10th International Workshop on Statistical Seismology

20-24 February 2017, Wellington, New Zealand

STATSEI

Programme and Abstracts

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Sponsors

Local Organising Committee

Annemarie Christophersen
David Rhoades
David Harte
Matt Gerstenberger
Ting Wang
Katy Kelly
Kat Hammond

Contents

The central shape of the logo presents a stylised version of the letter 'S', first letter of 'Statistical' and 'Seismology'. The spiral shape used to cut out the negative space of the 'S' is called 'koru'. Koru is the Māori word for loop. The shape is based on an unfurling fern and symbolises new life, growth, strength and peace. The koru is extensively used in Māori artwork and thus establishes a direct connection to New Zealand.

The 'X' in the background is the roman numeral for the number '10' and denotes the 10th continuance of our meeting.

The colours red and grey connect to GNS Science as host and key organiser of the workshop.

Designed by: GNS Science Graphics team

Programme

Monday, 20 February 2017 — Victoria University - DAY 1

10:00 - 12:00	**CORSSA tutorial 1 - Victoria University, room AM101** (Chair: Jiancang Zhuang)
	The Poisson assumption: applications in spite of clustering (Speaker: Dr Andy Michael, USGS)
13:00 - 15:00	**CORSSA tutorial 2 - Victoria University, room AM101** (Chair: Jiancang Zhuang)
	Statistical modelling of induced seismicity (Speaker: Dr Sebastian Hainzl, GFZ Potsdam)
17:00 - 19:00	**Icebreaker welcome function**
	Foxglove bar, 33 Queens Wharf

Tuesday, 21 February 2017 — Te Papa - DAY 2

08:30 - 10:00	**Opening** (Chair: Annemarie Christophersen)
08:30	Welcome (Ian Simpson, CEO of GNS Science)
08:40	Welcome (Richard Smith, Manager- Research Strategy and Science Investment, EQC)
08:45	A tale of Statsei (Annemarie Christophersen)
08:55	The 2016 Kaikoura earthquake: preliminary seismological report (Anna Kaiser)
09:15	Earthquake forecasts and their uptake in the wake of the 2016 Kaikoura earthquake (Matt Gerstenberger)
09:30	Mind the gap (David Jackson)
10:00 - 10:30	**Coffee and posters**
10:30 - 12:10	**Stochastic modelling of spatiotemporal earthquake occurrence** (Chair: Ting Wang, David Harte)
10:30	Markov-modulated Hawkes process with marks (Ting Wang, Mark Bebbington)
10:50	A failure process driven by a self-correcting model (Elisa Varini, Renata Rotondi)
11:10	Nonparametric estimation of the spatial distribution of aftershocks for space-time Hawkes point process models and performance evaluation of time-independent CSEP forecasts using both deviance residuals and Voronoi residuals. (Joshua S. Gordon, Frederic P. Schoenberg, Eric W. Fox)
11:30	A nonparametric Bayesian approach to seismic hazard modeling using the ETAS framework (Gordon Ross)
11:50	Discussion
12:10 - 13:10	**Lunch and posters**
13:10 - 14:50	**Earthquake forecasting and testing 1** (Chair: Tom Jordan, David Rhoades)
13:10	CSEP-Japan earthquake predictability experiment and testing results (Naoshi Hirata)
13:30	Statistical monitoring of the seismicity before and after the Kumamoto earthquakes (Takao Kumazawa, Yosihiko Ogata, Hiroshi Tsuruoka)
13:50	Could the Tohoku Mw9.0 earthquake be forecasted by the Pattern Informatics method? (Yongxian Zhang)
14:10	A spatiotemporal clustering model for the Third Uniform California Earthquake Rupture Forecast (UCERF3-ETAS) – Toward an operational earthquake forecast (Edward Field, other WGCEP participants)
14:30	Statistical space-time models for the evaluation of aftershock hazard (Yuh-Ing Chen)
14:50 - 15:10	**Coffee**
15:10 - 16:50	**Earthquake forecasting and testing 2** (Chair: Tom Jordan, David Rhoades)
15:10	Towards the implementation of the probability forecast of large earthquakes (Yosihiko Ogata)
15:30	Space-time forecasting of seismic events in Chile (Orietta Nicolis, Marcello Chiodi, Giada Adelfio)
15:50	Feasibility of automatic real-time aftershock forecasting in Japan (Takahiro Omi, Yosihiko Ogata, Katsuhiko Shiomi, Bogdan Enescu, Kaoru Sawazaki, Kazuyuki Aihara)
16:10	Testing planned USGS operational aftershock forecasts (Andrew Michael, Edward Field, Jeanne Hardebeck, Nicholas van der Elst)
16:30	Discussion
16:50 - 17:55	**Poster session with drinks and nibbles**
18:00 - 19:30	**Public lecture: Earthquake forecasting: Science and practice** (Soundings Theatre)

Wednesday, 22 February 2017

08:30 - 10:10	**Summary statistics, empirical relationships and data quality** (Chair: Bill Ellsworth, Gert Zöller)
08:30	Statistical analysis of seismicity characteristics in the United States (Xiaowei Chen, Yifang Cheng, Jackson Haffener, Colin Pennington, Yan Qin, Abraham Wallace)
08:50	Sampling uncertainties in the Aki-Utsu b-value estimation method, and the use of “true” b-value likelihoods to ascertain probabilities and confidence limits to b estimates. (Fidencio Alejandro Nava Pichardo, Lenin Ávila Barrientos, Francisco Ramón Zúñiga Dávila-Madrid, Victor Hugo Márquez Ramírez, Ivonne Torres Carreón)
09:10	Testing the spatial variation of the b-value of the Gutenberg-Richter law in Italy (Matteo Taroni, Federico Signora, Pierpaolo Brutti)
09:30	On the biased estimate of earthquake clustering parameters caused by short-term aftershock missing (Jiancang Zhuang, Ting Wang)
09:50	What really causes scatter in shear wave splitting measurements? (Martha Savage, Richard Arnold, Kenny Graham, Stefan Mroczek, Jessica Johnson, James Wookey, Yosuke Aoki)
10:10 - 10:40	**Coffee and posters**
10:40 - 11:40	**Summary statistics, empirical relationships and data quality continued** (Chair: Bill Ellsworth, Gert Zöller)
10:40	New statistical methods for tectonic stress estimation (Richard Arnold, Peter Jupp)
11:00	The magnitude of the extreme aftershock (Robert Shcherbakov, Jiancang Zhuang, Yosihiko Ogata)
11:20	Discussion
11:40 - 12:40	**Earthquake physics 1** (Chair: Jeanne Hardebeck, Sebastian Hinzl)
11:40	Capturing elastic rebound and source finiteness in empirical aftershock forecasting kernels. (Nicholas van der Elst, Bruce Shaw, Morgan Page)
12:00	Fault slip rates and seismic moment deficits on major faults in Ordos constrained by GPS observation (Shiyong Zhou, Yilei Huang, Bin Gao, Qinliang Wang)
12:20	Evolution of earthquake rupture potential along active faults, inferred from seismicity rates and size distributions (Thessa Tormann, Stefan Wiemer, Bogdan Enescu, Jochen Woessner)
12:40 - 13:40	**Lunch and posters**
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13:40	Improved understanding of earthquake triggering with waveform matching method (Zhigang Peng, Dongdong Yao, Chenyu Li, Chastity Aiken, Xiaofeng Meng)
14:00	To which level did the 2010 M8.8 Maule earthquake fill the pre-existing seismic gap? (Lifeng Wang, Sebastian Hainzl, Martin Mai)
14:20	Numerical simulations of co-seismic electromagnetic signals (Qinghua Huang, Hengxin Ren, Xiaofei Chen)
14:40	Glacier: an earthquake laboratory? (Evgeny Podolskiy, Sebastian Heimann, Danijel Schorlemmer, Shin Sugiyama, Fabian Walter, Martin Funk, Riccardo Genco)
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15:30 - 16:50	**Earthquake physics 3** (Chair: Bruce Shaw, Jeanne Hardebeck)
15:30	Focal mechanism distributions provide insight into static and dynamic stress triggering (Jeanne Hardebeck, Xiaofeng Meng, Chastity Aiken, Zhigang Peng)
15:50	Precise relative stress drops (Bruce E Shaw, William L Ellsworth, Nana Yoshimitsu, Yihe Huang, Gregory Beroza)
16:10	Towards stable stress drop measurements for induced earthquakes in Oklahoma (William Ellsworth, Nana Yoshimitsu, Gregory Beroza, Bruce Shaw)
16:30	Discussion
16:50 - 17:50	**Panel discussion: Software, data, education** (Chair: Jiancang Zhuang, Ting Wang)
	What existing data bases, software, and educational resources are useful for statistical seismology?
	What future development of data bases, software and educational resources would be beneficial to statistical seismology?
	Panellists: Bill Ellsworth, Natalie Balfour, Hiroshi Tsuruoka, David Harte, Sandy Steacy, Martha Savage
18:00 - 22:00	**Conference dinner**
	At Mac's Function Centre; doors open for drinks and nibbles at 6 pm; dinner from 7:30 pm

Thursday, 23 February 2017

Field Trip - DAY 4

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19:00	Return to Te Papa

Friday, 24 February 2017

Te Papa - DAY 5

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08:30	Development of an 8000 year record of large earthquakes on the Alpine Fault, New Zealand (Ursula Cochran, Kate Clark, Kelvin Berryman, Glenn Biasi, Robert Langridge, Pilar Villamor, Jamie Howarth, Russ Van Dissen)
08:50	Spatio-temporal patterns of rupture during great earthquakes on the Alpine Fault, New Zealand. (Jamie Howarth, Sean Fitzsimons, Rob Langridge, Ursula Cochran, Kate Clark, Glenn Biasi)
09:10	Completeness and interpretation of New Zealand's prehistorical earthquake record (Andy Nicol, Russ Van Dissen, Russell Robinson, Mark Stirling, Matt Gerstenberger)
09:30	A summary of fault ruptures and slip from the November 14th 2016 Kaikoura earthquake (Robert Langridge, Nicola Litchfield, Russ Van Dissen, William Ries, and the Earthquake Geology mapping teams)
09:50	Surface fault rupture during the November 2016 Mw 7.8 Kaikoura earthquake, and paleoseismology of the Kekerengu Fault - one of the country's fastest slipping onland active faults (Russ Van Dissen, Tim Little, Kaikoura Earthquake Surface Rupture Response Team)
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11:00	Long-term Probability of the Kanto M8 Class Earthquake along the Sagami Trough, Central Japan and its uncertainty (Masajiro Imoto, Nobuyuki Morikawa, Hiroyuki Fujiwara)
11:20	Balancing the seismic moment distribution across large timescales: inclusion of fault source models in PSHA for intraplate Australia (Jonathan Griffin, Dan Clark, Trevor Allen, Mark Stirling, Mark Leonard, Hadi Ghasemi)
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14:00	Coulomb / statistical models for aftershock forecasting (Sandy Steacy, Thomas Reverso)
14:20	Uncertainty and assessing long-term rates in low seismicity regions (Matthew Gerstenberger, Danijel Schorlemmer, John Aiken)
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16:00	Scoring ground motion models (Sum Mak)
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04 **Cumulative coulomb stress triggering as an explanation for the Canterbury (New Zealand) aftershock sequence: Initial conditions are everything?,** *Mark Bebbington, David Harte, Charles Williams*

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Abstracts

Presentation type: Oral
In time-schedule order

Opening

(Chair: Annemarie Christophersen)

08:45 **A tale of Statsei**

Annemarie Christophersen, David Rhoades, David Harte
GNS Science, Lower Hutt, New Zealand

The International Statistical Seismology (StatSei) workshop is a well-established biennial meeting focusing on recent developments in statistical seismology. The meetings cover a series of topics, including statistical descriptions of earthquake occurrences, earthquake physics, earthquake forecasting and forecast evaluations, earthquake triggering, and many more. Starting in 1998, the meeting was held in China (1998 and 2013), New Zealand (2001), Mexico (2003), Japan (2006), Italy (2007), the United States of America (2009), Greece (2011) and Germany (2015). We briefly follow previous Statsei meetings around the world. See whether you can spot yourselves during this brief photo journey.

08:55 **The 2016 Kaikōura earthquake: preliminary seismological report**

Anna Kaiser, Kaikoura earthquake response team
GNS Science, Lower Hutt, New Zealand

The 2016 Mw 7.8 Kaikōura earthquake is the latest of several damaging earthquakes to strike New Zealand in the last decade. We present a preliminary overview and seismological report on the earthquake and its impacts.

The effects were wide-ranging across the upper South Island including two fatalities, tsunami, tens of thousands of landslides, collapse of one building and damage to numerous structures. Ground motions during the earthquake exceeded 1g at both ends of the rupture and spectral accelerations exceeded 1 in 500 year design level spectra in numerous towns in the upper South Island, as well as parts of the capital city of Wellington at critical periods of 1-2 s corresponding to those of mid-rise structures.

The earthquake rupture was extremely complex involving at least thirteen separate faults extending over ~150km from the epicentre in North Canterbury to close to Cook Strait. The mechanism of the mainshock was oblique thrust, however individual fault ruptures and aftershocks show a range of thrust and strike-slip mechanisms. We use back projection and slip inversion methods to derive preliminary insights into the evolution of the rupture from south to north, identifying at least three distinct southwest to northeast propagating failures. The last phase is associated with a strong pulse of energy release in the northern half of the rupture zone in the vicinity of the largest surface displacements. New Zealand's National Seismic Hazard Model included the possibility of combined rupture of these northern dominant faults, but did not capture the full complexity and extent of fault rupture during the Kaikōura earthquake. Current work is focussed on unravelling details of the complex earthquake rupture and its implications for seismic hazard.

* This seismological summary was compiled based on work by the Kaikoura earthquake response team from GNS Science, NIWA, University of Canterbury, University of Otago, Victoria University of Wellington, University of Auckland, Land Information New Zealand and other partner institutions. Specific contributions to this presentation have been provided by: N. Balfour, B. Fry, C. Holden, N. Litchfield, M. Gerstenberger, E. D'Anastasio, N. Horspool, G. McVerry, J. Ristau, K. Gledhill, S. Bannister, A. Christophersen, K. Clark, W. Power, D. Rhoades, I. Hamling, L. Wallace, J. Mountjoy, Y. Kaneko, R. Benites, C. Van Houtte, C. Massey, S. Dellow, S. Hreinsdottir, K. Berryman.

09:15

Earthquake forecasts and their uptake in the wake of the 2016 Kaikoura earthquake

*Matt Gerstenberger and the Earthquake Forecasting Team**

The recovery effort following the Kaikoura earthquake has been distributed over a large area and has required a diverse response. We have provided model results ranging from aftershock probability tables through to detailed and specific engineering information. Increasing the complexity of our response, three slow slip events (SSE) were triggered by the Mw 7.8 on the Hikurangi subduction interface. These SSE are unique in character in our approximately 20 years of observations; there was a need to understand and include the implications of these SSE on our forecasts.

As has been the case in past New Zealand sequences, data quality issues, including changes to the main shock magnitude, have provided a challenge to forecast modelling. Similar to our practice during past sequences, we have used both short-term and medium-term clustering models in our hybrid forecasts. One change from previous practice is the use of a negative binomial distribution, constrained by ETAS simulations, to describe the uncertainty in the forecast rates. These uncertainties were used to generate stochastic event sets for hazard calculations feeding into engineering decisions (e.g., forecast design spectra as compared to the design standard, and probabilities of landslide occurrence). The aftershock productivity remains low when compared to average New Zealand aftershock productivity. In this presentation we will describe our experiences, including the models and outputs that we developed to meet the increasing and diverse range of end-users of the forecasts.

*Earthquake Forecasting team (in alphabetical order): Stephen Bannister, Julia Becker, Annemarie Christophersen, Bill Fry, David Harte, Nick Horspool, Sara McBride, Sally Potter, David Rhoades, and Laura Wallace

09:30

Mind the gap

David Jackson
UCLA, Los Angeles, CA, USA

Science involves testing hypotheses, but how? Prospective testing depends on sufficient data and precise statements of the hypotheses. The latter is the most creative and difficult part of the exercise. A good hypothesis should be quite specific, yet general enough not to depend on non-essential parameter choices. The Collaboratory for the Study of Earthquake Predictability (CSEP) can attest that a hypothesis acceptable to a journal editor may differ from a testable hypothesis, and vice versa. CSEP tests hundreds of forecast hypotheses expressed as the conditional rate density of epicenter occurrence in space, time and magnitude, but many important hypotheses are not well expressed that way, and often the conditions are not easily quantified. For example, earthquake fault rupture involves much more than epicenters, and conditions applicable to future occurrence may only be defined by a few past examples. One example is the "seismic gap" hypothesis, that large earthquakes are more probable where the time since the previous earthquake exceeds the average interval. Easy to say (and publish) but impossible to test prospectively without specifying the magnitude, location, and focal mechanism ranges and specific methods by which those will be measured. And you may ask, "More probable than what?" I'll discuss several common assumptions used in earthquake forecasting and hazard estimation, and I'll suggest ways to turn some into testable hypotheses. Most require observation of many large earthquakes, only possible in our lifetimes if the hypotheses apply on a global scale.

10:00

Coffee and posters

Stochastic modelling of spatiotemporal earthquake occurrence

(Chair: Ting Wang, David Harte)

10:30 Markov-modulated Hawkes process with marks

Ting Wang[1], Mark Bebbington[2]
[1]University of Otago, Dunedin, New Zealand, [2]Massey University, Palmerston North, New Zealand

Earthquake forecasting can involve attempting to identify statistical patterns in the occurrence of earthquakes. These patterns can be temporal, such as the Omori law for aftershocks or, more generally, spatio-temporal. The CSEP experimental apparatus includes magnitude as well. Hidden Markov models have observable variables, in this case the earthquakes, controlled by an unobservable state, which encapsulates the required pattern information. In this paper we develop two new types of continuous-time hidden Markov models; a Markov modulated Hawkes process with marks (MMHPM) and a spatiotemporal version of the MMHPM. These are used to investigate long-term seismicity rate holistically, using the entire earthquake record in a selected region in an attempt to identify hidden states correlated with subsequent large earthquakes, rather than the traditional way of hunting for individual foreshocks. A hybrid estimation procedure for the parameters of the models is derived by combining the Expectation Maximization algorithm and direct maximization of the log likelihood. The model is applied to earthquake catalogues from two regions in different tectonic environments, the Middle America Trench and Northern California. The features of the seismicity captured by the models for the two catalogues are compared.

