Date: Monday, 15/Jun/2015

8:30am - 8:40am Arcona Hotel, Havelpavillon	**Welcome** Session Chair: **Danijel Schorlemmer**
8:40am - 10:00am Arcona Hotel, Havelpavillon	**Modeling A - Part1: Modeling of seismicity: A. Statistical Problems and Solutions** Session Chair: **Gert Zöller**
10:00am - 10:30am Arcona Hotel, Havelpavillon	**Coffee Mon-1: Coffee break**
10:30am - 12:10pm Arcona Hotel, Havelpavillon	**Modeling A - Part2: Modeling of seismicity: A. Statistical Problems and Solutions** Session Chair: **Eric Warren Fox** Session Chair: **Joshua Seth Gordon**
12:10pm - 2:00pm Arcona Hotel: Restaurant	**Lunch Monday: Lunch**
2:00pm - 3:00pm Arcona Hotel, Havelpavillon	**Modeling B - Part1: Modeling of seismicity: B. Applications** Session Chair: **Jiancang Zhuang**
3:00pm - 5:00pm Arcona Hotel, Havelpavillon	**Poster 1: Poster session A (& Coffee)** Session Chair: **Danijel Schorlemmer**
5:00pm - 6:00pm Arcona Hotel, Havelpavillon	**Modeling B - Part2: Modeling of seismicity: B. Applications** Session Chair: **David Alan Rhoades**
6:00pm - 7:00pm Arcona Hotel, Havelpavillon	**Discussion - Mon: Discussion (optional)**

Date: Tuesday, 16/Jun/2015

8:30am - 10:10am Arcona Hotel, Havelpavillon	**Physics - Part1: Physics of earthquakes on different scales** Session Chair: **David Marsan**
10:10am - 10:40am Arcona Hotel, Havelpavillon	**Coffee Tue-1: Coffee break**
10:40am - 12:00pm Arcona Hotel, Havelpavillon	**Physics - Part2: Physics of earthquakes on different scales** Session Chair: **Sebastian Hainzl**
12:00pm - 2:00pm Arcona Hotel: Restaurant	**Lunch Tuesday: Lunch**
2:00pm - 3:20pm Arcona Hotel, Havelpavillon	**Induced - Part1: Understanding and quantifying induced seismicity** Session Chair: **Morgan Page**
3:20pm - 3:50pm Arcona Hotel, Havelpavillon	**Coffee Tue-2: Coffee break**
3:50pm - 5:10pm Arcona Hotel, Havelpavillon	**Induced - Part2: Understanding and quantifying induced seismicity** Session Chair: **Morgan Page**
5:10pm - 6:00pm Arcona Hotel, Havelpavillon	**Discussion - Tue: Discussion** Session Chair: **Morgan Page**

Date: Wednesday, 17/Jun/2015

8:30am - 10:10am Arcona Hotel, Havelpavillon	**Forcasting - Part1: New Perspectives in Probabilistic Earthquake Forecasting and Testing** Session Chair: **Matthew Gerstenberger**

10:10am - 10:40am Arcona Hotel, Havelpavillon	**Coffee Wed-1: Coffee break**
10:40am - 12:00pm Arcona Hotel, Havelpavillon	**Forcasting - Part2: New Perspectives in Probabilistic Earthquake Forecasting and Testing** Session Chair: **Warner Marzocchi**
12:00pm - 2:00pm Arcona Hotel: Restaurant	**Lunch Wednesday: Lunch**
2:00pm - 3:00pm Arcona Hotel, Havelpavillon	**Forcasting - Part3: New Perspectives in Probabilistic Earthquake Forecasting and Testing** Session Chair: **Stefan Wiemer**
3:00pm - 5:00pm Arcona Hotel, Havelpavillon	**Poster 2: Poster session B (& Coffee)** Session Chair: **Sebastian Hainzl**
5:00pm - 6:00pm Arcona Hotel, Havelpavillon	**Forcasting - Part4: New Perspectives in Probabilistic Earthquake Forecasting and Testing** Session Chair: **David Diether Jackson**
6:00pm - 7:00pm Arcona Hotel, Havelpavillon	**Discussion - Wed: Discussion (optional)**

Presentations

Modeling A - Part1: Modeling of seismicity: A. Statistical Problems and Solutions

Time: Monday, 15/Jun/2015: 8:40am - 10:00am · *Location:* Arcona Hotel, Havelpavillon
Session Chair: Gert Zöller

Some thoughts on the estimation of maximum and corner magnitude

Matteo Taroni[1], **Warner Marzocchi**[1], **Jeremy D. Zechar**[2]
[1]INGV, Italy; [2]ETH, Zurich; matteo.taroni@ingv.it

One of the most uncertain elements of Probabilistic Seismic Hazard Analysis (PSHA) is related to the estimation of the earthquake maximum magnitude (Mmax) for each zone. Usually, the problem of Mmax is tackled in one of a few ways. The most popular is to use a truncated Gutenberg-Richter frequency-magnitude relationship, where the truncation is done at Mmax. Another promising approach, that is not yet common in PSHA, uses a tapered Gutenberg-Richter law, where a sharp truncation of the frequency-magnitude relationship is replaced by a tapered function. In this model, Mmax is not interpreted as the maximum magnitude but a sort of corner magnitude, and the frequency-magnitude distribution leaves a small probability to have larger events.

In both cases, it is very hard to estimate Mmax from a set of data, in particular for small areas. In this work we explore a method to estimate Mmax for a tapered Gutenberg-Richter for Italy and for the globe, and we analyze which aspect of the frequency-magnitude distribution may depend on the tectonic regime. Finally, we discuss a comparison of our results with previous studies.

Statistical tests for the tail of the seismic-moment distribution of global shallow earthquakes

Isabel Serra, **Álvaro Corral**
Centre de Recerca Matemàtica, Spain; iserra@crm.cat

The Gutenberg-Richter (GR) law is not only of fundamental importance in statistical seismology but also a cornerstone of non-linear geophysics and complex-systems science. It states that, in terms of seismic moment M or released energy, the distribution of earthquake sizes is a power law. This has important physical implications, as it suggests an origin from a critical branching process or a self-organized-critical system. However, it presents also some conceptual difficulties, due to the fact that the mean value of M provided by the distribution turns out to be infinite. These elementary considerations imply that the GR law cannot be naively extended to arbitrarily large values of M, and one needs to introduce additional parameters to describe the tail of the distribution, coming presumably from finite-size effects.

Main and co-workers have examined the problem of the global earthquake-size distribution including recent data (shallow events only). Using a Bayesian information criterion (BIC), they compare the plain GR law with the so-called tapered GR distribution, and conclude that, although the tapered GR gives a significantly better fit before the 2004 Sumatra-Andaman event, the occurrence of this changes the balance of the BIC statistics, making the GR law more suitable; that is, the power law is more parsimonious, or simply, is enough for describing shallow global seismicity when the recent mega-earthquakes are included in the data.

We revisit the problem using distinct statistical tools and considering different parameterizations for the tail. A discussion of results will be presented.

Mmax

Matthias Holschneider, Gert Zoeller
University of Potsdam, Germany; matthias.holschneider@gmail.com

We discuss to which extend, the maximal possible magnitude of earthquakes can be inferred from observational data. We include the case of catalog data and geological data like slip rates and we show, that uncertainties are much larger than usually thought.

Self-similar aftershock rates

Joern Davidsen
University of Calgary, Canada; joern.davidsen@ucalgary.ca

Many empirical laws of seismicity are scale-invariant, with the noticeable exception of the Omori-Utsu law for the temporal decay of aftershock activity. We show that its form should be revised, as it is the magnitude difference between the main shock and a directly triggered aftershock, related to scale-free quantities as the ratio of released energies, that determines the relevant time-scales in the aftershock decay. An analysis of high-precision data from Southern California provides a clear example of such a behavior in nature and shows that a self-similar Omori-Utsu law allows a unified description of aftershocks and foreshocks. We discuss why these findings cannot be a simple consequence of short-term aftershock incompleteness and support our arguments by comparisons with an analysis of synthetic catalogs, generated either by the standard (scale dependent) "Epidemic Type Aftershock Sequence" model or by our self-similar model.

Modeling A - Part2: Modeling of seismicity: A. Statistical Problems and Solutions

Time: Monday, 15/Jun/2015: 10:30am - 12:10pm · *Location:* Arcona Hotel, Havelpavillon
Session Chair: Eric Warren Fox
Session Chair: Joshua Seth Gordon

A simple model for earthquake statistics compared to observations and experiments

Karin A. Dahmen[1], Yehuda Ben-Zion[2], Braden Brinkman[1], Thomas Goebel[3], Michael LeBlanc[1], Danijel Schorlemmer[3], Jonathan Uhl[4]

[1]Department of Physics University of Illinois at Urbana Champaign, USA; [2]Department of Earth Sciences, University of Southern California, Los Angeles, USA; [3]Geoforschungszentrum Telegrafenberg, Potsdam, Germany; [4]retired; dahmen@illinois.edu

The deformation of many solid materials is not continuous, but discrete, with intermittent slips similar to earthquakes. Here, we compare the predictions for the slip statistics from a simple earthquake model to data obtained from observations and experiments on a broad range of systems. Predictions for future experiments are also discussed. The studies draw on methods from the theory of phase transitions, the renormalization group, and numerical simulations.

Condensation of earthquake location catalogs and implications for earthquake triggering models

Yavor Kamer[1], Guy Ouillon[2], Didier Sornette[1], Jochen Woessner[3]

[1]ETHZ, Switzerland; [2]Lithophyse, France; [3]RMS, Switzerland; yaver.kamer@gmail.com

We present the “condensation” method that exploits the heterogeneity of the probability distribution functions (PDF) of event locations to improve the spatial information content of seismic catalogs. As its name indicates, the condensation method reduces the size of seismic catalogs while improving the access to the spatial information content of seismic catalogs. Ranked by decreasing location errors, the PDFs of events are successively condensed onto better located and lower variance event PDFs. The obtained condensed catalog differs from the initial catalog by attributing different weights to each event, the set of weights providing an optimal spatial representation with respect to the spatially varying location capability of the seismic network. As a result of this condensation, which preserves the overall spatial probability density distribution, a large portion of the events (~25%) can be discarded without reducing the information content of the original catalog. Applied to Southern California seismicity, the new condensed catalog highlights well major mapped fault traces and reveals possible additional structures. The condensation method allows us to account for location error information within a spatial analysis. We demonstrate this by comparing the multifractal properties of the condensed catalog locations with those of the original catalog. We evidence different spatial scaling regimes characterized by distinct multifractal spectra and separated by transition scales. We interpret the upper scale as the thickness of the brittle crust, while the lower scale (2.5km) might depend on the relocation procedure. Accounting for these new correlation dimension (D2) measurements put in the framework of the Epidemic Type Aftershock Model formulation, this suggests that, contrary to previous studies, large earthquakes dominate the earthquake triggering process. This implies that the limited capability of detecting small magnitude events cannot be used to argue that earthquakes are unpredictable in general.

Statistical Properties of Marsan-Lenglin\'e Estimates of Triggering Functions for Space-time Marked Point Processes

Eric Warren Fox, Rick Paik Schoenberg, Joshua Gordon

University of California at Los Angeles; eric.fox@stat.ucla.edu

Marsan and Lenglin\'e recently proposed a way to estimate the ETAS model (Ogata, 1998) for the conditional rate of earthquake occurrences non-parametrically using an Expectation-Maximization type algorithm. Their method works by first computing the probability that each earthquake is either a mainshock or an aftershock of a previously occurring earthquake (E-step). Using these probabilities the triggering function and background rate for the ETAS model are then estimated using probability weighted histogram estimators (M-step). The algorithm proceeds iteratively over these two steps until convergence is reached.

In this talk, we discuss the statistical properties of the nonparametric estimator for ETAS proposed by Marsan and Lenglin\'e. We investigate results on computing standard errors for the histogram estimates of the triggering function, asymptotic properties of model estimators, and the extension of the algorithm to incorporate non-stationary background rates.

Full nonparametric estimate of space-time ETAS model

Giada Adelfio, Marcello Chiodi

university of palermo, Italy; giada.adelfio@unipa.it

The conditional intensity function of generic branching-type process (like ETAS) is obtained as the sum of two terms: the long-term scale variation term and the small-term one, due to the interaction with the past.

Sometimes, in previous studies, we observed some lack of

fitting of the triggered component of the ETAS model, even if estimated by optimized procedure. Hence to get, for instance, a starting estimate of the triggered component in ETAS model, we introduce a more flexible approach, mostly suitable in explorative contexts.

In particular, in this paper, we provide a method to estimate the di
fferent components of the space-time intensity of the generating point process like above, by a full nonparametric approach. We propose a kernel based estimation method of the space-time intensity of a branching point process that incorporate the FLP (Forward Likelihood Predictive) procedure, following a forward predictive likelihood estimation approach to semi-parametric models (Adelfio, Chiodi, 2015 ; Chiodi Adelfi

o, 2011) applied to the ETAS model.

Moreover Monte Carlo technique, as Mohler et al. 2011 is used for faster computation.

Spatial distribution of aftershocks as a hallmark for different stress regimes

Eugenio Lippiello[1], Ferdinando Giacco[1], Cataldo Godano[1], Warner Marzocchi[2], Lucilla de Arcangelis[1]
[1]Second University of Naples, Italy; [2]INGV - Istituto Nazionale di Geofisica e Vulcanologia; eugenio.lippiello@unina2.it

We show that, together with the parameters b in the Gutenberg-Richter law and the time c in the Omori law, also the size of the aftershock zone

is a measure of the level of differential stress.

We find a positive correlations among parameters controlling aftershock

organization in time, energy and space as a stable feature of seismicity

independently of magnitude range and geographic areas.

We explain experimental findings by means

of a description of the Earth Crust as an heterogeneous elastic

medium coupled with a Maxwell viscoelastic asthenosphere.

Our results show that heterogeneous stress distribution in an elastic layer combined with a coupling to a viscous flow are sufficient ingredients to reproduce aftershock energy-spatio-temporal patterns.

