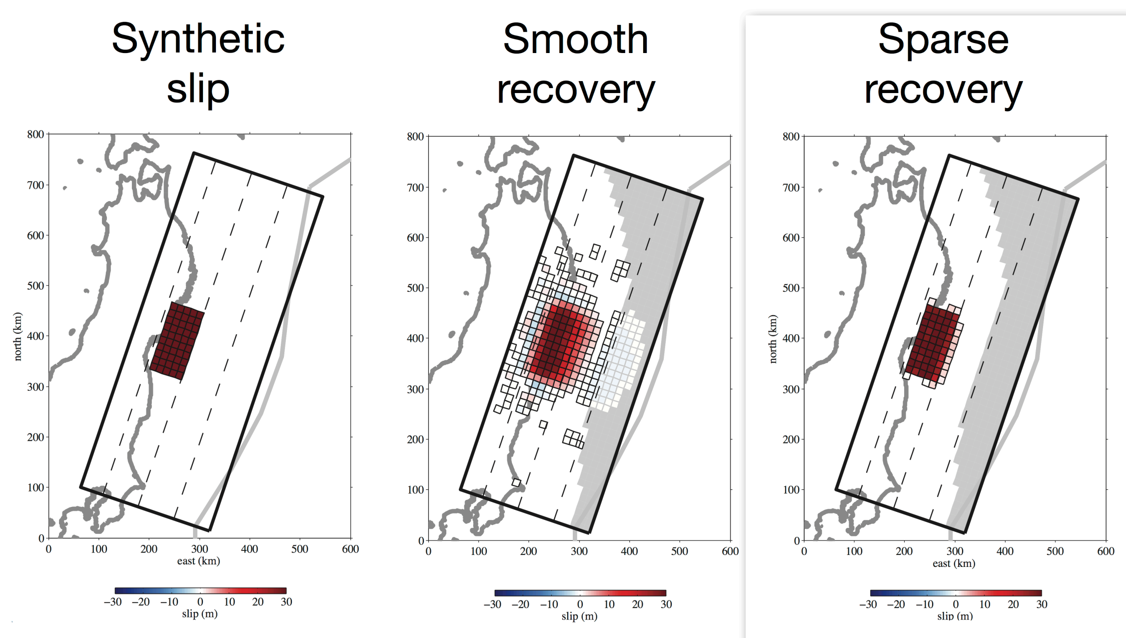
Geodetic observations of surface displacements during and following earthquakes such as the March 11, 2011 great Tohoku earthquake can be used to constrain the spatial extent of coseismic slip and postseismic afterslip, and characterize the spectrum of earthquake cycle behaviors. Slip models are often regularized by assuming that slip on the fault varies smoothly in space, which may result in the artificial smearing of fault slip beyond physical boundaries. Alternatively, it may be desirable to estimate a slip distribution that is spatially compact and varies sharply. Here we show that sparsity promoting state vector regularization methods can be used to recover slip distributions with sharp boundaries, representing an alternative end-member result to very smooth slip distributions. Using onshore GPS observations at 298 stations during and in the ~2 weeks following the Tohoku earthquake, we estimate a band of coseismic slip between 30 and 50 km depth extending 500 km along strike with a maximum slip of 64 m, corresponding to a minimum magnitude estimate of M_W=8.8. Our estimate of afterslip is located almost exclusively down-dip of the coseismic rup- ture, with a transition between 40 and 50 km depth and an equivalent moment magnitude M_W=8.2. This depth may be interpreted as coincident with the transition from velocity strengthening to velocity weakening frictional behavior, con- sistent with the upper limit of cold subduction estimates of the thermal structure of the Japan trench.



GSI activities in response to the 2011 off the Pacific coast of Tohoku Earthquake.

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Geospatial Information Authority of Japan (GSI) is the national mapping organization in the Japanese Government. With 700 staff members in geospatial field, the organization conducted various kinds of activities in response to the 2011 off the Pacific coast of Tohoku Earthquake. This paper summarizes its activities as well as achievements and challenges recognized.

Since the day of the occurrence of the earthquake, 11 March 2011, GSI has concentrated into disaster response activities. The major activity areas were: detection and analysis of crustal movements using GEONET (GNSS Earth Observation Network System operated by GSI) and In-SAR for understanding the earthquake; aerial photo survey and tsunami inundation mapping for recognition of the damage by the main shock and the following tsunami; revision of the result of control points and provision of base maps for reconstruction support and monitoring of postseismic deformation by GEONET.

Figure 1 shows the crustal movement caused by the earthquake.

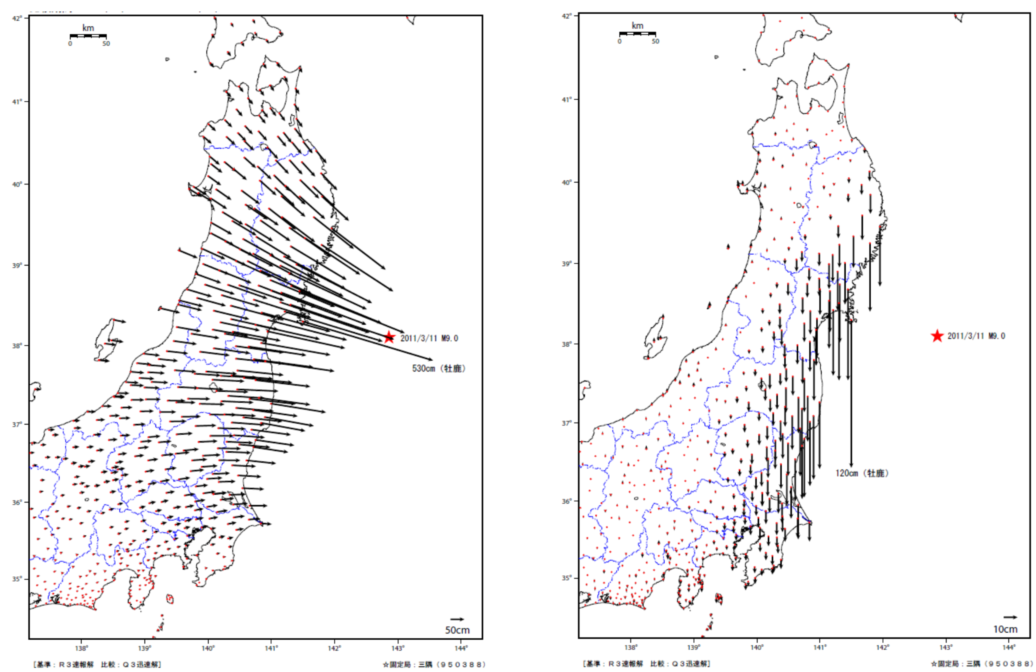

Figure 1. Horizontal and vertical displacements by the earthquake.

Because of large postseismic deformation, the ground surface in the Tohoku area is still moving 1-2 cm/month.

Figure 2 is an example of orthophoto map produced by GSI. It shows the severe damage by the huge tsumani.

Figure 2. An example of orthophoto map, Rikuzen takata City.

Major achievements of GSI's experience are; quick data gathering, development and provision; devising new arrangements for effective and efficient data delivery; and wider use of GSI's products in the society, particularly rescue and recover organizations.

Meanwhile the following challenges prompting further improvement are recognized: ensuring resiliency and redundancy of communication, energy and facilities; further rapid data development; data provision in appropriate methods satisfying diversified user needs.

As occurrence of natural disasters never ends, geospatial engineers always need to learn about their experiences mutually and collectively for better responses.

Session II

Abstracts

USGS Seismic Hazard Mapping Efforts: U.S. National Seismic Hazard Maps and Urban Seismic Hazard Maps Based on 3D Simulations

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The U.S. Geological Survey produces probabilistic seismic hazard maps for the United States for a firm-rock site condition, as well as urban seismic hazard maps for selected cities that include detailed maps of site conditions. My presentation will describe the U.S. national seismic hazard maps and the urban seismic hazard maps for Seattle, WA that incorporate 3D sedimentary basin effects, non-linear site response, and rupture directivity.

The U.S. national seismic hazard maps are based on geologic slip-rate and paleoseismic data on about 500 faults, historical and instrumental seismicity catalogs, crustal deformation measurements, and multiple ground-motion prediction equations (Frankel et al., 1996, 2002; Petersen et al., 2008). The hazard maps are constructed from the mean hazard curves derived from logic trees of alternative models of seismicity, magnitude-frequency distributions on faults, recurrence parameters, maximum magnitudes, ground-motion prediction equations, and other parameters. There is a wealth of associated products available from the website at eqhazmaps.usgs.gov, including hazard curves, uniform hazard spectra, deaggregation of hazard by magnitude, distance, and location, and earthquake probability maps.

The U.S. national maps are the basis for seismic provisions in building codes used in all 50 states (International Building and Residential Codes) and are also applied in bridge design, landfill regulations, earthquake insurance premiums, emergency management, and many other applications. There is an extensive workshop and review process during each 6-year update of the national maps, involving hundreds of scientists. The maps are currently being updated for release in 2014.

The hazard from M8-9 earthquakes on the Cascadia subduction zone (CSZ) has been included in the U.S. national maps since 1996. A 500 year average recurrence time for M9 earthquakes that rupture the entire CSZ was used, based on observations of coastal subsidence, tsunami deposits, and liquefaction over the past 5,000 years (e.g., Atwater and Hemphill-Haley, 1997; Kelsey et al. 2002; Nelson et al., 2006). The hazard from M8 earthquakes that could rupture anywhere along the length of the CSZ was also included. Recently published work by Goldfinger et al. (2012) described their analysis of turbidites from deep-sea cores to reconstruct the history of M8-9 earthquakes in the CSZ over the past 10,000 years. This work indicates that there have been numerous M8 earthquakes that have only ruptured the southern portion of the CSZ, in addition to the M9 earthquakes that likely ruptured the entire length of the CSZ. Onshore geologic observations also indicate that M8 earthquakes occurred along the southern portion of the CSZ (Nelson et al., 2006). There is also evidence from tsunami deposits that may indicate that M8 earthquakes can occur along the northern portion of the CSZ (Atwater and Griggs, 2012). We have developed a new logic tree for the recurrence parameters of Cascadia earthquakes incorporating these additional recurrence models, based on input from scientists during a workshop convened by the USGS (Frankel, 2011). Another key parameter to the hazard maps is the location of the down-dip edge of rupture for great CSZ earthquakes, since there is virtually no interface seismicity in most of the CSZ to constrain this location. In a second workshop that we convened, participants favored models for the rupture zone based on inversions of GPS and uplift data and the location of the up-dip edge of episodic tremor and slip events. We are also evaluating ground-motion prediction equations for great subduction-zone earthquakes to apply in the 2014 update, by comparing predicted values with observations from the Tohoku, Japan and Maule, Chile earthquakes.

We have also developed urban seismic hazard maps that include the effects of deep sedimentary basins and shallow soils. The Seattle urban seismic hazard maps are based on 541 three-dimensional simulations of earthquakes on the Seattle fault, Southern Whidbey Island fault (SWIF), the Cascadia subduction zone, and random shallow and deep sources (Frankel et al., 2007). The maps are for 1 Hz spectral acceleration and are based on the same earthquake recurrence probabilities used in the national maps. The 3D velocity model was validated by modeling waveforms and amplifications for several events including the M6.8 Nisqually earthquake. Observed waveforms in the Seattle Basin show substantial amplification caused by basin-edge focusing of S-waves and basin surface waves generated by conversion of S-waves at the edge of the basin. The amplification from these 3D basin effects would not be captured by modeling vertically-propagating S-waves. The Seattle maps also contain the non-linear amplification from the soft soils of fill and alluvium, using empirical factors based on the 30m averaged shear-wave velocity. Rupture directivity was also included in the simulations for earthquakes on the Seattle fault and SWIF. The maps show highest hazard for sites on soft soils within the Seattle basin. Next highest hazard is for stiff-soil sites within the basin and soft-soil sites outside the basin. The overall amplification for sites in the Seattle basin portrayed in the hazard maps is similar to the observed amplification from the Nisqually earthquake.

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National Policy and Project on the Earthquake Research after the 2011 Off the Pacific Coast of Tohoku Earthquake

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The gigantic earthquake off the Pacific coast of Tohoku (M9.0) required Japan’s national policy and program on earthquake research a serious amendment especially on the tsunami disaster mitigation and evaluation of large interplate earthquakes along subduction zone.

Japan’s researches on earthquakes in national level have been promoted based on a policy and a program. The former is “Basic comprehensive policy for the promotion of earthquake observation, measurement, surveys and research (hereafter, we call it basic comprehensive policy)”, which is issued by the Headquarters of Earthquake Research Promotion (HERP). The latter is “National observation and research program for the prediction of earthquakes and volcanic eruptions (hereafter, we call it prediction program)”, which is issued by the Council for Science and Technology. Both are revised or being revised through intensive discussions. As the amendment of the prediction program is still under progress, here I report how the basic comprehensive policy is revised.

The main cause of the devastating disaster in the earthquake was the tsunami that exceeded the hazard assessment in the coastal area of Tohoku region. More than 19,000 people died because the height and inundation of the tsunami extremely exceeded what they have anticipated before. The lessons from the earthquake should be applied immediately to another gigantic earthquakes, among which large interplate earthquakes along Nankai Trough that may produce extremely large tsunami. The Central Disaster Management Council (CDMC) recently released the disaster assessment, in which the death toll will be 320,000 in the worst case.

The problems opposing the existing basic comprehensive polity are 1) evaluation of largest-class interplate earthquakes, 2) rapid estimation of magnitude more than 8 in the earthquake early warning (EEW) system, and 3) evaluation and early warning of tsunami hazards.

The HERP has been evaluated the probability of earthquakes based on the historical and geological records of past earthquakes. The temporal limitation of the availability of the record is the main reason for the failure in the estimation of larger but less frequent event such as the 2011 Tohoku event. In the off the Pacific coast of Tohoku region the manner of earthquake occurrence is evaluated based on the well-studied records in the past 400 years. The recurrence interval of the 2011-type event, if exists, is estimated to be more than 500 years, and could not be properly evaluated only by the record of past earthquakes. The revised basic comprehensive policy states that the seafloor geodetic and seismic observations in addition to the geological survey on the past earthquakes are necessary to improve the reliability of long-term evaluation of earthquake occurrence.

The early information of earthquakes and tsunamis is also essential for rapid evacuation from large tsunamis. In addition to the difficulty to estimate the source region in real time, which has been pointed out, the present EEW system did not estimate the magnitude of the Off Pacific Coast of Tohoku Earthquake. The revised basic comprehensive policy states that seafloor observations in addition to the extensive use of land-based GPS network are necessary to improve the reliability of the EEW system. Real-time seafloor observation network, such as off-shore tsunami observation stations, should also be deployed for the real-time data utilization of tsunami, which will be used to improve the tsunami warning accuracy in combination with the development of rapid tsunami forecast method.

Tsunami hazard assessment has been made by CDMC and local governments based on the long-term evaluation of earthquakes by HERP. The reason why the tsunami hazard is underestimated in most of the Pacific coast of Tohoku is partly miscommunication among the organizations. The meaning of the long-term evaluation in the off the coast of the Tohoku region is not well informed. The revised basic comprehensive policy states that the HERP should provide appropriate methods of tsunami hazard assessment to the local governments for better tsunami disaster mitigation action.

E-DECIDER: Experiences Developing Earthquake Disaster Decision Support and Response Tools

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Within days following the devastating Tohoku-oki event, the E-DECIDER team worked with USGS International Charter representatives to provide remote sensing products to the Japanese government so they could assess damage from the tsunami and earthquake. The team provided geo-referenced maps of target areas identified by the Japanese International Charter representative, showing before and after high resolution optical images, including those of the Fukushima nuclear reactor. We provided our first change detection results within a few days and our image pair maps within a week, alongside other teams working with the US International Charter representatives.

Earthquake Data Enhanced Cyber-Infrastructure for Disaster Evaluation and Response (E-DECIDER) is a NASA-funded project developing new capabilities for decision-making, utilizing remote sensing data and modeling software, to provide decision support for earthquake disaster management and response. E-DECIDER incorporates the earthquake forecasting methodology and geophysical modeling tools developed through NASA's QuakeSim project.