10:50 A failure process driven by a self-correcting model

Elisa Varini, Renata Rotondi
CNR-IMATI, Milano, Italy

We consider a seismic sequence as the union of two disjoint subsets of events, hereinafter named the leaders and the subordinates. Based on the empirical evidence that earthquakes are typically clustered in time, leaders correspond to the events with magnitude greater than a threshold and are not aftershocks; the remaining events are labelled as subordinates.We introduce a new point process aimed to jointly model the evolution over time of these two components of the earthquake process. The leaders are assumed to be generated according to a self-correcting point process and, conditionally to the occurrence of the leaders, the subordinates follow a failure process which admits a bathtub hazard function. The point process is completely defined by its conditional intensity function $\lambda(t \mid Ht)$, which is the instantaneous expected rate of events at time t conditionally on previous history Ht. Different definition of $\lambda(t \mid Ht)$ are proposed in order to explore possible relationships among leaders and subordinates. We assume that the hazard function of the subordinates admits a bathtub shape (decreasing and then increasing over time) with the aim of providing a full description of the seismic activity between strong events; specifically, we consider the generalized Weibull distributions whose hazard functions admit different shapes. We analyse some seismic sequences drawn from the new Parametric Catalogue of Italian Earthquakes (CPTI15) and associated with seismogenic zones of ZS16 zonation (that will be officially delivered by Centro di Pericolosità Sismica of INGV).

11:10 **Nonparametric estimation of the spatial distribution of aftershocks for space-time Hawkes point process models and performance evaluation of time-independent CSEP forecasts using both deviance residuals and Voronoi residuals.**

Joshua S. Gordon[1], Frederic P. Schoenberg[1], Eric W. Fox[2]
[1]University of California Los Angeles, Los Angeles, USA, [2]US Environmental Protection Agency, Corvallis, USA

The spatial-temporal Epidemic Type Aftershock Sequences (ETAS) model of Ogata (1998) has been widely used to describe seismicity, and various forms for the spatial distribution of aftershocks have been proposed, including anisotropic and magnitude dependent spatial kernels. Nonparametric modelling procedures have also been developed by Marsan and Lenglin\'e (2008, 2010) for estimating the background and triggering rates, and their variability was investigated by Fox et al. (2016). In this study, we examine in detail the nonparametric estimation of the spatial-temporal triggering density as a function of the distance and angular separation from prior earthquakes relative to the estimate fault direction of the prior events, where these fault direction estimates are also constructed purely based on observed seismicity. Simulation studies are conducted to assess the methods and they are demonstrated on an earthquake catalogue for California from 1985 to 2015. Using the proposed extensions, multiple time-independent forecasts are developed, which provide five-year forecasts for magnitudes $m \geq 4.95$ in the California CSEP testing region. Model performance is evaluated by the comparison of our models to the long term forecast of Helmstetter et al. (2007) using both deviance residuals and Voronoi residuals. We observe slightly improved performance of the fully nonparametric estimation and forecasting approach compared to Helmstetter et al. (2007) in various regions.

11:30 **A nonparametric Bayesian approach to seismic hazard modelling using the ETAS framework**

Gordon Ross
University College London, London, UK

The epidemic-type aftershock sequence (ETAS) model is one of the most popular tools for modelling seismic risk. Under the ETAS model, the occurrence times of earthquakes are treated as a self-exciting Poisson process where each earthquake briefly increases the probability of subsequent earthquakes occurring soon afterwards, which captures the fact that large mainshocks tend to produce sequences of aftershocks. A triggering kernel controls the amount by which the probability increases based on the magnitude of each earthquake, and the rate at which it then decays over time. This triggering kernel is usually chosen heuristically, to match the parametric form of the modified Omori law for aftershock decay. However recent work has questioned whether this is an appropriate choice. Since the choice of kernel has a large impact on the predictions made by the ETAS model, avoiding misspecification is very important.We present a novel nonparametric version of ETAS which avoids making parametric assumptions, and instead learns the correct specification from the data itself. Our approach is based on the Dirichlet process, which is a modern class of Bayesian prior distribution which allows for efficient inference over an infinite dimensional space of functions. We show how our nonparametric ETAS model can be fit to data, and present results demonstrating that the fit is greatly improved compared to the standard parametric specification.

11:50 **Discussion**

12:10 Lunch and posters

Earthquake forecasting and testing 1

(Chair: Tom Jordan, David Rhoades)

13:10

CSEP-Japan earthquake predictability experiment and testing results

Naoshi Hirata
Earthquake Research Institute, the University of Tokyo, Tokyo, Japan

It is 6 years since we have established the Japanese testing center for the Study of Earthquake Predictability (CSEP) in Earthquake Research Institute, the University of Tokyo. During the period of testing, in 2011 March, Tohoku-oki earthquake with M9.0 occurred.

The testing experiment consists of 12 categories, with 4 testing classes with different periods (1 day, 3 months, 1 year and 3 years) and 3 testing regions called "AllJapan," "Mainland," and "Kanto." A total of more than 160 models are currently under testing in the CSEP Japan official suite. For three-month and one-year testing experiments, more than 25 runs of fully prospective experiments have been completed and evaluated.

After the 2011 Tohoku-oki event, most models show poor N-test performance due to large effects of the event. We found that the performance is improved if the effects were modeled explicitly by Omori-Utsu formula.

13:30

Statistical monitoring of the seismicity before and after the Kumamoto earthquakes

Takao Kumazawa[1], Yosihiko Ogata[1,2], Hiroshi Tsuruoka[2]
[1]Institute of Statistical Mathematics, Tachikawa, Tokyo, Japan, [2]Earthquake Research Institute, The University of Tokyo, Tokyo, Japan

It is expected that the probability gain of a large earthquake in an aftershock region can be elevated by the presence of the relative quiescence in seismicity sequence (Ogata 2001).

We first analyzed the seismicity in the Kumamoto region since 2010 before the occurrence of the M6.5 first foreshock. Although the ETAS model well fits the seismicity in the most subregions of the Kumamoto District, anomalous swarm activities are observed in the subregions to the north of the bending part of the focal faults on which the foreshocks of M6.5, M6.4 and the main shock M7.3 successively occurred. These anomalous swarm activities are characterized by the nonstationary ETAS model.

We then applied the ETAS model to the aftershock sequence of M6.5 event or of a few other major earthquakes which precedes the Kumamoto main shock, and revealed that there was relative quiescence. It is also seen that M6.5 aftershocks migrated deeper and closer to the M7.3 hypocenter.

We further applied the ETAS model and non-stationary ETAS model (Kumazawa and Ogata 2013) and also model of the b-value change estimate, to the sequence throughout the M6.5 foreshock sequence and M7.3 aftershocks. Moreover, we examined regionally different aftershock activities between the main and off fault zones. In particular, the aftershock productivity parameter K0(t) is high during the foreshocks, and decreased after the M7.3 main shock, whereas the background seismicity rate $\mu(t)$ stays constant through the entire period. The b-values show stepwise increasing changes at major events of the M6.5, M6.4, and M7.3.

13:50

Could the Tohoku Mw9.0 earthquake be forecasted by the Pattern Informatics method?

Yongxian Zhang
China Earthquake Networks Center, Beijing, China

In this study, PI method was employed for the retrospective forecasting study of the Tohoku Mw9 earthquake. The selected study region is (32.0°~46.0°N, 136.0°~148.0°E) around Japan and the selected beginning time is 1968. With calculating parameters of 1°× l° grid size and forecasting window of 8 years which were verified by former study of Wenchuan M8 earthquake as a set of proper calculating parameters with higher forecasting efficacy, the results show that in all forecasting windows containing the occurrence time of the Tohoku Mw9.0 earthquake, there exist hotspots in its epicentral grid or Moore neighborhood grids. The ROC test shows that the PI method performs far better than the random forecasting. The result also show that compared to other M≥7.0 earthquakes occurred in the forecasting durations, hotspots on the Tohoku Mw9.0 earthquake has wider distribution zone, longer lasting time and higher stability. The results of this study were also been compared with other PI study of the Tohoku Mw9.0 earthquake. We suggest that for the forecasting of large earthquakes above M7.0 by PI method, the selected region should be larger, the forecasting window should be longer, and the grid size should be bigger to obtain better forecasting efficacy.

14:10

A spatiotemporal clustering model for the third uniform California earthquake rupture forecast (UCERF3-ETAS) – Toward an operational earthquake forecast

Edward Field[1], other WGCEP participants[2]
[1]USGS, Golden, CA, USA, [2]Misc, Misc, USA

We present a spatiotemporal clustering model for the third Uniform California Earthquake Rupture Forecast (UCERF3), with the goal being to represent aftershocks and otherwise triggered events as a potential basis for OEF. Specifically, we add an ETAS component to the previously published time-independent and long-term time-dependent forecasts. This combined model, referred to as UCERF3-ETAS, collectively represents a relaxation of segmentation assumptions, the inclusion of multi-fault ruptures, an elastic-rebound model for fault-based ruptures, and a state-of-the-art spatiotemporal clustering component. It also represents an attempt to merge fault-based forecasts with statistical seismology models, such that information on fault proximity, activity rate, and time since last event are considered in OEF. We describe several unanticipated challenges that were encountered, including a need for elastic rebound and characteristic magnitude-frequency distributions on faults, both of which are required to get realistic triggering behavior. UCERF3-ETAS produces synthetic catalogs of M≥2.5 events, conditioned on any prior M≥2.5 events that are input to the model. We evaluate results with respect to both long-term (1,000-year) simulations, as well as for 10-year time periods following a variety of hypothetical scenario main shocks. While the results are very plausible, they are not always consistent with the simple notion that triggering probabilities should be greater if a main shock is located near a fault. Important factors include whether the magnitude-frequency distributions near faults includes a significant characteristic earthquake component, as well as whether large triggered events can nucleate from within the rupture zone of the main shock.

14:30

Statistical space-time models for the evaluation of aftershock hazard

Yuh-Ing Chen
National Central University, Jhongli, Taoyuan, Taiwan

The Reasenberg-Jones (RJ) model (Reasenberg and Jones, 1989) that combines the frequency-magnitude distribution (Gutenberg and Richter, 1944) and time-decaying occurrence rate (Utsu et al., 1995) is conventionally used to assess the aftershock hazard in a region near the epicenter of a large mainshock (Wiemer, 2000). However, the b values in the frequency-magnitude distribution of aftershocks in the study region usually decrease dramatically from background value after the mainshock and then gradually increase up. Hence, Chen et al. (2015) considered a time-dependent b values and proposed a modified RJ model (MRJ) to assess the aftershock hazard. Nevertheless, both the Wiemer (2000) and Chen et al. (2015) employed gridding techniques to portray the aftershock hazard in the study region. Note that the estimated aftershock hazard is usually sensitive to the choice of the grid size. Therefore, this paper considers space-time models that incorporate the space function (Ogata and Zhunag, 2006) in the RJ and MRJ models, respectively. Based on the space-time RJ or MRJ model, the hazard of aftershocks in the region, referred to as the hazard map, is constructed and used to depict the potential rupture area for future aftershocks. The Receiver Operating Characteristics (ROC) curves (Swets, 1988) is further used to evaluate the effectiveness of the hazard maps in exploring the spatial hazard of aftershocks in a short time after the M=7.3 Chi-Chi shock (1999, Taiwan) and M=9.0 Tohoku shock (2011, Japan), respectively.

14:50

Coffee

Earthquake forecasting and testing 2

(Chair: Tom Jordan, David Rhoades)

15:10 Towards the implementation of the probability forecast of large earthquakes

Yosihiko Ogata
The Institute of Statistical Mathematics, Tachikawa, Tokyo, Japan

I would like to present a prospect to realize practical operational probability forecasting of large earthquakes. First, we should develop suitable baseline space-time-magnitude models for various seismic activities in a wide area. The next issue is to obtain statistical uncertainties that lie in discriminating whether or not abnormal phenomena are precursors to large earthquakes. In fact, there are many delicate anomalies which can be revealed after a careful diagnostic analysis. Indeed, I have made many efforts to discuss and quantify seismicity anomalies by diagnostic analysis using the ETAS model. I then estimate their probability gains over the baseline seismicity model. After all, I will illustrate the examples of large earthquake forecasting using multi-element probability formula of Utsu or its extended version, incorporating long-term, intermediate-term and short-term predictions.

15:30 Space-time forecasting of seismic events in Chile

Orietta Nicolis[1], Marcello Chiodi[2], Giada Adelfio[2]
[1]Universidad de Valparaiso, Valparaiso, Chile, [2]Università di Palermo, Palermo, Italy

The aim of this work is to study the seismicity in Chile using the ETAS (Epidemic Type Aftershock sequences) space-time approach. The proposed ETAS model is estimated using a semi-parametric technique taking into account the parametric and nonparametric components corresponding to the triggered and background seismicity respectively. The model is then used to predict the temporal and spatial intensity of events for some areas of Chile where recent big earthquakes (with magnitude greater then 8.0M) happened.

15:50 **Feasibility of automatic real-time aftershock forecasting in Japan**

Takahiro Omi[1], Yosihiko Ogata[2], Katsuhiko Shiomi[3], Bogdan Enescu[4], Kaoru Sawazaki[3], Kazuyuki Aihara[1]
[1]The University of Toky, Meguro-ku, Tokyo, Japan, [2]The Institute of Statistical Mathematics, Tachikawa, Tokyo, Japan, [3]National Research Institute for Earth Science and Disaster Resilience, Tsukuba, Ibaraki, Japan, [4]Kyoto University, Sakyo-ku, Kyoto, Japan

Aftershock forecasting of a damaging earthquake is an important scientific goal and, in the same time, a social responsibility. During the last several years, statistical methods for early forecasting of aftershocks have been developed, and their retrospective performance has been successfully tested. On the other hand, these tests are not realistic enough to evaluate the forecast ability in an urgent situation because these retrospective tests have used revised data that are higher in quality than the real-time data. Here we retrospectively conduct forecast tests for some automatic real-time data, in Japan, from the High Sensitivity Seismograph Network (Hi-net) hypocenter catalog of the National Research Institute of Earth Science and Disaster Resilience (NIED). We first examine the aftershock sequences of seven M7 class inland mainshocks. These tests show that such forecasts outperform the generic model of the standard aftershock activity in Japan; and further show that the forecasts for large aftershocks (M>3.95) are comparable with the forecasts using the last version of the JMA unified catalog (Omi et al., BSSA, 2016). We also examine aftershocks of mainshocks that occurred in offshore areas, including the 2015 West Off Satsuma Peninsula earthquake (M7.1), as examples of much worse real time automatic data than for the inland areas, and present a method of practical forecasting that gives satisfactory performance for such cases as well.

Acknowledgements. We are grateful to JMA and NIED for providing the data.

16:10 **Testing planned USGS operational aftershock forecasts**

Andrew Michael[1], Edward Field[2], Jeanne Hardebeck[1], Nicholas van der Elst[3]
[1]USGS, Menlo Park, California, USA, [2]USGS, Golden, Colorado, USA, [3]USGS, Pasadena, California, USA

Tests of operational earthquake forecasts (OEF) by the Collaboratory for the Study of Earthquake Predictability (CSEP) are necessary to validate and improve OEF methods. The CSEP tests sometimes focus on 1-day forecasts, updated daily. That approach provides a simple set of independent forecasts but does not describe the aftershock forecasts planned for release by the USGS. The USGS aftershock forecasts will be released very shortly after large earthquakes, without waiting for the next day, and each forecast will include a variety of non-independent time windows such as the next week, month, and year. These forecasts will be updated on a regular basis and when significant aftershocks occur. These updates will occur before the previous time windows have all ended, resulting in an even larger set of non-independent forecasts. Do we need to test the forecast for each non-independent published window or is it sufficient to test the model and parameters which were used to calculate the individual forecasts and windows? Additionally, the USGS forecasts will provide non-Poissonian uncertainties that combine epistemic uncertainty in the parameters and aleatory variability. Thus, the Poisson formulations used in existing CSEP tests are inadequate. Fortunately, new simulation based methods under development within CSEP may provide the necessary foundation for new tests. Testing approaches that correspond to the way the USGS forecasts will be issued will enable meaningful retrospective tests of our methods before the system goes public and continual tests of prospective forecasts in the future.

16:30 **Discussion**

16:50 Poster session with drinks and nibbles

Summary statistics, empirical relationships and data quality

(Chair: Bill Ellsworth, Gert Zöller)

08:30 Statistical analysis of seismicity characteristics in the United States

Xiaowei Chen[1], Yifang Cheng[2], Jackson Haffener[1], Colin Pennington[1], Yan Qin[1], Abraham Wallace[1]
[1]University of Oklahoma, Norman, OK, USA, [2]University of southern California, Los Angeles, CA, USA

The surge of increased seismicity rate in the central United State has drawn significant interest in the "induced seismicity". While this phenomenon is easy to understand: fluid is being injected into subsurface, propagates in the crust, pore pressure rises and triggers earthquakes; the detailed characteristics such as earthquake clustering, aftershock productivity, fault dimension and maximum magnitude are still unclear. Here, we analyze induced and natural earthquake sequences in both California and Oklahoma, focusing on geothermal induced seismicity and wastewater disposal induced seismicity, and try to understand the differences between induced seismicity and natural seismicity in terms of the spatial-temporal clustering, aftershock productivity, and magnitude-frequency distribution and the dimension of the seismogenic faults.

Based on a high-resolution earthquake catalog from a local borehole network, we analyzed the detailed clustering behavior inside and outside of the Salton Sea Geothermal Field. These clusters are divided into aftershock-type clusters, swarm-type clusters and mixture-type clusters based on the timing of the largest earthquake and the skewness of moment release history. Detailed analysis reveals that the mixture-type clusters are dominately located within the geothermal field, and have higher aftershock productivity and non-Omori type temporal rate decay compared to aftershocks and swarms. We interpret this as a possible signature of induced seismicity. We are currently conducting similar individual cluster analysis in both non-geothermal area in Coso range (southern California) and Oklahoma, updated results will be presented at this workshop.

08:50 Sampling uncertainties in the Aki-Utsu b-value estimation method, and the use of "true" b-value likelihoods to ascertain probabilities and confidence limits to b estimates.