Modeling B - Part1: Modeling of seismicity: B. Applications

Time: Monday, 15/Jun/2015: 2:00pm - 3:00pm · *Location:* Arcona Hotel, Havelpavillon
Session Chair: Jiancang Zhuang

Empirical Estimation of Fault Directionality for Improved Non-parametric Estimation of Branching Models for Earthquake Occurrences

Joshua Seth Gordon

University of California Los Angeles, United States of America; joshuagordon@ucla.edu

We empirically estimate fault directionality using weighted least squares for use in a non-parametric estimation of an Epidemic-Type Aftershock Sequence triggering function. Directionality of the aftershock activity can be included in the estimation by modifying the triggering function g_i for each earthquake i such that it is instead a function

g(s, t, m_i, \theta_i), depending not only on the magnitude of the triggering earthquake

but also on the relative angular separation between events, relative to the estimated primary fault plane associated with the triggering event. For Southern California seismicity, we propose estimating these relative angles \theta_i using weighted least squares and all observed seismic activity with M>2.0 within 100km^2 of each main shock event, where the weighting is inversely proportional to distance from the main shock in question.

Predicting changing rates of swarm activity by volumetric strain changes

Takao Kumazawa[1], **Yosihiko Ogata**[1,2], **Kazuhiro Kimura**[3], **Kenji Maeda**[3], **Akio Kobayashi**[3]

[1]Institute of Statistical Mathematics, Japan; [2]The University of Tokyo; [3]Meteorological Research Institute; tkuma@ism.ac.jp

Near the eastern coast of Izu peninsula is an active submarine volcanic region in Japan, where magma intrusions have been observed many times. The forecast of earthquake swarm activities and eruptions are serious concern particularly in nearby hot spring resort areas. It is well known that temporal durations of the swarm activities have been correlated with early volumetric strain changes at a certain observation station of about 20 km distance apart. Therefore the Earthquake Research Committee (2010) investigated some empirical statistical relations to predict sizes of the swarm activity. Here we looked at the background seismicity rate changes during these swarm periods using the non-stationary ETAS model (Kumazawa and Ogata, 2013, 2014), and have found the followings. The modified volumetric strain data, by removing the effect of earth tides, precipitation and coseismic jumps, have significantly higher cross-correlations to the estimated background rates of the ETAS model than to the swarm rate-changes. Specifically, the background seismicity rate synchronizes clearer to the strain change by the lags around a half day. These relations suggest an enhanced prediction of earthquakes in this region using volumetric strain measurements. Hence we propose an extended ETAS model where the background rate is modulated by the volumetric strain data. Here we have also found that the response function to the strain data can be exponential functions with the same decay rate, but that their intersects are inversely proportional to distances between the volumetric strain-meter and the onset location of the swarm. Our numerical results by the same proposed model show consistent outcomes for the various major swarms in this region.

References

1. Earthquake Research Committee (2010). Report on "Prediction of seismic activity in the Izu Eastern Region" (in Japanese), http://www.jishin.go.jp/main/yosoku/izu/index.htm

2. Kumazawa, T. and Ogata, Y. (2013). Quantitative description of induced seismic activity before and after the 2011 Tohoku-Oki earthquake by nonstationary ETAS model, J Geophys.Res. 118, 6165-6182.

3. Kumazawa, T. and Ogata, Y. (2014). Nonstationary ETAS models fornonstandarearthquakes, Annals of Applied Statistics, 2014, Vol. 8, No. 3, 1825-1852.

Insights on stress-drop magnitude-dependency and source-variability from the analysis of accelerometric data and non-ergodic GMPEs

Fabrice Cotton[1], **Boumediène Derras**[2], **Stephane Drouet**[3], **Christian Molkenthin**[4]

[1]GFZ, Potsdam, Germany; [2]Institut de Sciences de la Terre (ISTerre), Grenoble, France; [3]Observatório Nacional, Rio de Janeiro, Brazil; [4]Institute of Earth- & Environmental Science, University of Potsdam, Germany; fcotton@gfz-postdam.de

Classical methodologies which have been adopted by a large number of source studies require corrections for individual earthquakes source radiation pattern, path attenuation and site amplification that ultimately introduce large uncertainties for stress-drop estimates and source properties variabilities. In this study we adopt a different strategy: we analyse directly large datasets of ground-motions (Y) datasets, their variabilities (sigma) and their dependencies with magnitude (M). The exponential increase of accelerometric data gives a unique opportunity to derive to remove the ergodic assumption, evaluate source and site effects and finally analyse the dependencies of ground-motions on earthquakes sources. We first show that stress-drop variabilities can be derived from those observed between-event ground-motion variabilities and suggest that these evalauations are more robust than those derived from source-parameter studies, that is, corner frequency analysis. We also show that the use of recorded accelerometric ground-data and non-ergodic ground-motion models provide new insights on the scaling of stress-drops with magnitude. We use simple stochastic models (e.g. Boore 2003) comprised of a Brune (1970,1971) source spectrum and various models of magnitude-dependent stress drops. We show that magnitude-dependent stress-drops and constant stress-drops models lead to different scaling of ground-motions (dlogY/dM) with frequency. Using the results of Molkenthin et al. (2014), we then analyze the magnitude dependency of NGA2 ground-motions for source-site configurations where stress-drops are the key controlling factors of ground-motions (moderate distances and rock-sites). The use of a neural network method allow to obtain fully records-driven evaluations of (dlogY/dM) with frequency both for simulated and observed records. The comparison between these observed and simulated (dlogY/dM) favors the constant stress-drop model for small magnitude earthquakes (M<4.5). We do not observe strong differences of the magnitude scaling of ground-motions between mainshocks and aftershocks.

Poster 1: Poster session A (& Coffee)

Time: Monday, 15/Jun/2015: 3:00pm - 5:00pm · *Location:* Arcona Hotel, Havelpavillon
Session Chair: Danijel Schorlemmer

A comment on Saichev and Sornette (2005, PRE), Ogata and Zhuang (2006, PRE) and Vere-Jones and Zhuang (2008, PRE): Three modes of the distribution of the largest event in the critical ETAS model

Jiawen Luo

Peking University, China, People's Republic of; paulljw@pku.edu.cn

This article corrects and extends the results of Saichev, Sornette, Ogata, Vere-Jones and Zhuang on the asymptotic behavior of the largest event in the epidemic-type aftershock-sequence model for earthquake occurrence when the process is critical. We prove that there exist three modes of asymptotic behavior in the critical case, which transits smoothly from one to another according a single parameter.

Accelerometric data analysis and frictional Properties Variations of the Subduction Interface in Northern Chile

Jesus Piña[1], Fabrice Cotton[2], Anne Socquet[1]

[1]ISTerre, France; [2]GFZ, Germany; jesus.pina-valdes@ujf-grenoble.fr

Recent teleseismic observations of megathrust earthquakes (Sumatra Mw 9.2 2004, Chile Mw 8.8 2010 and Japan Mw 9.0 2011) have shown that the deeper part of the subduction interface produces strong short period radiations and modest coseismic slip, while the shallow part generates less short periods but a larger coseismic slip. These features have been interpreted as along depth variations of the frictional properties on the subduction interface (Lay et al., 2012).

By analysing the spectral ratios of a series of moderate magnitude earthquakes, these results could be reproduced using near field strong motion data. This methodology has then been applied to the sequence of foreshocks and aftershocks associated with the Mw 8.2 Pisagua earthquake (2014/04/01, North Chile). This sequence provides an excellent opportunity to study the stress drop changes for similar earthquakes that occurred in the subduction interface before and after the mainshock. We compare the frequency contents of the strong motion records from the IPOC network of 126 intraplate earthquakes of moderate moment magnitudes in northern Chile, between january of 2007 and june of 2014.

We build a time series of the frequency contents variations for moderate moment magnitude subduction earthquakes, in the zone in front of Pisagua. The frequency content variations of this earthquakes sequence are analyzed in terms of time dependency, along-dip and along-strike variations, and compared with the interseismic coupling derived from geodetic analyses. These results are interpreted as variations of the frictional properties of the subduction interface.

Aggregated seismicity time series: Is there clear evidence of precursory patterns?

Angeliki Adamaki[1], Roland Roberts[1], IMO SIL Monitoring Group[2]

[1]Uppsala University, Sweden; [2]Icelandic Meteorological Office, Iceland; angeliki.adamaki@geo.uu.se

Developing methods for reliable short-term forecasting of strong earthquakes has been a major target in seismology over the years. Many phenomena prior to large events have been investigated in order to assess their possible predictive value, but generally with limited success. A group of such phenomena are those related to temporal changes in seismicity patterns preceding large events. We investigate inter-event times between earthquakes that occurred in a defined area as a time-specific proxy for seismicity rate. Both earthquake-generating processes prior strong earthquakes (foreshocks) and processes that follow such events (aftershocks) relate to the response of a similar volume of the Earth to stress changes. Therefore we investigate possible foreshocks, seismic quiescence and aftershock sequences. Using data from Greece we found evidence of seismicity changes but the patterns were not clear and consistent in order to judge these to be precursory activity or some more unrelated phenomenon. However, when we aggregated the proxy seismicity-rate data before many events, a more clear pattern emerged showing an acceleration in seismic activity for about 1 month prior to the events. This implies that genuine precursory signals do exist, although the existing data was insufficient to unambiguously identify them in individual cases. Therefore, significantly more sensitive networks might be very helpful when seeking precursory activity. We are now using similar tools to investigate data from Iceland where the advanced and highly sensitive network detects and analyses very small magnitude events.

An improved ETAS model for inverting the rupture geometry from seismicity triggerring

Yicun Guo[1], Jiancang Zhuang[2], Shiyong Zhou[1]

[1]Institute of Theoretical and Applied Geophysics, China, People's Republic of; [2]Institute of Statistical Mathematics, Tokyo, Japan.; guoyicun@pku.edu.cn

This study incorporates the rupture geometry of big earthquakes in the formulation of the Epidemic-Type Aftershock Sequence (ETAS) model, which is a point process model widely applied in the study of spatiotemporal seismicity, rather than regarding every earthquake occurring as a point in space and time. We apply the new model to the catalog from Sichuan province, China between 1990 and 2013, during which the Wenchuan Mw7.9 earthquake occurred in May 2008. Our results show that the modified model has better performance in both data fitting and aftershock simulation, confirming that the elliptic aftershock zone is caused by the superposition of the isotropic triggering effect from each patch of the rupture zone. Moreover, using the technique of stochastic reconstruction, we inverted the fault geometry and verified that direct aftershocks of the mainshock more likely occur around the parts of the mainshock fault area with large slips.

Analogue earthquakes: A test bed for physical and statistical models?

Michael Rudolf, Matthias Rosenau, Karen Leever, Onno Onken

GFZ Potsdam, Germany; mrudolf@gfz-potsdam.de

We explore the potential of stick-slip experiments to serve the community as a test bed for both physical and statistical models. Stick-slip experiments in a ring-shear tester using a variety of rock “analogue” materials show a surprisingly wide variety of slip patterns: from regular stick-slip characterized by archetypical saw-tooth like stress-strain curves consistent with rate-and-state

friction theory to queerly shaped, though highly reproducible, patterns diagnostic of preseismic slip transients which are not predicted by any physical model so far. Also, the “interseismic” period appears by no means to be a monotonous loading phase and is never pure “stick” but is characterized by “aseismic” creep which is sensitive to pressure, loading rate and precursory slip transients of any speed, including mimicries of foreshock sequences. We will present first results of an analysis of this data set focusing on the applicability of current physical and statistical models to the empirical data and vice versa seek natural phenomena which might show similarity to our experimental observations.

Anisotropic kernels for the estimation of space-time ETAS models

Giada Adelfio[1], Marcello Chiodi[1], Orietta Nicolis[2]

[1]university of palermo, Italy; [2]Universidad de Valparaiso, Chile; marcello.chiodi@unipa.it

The paper deals with a mixed technique to estimate the components of an ETAS model (Ogata, 1988) using the FLP (Forward Likelihood Predictive) technique (Chiodi and Adelfio, 2011), a new

estimation approach for space-time point processes accounting for

predictive properties of estimates.

The FLP method allows a simultaneous estimation of the different

model components, alternating parametric estimation steps for the triggered components (using maximum likelihood estimators) and nonparametric estimation steps for the background components (using the FLP approach to have good values of the smoothing parameters of the kernel estimator with variable metric). At each step each observation is weighted in the background intensity estimation, according to the probability of belonging to the background seismicity.

In order to study the spatial variations of the observed background seismicity and to take into account more realistic situations,

anisotropic kernel with variable smoothing parameters is

considered; it allows a variable metric following the different geographical orientation of observed seismicity.

The methodology will then be applied to the seismic catalog of Chile. The high seismicity of the country and its characteristic geometry of faults that run through the

state are important reasons that justify the use of the proposed approach combining the anisotropic kernels with the FLP estimation procedure.

Computations are implemented in the open source \texttt{R} package

\texttt{etasFLP} (Adelfio and Chiodi, 2015).

The package contains different options for the estimation of an ETAS model, allowing the choice between different background estimators, declustering weighting and so on. Many output options

are also provided, profile likelihood for parameters,

and graphical diagnostic tools with residual analysis.

Aseismic transient driving the swarm-like seismic sequence in the Pollino range, Southern Italy.

