Invited personnel：
Sylvain Barbot (Earth Observatory of Singapore, Nanyang Technological University)
James D P Moore (Earth Observatory of Singapore, Nanyang Technological University)

Host researcher：Bunichiro Shibazaki (International Institute of Seismology and Earthquake Engineering, Building Research Institute)

Period：Dec. 18, 2016 – Jan. 15, 2017
Sylvain Barbot: Dec. 18, 2016 – Jan. 15, 2017
James D P Moore: Jan. 4, 2017 – Jan. 18, 2017

Purpose：
Discussion on estimation of inelastic deformation and modeling of earthquake generation using integral equation method considering inelasticity.

Seminar information：

Date: Dec. 19 (Mon.), 2016
Venue: Research Center for Earthquake Prediction, Kyoto University
Guest Speaker: Sylvain Barbot (Nanyang Technological University, Singapore)
Title: A unified representation of quasi-dynamic deformation processes
Abstract :

The last three decades have witnessed an explosion of studies on fault processes, from kinematic modeling of geodetic data, to dynamic modeling of fault rheology. These studies were made possible by fundamental solutions that describe the stress and displacements caused by slip on a fault (e.g., Okada, 1985, 1992). In contrast, direct imaging of the kinematics of off-fault deformation is still impractical, and the dynamic modeling of viscoelastic relaxation or poroelastic rebound still relies on computationally intensive numerical methods (e.g., Barbot & Fialko, 2010). As a result, much less has been learned on the mechanics of deformation at plate boundaries away from faults. Here, we describe a novel approach that allows us to resolve distributed processes in kinematic inversions of geodetic data and to incorporate off-fault processes in numerical models of earthquake cycles. We quantify analytically the displacement and stress incurred by distributed inelastic strain in finite shear zones (Barbot, Moore & Lambert, submitted, 2016). We use these elementary solutions to simultaneously invert for slip on faults and distributed strain in the surrounding rocks. We apply this new technique to study post seismic relaxation in various tectonic contexts. For example, using a decade of geodetic data following the 2010 Mw 7.6 Chi-Chi, Taiwan earthquake we constrain the temperature in the lower crust. Exploiting the stress perturbation of the 2010 Mw 8.6 Wharton Basin earthquake, we place bounds on the width of the oceanic asthenosphere.

Our formulation also allows the dynamic simulation of earthquake cycles with distributed deformation using the integral method, an approach potentially many orders of magnitude faster

than classic finite-element techniques. We simulate earthquakes cycles within the lithosphere-asthenosphere system using rate-and-state friction and the power-law flow of olivine (Lambert & Barbot, submitted, 2016), revealing the prevalence of viscoelastic flow in the early stage of postseismic relaxation. We show models of earthquake cycles in poroelastic media, highlighting variations of the water table at time scales from days to decades. Our approach will be instrumental to building comprehensive physical models of stress evolution at plate boundaries.

Date: Dec. 22 (Thu.) , 2016
Venue: DPRI, Kyoto University
Guest Speaker: Sylvain Barbot (Nanyang Technological University, Singapore)
Title: Partial Rupture of Locked Segments: The Role of Fault Morphology
Abstract:

Assessment of seismic hazard relies on estimates of how large an area of a tectonic fault could potentially rupture in a single earthquake. Vital information for these forecasts includes which areas of a fault are locked and how the fault is segmented. Much research has focused on exploring downdip limits to fault rupture from chemical and thermal boundaries, and along-strike barriers from subducted structural features, yet we regularly see only partial rupture of fully locked fault patches that could have ruptured as a whole in a larger earthquake. Here we draw insight into this conundrum from the 25 April 2015 Mw 7.8 Gorkha (Nepal) earthquake. We invert geodetic data with a structural model of the Main Himalayan thrust in the region of Kathmandu, Nepal, showing that this event was generated by rupture of a décollement bounded on all sides by more steeply dipping ramps. The morphological bounds explain why the event ruptured only a small piece of a large fully locked seismic gap. We then use dynamic earthquake cycle modeling on the same fault geometry to reveal that such events are predicted by the physics. Depending on the earthquake history and the details of rupture dynamics, however, great earthquakes that rupture the entire seismogenic zone are also possible. These insights from Nepal should be applicable to understanding bounds on earthquake size on megathrusts worldwide.

