Banff International Research Station

for Mathematical Innovation and Discovery

13w2171: Statistics and Triggering of Earthquakes
Aug 30 - Sep 1, 2013

MEALS

Coffee Breaks: As per daily schedule, in the foyer of the TransCanada Pipeline Pavilion (TCPL) *(included in workshop)*

For meal options at the Banff Centre, there are food outlets on The Banff Centre campus such as Vistas Main Dining Room on the 4th floor of Sally Borden Building (breakfast: 7:00-9:30am; lunch: 11:30am-1:30pm; dinner: 5:30-7:30pm), Le Cafe (ground floor, Sally Borden Building) and the Maclab Bistro (Kinnear Centre). You will also find a good selection of restaurants in the town of Banff which is a 10-15 minute walk from Corbett Hall.

MEETING ROOMS

All lectures will be held in the new lecture theater in the TransCanada Pipelines Pavilion (TCPL). LCD projector and blackboards are available for presentations.

SCHEDULE

Friday

16:00	Check-in begins (Front Desk – Professional Development Centre - open 24 hours)
19:30	**Introduction & poster highlights**
20:30	**Poster session** (boards are 4'x6' in size) Beverages and a small assortment of snacks are available in the 2nd floor lounge, Corbett Hall, on a cash honor system.

Saturday

7:00-9:00	Breakfast
9:00	**I. Zaliapin**
9:30	**M. Naylor**
10:00	Discussions & Coffee Break, TCPL
11:00	**J. Fineberg**
11:30	**P. Johnson**
12:00	Discussions & Lunch
13:30	**D. Zigone**
14:00	**A. Velasco**
14:30	Discussions & Coffee Break, TCPL
15:30	**V. Durand**
16:00	**X. Meng**
16:30	**J. Davidsen**
17:00	Discussions
18:30	Dinner

20:30 **Poster session** (boards are 4'x6' in size)
Beverages and a small assortment of snacks are available in the 2nd floor lounge, Corbett Hall, on a cash honor system.

Sunday

7:00-9:00 Breakfast
9:00 **D. Eaton**
9:30 **N. van der Elst**
10:00 Discussions & Coffee Break, TCPL
11:00 Free discussions in smaller groups
Checkout by 12 noon.
12:00 Lunch
13:30 Free discussions in smaller groups
15:00 End

** 2-day workshops are welcome to use BIRS facilities (2nd Floor Lounge at Corbett Hall, TCPL, Reading Room) until 15:00 on Sunday, although participants are still required to checkout of the guest rooms by 12 noon. There is no coffee break service on Sunday afternoon, but self-serve coffee and tea are always available in the 2nd floor lounge, Corbett Hall. **

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ABSTRACTS

(in alphabetic order by speaker surname)

Speaker: Jörn Davidsen (University of Calgary)
Title: Triggering cascades and statistical properties of aftershocks
Abstract: Applying a simple general procedure for identifying aftershocks, we investigate their statistical properties for a high-resolution earthquake catalog covering Southern California. We compare our results with those obtained by using other methods in order to show which features truly characterize aftershock sequences and which depend on the definition of aftershocks. Features robust across methods include the *p* value in the Omori-Utsu law for large main shocks, Båth's law, and the productivity law with an exponent smaller than the *b* value in the Gutenberg-Richter law. The identification of a typical aftershock distance with the rupture length is a feature we confirm as well as a power law decay in the spatial distribution of aftershocks with an exponent less than 2.
Other results we obtain, but not common to all other works including Marsan and Lengliné (2008), Hainzl and Marsan (2008), and Zhuang et al. (2008), are (a) *p* values that do not increase with the main shock magnitude; (b) the duration of bare aftershock sequences that scales with the main shock magnitude; (c) an additional power law in the temporal variation, at intermediate times, in the rate of aftershocks for main shocks of small and intermediate magnitude; and (d) a *b* value for the Gutenberg-Richter law of background events that is sensibly larger than that of aftershocks. Tests on synthetic catalogs generated by the epidemic-type aftershock sequence model corroborate the validity of our approach.