Luigi Passarelli[1], Sebastian Hainzl[1], Simone Cesca[1,2], Francesco Maccaferri[1], Marco Mucciarelli[3,4], Dirk Roessler[1], Fabio Corbi[1], Torsten Dahm[1], Eleonora Rivalta[1]

[1]GFZ-German Research Centre for Giosciences, Germany; [2]Institute of Earth and Environmental Science, University of Potsdam, Potsdam, Germany; [3]Seismological Research Centre – National Institute of Oceanography and Experimental Geophysics (OGS), Udine, Italy; [4]School of Engineering University of Basilicata, Potenza, Italy; luigi.passarelli@gfz-potsdam.de

Non-volcanic seismicity swarms are thought to be driven in their spatio-temporal evolution by transient forcing acting on top of the secular tectonic loading. The nature of the transient forcing may vary across sequences and range from aseismic creeping or slow-slip events to diffusion of pore pressure pulses to fluid redistribution and migration within the seismogenic crust. Distinguishing among such forcing mechanisms may be critical to reduce epistemic uncertainties in the assessment of hazard due to seismic swarms. Furthermore, it can provide information on the frequency-magnitude distribution of the earthquakes (often deviating from the assumed Gutenberg-Richter relation) and on the expected source parameters influencing the ground motion (for example the stress drop). Here we study the ongoing Pollino range (Southern Italy) seismic swarm, a long-lasting seismic sequence with more than five thousand events recorded and located since October 2010. The two largest shocks of the sequence, i.e. Mw=4.2 and Mw=5.1, are among the largest earthquakes recorded in the Pollino area which represents a seismic gap in the Italian peninsula. The spatial distribution of earthquake suggests a complex system of graben-like structures activated by the seismic sequence. We investigate the temporal evolution of the swarm by calculating the statistics of frequency-size distribution, the interevent times and the productivity of the transient forcing through ETAS-based modeling. We find the temporal evolution of the sequence consistent with a strong transient forcing. Only 25% of the earthquakes in the sequence can be explained as afetrshocks, and the remaining 75% may be attributed to this transient forcing. The b-values change in time throughout the sequence, with low b-values correlated with the period of highest rate of activity and with the occurrence of the largest shock. We also calculate the focal mechanisms of the M>3 events in the sequence and the transfer of Coulomb stress on nearby known faults. In the light of recent studies on the paleoseismic and historical activity in the Pollino area, we identify two scenarios consistent with the observations and our analysis: This and past seismic swarms may have been 'passive' features, with small fault patches failing on largely locked faults, or may have been accompanied by an 'active', largely aseismic, release of a large portion of the accumulated tectonic strain. Those scenarios have very different implications for the seismic hazard of the area. More information on the crustal deformation and on the detailed spatio-temporal evolution of the seismicity is necessary to identify the specific underlying mechanism.

Bigger aftershocks happen farther away: non-separability of magnitude and spatial distributions of aftershocks

Nicholas van der Elst, Bruce Shaw

Lamont-Doherty Earth Observatory, United States of America; nicholas.vanderelst@gmail.com

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 elastic 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 size limitation, leaving them with a higher likelihood of propagating onward to themselves become large. This is consistent with anecdotal observations that aftershocks occur preferentially – but not exclusively – at the margins of slip 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.

Changes in seismicity and stress loading on subduction faults in the Kanto region, Japan, 2011 - 2014

Blandine Marie Gardonio[1], David Marsan[1], Olivier Lengliné[2], Bogdan Enescu[3], Michel Bouchon[1,4], Jean-Luc Got[1]

[1]ISTerre, France; [2]EOST, France; [3]University of Tsukuba, Japan; [4]CNRS, France; blandine.gardonio@ujf-grenoble.fr

Seismic activity has increased in the Kanto region, Japan, following the 2011 M9.0 Tohoku

earthquake. We here reassess this increase up to June 2014, to show that normal, Omori-like relaxation characterizes

the activity on crustal faults as well as on the Philippine Sea plate, but not on the deeper Pacific plate.

There, repeating earthquakes display a two-fold rate of occurrence (still on going in June 2014) as

compared to the pre-Tohoku rate, suggesting enhanced creep.

We compute the Coulomb stress changes on the upper locked portion of the Philippine Sea plate, which

last ruptured in 1923. We find that this fault was little affected by either the co-seismic, the

post-seismic, the accelerated creep, or the 2011 Boso silent slip event.

Characteristic of Upper Mantle Anisotropy Beneath Sunda Banda Transition Zone

Samsul Hadi Wiyono[1,2], Andri Dian Nugraha[2,3]

[1]Indonesia's Agency for Meteorology Climatology and Geophysics, Jakarta 10610, Indonesia, Indonesia; [2]Study Program of Earth Sciences, Faculty of Earth Sciences and Technology, Institute of Technology Bandung; [3]Global Geophysics Research Group, Faculty of Mining and Petroleum Engineering, Institute of Technology Bandung; shwiyono@gmail.com, nugraha@gf.itb.ac.id

Investigation of seismic anisotropy allows us for understanding more about the dynamics that occured in the mantle. We have analyzed 115 teleseismic events to identify seismic anisotropy beneath the Sunda Banda transition zone. Based on the analysis of shear wave splitting, we obtained a sufficient delay time varies between 0.4 to 3.2 seconds. We suspected that the anisotropy in this region is strongly influenced by the lattice preferred orientation of olivine that made up the upper mantle by oconsidering the dominant time delay which is about ~ 1.8 seconds. Moreover, we also observed the fast polarization direction which tends to be coherent with the direction of orientation in terms of absolute plate motion HS2-NUVEL 1A, which turned out to reinforce our expectation that the upper mantle transition zone Sunda Banda has contributed significantly to the anisotropy in the study area.

In addition, we also obtained the null measurements which can be interpreted as the effect of two layers anisotropy perpendicular to the polarization direction of the fast component, the distance of the seismic stations to the trench is greater than 100 km which effectively contribute the small delay time and null measurement, a very complicated structure anisotropy or may also caused by the initial polarization angle of S-waves that are parallel or perpendicular with polarization angle of the fast component.

Combining rate-based earthquake forecasting models with precursory information and with non-normalized models

Peter Shebalin[1,2], Clement Narteau[2], Jeremy Zechar[3]

[1]Institute of Earthquake Prediction Theory and Mathematical Geophysics, Moscow, Russian Federation; [2]Institut de Physique du Globe, Paris; [3]Institut f. Geophysik, Zürich; p.n.shebalin@gmail.com

During last years a significant progress in developing and testing earthquake forecasting models was demonstrated, especially due to the activity of the Collaboratory for the Study of Earthquake Predictability (SCEP). Large number of forecasting models have been installed for testing in SCEP centers, most of them forecasting earthquakes rates in various time scales (from days to years). The models demonstrating the best accordance with reality are based on spatial and/or temporal clustering of seismicity. Those models, however, deal with very low probabilities, or expected rates, of large earthquakes, the only exception is short-term forecasting right after largest earthquakes. The expected rates could be increased prior to earthquakes by incorporating

into the models precursory phenomena, for example earthquake swarms. The methods developed to combine several rate-based forecasting models are not adapted to combine models with precursory information or with non-normalized models including alarm-based ones. We propose a method to combine earthquake forecast rate-based models with any information that could locally increase the forecasted earthquake rates. We use the differential probability gain calculated in the Molchan diagram that evaluates the performance of the input information with respect to the rate-based model. Then, at each point in space and time, the new rate is the product of the current rate times the local differential probability gain. The main advantage of our combining method is its capacity to produce high expected event rates. The only restriction is that the input data have to bring additional amount of information with respect to the basic rate-based model. We demonstrate on several examples how the method works. The research was partially supported by Russian Foundation of Basic Research (Project N 13-05-00541).

Confidence Intervals for the Magnitude of the Largest Aftershock

Robert Shcherbakov

Western University, Canada; rshcherb@uwo.ca

Aftershock sequences, which follow large earthquakes, last hundreds of days and are characterized by well defined frequency-magnitude and spatio-temporal distributions. The largest aftershocks in a sequence constitute significant hazard and can inflict additional damage to infrastructure. Therefore, the estimation of the magnitudes of possible largest aftershocks in a sequence is of high importance. In this work (Shcherbakov, GRL v.41, 2014, p.6380), I propose a statistical model based on Bayesian analysis and extreme value statistics to describe the distribution of magnitudes of the largest aftershocks in a sequence. I derive an analytical expression for the Bayesian predictive distribution function for the magnitude of the largest expected aftershock and compute the corresponding confidence intervals. I assume that the occurrence of aftershocks can be modeled, to a good approximation, by a non-homogeneous Poisson process with a temporal event rate given by the modified Omori law. I also assume that the frequency-magnitude statistics of aftershocks can be approximated by Gutenberg-Richter scaling. I apply the analysis to 29 prominent aftershock sequences, which occurred in the last 30 years, in order to compute the Bayesian predictive distributions and the corresponding confidence intervals. In the analysis, I use the information of the early aftershocks in the sequences (in the first T=1, 10, 30 days after the main shock) to estimate retrospectively the confidence intervals for the magnitude of the subsequent largest aftershocks. I demonstrate by analysing past sequences that in many cases it is possible to constrain the magnitudes of the largest aftershocks. The proposed analysis can be used for the earthquake hazard assessment and forecasting associated with the occurrence of large aftershocks. The improvement in instrumental data associated with early aftershocks can greatly enhance the analysis and facilitate better forecasting and hazard mitigation. Aftershocks occur in other relaxation phenomena, for example, in fracture experiments on porous materials and acoustic emissions, in solar flares, after stock market crashes to mention a few, therefore, the results of this study can also be applicable to those problems.

Data-driven spatial b-value estimation with applications to California seismicity: To b or not to b

Yavor Kamer, Stefan Hiemer

ETHZ, Switzerland; yaver.kamer@gmail.com

In this paper we present a penalized likelihood-based method for spatial estimation of Gutenberg-Richter's b-value. Our method incorporates a non-arbitrary partitioning scheme based on Voronoi tessellation, which allows for the optimal partitioning of space using a minimum number of free parameters. By random placement of an increasing number of Voronoi cells we are able to explore the whole solution space in terms of model complexity. We obtain an overall likelihood for each model by estimating the b-values in all Voronoi regions and calculating its joint likelihood using Aki's formula. Accounting for the number of free parameters we then calculate the Bayesian Information Criterion (BIC) for all random realizations. We investigate the ensemble of the best performing models and demonstrate the robustness and validity of our method through extensive synthetic tests. We apply our method to the seismicity of California using two different time spans of the ANSS catalog (1984-2014 and 2004-2014). The results show that for the last decade years the b-value variation in the well instrumented parts of mainland California is limited to the range of [0.94±0,04-1.15±0.06]. Apart from the Geysers region, the observed variation can be explained by network related discrepancies in the magnitude estimations. Our results suggest that previously reported spatial b-value variations obtained using classical fixed radius or nearest neighbor methods are likely to have been overestimated, mainly due to subjective parameter choices. Thus, consequent physical interpretations based on spatial b-value variations, such as stress and material properties, should be viewed with scepticism.

Development of a Bayesian method to estimate a fault slip distribution of a large earthquake from the spatial aftershock distribution and rate- and state friction law: inclusion of information on magnitude as a prior distribution

Takaki Iwata

Tokiwa University, Japan; tiwata@tokiwa.ac.jp

A Bayesian approach to estimate a fault slip distribution of a large earthquake from its on-fault aftershock activity and rate- and state-dependent friction law (Dieterich, 1994) is being developed. In this approach, the amplitudes of slips of each of the subfaults of a target large earthquake are optimized to fit the observed spatial distribution of aftershocks with the expected one, which is derived from the friction law and point-process model. This approach is to optimize a huge number of parameters simultaneously, but such optimization is unrealistic. Therefore, a roughness penalty or flatness constraint on the spatial slip distribution is imposed to stabilize the optimization.

The imposition in the estimation can be attained by means of a construction of a Bayesian model, and a key point is the objective determination of the strength of the roughness penalty. Typically, it is determined through the maximization of the marginal likelihood with the Laplace approximation (e.g., Tierney & Kadane, 1986). However, because of some technical reasons, the Markov chain Monte Carlo method (e.g., Gamerman & Lopes, 2006) is applied to the developing approach instead of the Laplace approximation; it is difficult to compute the value of the marginal likelihood and to find the strength of the roughness penalty objectively.

To overcome this problem, incorporating the information on the magnitude of a target large earthquake is suggested, because empirically the strength of the roughness penalty has a strong correlation with the amplitudes of the slips. A prior probability distribution of the magnitude of a target earthquake is assumed to be follow a normal distribution of which mean is taken from the Global CMT catalogue and the standard deviation is provided from Kagan (2010). Then, the posterior probability distributions of the amplitudes of the slips of the subfaults and the strength are computed. As a demonstration, this approach is applied to the 2005 Miyagi-oki earthquake and the obtained slip distribution is not much different from that estimated from a waveform inversion.

Does the Spatial Analysis of 2012 Ahar-Varzeghan (Northwestern Iran) Seismic Sequence Corroborate the Tectonic Interpretations?

Pouye Yazdi[1], Miguel Ángel Santoyo García-Galiano[2]

[1]Universidad Politécnica de Madrid, UPM, Spain; [2]Universidad Nacional Autónoma de México, UNAM, México.; p.yazdi@alumnos.upm.es

The impact of cosiesmic static stress changes on nearby faults can explain the triggering or altering the timing of rupture. It also can explain the aftershocks nucleation and its interaction with the further fault activations. Validity of such prediction relies on our deep knowledge about the faulting system close to the seismic source. On August 2012 a doublet with Mw=6.5 and Mw=6.3 with 11 minutes difference occurred between towns of Ahar and Varzeghan, Northwestern Iran. The main effort in this paper was to study the Coulomb failure stress changes, using a smoothed elliptical source model but with different scenarios for the rupture planes. Because the faulting system in the area is not very well known historically and Northwestern Iran shows a spatially distributed deformation, taking alternative assumptions into account improves the best corroborating solution for the rupture planes. Thus, in order to understand whether the following seismic sequence verifies the changes in the static stress in the area, both tectonic interpretations of Copley et al. (2014) which are based on an observed EW surface rupture were examined. Moreover, for improving the spatial analysis, a re-localization of the data for a period of four months since August 2012 was done, based on double difference algorithm of Waldhauser and Ellsworth (2000) and using the associated velocity model for the Northwestern Iran. Then, applying the methodology of King et al. (1994) we disused the Coulomb failure stress changes in different scenarios for optimally oriented faults and likewise for the case of largest aftershock that occurred 3 month later in November 2012 with Mw=5.7. At the end the best explanation for the most likely stress-loaded locations was explored regarding to the results from Coulomb failure stress changes and aftershocks nucleation.