Fidencio Alejandro Nava Pichardo[1], Lenin Ávila Barrientos[1], Francisco Ramón Zúñiga Dávila-Madrid[2], Victor Hugo Márquez Ramírez[3], Ivonne Torres Carreón[4]
[1]CICESE, Ensenada, B.C., Mexico, [2]Geociencias, UNAM, Juriquilla, Qro., Mexico, [3]SisVoc, U. Guadalajara, Puerto Vallarta, Jal., Mexico, [4]B.Univ.Aut.Puebla, Puebla, Pue., Mexico

Misuse of the Aki-Utsu b-value estimation method is quite common: for any given b, small to medium-sized samples result in a wide range of estimated values, and usually no correction is made for large magnitudes being under- or over-represented in the sample. We propose a method to determine, based on a given estimate of b, the linearly distributed magnitude range in the Gutenberg-Richter relation, and the number of magnitudes within this range to estimate the most likely "true" b-value corresponding to the observation, and its confidence limits.

09:10

Testing the spatial variation of the b-value of the Gutenberg-Richter law in Italy

Matteo Taroni[1], Federico Signora[2], Pierpaolo Brutti[2]
[1]INGV, Rome, Italy, [2]Sapienza University, Rome, Italy

The magnitude distribution of the earthquake, also known as Gutenberg-Richter law, is one of the most important law for seismic hazard analysis. This law, from a probabilistic point of view, correspond to the exponential distribution. The exponential distribution depends on one parameter, that is the b-value in the Gutenberg-Richter law. Regarding the b-value, there are two main different opinions: a unique b-value, without spatial variation, and a b-value that varies with space, usually according to the fault mechanism. Even if this topic is largely debated and discussed, the current literature and research lacks in testing the statistical significance of the observed differences in b-value. In this work we analyze the spatial variation of the b-value of the Gutenberg-Richter law in Italy; the main goal is to test if the variations that we observe in the b-values in different zones are large enough to reject the null hypothesis of equal b-value for all zones.

The research will be developed by using a classical non parametric test, the Kruskal-Wallis test, particularly suitable for asymmetric distributions such the exponential one.

First results suggest that the Italian data are compatible with an equal b-value for all zones.

09:30

On the biased estimate of earthquake clustering parameters caused by short-term aftershock missing

Jiancang Zhuang[1], Ting Wang[2]
[1]Institute of Statistical Mathematics, Tokyo, Japan, [2]Universtiy of Otago, Dunedin, New Zealand

Short-term missing of aftershock in the early stage after the mainshock always biases the estimates of earthquake clustering models such as the ETAS model and the Omori-Utsu formula. For example, the parameters c and p in the Omori-Utsu formula change with the cutoff magnitude threshold. To correct the biases caused by such short-term aftershock missing, we apply a method developed by Zhuang et al (2016) to replenishing missing data. The basic idea of this method is that, if a temporal point process with time independent marks is completely observed, the whole process can transformed into a homogeneous Poisson process on the unit square by a biscale empirical transformation. Using this method, we can simulate the missing events and re-estimate model parameter with the replenished dataset. For example, applying this method to the aftershock sequence following the 2008 Wenchuan Ms7.9 earthquake in southwestern China, the results show that the Omori parameters c and p do not change with magnitude threshold anymore and that the missing of small events in the early stage of the aftershock sequence causes the inconsistent estimate of the earthquake clustering models. We also apply this method to replenish the short-term missing data in the Kumamoto aftershock sequence, occurring from 2016-4-15, in the JMA catalog. The results show that the MLEs of the ETAS parameters vary when this model is fitted to the recorded catalog with different cut-off magnitudes, while the MLEs of the ETAS parameters keep stable for the replenished dataset.

09:50 **What really causes scatter in shear wave splitting measurements?**

Martha Savage[1], Richard Arnold[1], Kenny Graham[1], Stefan Mroczek[1], Jessica Johnson[2], James Wookey[4], Yosuke Aoki[3]
[1]Victoria Univerity of Wellington, Wellington, New Zealand, [2]University of East Anglia, Norwich, UK, [3]University of Tokyo, Tokyo, Japan, [4]University of Bristol, Bristol, UK

Seismic anisotropy measured by shear wave splitting has been used for over thirty years to try to characterize the stress field and to determine whether time variation in stress or fluids is related to the occurrence of earthquakes or volcanic eruptions. Yet measurements using local earthquakes as sources are often scattered and make interpretation difficult. Four likely sources causing scattered measurements are:

1) Even with constant anisotropic properties in a medium, splitting measurements will depend upon the propagation direction with respect to the anisotropic symmetry system, so that varying source locations will yield different splitting measurements at a single station.
2) The scatter has sometimes been considered to be a time-varying effect caused by changing stress or pore fluid pressure.
3) Spatial variations of anisotropy may cause varying results for different paths traversed - so that tomographic techniques are used to try to determine variation of crack density or pore pressures with location.
4) Finally, waves that have scattered (reflected or refracted) from nearby inhomogeneities could interfere with the direct waves and cause apparent anisotropy variations.

Recently automatic measurement techniques have led to large datasets that can be used to test some of these different possibilities. Here we report on an effort to try to systematize shear wave splitting measurements, to compare different quality criteria for individual measurements and group averages, and to determine how best to minimize the effects of symmetry systems and of different types of scatterers to determine variations in material properties with time and space.

10:10 Coffee and posters

Summary statistics, empirical relationships and data quality continued

(Chair: Bill Ellsworth, Gert Zöller)

10:40

New statistical methods for tectonic stress estimation

Richard Arnold[1], Peter Jupp[2]
[1]Victoria University of Wellington, Wellington, New Zealand, [2]University of St Andrews, St Andrews, Scotland, UK

Tectonic stress estimation involves the interpretation of data that are intrinsically directional, or more commonly axial (e.g. focal mechanism solutions, shear wave splitting measurements). These observations are subject to observational error, noise (background as well as scattered seismic waves), axial ambiguities (e.g. strike directions) and physical ambiguities (fault normal vs slip direction). Robust inference from observational data requires properly formulated statistical models which use representations of oriented objects (vectors, planes, axes, frames), suitable statistics derived from these, and probability distributions describing their uncertainties. We discuss some recent developments in directional statistics that are relevant to the problem of stress estimation, as well as future research directions.

11:00

The magnitude of the extreme aftershock

Robert Shcherbakov[1], Jiancang Zhuang[2], Yosihiko Ogata[2]
[1]The University of Western Ontario, London, Ontario, Canada, [2]Institute of Statistical Mathematics, Tokyo, Japan

The occurrence of extreme earthquakes is a manifestation of self-similar nature of the frequency-magnitude statistics of seismicity. Among extreme earthquakes large aftershocks constitute significant hazard and can inflict additional damage to the already weakened by the main shock infrastructure. Therefore, constraining the magnitude of the largest event in an earthquake sequence is an important problem in statistical seismology. In this work, we combine the extreme value statistics with Bayesian analysis to derive the Bayesian predictive distribution for the magnitude of the largest event in a sequence of earthquakes. To accomplish this, we use the information of the early events in the sequence to constrain the variability of the model parameters describing the frequency-magnitude statistics and the occurrence rates. We assume that the occurrence of earthquakes in the sequence can be described by a non-homogeneous Poisson point process. One typical example of such a sequence of events is ubiquitous aftershock sequences. Large foreshocks, which in turn generate their own aftershock sequences, can also initiate a sequence of earthquakes culminating in the occurrence of a main shock. We analyze both types of sequences associated with prominent past main shocks to estimate the probabilities of having a large aftershock following the main shock and also of the main shock following the preceding foreshock. As a main result of this work, we provide a robust scheme in estimating the above probabilities, where we incorporate all the uncertainties associated with the model parameters.

11:20

Discussion

Earthquake physics 1

(Chair: Sebastian Hainzl, Bruce Shaw)

11:40 Capturing elastic rebound and source finiteness in empirical aftershock forecasting kernels.

Nicholas van der Elst[1], Bruce Shaw[2], Morgan Page[1]
[1]USGS, Pasadena, CA, USA, [2]Lamont Doherty Earth Observatory of Columbia Univ., New York, NY, USA

Earthquakes set off cascading sequences of aftershocks in the surrounding region, some of which can be as large or larger than the initial mainshock. Aftershocks may be driven by stress concentrations due to heterogeneous slip in the main rupture, or by stress transfer along the fault and onto neighboring strands. Physical intuition suggests that aftershocks on or near the main rupture should be limited in size, because the typical length scale of the remaining stress heterogeneities should be smaller than the length scale of the primary rupture. On the other hand, aftershocks that occur outside the main rupture should have no such limitation, and be more likely to propagate onward to become large. This is consistent with anecdotal observations that large aftershocks occur preferentially at the margins of mainshock rupture patches. We investigate high-precision Double-Difference earthquake catalogs in California for evidence that the magnitude distribution of aftershocks is affected by proximity to the mainshock. We measure the location of aftershocks with respect to the centroid location of all previous activity in the aftershock sequence, which we take to represent the mainshock rupture centroid. We find preliminary evidence that larger aftershocks tend to occur farther from the centroid of previous activity than do smaller aftershocks. We argue that the signature of elastic rebound is evident in aftershock spatial distributions, and discuss ways to model these distributions through modifications to existing aftershock probability kernels. Probabilistic forecasting of large aftershocks may be much improved by incorporating magnitude-dependence into the spatial prediction kernels.

12:00 Fault slip rates and seismic moment deficits on major faults in Ordos constrained by GPS observation

Shiyong Zhou[1], Yilei Huang[1], Bin Gao[1], Qinliang Wang[2]
[1]Peking University, Beijing, China, [2]Second Mornitor Center of China Earthquake Administration, Xian, China

The Ordos block surrounded by numerous active faults is a relatively rigid but risky area with many strong earthquakes in history. We derive the block rotation velocity and fault slip rates of this area by using GPS data recorded from 1999 to 2007 and an elastic block model. Different from most previous studies which set the faults vertical, we use an improved method to inverse the dip angles of the faults and construct a closed 3-D fault system of Ordos in our inversion. The predicted slip rates range from about 10mm/yr to less than 1mm/yr. The results are roughly consistent with geological observations and earthquake focal mechanisms. Using the estimated slip rates, seismic moment accumulation is estimated. Released moment is also calculated from historical earthquake catalogs from the 1500s. Comparison of the two indicates that the northern and south-western fault zones respectively have the capability to produce an Mw 7.9 and an Mw 7.3 earthquake. Through this study, we demonstrate the movement of the faults in Ordos and their seismic hazard potential.

12:20

Evolution of earthquake rupture potential along active faults, inferred from seismicity rates and size distributions

Thessa Tormann[1], Stefan Wiemer[1], Bogdan Enescu[2,3], Jochen Woessner[4]
[1]ETH Zurich, Zurich, Switzerland, [2]Kyoto University, Kyoto, Japan, [3]The Institute of Statistical Mathematics, Tokyo, Japan, [4]Risk Management Solutions Inc., Zurich, Switzerland

One of the major unresolved questions in seismology is the evolution in time and space of the earthquake rupture potential and thus time-dependent hazard along active faults. What happens after a major event: is the potential for further large events reduced as predicted from elastic rebound, or increased as proposed by current-state short-term clustering models? How does the rupture potential distribute in space, i.e. does it reveal imprints of stress transfer? We combine temporal variability in local seismic activity rates and size distributions to estimate the evolution of a new metric, the normalized rupture potential (NRP). We investigate spatial distributions and temporal changes of rupture potential for different target magnitudes. We establish this technique based on the rich earthquake record from the Pacific Plate along the Japanese coastline, including the massive 2011 M9 Tohoku earthquake and its aftermath. The results of our study suggest the hypothesis that today's distribution of earthquake potential for large and hazardous events is possibly more precisely estimated by careful analysis of the most recent local small events than by parameters derived from averaging observations of moderate to large events over larger regions and the longest available time periods. Consequently, we advance the technique to estimate instantaneous normalized rupture potential (INRP), and apply it to a number of subduction zones and onshore regions, for which sufficiently well recorded seismicity data is available.

12:40

Lunch and posters

Earthquake physics 2

(Chair: Sebastian Hainzl, Bruce Shaw)

13:40

Improved understanding of earthquake triggering with waveform matching method

Zhigang Peng[1], Dongdong Yao[1], Chenyu Li[1], Chastity Aiken[2], Xiaofeng Meng[3]
[1]Georgia Institute of Technology, Atlanta, USA, [2]University of Texas, Austin, USA, [3]University of Washington, Seattle, USA

Large earthquakes are generally followed aftershocks, and sometimes preceded by foreshocks. In addition, they are capable of triggering seismicity at long-range distances. While these triggering phenomena have been widely observed, their physical mechanisms are still in debate. One potential difficulty is that the catalog is not complete, especially right before and after the mainshock when the seismicity rate is high. These missing events could be identified by an automatic matched filter technique, which uses waveforms of existing events as templates to scan through continuous data for new events with high similarities. Here I report our group's recent efforts on systematic detections of missing earthquakes around the world with this technique. Using the newly detected catalogs, we are able to distinguish seismicity triggered by static and dynamic stress changes of mainshocks in the near field. A certain fraction of foreshocks or aftershocks have nearly identical waveforms, generally known as repeating earthquakes. The mere existence of these repeating sources suggests that they are small asperities surrounded by aseismic slip. We also detected remotely triggered microseismcity in volcanic or anthropogenically disturbed regions (e.g., mining area, reservoirs, geothermal and injection sites), and deep tectonic tremor along major active faults, indicating that these regions are critically stressed and extremely stress sensitive. Finally, we also apply the same method to detect seismicity before and after deep focus earthquakes (e.g., depth larger than 100 km). The newly detected events can be used to outline the faulting geometry and decipher physical processes deep inside the Earth.

14:00

To which level did the 2010 M8.8 Maule earthquake fill the pre-existing seismic gap?

Lifeng Wang[1], Sebastian Hainzl[2], Martin Mai[3]
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It has been a long-standing debate whether or not the 2010 M8.8 Maule earthquake filled a pre-existing seismic gap. Utilizing the inversion approach that considers strain accumulation and strain release in the earthquake cycle, we investigate the inter- and co- seismic slip balance for the 2010 M8.8 Maule earthquake. The coseismic slip model is delineated as the product of three components: interseismic backslip rate, the strain accumulation time that implies the recurrence interval of the regional mega-earthquakes, and the fraction of slip potency released during the coseismic rupture that may either fully or partially release the local strain. The results demonstrate that two slip clusters, located north and south of the hypocenter, are required to model the geodetically measured coseismic displacements. The slip patch south of the hypocenter is located in a strongly coupled zone, and strain release there is possibly complete during the coseismic rupture. The large slip area north of the hypocenter overlaps the interseismically creeping zone in which strain build-up is supposedly low. The northern slip patch released higher slip potency than that accumulated during the interseismic phase, suggesting a dynamic overshoot during the coseismic rupture. Our results demonstrate that the Maule earthquake released ~66-72% of the local strain, suggesting that a large part of the accumulated strain in this region has been released, and that the potential for a large earthquake in the near future is low.

14:20 **Numerical simulations of co-seismic electromagnetic signals**

Qinghua Huang[1], Hengxin Ren[2], Xiaofei Chen[2]
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Field electromagnetic observations showed the positive evidence of the electromagnetic signals accompanying with natural earthquakes. Such signals, which are known as co-seismic electromagnetic signals, may provide some information of earthquake rupture process. Based on the our numerical technique, which can simulate the coupled seismic and electromagnetic signals in porous media, we investigated numerically the co-seismic electromagnetic signals for a double couple point source and a finite fault planar source. Besides the source effect, the simulation results showed that both medium structure and medium property could also affect the co-seismic electromagnetic signals. The waveform of coupled signals for a layered structure is more complicated than that for a simple uniform structure. Different from the seismic signals, the electromagnetic signals are sensitive to the medium properties such as fluid salinity and fluid viscosity. The results may provide some insights of understanding the difference in the detectability of co-seismic electromagnetic signals in different geological regions.

14:40 **Glacier: an earthquake laboratory?**

Evgeny Podolskiy[1], Sebastian Heimann[3], Danijel Schorlemmer[3], Shin Sugiyama[2], Fabian Walter[4], Martin Funk[4], Riccardo Genco[5]
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Glaciers generate seismic events that are detectable at local and teleseismic distances. Moreover, they produce events at rates higher than in tectonic environments, thus providing a unique natural laboratory to study the statistic aspect of earthquake phenomena. Furthermore, outlet glaciers in Greenland have retreated and lost mass over the past decade. Studying the dynamics of tidewater glaciers is crucial for forecasting sea-level rise and for understanding the future of the Greenland Ice Sheet, given the buttressing support that tidewater glaciers provide to inland ice.

Here, we present analyses of data recorded by a temporary seismic network deployed at a tidewater glacier (Bowdoin Glacier, Greenland). Some stations were installed on ice at distances as close as ~250 m from the calving front, representing the closest such deployments to date. These observations, supported by GPS measurements of ice velocity and local weather-station records, show that background seismic activity depends on the tidal phase, which controls the surface strain-rate. This result reveals that the timing of seismic activity at Bowdoin is controlled by extension related to tide-modulated variations in horizontal ice flow, with more intense fracturing during the lowest tides.

For constraining ice-quake source mechanisms, which can be distinct from (or similar to) those of tectonic earthquakes, and to understand a possible similarity between the two, we developed an event detector to analyze the dataset. Here we discuss the features and robustness of the retrieved spatio-temporal statistics.