Geodetic imaging data, including from inteferometric synthetic aperture radar (InSAR) and GPS, as well as other remotely sensed data, have proven to be useful in earthquake research. As more of these types of data have become increasingly available they have also shown great utility for providing key information for disaster response.

Work has been done to translate these data into useful and actionable information for decision makers in the event of an earthquake disaster. In addition to observed data, modeling tools provide essential preliminary estimates, while data are still being collected and/or processed, which can be refined as data products become available. Now, with more data and better models, we are able to provide these to responders who need easy tools and routinely produced data products. These data products can be used to help focus response efforts in the wake of an earthquake disaster, as well as aid in long-term planning and mitigation.

Our experiences with the Japan earthquake, and other recent global earthquakes like the Haiti event, have highlighted which remote sensing products were most readily available in the aftermath of a large disaster. In most cases high resolution optical data was most rapidly and readily accessible, rather than radar or other sources. These events also revealed the lack of collaborative infrastructure and also demonstrated the lack of worldwide hazard modeling services. Other issues revealed included limited search capability of available data (and often limited access to data), no automated data quality filter (which hindered rapid analysis), distribution of data across multiple providers with no standard interface, no automated delivery system, and user-restricted data – which requires time to negotiate the restrictions and takes precious time when responding to a disaster.

These lessons and experiences have helped us to evaluate the needs of end-users for decision support products and have driven the development of our capabilities for supporting disaster response in both California and other regions.

Some considerations for improvement of the National Seismic Hazard Maps for Japan

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The Tohoku-oki earthquake (Mw 9.0) of March 11, 2011, was the largest event in the history of Japan and was recorded by nearly 1200 K-NET/KiK-net stations with a peak ground accelerations of 2933 gals and more than 1g at 10 sites. This mega-thrust earthquake was not considered in the national seismic hazard maps for Japan that were published by the headquarters for earthquake research promotion of Japan. By comparing results of the seismic hazard assessment and observed strong ground motions, we understand that the results of assessment were underestimated in Fukushima prefecture and northern part of Ibaraki prefecture. Its cause primarily lies in that it failed to evaluate the M9.0 mega-thrust earthquake in the long-term evaluation for seismic activities. On the other hand, another cause is that we could not have established the functional framework which is prepared for treatment of uncertainty for probabilistic seismic hazard assessment. We consider problems and issues to be resolved for probabilistic seismic hazard assessment based on the lessons learned from this earthquake disaster and make new proposals to improve probabilistic seismic hazard assessment for Japan.

We have made a revision of the seismic hazard assessment based on the revised version of the "Long-term evaluation of seismic activity for the region from the off Sanriku to the off Boso" by the ERCJ. Revision of seismic activity model for other regions of Japan has been undergoing. After the revision of long-term evaluation for whole of Japan, we will recalculate seismic hazard. The followings are problems to be solved in the future.

(1) Modeling of seismic activity with no oversight to low-probability earthquakes

For both subduction zone earthquakes and earthquakes at active faults, it is necessary to aim to model seismic activity that can be considered to events about once several thousands or several tens thousands of years. To achieve this goal, we need to model background earthquakes that include a low probability of earthquakes by using the Gutenberg-Richter formula or other statistical techniques to compensate the long-term evaluation.

(2) Preparation of strong ground motion maps considering low-probability earthquakes

In addition to emphasize the urgency of the earthquake occurrence by showing the probability, by going back to the original purpose of the evaluation of probabilistic seismic hazard, we should prepare the maps that show the strong-motion level for earthquake preparedness. For example, based on the averaged long-term seismic hazard assessment, evaluating strong-motion level for about 10,000-100,000 years return period, we should prepare the maps that show the distribution of strong-motion level. Regarding the seismic hazard assessment for low probability, at present, it is insufficient to evaluate the uncertainty of ground motion prediction for low probability M8 class earthquakes and it is necessary to improve techniques for them.

(3) Development of methodology for selecting appropriate scenario earthquakes from probabilistic seismic activity model

In the seismic activity model considering low-probability earthquakes, not only earthquakes with specified faults, but also earthquakes without specified faults are included. From the seismic activity model, it is necessary to establish a methodology that can be selected as appropriate scenario earthquakes for purposes of earthquake preparedness.

(4) Development of methodology for prediction of strong ground motions for mega earthquakes

In order to perform seismic hazard assessment considered the low-probability events, it is necessary to predict strong ground motions for large earthquakes that have not been recorded by the modern seismic observation network. For the "Method for prediction of strong ground motion for earthquakes with specified faults (recipe)", which is currently being used for strong motion prediction, the subduction zone earthquakes up to about M8 and earthquakes on active fault up to about 80km in length are only verified its scope. The sophistication of techniques that can be applied to the prediction of strong ground motions for super large earthquakes are required.

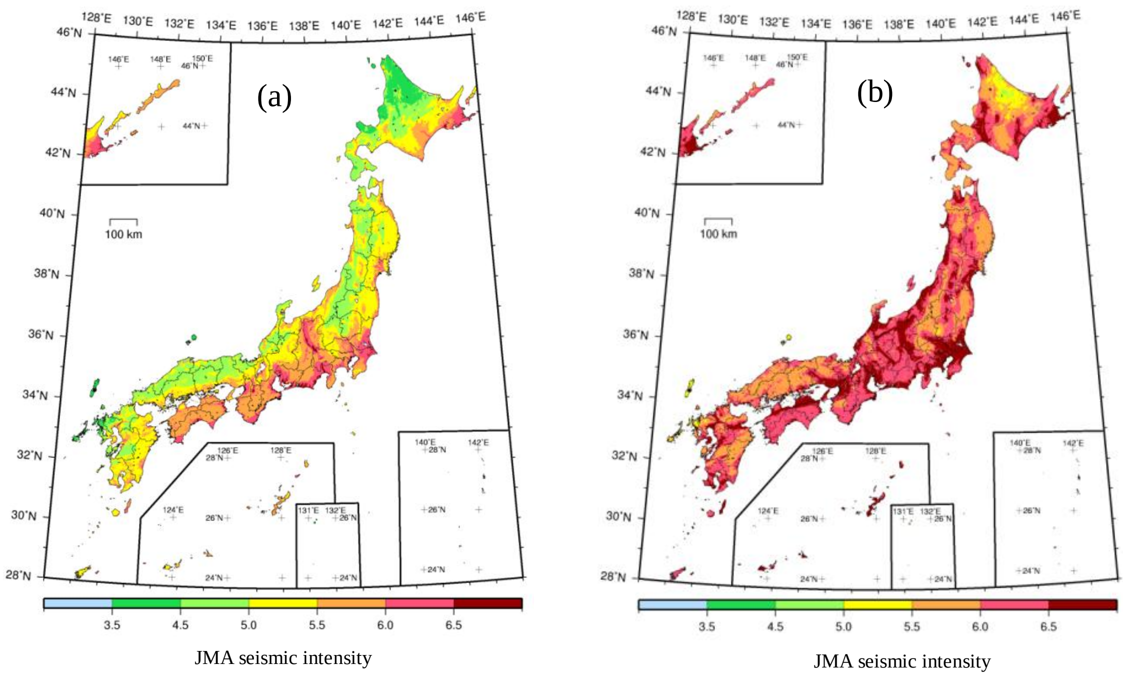

Figure 1. Maps for distribution of seismic intensity corresponding to (a) return period of 1,000 year and (b) that of 100,000 year.

Time-independent earthquake forecasts for the Intermountain West, United States

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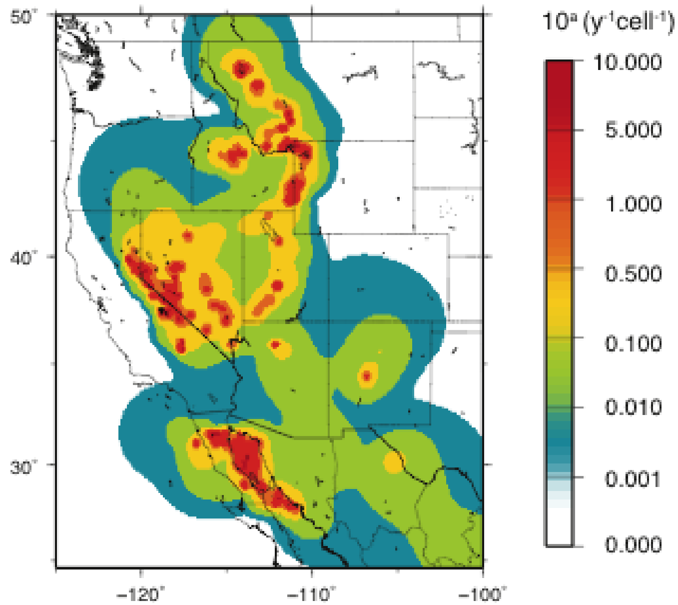

We generate a high resolution, time-independent earthquake forecast for the Intermountain West (IMW), United States by spatially smoothing the seismicity rates of M4+ earthquake epicenters. We calculate information gain parameters to determine the smoothing method that best predicts the spatial distribution of seismicity rates from an independent sub-catalog. Models are generated from a declustered earthquake catalog with magnitude completeness levels at M4, M5 and M6. The forecast assumes that the Gutenberg-Richter relation describes the magnitude-frequency distribution and that the locations of smaller earthquakes (M4+) can identify the locations of future large, and damaging, earthquakes. Spatially smoothed seismicity rate models are generated with isotropic and anisotropic smoothing kernels, using Gaussian and power-law functions with fixed and adaptive bandwidths. We implement the adaptive smoothing method of Helmstetter et al. (2007), which varies smoothing bandwidth based on the local seismicity density, for isotropic smoothing and modify the method for anisotropic smoothing kernels. To identify an optimal smoothing method for long-term earthquake forecasting, we divide the IMW earthquake catalog, by date, into two independent sub-catalogs. Smoothing methods are applied to the earlier catalog to generate forecast models, which are then compared with the later catalog. We calculate likelihood values for all smoothed seismicity models, by assuming a Poisson distribution for earthquake occurrence, and select the smoothed seismicity model that maximizes an information gain parameter. For the isotropic models, adaptive smoothing methods with Gaussian kernels provide the highest information gain values and are used to generate the final time-independent earthquake forecast for the IMW. We also investigate the use of different magnitude thresholds for the smoothed seismicity models and find that the incorporation of smaller earthquakes (M4+) improves the forecast of M5+ earthquakes compared to the use of only larger magnitude (M5+) earthquakes.

Session III

Abstracts

Assessing Tsunami Hazard from Paleotsunami Deposits

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The 11 March 2011 Tohoku-Oki tsunami dramatically demonstrated the vulnerability of the world's coastlines to the impact of tsunamis. Although northeast Japan had experienced large tsunamis in the past, there was no historical precedent for the March 11 tsunami. Many areas of the world capable of receiving such catastrophic tsunamis have not experienced them during the short period of written history. Sedimentary deposits left by tsunamis are being used to extend the record of tsunamis back through time. The state of the science for tsunami deposits has now evolved to a point where false positives (e.g. misinterpreting a storm deposit as a tsunami deposit) are less frequent. Tsunami hazard assessment is beginning to incorporate the spatial distribution of tsunami deposits and the record of tsunami recurrence.

A recent development in the use of tsunami deposits for tsunami risk assessment is to obtain tsunami magnitude estimates by applying sediment transport models to replicate the observed deposits. Models have focused on estimating two parameters, tsunami height and flow speed. These models are developed and tested using data sets collected from recent tsunamis (Papua New Guinea 1998, Peru 2001, Indian Ocean 2004, Samoa 2009, Chile 2010, and most recently, Tohoku-Oki 2011). One fundamental question is whether tsunamis leave a deposit to the limit of inundation. Field data collected from 1998 to 2010 showed that the extent of tsunami deposits were less than the maximum inundation, but typically were within 10% on gently sloping coastal plains. However, recent field investigations on the coastal plain of Sendai, Japan after the 2011 tsunami bring into question whether the extent of deposits for extremely large tsunamis are a good proxy for maximum inundation distance. There, because of sediment source limitations, an easily recognizable deposit (sand thickness >0.5 cm) only extended about 2/3 of the way to the limit of inundation. This new data highlights the need to incorporate other proxies such as geochemical signatures and approaches such as sediment transport modeling in tsunami hazard assessment.

Strategy for evaluating giant earthquake and tsunami by coastal paleoseismology

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The Great Off-Tohoku Earthquake (M 9.0) of 2011 turned out to be an unprecedented disaster due to the giant tsunami that invaded the Pacific coast, and it is often said that its magnitude was "unexpected." However, geological data such as tsunami deposit obtained from the coast facing the Japan Trench suggested that the giant tsunami as large as the 2011 event had repeatedly occurred for several thousand years, including the Jogan Earthquake (greater than M 8.4) of 869. Subduction Zone Earthquake Research Team in GSJ has conducted paleoseismological survey to evaluate the recurrence time, tsunami inundation area and source of the Jogan Earthquake and its predecessors since 2004. Eventually, the inundation area of the tsunami in 2011 was very similar to the estimated tsunami inundation area of the Sendai Plain at the time of the Jogan Earthquake (Fig. 1). What this implies is that if the magnitudes of past earthquakes and tsunamis are elucidated and if histories of occurrence are reconstructed, we will be able to make a rough assumption of the magnitude and imminence of future probable earthquakes and tsunamis.

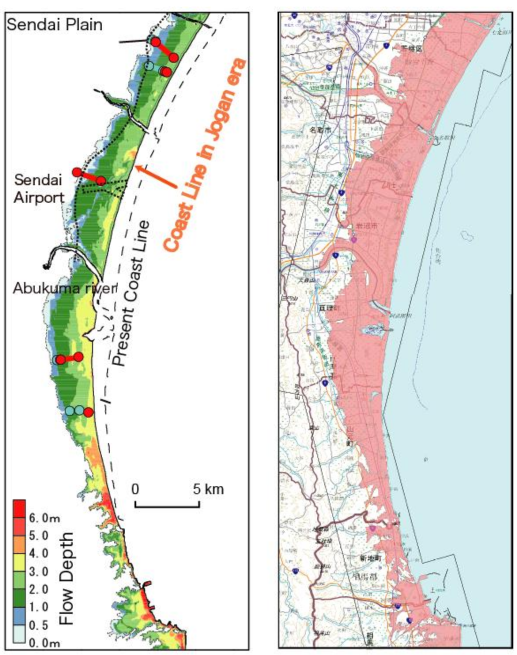

Figure 1. Comparison of spatial distributions of the present tsunami inundation (Right figure) with old tsunami deposits brought by the AD 869 Jogan earthquake (Left figure). The right figure is from a WEB site of Geospatial Information Authority of Japan. Color contours in the left figure shows maximum flow depth computed for the AD 869 Jogan earthquake source model.

After the 2011 earthquake, GSJ urgently surveyed to observe the distribution and sedimentological characters of tsunami deposit which was derived from the 2011 tsunami. This is for improving a reconstruction technique of past tsunami inundation. From the results of this survey, it is recognized that actual tsunami inundation is able to reach 1-2 km further inland than the landward limit of the distribution of tsunami deposit. For more reliable estimation of future tsunami inundation area, it is highly important that we not only focus on the distribution of past tsunami sand layer, but also evaluate the scale of tsunami inundation by methods such as chemical component analysis in combinating with tsunami simulations. This instruction should be immediately apply to other coastal areas facing subduction zone which have potential of giant tsunami in near future such as the Nankai Trough. GSJ therefore is conducting field survey along the Pacific coast of Japan.

On the other hand, regardless of paleoseismology, recently the government announced the estimation of disaster for future giant earthquake and tsunami in the worst case simulated from the largest source. However the evidence of such largest event has not yet been found in any records not only historically but also geologically. Therefore a role of paleoseismological study was oppositely changed. Before the 2011 event, paleoseismologists suggested the possibility of future giant earthquake from field survey data by inductive approach. But after the 2011 event, paleoseismologists must evaluate by deductive approach whether such the largest event suggested by the government exist or not from the evidence of field survey data.