Efficient identification of fault and auxiliary planes from focal mechanisms using EM-based cluster analysis

Sebastian Specht, Fabrice Cotton

GeoForschungsZentrum Potsdam, Germany; specht@gfz-potsdam.de

Two of the most crucial parameters in strong ground motion seismology are the rupture plane distance and the style of faulting. The rupture plane distance is defined as the shortest distance between the fault plane and the sensor. In order to estimate the rupture plane distance, the location as well as the size and orientation of the fault plane must be known, information which is avaialble for few large events only. In most cases, a simple approximation of the rupture plane is modelled by a magnitude based relation for the planes extension and the planes orientation is derived from the focal mechanism. However, the focal mechanism always gives two solutions of plane orientations (nodal planes) which are perpendicular to each other. The identification of the style of faulting and nodal planes as the actual fault plane and the auxiliary plane is either done by investigating the focal mechanism catalog event by event or by arbitrary classification including other parameters such as hypocenters and other geological information, e.g. known fault orientations. While the first method is tedious and only applicable to smaller catalogs, the latter can lead to biased results.

We introduce "ace" - (a)ngular (c)lassification with (e)xpectation-maximization - to efficiently identify fault and auxiliary planes as well as the style of faulting in one purely data-driven algorithm. Ace only uses the strike, rake, and dip of both nodal planes from focal mechanism catalogs to identify clusters belonging to the two types of nodal planes and different styles of faulting. Since many of these catalogs cover nowadays more than 40 years with thousands of events, statistically stable solutions can be obtained for many regions througout the world.

We present results of the classification for the South American coast and the adjacent Nazca plate showing the identification of thrust, normal, and strike slip events and their respective separation in fault and auxiliary planes.

Energy release, source parameters and fault plan solution of July 18 and 22, 2014 Gulf of Suez earthquakes

abdelaziz khairy, Gad-Elkareem Mohamed, ahmed badawy

national research institute of astronomy and geophysics, Egypt; dewaky@yahoo.com

On 18 and 22 of July, 2014 two moderate size earthquakes of local magnitudes 4.2 and 4.1 struck the northern part of Gulf of Suez near Suez City. These events are instrumentally recorded by Egyptian National Seismic Network (ENSN). The events have been felt at Suez city and greater Cairo metropolitan area while no casualties were reported. In the present study, energy release, source mechanism and source parameters of the studied earthquakes were estimated using the near-source waveform data recorded by very broadband stations of Egyptian National Seismic Network (ENSN) and validated by the P-wave polarity data of short period stations. The new inversion method and software used in this study treat the effect of the source time function, which has been neglected in most of the program sets of the moment tensor inversion analysis with near source seismograms. The obtained results from inversion technique indicate to the estimated Seismic moments of both earthquakes are 0.6621E+15 Nm and 0.4447E+15 Nm corresponding to a moment magnitude Mw 3.8 and 3.7 respectively. The fault plan solutions obtained from both inversion technique and polarity of first-arrival indicate the dominance of normal faulting. The principal strain axis shows that the deformation is taken up mainly as an extension in the E-W and NE–SW direction.

Fault-Zone Maturity Defines Maximum Earthquake Magnitude

Marco Bohnhoff[1,2], Fatih Bulut[1,3], Eva Stierle[1], Patricia Martinez-Garzon[1], Yehuda Ben-Zion[4]

[1]GFZ Potsdam, Germany; [2]Freie Universität Berlin, Germany; [3]AFAM Research Center, Istanbul Aydın University, Turkey; [4]University of Southern California, Los Angeles, USA; bohnhoff@gfz-potsdam.de

Estimating the maximum likely magnitude of future earthquakes on transform faults near large metropolitan areas has fundamental consequences for the expected hazard. Here we show that the maximum earthquakes on different sections of the North Anatolian Fault Zone (NAFZ) scale with the duration of fault zone activity, cumulative offset and length of individual fault segments. The findings are based on a compiled catalogue of historical earthquakes in the region, using the extensive literary sources that exist due to the long civilization record. We find that the largest earthquakes (M~8) are exclusively observed along the well-developed part of the fault zone in the east. In contrast, the western part is still in a juvenile or transitional stage with historical earthquakes not exceeding M=7.4. This limits the current seismic hazard to NW Turkey and its largest regional population and economical center Istanbul. Our findings for the NAFZ are consistent with data from the two other major transform faults, the San Andreas fault in California and the Dead Sea Transform in the Middle East. The results indicate that maximum earthquake magnitudes generally scale with fault-zone evolution.

Identifying stages in the aftershock generation process by inter-event times analysis.

F. Ramón Zúñiga, Angel Figueroa-Soto, Víctor Hugo Márquez, Marisol Monterrubio
UNAM, Mexico; ramon@geociencias.unam.mx

Several mechanisms have been proposed to describe the generation of aftershocks, including but not limited to: viscoelastic relaxation processes (Dieterich, 1972; Hainzl et al., 1999), stress changes on faults (Ito and Matsuzaki, 1990), rate-and-state model (Dieterich, 1994) and viscoelastic damage rheology (Ben-Zion and Lyakhovsky, 2003; Shcherbakov and Turcotte, 2004). However, few have dealt with the issue of different stages in the generation process, since these effects are difficult to discern.

The inter-event time behavior of seismic aftershock sequences following selected earthquake mainshocks, which took place at different tectonic regimes, are investigated with the aim of gaining further information on the aftershock process. To this end we studied some well-defined aftershock sequences and analyzed the fractal behavior of the logarithm of inter-event times (also called waiting times) of aftershocks by means of Holder´s exponent and other statistical techniques, as well as their magnitude distribution and relative spatial location based on the methodology proposed by Zaliapin and Ben Zion which accounts for the clustering properties of the sequence. Our goal was the identification of different dynamical stages acting during the aftershock generation process.

Several results stem from this study. In most cases, more than two coherent process stages can be discerned following the main rupture, evidencing that the mechanism behind the generation of aftershocks cannot be generalized even though the temporal rate and general fractal character appear to be unique (as in a single Omori´s p value). We found that aftershock processes indeed show multi-fractal characteristics, which may be related to different stages in the process of diffusion, as seen in the temporary-spatial distribution of aftershocks. Our method provides a way of defining the onset of the return to seismic background activity and the end of the main aftershock sequence.

Kinematic Study of Pisagua Earthquake 2014 - Northern Chile: Analysis of the Frequency Content and its Impact on the Understanding of the Seismogenic Zone

Jorge Jara[1], Jesus Pina-Valdes[1], Anne Socquet[1], Fabrice Cotton[2], Javier Ruiz[3], Andrea Walpersdorf[1], Nathalie Cotte[1]
[1]ISTerre, France; [2]GFZ, Germany; [3]Universidad de Chile, Chile; jorge.jara@ujf-grenoble.fr

Recent megathrust earthquakes that occurred in Chile (2010) and Japan (2011) revealed a segmentation with depth of the megathrust interface: short period radiations were emitted from the deeper portion of the seismogenic zone (35-55km depth), while large coseismic slip, associated with little short period radiation and responsible for the tsunami generation, occurred on the shallower part of the subduction interface.

On April 1, 2014, a Mw 8.2 earthquake occurred close to the city of Pisagua in the central part of the seismic gap of southern Peru - northern Chile. This earthquake occurred in a densely instrumented area in a joint effort between Chilean, French, German and USA institutions. It is therefore an excellent case study to better understand the seismic rupture process on the subduction seismogenic interface. The availability of collocated cGPS and strong motion data (IPOC network: Integrated Plate Boundary Observatory Chile) offers a unique opportunity to study the seismic source, compare the results derived from both type of data and study the variability of the seismic source with the frequency.

We perform a detailed comparison of the co-seismic movements registered by cGPS and three-component accelerograms. Then, we carry out a series of inversions to study the kinematic rupture associated with this earthquake. For this purpose, we use the accelerometer (9 stations) and high-frequency GPS (1 Hz, 13 stations) independently and jointly. We use a two-step inversion method proposed by Hernandez et al. (1999), where we use the contribution of GPS in obtaining the static displacement and then carry out the kinematic inversion using the method in frequency domain (Cotton & Campillo, 1995). Finally we study the dependency of the Mw8.2 Pisagua seismic source with the signal frequency. Data are filtered in different frequency bands and then frequency dependent inversions are conducted to explore the segmentation of the seismogenic zone in the area affected by the earthquake. In particular, we aim at testing whether a Mw8.2 earthquake can show a frequency dependency similar to the one observed for megathrust events, characterize this dependency and define segmentation along depth and along strike of the seismogenic zone, compare this segmentation with the one issued from GPS-derived interseismic coupling maps.

Long-term effects of rifting-induced stress changes on the earthquake statistics in the Tjörnes Fracture Zone (North Iceland)

Masoud Allahbakhshi, Luigi Passarelli, Francesco Maccaferri, Eleonora Rivalta
Helmholtz Center Potsdam (GFZ), Germany; masoud.a.bakhshi@gmail.com

The Tjörnes Fracture Zone (TFZ) is a WNW trending en-echelon transform zone connecting the rift of the Kolbeinsey Ridge with that of the North Volcanic Zone of Iceland (NVZ). The TFZ is 120-km-long and 80-km-wide and is composed of three main sub-parallel lineaments: the Grimsey Oblique Rift (GOR) to the north, the Husavik Flatey fault (HFF) to the center and the Dalvik lineament (DL) to the south. Nowadays the GOR and the HFF are the most active structures of the TFZ: they accommodate practically all the deformation due to the rift opening and have relatively high rate of seismicity.

On the other hand the DL shows very low seismic rates and does not contribute significantly to the deformation of the area. However in the past 200 years the DL had hosted at least 3 historical seismic events with magnitude greater than 6. We propose that the 1975-1984 Krafla rifting episode, which is the last rifting episode occurred in the NVZ, have changed the way of releasing the deformation in the TFZ, locking the east HFF and the DL. This mechanism is potentially still active in the area and a better understanding of the interplay between the Krafla rifting episode and the actual state of stress on the DL would have important implications for the risk assessment of the region. We modeled the Coulomb Stress Change due to the Krafla rifting episode on the DL. We compare the stress change with seismological observation from the SIL catalogue (1995-2014) in north Iceland. We find that the Coulomb Stress Changes vary from negative (clamping) to positive values (unclamping) from east toward west. We separated the Tjörnes Fracture Zone into rectangular boxes, calculated b-value and Magnitude of completeness and examined the seismicity rate in the interval 1996-2014.

Near-source ground motion observations of large earthquakes are inconsistent with concept of deterministic rupture propagation

Men-Andrin Meier[1], Tom Heaton[2], John Clinton[1]
[1]Swiss Seismological Service, ETH Zurich, Switzerland; [2]California Institute of Technology, Seismological Laboratory, USA; men-andrin.meier@sed.ethz.ch

The feasibility of Earthquake Early Warning (EEW) applications has revived the discussion on whether earthquake rupture development follows deterministic principles or not. If it does, it may be possible to accurately predict final earthquake magnitudes while the rupture is still developing. Most EEW algorithms use magnitude estimation schemes that are based on 3-4 seconds of near-source p-wave data. It is well established that such schemes work well for small to moderate size earthquakes. However, for this magnitude range, the time window used for the magnitude estimation is larger than the source duration of the event; hence the estimation is observational, rather than predictive. Whether the magnitude estimation schemes also work for events in which the source duration exceeds the estimation time window is debated. Due to the scarcity of near-source waveform data for large events, and because a variety of estimation methods have been used, different authors have reached different conclusions.

In our study we have compiled an extensive high-quality data set of near-source seismic recordings using maximally objective selection criteria. We use non-parametric tests to show that the onset of large (M7+) events is indistinguishable from that of medium sized events (M6-M7) until the source durations of the medium sized events are over. This simple observation implies that whether an initial rupture pulse evolves into a large earthquake, or terminates to become a M6 event, is not determined at the event origin and contradicts recent claims that magnitudes as high as Mw9.0 can be estimated based on only 3-4 seconds of p-wave data. If, then, EEW magnitude estimations are observational rather than predictive, EEW can still be useful but this limitation has to be taken into account in alert messaging and response design.

Nucleation, propagation and arrest of transient slip in seismic swarms in the Tjörnes Fracture Zone (North Iceland)

Eleonora Rivalta[1], Luigi Passarelli[1], Francesco Maccaferri[1], Sigurjon Jonsson[2]
[1]GFZ Potsdam, Germany; [2]KAUST, Saudi Arabia; rivalta@gfz-potsdam.de

The Tjörnes Fracture Zone (TFZ) connects the Northern Volcanic Zone to the Mid-Atlantic ridge north of Iceland. It primarily consists of two transform structures, the Húsavík-Flatey Fault (HFF) and the Grímsey Oblique Rift (GOR), which together have experienced about ten M>6 earthquakes since 1750. There is growing concern that a large earthquake may be due in the TFZ and therefore the area has been monitored with a high-quality seismic network since 1996. The GOR and the northwestern part of the HFF have been seismically very active during the past two decades, often in the form of seismic swarms of various intensity and duration. The most energetic swarms during this period took place in October 2012 and March 2013, with several M>5 earthquakes. These and previous swarms occurred offshore and are poorly understood, in particular regarding the physical mechanism behind their generation and to what extent the swarm-like activity might temporally or permanently modify the hazard in the entire TFZ.

Here we study the spatio-temporal pattern of earthquake swarms occurring in the TFZ since 1996. We find that the swarms show spatial complementarity, i.e., in general they do not overlap spatially with earlier swarms. Moreover, together they have progressively filled up the entire GOR and the western half of the HFF. Each swarm shows a clear migration of hypocenters on their respective fault planes. This is particularly visible in the September-October 2012 and March 2013 sequences, where the earthquakes expanded concentrically from a central, focused patch on the fault to the entire fault area excited by seismicity. The swarms typically start as very localized microseismicity, lasting for a few hours to a few days. Then, the hypocenter area starts to expand, with earthquakes migrating at velocities ranging from 1 km/day up to 1 km/h. The migration sometimes accelerates or decelerates, depending on the case. However, as soon as the earthquakes have migrated a distance of about 10 km, the migration comes to a sudden stop, with microseismicity continuing on the fault plane for a few days or weeks. Fluid diffusion driven by overpressure tends to cause earthquakes to spread proportional to t^(-1/2), with migration velocities lower than a fraction of km/h. Higher migration velocities in the range 0.1- 1 Km/h have instead been associated to slow slip in subduction zones or on transform faults. The high swarm migration velocities and velocity changes we observe in the TFZ therefore point to an interesting sequence of nucleation, propagation and arrest of transient slip in a fault zone with a complex rheology.