15:00 Coffee and posters

Earthquake physics 3

(Chair: Bruce Shaw, Jeanne Hardebeck)

15:30 **Focal mechanism distributions provide insight into static and dynamic stress triggering**

Jeanne Hardebeck[1], Xiaofeng Meng[2], Chastity Aiken[3], Zhigang Peng[4]
[1]US Geological Survey, Menlo Park, California, USA, [2]University of Washington, Seattle, Washington, USA, [3]University of Texas, Austin, Texas, USA, 4Georgia Institute of Technology, Atlanta, Georgia, USA

A population of earthquake focal mechanisms can be characterized as a joint PDF of strike, dip, and rake. Statistically significant changes in the mechanism PDF at the times of large earthquakes can provide insight into how fault systems respond to static and dynamic stress changes. For four Southern California M≥6.7 mainshocks, the static stress changes have two observed impacts. First, the mechanism PDF changes to favor mechanisms with increased shear stress. These changes in the PDF are significant for absolute stress changes of ≥0.02 MPa, and for up to ~20 years. Second, the spatial distribution of seismicity changes to favor locations where the static stress change aligns with the background stress. This result can inform earthquake forecasts, suggesting spatial kernels based on the similarity between the background stress field and the static stress changes. This approach produces forecast maps similar to the common method of calculating Coulomb stress changes on optimally oriented planes, which may explain the success of this practice despite evidence that aftershocks do not generally occur on optimally oriented planes. The dynamic stress changes from the M≥6.7 mainshocks similarly significantly affect both the mechanism PDF and the seismicity locations, implying that dynamic triggering works through shear stress loading in the direction of fault slip. For remote dynamic triggering at the Geysers geothermal field, however, no significant change in the mechanism PDF is observed. This suggests that dynamic triggering in geothermal systems is due to isotropic fluid pressure changes, although further study of other geothermal fields is needed.

15:50 **Precise relative stress drops**

Bruce E Shaw[1], William L Ellsworth[2], Nana Yoshimitsu[2], Yihe Huang[2], Gregory Beroza[2],
[1]Columbia University, Palisades, NY, USA, [2]Stanford University, Palo Alto, CA, USA

Earthquake stress drops are generally observed to be independent of seismic moment but vary by three orders of magnitude or more for any moment value. If correct, this predicts far greater variability in high-frequency ground motions than is observed. Because stress drop depends on the cube of the corner frequency, the question has been raised if stress drop variability is a source effect or measurement error. To address this problem, we present a new method that gives precise relative stress drop values for pairs and populations of earthquakes. Based on spectral ratios for nearby events, this approach uses the low- and high-frequency asymptotic values of spectral ratios and avoids the need to estimate corner frequencies. By avoiding the spectral shape near the corner frequency and attendant source complexity, the method produces precise stress drop ratios for pairs of events. The method is only weakly dependent on the assumed high-frequency asymptotic behavior of the spectrum. Closure rules for connected sets of ratios enable quantitative measures of method uncertainties and extension of the measurements from pairs to populations of earthquakes. Validation results comparing stress drop ratios with more traditional corner frequency based methods will be presented. Further results showing underlying intrinsic variability in stress drops, a question relevant to ground motion hazard estimates, will be presented.

16:10 **Towards stable stress drop measurements for induced earthquakes in Oklahoma**

William Ellsworth[1], Nana Yoshimitsu[1], Gregory Beroza[1], Bruce Shaw[2]
[1]Stanford University, Stanford, California, USA, [2]Lamont Doherty Earth Observatory, Columbia University, Palisades, New York, USA

Stress drop is a key source parameter that influences the earthquake hazard through the energy radiated around the corner frequency and the level of the acceleration spectrum at higher frequency. Stress drop measured using body wave spectra corner frequencies is scale-invariant (independent of seismic moment) but varies by orders of magnitude for events with the same seismic moment. It has long been noted that this degree of variability is inconsistent with the much smaller range of the r.m.s. acceleration in modern ground motion prediction equations (GMPEs). More precise measurements of stress drops of induced earthquake would facilitate their comparison to natural events and facilitate the use of existing GMPEs for seismic hazard. Making accurate stress drop measurements has been a challenging issue because of the strong dependence of stress drop on the corner frequency. Shaw et al. (in this meeting) introduces a new approach for the stable stress drop ratio estimation using the high- and low-frequency asymptotic level of the spectral ratio that avoids the need to measure corner frequencies. An important advantage of the new method is the ability to mesure the stress drop ratio even when the earthquakes have the same seismic moment. We compared the stress drop ratio of earthquakes in Oklahoma, measured by this new approach, with stress drops measured by the traditional approach based on the spectral fitting. Result suggest that the stress drop ratio based on the spectral asymptotes reduce the uncertainty in the value, improving our ability to characterize true stress drop variability.

16:30 **Discussion**

16:50 **Panel discussion: Software, data, education**

- What existing data bases, software, and educational resources are useful for statistical seismology?
- What future development of data bases, software and educational resources would be beneficial to statistical seismology?

Panellists: Bill Ellsworth, Natalie Balfour, Hiroshi Tsuruoka, David Harte, Sandy Steacy, Martha Savage

Chair: Jiancang Zhuang and Ting Wang

Modelling of earthquake occurrence from paleoseismic data 1

(Chair: Andy Nicol, Jamie Howarth)

08:30 Development of an 8000 year record of large earthquakes on the Alpine Fault, New Zealand

Ursula Cochran[1], Kate Clark[1], Kelvin Berryman[1], Glenn Biasi[2], Robert Langridge[1], Pilar Villamor[1], Jamie Howarth[1], Russ Van Dissen[1],
[1]GNS Science, Lower Hutt, New Zealand, 2University of Nevada-Reno, Nevada, USA

We used sedimentary sequences from two wetlands adjacent to the Alpine Fault in Southland, New Zealand to develop a history of surface-rupturing earthquakes. Although dominantly strike-slip, a small vertical component of slip on the South Westland section of the Alpine Fault causes uplift to the northwest (opposite sense to that observed on the central and North Westland sections) so drainage from mountains to the east is impeded by the fault scarp. At Hokuri Creek and John O'Groats River, transient wetlands on the upstream but downthrown side of the Alpine Fault iteratively recorded the hydrological and sedimentological responses to earthquakes over many millennia. We used surveying, ground penetrating radar, sedimentology, micropaleontology and radiocarbon dating to identify these cyclic records of past earthquakes and obtain age estimates.

Our analysis indicates that up to 27 surface-rupturing earthquakes occurred on the South Westland section of the fault over the last 8000 years. The coefficient of variation for the dataset (estimated at 0.41) indicates quasi-regular occurrence of these earthquakes in time. Our record only includes evidence for earthquakes large enough to break the ground surface, it may be missing an occasional large earthquake, and records from smaller earthquakes would not be preserved. Nevertheless, the data clearly indicate the occurrence of relatively regular, large earthquakes. This is consistent with the structural maturity of the Alpine Fault and the high proportion of plate-boundary motion it accommodates. It suggests that time-dependent recurrence models are appropriate for seismic hazard estimation on this and similar faults.

08:50 Spatio-temporal patterns of rupture during great earthquakes on the Alpine Fault, New Zealand.

Jamie Howarth[1], Sean Fitzsimons[2], Rob Langridge[1], Ursula Cochran[1], Kate Clark[1], Glenn Biasi[3],
[1]GNS Science, Lower Hutt, New Zealand, [2]University of Otago, Dunedin, New Zealand, [3]Nevada Seismological Laboratory, Reno, USA

Plate boundary transform faults have the potential to produce great earthquakes that rupture many hundreds of kilometres of their along-strike length. Best available data for modelling the seismic hazard posed by such faults are developed through paleoseismic investigations of the timing and length of past fault ruptures. We use lake sediments to study past ruptures of the Alpine Fault in New Zealand. The earthquake record, spanning 3,500 years and ~400 km of the fault length, is constructed from seismically triggered deposits in six lakes situated adjacent to the fault. The lake sediments act as natural seismometers recording high-intensity shaking as deposits formed both by subaqueous mass-wasting and by large increases in sediment influx from catchments caused by co-seismic landsliding. These large increases in sediment influx only occur when shaking intensities equal Modified Mercalli Intensity (MM) IX. Chronologies derived from Bayesian modelling of hundreds of 14C dates precisely constrain the timing of earthquakes at the lake sites. Rupture lengths are inferred from the extent of MM≥IX shaking reconstructed using along-strike correlations based on event dating. The result is a record of timing and rupture lengths for more than 20 Alpine Fault earthquakes. The implied magnitude-frequency distribution for the fault favors a characteristic distribution, but it is possible that moderate magnitude events have not been recognized. Half of the ruptures terminate near boundaries between geometric fault segments, demonstrating that earthquake segmentation is influenced by subtle changes in fault geometry. These changes are not currently accounted for in the National Seismic Hazard Model.

09:10

Completeness and interpretation of New Zealand's prehistorical earthquake record

Andy Nicol[1], Russ Van Dissen[2], Russell Robinson[2], Mark Stirling[3], Matt Gerstenberger[2]
[1]University of Canterbury, Christchurch, New Zealand, [2]GNS Science, Wellington, New Zealand, [3]University of Otago, Dunedin, New Zealand

Paleoearthquake records provide key inputs for seismic hazard models and are subject to sampling limitations. To understand these sampling issues and place meaningful interpretations on the paleoseismic information we have compiled earthquake data for 24 active faults. Geological data are complemented by earthquakes from numerical simulations and the historical record since 1840 and the results preliminary. In regions of strike-slip and reverse faulting no events of < Mw 7 ruptured the ground surface historically and Mc values of Mw ~7-7.3 may apply to the paleoseismic data. Given these Mc values the magnitudes are quasi-Characteristic and cannot be used to differentiate between Characteristic and Gutenberg-Richter earthquake models. In addition, active faults in low strain-rate regions are generally poorly sampled by paleoseismic data in part because fault-slip rates are slower than the rates of surface processes and the active faults poorly preserved at the ground surface. In cases where paleoearthquakes ruptured the ground surface the recurrence interval (RI) and single-event slip (SES) on individual faults can vary by >10 times. Monte Carlo construction of probability density functions for paleoseismic data and numerical simulations suggest that RI values are positively skewed with long recurrence tails (~3 times the mean), while SES are normally distributed with less variability (coefficient of variation, Cv, 0.6±0.2 versus 0.4±0.2). Variations in RI are larger on slower moving faults and reach long-term averages over five or more events. Armed with these paleoseimic data and their completeness they can be used in seismic hazard analysis for modelling the RI and SES variability.

09:30

A summary of fault ruptures and slip from the November 14th 2016 Kaikoura earthquake

Robert Langridge, Nicola Litchfield, Russ Van Dissen, William Ries, and the Earthquake Geology mapping teams*

The Mw 7.8 14th November, 2016 Kaikoura Earthquake was remarkable for the large number of ground-surface fault ruptures straddling the Kaikoura coast. At the time of writing the fault response teams have documented m-scale displacement on at least 12 faults, and cm-scale displacement on at least 3 faults. InSAR data indicate that additional faults ruptured at depth and further ground surface ruptures will likely be identified from analysis of satellite, LiDAR, and submarine survey data. The length of surface rupture, as generalised by two straight-line segments, is approximately 180 km, though the true length is longer because of the complex, multiple-orientation, overlapping surface ruptures. Most of the faults that ruptured were previously identified as active and included in the 2010 New Zealand National Seismic Hazard Model (NZ NSHM). The 2010 model included only a few segment options, but notably included one for the faults with some of the largest displacements in the Kaikoura Earthquake – the Jordan Thrust (up to 7-9 m dextral), Kekerengu Fault (10-12 m dextral), and the Needles Fault. Previously unrecognised faults include a number of NNW-striking faults which may act as link structures between the major NE-striking faults. In the south these are very complex ruptures with displacements as much as 2 m vertical (up to the NW) and 1-2 m dextral. In the central part this includes the Papatea Fault, for which activity was previously unclear, and had displacements of as much as 6-7 m vertical and 5-6 m sinistral. The highest coastal uplift of about 5 m also occurred between two strands of the Papatea Fault. Several of these faults, including The Humps Fault Zone, likely have recurrence intervals of tens of thousands of years, whereas faults such as the Kekerengu Fault are as short as 300-400 years. The Papatea and the Hundalee faults probably have intermediate recurrence intervals This suggests that earthquakes involving this combination of faults are not typical and should be considered in future updates of the NZ NSHM.

*GNS Science, NIWA, Universities of Canterbury, Otago, Auckland, Victoria and Southern California, and US GEER teams

09:50 Surface fault rupture during the November 2016 Mw 7.8 Kaikoura earthquake, and paleoseismology of the Kekerengu Fault - one of the country's fastest slipping onland active faults

Russ Van Dissen[1], Tim Little[2], Kaikoura Earthquake Surface Rupture Response Team[3] ,[2]
[1]GNS Science, Lower Hutt, New Zealand, [2]Victoria University of Wellington, Wellington, New Zealand, [3]Many, others, New Zealand

The Mw 7.8 Kaikoura earthquake of 14 November, 2016 (NZDT) was a complex event. It involved ground-surface (or seafloor) fault rupture on at least a dozen onland or offshore faults, and sub-surface rupture on a handful of additional faults. Most of the surface ruptures involved previously known (or suspected) active faults, as well as surface rupture on a few hitherto unrecognised active faults. Surface rupture displacements on specific faults involved in the Kaikoura Earthquake span approximately two orders of magnitude. For example, maximum surface displacement on the Heaver's Creek Fault is cm- to dm-scale in size; whereas, maximum surface displacement on the nearby Kekerengu Fault is approximately 10-12 m (predominantly in a dextral sense).

The Kekerengu Fault has a Late Pleistocene slip-rate rate of 20-26 mm/yr, and is possibly the second fastest slipping onland fault in New Zealand, behind the Alpine Fault. Located in the northeastern South Island of New Zealand, the Kekerengu Fault - along with the Hope Fault to the southwest and the Needles Fault offshore to the northeast - comprise the fastest slipping elements of the Pacific-Australian plate boundary in this part of the country. In January 2016 (about ten months prior to the Kaikoura earthquake) three paleo-earthquake investigation trenches were excavated across pronounced traces of the Kekerengu Fault at two locations. These were the first such trenches dug and evaluated across the fault. All three trenches displayed abundant evidence of past surface fault ruptures (three surface ruptures in the last approximately 1,200 years, four now including the 2016 rupture). An interesting aspect of the 2016 rupture is that two of the trenches received surface fault rupture, and are now dextrally offset by about 9 m, while the third trench did not have any 2016 surface rupture pass through it. In this instance, ground-surface rupture along this trace of the fault died out within tens of metres of the trench.

The 2010 New Zealand National Seismic Hazard Model included only a few multi-segment / multi-fault earthquake sources; however, notably it did include one active fault earthquake source that encompassed the faults in the Kaikoura earthquake that joined to form the single longest continuous rupture and that had some of the largest displacements - teh Jordan Thrust (3-4 m dextral), Kekerengu Fault (10-12 m dextral), and the Needles Fault (submarine).

Another salient aspect of the Kaikoura earthquake is that the determined (or estimated) recurrence intervals of the faults that ruptured the ground surface vary by an order of magnitude or more. This strongly implies that the ensemble of faults that ruptured with the Kekerengu Fault in the 2016 earthquake has not always been the same for past earthquakes. Possible reasons for this could include the state of stress at the time of a specific earthquake, the direction of rupture propagation, and whether or not rupture on one fault system cascades into rupture on another as is suspected to have happened in the Kaikoura earthquake.

*Kaikoura Earthquake Surface Fault Rupture Response Team (alphabetical order by first name):

Benson, A., Bischoff, A., Hatem, A., Barrier, A., Nicol, A., Wandres, A., Lukovic, B., Hall, B., Gasston, C., Asher, C., Grimshaw, C., Madugo, C., Fenton, C., Hale, D., Barrell, DJA., Heron, DW., Strong, DT., Townsend, DB., Noble, D., Howarth, JD., Pettinga, J., Kearse, J., Williams, J., Manousakis, J., Borella, J., Mountjoy, J., Rowland, J., Clark, KJ., Pedley, K., Sauer, K., Berryman, KR., Hemphill-Haley, M., Stirling, MW., Villeneuve, M., Cockroft, M., Khajavi, N., Litchfield, NJ., Barnes, P., Villamor, P., Carne, R., Langridge, RM., Zinke, R., Van Dissen, RJ., McColl, S., Cox, SC., Lawson, S., Little, T., Stahl, T., Cochran, UA., Toy, V., Ries, WF., Juniper, Z.

10:10 Coffee and posters

Modelling of earthquake occurrence from paleoseismic data 2

(Chair: Andy Nicol, Jamie Howarth)

10:40

Rethinking magnitude-frequency distributions for fault sources in New Zealand

Mark Stirling[1], Matt Gerstenberger[2], Ramon Zuniga[3]
[1]University of Otago, Dunedin, New Zealand, [2]GNS Science, Lower Hutt, New Zealand, [3]UNAM, Querétaro, Mexico

The ongoing process of updating the national seismic hazard model for New Zealand provides an opportunity to revisit the question of whether the magnitude-frequency distributions for fault sources are best modelled according to the Gutenberg-Richter (GR) relationship or Characteristic Earthquake (CE) model. The last three versions of the national seismic hazard model utilised the CE model. We evaluate the alternative applicability of the GR relationship by constructing GR magnitude-frequency distributions for four major fault sources (Alpine, Hope, Wellington and Ohariu). Slip rate and fault plane dimensions are used to develop seismic moment rate-balanced GR magnitude-frequency distributions. The resulting distributions show: (1) recurrence intervals for the largest earthquakes that are compatible with the recurrence intervals derived from paleoseismic data when uncertainties are considered, and; (2) rates of M>5 earthquakes that are considerably greater than the rates observed in the 1964-2014 period of computerised instrumental records. However, we consider these GR-predicted M>5 rates to be compatible with the expected productivity of aftershocks early in the earthquake cycle of each fault, rather than during the relative quiescence of 1964-2014. Our results therefore justify the use of the GR relationship for characterising the magnitude-frequency distributions of the four fault sources. However, the issue of scale-dependency may prevent the general application of these results to the other fault sources, based on additional examination of the Canterbury earthquake sequence. An appropriate method of treatment for all fault sources will therefore need to include scale-dependency considerations.

11:00

Long-term probability of the Kanto M8 class earthquake along the Sagami Trough, Central Japan and its uncertainty

Masajiro Imoto, Nobuyuki Morikawa, Hiroyuki Fujiwara
National Research Institute for Earth Science and Disaster Resilience, Tsukuba, Japan

We discuss the uncertainty of the long-term probability of the Kanto M8 earthquake along the Sagami trough, central Japan. The Earthquake Research Committee, the Government of Japan has reported that the probability of the Kanto earthquake occurring in the next 30 years is less than 1%, which is estimated based on earthquake sequences to match origin times of nine earthquakes. The origin times of the earthquakes are assigned with a few hundred-year intervals on geological and geomorphological evidence. In generating earthquake sequences, we adopt a prior distribution consistent with historical earthquakes. We examine the epistemic uncertainty originating from the existence of the historical Meio Kanto earthquake and completeness of the paleoearthquakes. The frequency distribution of inter event times in the simulated sequences exhibits a bimodal distribution due to the peak at the longer interval consists of five former inter event times and the other peak at the shorter interval consists of three latter inter event times. This suggests missing earthquakes in the former part of the paleoearthquake series. Considering these factors, we attempt to estimate the long-term probability of the Kanto earthquake based on alternative sets of paleoearthquakes and historical events. Probabilities thus obtained are larger than the current value.