Speaker: Virginie Durand (CNRS)
Title: Observations of seismic interactions along the North Anatolian Fault
Abstract: In the northwestern Turkey, two tectonic regimes exist, with the transform North Anatolian Fault and extension clusters around it. We show that these two systems strongly interact, but respond differently to Izmit earthquake (1999) stimulation. The North Anatolian Fault is immediately activated, at short distances from the rupture, whereas the activation of the clusters is delayed (from several days to several months) and occurs at greater distances. We have investigated the role of the dynamic and static stress changes after the 1999 Izmit earthquake, on four pre-existing seismic clusters located in the eastern Marmara sea, beyond the western end of the earthquake rupture. These four clusters show long-lasting modifications in their seismicity rate. We observe that these seismic activity variations are strongly related to the stress changes. Where the dynamic stress changes are important, the activation is instantaneous, whereas when the static stress changes are positive and large, the activation lasts longer. When static stress changes are negative, we observe the appearance of a seismicity shadow. However, one of the clusters, the Yalova cluster, does not reply in this way. In spite of a negative stress change, its activity is strongly increased for a long duration. We infer that this activation is due to an increase of the pressure after the earthquake.

Speaker: David Eaton (University of Calgary)
Title: Importance of stratabound fracture networks for magnitude-recurrence characteristics and hazard assessment of hydraulic fracturing
Abstract: Hydraulic fracturing, a powerful completion technique used to enhance oil or gas production from impermeable strata, may trigger unintended earthquake activity. The primary basis for assessment of triggered and natural seismic hazard is the classic Gutenberg-Richter (G-R) relation, which expresses scale-independent behavior of earthquake magnitudes. Here, we show that magnitude-distance trends for microearthquakes induced by hydraulic fracturing may deviate significantly from the G-R relation. This breakdown in the power-law scaling paradigm can be explained by a new model based on the activation of stratabound fracture networks, in which fracture height growth is limited by mechanical bed thickness. The reservoir strata considered in three examples exhibit a lognormal bed-thickness distribution, which predicts a Gaussian decay in the magnitude-frequency distribution that provides an excellent fit to the observations. This new relationship has profound implications for fundamental scaling behavior of induced microearthquakes, as well as for forecasting the probability of larger earthquakes triggered by hydraulic fracturing in oil and gas development.

Speaker: Nicholas van der Elst (Lamont-Doherty Earth Observatory)
Title: Remote triggering at sites of anthropogenic fluid injection and induced seismicity.
Abstract: Remote triggering by seismic waves has been most consistently documented in volcanic and hydrothermal systems. While this may in part reflect observational biases, it may also demonstrate the importance of fluids in the dynamic triggering mechanism. A recent dramatic increase in seismicity in the midwestern United States is likely related to deep wastewater injection, making these areas potential analogs of natural hydrothermal systems. A new study has demonstrated that sites of fluid-induced earthquakes are also more susceptible to earthquake triggering from transient dynamic stresses. Sensitivity to remote triggering is most clearly seen in sites with a long delay between the start of injection and the onset of seismicity, and only in regions that went on to host moderate magnitude earthquakes (Mw 4.5-5.7) within 6 to 20 months. Enhanced triggering susceptibility in these settings is linked to the presence of pressurized fluid flow and critically loaded faults. A mechanism involving fracture clogging and unclogging or dynamic permeability enhancement may therefore explain at least some fraction of remotely triggered earthquakes.

Speaker: Jay Fineberg (The Hebrew University of Jerusalem)
Title: How Things Slide: Rapid Dynamics at the Onset of Friction
Abstract: The dynamics of how two rough frictional interfaces detach is a fundamental question in fields ranging from material science to geophysics. On the one hand, the onset of frictional motion is thought to be characterized by the static friction coefficient that couples two materials. For hundreds of years, this has been considered to be a material constant. On the other hand, the same processes that give rise to the onset of frictional motion also cause earthquakes, when tectonic plates locked together by friction start to slip. The frictional interface that locks two macroscopic blocks of material together composed of an ensemble of discrete microscopic contacts that give the interface its strength. We will present new experiments that show how the onset of frictional motion is caused by the dynamic fracture of these contacts. We'll first show that the stress fields driving this motion are closely described by the singular fields that, classically, describe rapidly propagating cracks. We'll then show that the "static friction coefficient" is not a material constant at all, but is intimately related to the details of how forces are applied to a system. We'll then look at examples of when slight perturbations can trigger a seismic event that may be understood using a fracture criterion for the onset of slip.