One of the solutions to evaluate the largest event was identified in the Shionomisaki Cape, where we found tsunami boulders which were moved at only the timing of giant earthquake generated from the Nankai Trough such as the 1707 Hoei earthquake (M 8.6) (Fig. 2). The boulders are distributed over the range of ca. 200 m from shoreline, but nothing was found on the Holocene terrace of 2-4 m in altitude just behind them. Because the terrace was probably emerged during 6000 years ago, the largest tsunami in the past 6000 years must be not able to transport the boulders over the terrace. Then it can evaluate the actual magnitude of largest tsunami locally.

Figure 2. Tsunami boulders in the Shionomisaki Cape

JMA's response to the 2011 off the Pacific coast of Tohoku Earthquake and planned Improvements of Tsunami Warning

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At 14:46 JST, March 11 2011, the 2011 off the Pacific coast of Tohoku Earthquake started its fault rupture from off coast of Miyagi Prefecture. The Japan Meteorological Agency (JMA) estimated its magnitude as 7.9 (Mj: JMA magnitude) in 3 minutes and disseminated the first tsunami warning at 14:49, in which estimated tsunami heights were stated as 6m for Miyagi Pref. and 3m for Iwate and Fukushima Pref. With near-shore GPS buoys as well as tide gauges along the coast, the JMA successively updated tsunami warning until 03:20 JST, March 12, when the whole Japanese coastlines were covered by warnings/advisories.

The main issue of the JMA's tsunami warning for this event was the underestimated first warning based on the underestimated Mj7.9, and it might have resulted in the delay of evacuation. To deal with this problem, the JMA has been introducing tools with which validity of Mj estimation can be evaluated before the first tsunami warning. If the possibility of much larger magnitude than Mj is detected, the JMA will issue tsunami warning by replacing the Mj with the expected maximum magnitude in the region. In this case, as there is large uncertainty of tsunami height estimation, the JMA will not inform the estimated height numerically but qualitatively by an expression conveying emergency situation to the people. Also some changes in warning statements: tsunami height classification will be decreased from eight (0.5m, 1m, 2m, 3m, 4m, 6m, 8m, >=10m) to five (1m, 3m, 5m, 10m, >10m) taking into account the realistic variety of countermeasures in time of emergency and forecast error range, for instance.

In addition, some causes of the delay of tsunami warning update were pointed out. The JMA could not calculate Mw of the main shock within 15 minutes as with the JMA's normal operation because very large seismic waves went off the scale of most of the JMA's broadband seismographs (STS-2) in Japan. And data from offshore ocean-bottom pressure gauges could not be applied for tsunami warning update. In order to deal with these issues, the JMA will deploy 80 new "broad-band strong motion" seismographs which ensure Mw within 15 minutes even in case of near-field huge earthquakes, and will promote the utilization of ocean-bottom pressure gauges including 3 DART buoys which will be installed by the JMA.

The above described tsunami warning improvement measures will be put into operation by March 2013, subject to the system modification of both the JMA and organs responsible for transmitting and using tsunami warning.

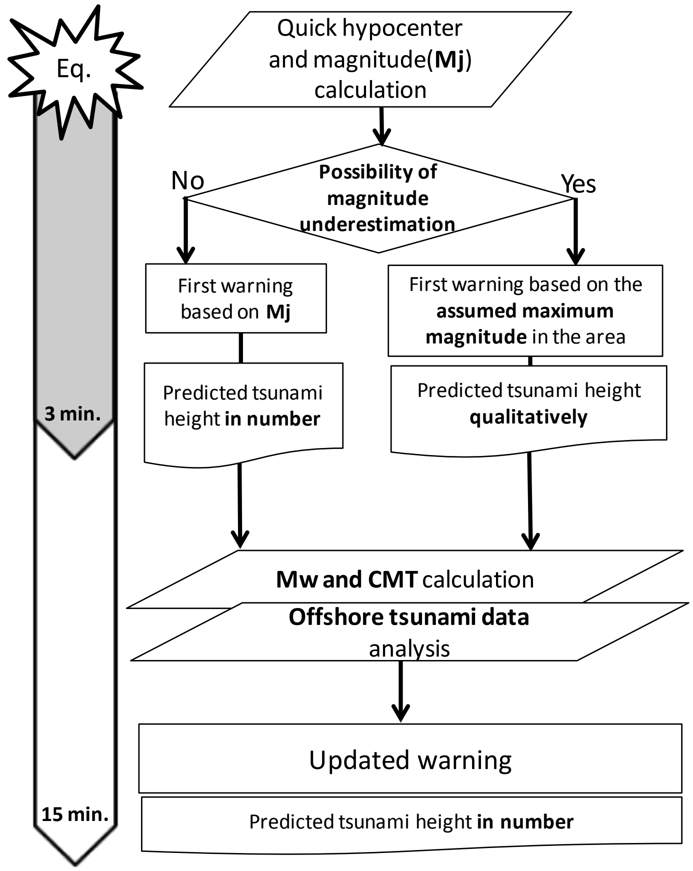

Figure 1. Flowchart of planned improved tsunami warning procedure

Category		Present	Improvement Plan		
		Expression of Tsunami height	Expression of Tsunami height		Predicted height
			Numerical	Qualitative	
Tsunami Warning	Major Tsunami	**10m or more, 8m, 6m, 4m, 3m**	**Over 10m**	Huge	**10m -**
			10m		**5m to 10m**
			5m		**3m to 5m**
	Tsunami	**2m, 1m**	**3m**	High	**1m to 3m**
Tsunami Advisory		**0.5m**	**1m**	(Blank)	**0.2m to 1m**

Table 1. Categories and classes of tsunami warning and tsunami height prediction

Session IV

Abstracts

Nonlinear site and topography effects in ground motion predictions: Observations, Hypotheses and Lessons to be learned

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We present results from our recent work on site and topographic amplification of strong seismic motion. Goal of our research is the efficient integration of realistic soil models in broadband ground motion simulations, that will allow nonlinear effects to be accounted for in seismological predictions while avoiding the pitfalls associated with the need for scarce and sparse geotechnical input data, and the tremendous computational effort associated with the spatial and temporal resolution of nonlinear site response simulations, had the geotechnical data been available at every grid point.

First, we present the development of an empirical relationship between nonlinear site response, soil properties, and ground motion. Using 24 downhole array sites in Southern California and a series of broadband ground motion synthetics corresponding to various magnitudes and distances from a strike-slip fault rupture, we quantify soil nonlinearity in site-specific response analyses, and show that the factors controlling how strongly nonlinear is site response –or how large is the error introduced in ground motion predictions by not accounting for nonlinear site response– are soil stiffness, soil-rock impedance contrast, and ground motion intensity and frequency content. Based on real geotechnical input data and synthetic ground motions, our study indicates that to characterize the susceptibility of a soil profile to nonlinear effects at a given ground motion intensity, ground motion prediction equations should be complemented by measures of the soil-rock impedance contrast to indicate the potential of the site to trap seismic energy in the near surface, as well as measures of the ground motion frequency content, to quantify the likelihood of incident seismic wave amplification. We next present results of our work on nonlinear response for sites with irregular surface topography. Our hypothesis is that coupling between topography effects and soil amplification, namely the presence of irregular surface topography on the surface of stratified media, cannot be predicted by the superposition of topography and stratigraphy effects alone. We test this hypothesis using numerical simulations and centrifuge experimental data. Our preliminary analyses show that topography-stratigraphy effects comprise seismic waves trapped in the near surface soil layers, amplified or de-amplified as a consequence of soil-bedrock impedance and nonlinear response, and further amplified due to scattering, refraction, mode conversion and interference caused by the non-horizontal ground surface. Our numerical and small scale experimental data are currently being compiled to determine the conditions when coupling of site and topography effects yields amplification in excess of the superposition of the two phenomena, and accordingly develop simplified space- and frequency-dependent amplification factors that could be used in ground motion predictions to account for topography effects for strong ground motion.

While the number of downhole array stations has significantly increased in the US in general, and Southern California in particular, the amount of ground motion data recordings that elicit nonlinear response are –with a few West Coast exceptions– not statistically significant to allow a parametric study on the role and efficient integration of nonlinear effects in seismological models. Similarly, recorded evidence of topography effects in the US and Europe is almost exclusively from small or distant events, producing by and large weak motion data that may or may not be applicable to describe topographic effects for strong motion shaking. In fact, there are no fully documented case histories of topographic effects under strong ground motion, while there exist very few comprehensive parametric studies of the effects of soil nonlinearity on topographic amplification. The unprecedented quality and amount of seismic data recorded by surface and downhole seismogram arrays in Japan such as KIK-Net and K-Net provide research opportunities to advance our understanding of nonlinear site response, and to statistically test, evaluate and improve our predictive models, but more importantly, to open communication avenues across disciplines and across continents. To that end, rather than lessons learned, this presentation focuses on opportunities for lessons to be learned on nonlinear site response via international and interdisciplinary collaboration.

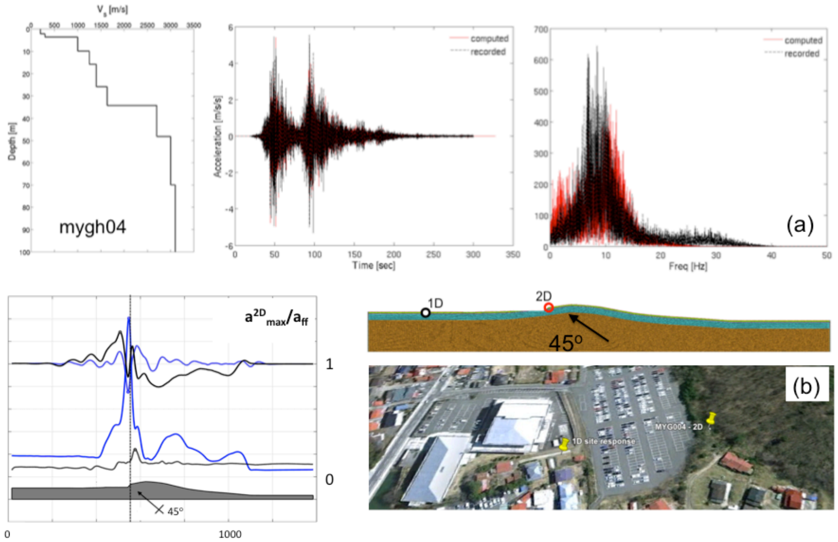

Figure: (a) Comparison of nonlinear site response model predictions by Assimaki and co-workers to strong motion recorded during the 2011 M9.0 Tohoku-Oki event at KIK-Net station mygh004; (b) Google earth satellite view, finite element numerical model and parametric study on the ground surface amplification of horizontal and vertical acceleration relative to the far field for vertical and inclined incidence of seismic waves at K-Net station myg004, which recorded a PGA=2.74g during the 2011 M9.0 Tohoku-Oki event.

Strong motion characteristics of the 2011 Tohoku-Oki earthquake observed by K-NET and KiK-net

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Hiromitsu Nakamura, and Hiroyuki Fujiwara
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During the Tohoku-Oki earthquake (Mw 9.0), which was the largest earthquake occurring in and around Japan since the recorded history, the ground motions were recorded at 1224 K-NET and KiK-net stations. The peak ground accelerations (PGA) exceeded 1g at 20 sites and the largest PGA, 2933 gals, was observed at the K-NET Tsukidate station (MYG004). We estimated the precise spatial distribution of seismic intensity from the observed data considering the near-surface amplification, and found that roughly twenty million people were exposed to a shaking of JMA seismic intensity 5+ or larger (>MMI 7). Huge numbers of large aftershocks and triggered earthquakes have occurred, some of which were located much nearer to the populated urban areas than the main shock and fatalities as well as severe building damages were caused by large ground shakings.

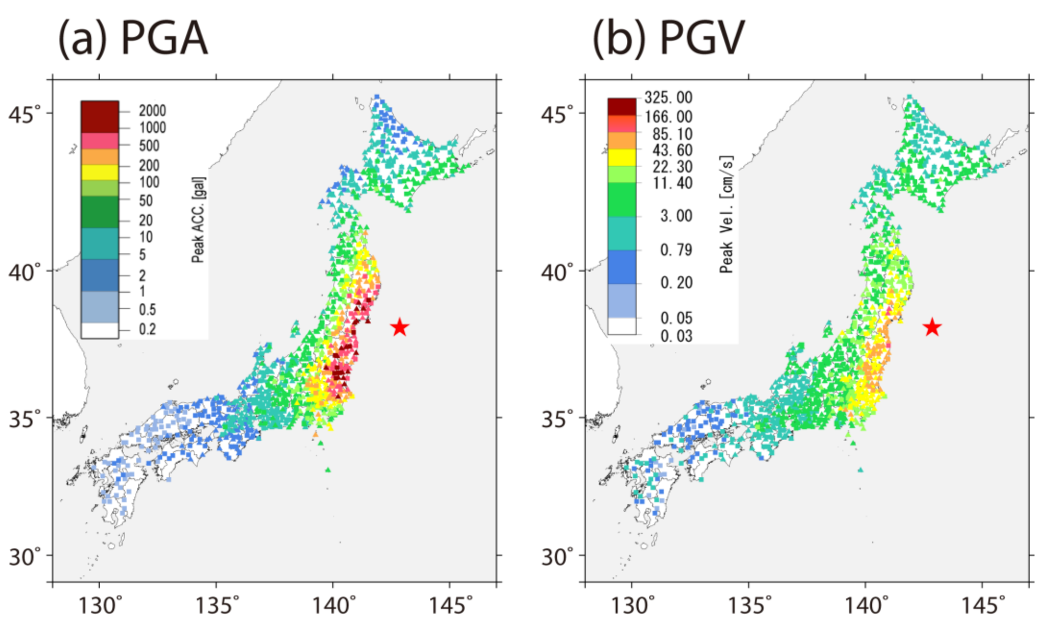

Figure 1. Peak ground accelerations (left) and velocities (right) observed by K-NET (triangular) and KiK-net (square) during the 2011 Tohoku-Oki earthquake.

Strong motions of this earthquake are characterized by large JMA seismic intensities and PGAs, long durations, and wideness of the area that experienced intense shaking. Although the tsunamis were the primary cause of damage, the strong shaking, liquefaction and landslides also brought serious destruction. However, it was reported that the damage ratios of houses and buildings directly due to shaking were not as high as those for the former earthquakes having comparable seismic intensities and PGAs. The recorded ground motions at most stations where the seismic intensities and PGAs were large had dominant periods shorter than 0.5 s and relatively weak power in the 1 - 2 s period range which has strong influence on the damage of few-stories wooden houses. The main reason for the short-period predominance is the amplification due to the low-velocity superficial layer and can be roughly explained by empirical amplification factors for 0.1 - 0.5 s periods rather than 1 - 2 s.

Reconciling precariously balanced rocks with large earthquakes on the San Andreas fault system

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Precariously balanced rocks (PBRs) are fragile landforms (Figure 1) susceptible to toppling by earthquakes such that the distribution of PBRs provides insight into the magnitude and distribution of earthquake ground motions over thousands of years. We report anomalous PBRs near the junction of the San Andreas and San Jacinto plate boundary faults in California, and compare PBR fragility to expected ground motions from seismic hazard maps and rupture scenarios. Results suggest that groups of PBRs survive in shadow zones of persistent low ground motions adjacent to areas of fault complexity where ground motions are attenuated. The intersection of the San Andreas and San Jacinto faults appears to be a trans-tensional step-over where strain is transferring between the faults. Paleoseismic data permit correlation of rupture on both faults, suggesting that simultaneous rupture can occur, with important implications for hazard analysis and modeling of fault systems.

Figure 1
Stack of precariously balanced rocks ~12 km from the San Andreas fault at its junction with the San Jacinto fault.