Date: Dec. 27 (Tue.) -28 (Wed.), 2016
Venue: Department of Earth and Planetary Science, The University of Tokyo
Guest Speaker: Sylvain Barbot (Nanyang Technological University, Singapore)
Title: From Crustal To Lithosphere Dynamics: New Perspectives
Abstract:

Crustal dynamics involves the nonlinear interactions of faulting, ductile flow, and fluid migration, complicated by a complex thermal and metamorphic history. The rheological properties (describing how materials deform under stress) of mantle and crustal rocks control many important tectonic processes ranging from continental drift to earthquake triggering, thereby playing a crucial role in the distribution of seismic hazards. Yet the details of their spatial distribution in Earth's interior remain poorly known. We exploit the large stress perturbation incurred by the 2016 earthquake sequence in Kumamoto, Japan to directly image localised and distributed deformation at unprecedented resolution, taking advantage of the dense spatial coverage of the Japanese continuous geodetic network (GEONET), and the rapid acquisitions of the European Sentinel-1A satellite. The earthquakes illuminated distinct regions of low effective viscosity in the lower crust, notably beneath the Mt Aso and Mt Kuju volcanos, surrounded by larger scale variations of viscosity across the back-arc ranging from as low as 5E16 Pa s up to 1E18 Pa s, commensurate with predictions for transient creep of a thermally activated non-linear rheology. This study demonstrates a new potential for geodesy to probe rock rheology in situ across many spatial and temporal scales.

Title: Water stratification in the Indian Ocean lithosphere
Abstract:

Water, the most abundant volatile in Earth's interior, preserves the young surface of our planet by catalysing mantle convection, lubricating plate tectonics and feeding arc volcanism. Since planetary accretion, water has been exchanged between the hydrosphere and the geosphere, but its depth distribution in the mantle remains elusive. Water drastically reduces the strength of olivine and this effect can be exploited to estimate the water content of olivine from the mechanical response of the asthenosphere to stress perturbations such as the ones following large earthquakes. Here, we exploit the sensitivity to water of the strength of olivine, the weakest and most abundant mineral in the upper mantle, and observations of the exceptionally large (moment magnitude 8.6) 2012 Indian Ocean earthquake to constrain the stratification of water content in the upper mantle. Taking into account a wide range of temperature conditions and the transient creep of olivine, we explain the transient deformation in the aftermath of the earthquake that was recorded by continuous geodetic stations along Sumatra as the result of water-and stress-activated creep of olivine. This implies minimum water content of about 0.01 per cent by weight -or 1,600 H atoms per million Si atoms -in the asthenosphere (the part of the upper mantle below the lithosphere). The earthquake ruptured conjugate faults down to great depths, compatible with dry olivine in the oceanic lithosphere. We attribute the steep rheological contrast to dehydration across the lithosphere-asthenosphere boundary, presumably by buoyant melt migration to form the oceanic crust.

Title: The Parkfield tremors reveal slow and fast rupture on the same asperity
Abstract:

The deep extension of the San Andreas Fault is believed to be creeping, but the recent observations of tectonic tremors from these depths indicate a complex deformation style. In particular, an isolated tremor source near Parkfield has been producing a sequence of low-frequency earthquakes that indicates an uncommon mechanism of stress accumulation and release. The tremor pattern regularly oscillated between three and six days from mid-2003 until the 2004 magnitude 6.0 Parkfield earthquake disrupted it. After that event, the tremor source ruptured only about every three days, but over the next two years, it gradually returned to its initial alternating recurrence pattern. The mechanism that drives this recurrence pattern is unknown. We use physics-based models to show that the same tremor asperity–the region from which the low-frequency earthquakes radiate–can regularly slip in slow and fast ruptures, naturally resulting in Recurrence intervals alternating between three and six days. This unusual slip behavior occurs when the tremor asperity size is close to the critical nucleation size of earthquakes. We also show that changes in pore pressure following the Parkfield earthquake can explain the sudden change and gradual recovery of the recurrence intervals. Our findings suggest a framework for fault deformation in which the same asperity can release tectonic stress through both slow and fast ruptures.

Title: Partial rupture of fully locked patches: The role of fault morphology
Abstract:

Assessment of seismic hazard relies on estimates of how large an area of a tectonic fault could potentially rupture in a single earthquake. Vital information for these forecasts includes which areas of a fault are locked and how the fault is segmented. Much research has focused on exploring downdip limits to fault rupture from chemical and thermal boundaries, and along-strike barriers from subducted structural features, yet we regularly see only partial rupture of fully locked fault patches that could have ruptured as a whole in a larger earthquake. Here we draw insight into this conundrum from the 25 April 2015 Mw 7.8 Gorkha (Nepal) earthquake. We invert geodetic data with a structural model of the Main Himalayan thrust in the region of Kathmandu, Nepal, showing that this event was generated by rupture of a décollement bounded on all sides by more steeply dipping ramps. The morphological bounds explain why the event ruptured only a small piece of a large fully locked seismic gap. We then use dynamic earthquake cycle modeling on the same fault geometry to reveal that such events are predicted by the physics. Depending on the earthquake history and the details of rupture dynamics, however, great earthquakes that rupture the entire seismogenic zone are also possible. These insights from Nepal should be applicable to understanding bounds on earthquake size on megathrusts worldwide.