11:20 **Balancing the seismic moment distribution across large timescales: inclusion of fault source models in PSHA for intraplate Australia**

Jonathan Griffin[1], Dan Clark[1], Trevor Allen[1], Mark Stirling[2], Mark Leonard[1], Hadi Ghasemi[1]
[1]Geoscience Australia, Canberra, ACT, Australia, [2]University of Otago, Dunedin, Otago, New Zealand

Palaeoseismological studies of neotectonic faults in Australia reveal episodic recurrence behaviour, with quiescent periods lasting 10,000s to more than a million years followed by shorter active periods. The present observed moment release rate for an area may therefore not be equal to the long-term moment release rate. Low strain rates mean geodetic data do not provide a good constraint on the long-term rate either. This poses challenges for integrating fault source models with classical PSHA area source models based on recent instrumental and historical seismicity. This paper discusses different approaches to balancing the seismic moment rate between fault and area sources zones when the true long-term and present seismic moment rate is uncertain. This is further complicated by uncertainties around the most appropriate magnitude-frequency distribution (characteristic or Gutenberg-Richter) for fault source models and in the limited available palaeoseismic data. Sensitivity analysis of seismic hazard calculations is presented, with initial results indicating greater sensitivity at shorter return periods.

11:40 **Constraining the long-term average of earthquake recurrence intervals from paleo- and historic earthquakes by assimilating information from instrumental seismicity**

Gert Zöller
University of Potsdam, Potsdam, Germany

Paleo- and historic earthquakes are the most important source of information for the estimation of long-term recurrence intervals in fault zones, because sequences of paleoearthquakes cover more than one seismic cycle. On the other hand, these events are often rare, dating uncertainties are enormous and the problem of missing or misinterpreted events leads to additional problems. Taking these shortcomings into account, long-term recurrence intervals are usually unstable as long as no additional information are included. In the present study, I assume that the time to the next major earthquake depends on the rate of small and intermediate events between the large ones in terms of a “clock-change’’ model that leads to a Brownian Passage Time distribution for recurrence intervals. I take advantage of an earlier finding that the aperiodicity of this distribution can be related to the Gutenberg-Richter-b-value, which is usually around one and can be estimated easily from instrumental seismicity in the region under consideration. This allows to reduce the uncertainties in the estimation of the mean recurrence interval significantly, especially for short paleoearthquake sequences and high dating uncertainties. I present illustrative case studies from California and compare the method with the commonly used approach of exponentially distributed recurrence times assuming a stationary Poisson process.

12:00 **Discussion**

12:20 Lunch and posters

Earthquake forecasting and testing 3

(Chair: Warner Marzocchi, Matt Gerstenberger)

13:20 The initiation and tail of the aftershock decay

Sebastian Hainzl[1], Annemarie Christophersen[2]
[1]GFZ German Research Centre for Geosciences, Potsdam, Germany, [2]GNS Science, Lower Hutt, New Zealand

The rate of aftershocks triggered by a mainshock is usually fitted by a power-law decay, the so-called Omori-Utsu law. While the decay is well-established for the time span between a few hours/days and a few months/years after the mainshock, the initiation phase and tail of the decay is controversially debated. Empirical data show a mainshock magnitude dependent deviation from the power-law in the initial phase. Whether this is only an artefact of missed events or manifests properties of the underlying physical triggering mechanism remains controversial. The tail of the decay is difficult to decipher because of overlaying background activity and secondary aftershock triggering. It is often modelled by an unlimited power-law, which leads to an instability of the epidemic-type aftershock sequence (ETAS) model if the decay exponent p is smaller than one.

Here we will focus on both debated phases of the decay. In particular, we firstly analyse the apparent decay function based on the limited resolution of phase-picking algorithms in phases of high activity which leads to missed recordings in empirical catalogues. We show that the observed magnitude-dependent delay of the power-law initiation is well explained by missed events and does not reflect physical processes. Secondly, we implement alternative decay functions in the framework of the ETAS model to analyse the performance of different assumptions concerning the tail of the distribution. For earthquake sequences from global and regional catalogues, we find that a limited length of the decay is in most cases preferred based on information criteria.

13:40 Earthquake number forecasts testing

Yan Kagan
EPSS, UCLA, Los Angeles, California 90095, USA

We study the distributions of earthquake numbers in the Global Centroid-Moment Tensor (GCMT) and Preliminary Determinations of Epicenters (PDE) global catalogs. The distributions are needed to develop the number test for our forecasts of future seismic activity rate, organized by the Collaboratory for Study of Earthquake Predictability (CSEP). A common assumption in CSEP tests is that the numbers are described by the Poisson distribution. However the Poisson distribution, with just one parameter, fails for catalogs with many small earthquakes. In contrast, the negative-binomial distribution (NBD) has two parameters, and the second one can characterize the clustering, or over-dispersion, of a process. For both catalogs we investigate the dependence of parameters on the magnitude threshold and the time interval length. Can the Poisson law generally be rejected?

For most important cases, the NBD fits significantly better. Does either distribution fit the seismicity well enough? For this purpose we study upper statistical moments (skewness and kurtosis) of earthquake numbers and compare them to the theoretical values. Empirical values for skewness and kurtosis increase as the magnitude threshold decreases, and as the catalogs are partitioned into small time intervals. Like the empirical values, NBD skewness and kurtosis increase with decreasing magnitude threshold and smaller time intervals. However, the observed values of skewness/kurtosis rise even faster. Thus for small time intervals the earthquake number distribution is even more heavy-tailed than the NBD.

14:00 **Coulomb / statistical models for aftershock forecasting**

Sandy Steacy, Thomas Reverso
The University of Adelaide, Adelaide, Australia

The past 5 years has seen a rapid increase in the development of models for the probabilistic forecasting of future earthquakes. Most commonly, these models are used for forecasting aftershock rates – both because of the disproportionate damage caused by aftershocks and because these sequences provide more data for model testing than large events on their own. One set of end member models (ETAS, STEP) involves purely statistical combinations of the Gutenberg-Richter and Omori-Utsu relations whereas the physics approach (Coulomb rate-state) is based on earthquake induced stress changes and laboratory experiments of fault zone friction.

Here we investigate a series of hybrid models which are designed to combine the temporal skill of the statistical models with the spatial skill of the Coulomb approach. Specifically, we retrospectively test combinations of STEP/Coulomb and ETAS/Coulomb on California and New Zealand aftershock sequences. We find that the hybrid models perform at least as well as the statistical models on their own, and that their skill is enhanced by using early data to assess the extent to which the Coulomb stress 'maps' describe the spatial distribution of aftershocks. Our results support the view that hybrid earthquake forecasting models are more robust than those based on a single approach and suggest that the inclusion of Coulomb stress changes can increase the skill of earthquake forecasts.

14:20 **Uncertainty and assessing long-term rates in low seismicity regions**

Matt Gerstenberger[1], Danijel Schorlemmer[2,3], John Aiken[2]
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Typically forecast model development and testing is focussed on regions where seismicity and geological strain rates are moderate to high. These are considered the regions of highest hazard and where observational data is available to test model skill. However, understanding the hazard in regions where fewer historical events have been observed can be important from a risk perspective when low-seismicity regions correspond to population centres. Some regions of interest are Auckland, the mid-continent region of the USA, populated regions of the Australian continent, and urban areas in central Europe. For understanding the risk, the uncertainties in the estimated hazard become important. We are aiming to better quantify the uncertainties in long-term rates of such regions using the variability of earthquake rates in high seismicity regions of Japan and New Zealand. In a preliminary study we have developed multiple block-boostrapped catalogues of varying sizes from 5 to 500 M>3.95 earthquakes. For each catalogue we developed a simple smoothed seismicity (SS) forecast, such as is typical in seismic hazard analysis, and compared to a Spatially Uniform Poisson (SUP) forecast. Testing results on M>4.95 indicate that when using only a few hundred events, SS forecasts, were worse than SUP forecasts, more often than not. These preliminary results suggest that uncertainties in earthquake rates in low seismicity regions may be much higher than the Poisson temporal uncertainty that is currently considered.

14:40 Coffee and posters

Earthquake forecasting and testing 4

(Chair: Warner Marzocchi, Matt Gerstenberger)

15:40

Experimental concepts for testing seismic hazard and earthquake forecasting models

Warner Marzocchi[1], Thomas Jordan[2]
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To account for the randomness (aleatory variability) and limited knowledge (epistemic uncertainty) of earthquake processes, seismologists must formulate and test hazard and forecasting models using the concepts of probability. In this presentation, we will address the scientific objections that have been raised over the years against probabilistic seismic hazard analysis (PSHA), and, more in general, against the possibility to test probabilistic models, in particular when such models rely on expert opinion to quantify the epistemic uncertainties. In a recent paper (PNAS, 111, 11973-11978) we have introduced a probabilistic framework, which addresses the critics and allows probabilistic models to be tested against data. This framework is based on the definition of appropriate "experimental concepts." An experimental concept specifies collections of data, observed and not yet observed, that are judged to be exchangeable (i.e., with a joint distribution invariant to the data ordering) when conditioned on a set of explanatory variables. We illustrate, through concrete examples, experimental concepts useful in the testing of PSHA and earthquake forecasting models for ontological errors in the presence of aleatory variability and epistemic uncertainty. In particular, we describe in detail possible strategies to test PSHA models considering exceedances observed in different sites that may be spatially correlated. We also address some challenging issues for CSEP in testing earthquake forecasting models, such as the need to incorporate the epistemic uncertainty, and to address the spatial correlation of the observations.

16:00

Scoring ground motion models

Sum Mak
GFZ-Potsdam, Potsdam, Germany

The ground motion model (GMM) is an important component of a seismic hazard model. It provides a probabilistic forecast of ground motion occurrence for prescribed earthquake magnitude, location, and other source and site parameters. A probabilistic seismic hazard model adopts one or multiple GMMs among a large number of candidates. The selection of the most suitable GMM(s) is critical in determining the output hazard of a hazard model. The empirical evaluation of GMMs has been an active research field in the seismic hazard modelling community. I review the common methods of empirical GMM evaluation. The likelihood-based scoring of GMMs is an attractive method due to its objectivity in implementation, simplicity in interpretation and model ranking, and well-accepted theoretical foundation. I discuss its use in GMM selection, particularly under the context that ground motions are usual hierarchical. I give examples of how the correlation among observations will affect the empirical evaluation of GMMs.

16:20 **Ensemble smoothed seismicity model for the 2016 Italian probabilistic seismic hazard map**

Aybige Akinci[1], Morgan P. Moschetti[2], Matteo Taroni[1]
[1]INGV, Rome, Italy, [2]USGS, Golden, USA

The smoothed seismicity models plan to be introduced into the 2016 Italian Probabilistic Seismic Hazard Maps. In this study we report progress on the use of smoothed seismicity models developed by using fixed and the adaptive smoothing algorithms. The approach of using spatially smoothed historical seismicity is different from the one used previously for Italy, in which source zones were drawn around the seismicity and the tectonic provinces and is the first to be used for the new probabilistic seismic hazard maps for Italy. We develop two different smoothed seismicity models following the well-known and widely applied fixed (Frankel, 1995) and adaptive smoothing methods (Helmstetter et al., 2007) and compare the resulting models (Moschetti, 2015) by calculating and evaluating the likelihood test. In this framework, the smoothed seismicity models are constructed by using both the historical and the instrumental Italian catalog and their associated completeness levels to produce a space-time forecast of the future Italian seismicity. We follow guidance from previous studies to optimize the correlation distance as well as the neighboring number by comparing model likelihood values, which estimate the likelihood that the observed earthquake epicenters from the recent catalog are derived from the smoothed rate models. We compare likelihood values from all rate models to rank the smoothing methods. We also compare two models with the Italian CSEP experiment models, to check their relative performances. Finally we create anensemble model using two different smoothing models, which are weighted equally through a logic-tree approach to improve the forecast capability.

16:40 **Discussion**

17:00 **Closing discussion**

Abstracts

Presentation type: Poster
by topics and poster number

Stochastic modelling of spatiotemporal earthquake occurrence

(01 - 09)

01 Accurate earthquake rates in swarm-dominated areas without the need for declustering

Carolin Boese
School of Geography, Environment and Earth Science, Victoria University of Wellington, Wellington, New Zealand

Earthquake rates are often assumed to be constant and are used as input into hazard models. However, time variability in the earthquake activity may not be accurately accounted for when average rates are used. In particular, a constant background rate may not be an accurate description of the earthquake activity in areas where earthquakes swarms are commonly observed. To distinguish high-activity earthquake periods from background states requires the knowledge of the frequency of occurrence of earthquakes above the completeness magnitude. When declustering of earthquake catalogues is applied to determine a background rate, this already makes assumptions about relations between earthquakes in the catalogue. We apply statistics of screwed distributions for swarm-dominated catalogues. In the box-and-whisker plots of daily, 2-daily, monthly and other time scale distributions, the swarms are often more easily identified as outliers to the distribution without making any assumptions about them. For a New Zealand earthquake catalogue, we have identified a cyclic median background activity and a typical time scale over which earthquake swarms occur. This has previously not been identified when average rates were determined from the cumulative number of events with time plots.

02 Aftershock productivity imaging on main shock fault plane by seismicity triggering modelling

Yicun Guo[1], Jiancang Zhuang[2], Naoshi Hirata[1]
[1]Earthquake Research Institute, Tokyo, Japan, [2]Institute of Statistical Mathematics, Tokyo, Japan

We develop an iterative finite Epidemic Type Aftershock Sequence (ETAS) model to improve the aftershock triggering ability of the main shock, in which the main shock is taken as a finite source instead of point source when triggering aftershocks. We apply the new model to Japan Meteorological Agency catalogue by taking 7 main shocks with magnitudes larger than 7.5 after 1980 as finite sources and reconstruct the aftershock productivity patterns on these main shock rupture surfaces.

03 A 2D hidden Markov model for the recurrence patterns of non-volcanic tremors

Ting Wang[1], Jiancang Zhuang[2,3], Kazushige Obara[4], Hiroshi Tsuruoka[4], Jodie Buckby[1]
[1]Department of Mathematics and Statistics, University of Otago, Dunedin, New Zealand, [2]Institute of Statistical Mathematics, Tokyo, Japan, [3]Department of Statistical Science, Graduate University for Advanced Studies, Tokyo, Japan, [4]Earthquake Research Institute, University of Tokyo, Tokyo, Japan

Non-volcanic tremor activity has been observed in many places worldwide. In some regions, their activity has been observed to be accompanying slow slip events. Before examining whether non-volcanic tremor activity is related to slow slips and how they are related, it is essential to first understand the spatiotemporal migration patterns of non-volcanic tremors. We extended our 1D hidden Markov model (HMM), where the epicentres are projected orthogonally onto a line, to a 2D model in order to understand the behaviour of tremor activity in complicated tectonic environments. We applied this model to the regions Kii and Shikoku in the Nankai subduction zone, southwest Japan. The models classify the tremor source regions into distinct segments in 2D space (14 segments in the Kii region and 19 segments in the Shikoku region) and found some spatiotemporal migration patterns among these segments. The boundaries of the subsystems formed by these distinct segments strongly relate to isodepth contours of the oceanic Moho discontinuity in these regions.

04 Cumulative coulomb stress triggering as an explanation for the Canterbury (New Zealand) aftershock sequence: Initial conditions are everything?

Mark Bebbington[1], David Harte[2], Charles Williams[2]
[1]Massey University, Palmerston North, New Zealand, [2]GNS, Wellington, New Zealand

Using two years of aftershock data, and three fault-plane solutions for each of the initial M7.1 Darfield earthquake and the larger (M>6) aftershocks, we conduct a detailed examination of Coulomb stress transfer in the Canterbury 2010--2011 earthquake sequence. Moment tensor solutions exist for 283 of the events with M≥3.6, while 713 other events of M≥3.6 have only hypocentre and magnitude information available. We look at various methods for deciding between the two possible mechanisms for the 283 events with moment tensor solutions, including conformation to observed surface faulting, and maximum ΔCFF transfer from the Darfield main shock. For the remaining events, imputation methods for the mechanism including nearest-neighbour, kernel smoothing and optimal plane methods are considered. Fault length, width and depth are arrived at via a suite of scaling relations. A large (50% to 70%) proportion of the faults considered were calculated to have initial loading in excess of the final stress drop. The majority of faults that accumulated positive ΔCFF during the sequence were `encouraged' by the main shock failure but, on the other hand, of the faults that failed during the sequence, more than 50% of faults appeared to have accumulated a negative ΔCFF from all preceding failures during the sequence. These results were qualitatively insensitive to any of the factors considered. We conclude that there is much unknown about how Coulomb Stress triggering works in practice.

05 Designing catastrophe bonds for earthquakes in northern China

Ziyao Xiong, Shiyong Zhou
Peking University, Beijing, China

In this study, we design a catastrophe bond for earthquakes in Northern China. Our study contains three key steps: constructing the earthquake hazard model, building the corresponding loss model and designing the catastrophe bonds for earthquakes.

Firstly, we generate the Theoretical Earthquake Catalog. First of all, we select the earthquake datasets from Northern China since 1970 and collect the corresponding focal mechanisms. After meshing the study region, with the Multidimensional Stress Release Model(MSRM), the space-time Epidemic-Type Aftershock Sequence(ETAS) model and the Poisson model, we can get three kinds of spatial variation conditional intensity function λ. In the meantime, using of Yujie Zheng's codes can generate the spatial variation b-value. Having λ and b, we can get the Theoretical Earthquake Catalog in Northern China.

Secondly, we obtain a robust and reliable earthquake loss model. We establish the loss model with the loss datasets related to the population and magnitudes from China since 1970. To verify its reliability, we simulate 100 groups of loss datasets based on it and compare them with the actual loss datasets. After several times of simulation, comparison and calibration, an ideal model can be achieved.

In the future, our job is to accomplish the third step cooperating with the UCL(University College London), and constantly improve our model.