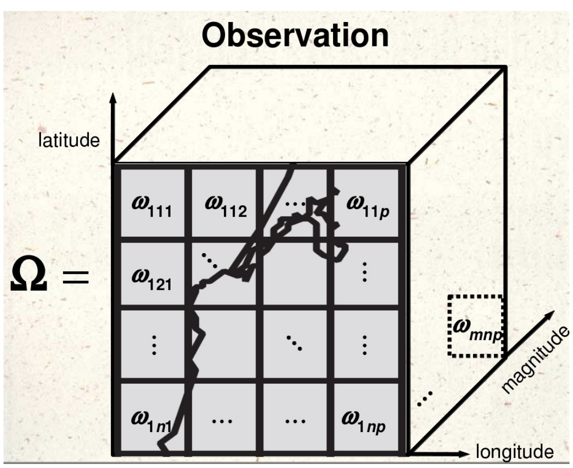
Session V

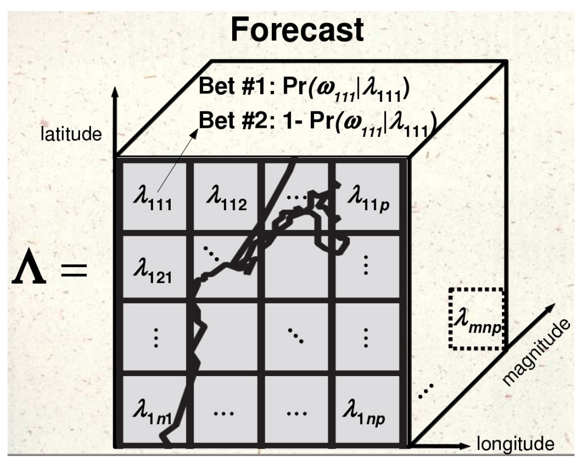
Abstracts

Betting against the house and peer-to-peer gambling: a Monte Carlo view of earthquake forecasting

J. Douglas Zechar & Jiancang Zhuang

Using an analogy between prediction and gambling, we consider earthquake forecasts as wagers of professional reputation. We have previously discussed a "gambling score" based on comparing earthquake predictions with a reference model, and this is akin to betting against the house: the reference model is the oddsmaker and a gambler can win a large amount in a single bet. One might criticize this as an unstable score because it is sensitive to the occurrence of low-probability events, and constructing an appropriate reference model is itself a difficult problem. There is another gambling paradigm in which bettors compete directly against each other and share the winnings among themselves--this is sometimes called peer-to-peer betting. This too has an analogue in earthquake forecasting and model development, where it is increasingly common to compare and rank multiple forecasts which have a common format. In this presentation, we consider the case of gridded rate forecasts, in which one wants to forecast the distribution of seismicity (in space, time, magnitude, etc.) rather than individual events. We treat each grid node as a separate wager in which each forecast can abstain or bet one credit of reputation distributed over the number of expected earthquakes. After the observation period, each forecast that bet on this node is rewarded with an amount that is proportional to its correct wager. We applied this method to compare forecasts from the RELM (Regional Earthquake Likelihood Models) five-year experiment in California. In this presentation, we demonstrate how a peer-to-peer gambling score can be calculated in a roundtable setting to simulataneously compare multiple earthquake forecasts, and we also present a head-to-head mode which we compare to using a likelihood ratio metric. We also discuss how the gambling score can be used when developing new seismicity models.





Information services on earthquake prediction and forecast of JMA

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The Japan Meteorological Agency (JMA), as the sole national authority responsible for issuing weather/earthquake/tsunami warnings in Japan, is required to provide reliable and timely information to governmental agencies and residents for the purpose of prevention and mitigation of natural disasters. On earthquake prediction and forecast, the JMA issues three different types of information: information on the Tokai Earthquake, information on seismic activity in the eastern Izu district and information on prospect of aftershock activity for major earthquakes.

Prediction and Information Services for the Tokai Earthquake

The Tokai Earthquake is a megathrust earthquake expected to occur in the near future along the Suruga Trough (Figure 1). Historically, the plate boundary along the Suruga trough has been ruptured every 100-150 years as a part of focal regions of similar megathrust earthquakes along the Suruga and Nankai Trough. However, in the last Tonankai Earthquake (1944, M7.9) and Nankai Earthquake (1946, M8.0), the plate boundary along the Suruga trough was not ruptured. This seismic gap area of the plate boundary, assumed as the focal area of the Tokai Earthquake, has not slipped for more than 150 years.

Since the expected damage caused by the Tokai Earthquake is enormous, and there lies a possibility of short-term prediction, the Japanese government enacted the Act on Special Measures for Large-scale Earthquakes for disaster prevention. In the framework of this law, the JMA has undertaken the duty for predicting the Tokai Earthquake.

The prediction of the Tokai earthquake is to be performed based on the detection and identification of pre-slip, derived from friction constitutive law.Such pre-slip is expected to occur on the upper boundary of the Philippine Sea Plate before the Tokai Earthquake. In order to detect the pre-slip, the JMA monitors crustal deformation with various kinds of observation instruments, such as strainmeters, tiltmeters and GNSS equipments installed in and around the assumed focal region of the Tokai Earthquake in collaboration with related institutes, on around-the-clock basis. Seismometers are also more densely installed in this region than in the other regions in Japan.

If some anomaly is detected, the JMA issues Information on the Tokai Earthquake to enable preparatory actions and emergency measures for earthquake disaster prevention. According to the probability of the anomaly as a precursor, the information is categorized into three types: Investigation Report on Tokai Earthquake Prediction, Tokai Earthquake Watch, and Explanatory Information on Tokai Earthquake Warning.

Information on Seismic Activity in the Eastern Izu District

The eastern Izu district, one of active volcanic regions in Japan, has suffered Earthquake swarms many times. Investigation of past 49 earthquake swarms since 1978 has clarified that earthquake swarms in this district are controlled by magma behavior, and can be quantitatively forecast in terms of crustal deformation around the swarm area. Using this relation, the number of earthquakes in the whole period of the seismic activity can be estimated from the amount of strain change observed at the neighboring site in the early stage of the activity, which reflects the amount of magma injection. From the estimated number of earthquakes, we estimate the number of earthquakes by magnitude assuming the Gutenberg-Righter law. With this method, the JMA is to announce the expectation for maximum magnitude, maximum seismic intensity, duration of the activity and number of earthquakes to be felt as the information on seismic activity in the eastern Izu district since 2011.

Prospect of Aftershock Activity

The JMA has issued the information on prospect of aftershock activities for remarkable earthquakes since 1999 based on two well-known empirical relations. One is the modified Omori formula which expresses the way aftershocks decrease. The other is Gutenberg-Righter law, which can also explain aftershock activities well. Combining these relations enables probabilistic evaluation for aftershock activity with seismic data available at an arbitrary time. The information on prospect of an aftershock activity includes description of the expectation for the number of earthquakes larger than a certain magnitude expected to occur for the next several days and its probability value, duration of the activity, and maximum intensity in addition to description of the observed earthquake activity.

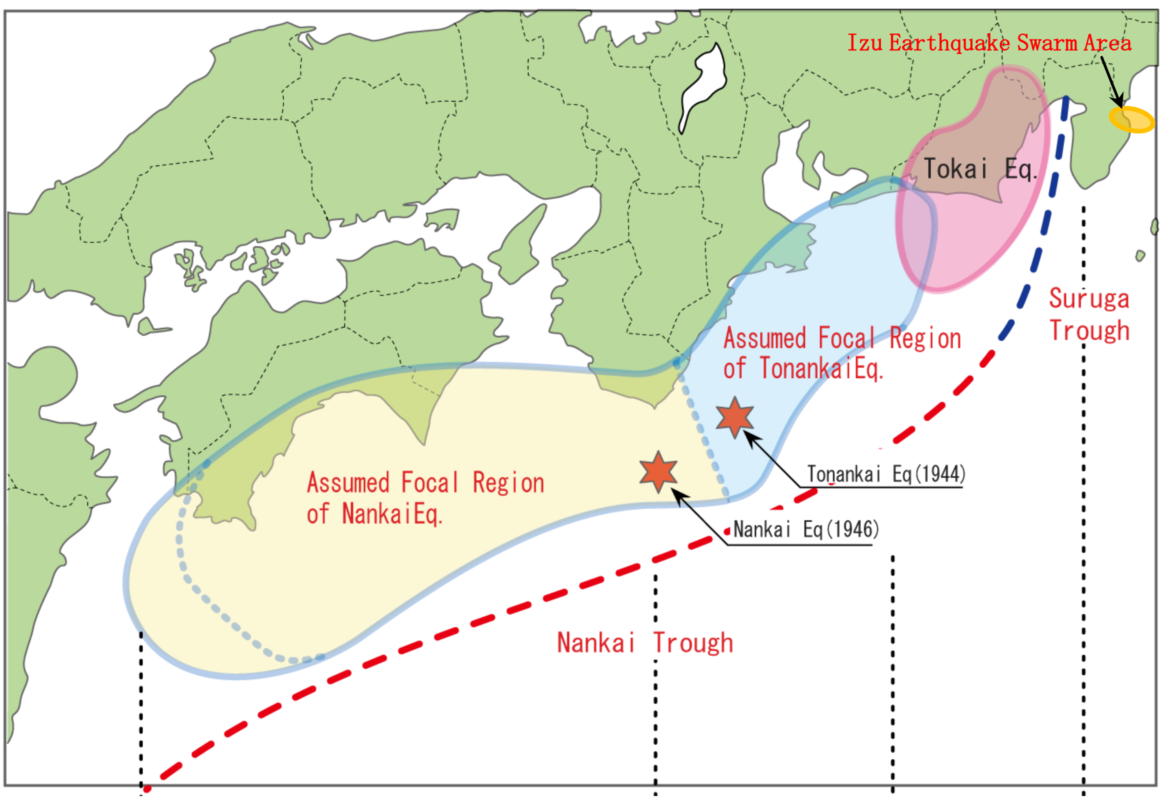

Figure 1. Assumed focal regions of the Tokai, Tonankai and Nankai Earthquakes and Izu earthquake swarm area.

Earthquake Early Warning of JMA

- The 2011 off the Pacific coast of Tohoku Earthquake and its aftershocks –

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Earthquake Early Warning (EEW) is to announce the expected seismic intensity and arrival time of strong motion before its arrival by detecting and quickly analyzing seismic waveform data at stations near the epicenter. The Japan Meteorological Agency (JMA) started to provide EEW to a limited number of users from August 2006 and to the public through TV and radio in October 2007. The Meteorological Service Act was amended in December 2007 to legally provide that the EEW be announced as ”forecast” and ”warning” of strong ground motion caused by an earthquake. EEW (warning) is issued when seismic intensity of 5-lower or larger (on JMA scale) is estimated, whereas EEW (forecast) is issued when the estimated intensity is between 3 and 4, or magnitude of the detected earthquake exceeds 3.5.

EEW is updated as available data increases with elapsed time. Accordingly EEW is issued repeatedly with improving accuracy for a single earthquake.

On March 11 2011, the 2011 off the Pacific coast of Tohoku Earthquake (Mw9.0) occurred and caused strong ground motion around northeastern Japan.

The fault rupture started at 14:46:18.1 (JST), and the EEW system was triggered when station OURI (138km from the epicenter) detected the initial P wave at 14:46:40.2. The first EEW (forecast), among the 15 announcements for the mainshock, was issued 5.4 seconds after the detection. The waveform started with small amplitude, which was comparable to noise level for displacement. The small amplitude did not indicate that the initial rupture of the Mw 9.0 event was large, and did not suggest that the entire scale went to be incredibly enormous. Eight point six (8.6) seconds after the detection, the estimated intensity exceeded the warning threshold (5-lower) and the JMA issued the fourth EEW (first warning) to Tohoku district. The warning was automatically broadcast through TV, radios and cellular phones (by using Cell Broadcast Service) more than 15 seconds before the actual intensity of ground motion reached to the threshold. However, warned area was apparently smaller than the area where seismic intensity 5-lower or more was observed, due mainly to the focal area extent underestimation.

After the mainshock to December 2011, the JMA issued 96 warnings and 3751 forecasts for its quite active aftershocks and induced earthquakes. (Note that, from October, 2007 to March, 2011 (41 months), the JMA issued 17 warnings and 1928 forecasts).

On the other hand, some inaccurate warnings were issued after the mainshock. From March to December 2011 the JMA issued 27 ”false-alarms” in which seismic intensity 5-lower or larger was expected but the real intensities were 2 or lower.

The cause was investigated and was found out that two or more earthquakes occurred simultaneously over the wide area, which tricked the system as if one huge event happened in somewhere.

In this presentation, we will present evaluation of the performance of EEW issuance, lessons learned from the earthquakes and various efforts to improve EEW of the JMA.

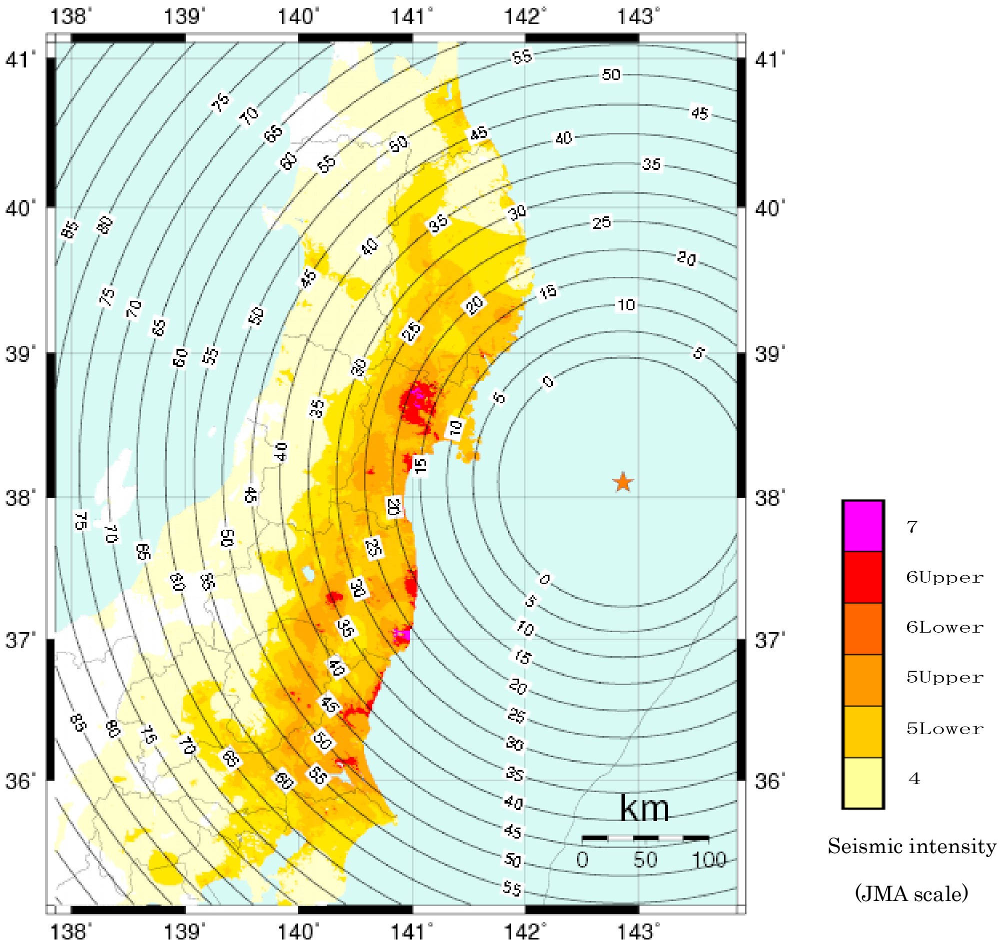

Figure 1. EEW lead time (in seconds) and observed seismic intensity at the 2011 off the Pacific coast of Tohoku Earthquake

Early Warning on the US West Coast

John E. Vidale and Paul Bodin

I'll quickly review the status of US West Coast earthquake early warning (EEW) efforts funded by the USGS and the Moore Foundation, then highlight the particular challenges of EEW for Cascadia.

The Cascadia subduction zone offers great utility from earthquake early warning for the Puget Sound, Portland, Vancouver, and the tsunami-vulnerable coast. The 1000-km length allows minutes of warning when a megaquake starts at a distance, as is likely. The 10,000-year record of the last several dozen great earthquakes from offshore turbidites allows good guessing of the chance of a big earthquake growing into a turbulent giant. We are far enough into the 500-year M9 cycle to have 150% of the long-term odds – 1/300 odds each year. The southern stretch of Cascadia, which is prone to M8s as well as M9s, is even more primed for action.

Challenges are also outsized. Instrumentation is relatively sparse. Discrimination between a wide range of possible styles and depths of strong earthquakes will be difficult. Means of relaying warnings, discussions with potential users, and long-term funding are not yet mature.