Speaker: Paul Johnson (LANL)
Title: Elastic Linear and Nonlinear Induced by Dynamical Excitation In the Earth
Abstract: When a large amplitude seismic surface traverses a region of active slip, the elasticity of the fault gouge as well as the surrounding material may be perturbed. The elastic perturbation may lead to instability and slip (triggering) in regions of active faulting, meaning the effect may be potentially long in duration. Our view is that triggering, especially delayed triggering, is one manifestation of the elastic perturbation. We are attempting to identify other potential signatures associated with this perturbation, and as well as its duration and its implications to seismic hazard. It may be that changes in earthquake occurrence time (recurrence) are one signature that can be used. Velocity change and thickness or volume change are also potential signatures of interest. A number of laboratory and field observations will be described that suggest the elastic change can be measured and characterized.

Speaker: Xiaofeng Meng (Georgia Tech)
Title: Testing static vs dynamic triggering following large earthquakes in California
Abstract: Whether static or dynamic stress changes are the dominant mechanism for triggering earthquakes in the near field is currently unclear. Studies on earthquake triggering usually depend on seismicity rate changes from earthquake catalogs. However, such catalogs are often incomplete immediately after the mainshock, which may cause apparent seismicity rate changes unrelated to stress changes. Applying a recently developed matched filter technique, we detect ~8 times more earthquakes than the NCSN catalog near the Parkfield section of the San Andreas fault around the 2003 Mw6.5 San Simeon earthquake. The newly identified events along the creeping section of the San Andreas fault show a statistically significant decrease following the San Simeon main shock, which correlates well with the negative static shear stress changes (i.e., stress shadow) cast by the main shock. However, a moderate increase of seismicity is observed near Parkfield where the static shear stress increased. Such pattern is consistent with an independent observation of tremor rate changes around the San Simeon main shock. We also conducted a similar study in southern California around the 2010 Mw7.2 El Mayor-Cucapah earthquake, focusing on the Salton Sea geothermal field (SSGF) and San Jacinto fault zone (SJFZ). Using continuous borehole recordings, we detect ~20 times more events than listed in the SCSN catalog. The seismicity rate near SSGF and SJFZ both experienced significant increase immediately following the main shock. However, the seismicity rate near SSGF, where static Coulomb stress decreased, dropped below the pre-shock level after ~50 days. On the other hand, the seismicity rate near SJFZ with positive Coulomb stress changes remained higher than the background rate for several years. Such pattern is consistent with dynamic stress changes being dominant in the short period following the main shock, while static stress changes may take over in the longer term.

Speaker: Mark Naylor (University of Edinburgh)
Title: TBA
Abstract: TBA

Speaker: Aaron Velasco (University of Texas at El Paso)
Title: Difficulties Auto-Processing Large Data Sets to Detect Remote Earthquake and Non-Volcanic Tremor Triggering
Abstract: In recent years, dynamic triggering has been documented to occur in a variety of tectonic environments, caused by a number of large earthquakes. Although widespread, clear documentation of regions of common triggering is sparse. Furthermore, clearly identifying dynamic and delayed triggering requires searching thousands of waveforms for small, isolated, single events (earthquakes and non-volcanic tremor). The detection of events must also take into account background seismicity rates, thus require analysis of each

stations hours prior and after a large earthquake. The challenges with detecting triggering occur as a result of significant higher frequency noise, the frequencies used to detect local earthquakes. Typical methods rely on automated algorithms, such as a short-term average, long-term average ratio (STA/LTA) detection algorithm performed on a single, high-pass filtered channel. Review of all data by an analyst presents significant challenges in data management and time. However, automated methods detect not only small events, but also noise that can result in false detections. Innovative techniques must be developed to overcome the challenges presented with automated techniques to fully explore the extent of dynamic triggering.