On the focal mechanism distributions of background seismicity and triggered seismicity in the Japan region

Minzhen Wang[1], Jiancang Zhuang[1,2]
[1]The Institute of Statistical Mathematics, Japan; [2]Department of Statistical Science, the Graduate University for Advance Studies, Tokyo, Japan; minzhen@ism.ac.jp

Following the work by Kagan, the distribution of focal mechanisms is characterized by a mean focal mechanism and other parameters describing how the rotation angle of individual focal mechanisms deviates from the mean. By applying the space-time ETAS model and the stochastic declustering method to the F-net catalog from the Japan region, reconstruct the probabilities that each event is a background or triggered by a previous event. We then estimate the probability distributions of the focal mechanisms of the background events and of the triggered events conditioning on the magnitudes of their parent

earthquakes. Based on these results, we proposed a space-time ETAS model where the focal mechanism component is incorporated.

Parametric and Non-Parametric Procedures for Estimating Maximum Magnitude of Earthquakes in Different Seismotectonic Provinces of Iran

Mona Salamat, Mehdi Zare

International Institute of Earthquake Engineering and Seismology, Iran, Islamic Republic of; salamat.mona@gmail.com

The existence of numerous active faults and history of earthquake casualties, present Iran as one of the most hazardous country in Alp Himalayas border. The close relevance between earthquake hazard maps and maximum magnitude of earthquakes shows the predominant effect of precise estimation of this factor. Thus, the accurate estimation of maximum magnitude for any seismotectonic zones plays a vital role in seismic hazard and risk analysis. This evaluation can be done deterministically or probabilistically by using earthquake catalogs and statistical procedures. This article was applied probabilistic procedures using different statistical methods for exact estimation of Mmax.

There are different statistical procedures for accurate estimation of Mmax with their weak and strong points based on its derivation, bias and condition for validity. In this study, the estimation procedures are categorized into two sections, parametric and Non-parametric estimators. Parametric estimators could be applied when the parametric models of the frequency-magnitude distributions are known. Three procedures, such as Tate-Pisarenko, Kijko-Sellevoll, and Kijko-Sellevoll-Bayes will be investigated in this paper. When the empirical distribution of earthquake magnitudes are unknown or multi-modal character, non-parametric procedures must be replaced. Non-parametric with Gaussian Kernel and based on order statistics are categorized in this part.

For this purpose, Iran was divided into 6 seismotectonic zones named Alborz, Azerbaijan, Zagros, Markazi, Makran and Kopeh-Dagh. Comparing different de-clustering methods, Gardner and Knopoff was selected as a final choice for de-clustering the catalogue. Based on calculated magnitude of completeness in different spatial-temporal windows of Iran, seismic parameters were estimated by Aki-Utso extension method. At the end, maximum magnitude of earthquakes were estimated in each regions based on mentioned statistical procedures.

Relationship between aftershock parameters and physical properties of the crust.

Olga Zakharova[1], Sebastian Hainzl[1], Bogdan Enescu[2]

[1]GFZ, Potsdam, Germany; [2]University of Tsukuba, Japan; olgaza@gfz-potsdam.de

The resent development and a wide deployment of the geodetic and seismic instruments gives an opportunity to investigate aftershock sequences on a relatively local scale. In particular, we study the dependencies between aftershock sequences properties and slip/coupling models on a scale of one mega earthquake. For this goal we use, on one hand, physical models of the crust derived by different authors and, on the other hand, aftershock parameters, obtained by the modified ETAS model. The altered ETAS model takes into account the mainshock rupture extension and is able to distinguish between primary and the secondary aftershock input into the total seismicity rate. Using the statistical approach to the problem we estimate the Spearman's correlation coefficients between the spatially distributed aftershock parameters, estimated using the modified ETAS model, and crustal physical properties for the Maule 2010 Mw8.8 and the Tohoku 2011 Mw9.0 aftershock sequences. We find that the aftershock occurrence and their seismic moment release are maximal in the areas of high coseismic slip gradient, postseismic slip and interseismic coupling.

Relationship between changes in rate of background earthquakes and slow slip in Boso, Japan

Thomas Reverso, David Marsan, Agnès Helmstetter

ISTerre, France; thomas.reverso@univ-savoie.fr

The Boso Peninsula in Japan is situated in a tectonically area

where the Philippine plate and the Pacific plate converge. The

peninsula is moving in the northwest direction ; however , the GPS

stations showed south-southeast movements in 1996 , 2002, 2007, 2011,

2014 , revealing transients caused by slow slip events (SSEs) (Ozawa

et al. , 2007, Kato et al ,2014, Ozawa,2014). These transients can

produce an increase in tectonic stress loading locally and can

affect earthquake dynamics, if they occur close to or within seismically active zones.

In Boso Peninsula, SSEs are systematically accompanied by seismic swarms,

which do not obey usual mainshock-aftershock patterns. These seismic swarms

contribute only as 1% of the total energy

relaxed during the SSEs (Ozawa et al. , 2007).

Using the method developed by Reverso et al, 2015, we compute

the increase in background aseismic rate during these events. To do so, we use an ETAS model, that helps separating the seismicity rate lambda as

two distinct contribution : a background rate mu and a seismic rate

nu that can be modeled. This study enables us to compare the change in

background rate with the change in aseismic slip that is inverted from

GPS measurements, and to investigate how the two relate through distinct

instances of aseismic deformation episodes in Boso.

Significant Relative Quiescence along the western end part of Kuril subduction zone more than 5 years

Ritsuko S. Matsu'ura

Association for the Development of Earthquake Prediction, Japan; matsuura@adep.or.jp

It is already 120 years since an M7.9 earthquake occurred off the Nemuro Peninsula, the northeastern part of Japan, in 1894. The significant relative quiescence of the seismicity of M>=5.7 in the much wider area off the southeastern part of Hokkaido, which is located at the western end of Kuril trench, has been continuing since 2009 both in Japanese and International earthquake catalogues from 1965 to the present. The relative quiescence was measured as the deviation from the maximum likelihood model of ETAS-type. The similar significant relative quiescence was also existed in the wide area off the east coast of Tohoku district for 10 years before the M9.0 off Tohoku Pacific earthquake in 2011 (e.g. Matsu'ura, 2008), and noticeable even from the raw data. The present quiescence in the western end part of Kuril subduction zone is also noticeable as the low frequency of felt earthquakes in the eastern part of Hokkaido district of Japan now. Since the quiescence is enhanced after the occurrence of the M9.0 event along the Japan trench in 2011, the recovery of the activity from the quiescence prior a large event might not be detectable in the current case. Several-year calm tracking of this quiescence is necessary. It is recommended to enhance the cooperation of Japan and Russia on observations, and we should watch the seismicity in the southern part of Kuril subduction zone for at least a few years.

Spatial-Temporal Analysis of b-value in M6.3 Southwest Iran Earthquake of 09 April 2013, as an earthquake precursor

Zari Bordbar[1], Mohammad Reza Hatami[2]

[1]University of Tehran, Iran, Islamic Republic of; [2]University of Tehran, Iran, Islamic Republic of; zbordbar@ut.ac.ir

Seismicity parameters can be a tool for monitoring earthquake precursory variation (Gutenberg-Richter, 1944). Magnitude-frequency distribution is specifically used in relation to earthquake precursory and seismic hazard assessments. The b-parameter as the slope of the magnitude-frequency distribution plot is related to the seismicity of the study area and its variation can indicate the structural heterogeneity or the spatial distribution of the stress in the region. Changes in b values are inversely related to the changes in the stress.

An increase in the shear stress or effective stress decreases the value of the b-parameter (Urbancic at al., 1992). Smaller values of the b-parameter probably mean that there is a high stress in the region under study. A decrease in the value of the b-parameter can, in relation to an increase in the effective stress, lead to occurrence of a great earthquake (Kanamori, 1981).

$$b=1/(\bar{M}- M_{min}) \log e$$

M, the middle magnitude, and Mmin, the minimum magnitude, are given in the sample.

For the analysis, a catalog with a large number of events was necessary so that it could be divided into events of smaller size. Given the large number of the events, the resolution problem is very important for reliable estimates, especially in areas where few events have been recorded. At 11:52:49 on 9 April 2013, an earthquake took place with a magnitude of 6.3 on a scale of Mw in Kaki, located in the south west of Iran with coordinates 28.467 °N and 51.568 °E. This earthquake was the largest earthquake in the period of this study. The study area was surrounded by the 27.00 – 30.50 °N and 49.50 – 52.85 °E. The Earthquake Catalog of Iranian Seismological Center (Institute of Geophysics, University of Tehran, Iran) was used to extract the desired data with magnitudes M≥1.5, from 1 January 2006 to 17 April 2014. Number of the earthquakes examined in this study was 2942. Indeed, the distribution map of Mc indicates that spatial extension of the catalog, which specifies a higher quality (Wiemer and Wyss, 2000). Accordance to this map, northeastern parts of the region have a uniform distribution of lower Mc values. Values of b and a were estimated from FMD, as a function of Mmin, based on events with M ≥ Mi using the Maximum Likelihood Estimation method (Bender, 1983).

In this way, the spatial distribution of the b parameter in the time period 1 January 2006 to 09 April 2013 showed a variation from 0.6 to 1.85 in the study area. These are consistent with the earthquakes M≥5 roughly in the study area (Fig.1). A non-uniform distribution of the b parameter is clear in this map. Kaki occurrence has been cleared in values less than 0.8, with dark blue (Fig. 2). In the second step, the temporal distribution of the b parameter in the time period 1 January 2006 to 17 April 2014 is plotted (Fig. 3). Kaki occurrence was well consistent with the decreasing trend in the plot.

Spatio-temporal behavior on simulated aftershock sequences using the Fiber Bundle Model

MARISOL MONTERRUBIO, RAMON ZUÑIGA, VICTOR HUGO MARQUEZ, ANGEL FIGUEROA-SOTO

UNIVERSIDAD NACIONAL AUTONOMA DE MEXICO, Mexico; mmonterrubio@geociencias.unam.mx, ramon@geociencias.unam.mx, marvh@geociencias.unam.mx

The spatial, temporal and magnitude patterns in a aftershocks series are studied by simulated rupture sequences obtained by a modified version of the Fiber Bundle Model (FBM). The FBM, is a cellular automata type model with a self-organization critical behavior, but with specific rules that approximate the rupture process in a wide range of disordered systems under external forces with the interaction between the constitutive elements suitable for the type of rupture under study. New rules have been added to the FBM, with the purpose of reproducing not only the temporal behavior of aftershocks but also the spatial characteristics. In particular, the influence of the spatial configuration of the initial stresses on the final spatial pattern. Our main aim is to simulate observed aftershock patterns such as the spatial clustering around the mainshock following assumed crustal stresses and the temporal behavior of clusters. We hypothezise that the changes of the activity (accelerations and/or quiescence) can be interpreted as the superposition of a lasting relaxation stress process and numerous short episodes of sudden stress release. We find critical values of two parameters of the algorithm, namely the fraction, P, of the initial stresses that are spatially ordered with respect to a central region, simulating the main rupture; and the dissipative stress percentage, π, that indicates the stress percentage that the system loses during the simulation. Beyond these critical values (P=0.30 and π=0.70) the spatial-temporal patterns and the magnitude behavior obtained from the numerical simulation, do not reproduce the real aftershocks sequence behavior. Results are also viewed in terms of the frequency-magnitude (F-M) distributions obeying the Gutenberg-Richter relations resulted from the simulations without imposing any magnitude distribution. We notice, that, under certain initial conditions, some F-M curves resemble distributions with preferred or characteristic magnitude events, which have been observed at some regions in the crust such as segments of the subduction regime in Oaxaca, Mexico.

Spatiotemporal variation of b-value in Molucca Collision Zone using high precision relocated hypocenters

Hasbi Ash Shiddiqi[1], Sri Widiyantoro[2], Andri Dian Nugraha[2], Mohamad Ramdhan[3], Wandono Wandono[3], Sutiyono Sutiyono[3], Titi Handayani[3]

[1]Earth Sciences Graduate Program, Faculty of Earth Sciences and Technology, Institut Teknologi Bandung, Jl. Ganesha 10, Bandung 40132, Indonesia; [2]Global Geophysical Research Group, Faculty of Mining and Petroleum Engineering, Institut Teknologi Bandung, Jl. Ganesha 10, Bandung 40132, Indonesia; [3]Agency for Meteorology, Climatology, and Geophysics (BMKG), Jl. Angkasa 1 No. 2, Kemayoran, Jakarta, Indonesia; h.a.shiddiqi@gmail.com

High seismicity in the Molucca Collision Zone (MCZ) is a result of complex tectonic setting in and around this region. We have relocated more than 7500 earthquakes from the Indonesian Meteorology, Climatology, and Geophysical Agency (BMKG) catalog from April 2009 to January 2015. Relocation process was conducted using teleseismic double-difference method by combining local, regional, and teleseismic P-wave arrival times. Our relocation results clearly depict the Wadati-Benioff zone of two opposing slabs beneath the Molucca Sea, and clustered earthquakes at the center of MCZ with north-northeast trend. These clustered earthquakes reveal the most active shallow region in the MCZ, where at least 12 major earthquakes with Mw = 6.5 or greater have occurred since the last two decades. We analyzed spatiotemporal variation of b-value in this region from the relocated BMKG catalog and ISC catalog (from 1980 to 2015) data. We shifted epicenters and depths of earthquakes from the ISC catalog randomly with a value between 10 km to 20 km in order to test the sensitivity of b-value result due to hypocenter uncertainty. We find that the b-value result for lateral variation is not sensitive to the uncertainty of the epicenter location, but depth variation of b-value suffers a bias due to errors in earthquake depth. Therefore, we used relocated BMKG catalog data that are considered to be of high precision. In addition we also analyzed the ISC catalog data in order to obtain better understanding of b-value spatiotemporal variation over longer period. Spatial variation from both BMKG and ISC catalog data reveals a low b-value zone with north-northeast direction at the center of MCZ. Variation in b-value at cross-section of the Molucca sea plate depicts a low anomaly of b-value at the shallow part of the slabs (i.e. less than 100 km). This low b-value anomaly is related to high stress due to subduction zone processes in the shallow part of this region. From temporal analysis, major earthquakes over the last two decades in MCZ are marked by decreasing b-value before earthquakes occur. Furthermore, we also analyzed the distribution of P-axes of major earthquakes from global centroid moment tensor catalog, where data are available. We find that subducted slabs are under compression, where P-axes are perpendicular with the slabs.