The UW and UC Berkeley, with the support of the Moore Foundation, are constructing a prototype early warning system. We are beginning with duplicate installations of the ElarmS algorithm in Seattle and Berkeley, and sharing data across borders. We are also exploring inclusion of GPS displacements in verifying the magnitude and development of large earthquakes.

Session VI

Abstracts

Potential contributions of Seafloor Geodesy to understanding slip behavior along the Cascadia Subduction Zone

C. David. Chadwell,

Scripps Institution of Oceanography, University of California San Diego

We propose an experiment to measure crustal deformation along Cascadia that crosses the entire region of a subduction zone from the incoming plate, the offshore continental slope and the sub-aerial continent (See Figure). There are two primary objectives to address with seafloor geodetic monitoring of Cascadia. What is the stick-slip behavior along the subduction thrust fault from the deformation front toward the coast where land geodetic data are controlling? Where is this offshore behavior located? Generally there are three possibilities. Stable sliding could occur from the deformation front to landward, i.e., no stick behavior and no transfer of elastic strain to the upper plate. This has a low probability as elastic strain is observed onshore along Cascadia, except at approximately 44°40´ where *[Burgette et al., 2009]* observe no significant uplift along a leveling line and note that no stick or locking is required on the thrust fault to fit their data.

The second possibility is reported in most of the published models *[Fluck et al., 1997; Wang et al., 2003; McCaffrey et al., 2007; Burgette et al., 2009]*. They assume stick behavior from the deformation front to some distance landward where it decays linearly or exponentially to completely stable sliding. Land geodetic data are too far from the deformation front to resolve whether or not stick starts at the front. Likewise, though land geodetic data are best fit with a transition from fully stick or locked to a decay and ultimately fully stable sliding, this boundary occurs offshore and is not strongly resolved leading to variability among the published models. Seafloor geodetic data located directly above the thrust fault where the changes in slip behavior occur should be able to resolve more strongly their magnitude and location.

The third possibility is a variation of the second where at the toe material is assumed to require some time and space to consolidate before supporting stick-like behavior. The situation is a subtle one because even though the material at the toe may not be under elastic strain it most likely moves with the material that is just downdip and locked. *Wang [2007]* has shown three scenarios. *Gagnon et al., [2005]* observed the toe offshore Lima Peru contracting significantly. This suggests it is reasonable to conclude the toe is not stationary with respect to the upper plate, but that generally it must move either under elastic strain or simply kinematically with the material downdip. Though the difference is small between frictionless and locked it could be detected with sufficient duration of seafloor geodetic monitoring. This would address the question directly as to the state of stick slip behavior out near the front as noted by *[Avouac, 2011]*.

An additional target for seafloor geodesy is measuring any interseismic elastic deformation of the incoming plate and what role this may have in understanding the stick slip behavior on the thrust fault near the deformation front. This topic has received scant attention to date primarily due to a lack of observations. There are two recent examples, however, that suggest that some amount of the elastic strain due to convergence is accumulated in the incoming plate. *Lay et al. [2009]* observed in the Kuril Islands a subduction thrust fault earthquake in 2006 followed by a normal fault earthquake in 2007 in the incoming plate. They suggest that about half of the interseismic strain accumulation was accommodated elastically within the incoming plate. *Chadwell [2007]* reported an observation with GPS-Acoustics at 44°40´ offshore central Oregon that is about half the expected long-term rate based on the geomagnetic anomaly reconstructions. A likely interpretation is that a significant amount of the convergent motion is accumulated as elastic strain in the plate offshore. Interestingly, this would be consistent with *Burgette et al., [2009]* finding that no stick (or locking) is required to fit the leveling data at this same latitude along the CSZ.

Geodetic arrays in place before a subduction thrust earthquake provide more direct measurements of slope response than relying on land geodetic data alone. This was first demonstrated by *Matsumoto et al. [2006]* offshore Japan and of course most recently following the Tohoku-Oki Earthquake where 24 m was observed at one GPS-A site and 31 at another *[Sato et al., 2011; Kido et al., 2011]*. These measurements on the sea floor along with modeling of tsunami waves passing over deep sea pressure sensors imply 40-50 m displacement on the thrust fault. Early result based solely on land geodetic data estimated only about 25 m of shift along the thrust fault. The direct observation of the co-seismic displacement is unprecedented. However, the more important contribution from seafloor geodesy may be measurements of interseismic strains in the slope and incoming plate and using these observations to map the behavior of stick-slip for estimating more precisely the rupture potential. Figure shows a notional design of a seafloor geodetic array for Cascadia to be further refined with community input.

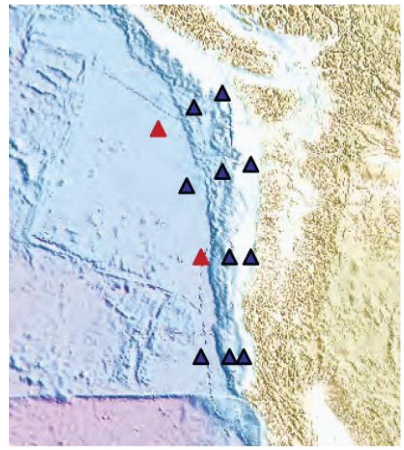

Figure 5: Notional array seafloor array (black triangles). Red existing, but presently inoperable GPS-A sites that could be reactiviated.

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Performance Tests of Real-Time Permanent Displacement Estimates and Rapid Rupture Characterization From Real-Time High-Rate GPS

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Real-time high-rate GPS data present many advantages for rapid estimation of earthquake ruptures. Chief among them is the ability to provide spatial resolution of an earthquake rupture's static slip distribution and to obtain rapid moment estimates that do not saturate for large events. Although real-time high-rate GPS data suffer from relatively high noise, low sensitivity to small earthquakes, and a dearth of operating and telemetered instruments, these data still provide a valuable enhancement to existing seismic monitoring.

We will present a prototype framework for rapid estimation of distributed slip models from real-time estimates of permanent surface displacement. In order to assess the immediate threat posed by an earthquake, such models must be accompanied by realistic confidence bounds on model parameters. Our goal is to develop an approach that balances computational efficiency with inversion methodologies that properly estimate the uncertainties in finite source models. If this modeling process can be made sufficiently speedy, the slip model could potentially be updated in near-real-time as the earthquake rupture evolves.

The first part of our presentation focuses on performance tests of new methods relative to existing techniques for calculating the accumulated permanent displacement in real-time from GPS waveforms from a variety of earthquakes of different magnitudes and located in different tectonic settings. These methods need to be evaluated for both large earthquakes whose coseismic time series are dominated by static offsets and moderate magnitude earthquakes for which the dynamic offsets dwarf the static component of deformation. We compare the various algorithms based on how quickly they provide an initial estimate of accumulated displacement and the delay (if any) following the passing of the seismic waves in returning a final, accurate measurement of the permanent surface displacement. Variation in rupture and data characteristics can greatly affect the performance of real-time offset-estimation, and different methodologies may be preferable depending on whether an application prizes earlier information over more accurate information about the evolving static offset.

In the second part of our presentation, we discuss how to best estimate a distributed coseismic slip model in near-real-time. While real-time high-rate GPS data is becoming more widely available, especially for regions of high seismic hazard in California and the Pacific northwest, station coverage is still limited and thus the spatial extent of rupture can still be quite poorly constrained. To handle this situation, we are developing techniques which combine Bayesian inference with linear regression to quickly produce rupture models with robust confidence bounds that can be used to evaluate the quality of the inversion results.

Integrating GPS and Radar Geodetic Imaging Observations with Models for Earthquake Response and Planning Additional Data Collection

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Geoff Blewitt
University of Nevada Reno

John Rundle
University of California, Davis

UJNR Abstract

For session: Real-time Monitoring of seismic, geodetic and strain measurements, Seafloor GPS

Rapid GPS solutions are making it possible to quickly infer details of fault ruptures, which can provide information about fault activity, areas of damage, and potential aftershocks. Radar in the form of UAVSAR and spaceborne interferometric synthetic aperture radar (InSAR) also provides information about crustal deformation, though often not as rapidly. However, the results have proved useful to showing where creep has occurred on faults neighboring a major rupture such as occurred in the 2010 El Mayor – Cucapah event. Software such as QuakeSim's simplex program has been used to rapidly invert for one or more faults following events, often identifying moment release larger than the seismic moment and deformation on faults off the main rupture. Rapidly and readily available geodetic data and reliable and iteratively refined models from QuakeSim are fed into decision support systems such as E-DECIDER to produce products for decision makers that can be used to help focus response efforts. These include deformation gradient maps and tilt maps that can be calculated and produced both from observed data and models. Fault parameters can also be ingested into models such as Virtual California to infer aftershock location and likelihood and probabilities of future large earthquakes. Such models are being run to estimate earthquake likelihood in Los Angeles due to the El Mayor – Cucapah and Landers earthquake. Detailed potential surface deformation can be calculated to steer future data collection efforts to areas of high probability for additional earthquakes or ground deformation. UAVSAR data will be collected in late September 2012 over the Brawley swarm region to further understand the regional deformation pattern associated with that event. Statistical models of time series implemented in the RDAHMM software and its extension allow for the detection of local or regional anomalies observed in GPS data. Application of these models to high rate GPS collected before and after the 2011 Tohoku-Oki earthquake provided deeper understanding of the dynamics of the crustal motion around the time of the earthquake as well as indications of subsequent aseismic activity at a distance from the main rupture zone.

Rapid assessment of high seismic intensity areas for mega-earthquake using satellite SAR data

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The 2008 M_w 7.9 Wenchuan earthquake devastated huge regions and triggered over 11,000 catastrophic landslides, slope collapses and debris flows spanning 300 km along the Longmen Shan (LMS) fault zone. The great disaster resulted in over 80,000 fatalities, 350,000 injuries and 46,574 affected villages.

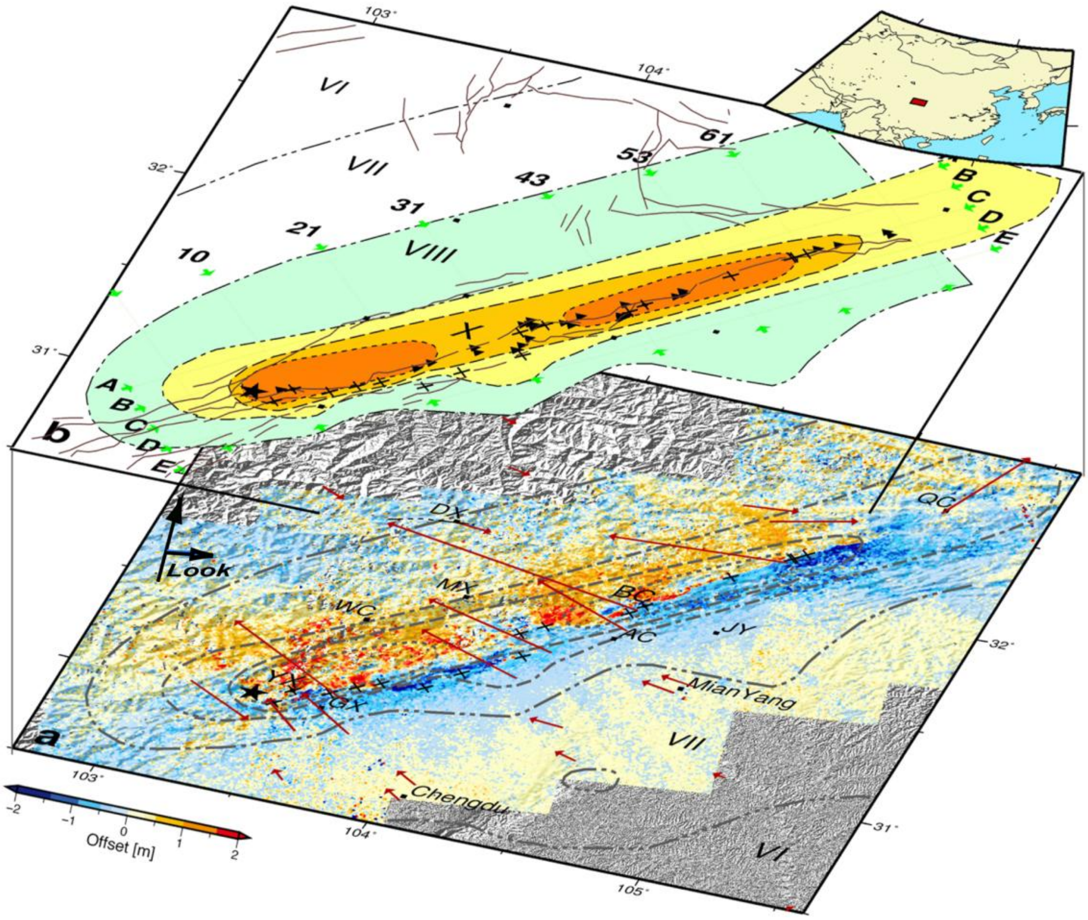

Figure 1. A comparison of the displacement using a pixel-offset analysis with isoseismal contours obtained from field investigations for the Mw7.9 Wenchuan earthquake (star, epicenter). (a) The displacements, indicated by offset [m] with ± and warm/cold color scales, represent the forward or away from the satellite in the ground-to-satellite line of sight direction, superimposed by GPS-observed coseismic offsets (red arrows, scale proportional to 2.43 m of maximum horizontal displacement), and by locations (plus signs) of the major coseismic fault scarp. (b) The isoseismal contours indicated by intensity VI to XI, superimposed by locations of the major landslides (solid triangles), and active faults (brown lines). (Higher resolution images can be found (Hao *et al.*, 2012).

The M_w 7.9 earthquake epicenter was located on the southwestern end of the LMS faults; however, the most damaged regions were Yinxue (YX, seismic intensity XI), Beichuan (BC, XI) and Qingchuan (QC, IX), distributed over a distance of 290 km toward the northeast as the LMS faults ruptured (Hao *et al.,* 2009). Lack of information on inaccessible areas such as mountainous regions led to more fatalities and injuries.

On-line instrumental surveys of seismic intensity have dramatically revolutionized the method for assessing earthquake damage from the conventional field investigations. More than 4,200 strong-motion seismographs were installed to survey seismic intensity in Japan and allow information to be automatically publicized within minutes following an earthquake. Unfortunately, the other countries frequently affected by earthquakes lack such dense array of the seismographs leading to delayed reporting. For example, after the Wenchuan earthquake, a field investigation-based seismic intensity map (Figure 1b) was not produced until 14 weeks post-quake due to widespread damages. As earthquake survivors in devastated regions waited for rescue, responders had no detailed knowledge of seismic intensity distribution. An assessment of damage intensity is crucial to quickly determine extreme disaster regions without reliance on slower, resource intensive methods such as ground observations and field surveys.

A novel method of rapidly assessing high seismic intensity areas is proposed by using satellite geodetic surveys after the Wenchuan earthquake. We re-compute pixel displacements using ALOS/PALSAR data (Kobayashi *et al.,* 2009), and densely setup the profiles of the pixel displacements across the region. Our profiles provide detailed information of areas within higher seismic intensity contours, especially for high mountainous areas where limited information was available. Vast amounts of field investigations provide valuable supplementary information about field fault scarps, landslides and seismic intensity contours. By analyses of displacements and seismic intensity contours, we propose a criterion of the displacement-to-intensity to qualitatively judge if high seismic intensity has occurred. Displacements of => 1 m may correspond to areas where higher intensities has occurred (> IX), and displacements of < 1 m may relate to areas where intensity < VII has occurred. We reveal that seismic intensity IX extended into VIII areas in western mountainous regions based on the criterion. Following mega (i.e. > M7) inland earthquakes, ground displacements of above one meter may indicate the possibility that the area suffers from high seismic intensities. This result calls for further study and cooperation; such as reduce the latency with more dedicated cooperation and improving accuracy.