06 Mixture of a rate- and state-dependent seismicity and the ETAS models and its application to earthquake swarms

Takaki Iwata
Tokiwa University, Mito, Ibaraki, Japan

To improve a performance of seismicity model, the idea to construct a mixture of different seismicity models has been suggested [Rhoades and Gerstenberger, 2009, BSSA]. The ETAS model [Ogata, 1988, JASA] generally performs well to fit earthquake sequences, and therefore it is currently regarded as a standard seismicity model. Occasionally, however, its performance is unsatisfactory, particularly for swarm-type earthquake sequences.

To cover this point, in this study, the mixture model of the ETAS model and seismicity model proposed in Iwata [2016, Pageoph] is examined. The latter model is a modified version of the seismicity model derived from the rate-and-state friction [Dieterich, 1994, JGR] to include the influence of secondary aftershocks (aftershocks caused by earlier aftershocks). The mixture model is represented as the sum of the two models, and the mixing ratio and parameters contained in the two models are estimated by maximum likelihood. Its (relative) performance is statistically evaluated with Akaike Information Criterion (AIC).

This mixture model is applied to two earthquake swarms: the 1965-1970 Matsushiro and 2000 Izu earthquake swarms in Japan. For the Matsushiro and Izu swarms, the AIC values of the mixture models are 5.8 and 125.7 smaller (better) than those of the ETAS model, respectively. This indicates that the examined mixture model achieves significant improvement of the ETAS model for earthquake swarm activity.

07 Predicting seismic activity beneath the Greater Tokyo area

Yosihiko Ogata[1,2], Koichi Katsura[2], Hiroshi Tsuruoka[1], Naoshi Hirata[1]
[1]Earthquake Research Institute, University of Tokyo, Bunkyo-Ku, Tokyo, Japan, [2]The Institute of Statistical Mathematics, Tachikawa-city, Tokyo, Japan

We consider the short-term and long-term forecasts beneath the Metropolitan area (Kanto region) using the space-time ETAS (epidemic-type aftershock sequence) models that is extended taking account of the induced effect of the 2011 Tohoku-Oki earthquake of M9.0. In particular, owing to the complex configuration of tectonic plates beneath the Kanto region, location-dependent space-time ETAS model for the seismicity in 3D space (longitude, latitude and depth) down to 100km depth is required. Furthermore, for forecasting future large earthquakes, we need to estimate the location-dependent Gutenberg-Richter law of magnitude frequency.

08 Quantifying radiated seismic energy: a new approach for statistical seismology applied to the Kaikoura Mw7.8 earthquake

Bill Fry[1], Matt Gerstenberger[1], David Rhoades[1], Honn Kao[1,2]
[1]GNS Science, Lower Hutt, New Zealand, [2]PGC, Sidney, Canada

Difficulties in assessing seismic hazard using routine earthquake catalogues based on traditional algorithms are numerous. They include limitations arising from event detection, inverting phase arrival time data for location, and defining magnitude based on observations of instantaneous ground motion amplitude. Waveform inversion is useful for cataloguing large events, but technical limitations preclude its use in routinely describing events with magnitude less than about Mw4.0. In this work, we present a new approach to generating catalogues of radiated energy that overcome many of the difficulties of earthquake catalogueing. We further suggest that maps of radiated energy can be used in seismic hazard assessment in much the same way that discrete earthquake catalogues are currently used.

The energy mapping method is based on back projection of continuous velocity squared waveforms and defines the relative likelihood of quantifiable energy radiation fromevery element in a 3D earth model in short, discrete time steps. We apply this method to central New Zealand and to the Mw7.8 Kaikoura earthquake sequence. In the future, we will test the usefulness of the resulting time-dependent radiated energy maps by measuring their earthquake predictive power within the framework of the multiplicative hybrid modelling approach.

09 What is the impact of the August 24, 2016 Amatrice earthquake on the seismic hazard assessment in the central Italy?

Matteo Taroni, Maura Murru, Aybige Akinci, Giuseppe Falcone
INGV, Rome, Italy

The August 24, 2016 Amatrice earthquake occurred at 03:36 a.m. local time in Central Italy in a zone of seismic gap, causing extensive damage in the Amatrice town and surrounding areas. This earthquake occurred while there has been an ongoing effort to update the 2004 seismic hazard map (MPS04) prompted in 2015 by the Italian Civil Protection Agency to the Center for Seismic Hazard (CPS) of the Istituto Nazionale di Geofisica e Vulcanologia INGV. The recent event motivated us to study and provide better understanding on the seismic hazard assessement in the macro area defined as “Central Italy”. Therefore, in this study we bring to our attention new earthquake source data and recently developed ground-motion prediction equations (GMPEs) and validate whether the seismic hazard assessment has changed with respect to 2004, year in which it was released the official map of the seismic hazard for the Italian territory (MPS04). In order to understand the impact of the recent earthquakes on the seismic hazard assessment in the central Italy we compared the annual seismic rates calculated using the smoothed seismicity approach over two different periods of catalogs; the Parametric Catalog of the Historical Italian earthquakes (CPTI15) from 1871 to 2003 and the historical and instrumental catalogs from 1871 up to 31 August 2016 . Results are presented also in terms of peak ground acceleration (PGA), using recent ground-motion prediction equations at one site, Amatrice, interested by the 2016 sequence.

Summary statistics, empirical relationships and data quality

(10 - 19)

10 A Bayesian framework for estimating moment magnitude and its uncertainty from macroseismic intensity measures

Emily Kawabata[1], Ian Main[1], Mark Naylor[1], Richard Chandler[2]
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In moderate seismicity areas such as the UK, earthquakes represent a small but not negligible risk to sensitive structures. As a part of the safety case in the planning and regulation of such structures, seismic activity must first be monitored and quantified to form a catalogue of past events. In a moderate seismicity zone, most of our knowledge of the most significant events comes from macroseismic intensity measures from the pre-instrumental period. These historical records must then be calibrated with modern instrumental data on a common source magnitude scale, namely the moment magnitude. The result is a unified catalogue that can be used for probabilistic seismic hazard analysis.

We demonstrate a method for constructing isoseismal maps objectively from macroseismic intensity measures and their observed locations. It involves using mathematical expressions to represent concentric ellipses for the contours and estimating their optimal parameters and uncertainties in a Bayesian framework. Inferred fault orientations in the UK are predominantly vertical, so the elliptical assumption is reasonable as a null hypothesis. Available relevant physical constraints are used as priors. The resulting posterior distributions are used to calculate felt area at a given intensity, as well as a probability density function for the inferred epicentre.

We then describe another Bayesian approach for deriving moment magnitude from felt areas based on their relationship. The use of Bayesian inference allows us to quantify uncertainty inherent in the intensity measures and to propagate it through formally to a probability density function for the inferred moment magnitude.

11 Aftershock productivity on volcanoes: What can it tell us about interpreting aftershocks?

Ricardo Garza-Giron[1], Emily E. Brodsky[1], Stephanie G. Prejean[2]
[1]University of California, Santa Cruz, Santa Cruz, California, USA, [2]USGS, Anchorage, Alaska, USA

Most earthquakes have aftershocks and in some systems, it is thought that the majority of the earthquake rate is comprised of aftershocks. However, volcanic earthquakes are intrinsically different from tectonic ones in that magmatic movement can stress rocks more quickly than plate tectonics and elastic strain can be more difficult to sustain over long periods of time. In this study, we measure the aftershock productivity of 29 volcanoes in the Alaska Peninsula and the Aleutian Islands. We utilize a standard model of aftershock production developed for tectonic systems where it is usually observed that the number of aftershocks of a mainshock magnitude M is equal to K10a(M-¬Mref) where K and a are constants that vary regionally and Mref is a reference magnitude. Of the volcanoes studied here, 23 showed a mainshock-¬aftershock behavior such as the one observed in global or regional tectonic regimes. The remaining volcanoes did not have enough seismicity for us to make a clear assessment. Of those, 13 volcanoes are well¬fit by the model with p¬values below 0.01. Those that are well¬fit have a level of aftershock productivity similar to an ordinary tectonic system like the San Andreas Fault System in California. Our results help us understand the dynamic triggering behavior in volcanoes and it opens a window to further exploit this phenomenon and to make a link with the eruptive behavior of different systems. The study of aftershock productivity in volcanic systems hint that this may be a useful indicator of stress accumulation in the crust.

12 Assessing variations in shear wave splitting measurement from simulated waveforms

Kenny Graham[1,2], Martha Savage[1], Richard Arnold[2]
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It has long been presumed that the ability to monitor changes in stresses within the Earth's crust might assist in hazard prediction and resource extraction. Measuring seismic anisotropy through shear wave splitting, SWS, has proven to be a potential tool to infer these stress changes. Thus changes in stress can be related to changes in average delay-time of SWS parameters. However, this potentially powerful tool has yet to be realized in part because measurements on local earthquakes are sometimes challenging and gives varying results. Many studies have attempted and suggested using different statistical techniques (like moving averages; least square and curve fitting) to account for the variations in the measurements. Other studies also attribute these variations to scattering of seismic energy by inhomogeneities in the wave's propagation path and other possible effect (such as; horizontal layers of anisotropy, dipping symmetry axes, lateral variations in anisotropy, and other sources of noise). To explore the effects of these proposed mechanisms of variation in SWS measurements, we generate synthetic waveforms using 1-D reflectivity technique and 3D Spectral-Finite element method. The Silver and Chan analysis technique is applied through the Mfast automatic shear wave splitting algorithms to estimated SWS measurements of the simulated waveforms. We present an account of simulated SWS measurement from possible causes of the variations and show how these affect the SWS measurement. We will also look at developing a robust statistical model to account for these variations and hopefully propose a tentative approach to improving seismic anisotropy measurement.

13 Fluid filled fractures and shear wave splitting: a study of two geothermal fields in the Taupo Volcanic Zone

Stefan Mroczek, Martha Savage
Victoria University of Wellington, Wellington, New Zealand

To investigate the fracture orientation and density, in the Mercury geothermal fields at Ngatamariki and Rotokawa, we fit a fluid filled fracture model to shear wave splitting measurements. We have determined shear wave splitting across both fields for 1919 earthquakes measured on 22 stations during 2015. Measurements were made using the Multiple Filter Automatic Splitting Technique (MFAST).

Shear wave splitting measurements display a significant amount of scatter so, to obtain accurate estimates of fracture orientation and density, we apply several forms of clustering and error analysis.

The delay time between the split shear waves (the measured analogue of fracture density) can vary dramatically with incoming angle and back azimuth. The process of fitting the data to the fluid filled fracture model allows us to account for this variation which, in turn, allows us perform more accurate delay time tomography estimation.

Preliminahry results indicate that peak delay times for the region occur within each field. Fracture orientation also appears to range from N-S within Rotokawa through to ENE-WSW within Ngatamariki and surrounding areas

14 **Characterizing the effect of automatic S-picks on location uncertainty of microseismicity at geothermal areas, North Island, New Zealand**

Chet Hopp[1], Martha Savage[1], Stefan Mroczek[1], John Townend[1], Steve Sherburn[2]
[1]Victoria University of Wellington, Wellington, New Zealand, [2]GNS Science, Wairakei, New Zealand

Monitoring patterns in local microseismicity gives clues to the existence and location of subsurface structures. At geothermal reservoirs, subsurface structures often indicate areas of high permeability and are vitally important in understanding fluid flow within the resource. However, detecting and locating microseismic events within an area of power generation is often challenging due to high levels of noise associated with nearby power plant infrastructure. In addition, geothermal reservoirs are often characterized by highly attenuating geology and significant lateral heterogeneity. This makes caculating precise locations difficult, especially when the 3-D velocity structure is poorly understood. These issues lead to large location uncertainties and limit our ability to infer fracture orientations within the reservoirs from patterns in seismicity. For certain Mercury geothermal fields it has been reported that including S-picks in the location of earthquakes increases the overall location uncertainty for a given event. We applied a matched filter routine to a one-year dataset for the geothermal areas at Rotokawa and Ngatamariki, which expanded the known earthquake catalog to nearly 21,000 events. P-picks were made by cross correlation of the matched filter templates with the continuous seismic data. We then incorporated select automatically picked S-arrivals for 2418 of these events. This study aims to quantify the effect that these S-picks have on the maximum-likelihood hypocenters, location uncertainties and the extents of the location PDFs. It will also assesses any value these picks add to the analysis of seismicity at these fields given our current understanding of the three-dimensional velocity structure.

15 **Towards a continuous micro-earthquake catalogue in New Zealand's central Southern Alps**

Konstantinos Michailos, John Townend, Martha Savage, Calum Chamberlain
Victoria University of Wellington, Wellington, New Zealand

The Alpine Fault is one of the most prominent tectonic features in the South Island, New Zealand, and based on paleoseismological evidence is inferred to be late in its seismic cycle of M7-8 earthquakes. Despite this, the Alpine Fault displays low levels of contemporary seismic activity, with little documented on-fault seismicity. This low magnitude seismicity, often below the completeness level of the GeoNet national seismic catalogue, may inform us of changes in fault character along-strike and might be used for rupture simulations and hazard planning.

Areas of low seismic activity (e.g. central Alpine Fault area) require data recorded over a long duration to reveal temporal and spatial seismicity patterns and provide a better understanding for the processes controlling seismogenesis. The continuity and density of the Southern Alps Microearthquake Borehole Array (SAMBA; deployed in late 2008) allows us to study seismicity in the Southern Alps over an extended time period. Furthermore, by using data from other temporary networks (e.g. WIZARD, ALFA08, DFDP-10) we are able to extend the region covered.

To generate a spatially and temporally continuous catalogue of seismicity in New Zealand's central Southern Alps, we will use automatic detection and phase-picking methods. We utilise an automatic phase-picking method for both P- and S- wave arrivals proposed by Rawles and Thurber [2015]. Preliminary results obtained from three months of data show that the phase picks are reasonably accurate: comparison with analyst picks yields differences of less than 0.2 seconds for 95 per cent of the data.

16 ## Distant, delayed, Darfield: triggering of the Canterbury earthquake sequence

Yifan Yin[1], Bill Fry[2], J. Douglas Zechar[1], Stefan Wiemer[1]
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Continuous GPS records suggest that the 2010 Darfield earthquake may have been triggered by the 2009 Dusky Sound earthquake: several stations in the central South Island captured prolonged westward movement after the Dusky Sound event, which occurred ~500 km away. The trend continued for almost two years leading up to the Christchurch earthquake. We want to know if this aseismic deformation is accompanied by a change of micro-seismicity rate in the Canterbury region.

The routine detection of the GeoNet national network does not provide such sensitivity for small events, so we use the GeoNet catalog as a baseline and expand it using template matching techniques. The technique uses waveforms of known and well-located events as templates. The templates then cross-correlate with continuous seismic records. Peak correlation values above a chosen threshold are considered detected events. To look for rate change of seismicity in the Canterbury region prior to Darfield earthquake, we concentrate on station OXZ, which is closest to the Darfield epicenter. We cut templates from OXZ using arrival times from the GeoNet catalog prior to Darfield earthquake. In this presentation, we show the first results of our analysis, having looked at the frequency band of tremors and earthquakes to detect seismicity rate changes leading up to the deadly Christchurch earthquake.

17 ## Exploring temporal and magnitude variations in declustered catalogues in New Zealand

Katrina Jacobs, Martha Savage, Euan G.C. Smith
Victoria University of Wellington, Wellington, New Zealand

To investigate temporal variations of earthquake rate, we decluster the New Zealand earthquake catalogue using the Gardner and Knopoff and CuRate techniques. For each method we use the biggest spatial and temporal limits that return Poisson declustered catalogues. The Poisson nature of the catalogues is verified using a chi-squared test and by calculating dispersion values. The chi-squared test is performed a number of times by shifting the bin start times by small amounts to test for sensitivity to bin size. Both declustering methods display some sensitivity to binning. If the declustered catalogues fail the Poisson tests, the catalogues are further split into smaller temporal and spatial catalogues until all portions of the declustered catalogue show Poisson behavior. To be most effective, the CuRate method needs catalogues that have a spatially and temporally consistent background rate. The need to split Curate catalogues into multiple time periods suggests variation in the background rate with time. The traditional Gardner and Knopoff method also requires smaller spatial and temporal subsets to achieve Poisson declustered catalogues, albeit to a lesser degree than the CuRate method. Some temporal subsets may be associated with changes in station distribution but other causes also exist. We also show that for both declustereing methods dispersion values increase with magnitude cut-off even when the magnitude cut-offs are above the magnitude of completeness. We suggest that this indicates clustering that exists at all magnitude levels, but is more easily detected at low magnitudes due to the larger overall catalogue size.

18 Regional evolution of network detection completeness in Japan

Danijel Schorlemmer[1,2], Naoshi Hirata[3], Yuzo Ishigaki[4], Kazuyoshi Nanjo[5], Hiroshi Tsuruoka[3], Thomas Beutin[1], Fabian Euchner[6]
[1]GFZ Potsdam, Potsdam, Germany, [2]University of Southern California, Los Angeles, California, USA, [3]University of Tokyo, Tokyo, Japan, [4]Japan Meteorological Agency, Tokyo, Japan, [5]University of Shizuoka, Shizuoka, Japan, [6]ETH Zurich, Zurich, Switzerland

An important characteristic of any seismic network is its detection completeness, which should be considered a function of space and time. Many researchers rely on robust estimates of detection completeness, especially when investigating statistical parameters of earthquake occurrence like earthquake rates. Contrary to traditional approaches, we do not estimate completeness using methods in which the completeness magnitude is defined as the deviation of the frequency-magnitude distribution from the linear Gutenberg-Richter relation. Here, we present a method based on empirical data only: phase data, station information, and the network-specific attenuation relation.

For each station of the network we estimate a time-dependent distribution function describing the detection capability depending on magnitude and distance to the earthquake.

For each point in time, maps of detection probabilities for certain magnitudes or overall completeness levels are compiled based on these distributions. Therefore, this method allows for inspection of station performances and their evolution as well as investigations on local detection probabilities even in regions without seismic activity.

We present a full history of network detection completeness for Japan and discuss details of this evolution, e.g. the effects of the Tohoku-oki earthquake sequence.

For practical purposes we deliver completeness estimates for catalog data of selected regions and document the conservative completeness estimates researchers can use when investigating the JMA catalog in different regions over different periods. All presented results are published on the CompletenessWeb (www.completenessweb.org) from which one can download completeness data from all investigated regions, software codes for reproducing the results, and publication-ready and customizable figures.