Static stress triggering explains the empirical aftershock distance decay

Sebastian Hainzl[1], Javad Moradpour[2], Jörn Davidsen[1,2]

[1]GFZ, German Research Centre for Geosciences, Potsdam, Germany; [2]Complexity Science Group, Department of Physics and Astronomy, University of Calgary, Canada; hainzl@gfz-potsdam.de

The shape of the spatial aftershock decay is sensitive to the triggering mechanism and thus particularly useful for discriminating between static and dynamic stress triggering. For California seismicity, it has been recently recognized that its form is more complicated than typically assumed consisting of three different regimes with transitions at the scale of the rupture length and the thickness of the crust. The intermediate distance range is characterized by a relative small decay exponent of 1.35 previously declared to relate to dynamic stress triggering. We perform comprehensive simulations of a simple clock-advance model, in which the number of aftershocks is just proportional to the Coulomb-stress change, to test whether the empirical result can be explained by static stress triggering. Similarly to the observations, the results show three scaling regimes. For simulations adapted to the depths and focal mechanisms observed in California, we find a remarkable agreement with the observation over the whole distance range for a fault distribution with fractal dimension of 1.8, which is shown to be in good agreement with an independent analysis of California seismicity.

Systematic assessment of the static stress-triggering hypothesis using inter-earthquake time statistics

Shyam Nandan[1], Guy Ouillon[2], Jochen Wössner[3], Didier Sornette[4], Stefan Wiemer[1]

[1]ETH, Swiss Seismological Service, Zurich; [2]Lithophyse, Nice; [3]RMS, Zurich; [4]ETH, Department of Management, Technology and Economics, Zurich; shyam4iiser@gmail.com

A likely source of earthquake clustering is static stress transfer between individual events. Previous attempts to quantify the role of static stress for earthquake triggering generally considered only the stress changes caused by large events, and often discarded data uncertainties. We test the static stress change hypothesis empirically by considering all events of magnitude M≥2.5. We additionally scrutinize the influence of location and focal mechanism uncertainties provided by catalogs for Southern California between 1981 and 2010.

Prior to computing Coulomb stress interactions between all causal source-receiver pairs, we resolve focal plane ambiguity for all earthquakes present in the focal mechanism catalog (Yang et al., 2012) using the clusters of earthquakes present in the relocated catalog (Hauksson et al., 2012). Within each cluster of the relocated catalog, we use a Gaussian mixture approach

implemented through an expectation-maximization (EM) procedure to obtain the optimal decomposition of a given cluster into well-defined individual planes. Each of these sub-clusters are then used to resolve the focal plane ambiguity for all the associated earthquakes with available focal mechanisms. We also compute Coulomb stress changes after randomly choosing among the nodal planes for each earthquake for comparison of results.

We quantify at first how the waiting time between each pair of earthquakes relates to the Coulomb stress changes induced by each source event on each receiver event. We empirically model the waiting time distributions, conditioned on sign and amplitude of Coulomb stress changes, by using a kernel consisting of triggering (Omori decay modulated by exponential taper with characteristic time, T) and background rate components tapered by an exponential term to model the finiteness of the catalog. The parameters are obtained by maximizing the log likelihood. We also compute the fraction of source-receiver pairs with positive Coulomb stress interaction (Coulomb Index or CI) as a function of waiting time for all the Coulomb stress bins. We assess the static triggering hypothesis using three metrics: ratio of the triggering to the background rates at t=0 (R), maximum log likelihood (MLL) of the model, and CI.

We observe that R and MLL increase with absolute value of Coulomb stress change and are significantly larger for positive (R+, MLL+) than for negative (R-, MLL-) stresses. We also find that CI values are significantly larger than the mean-field coulomb index (MFCI), derived from a time-independent structure of the fault network, below a waiting time threshold (TCI), which varies between ~250 days and ~446 days. The characteristic time T varies only marginally with the absolute value of Coulomb stress changes, between ~100 days and ~175 days. We also find that R+, MLL+ and CI values are larger when we make informed choice of the nodal planes compared to the case when the nodal planes were randomly chosen. Moreover, R- and MLL- are smaller for the former compared to the latter.

Considering the fact that there is a mixing of waiting times between positive and negative Coulomb stress bins due to uncertainty in the computed Coulomb stress change, our observations could only be explained if there exists preferential triggering in areas that received a positive Coulomb stress change from preceding earthquakes, compared to areas that were relaxed by negative Coulomb stress change. Our results are thus supporting the static triggering hypothesis. Decreasing the uncertainty in the Coulomb stress change by making more informed choices of fault planes further enhances the evidence of the static triggering hypothesis. The characteristic times T and TCI can be thought of as the largest time scale until the memory of the past stress changes survives. Both quantities are roughly comparable as they are the manifestation of the same mechanism. Since the memory of past stress changes is deleted beyond this time scale, forecasts based on Coulomb stress changes should not be possible, on average, over horizons much larger than T.

In the future, we plan to use these phenomenological observations to develop statistical models and compare their performance in explaining the observed seismicity to more popular isotropic models such as ETAS.

The national Spanish earthquake catalogue: Magnitude of completeness, location precision, and mine blasts

Álvaro González

Universidad de Zaragoza, Spain; Alvaro.Gonzalez@unizar.es

The national Spanish earthquake catalogue reports data of over 100,000 earthquakes occurred since the IV century to the present in a wide geographic area which embraces the Iberian Peninsula, Canary Islands and neighbour regions (Spain itself, Portugal, Andorra, and parts of France, Morocco and Algeria). It is compiled, and updated online in real time, by the Instituto Geográfico Nacional (www.ign.es).

Remarkably, it includes the largest earthquakes known in Western Europe (Lisbon 1755, Mw≈8.5, and other great offshore earthquakes). At the other extreme, events with M≈0 are nowadays routinely recorded in the areas where the seismological network is densest.

This work analyses the magnitude of completeness and location precision of earthquakes in the catalogue, focusing especially in the modern instrumental era (since the 1960's, and with more detail since the 1980's). Different periods are considered, which are separated by milestones in the development of the seismic network, or by changes in the procedures for calculating magnitudes or for locating hypocentres.

Successive detailed maps of magnitude of completeness show an overall improvement with time, particularly intense in the early 2000's, thanks to the deployment of the broadband network. The precision of hypocentral locations also improved along the decades, especially in late 1997, when real-time automatic procedures for phase picking and earthquake location were implemented.

Substantial spatial heterogeneities are highlighted. Both the completeness of the database and the location precision are much better onshore the Iberian Peninsula than offshore, and are especially poor in the most distant areas. Nowadays all onshore earthquakes with M≥2.0 seem to being recorded, and located with typical precisions (90% confidence interval) of 5 km or better.

Examples of catalogue contamination by artificial events (blasts) are also addressed. For safety reasons, rock blasting is typically performed at daylight hours, whereas natural earthquakes are more frequently recorded during night hours, thanks to the lower artificial noise. Consequently, contamination by blasts in an earthquake catalogue is usually evidenced by a locally high day-to-night ratio of events. However, blasts recorded at large-scale underground mines in Spain and Portugal highlight a more complicated hourly pattern: Blasts can also be preferentially scheduled at specific night hours when workers are out of the mine.

The role of small earthquakes in modeling foreshock occurrence with ETAS

Stefanie Seif, Arnaud Mignan, Jeremy Zechar, Stefan Wiemer

ETH Zürich, Switzerland; stefanie.seif@sed.ethz.ch

There is a debate within the seismological community regarding the potential to use foreshock occurrence to forecast large earthquakes. This is mainly due to the fact that foreshocks do not show systematic patterns, or they are indistinguishable from normal seismicity. Foreshock studies are limited by the number of available data: regional case studies often feature a single mainshock that, thanks to low detection thresholds in dense regional networks, can have a large number of foreshocks. On the other side, global studies can include many mainshocks but, because global networks cannot record smaller events, often have only a few foreshocks per mainshock. It is equally problematic to draw general conclusions from case studies, as it is to rely on data limited to high magnitudes in global studies which might exclude important information for foreshock statistics.

To address these shortcomings we investigate systematically a large set of foreshock sequences of regional catalogs with low magnitude thresholds and thus obtain multiple mainshocks preceded by an increased number of potential foreshocks. We consider the Epidemic-Type Aftershock Sequence (ETAS) model - which assumes a uniform triggering mechanism of earthquake generation - and compare its predictions of foreshocks against observed foreshock data in southern California, northern California, Italy, and elsewhere.

Estimating ETAS parameters for small magnitude cutoffs is non-trivial: (1) The estimates can be influenced by incomplete aftershock sequences; and (2) the assumption of spatially isotropic aftershock distribution may affect the parameter estimates. We investigate the effect of these potential biases via synthetic earthquake catalogs; based on these findings we consider different sets of ETAS parameters and compare the number of foreshocks in ETAS simulations with the number in observed seismicity.

The spatial and temporal variation of the b-value in Southwest of China

Shiyong Zhou, Shenjian Zhang

Peking University, China, People's Republic of; zsy@pku.edu.cn

In our study, we use an improved Bayesian method based on B-spline to estimate the spatial and temporal variations of b-value in Southwest China. We propose that the b-value combined with seismicity and tectonic background can give a pretty clear stress condition and can be used in earthquake hazard analysis. The very low b-value in Southwest China shows the feature of the 2008 Ms8.0 Wenchuan earthquake. We also suggest that the decreasing trend of b-value in Longmen Shan area in 2000 to 2008 can be an indicator of the 2008 Ms8.0 Wenchuan earthquake.

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Rate-and-State California Earthquake Forecasts: Resolving Stress Singularities

Anne Strader, David D. Jackson

UCLA; astrader@ucla.edu

In previous studies, we pseudo-prospectively evaluated time-dependent Coulomb stress earthquake forecasts, based on rate-and-state friction (Toda and Enescu, 2011 and Dieterich, 1996), against an ETAS null hypothesis (Zhuang et al., 2002). At the 95% confidence interval, we found that the stress-based forecast failed to outperform the ETAS forecast during the first eight weeks following the 10/16/1999 Hector Mine earthquake, in both earthquake number and spatial distribution. The rate-and-state forecast was most effective in forecasting far-field events (earthquakes occurring at least 50km away from modeled active faults). Near active faults, where most aftershocks occurred, stress singularities arising from modeled fault section boundaries obscured the Coulomb stress field. In addition to yielding physically unrealistic stress quantities, the stress singularities arising from the slip model often failed to indicate potential fault asperity locations inferred from aftershock distributions. Here, we test the effects of these stress singularities on the rate-and-state forecast's effectiveness, as well as mitigate stress uncertainties near active faults. We decrease the area significantly impacted by stress singularities by increasing the number of fault patches and introducing tapered slip at fault section boundaries, representing displacement as a high-resolution step function. Using recent seismicity distributions to relocate fault asperities, we also invert seismicity for a fault displacement model with higher resolution than the original slip distribution, where areas of positive static Coulomb stress change coincide with earthquake locations.

Modeling B - Part2: Modeling of seismicity: B. Applications

Time: Monday, 15/Jun/2015: 5:00pm - 6:00pm · *Location:* Arcona Hotel, Havelpavillon
Session Chair: David Alan Rhoades

Detecting spatial variations of earthquake clustering parameters via maximum weighted likelihoods estimates

Jiancang Zhuang

Institute of Statistical Mathematics, Japan; zhuangjc@ism.ac.jp

The ETAS model has been used to describe the clustering features of seismicity with just several parameters. To see how the clustering parameters and background rates change spatially, in this study, the earthquake data from the JMA catalog are used and these model parameters are estimated by using the maximum weighted likelihood estimate (MWLE) method. Even though this MWLE method is not as sophisticated as the HIST-ETAS model, which is built on a more rigorous basis of the Bayesian procedure with the smoothness prior, MWLE is simpler to implement, in both parallel and non-parallel computing environments, without loss of detecting resolution of the spatial variation of earthquake clustering parameters.

The data analysis shows that the spatial variation of the MWLEs of each parameter shows different features between tectonic regions. Also, applying the MWLE method has the potentials for improving the forecasting performance of the space-time ETAS model in evaluating earthquake probabilities.

Short-term foreshocks and their predictive value

Gerassimos Papadopoulos[1], Markos Avlonitis[2], Boris Di Fiore[1], George Minadakis[1]

[1]Institute of Geodynamics, National Observatory of Athens, Greece, Greece; [2]Department of Informatics, Ionian University, Platia Tsirigoti 7, Corfu, Greece.; papadop@noa.gr

Foreshocks preceding mainshocks in the short-term, ranging from minutes to a few months prior the mainshock, have been known from several decades ago. Understanding the generation mechanisms of foreshocks was supported by seismicity observations and statistics, laboratory experiments, theoretical considerations and simulation results. However, important issues remain open. For example, (1) Why only some mainshocks are preceded by foreshocks and not others? (2) Is the mainshock size dependent on some attributes of the foreshock sequence? (3) Is that possible to discriminate foreshocks from other seismicity styles (e.g. swarms)? To approach possible replies to these issues we reviewed about 400 papers, reports, books and other documents referring to foreshocks as well as to relevant laboratory experiments. We found that the ratio of mainshocks preceded by foreshocks increases with the increase of monitoring capabilities and that foreshock activity is dependent on source mechanical properties and favoured by material heterogeneity. Also, the mainshock size does not depend on the largest foreshock size but rather by the foreshock area. Seismicity statistics may account for an effective discrimination of foreshocks from other seismicity styles. Our literature survey showed that only the last years the seismicity catalogs organized in some well monitored areas are adequately complete to search foreshock activities. Therefore, we investigated for a set of “positive foreshock examples” covering a wide range of mainshock magnitudes from 4.5 to 9 in Japan, S. California, Italy and Greece. The positive examples used indicate that foreshocks bear important value not only for the mainshock prediction but also for the operational discrimination between different styles of activity such as background seismicity, swarms, foreshocks, aftershocks.