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Real-Time Monitoring at the USGS National Earthquake Information Center: Past, Present, Future

G.P. Hayes, P.S. Earle, H.M. Benz, D.W. Wald
UJNR Panel Meeting, Denver, October 2012

Over the past decade, the US Geological Survey (USGS) National Earthquake Information Center (NEIC) has evolved from an operation primarily targeting the reporting of basic earthquake parameters in near-real time (i.e., location, origin time, magnitude) to one which leads global response to significant earthquakes through the production of a number of sophisticated products aimed at a broad characterization of source parameters and earthquake impact. This has been facilitated through (1), the evolution of the NEIC into a 24/7 operational facility, rather than being dependent on on-call analysts and researchers: (2), the development and operation of a new generation of seismic acquisition, processing and distribution system known as Bulletin Hydra: (3), expansions in global monitoring, seismic station density and quality: (4), accompanied improvements in our ability to rapidly characterize earthquake magnitude, using methods such as Empirical Green's Function deconvolution and the W-phase centroid moment tensor (CMT) inversion, and (5), the production and implementation of a number of key products – for example, ShakeMap, PAGER, and Finite Fault Modeling – via both in house expertise and academic partnerships.

In 2004, the NEIC lacked a comprehensive set of tools to provide rapid and robust magnitudes of the M 9.1 Sumatra earthquake, and to properly characterize the source mechanism and societal impact of the event. Thanks to the developments since, discussed in more detail in this presentation, following the 2011 Tohoku earthquake the world was aware of the great size of the event in minutes, instead of the hours to days it took for similar information to be disseminated in 2004.

Today, our response challenge has evolved to one of addressing how we refine the tools we use to work better in tandem, and how to better streamline our external coordination efforts with other global and national earthquake agencies. Our research interests are aligned with the identification and application of approaches that help improve the speed and accuracy of earthquake response, and advance studies of earthquake risk reduction. We conclude by discussing some of these applications and developments, how they are being used for both real-time activities and longer-term research, and how we hope to use them to drive further improvements in earthquake monitoring and response in the future.

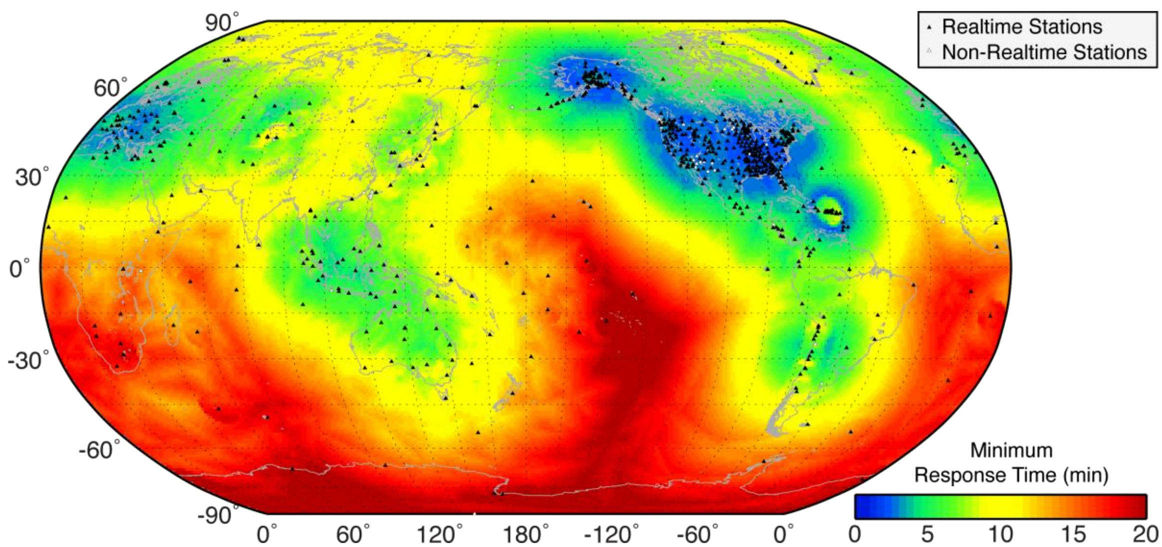

Figure: Idealized response capabilities using regional applications of the W-phase CMT inversion, based on real time data streams available at the NEIC, and statistics of data requests versus usage in past W-phase inversions. Given a rapid trigger of approximate earthquake location and size, colors indicate how quickly an accurate magnitude and CMT mechanism could be available at a given location, assuming that approximately 20 data channels of data are needed beyond 5 degrees from the source to produce a reliable solution.

NSF's EarthScope Program – Introduction and Updates

Chuck Estabrook
Program Director for EarthScope

In the 90's started the EarthScope program. EarthScope is an ambitious, multifaceted program to investigate the structure, dynamics, and history of the North American continent. EarthScope's vision is to use North America as a natural laboratory to gain fundamental insight into how Earth operates. EarthScope provides researchers with rich data sets to image, sample, and monitor the continent and underlying mantle at a resolution never before attempted.

The program is an initiative of the Division of Earth Sciences at the National Science Foundation, and it began as a multiyear effort in 2003. Ideas for the program started in the 90's. It is now in its ninth year and is expected to continue until 2018.

At NSF EarthScope is divided into the *Facility*, the *Science* program, the *National Office* and *Education and Outreach*. The *Facility* is composed of four parts: USArray (a seismic and magnetotelluric network including the Transportable Array which is now approaching Washington DC), the Plate Boundary Observatory (geodetic and seismic network), San Andreas Fault at Depth (SAFOD), and GeoEarthScope (imagery and geochronology). The *Science* funds about 20 projects/year that use data from the ES *Facility*.

This talk will concentrate on presenting some of the latest results from EarthScope with an emphasis of topics of interest to NASA. Presently there are 400 seismic stations in the eastern North America with plans for moving the equipment to Alaska. PBO is fully deployed and operational, and NSF is now accepting proposals for the future use of the SAFOD facility.

Session VII (Posters)

Abstracts

Ocean bottom seismic and tsunami network along the Japan Trench

Toshihiko Kanazawa, Kenji Uehira, Shin'ichi Noguchi, Shin Aoi, Takashi Kunugi, Takumi Matsumoto, Yoshimitsu Okada, Shoji Sekiguchi, and Katsuhiko Shiomi

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Huge tsunami, which was generated by the 2011 off the Pacific Coast of Tohoku Earthquake of M9 subduction zone earthquake, attacked the coastal areas in the north-eastern Japan and gave severe casualties (about 20,000 people) and property damages in the areas. The present tsunami warning system, based on land seismic observation data, did not work effectively in the case of the M9 earthquake. For example, real tsunami height was higher than that of forecast by this system. It is strongly acknowledged that marine observation data is necessary to make tsunami height estimation more accurately. Therefore, new ocean bottom observation project has started in 2011 that advances the countermeasures against earthquake and tsunami disaster related to subduction zone earthquake and outer rise earthquake around the Japan and Kuril Trenches. A large scale ocean bottom cabled observation network is scheduled to be deployed around the Japan Trench and the southern Kuril Trench by 2015. The network is consisted of 154 ocean bottom observation stations. Ocean bottom fiber optic cables, about 5800 km in total length, connect the stations to land. Observation stations with tsunami meters and seismometers will be placed on the seafloor off Hokkaido, off Tohoku and off Kanto, in a spacing of about 30 km almost in the direction of East-West (perpendicular to the trench axis) and in a spacing of about 50 - 60 km almost in the direction of North-South (parallel to the trench axis). Two or more sets of tsunami meters and seismometers will be installed in one station for redundancy. Two sets of three component servo accelerometers, a set of three component quartz type accelerometers (frequency outputs), a set of three component velocity seismometers will be installed, and two sets of quartz type depth sensors (frequency outputs) will be installed as tsunami meters. Tsunami data and seismometer data will be digitized at sampling frequency of 10 Hz and 100 Hz, respectively, and will be added clock information at land stations. These digitized data will be transmitted to the NIED data centers, JMA, universities and so on, using IP network. The network is capable of quickly and precisely catching seismic motions and sea level changes near earthquake sources along remote subduction zone, which will be utilized to monitor large earthquakes and tsunamis, to transfer prompt and precise warnings, and to clarify the detailed crustal structure.

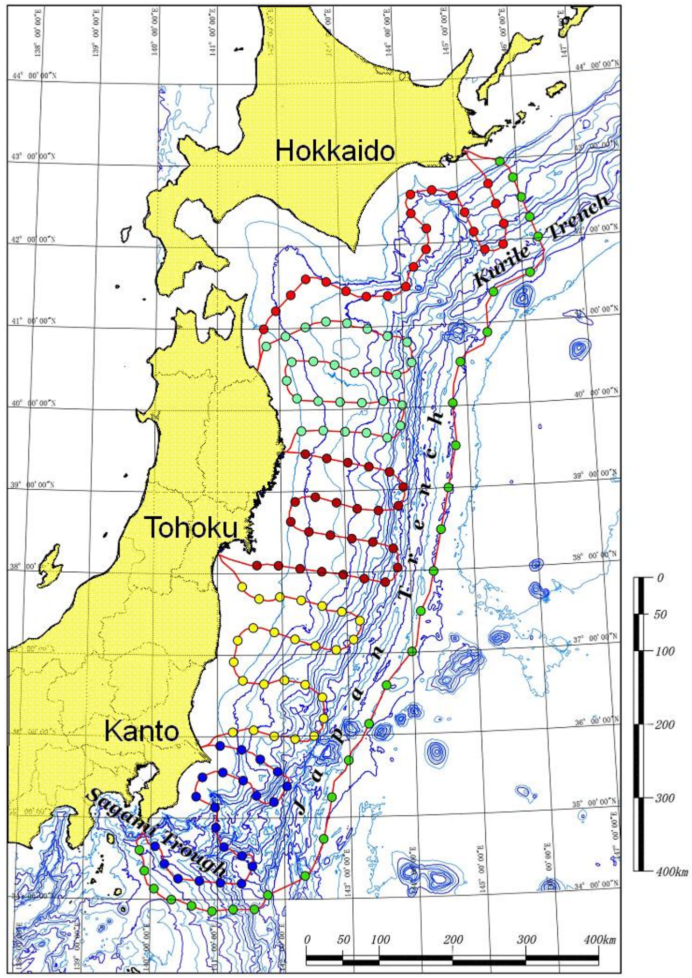

Figure 1. An ocean bottom cabled observation network composed of seismometers and tsunami meters is planned to be deployed at 154 locations on the deep sea bottom along the southern Kuril Trench, the Japan Trench and the Sagami Trough.

Developing a GEONET Real-time Processing System for Rapid Earthquake Modeling

Satoshi Kawamoto [1], Kohei Miyagawa [1], Basara Miyahara [1], Kazunori Yamaguchi [1], Tomoaki Furuya [1], Kazuki Sakai [1], Yuki Hatanaka [1], Takuya Nishimura [1], Satoru Nemoto [1], Hiromichi Tsuji [1], Yusaku Ohta [2], Ryota Hino [2], Motoyuki Kido [2], Takeshi Iinuma [2], Hiromi Fujimoto [2] and Satoshi Miura [3]

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1. Introduction

The 2011 off the Pacific Coast of Tohoku Earthquake (M_w 9.0; hereafter Tohoku earthquake) caused catastrophic tsunami damage. It indicates us several problems for improving a tsunami early warning system. Overcoming magnitude saturation is one of the keys to improve forecasting of the large tsunami. It has been suggested that real-time GNSS processing could contribute a rapid determination of earthquake magnitude (e.g., Blewitt et al., 2006) and that it could supplement the operating tsunami warning system mainly based on the seismometer network. “GEONET” could contribute it, which is Japan’s nationwide GNSS network consists of over 1,200 permanent stations streaming 1Hz data. Here, we describe our challenge to determine the earthquake magnitude with GEONET data in real-time.

2. System Overview

Now GSI and Tohoku University are underway to develop a new GEONET real-time processing system together to help fast tsunami forecast. The goal of the system is to provide displacements fields and earthquake magnitude as fast as possible after earthquakes. The system features include:

- implementation of “RTKLIB 2.4.1” (Takasu, 2011) for processing real-time GNSS data of whole GEONET network;
- detecting large earthquakes automatically without seismometer;
- estimation of a rectangular fault model including moment magnitude;
- providing the results described above as a forecast guidance;

3. Development Progress

Starting on 6 April 2012, the prototype has implemented “RAPiD” (Ohta et al.

2012), which was developed as an algorithm for auto-detection of permanent displacements from timeseries of GNSS positioning, and being in operation processing about 150 baselines with RTKLIB 2.4.1. If the system detects displacements, it will start monitoring ground motions of rover stations. When the strong ground shaking is over, the prototype sends permanent displacement field and detected time via e-mail to operators.

Real-time GNSS processing shows the standard deviation of 1.6 cm in horizontal component for two months of operation. It suggests that the real-time positioning is enough precise to detect a giant earthquake like the 2011 Tohoku earthquake adequately. However, false detections of permanent displacements were often found during this experimental period. These are caused by large noises of GNSS positioning due to atmospheric signal delays and temporary suspension in real-time streaming data. Therefore we are continuing to refine the prototype.

4. Future Plan

The false detections found would be problem. Kobayashi et al. (2012) proposed a new algorithm that used adjacent stations simultaneously and demonstrated it would dramatically reduce false detections. By the end of this year, we will upgrade the prototype with implementing the algorithms for reducing false detections as well as estimation of a rectangular fault model.

The system is planned to be in full operation after the next fiscal year. Then we will start to provide the results to disaster prevention organizations.

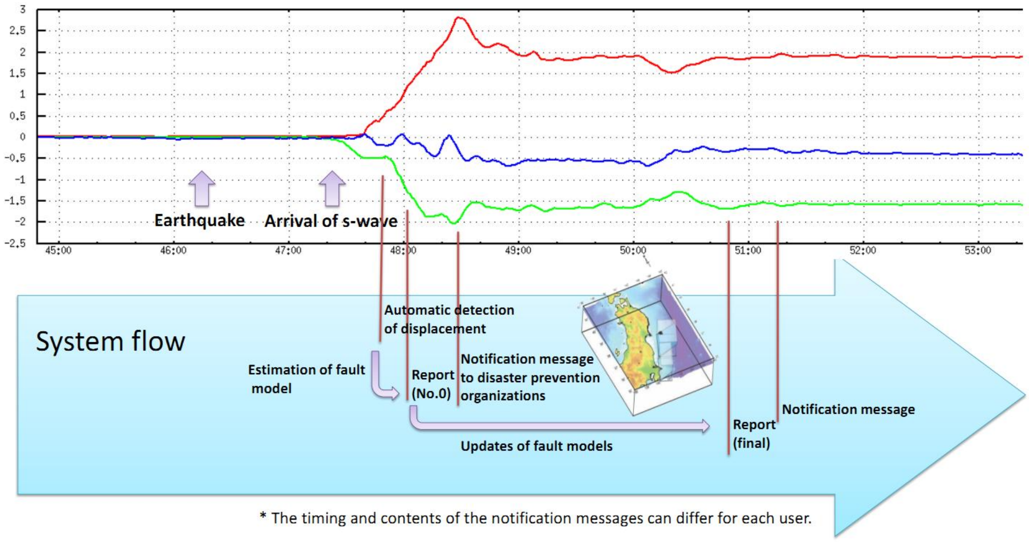

Figure 1. An example of flow of the information provided by the system.

Asia-Pacific Region Global Earthquake and Volcanic Eruption Risk Management (G-EVER) project

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The first Workshop of Asia-Pacific Region Global Earthquake and Volcanic Eruption Risk Management (G-EVER1) was held in Tsukuba on February 22-24, 2012. The workshop focused on the formulation of strategies to reduce the risks of disasters worldwide caused by the occurrence of earthquakes, tsunamis, and volcanic eruptions. The workshop was attended by 152 participants from 12 countries and regions representing 56 national and international institutes. The participants were encouraged by some successful risk mitigation activities and progress of some local and global risk reduction efforts. Collaboration between geohazard institutes and organizations in the Asia-Pacific region can advance the science of natural hazards and contribute to the reduction of the loss of lives and properties caused by the occurrence of earthquakes, tsunamis, and volcanic eruptions.