19 Seismic swarms, near the capital of Mongolia, investigated using double-difference tomography: analysis of the geometry of active structures, space and time evolution of swarms.

Adiya Munkhsaikhan
IAG, Ulaanbaatar, Mongolia

Since 2005, we have been observing a moderate-sized high seismic activity (seismic swarm) about 10 km northwest from capital of Mongolia. This activity occurs along a newly discovered active fault, the Emeelt fault (named after the nearest sub city), with paleo-surface ruptures evidenced from field survey, geomorphology and paleoseismology.

The seismic activity is regularly increasing. At the beginning of the swarm, the delay time between two events decreased swarm by swarm. After each crisis, the minimum delay decreases, down to 4 seconds for the 2014 crisis. The rate of seismicity increases with time but also the b value moves from 0.8 to 1.4 with the first swarm activity, and then it decreases progressively until a value of 1.1 for the last period. We still do not know if the Emeelt seismic activity observation is a sign of a large event in a short time (days, months or few years) but we know that Emeelt fault was in the past the place of a large event, between a magnitude 6 to 7 and that it will occur again in the future.

In additionally, the procedure for identifying seismically active faults near the Ulaanbaatar and surroundings is described, while their earthquake potential and expected ground acceleration are also estimated. Based on the existing data, the maximum expected earthquake magnitude is 6.4 and 7 for Emeelt fault.

Earthquake physics

(20 - 26)

20 Dynamic stress triggering in the 2010-2011 Canterbury earthquake sequence

Caroline Holden, Charles Williams, David Rhoades
GNS Science, Lower Hutt, New Zealand

The Canterbury earthquake sequence started in 2010 with the M7.1 Darfield earthquake. It was followed by over 10,000 aftershocks including the tragic M6.2 February 2011 Christchurch earthquake and the latest M5.7 Valentine earthquake (Kaiser et al., 2016). Steacy et al. (2013) suggest that 100% of the M5.5+ aftershocks occur in regions of increased static Coulomb stress changes. In this study we investigate the role of dynamic stress triggering on aftershock production, with a particular emphasis on the static and dynamic effects on smaller aftershocks.

Based on the kinematic source models of Holden (2011, 2012), we calculate dynamic stressgrams: expressions of the evolution in time of the stress tensor at specific locations. We then derive time-dependent Coulomb failure stress values and respective peak dynamic stress values, as well as other stress-related quantities. For comparison, we also compute static stress values using both the same source models as the dynamic calculations, as well as more complex source models based on geodetic inversions. We produce interpolated maps of these metrics.

Finally we statistically compare the correlation of aftershock production with the static and dynamic approaches. We do so for a range of triggering times and a range of magnitudes.

21 Ground shaking due to earthquakes on creeping faults

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We investigated the peak ground motions from the largest well-recorded earthquakes on creeping strike-slip faults in active-tectonic continental regions. Our goal was to evaluate if the strong ground motions from earthquakes on creeping faults are smaller than the strong ground motions from earthquakes on locked faults. Smaller ground motions might be expected from earthquakes on creeping faults if the fault sections that strongly radiate energy are surrounded by patches of fault that predominantly absorb energy. For our study we used the ground motion data available in the PEER NGA-West2 database, and the ground motion prediction equations that were developed from the PEER NGA-West2 dataset. We analyzed data for the eleven largest well-recorded creeping-fault earthquakes, that ranged in magnitude from M5.0-6.5. Our findings are that these earthquakes produced peak ground motions that are statistically indistinguishable from the peak ground motions produced by similar-magnitude earthquakes on locked faults. These findings may be implemented in earthquake hazard estimates for M5.0-M6.5 earthquakes in creeping-fault regions. Additional observations and further investigation is necessary to determine if this result will also apply to larger earthquakes.

22 Physics based earthquake rupture scenarios inferred from interseismic locking distributions in the Nicoya Peninsula, Costa Rica

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Interseismic locking distributions derived from geodetic observations are often used to qualitatively evaluate the potential for future earthquakes. However, it has been suggested for a known locking model that the earthquake magnitudes are dependent on where the earthquakes initiate, and consequently poses a significant challenge to accurately predict the sizes of future earthquakes. Here we report our quantitative estimates of coseismic slip of the 2012 Mw7.6 Nicoya earthquake from the interseismic locking distributions using numerical simulations of dynamic ruptures. Using a curved subduction interface geometry and homogeneous material domain, we compute the stress distributions on the megathrust and then nucleate earthquakes. Our model predictions of final slip, rupture duration, and moment rate function are well consistent with observations of the 2012 earthquake, presenting a framework to quantitatively link interseismic locking with eventual coseismic slip. We have also set the nucleation zone at different positions and find that the final coseismic slip and seismic moment show obvious variations with different epicenter locations. More than half of the earthquakes within medium locking region (50% locking) can develop into large events (Mw>7). However, the other half shows much smaller magnitudes because the epicenters are located at regions with relatively low initial stress. Given the heterogeneous stress conditions on seismogenic faults shown in lock distributions, our results suggest that it is necessary to conduct quantitative evaluations of earthquake sizes for better seismic hazard assessment.

23 Power-law rheology controls aftershock triggering and decay

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Aftershocks are ubiquitous in nature. They are the manifestation of relaxation phenomena observed in various physical systems. In one prominent example, they typically occur after large earthquakes. They also occur in other natural or experimental systems. The observed aftershock sequences usually obey several well defined non-trivial empirical laws in magnitude, temporal, and spatial domains. In many cases their characteristics follow scale-invariant distributions.

In this work, we consider a slider-block model to mimic the behavior of a seismogenic fault. In the model, we introduce a nonlinear viscoelastic coupling mechanism to capture the essential characteristics of crustal rheology and stress interaction between the blocks and the medium. For this purpose we employ nonlinear Kelvin-Voigt elements consisting of an elastic spring and a dashpot assembled in parallel to introduce viscoelastic coupling between the blocks and the driving plate. By mapping the model into a cellular automaton we derive the functional form of the stress transfer mechanism in the model. We show that the nonlinear viscoelasticity plays a critical role in triggering of aftershocks. It explains the functional form of the Omori-Utsu law and gives physical interpretation of its parameters. The proposed model also suggests that the power-law rheology of the fault gauge and underlying lower crust and upper mantle control the decay rate of aftershocks. To verify this, we analyze several prominent aftershock sequences to estimate their decay rates and correlate with the rheological properties of the underlying lower crust and mantle.

24 Spatial distribution and energy release of non-volcanic tremor at Parkfield, California

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Non-volcanic tremors (NVTs) are observed in transition zones between freely slipping and locked sections of faults and normally occur below the seismogenic zone. Based on NVT recordings in the Parkfield region of the San Andreas Fault, we provide a novel approach to assess the energy release of these events and assign magnitudes (Me) that are compatible with size estimates of small earthquakes in the same region. To assess the energy magnitude of a detected tremor, we refine the estimate of its duration and perform a spectral analysis that accounts for local attenuation.

For the 218 NVTs that we were able to process, we resolve Me values in the range of -0.67 to 0.84. For events, which we could not process using the spectral analysis technique, we propose a statistical model to estimate Me values using observable characteristics, such as peak amplitude, spectral velocity at the source corner frequency and duration. We furthermore provide seismic moment and moment magnitude estimates and calculate stress drops in a range of 3-10kPa.

As a result of our spectral analyses, we find strong indications regarding the on-going debate about potential NVT location hypotheses: the Parkfield NVTs have a higher probability to be located in the proposed three-dimensional cloud-like cluster than in any other suggested location distribution.

25 The mechanics of rupture nucleation in laboratory experiments and its implications for foreshock generation processes

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Precursory aseismic slip lasting days to months prior to the initiation of earthquakes has been inferred from seismological observations. Similar precursory slip phenomena have also been observed in laboratory studies of shear rupture nucleation on frictional interfaces. However, the mechanisms that govern rupture nucleation have been widely debated. Here we show that a physics-based model incorporating rate-and-state friction laws and elastic continuum can reproduce the behaviors of rupture nucleation seen in laboratory experiments. In particular, we find that both in laboratory experiments and simulations with a range of normal stresses, the nucleation consists of two distinct phases: initial slow quasi-static propagation phase and faster acceleration phase, both of which are aseismic processes, followed by rapid dynamic rupture propagation that radiates seismic waves. Applying this model of rupture onset to data acquired during the San Andreas Fault Observatory at Depth (SAFOD) experiment, we predict what the nucleation phase will look like for magnitude-2 repeating earthquakes at a 3-km depth. Our results suggest that precursory slow slip associated with the earthquake nucleation phase may be observable in the hours before the occurrence of the magnitude-2 earthquakes by strain measurements close (a few hundreds meters) to the hypocenter, in a position reached by the existing borehole. I will also discuss implications of our results for the nucleation of other crustal earthquakes and their foreshock generation processes.

26 Using repeating earthquakes as probes for diverse fault slip behaviors

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Repeating earthquakes are clusters of microseismic events occurring at the same region and generating very similar waveforms. They likely represent asperities surrounded and loaded by aseismic creep, and can be used as an in-situ creep meter to quantify variable fault slip behaviors at depth. Here we show repeating earthquakes in three different regions: the aftershock zone of the 2013 Mw6.6 Lushan earthquake in China and the 2016 Mw7.8 Kaikoura earthquake, and the transition zone from fully locked to creeping section of the Hikurangi subduction zone in New Zealand. In each region we first obtain event-based waveforms listed in local catalogs. Then we apply a band-pass-filter to the raw data, and compute cross correlations using a fixed time window around the analyst-picked phase arrivals. Next, we select event pairs with cross-correlation (CC) values larger than 0.5, and compute a mean value for all possible stations. Event pairs with mean CC values larger than 0.9 are considered as potential doublets, and further grouped into potential repeating clusters using an equivalency class (EC) algorithm. Our preliminary results show abundant repeating clusters following the mainshocks in the first two regions, suggesting that they are likely driven by the ongoing afterslip of the mainshocks or triggered slow-slip at nearby faults. In the third case, repeating earthquakes appear to respond to episodic shallow slow-slip events on the Hikurangi subduction zone. Our next step is to relocate these potential repeating clusters, and compare with geodetically inverted afterslip or slow-slip. Updated results will be presented at the meeting.

Earthquake forecasts and testing

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27 **Bayesian prediction for modified Omori law and ETAS models for forecasting future aftershocks using early aftershock data**

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Forecasting future earthquakes is a very difficult task. Uncertainties existing in the measurement of magnitudes, locations and shaking intensities of the earthquakes make it even more difficult. A large earthquake is generally followed by a number of additional earthquakes, known as aftershocks. In most cases, seismograms fail to detect aftershocks with very small magnitudes. Therefore, the problem of Short Term Aftershock Incompleteness (STAI) occurs. This might adversely affect the forecasting process.

It is well known that the aftershock sequences can be characterized by the modified Omori law and the frequency-magnitude relationship of the aftershocks can be expressed by the Gutenberg-Richter law. Our research focuses on finding a Bayesian predictive distribution for both the modified Omori law and the Epidemic Type Aftershock Sequence (ETAS) model, based on available early aftershock data. For this purpose, the parameters of each of these two models are estimated using the first-month of data, the first three-months of data, and the first six-months of data after a large earthquake. A comparison of the predictions made by both models for future aftershocks is conducted afterwards to choose the best model. This, in turn, results in finding a trade of model between these two models which emphasizes on using the data prior to the mainshock for a better forecasting in the presence of incompleteness problem.

28 **Assessment of pre-earthquake land surface temperatures in 20 case studies worldwide**

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Anomalous TIR emissions have been proposed as a potential precursor to earthquakes. So-called thermal anomalies of (+2)-(+13)oC in air, at-sensor and land surface temperatures (LST) have been reported, usually within a month before large earthquakes. However, distinguishing normal from anomalous, potentially earthquake-related emissions is challenging because of the variety of factors that influence the satellite signal, like atmospheric composition, land cover and geomorphology.

We use geostationary-based, hypertemporal, atmospherically-corrected LST data.We examine time series before and after 20 earthquake cases between 2010-2015 around the globe. We study earthquakes of magnitude between M5.7 and M9.0, of different focal mechanisms and of shallow focal depth (with the exception of the medium-focus M7 Ecuador 2010 earthquake). Eighteen earthquakes in our study were land-based, and two offshore. We apply a recently published methodology which can distinguish localized signal fluctuations as low as 2K. We study the same areas in years with and without earthquake occurrence, and we also apply the methodology in areas where no earthquake has been registered. We estimate the uncertainty of our findings, accounting for positional, sensor-related and atmospheric influences. We assess our results considering physically realistic distances, relation to causative faults and geographical and geological environmental settings.

29 A study on seismicity in the Yunnan region by using multidimensional stress release model

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The long-term seismic activity in Yunnan region has been given high attention to due to frequent occurrence of disastrous earthquakes in this region. We investigated seismicity of the Yunnan region using multidimensional stress release model (MSRM) developed by Jiang et al. (2011) in order to evaluate long-term strong earthquake hazard in this area. MSRM combines three effects that influencing earthquake occurrence: initial stress background, tectonic loading, and coseismic stress transfer, and can be used to simulate and forecast the space-time-magnitude variations of seismicity rate. In this research we have calculated the temporal variations of earthquake occurrence rate, and carried out a forward forecasting experiment on the activity within five years, taking into consideration the 32 strong earthquakes with M≥6.5 since 1800. Comparisons between the seismic rates at the epicenter locations just before and after each strong earthquake, showed that strong earthqukes occurred at locations with high seismic activity but not the highest. After the earthquakes, the seismic occurrence rate in the vicinity of the epicenters significantly decreased. The plot of expected earthquake rates on Jan.1st, 2020 indicates that strong earthquake risks in the regions of south of Xiaojiang fault, northeast of Ninglang, and Puer should be paid attention to, while the middle segment of the Red River fault remains with low seismic activity.

30 A hybrid ETAS-Coulomb approach to evaluate spatio-temporal aftershock rates

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The ETAS ("Epidemic-Type Aftershock Sequence", e.g. Ogata 1988; Ogata & Zhuang 2006) is a common approach to aftershock forecasting. This model, based on the statistical approach and scaling laws such as the Omori-Utsu law or Gutenberg-Richter law leads to a good estimation of the statistical characteristics of seismicity in a specific region. However, the model is weak in characterizing the location of aftershocks for a specific mainshock-aftershock sequence. In contrast, the physics-based Coulomb method permits the computation of static stress changes due to co-seismic slip which can strongly impact the spatial events distribution after a major earthquake (King et al., 1994; Steacy et al. 2005).

Here we investigate a hybrid model which combines these approaches. Specifically, we use the ETAS model to calculate and forecast the number of aftershocks per day induced by previous earthquakes with the Coulomb method to spatially constrain their distribution. We test 5 variations of this model on the 1992 Mw=7.3 Landers sequence over a period of 188 days from the mainshock occurrence and compare the results to the classic ETAS model. For all but 10 of the 188 one day forecasts, we find that a hybrid model outperforms classical ETAS but that the forecasting skill of the hybrids varies in time. Our preliminary results suggest that the incorporation of Coulomb information may lead to better earthquake forecasts.

31 **A tale of two disasters: biases in risk communication**

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Risk communication is essential to disaster management but psychological research has identified multiple biases that affect people's interpretation of probabilities/risk. For example, 'availability bias' is known to confound probability estimates, while the description-experience gap (D-E Gap) shows low probability events being over-weighted when described and under-weighted when learnt from laboratory tasks. Here we examine how probability descriptions interact with real world experience of events. Responses from 294 participants showed that, given the same probabilities and consequences, people's responses altered according to their familiarity with the disaster (bushfire vs earthquake) and its personal salience.

32 **Communicating probabilities across geohazards: a probability translation table for GeoNet, New Zealand**

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Following a large earthquake, a number of critical challenges arise in emergency management and public decision-making. Scientific advice, which is increasingly in the form of probabilistic forecasts, helps to inform some of those decisions. Psychological research into the understanding of different phrasings of probability has identified that verbal and linguistic probabilities (including phrases such as unlikely, likely, certain, and uncertain) are understood differently across individuals, affecting their actions. For example, the term 'likely' could be interpreted as anything from 51% to 83%. To address this, the leading international best practice by the Intergovernmental Panel on Climate Change and the World Meteorological Organization, is to adopt probability translation tables to improve the communication of verbal likelihoods and numerical probabilities, as they are perceived by the general population.

Based on this best practice, the GeoNet monitoring programme at GNS Science in New Zealand has adopted a probability translation table, modified to account for recent research into the most suitable translation values. The table is used to effectively communicate likelihoods of hazardous events (such as aftershocks, volcanic eruptions, landslides, and tsunami) with stakeholders and the public, particularly when exact probabilistic forecasts are not available, and allows for consistency across communications by GNS Science. We will present the motivation and background behind this probability translation table, and the process by which this table was developed. We will also present answers to some frequently asked questions about these tables, present the current GeoNet table, and present examples of its use in communication products.

33 Towards the effective communication of operational earthquake forecasts (OEF) to stakeholders in New Zealand

Julia Becker, Sally Potter, Sara McBride, Matt Gerstenberger, Annemarie Christophersen
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Operational Earthquake Forecasts (OEF) have been communicated in New Zealand following large earthquakes since 2010, using a variety of channels, including maps, text, tables, graphs and scenarios. However, there are numerous challenges in using OEF.

We held a workshop with 14 key stakeholders in Wellington, New Zealand, in October 2015 to help GNS Science improve the communication of forecasts for the timeframes of before a major earthquake, and after a major earthquake. We investigated what the participants thought the term "earthquake forecasting" meant, how earthquake forecasting might be of use to them, and how they would like a forecast communicated to them.

The results indicate that:

• participants were reasonably familiar with the concept of earthquake forecasting

• information wanted by participants was mainly likelihood, location and intensity of the forecasted earthquakes, with less desire for advice on suggested actions, frequency of earthquakes, geotechnical information, or potential consequences of the forecasted shaking.

• Potential uses of the forecasts included for preparedness, response and recovery planning, cost-benefit analysis, resilience improvements for infrastructure, communicating the message on to the public, and situational awareness.

• Most sectors would want a warning threshold of MMI5<6 for their decision-making, and a timeframe of 1 year for forecasts

• Participants overwhelmingly preferred to receive a suite of information products to meet their varying needs.