Hidden Markov Modeling of Sparse Time Series from Non-volcanic Tremor observations

Ting Wang[1], Jiancang Zhuang[2,3], Kazushige Obara[4], Hiroshi Tsuruoka[4]

[1]Department of Mathematics and Statistics, University of Otago, Dunedin, New Zealand; [2]Institute of Statistical Mathematics, Tokyo, Japan; [3]Department of Statistical Science, the Graduate University for Advanced Studies, Tokyo, Japan; [4]Earthquake Research Institute, University of Tokyo, Tokyo, Japan; ting.wang@otago.ac.nz

Since the first discovery of non-volcanic tremors in the Nankai subduction zone, southwest Japan, more tremor activities have been detected in various tectonic areas worldwide. Though tremors themselves do not cause catastrophic damage, a better understanding of their characteristics will aid with the investigation of interplate slip. To date, there has not been any statistical analysis to examine the temporal and spatial migration of tremors. The tremor activities are observed to be spatially segmented and temporally recurrent, with a quasi-periodic transition among tremor locations. We design a type of hidden Markov models (HMMs) to investigate this phenomenon, where each state can be used to describe a distinct segment of tremor sources. Since the tremor clusters are very sparse in time, we introduce a mixture distribution of a Bernoulli variable and a continuous variable into the HMM to solve the problems caused by the sparseness of the data. Applying this model to systematically analyse the tremor data from the Tokai region in southwest Japan, we have found that the tremors in this region concentrate around several distinct centres. We also found: (1) Tremors tend to last longer in the middle of this region; (2) After the system migrates to the northeastern part of the Tokai region, it is most likely to be followed by a long period of quiescence; and (3) after a long period of quiescence, tremors are slightly more likely to restart at the northeastern tip or the southwestern tip of the Tokai region.

Physics - Part1: Physics of earthquakes on different scales

Time: Tuesday, 16/Jun/2015: 8:30am - 10:10am · *Location:* Arcona Hotel, Havelpavillon
Session Chair: David Marsan

Slow slip transients and large earthquakes

Aitaro Kato

Nagoya University, Japan; aitaro@seis.nagoya-u.ac.jp

Growing number of geophysical evidence has illuminated that a major fault zone along a plate interface hosts both unstable fast sliding during ordinary earthquake ruptures and slow-slip transients without any seismic radiation (i.e., silent sliding). To understand the generation process of earthquakes, it is quite important to reveal an interplay between seismic and aseismic slip along the plate boundary fault.

Here, we focus on an intensive foreshock sequence prior to the 2014 Iquique, Chile Mw 8.1 earthquake (1 April, 2014). To obtain a precise record of the foreshock sequence, we applied a matched-filter technique to continuous seismograms recorded near the source region, for over 6 years before the mainshock. We newly detected about 17 times the number of seismic events listed in the routinely constructed USGS earthquake catalog.

We identified multiple sequences of earthquake migrations, both along-strike and down-dip on the fault plane, up-dip of the mainshock area from the summer in 2013 to the mainshock origin. The migration speeds of earthquakes accelerated from ~ 0.1 km/day to ~ 10 km/day with an increasing time toward the mainshock rupture. In addition, we found out repeating earthquakes from the newly detected events, likely indicating aseismic slip along the plate boundary fault. The amount of aseismic slip change during an each slow-slip transient (deduced from the repeating earthquakes) gradually increased from the summer in 2013 with an increasing time toward the mainshock rupture. These observations suggest that multiple slow-slip events took place from the summer in 2013, up-dip of the mainshock area. Both multiple slow-slip events and coseismic-slip produced by the intensive foreshocks resulted in a gradual unlocking near the updip edge of the major mainshock rupture area. We thus interpret that several parts of the plate boundary fault perhaps slipped slowly and quickly, causing stress loading on the prospective largest slip patch of the mainshock rupture.

We found out similar foreshock migrations prior to some shallow crustal major earthquakes in Japan. The foreshocks appear to come close to the initiation point of mainshock rupture. Although we are not able to detect repeating earthquakes, these foreshock migrations are likely explained by slow-slip transients. Major fault planes of the shallow crustal earthquakes also might slipped slowly before the mainshock rupture, leading up to the unstable mainshock rupture.

Quantitative evaluation of slip balance between co- and inter- seismic phase

Lifeng Wang

CENC, China, People's Republic of; chsxwlf@hotmail.com

Slip on faults has to follow on average the plate motion, but slip deficit might be accumulated over shorter time scales (e.g., between the large earthquakes). Accumulated slip deficits which can be estimated from interseismic displacement rates or coupling map have to be released by coseismic ruptures and transient aseismic processes. In this study, we propose an approach to invert for coseismic slip, taking the geodetically determined interseismic slip deficit as prior information. We assume a linear correlation between the coseismic slip and the interseismic slip deficit, and their coefficients that are inverted from the coseismic displacements describe the recurrence time and seismic release level during the earthquake. We apply this approach to the 2011 M9 Tohoku-Oki earthquake, the 2004 M6 Parkfield earthquake and the 2010 M8.7 Maule earthquake. The results indicate that the strain accumulated along the segment relating to the Tohoku-Oki earthquake is almost fully released. The rest slip deficit is fulfilled by the postseismic processes. Similar conclusions are also obtained for the 2004 M6 Parkfield earthquake. However, our investigation indicates that the 2010 M8.7 Maule earthquake is far to fill the pre-existing seismic gap, and the seismic potential is still high in this region.Using the new inversion approach, we estimate the recurrence time for the 2004 M6 Parkfield earthquake has an optimal value of 25.1 year, in a confidence interval of [17.2, 42.8] year. For the Tohoku-Oki earthquake, we estimate the recurrence time is about 400-600 year. The recurrence time of M8.7 Maule earthquake is about 350 year. This inversion approach for coseismic slip and recurrence time can be generally applied to any earthquake where geodetic measurements are adequate.

Earthquakes versus interseismic coupling in the North Chile - South Peru seismic gap

Anne Socquet[1], Jorge Jara[1], Marta Bejar Pizzaro[2], Marianne Métois[3], Daniel Carrizo[4], Nathalie Cotte[1], Edmundo Norabuena[5], Mohamed Chlieh[6]

[1]ISTerre, France; [2]Instituto Geologico y Minero de España; [3]INGV, Rome, Italy; [4]Universidad de CHile; [5]INstituto Geofisico del Peru; [6]Institut de Recherche et de développement (IRD); anne.socquet@ujf-grenoble.fr

Understanding the factors that limit the extent of seismic ruptures is crucial for risk mitigation and for understanding physical processes that govern the behavior of seismogenic faults. Devastating megathrust earthquakes in Chile in 2010 and Japan in 2011 ruptured subduction segments that were documented to be highly coupled before the earthquake, while ruptures terminated in regions that were relatively uncoupled. So it appears crucial to evaluate interseismic coupling and its spatial variation in seismic gaps to assess seismic potential.

The subduction zone at the latitude of the Central Andes did not experience a Mw>8.5 earthquake since the 19th century, and forms a ~500km long seismic gap in North Chile - South Peru. In November 2007, the Mw7.9 Tocopilla earthquake, ruptured the deeper part of the seismogenic interface, at the southern extremity of the gap. More recently, on the 1st of April 2014 a Mw8.2 earthquake in front of Pisagua, ~150 km south of the Chile-Peru Border. In spite of its already large magnitude, that earthquake was smaller expected in the area, and has most probably increased the stress in the unbroken segments at both edges. Despite of these two events, most of the North Chile-South Peru subduction area remains unbroken.

We propose here to estimate the interseismic coupling in the Chile - Peru area by combining InSAR together with continuous and campaign GPS measurements describing a unique and dense velocity field spreading through the Chile Peru border. We show that the subduction interface, is accumulating interseismic elastic strain, likely to rebound into a large megathrust Earthquake. In particular this provides a unique assessment on the pre-earthquake interseismic coupling at the latitude of the Arica bend, often described as a seismic barrier, and therefore expected to slip aseismically. Results of the GPS derived interseismic segmentation are compared with the seimicity and geomorphic features in the area.

Applying Statistical Seismology to Image the Physical Properties of the Crust

Egill Hauksson

California Institute of Technology, United States of America; hauksson@caltech.edu

We use 34 years of southern California relocated seismicity and refined focal mechanisms to analyze the heterogeneity in seismicity in the context of crustal properties. The seismicity catalog consists of three M>7 mainshock-aftershock sequences as well as numerous smaller sequences and background seismicity. We analyze the seismicity to improve our understanding of the spatial and temporal variability of the heterogeneity in seismogenic thickness, state of stress, and derived properties such as stress drops, and b-values. To synthesize the seismicity in the context of crustal properties, we analyze the statistical properties of seismicity iso-surfaces across southern California: 1) 5% shallow depth (D5%); 2) mean and median focal depths; 3) the D95% and D99% focal depths at the bottom of the seismogenic zone; 3) maximum b-value; and 4) stress directions. Almost no seismicity occurs at shallow depths between ~1 and ~3 km which is likely caused by the predominance of velocity strengthening friction. As confining pressure increases with depth within the seismogenic zone, the macroscopic behavior becomes more ductile. Below the seismogenic zone, pure ductile behavior and velocity strengthening dominate. To understand this brittle-ductile transition, we also analyze focal mechanisms of adjacent earthquakes that may exhibit a decrease in the internal friction angle as pressure increases with depth, near the bottom of the seismogenic zone. We search for such a weak zone in the lower crust using the horizontal moment tensor element of focal mechanisms to map decreasing horizontal shear tractions at the base of the seismogenic zone, especially beneath major Principal Slip Zones (PSZs). We interpret our results in the context of the previously determined regional velocity structure, depth to Moho, proximity to major PSZs as well as geophysical parameters of the crust such as heat flow and tectonic strain rate. The new interpretation will provide an image of the statistical properties of seismicity as they vary from one crustal block to the next and in the vicinity of major PSZs.

What is characteristic about a characteristic earthquake? Implications from multi-scale studies of the relative earthquake size distribution

Stefan Wiemer, Thessa Tormann

ETH Zurich, Switzerland; stefan.wiemer@sed.ethz.ch

Constraining the recurrence of the largest earthquakes in a system is genuinely important for hazard assessment and mitigation. The prevailing approach to model such events relies on zone segmentation and quasi-periodic recurrence due to constant tectonic loading. However, while for some faults the paleoseismic evidence is in good agreement with historical and instrumentally recorded seismicity, in others a large mismatch is observed. We suggest that the analysis of the relative earthquake size distribution of earthquakes as a function of space and time can help to determine the current loading state of a fault and thus allow to constrain the current hazard state. Analysing, for example, the earthquakes recorded along a 1,000-km-long section of the subducting Pacific Plate beneath Japan since 1998, we find that the relative frequency of small to large events varies spatially, closely mirroring the large-scale tectonic regimes, and suggesting a laterally unsegmented mega-thrust interface. Starting some years before it broke, the Tohoku source region is imaged as a region of high stress concentration. Following the 2011 M9 earthquake, the size distribution changes significantly and most dramatic in the areas of highest slip. However, we discover that it returns within just a few years to its longer-term characteristics as observed prior to the mega-thrust event. This indicates a rapid recovery of stress and implies that such large earthquakes may not have a characteristic location, size or recurrence interval, and might therefore occur more randomly distributed in time. In presentation, we compared the evidence from a wide range of studies that have mapped b-values and local recurrence times in various places around the world, and investigate the implications for the notion of characteristic earthquakes.

Physics - Part2: Physics of earthquakes on different scales

Time: Tuesday, 16/Jun/2015: 10:40am - 12:00pm · *Location:* Arcona Hotel, Havelpavillon
Session Chair: Sebastian Hainzl

Relative quiescence associated with the 2011 Tohoku-oki earthquake in the preceding aftershock sequences: What controls seismic sensitivity to negative stress change?

Yuhei Suzuki[1], Shinji Toda[1], Keisuke Yoshida[2], Tomomi Okada[1]

[1]Tohoku University, Japan; [2]National Research Institute for Earth Science and Disaster Prevention; toda@irides.tohoku.ac.jp

Static stress shadow, where seismicity rate decreases responding to a sudden stress drop, is only detectable when the preceding seismicity is sufficiently high. To fulfill the requisite condition, on-going aftershock sequence is often applied. Here we use a combination of the 2011 Mw=9.0 Tohoku-oki earthquake and the preceding 2008 Mw=6.9 Iwate-Miyagi mainshock-aftershock sequence and then argue that stress shadowing is controlled by not only diversity of receiver faults but also stress perturbation history.

To detect relative quiescence in the 2008 aftershock sequence, we first employ the Epidemic Type Aftershock Sequence (ETAS) model with "change point" technique (Ogata, 1992). To compare the goodness-of-fit of the models, we compared the Akaike's Information Criterion (AIC) for the entire 2008 aftershock sequence (AICall) with a summation of two periods of AIC1 and AIC2 divided by the change point. We found the AICall – (AIC1 + AIC2) is maximum when the change point is set at 3 days after the occurrence time of Tohoku-oki, which means the seismic quiescence after March 11 2011 is statistically significant.

We then seek the physical reason why the relative quiescence of the 2008 aftershocks occurred after the Tohoku-oki earthquake. We used newly determined 3727 focal mechanisms of the Iwate-Miyagi aftershocks occurred until 10 March 2011, as a proxy for hidden active faults. We then compute Coulomb stress change on all nodal planes using a coseismic variable slip model of the Tohoku-oki earthquake in an elastic half-space with a wide range of apparent friction μ' of 0.0, 0.4 and 0.8. Eighty percent and 50% of the resolved Coulomb stress changes on all the planes are negative under μ'=0.0 and 0.8, respectively. In contrast, positive Coulomb stress changes are obtained mostly from strike-slip nodal planes occupied in the western 2008 rupture zone. Post-Tohoku-oki activity of the 2008 aftershocks was predominantly observed in the western rupture zone where strike-slip faults dominate, while northern and southern peripherals of the 2008 aftershock zone occupied by thrust faults was in significant relative quiescence. These active and dormant responses and their time series are well explained by the Coulomb stress transfer incorporating rate/state friction of Dieterich (1994). However, the 2008 aftershock center has not responded to the significant Tohoku-oki stress drop, which cannot be explained by a conventional Coulomb model. Here we hypothesize that such a seismic insensitivity to stress decrease is attributed to the ratio of 2011 stress drop to the 2008 stress increase. The ratio is large in the peripherals of the 2008 source. In contrast, the ratio is small in the center of the aftershock zone due to the immense stress increase and heterogeneity born at the 2008 earthquake. In rate/state friction, the latter case also reproduces a stress shadow but recovers much faster than the former case. We thus think that such quick recovery process at the 2008 aftershock center made the short-lived effect of stress shadow inconspicuous and undetectable.