During the workshop, the G-EVER1 accord was approved by the participants. The Accord consists of 10 recommendations:

- Establish a consortium of Asia-Pacific geohazard research institutes, with the goal of enhancing collaboration, sharing resources, and making information about risk from earthquakes and volcanic eruptions freely available and understandable.
- Promote the use of hazard information in decision-making by citizens, governments, and businesses, so our science supports mitigation actions.
- Develop a website hub for the consortium in English and major Asian languages, which would link to websites of allied global efforts, such as VHub, GEM Nexus, and the International Seismological Centre (ISC).
- Establish or endorse data interchange standards and standardized analytical methods for geohazard institutes of the world to promote data sharing and comparative analyses.
- Actively participate in related global risk reduction efforts, such as Integrated Research on Disaster Risk (IRDR) Program, Global Earthquake Model (GEM), Global Volcanic Model (GVM) and their component databases like World Organization of Volcano Observatories Database (WOVOdat) and GEM Faulted Earth.
- Promote "the borderless world of science" with trans-border hazard maps built using common data sets, and more uniform and advanced methods and software than has been possible in the past.
- Promote exchange visits among researchers of the consortium, and encourage opportunities for graduate study in geohazards.
- Encourage the formation of working groups for broad, multi-disciplinary, unifying themes.Promote best practice training on interaction with the media, on outreach to citizens and school children on hazard preparedness, and on

interaction between volcano scientists and Volcanic Ash Advisory Centres in the region.

- Convene a G-EVER workshop every 2 years in Asia-Pacific countries in conjunction with major regional events (such as AOGS, WPGM and AGU meetings).

The G-EVER Hub website (http://g-ever.org) was established to promote the exchange of information and knowledge among the Asia-Pacific countries. Several G-EVER working groups and task forces were proposed such as: (1) large-scale earthquake risk assessment, (2) large-scale volcanic eruption risk assessment, (3) next-generation real-time volcano hazard assessment, and (4) Asia-Pacific region earthquake and volcano hazard mapping. Establishing or endorsing data interchange standards and standardized analytical methods for geohazard institutes of the world to promote data sharing and comparative analyses were also considered important target.

Group photo at the G-ever1 workshop held in Tsukuba on Feb. 22-24, 2012

Session VIII

Abstracts

Dynamics of Migrating Earthquake Swarms at Yellowstone and Mount Rainier Volcanic Areas: Evidence for Fluid Triggering?

David R. Shelly, Seth C. Moran, David P. Hill, Frédérick Massin, Jamie Farrell, Robert B. Smith

Volcanic and hydrothermal regions often exhibit high rates of seismicity and frequent seismic swarms. Two recent examples include a swarm September 20-23, 2009, beneath Mount Rainier and a January 15-February 6, 2010 swarm near the northwest rim of Yellowstone Caldera (Madison Plateau) in Yellowstone National Park. To help illuminate the underlying processes driving the activity, we attempt to identify low signal-to-noise earthquakes and to locate them precisely along with numerous cataloged events.

For each swarm, we use the waveforms of cataloged events to scan the continuous seismic data, with the goal of improving both event identification and relative locations. To do this, we measure both the height and precise timing of the correlation peaks between catalog events and the continuous waveform data. We then input the resulting differential times to a double-difference relative relocation algorithm. This results in successful location of a factor of ~4 more events than included in the catalog, or roughly 800 and 8000 events for the Rainier and Yellowstone sequences, respectively.

Despite differences in the depth range (2-3.5 km below mean station elevation at Rainier versus 6-11 km in Yellowstone), the swarms share many common characteristics. Both seismic swarms exhibit clear migration of event centroids, and in each case activity expands systematically outward in a largely planar pattern with time. Expansion of the seismicity front is episodic and seems to be led by smaller events, even when accounting for differences in source dimensions. Both the Rainier and Yellowstone swarms activate shallower, seismically disconnected structures later in the swarm evolution. A further similarity is that dominant structures, as defined by the earthquake locations, strike perpendicular to the direction of minimum regional compressive stress, and neither nodal plane of double-couple-constrained focal mechanisms generally matches the trend of event locations. This suggests the possibility of en echelon faulting and/or a component of fault opening, perhaps in a fracture mesh geometry similar to that envisioned by Hill [1977]. We hypothesize that both swarms were driven by sudden fluid pressure increases diffusing through the crust along pre-existing fractures, in combination with stress transfer from preceding events. If so, these swarms may represent natural analogs for seismicity induced by industrial injection.

Detection of short-term slow slip events along the Nankai trough, southwest Japan using GNSS data

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Short-term slow slip events (SSEs) along the Nankai trough, southwestern Japan have been observed only by tiltmeters and strainmeters. Here, we present a method to detect the deformation associated with the SSEs and fault models of the SSEs on the plate interface of the Philippine Sea plate inverted from GNSS data. We also compare them with a tremor activity (Maeda and Obara, 2009; Obara et al., 2010) and the fault models of the SSEs estimated from tilt data (Sekine et al., 2010).

Daily coordinates of 565 GEONET stations in southwestern Japan were used to detect the deformation of the SSEs. We fitted a step function to the filtered daily coordinates to detect displacements in a direction of N130ºE which is opposite to the relative plate motion between the Philippine Sea plate and southwestern Japan. The candidate dates of the SSEs are determined if the significant displacements were detected. And three components (i.e., EW, NS, and UD) of the displacement on the date were inverted to estimate a rectangular fault model (Fig. 1). We finally recognized SSEs if the observed displacement were well reproduced by the fault model.

209 candidates of SSEs were found in a period from June 19, 1996 to January 7, 2012. They were categorized into 97 certain SSEs including 3 double-counted events, 63 possible SSEs and 49 non-SSEs. Moment magnitude (M_w) of 157 "certain" and "possible" SSEs ranges between 5.5 and 6.4. SSEs with $M_w \geq 6.2$ have occurred only in western and central Shikoku 5 times. No certain SSEs (Fig. 2) occurred in the Kii Channel (around 135.0ºE) and east of 137.5ºE (Lake Hamana). A couple of certain SSEs have occurred in Ise Bay where the tremor activity is weak.

Comparing the fault models from GNSS with those from tilt data (Sekine et al., 2010), we found 27 SSEs included in both catalogues. There is no systematic difference of their M_w estimated from GNSS and tilt. SSEs with $M_w \geq 6.1$ were included in both catalogues. However, 25 and 17 SSEs were detected solely from GNSS and tilt data, respectively. It, therefore, suggests that the detectability of neither GNSS nor tiltmeter is perfect for small SSEs. Space-time plot of the SSEs (Fig. 2) shows a variety of size and recurrence times, though it may be apparent due a lot of events missed by GNSS. However, we recognize that the number of the SSEs increases around 2004 in eastern Shikoku. The increase may reflect a long-term change of conditions on the plate interface because similar increase is also observed in tremor activities (Obara et al., 2010).

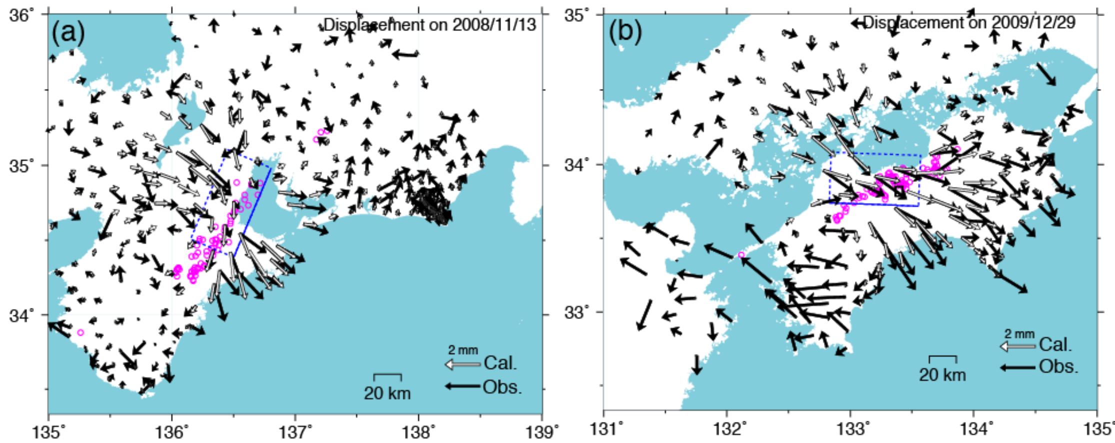

Figure 1. Observed and calculated displacements for "certain" SSE along the Nankai trough, western Japan. Black and white vectors are observation and calculation using a rectangular fault model, respectively. Purple circles are epicenter of nonvolcanic tremors for 5 days centering the certain day. (a) An event on November 13, 2008. (b) An event on December 29, 2009.

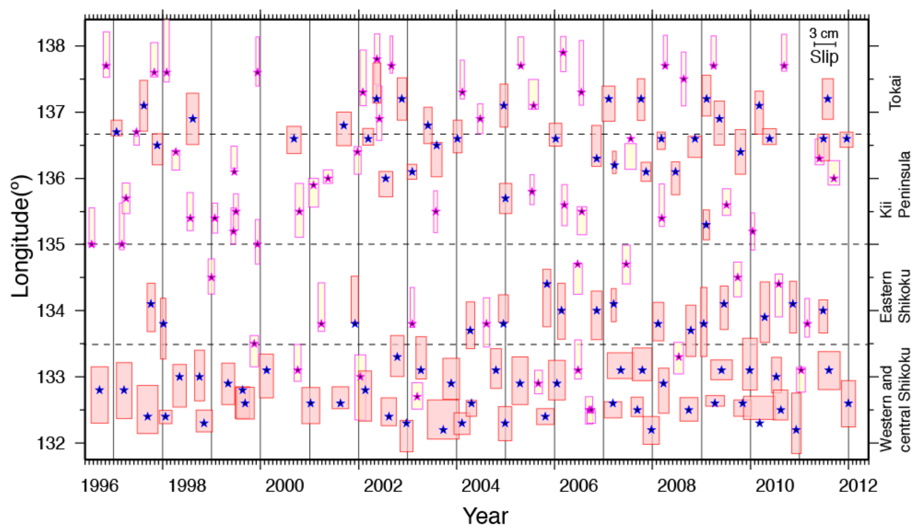

Figure 2. Space-time plot of the SSEs. Red and yellow rectangles show fault models of "certain" and "possible" SSEs, respectively. The horizontal axis indicates the date and the slip amount for each SSE. Blue and purple stars represent dates of the "certain" and "possible" SSEs, respectively.

Mitigation of Earthquake Hazards with a Seismogeodetic Model as Demonstrated for the 2011 Mw 9.0 Tohoku-oki Earthquake

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Saturation of broadband seismometers in the near field and problems with the double integration of accelerometer data into displacements in real time degrade early warning and rapid source characterization for large earthquakes. An integrated seismogeodetic network model overcomes these limitations to estimate, on the fly, the full spectrum of seismic motions, allowing for an order of magnitude improvement in response time compared to traditional seismic methods as demonstrated for the 2011 Mw 9.0 Tohoku-oki earthquake in Japan. Replaying local data in a simulated real-time mode from 785 GPS GEONET stations and 190 accelerometers from the K-NET and KiK-net networks, we demonstrate that an accurate centroid moment tensor solution to ascertain the type of earthquake, immediately followed by a finite fault slip model could have been obtained in about 3 minutes, providing more accurate and timely warnings of the severity of the impending tsunami and assisting first responders with evacuation and recovery efforts. We use the rapid slip inversion to model the ensuing tsunami. The seismogeodetic network model is sufficiently accurate to detect P wave arrivals in the near field for large events, leading to improved earthquake early warning (EEW) methodologies that predict the arrival and intensity of S waves. We are currently applying the seismogeodetic approach and the lessons learned from the Tohoku-oki earthquake to a NASA-supported earthquake early warning system for Western North America (http://sopac.ucsd.edu/projects/realtime/READI/).

Short-term slow slip events in the Kii peninsula by joint analysis of the AIST borehole strainmeter array and the NIED Hi-net tiltmeter array

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Geological Survey of Japan, AIST has constructed fourteen observatories in and around expected focal zones of the Nankai and Tonankai earthquakes to monitor groundwater and borehole strain during 2006 - 2010. The 30, 200 and 600 m-depth wells are constructed in one observatory. The multi-component borehole strainmeter and borehole tiltmeter are installed at the bottom of either the 600 m-depth well or the 200-m depth well. The purposes of this observation array are i) detection of groundwater level and/or strain changes associated with the possible preseismic, co- and afterseismic crustal deformation, ii) precise mapping of Short-term slow slip events (SSEs).

For the borehole strainmeter data, we applied in-situ calibration methods by using response of each strain gauge to the Earth tides (Gladwin and Hart, 1985; Roeloffs, 2010), because the observed borehole strain data is different from the strain in the surrounding rocks which is caused by inclusion of host rocks, grout and housing of strainmeter. Then, the calibration matrix estimated by the tidal response is validated by using theoretical and observed strain produce by long-period surface wave.

Geological Survey of Japan, AIST and the National Research Institute for Earth Science and Disaster Prevention (NIED) started to exchange AIST borehole strainmeter data with the NIED Hi-net tiltmeter data on a real-time basis since 2011. Fault models of SSEs are estimated using data from both the AIST borehole strainmeter array and the NIED Hi-net tiltmeter array by grid search method. The mapping accuracy of the fault models of SSEs is improved by the joint analysis of AIST strainmeter and the NIED Hi-net tiltmeter data.

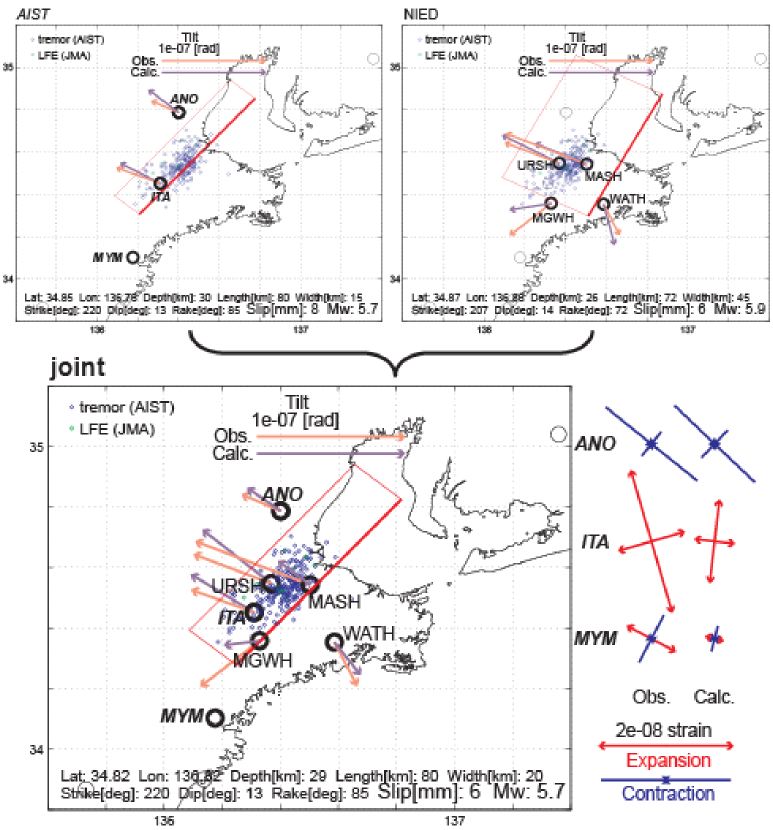

Figure 1 Fault model of SSE occurred on June, 2011 estimated by AIST strainmeter/tiltmeter data (top left), fault model by using the NIED Hi-net tiltmeter data (top right) and fault model by using both AIST strainmeter/tiltmeter and Hi-net tiltmeter data (bottom)

3D quasi-dynamic modeling of cycles of megathrust earthquakes along the Japan Trench subduction zone considering high-speed friction

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We investigate the generation mechanism of the 2011 Tohoku-oki earthquake (M 9.0) by performing 3D quasi-dynamic modeling with high-speed friction. Many studies on this earthquake indicate that large slips occurred near the trench off Miyagi and off Fukushima [e.g. Fujii et al., 2011; Satake et al., 2012] and that significant stress drop occurred in this region [e.g. Hasegawa et al., 2011]. These observational studies suggested that the 2011 Tohoku-oki earthquake released roughly all of the accumulated elastic strain on the plate interface owing to considerable weakening of the fault. Recent studies on high-speed friction show that considerable weakening can occur at a high slip velocity because of thermal pressurization or thermal weakening processes [Noda and Lapusta, 2010; Di Toro et al., 2011, Tsutsumi et al., 2011].