More detailed results of the workshop will be presented, including participants' thoughts on the inclusion of model uncertainty, and their perceptions of the weaknesses and likely challenges of OEF.

34 Validating induced seismicity models: test bench and ensemble models

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Induced earthquakes often accompany fluid injection. This unavoidable consequence of fluid injections is an important element to monitor reservoir creation, however, it also poses hazard on the population and the infrastructure in the vicinity of the projects. In our view, models to monitor and control induced seismic hazard with traffic light systems should be probabilistic, forward-looking, and updated as new data arrive. Here, we propose an Induced Seismicity Test Bench to test, validate and rank such models. This test bench can be used for model development, model selection, and ensemble model building. We apply the test bench to data from the Basel 2006 and Soultz-sous-Forêts 2004 geothermal stimulation projects. We assess forecasts from two models: Shapiro and Smoothed Seismicity (SaSS) and Hydraulics and Seismics (HySei). These models incorporate a different mix of physics-based elements and stochastic representation of the induced sequences. Our results show that none of the models is fully superior to the other and the shut-in phase is a difficult moment for both models in both reservoirs: the models tend to underpredict the seismicity rate around, and shortly after, shut-in. As a next step, we are calibrating an additional model, the TOUGH2Seed model. This model incorporates additional physical considerations compared to earlier models, such as a 3-dimension modeling formulation, and also allows to test the role of Coulomb stress transfer. We intend to report on the performance of this model as well as the ensembles of three different models on the Basel data set.

35 Operational earthquake forecasting (OEF) system in Italy

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Recently, the seismic hazard center (Centro di Pericolosità Sismica, CPS) at the Istituto Nazionale di Geofisica e Vulcanologia (INGV) established a OEF procedure for gathering and disseminating authoritative information about the time dependence of seismic hazards. Since the most striking time dependency of the earthquake occurrence process is the time clustering, which is particularly pronounced in time windows of days to months, the earthquake forecasting system is focused on the short- and medium-term. This activity is still in its infancy, but a backbone philosophy for this system has been already in place. The philosophy of the system rests on a few basic concepts: transparency, reproducibility, and testability. Although the authoritativeness of a source is usually assigned by the interested stakeholders, we think that delivering information grounded on these principles is of paramount importance to become an authoritative source for a wide range of potentially interested stakeholders, including lay people. In particular, the OEF system developed at CPS is based on ensemble modeling of three earthquake forecasting models (two flavors of ETAS model, and one STEP model) that are presently under testing in experiments carried out by the Collaboratory for the Study of Earthquake Predictability (CSEP) network. Here, we report the results from OEF's 1-day and 1-week earthquake forecasting during the principal sequence since 2010, and the challenges that we have to address in the next future.

36 ## Time-independent annual occurrence rates computed for seismic hazard assessment in Italy

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In 2015 the Italian Department of Civil Protection, started a project for upgrading the official Italian seismic hazard map (MPS04) inviting the Italian scientific community to participate in a joint effort for its realization. We participated providing spatially variable time-independent (Poisson) long-term annual occurrence rates of seismic events on the entire Italian territory, using the smoothing method introduced by Frankel (1995). Three different datasets were considered (recent versions of the historical and instrumental seismic catalogs and the database of the individual seismogenic sources). We determined for each dataset a distinct annual rate value considering cells of 0.1°x0.1°- from M4.5 up to M9.0 for magnitude bin of 0.1 units. The following criterion was adopted: if the cell falls within one of the recognized seismogenic faults, we adopted the respective value of occurrence rate, only referred to the magnitude bin of the characteristic event. This value was divided by the number of grid cells that fall on the horizontal projection of the source. If, instead, the cell falls outside of any seismic source, we considered the rates of earthquakes exceeding an Mw4.5 minimum magnitude obtained from the historical and the instrumental catalog. In order to give an average rate, the two rates were first normalized to the same period of time and then merged together by a weighted average based on the temporal duration of the catalogs. Here we present the final results of our study to be used for the new Italian seismic hazard map.

37 ## Dynamic risk quantification - development of a global, data-driven and testable seismic hazard model.

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We propose an innovative approach to seismic hazard and risk analysis, using testable time-dependent models that comprise all aspects of the computational chain of seismic risk. We call this new method Dynamic Risk Quantification (DRQ). Our proposed computational platform connects existing testing centers on earthquake-forecast models and ground-motion prediction & seismic hazard, with a global dynamic exposure model.

Coupling these computational engines to a physics-based earthquake-rupture & ground-motion simulation module allows us to compute the ensuing seismic risk in a transparent, testable, and data-driven way. Expert-opinion based decision making in seismic hazard analysis will be replaced by an algorithmically driven, data-informed and adaptive computational framework.

We started with introducing the SHIFT and GEAR1 models for forecasting earthquake activity. To combine the forecast with the appropriate tectonic class of GMPEs, we apply a purely data-driven regionalization scheme. Like the earthquake forecast, the GMPEs and the resulting hazard will be included in constant testing. Implementing multiple models will allow for test-driven model selection or model improvements.

Finally, the resulting hazard will be augmented by a global dynamic exposure model to provide earthquake risk assessments.

38 **Improvement of seismicity simulation method and its application in Taiyuan region of China**

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We improved the seismic activity simulation method built and improved by Robinson and Zhou, so that the improved model can use fault rupture velocity inverted by GPS data as stress loading to simulate the seismicity of the region. The improved simulation model has been tested by a simple model of two parallel faults with dip of 90°. According to the test result, the orientation and size of annual rupture distance of seismic zone is accordant with that of creep zone. In addition, the accumulated strain energy in 20000 years is on the same order of magnitude with the accumulated energy of all the simulated earthquake in the same period time, which prove that our improvement is reasonable. The improved model is applied in Taiyuan Region of China, the magnitude-frequency curve of the simulated catalogue matches well with that of observed catalogue. Simulated earthquake with magnitude Ms ≥6 in Taiyuan Region can be well approximated by Poisson model. However, the simulated earthquake on some of the single faults in the region cannot be approximated by Poisson model, especially for those faults with low occurrence probability. According to, the Taiyuan Basin is under the seismic risk of earthquake with Ms ≥7, even though there have not been any earthquakes with Ms ≥7 here before.

39 **Incorporating strain rates into hybrid earthquake likelihood models for New Zealand**

David Rhoades, Annemarie Christophersen, Matt Gerstenberger
GNS Science, Lower Hutt, New Zealand

Multiplicative models are useful for forming hybrid earthquake likelihood.models from sets of existing models or gridded data inputs. We consider the problem of incorporating strain rate estimates into earthquake likelihood models based on earthquake and fault data for the New Zealand CSEP testing region. Cell rates in a spatially uniform baseline model are scaled using multiplicative combinations of covariates derived from the earthquake catalogue, fault data, and strain rate estimates. We consider three components of the strain rate estimated from GPS data over the period 1991-2011: the shear, rotational and dilatational strain rates. Hybrid model parameters are fitted to target earthquakes of M 5 and greater over the period 1987-2006 and independently tested on earthquakes from the period 2012-2015. According to information gain statistics, the shear strain rate is the most informative individual covariate in the fitting and testing periods, and this is confirmed by Molchan error diagrams. Most models including strain rates are significantly more informative than the best models that can be constructed without them. A hybrid model that combines the shear and dilatational strain rates with a smoothed seismicity covariate is the most informative model in the fitting period, and a simpler model without the dilatational strain rate is the most informative in the testing period. These results suggest that incorporating strain-rate estimates is likely to improve the background earthquake rate component of long-term earthquake occurrence models, such as those used for standard seismic hazard analysis and possibly also of medium-term and short-term earthquake forecasting models.

40 The difference between local and moment magnitude and what it means for earthquake forecasting in New Zealand

Annemarie Christophersen, David Rhoades
GNS Science, Lower Hutt, New Zealand

In New Zealand, GeoNet is the official source of geological hazard information. It operates the seismic network and provides the earthquake catalogue. In 2012 GeoNet changed the earthquake processing from the CalTech-USGS seismic processor (CUSP) system to the more automatic SeisComP3 (SC3) system. SC3 was installed with the original Californian distance terms derived by Richter in the 1930s. However, GeoNet plans to implement newly derived distance attenuation terms that make ML estimates consistent with the moment magnitude Mw. Regional moment tensor solutions and Mw have been calculated regularly for New Zealand since early 2007. These calculations have not changed over the transition period from CUSP to SC3. Here we carefully investigate the relationship of CUSP ML and Mw and derive a regression relationship to make CUSP data consistent with Mw.

The relation between Mw and ML appears to be curvilinear when all available data are considered but, to avoid possible bias, we restrict the relation to the range of completeness for Mw. Within this range, a linear regression relation fits the data well. We use this regression to correct individual magnitudes with dramatic effect: the expected annual number of M5 and larger is overestimated by a factor of two by ML compared to Mw. When applying the regression to a gridded forecast the maximum annual probability of MM7 for the Kaikoura sequence as calculated two months after the earthquake reduces from 60 to 40%. The probability of experiencing MM6 in Wellington for the same forecast period drops from about 40 to 20%

41 Investigation of seismicity patterns using aggregated seismicity time series

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Forecasting the occurrence of large earthquakes is an important goal for seismologists, who have been using statistical approaches to investigate the significance of precursory activity that is sometimes, yet not always, observed prior to strong earthquakes which are either considered as mainshocks or large aftershocks of preceding events. As precursors, such as foreshocks, are not generally unambiguously observed in catalogue data, we superimpose seismicity series to investigate the possible existence of a generic behaviour in the aggregated data, e.g. changes in the observed seismicity rates preceding larger events, and apply randomized tests to assess whether such changes are significant and can be considered as potentially useful precursors. Aggregating empirical local seismicity time series prior to relatively larger events observed e.g. in and around Greece, reveal a statistically significant increasing rate of seismicity over about 20 days prior to M>3.5 earthquakes. This increase cannot be explained by simple tempo-spatial cluster-type models, implying genuine changes in the mechanical situation just prior to larger events and thus the possible existence of useful precursory information. In the same framework, using synthetic catalogs produced based on different clustering models and different presumed system sensitivities might enable us to investigate further the robustness of such apparent characteristics in generic precursory patterns and whether these can be used in routine forecasting of larger events.

42 **Preliminary study of earthquake models incorporating seismo-electromagnetic data**

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Although early studies suggested a certain amount of precursory information in both earthquake catalogs and non-catalog observations, the earthquake forecast is still far from satisfactory at present. In most case, the precursory phenomena were studied individually. An earthquake model that combines self-exciting and mutually exciting elements was developed by Ogata and Utsu from the Hawkes process. The core idea of this combined model is that the status of the event at present is controlled by the event itself (self-exciting) and all the external factors (mutually exciting) in the past. In essence, the conditional intensity function is a time-varying point process, which is composed of the background rate term, the self-exciting term (the information from past seismic events), and the external excitation term (the information from past non-seismic observations). This model shows us a way to integrate the catalog-based forecast and non-catalog-based forecast. Meanwhile, electromagnetic measurements from the space to the ground have documented accumulative signals associated with large earthquakes during the past few decades. To date, a large number of statistical investigations have shown the correlation between electromagnetic anomalies and large earthquakes. As an attempt, we are trying to develop new earthquake models which incorporate information from both earthquake catalog and geo-electromagnetic observations. Preliminary results will be shown in the presentation.

43 **Statistical discrimination of foreshocks and real-time mainshock forecasting**

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Foreshock discrimination is one of the most effective ways for short-time forecast of large earthquakes. Though many large earthquakes accompany their foreshocks, discriminating them from enormous small earthquakes is difficult and only probabilistic discrimination may be available. Generalized additive model is the statistical learning method best suited to such binary pattern recognition problems where estimates of a-posteriori probability of class membership are required. Statistical learning methods can keep learning discriminating features from updating catalog and give probabilistic recognition of forecast in real time. By using spline functions, we can composite non-linear function of foreshock ratio by smooth spline functions and evaluate the possibility of coming mainshocks by logit functions. In this research, we compose earthquake clusters from earthquake catalog by the Japan Meteorological Agency and evaluate foreshock probabilities from their magnitudes, epicentral locations and time periods. We also implement a back test to validate predictive performance of the model by this catalog.

44 Testing Indonesia's national seismic hazard assessment using historical intensity data

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The intensities of historically damaging earthquakes (1681 – 1877) from the Wichmann catalogue of earthquakes in Indonesia are used to independently test ground motion predictions in Indonesia's current (2010) national probabilistic seismic hazard assessment (PSHA). Using a Poisson process we stochastically generate many realisations of ground motion based on the hazard model to estimate the probability of observing the historical intensities, including uncertainties between instrumental ground motions and intensity observation. From our results we cannot statistically reject Indonesia's current PSHA for key cities in Java; however, they do suggest that seismic hazard may be underestimated for the megacity Jakarta. Identification of plausible source models for large damaging events through scenario ground motion modelling is used to test if the seismic source model for the current PSHA captures the location and magnitude of historical earthquakes. The results demonstrate that the current PSHA underestimates maximum magnitudes on a number of presently mapped faults, including the Flores Thrust, and for intraslab events.

45 The 2015 San Ramon, CA swarm: Operational earthquake forecasting and background rate changes

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Earthquake swarms, typically modeled as time-varying background seismicity, present a challenge for operational earthquake forecasting (OEF), which often uses earthquake clustering rather than background rate changes. While the duration of clustering can be estimated with the modified-Omori law, it is difficult to forecast how long a change in background rate will last. To explore these issues, we apply the Epidemic-Type Aftershock Sequence (ETAS) model (Ogata, JASA, 1988) to the 2015 San Ramon swarm, which lasted several weeks and had almost 100 $2 \leq M \leq 3.6$ earthquakes. For the swarm, the best-fitting ETAS model's background rate increased by almost two orders of magnitude over previous seismicity but had a decreased triggering productivity.

Compared to earlier swarms in the region, the 2015 swarm involves a larger increase in background rate. A higher fraction of the swarm consists of background events, suggesting there may have been a change in driving mechanism. However, an ETAS model fit to the earlier swarms forecasts daily rates during the 2015 swarm well (with 90% of the observations in the 95% confidence limits of the forecast, despite a lower background rate), perhaps due to model tradeoffs between background rate and aftershock productivity. This suggests that in regions with swarms, an earthquake rate model based on previous swarm behavior can be developed to forecast rates specifically during swarms. However, it remains a challenge to determine when a swarm starts and such a model should be applied, and when a swarm ends and a model based on non-swarm seismic activity can be used.

46 Time-dependent earthquake forecasts on mid-ocean ridge transform faults

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Many moderate to fast-slipping oceanic transform faults exhibit small maximum magnitudes (Mw ~6.0-6.6) and short seismic cycles (5-20 years), making these faults ideal for investigating whether time-dependent models, which concentrate hazard towards the end of a seismic cycle, are appropriate for geometrically simple plate boundary faults. Using a surface wave cross-correlation relocation technique, we identify 17 fault patches on oceanic transform faults on the East Pacific Rise and Juan de Fuca Ridge, with multiple overlapping ruptures between 1990-2016. The most well-studied sequence is on the western end of Gofar Transform Fault (G3W) and includes 6 overlapping events of $5.7 \leq Mw \leq 6.2$. Interevent times on G3W were 4-6 years, until the most recent cycle when the smallest event in sequence occurred after only 1.3 years. To account for partial ruptures, as likely occurred on G3W, we will construct recurrence models giving each event a weight dependent on its relative magnitude and location, such that each rupture patch is expected to be fully coupled over the seismic cycle. We will use the Bayesian combination of the Brownian Passage Time model, lognormal distribution, and the Weibull distribution for each rupture patch. We will then compare our updated models to those we submitted to CSEP in 2010. We expect that our updated models, without hard cutoffs in magnitude and location, will better reflect the observed seismic sequences with lower coefficients of variation.

47 Uncertainty in earthquake forecasts: the 2016 Kaikoura sequence

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The M7.8 Kaikoura earthquake started at 2016-11-13 11:02:56 (UTC) with epicentre 173.02E, 42.69S, 15km NE of Culverden, and lasted for about two minutes. It caused multiple fault ruptures to the north as far as Seddon, the location of a large sequence in 2013. Since the mainshock, the bulk of the aftershock activity has also migrated to the north.

We present probability forecasts based on an ETAS model. Forecasts are derived by simulating the model forward over the required time interval. We then evaluate these forecasts by comparing the number of events that eventually occurred. Further, the spatial and temporal forecast characteristics can be evaluated by comparing the actual log-likelihood with that of the simulations. We show that the model is forecasting too many aftershocks compared to the numbers that actually occur. This is probably caused by a magnitude discrepancy between the CUSP software, which was used until the end of 2011, and the SeisComp3 software, used since 2012. The model parameters were estimated using catalogue data until the end of 2011 (CUSP). Other catalogue discrepancies are also briefly discussed.

48 Determining the probability distribution of earthquake forecasts

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The Epidemic Type Aftershock Sequence (ETAS) model is probably the most successful model yet at forecasting earthquake aftershocks. It is a branching process using an analogy with the spread of an epidemic. All events in the history of the process increase the intensity at the current time at all points in space, the size of the effect being related to the space-time distance back to the historical event.

Earthquake forecasts based on a self-exciting model, like ETAS, are often produced by simulation (two plots on right). From these simulations, an empirical probability distribution can be derived for a forecast in a specified space-time-magnitude volume.

We characterise the forecast distribution using probability generating functions (PDF). This shows how deeply complex the dependency structure is in such a model. While of theoretical interest, the PDF remains intractable to me in a practical sense.

We then consider whether the forecast distribution can be approximated, using less computation than that required for simulation, by a "standard" multi-parameter probability distribution. The multiple parameters gives us the ability to at least fit a distribution with comparable mean and variance to that of the forecast distribution. One of the main questions is how to rapidly determine the forecast mean and variance.

Other

49 Development of seismicity analysis software: XETAS

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We developed seismicity analysis tool that analyze ETAS parameters using GUI interfaces. This tool was based on the package of SASeis2006 (Ogata, 2006) and has an easy usage to get results with any catalog.

ETAS analysis is non-linear inversion method. So, it is very important to set initial parameters. This tool automatically set proper values and run a process until a solution converges. Especially, we can set a time parameters by using GUI plotting M-T diagram, and run ETAS analysis with a simple procedure. This tool contains detecting seismicity anomaly module and simulation module with any ETAS parameters.

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