Date: Jan. 12 (Thu.), 2017

Venue: Dept. Earth Sci., Tohoku University.

Speaker: Sylvain Barbot (Nanyang Technological University, Singapore)

Title: Upper-mantle water stratification inferred from observations of the 2012 Indian Ocean earthquake

Abstract:

Water, the most abundant volatile in Earth's interior, preserves the young surface of our planet by catalysing mantle convection, lubricating plate tectonics and feeding arc volcanism. Since planetary accretion, water has been exchanged between the hydrosphere and the geosphere, but its depth distribution in the mantle remains elusive. Water drastically reduces the strength of olivine and this effect can be exploited to estimate the water content of olivine from the mechanical response of the asthenosphere to stress perturbations such as the ones following large earthquakes. Here, we exploit the sensitivity to water of the strength of olivine, the weakest and most abundant mineral in the upper mantle, and observations of the exceptionally large (moment magnitude 8.6) 2012 Indian Ocean earthquake to constrain the stratification of water content in the upper mantle. Taking into account a wide range of temperature conditions and the transient creep of olivine, we explain the transient deformation in the aftermath of the earthquake that was recorded by continuous geodetic stations along Sumatra as the result of water- and stress-activated creep of olivine. This implies a minimum water content of about 0.01 per cent by weight—or 1,600 H atoms per million Si atoms—in the asthenosphere (the part of the upper mantle below the lithosphere). The earthquake ruptured conjugate faults down to great depths, compatible with dry olivine in the oceanic lithosphere. We attribute the steep rheological contrast to dehydration across the lithosphere–asthenosphere boundary, presumably by buoyant melt migration to form the oceanic crust.

Date: Jan. 12 (Thu.), 2017

Venue: Dept. Earth Sci., Tohoku University.

Speaker: James D. P. Moore (Nanyang Technological University, Singapore)

Title: From quiescence to unrest and back again: 150 years of geodetic measurements at Santorini volcano, Greece

Abstract:

Historical bathymetric charts are a potential resource for better understanding the dynamics of the seafloor and the role of active processes, such as submarine volcanism. The British Admiralty, for example, have been involved in lead line measurements of seafloor depth since the early 1790s. Here, we report on an analysis of historical charts in the region of Santorini volcano, Greece. Repeat lead line surveys in 1848, late 1866, and 1925–1928 as well as multibeam swath bathymetry surveys in 2001 and 2006 have been used to document changes in seafloor depth. These data reveal that the flanks of the Kameni Islands, a dacitic dome complex in the caldera center, have shallowed by up to 175 m and deepened by up to 80 m since 1848. The largest shallowing occurred between the late 1866 and 1925–1928 surveys and the largest deepening occurred during the 1925–1928 and 2001 and 2006 surveys. The shallowing is attributed to the emplacement of lavas during effusive eruptions in both 1866–1870 and 1925–1928 at rates of up to 0.18 and 0.05 km^3 a^{21}, respectively. The deepening is attributed to a load- induced viscoelastic stress relaxation following the 1866– 1870 and 1925–1928 lava eruptions. The elastic thickness and viscosity that best fits the observed deepening are 1.0 km and 10^{16} Pa s, respectively. This parameter pair, which is consistent with the predictions of a shal- low magma chamber thermal model, explains both the amplitude and wavelength of the historical bathymet- ric data and the present day rate of subsidence inferred from InSAR analysis.

Date: Jan. 17 (Tue.), 2017

Venue: Research Center for Earthquake Prediction, Kyoto University

Speaker: James D P Moore (Nanyang Technological University, Singapore)

Title: Lithospheric flexure, cycles of deposition in a sedimentary basin, the Earth's gravity field and mantle dynamics

Abstract:

An understanding of the finite strength of the lithosphere and how it develops over time is key to understanding many geological and geodetic observations. For example, when consideration is given to the fact that the long-term strength of the lithosphere depends on both thermal and load age we are able to model stratal geometries in sedimentary basins that not only closely resemble stratigraphic observations, but do not require either long-term sea-level or sediment flux changes in order to explain them. Furthermore, power spectral studies of the Earth's gravity field show that it is dominated at short wavelengths by the gravity effect of topography and its isostatic compensation and at long wavelengths by mantle dynamics where the switchover between these mechanisms is governed by the strength of the lithosphere. Using flexural transfer functions and admittance equations we can move beyond Airy isostasy and remove the isostatic contribution of regional compensation to independently examine the global gravity field for flexural effects and the signature of mantle dynamics.