Speaker: Ilya Zaliapin (University of Nevada, Reno)
Title: Earthquake clusters in southern California: Identification and relation to physical properties of the crust
Abstract: We discuss a robust method for comprehensive detection and analysis of earthquake clusters. The method is based on nearest-neighbor distances of events in space-time-energy domain. The method is applied to a 1981–2011 relocated seismicity catalog of southern California having 111,981 events with magnitudes $m \geq 2$ and corresponding synthetic catalogs produced by the Epidemic Type Aftershock Sequence (ETAS) model. Analysis of the ETAS model demonstrates that the cluster detection results are *accurate* and *stable* with respect to (1) three numerical parameters of the method, (2) variations of the minimal reported magnitude, (3) catalog incompleteness, and (4) location errors. Application of the method to the observed catalog separates the 111,981 examined earthquakes into 41,393 statistically significant *clusters* comprised of *foreshocks, mainshocks,* and *aftershocks*. Systematic analysis with our method allows us to detect several new features of seismicity that include (1) existence of a significant population of *single-event clusters,* (2) existence of foreshock activity in natural seismicity that exceed expectation based on the ETAS model, and (3) dependence of all cluster properties, except area, on the *magnitude difference* of events from mainshocks but not on their absolute values. Next, the detected families are analyzed using their representation as time oriented tree graphs. The results (1) demonstrate that the clustering associated with the largest earthquakes, m>7, is statistically different from that of small-to-medium earthquakes; (2) establish the existence of two dominant types of small-to-medium magnitude earthquake families—burst-like and swarm-like sequences—and a variety of intermediate cluster forms obtained as a mixture of the two dominant types; (3) suggest a simple new quantitative measure for identifying the cluster type based on its topological structure; (4) demonstrate systematic spatial variability of the cluster characteristics on a scale of tens of kilometers in relation to heat flow and other properties governing the effective viscosity of a region; and (5) establish correlation between the family topological structure and a dozen of metric properties traditionally considered in the literature (number of aftershocks, duration, spatial properties, b-value, parameters of Omori-Utsu and Båth law, etc.). The burst-like clusters likely reflect highly brittle failures in relatively cold regions, while the swarm-like clusters are likely associated with mixed brittle-ductile failures in regions with relatively high temperature and/or fluid content.

Speaker: Dimitri Zigone (University of Southern California)
Title: Observations, triggering and modeling of slow slip events and non-volcanic tremor in the Guerrero subduction zone (Mexico)
Abstract: In this study we examine the relations between Slow Slip Event (SSE), Non Volcanic tremor (NVT) and regular earthquakes in the Guerrero subduction zone in order to clarify the phenomenology and physics of these manifestations of fault slip.
We investigate the triggering of seismic tremor and slow slip event in Guerrero by the February 27, 2010 Maule earthquake (Mw 8.8). Triggered tremors start with the arrival of the S wave generated by the Maule earthquake, and continue to occur during the passing of ScS, SS, Love and Rayleigh waves. The Rayleigh wave dispersion curve footprints the high

frequency energy envelope of the triggered tremor, indicating a strong modulation of the source of NVT by the passing surface waves. This correlation and modulation by the passing waves is progressively lost with time over a few hours. The tremor activity continues during the weeks/months after the Maule earthquake. GPS time series suggest that the second sub-event of the 2009-2010 SSE in Guerrero is also triggered by the Maule earthquake. The southward displacement of the GPS stations starts coincidently with the earthquake and NVT. The long duration of NVT indicates a continuing deformation process at depth, which we propose to be the second sub-event of the 2009-2010 SSE. We show a quasi-systematic correlation between surface displacement rate measured by GPS and tremor activity, suggesting that the NVT are controlled by variations in the slip history of the SSE.

To explore the range of conditions associated with the observed long-term evolution of NVT in relation to SSE and earthquakes, we use a numerical model with a planar interface governed by space-varying static/kinetic friction and dislocation creep in elastic solid. The model is tailored through the employed dimensions, distribution of rheological properties and boundary conditions to the Guerrero segment, with particular attention to conditions of the past 15 years for which observations are available. A section of the fault with zero weakening during frictional slip fails in a mode corresponding to a "critical depinning transition" that produces many observed features of NVT. When a high creep patch representing a section sustaining SSE is added, strong interactions between NVT and SSE are observed as in the natural fault system. We also examine triggering of NVT by larger remote earthquakes, implemented by adding periodic triggering oscillations to the regular tectonic loading. In addition to modeling observations of NVT and SSE made in Guerrero during the past 15 years, the simulations allow us to distinguish aspects of the observed behavior that are robust over long time intervals from aspects that change during intervals longer than the observational period.