Based on experimental results by Tsutsumi et al. [2011], Shibazaki et al. [2011] propose a rate- and state-dependent friction law with two state variables that exhibit weak velocity weakening or strengthening with a small critical displacement at low to intermediate velocities, but a velocity weakening with a large critical displacement at high slip velocities. We use this friction law for 3D quasi-dynamic modeling of cycles of the Tohoku-oki earthquake and other large earthquakes along the Japan Trench subduction zone. We set several asperities where velocity weakening occurs at low to intermediate slip velocities. Outside of the asperities, velocity strengthening occurs at low to intermediate slip velocities. At high slip velocities, strong velocity weakening occurs both within and outside of the asperities. The rupture of asperities occurs at intervals of several tens of years, whereas megathrust events occur at much longer intervals (several hundred years). Megathrust slips occur even in regions where velocity strengthening occurs at low to intermediate slip velocities. Following M 9 class events, large afterslips occur in an area where the coseismic slip is not large, complementing the large coseismic slip zone. At points located in the velocity strengthening region at low slip velocity, even when coseismic slips occur, afterslips can occur as a result of velocity strengthening at low slip velocity. We also report the quasi-dynamic 3D model [Shibazaki et al., 2012] for the Tohoku-oki earthquake considering a rate- and state-dependent friction law and thermal pressurization by using a spectral solver [Noda and Lapusta, 2010] to efficiently calculate the temperature and pore-pressure evolution on a fault plane.

Advantages and Limitations of Cluster Analysis in
Interpreting Regional GPS Velocity Fields in California and Elsewhere

Wayne Thatcher, James C. Savage, Robert W. Simpson

Cluster analysis offers a simple, visual exploratory tool for the initial investigation of regional Global Positioning System (GPS) velocity observations, which are providing increasingly precise mappings of actively deforming continental lithosphere (Simpson et al., 2012 GRL). Here we describe new results applying cluster analysis to GPS velocities from three regions, the Mojave Desert and San Francisco Bay Area in California, and the Aegean in the eastern Mediterranean. Our goal is to illustrate the strengths and shortcomings of the method in searching for spatially coherent patterns of deformation including evidence for and against block-like behavior in these 3 regions.

The deformation fields from dense regional GPS networks can often be concisely described in terms of relatively coherent blocks bounded by active faults, although the choice of blocks, their number and size, is subjective and usually guided by the distribution of known faults. Cluster analysis provides a completely objective method for identifying blocks ranging in size from 10s to 100s of km in characteristic dimension. Statistically significant clusters are almost invariably spatially compact, fault bounded, and define elastic blocks that deform significantly only on their boundaries. Often, higher order clusters that are not statistically significant are also spatially compact, suggesting the existence of additional blocks, or defining regions of other tectonic importance (e.g. zones of localized elastic strain accumulation near locked faults). These results can be used to both formulate tentative tectonic models with testable consequences and suggest focused new measurements in under-sampled regions.

Cluster analysis has several noteworthy limitations. First of all, the method typically identifies only a small number of statistically significant clusters in a given region, usually 5 or less. Thus we often cannot preclude existence of more clusters that define smaller blocks, although this shortcoming can sometimes be overcome by applying the method to smaller sub-regions. Finally, GPS data precision and spatial density limits the degree to which distinct clusters can be defined, pointing to the importance higher precision (e.g. semi-continuous and continuous GPS sites) and incorporation of other data types like InSAR deformation maps into the method.

Characteristic activity of tremor as proxy for slow slip in the transition zone along the subducting plate interface

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Non-volcanic tremor has been detected accompanied by slow slip event in subduction zone with young oceanic plate. Tremor is considered as a proxy for slow slip because duration of major tremor bursts measured seismologically in southwest Japan and Cascadia is proportional to the moment release of slow slip measured geodetically. Therefore, the activity style of tremor reflects occurrence and rupture process of slow slip. In this paper, we review characteristic activity of tremor to reveal the nature of slow slip along the subducting plate interface.

Subduction tectonic tremor in southwest Japan and Cascadia is distributed within a narrow belt-like zone with a length of 600 and 1200 km along the strike of the slab, respectively. Along-strike segmentation of tremor is defined by coherent zones with different recurrence intervals and time offsets. The segmentation may be related to tectonics. In southwest Japan, 2 large gaps, which reflect segment boundaries, correspond to the topographic highs of the subducting Philippine Sea plate due to its bending. Tremor episodes in both sides of Ise bay area, that is one of large gaps, usually occur independently; however, the migrating tremor in the Kii segment rarely continues to the Tokai segment beyond the gap. Similar migration of tremor activity is frequently observed between central and eastern Shikoku; there exists a small gap in tremor activity, less than 10 km in length horizontally. A tremor activity usually occurs along the extrapolation from migration in another side of tremor cluster with a time difference of 1 or 2 days. These continuity of tremor migration including a gap suggests that slow slip propagates through the inactive tremor zone.

Even though there is a possibility to exist aseismic slow slip propagation, tremor activity is a good proxy for slow slips within tremor zone, then we understand detail rupture process of slow slip from tremor migration. There are mainly three migration modes; along-strike long-term migration at a speed of about 10 km/day; rapid tremor reversal (RTR), which involves along-strike migration at speeds on the order of 100 km/day, propagating in the opposite direction to the long-term migration; and much faster slip-parallel migration at speeds on the order of 1000 km/day. The improvement of tremor location method enabled to clarify the systematic along-dip variation in the activity style within the narrow tremor zone. The updip tremor activity is modulated by the major burst infrequently occurring at regular recurrence interval; however, the downdip tremor activity is composed of more frequent occurrence of minor burst. Major tremor burst, which was recognized as characterized by along-strike migration, usually starts from the downdip edge and migrates updip. That is to say, the long-term migration propagates radially. Recently, Obara et al. (2012) revealed the existence of along-strike migration with a speed of 10–20 km/hr concentrated at the updip side of the tremor zone whereas the faster slip-parallel migration is distributed over the entire zone. The migration events include both of reverse and forward direction relative to the long-term migration. The reverse migration is considered as a seed of RTR. The long-term migration seems to consist of and be excited by the propagation of forward along-strike creep at the updip part. Systematic variation in recurrence and migration mode within the tremor zone must reflect the change in frictional property and fluid contents along the plate interface due to the temperature and material changes.

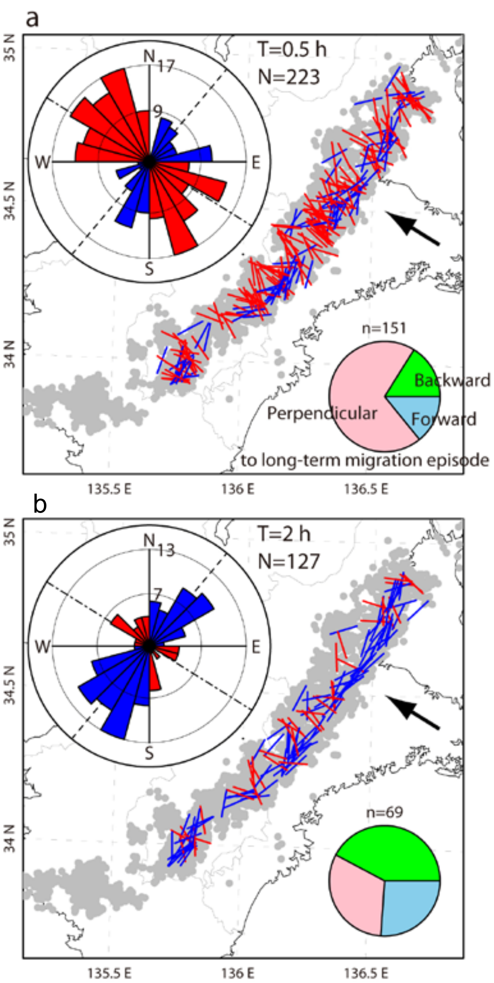

Figure Distribution of the migration direction of extracted migrating tremor sequences for two different time scales. Short lines on the map view indicate the migration direction plotted on the centroid location for its extracted migrating tremor sequence. The rose diagram at top left indicates the azimuthal distribution of the tremor migration in 15-degree bins. The diameter of the outer circle is normalized by the maximum number in each bin. Red color indicates the migration direction within the first or third quadrant, which is to the northeast or southwest along the strike of the slab, respectively. Blue color indicates a migration direction within the second or fourth quadrant, which is downdip or updip along the slip direction, respectively. The length of the time scale (T) is (a) 0.5, and (b) 2.0 hours. N is the total number of migrating tremor sequence for each time scale. Arrow indicates the relative plate motion [Miyazaki and Heki, 2001]. Dashed and chained lines indicate the directions of the average strike of the tremor zone and plate convergence, respectively. The pie chart at bottom right indicates the percentage of each migration direction during the background long-term migration episodes, showing clear propagation to the northeast or southwest. The term ‘Perpendicular’ indicates a detected tremor sequence with a migration direction within the second or fourth quadrant. Other events composed of ‘Backward’ and ‘Forward’ have a migration direction within the first or third quadrant. The terms ‘Backward’ and ‘Forward’ indicate a detected tremor sequence migrating in the opposite or same direction to the direction of the long-term migration episode, respectively. The total number of detected tremor sequences within long-term migration episodes with clear propagation to the northeast or southwest is shown on the top of the circle.

Repeating Earthquakes on the Parkfield Segment of the San Andreas: Do They Reload Themselves?

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Repeating earthquakes in the Parkfield segment of the San Andreas Fault are nearly periodic but deviate slightly in a manner that suggests more rapid reloading early in their cycle. We propose a self re-loading model where an asperity slips, causing creep in the surrounding volume. This creep, in turn, rapidly reloads the asperity, which is then further loaded at a tectonic rate.

Repeating earthquakes in the Parkfield section of the San Andreas Fault exhibit slip-predictable scaling, whereby moment increases with the preceding inter-event time. However, statistical analysis of these events indicates that while the repeaters exhibit a slip-predictable sense scaling, in a strict sense they are neither slip- nor time-predictable (*Rubinstein et al.*, 2012). While the size of the repeating earthquakes does appear to scale linearly with inter-event time, this scaling predicts that at zero recurrence interval an earthquake would have non-zero size (incomplete stress drop). The slip-predictable model requires both a constant loading rate and a complete stress drop, hence it fails to explain our observations.

As an alternative to the slip predictable model, we suggest that the reloading of the slip patch is nonlinear. In this model, the stressing rate on the fault patch increases immediately following an earthquake and decays with time to a constant background rate. This would give a rapidly increasing slip-budget immediately following an earthquake with the loading of the patch eventually slowing to a constant rate. We believe that our observations of the repeating events lie within this time period where the slip-deficit rate is constant, such that we see a linear relationship between slip and recurrence interval. The combination of the nonlinear loading and observations only during a period of constant loading would yield observations like ours, i.e. an apparent constant loading rate and incomplete stress drop. A nonlinear slip deficit rate and complete stress drop could come from two scenarios: 1) nonlinear loading rate of the fault patch from outside the fault patch, e.g., afterslip, or 2) a nonlinear increase in fault strength.

To determine whether loading rate or fault strength can reproduce our observations we need to find an analogous situation where we know that the slip-deficit rate rapidly increases and decays back to a constant level. The aftershocks of the 2004 M 6.0 Parkfield Earthquake present this opportunity. Moment rates of the repeating earthquakes spiked immediately following the mainshock and decayed back to a constant level within 1-2 years, thus we can use these events to distinguish whether a variable loading rate or variable fault strength recovery can explain our observations. Analysis of the aftershocks indicates that a variable loading rate is the preferred model. The fault strength model would predict that fault strength will dramatically decrease at the time of the mainshock, recovering with time. Monotonically increasing fault strength would allow for larger and larger earthquakes with increasing time since the mainshock. Our observations yield the opposite, where the repeating events get smaller with increasing time since the mainshock. Additionally, we prefer the variable loading rate model because we find that the moment rate of the repeating events matches the observed afterslip pattern. This would indicate that afterslip is driving the increased moment rate observed in the aftershocks.

Keynote Talks

Abstracts

Earthquake loss modeling on a global scale: balancing empirical & physics-based approaches

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National Earthquake Information Center, Golden, CO

The USGS Prompt Assessment of Global Earthquakes for Response (PAGER) system provides rapid and automated alerting of estimated economic and human impacts following earthquakes around the globe. Although PAGER's primary purpose is to quantitatively any earthquake's severity for situational awareness and response decision-making, the underlying tools developed are utilized for many other scientific and mitigation efforts. There are four components of the PAGER system. First, earthquakes trigger rapid source characterization; second, these source parameters inform our estimates of shaking-distribution (e.g., ShakeMap). Third, losses are then modeled by computed populations exposed per shaking intensity level, and country-specific and shaking-dependent loss functions are used to provide estimates of economic impact and potential casualties. Finally, these uncertain loss estimates are communicated in an appropriate form for actionable decision-making among a variety of users. Rapidly and automatically assessing the wide range of seismological, demographic, building inventory, and vulnerability information necessary to make such loss estimates entails a requisite balance of empirical & physics-based modeling strategies. Several aspects of our problem cannot yet be adequately solved with purely empirical, nor solely mechanistic, approaches. The "physics-based" model components of the PAGER system are essential for informing empirical models where they are data-limited, and for providing a framework for better understanding the causative pathways that dominate earthquake losses around the globe. In the course of explaining the end-to-end strategies and science/engineering employed by the PAGER system, I also describe what pragmatic choices were made in balancing the uncertainties in and benefits provided by our empirical, semi-empirical, expert-opinion, and physical models. Recognizing and reconciling the complimentary benefits of data-driven verses theoretical problem-solving is at the core of the PAGER system, as it is for a wide variety of other challenges within the earth sciences.

UNAVCO: Recent Earthquake Responses, Multi-hazard Networks, and Technology Development

M. Meghan Miller, UNAVCO, Inc., 6350 Nautilus Drive, Boulder Colorado 80301

UNAVCO, a non-profit university-governed consortium that facilitates geoscience research and education using geodesy, provides services to advance learning in response to significant earthquakes of interest to its science community. One hundred and four U.S. academic Members and 78 non-academic or international Associate Members share UNAVCO's mission and community vision to transform human understanding of the changing Earth by enabling the integration of innovative technologies, open geodetic observations, and research, from pole to pole. The consortium operates a facility that provides engineering, data, and educational services to its investigator community, and the Plate Boundary Observatory, the geodetic component of the EarthScope Facility.

UNAVCO resources include field engineering services; permanent, real-time/high rate, and campaign GPS deployment; new solutions for data communications and power systems; borehole tiltmeter, strainmeter, and seismometer deployments; ground-based LiDAR measurements and airborne LiDAR project management; InSAR data acquisition; assistance with education and outreach activities; data archiving and processing services; a messaging forum for coordination of communications among stakeholders, and hosting of an event website for posting of early results.

Since 2011, UNAVCO has mounted a formal response to each of three events: the 23 August 2011 Mw=5.8 Virginia earthquake, the 2011 March 11 Mw=9.0 Tohoku, Japan earthquake and tsunami, and the 2012 September 5 Mw=7.6 Nicoya Peninsula earthquake, Costa Rica. Initially developed for the 2008 Shake Out earthquake drill in southern California, UNAVCO's organizational event response capabilities were tested and refined to ensure robust protocols for decision-making and geodetic observations in the wake of a natural disaster, with the goal of preparedness for rapid deployments when geodetic observations are required to strengthen geohazards science.

For each of these earthquakes, a different UNAVCO staff member is appointed to serve as Event Response Coordinator, and manage communications, support requests, logistics and decision-making both within UNAVCO and the community at-large. The community activities, science contributions, and other resources are available at: http://www.unavco.org/support/event-response/event-response.html. These events have supported the science community in the collection of key data sets for the advancement of hazards science.

In addition to these event-specific activities, UNAVCO has advanced two community multi-hazards GPS networks, in Africa (AfricaArray) and the Caribbean (COCONet). These provide an observational backbone to support a broad range of Earth and atmospheric science investigations with a focus on earthquake, sea level, and hurricane hazards. UNAVCO Development and Testing has furthered more robust remote BGAN communications for rapid deployments and has conducted shake table testing of various GPS antenna – receiver systems.