Exploring aftershock properties with depth

Peter Shebalin[1,2], Clement Narteau[2]

[1]Institute of Earthquake Prediction Theory and Mathematical Geophysics, Moscow, Russian Federation; [2]Institut de Physique du Globe, Paris; p.n.shebalin@gmail.com

Stress magnitudes and frictional faulting properties vary with depth and may strongly affect earthquake statistics. Nevertheless, if the Anderson faulting theory may be used to define the relative stress magnitudes, it remains extremely difficult to observe significant variations of earthquake properties from the top to the bottom of the seismogenic layer. Here, we concentrate on aftershock sequences in strike-slip faulting regimes to isolate specific temporal properties of this major relaxation process with respect to depth. We consider the major strike-slip faults in California, alone and all together. We find very clear and stable dependence on depth of the duration of the early stage of aftershock activity that does not fit with the power-law regime (c-value in the Omori-Utsu law). At depths from 5 to about 15 km the logarithm of c-value demonstrates linear decay with increasing depth. We show that this gradient may be numerically converted to the values of friction coefficient. We discuss an opposite dependence on depth in a range from 0 to 5 km which is particularly clear for the seismicity in zones of geothermal fields (Geysers, Salton Sea, Mammoth Lakes). We show that the analysis of the c-value of the Omori-Utsu law for the aftershock decay rates in our specific task may be replaced by a non-parametric analysis of the aftershock times relative to the moments of the main shocks. We demonstrate that the logarithm of geometric average of times, normalized with the geometric average of the beginning and of the end of the considered interval, strongly correlates with the c-value estimates at a condition of the fixed p-value. The research was partially supported by Russian Foundation of Basic Research (Project N 13-05-00541)

Deterministic Model of Earthquake Clustering Shows Reduced Stress Drops for Nearby Aftershocks

Bruce Edward Shaw[1], Keith Richards Dinger[2], James H Dieterich[2]

[1]Columbia University, United States of America; [2]University of California, Riverside, United States of America; shaw@ldeo.columbia.edu

The clustering of earthquakes in space and time is a well established phenomena. A number of viable physical mechanisms have been offered to explain the tempora 1/t Omori law decay of aftershocks following a mainshock. In contrast, the spatial clustering of aftershocks have posed a challenge for physical models, in particular the intense productivity of aftershocks very near the area which ruptured in the mainshock. Here we present a new deterministic physical model capable of reproducing both the spatial and temporal clustering seen in earthquakes. We apply this new model to a very puzzling question raised by recent Ground Motion Prediction Equation (GMPE) empirical regressions of recorded seismograms, wherein a number of prominent GMPEs suggest nearby aftershocks show reduced median ground motions. Examining sequences of events in the model, we find a physical basis for these observations in reduced median stress drops for nearby aftershocks compared with similar magnitude mainshocks. We find the reason the smaller stress drops are occurring in the model are due to nearby aftershocks rerupturing parts of the fault which ruptured in the mainshock, which then have lower strength drops due to slow rehealing of the faults in the rate-and-state friction framework.

Varibility in aftershock productivity, and its relationship with stress drop

David Marsan[1], **Agnès Helmstetter**[2]

[1]ISTerre, Université de Savoie, CNRS, Le Bourget du Lac, France; [2]ISTerre, Université Joseph Fourier, CNRS, Grenoble, France; dmars@univ-savoie.fr

Aftershock production is found to vary with the magnitude of the mainshock as N(m) = K * exp(a * m). While this ensemble-averaged law has thus been studied in great details, departure from it from one mainshock to the other have attracted little attention. However, it is known that mainshocks of equal magnitudes can trigger variable number of aftershocks, this variability going beyond the simple Poisson fluctuations around the mean number N(m). Much of this variability can be attributed to the occurrence (or absence of) of large aftershocks, which will in turn trigger more aftershocks (« indirect » aftershocks, as opposed to « direct » aftershocks that are triggered by the mainshock itself), strengthening the « natural » variability of the process. But it can be expected that the variability in the number of aftershocks is also partly linked to characteristics of the mainshock itself, that are not captured by its magnitude alone. We here aim at estimating the level of fluctuations of the number N(m) of aftershocks, that are not due aftershocks triggering their own aftershocks. We thus investigate direct aftershocks only, in an attempt to grasp the dependence of N(m) on mainshock characteristics. We analyze Californian seismicity, to find that the pre-factor K is log-normally distributed, with a standard deviation of about 70 % of its mean. We check that model errors, in particular using hypocentral distances rather than distance to the fault, do not significantly alter this estimate. We further show that this distribution is compatible with triggering being governed by the mainshock stress drop. However, direct correlation of stress drop with the productivity pre-factor K for small mainshocks, using the results of Shearer et al. (2006), is made artificially very low by discretization effects, making impossible the direct comparison between these two quantities.

Induced - Part1: Understanding and quantifying induced seismicity

Time: Tuesday, 16/Jun/2015: 2:00pm - 3:20pm · *Location:* Arcona Hotel, Havelpavillon
Session Chair: Morgan Page

Earthquake scaling laws for the 2000 dike at Miyakejima (Japan) and relation to stress changes and focal mechanisms.

Eleonora Rivalta[1], Luigi Passarelli[1], Simone Cesca[1,2], Yosuke Aoki[3]

[1]GFZ Potsdam, Germany; [2]University of Potsdam, Germany; [3]Earthquake Research Institute, Tokyo University, Japan; rivalta@gfz-potsdam.de

The statistics of earthquakes from volcanic seismicity is often significantly different from the statistics of tectonic seismicity. b-values significantly different from 1 are not rare, the Omori-Utsu law for therate of aftershocks cannot describe the temporal evolution of the seismicity, and often the Gutenberg-Richter law offers a non satisfying match with the observed frequency-magnitude distribution. Volcanic swarms share many similarities with non-volcanic swarm sequences, both deriving from tectonic processes and induced by hydrofracturing, and it is useful to investigate how the scaling laws of volcanic earthquakes are related to the underlying physical processes. Here we study how the scaling laws of the earthquakes induced by the 2000 dike intrusion at Miyakejima (Izu Archipelago, Japan) are related to the faulting style of the earthquakes and to the Coulomb Stress changes due to the magmatic intrusion. For this study we use a focal mechanisms catalog (NIED, Japan). We identify the families of focal mechanisms (FMs) through an objective clustering analysis and relate them to the dike stress field and to the scaling relationships of the earthquakes. We calculate the frequency-size distribution of the clustered sets finding that focal mechanisms with a large strike-slip component are consistent with the Gutenberg-Richter relation with b~1. Conversely, events with large normal faulting components deviate from the Gutenberg-Richter distribution with a marked roll-off on its right-hand tail suggesting a lack of large magnitude events (Mw>5.5) in proportion to the observed frequency of smaller magnitude events. This can be interpreted as resulting from the interplay of the limited thickness and lower rock strength of the layer of rock above the dike, where normal faulting earthquakes are expected and observed, to lower stress levels linked to the faulting style and low confining pressure. We find that the Tension axes of all FMs is consistent with the dike-induced extensional stresses while the Pressure and Null axes cover all possible values from normal to strike-slip mechanisms, consistent with optimally-oriented faults according to the expected pattern of Coulomb stress changes induced by the dike.

Seismological characterization of micro- and macrofracturing processes in a fault zone: A comparison of laboratory stick-slip friction experiments and close-by monitoring of Mw1.9 fault in a deep South African gold mine

Grzegorz Kwiatek[1], Katrin Plenkers[2], Thomas Goebel[3], Georg Dresen[1]

[1]Helmholtz Centre Potsdam GFZ German Research Centre for Geosciences, Potsdam, Germany; [2]Gesellschaft für Materialprüfung und Geophysik mbH, Bad Nauheim, Germany; [3]California Institute of Technology, Seismological Laboratory, Pasadena, CA, United States; kwiatek@gfz-potsdam.de

Nearly 50 years have passed since the seminal work of Brace and Byerlee who first suggested that the stick-slip events frequently accompanying frictional sliding in laboratory experiments may be regarded as an experimental analog of shallow earthquakes. Since then numerous studies have investigated physical processes and characteristics of frictional sliding, extending the link between microseismicity in the laboratory and nature. Extrapolating these laboratory observations to the field scale may provide important insights into the physics governing source processes of earthquakes. The understanding of faulting and rupture processes can significantly be advanced by integrating across a range of scales. Such a wide spectrum of scales is represented in the here analyzed mining induced seismicity and laboratory stick-slip experiments.

In this study, we compare the physical and statistical properties of the atto-seismicity (M -8 to -6) recorded in the laboratory stick-slip experiments on rock samples with nano- and pico-seismicity (M -4 to 0) recorded in-situ before and after a Mw1.9 earthquake. The microfracturing processes were investigated for the two laboratory stick-slip friction experiments performed on Westerly granite samples containing a planar saw-cut fault and a fault developed from a fresh fracture surface. We examined temporal changes of seismic moment tensors, source parameters, p- and b-values of acoustic emission events that occurred during multiple seismic cycles. This study is compared with characteristics of seismicity preceding and following the Mw1.9 earthquake that occurred in a 3.5km deep South African gold mine. The mainshock was followed by an aftershock sequence composed of more than 25000 seismic events recorded using a high frequency seismic network composed of accelerometers and acoustic emission sensors. Close source-receiver distances (<30m from the hypocenter) allowed to investigate the physical processes occurring before and after the main rupture in the fault zone in a very fine details allowing to form a link between laboratory and in-situ observations.

The analysis indicated that the source characteristics of seismicity as well as b values can be used to describe the micromechanical processes occurring in the fault zone reflecting the macroscopic deformation and stress changes during the seismic cycle(s). We found similar statistical and physical properties of seismicity preceding and following the mainshock comparable for Mw1.9 and lab fault developed from fresh fracture surface. The temporal evolution of b-values and source mechanisms indicated a development and quick maturation of newly created and young fault zone. On the other hand, the dominance of shear faulting in saw-cut lab experiment suggested the saw-cut fault may be an analog of mature fault zone. The study emphasizes the importance of close-by monitoring of fault zone as an essential tool to understand the processes in the fault zone.

Assessing Earthquake Hazards in the Anthropocene: Induced Seismicity in the Central and Eastern US

Andrea L. Llenos[1], Justin L. Rubinstein[1], William L. Ellsworth[1], Charles S. Mueller[2], Andrew J. Michael[1], Arthur McGarr[1], Mark D. Petersen[2], Matthew Weingarten[3], Austin A. Holland[4]

[1]United States Geological Survey, Menlo Park, CA, United States of America; [2]United States Geological Survey, Denver, CO, United States of America; [3]University of Colorado, Boulder, CO, United States of America; [4]Oklahoma Geological Survey, Norman, OK, United States of America; allenos@usgs.gov

The rate of M≥3 earthquakes in the central and eastern US (CEUS) has increased dramatically since 2009, primarily in areas where oil and gas production take place. We present a method to identify where and when the seismicity has increased

significantly, based on using Poisson tests to identify where observed earthquake rates exceed those forecast by the 2008 National Seismic Hazard Map. We then apply this method to investigate the evolution of seismicity in Oklahoma, which is by far the greatest contributor to the CEUS seismicity increase. In 2013, seismicity expanded to the northern part of the state that contains the Mississippi Lime play, where the number of well completions rose greatly the year before the seismicity increase. This suggests a link to oil and gas production either directly or from the disposal of significant amounts of produced water within the play.

Quantifying the hazard due to these potentially induced earthquakes is a nontrivial task for a number of reasons. First, the earthquake rates are non-stationary and can potentially depend on economic factors, as seen by the seismicity increase following the drilling increase in northern Oklahoma. This makes it difficult to determine appropriate time windows into the past to estimate seismicity rates and time windows into the future over which to compute hazard. Second, induced earthquakes may have different clustering characteristics than natural earthquakes (e.g., Llenos and Michael, BSSA, 2013). In Oklahoma and other areas of suspected induced seismicity, we find that earthquakes since 2009 tend to be considerably more clustered in space and time than before 2009, which suggests that alternative declustering methods and/or a smaller spatial smoothing kernel may be more appropriate for induced seismicity. Also aftershocks may be a more important source of hazard in induced seismicity regions than in tectonic regions, where they are generally removed from consideration. Finally, induced earthquake sequences may have higher b-values (e.g., Bachmann et al., GJI, 2011) or a different Mmax (e.g., McGarr, JGR, 2014). While differences in reported magnitude types between various regional and national catalogs leave unclear whether there are significant changes in magnitude distribution in the CEUS, these parameters play a key role in extrapolating the Gutenberg-Richter distribution to higher magnitudes.

A Ground Motion Discriminant for Injection-Induced Earthquakes

Susan E. Hough

US Geological Survey, United States of America; hough@usgs.gov

Since 2009 there has been a sharp increase in observed seismicity rates in parts of the United States. A growing body of peer-reviewed literature supports the conclusion that the increase is due to increased activities associated with fossil fuel extraction, specifically the injection of wastewater in deep wells. To characterize the hazard from induced earthquakes it is necessary to not only characterize their expected rates but also characterize ground motions produced by these events. Instrumental data are sparse for the central and eastern United States (CEUS). However, the USGS "Did You Feel It?" system now routinely produces spatially rich intensity data for felt events, yielding Community Decimal Intensity (CDI) values that have been shown to provide good proxies for ground motion parameters such as peak ground acceleration (e.g., Atkinson and Wald, 2007). Consideration of DYFI data from a set of moderate CEUS events reveals a distinct intensity signature of induced events, with relatively high intensities within approximately 10 km of the source, and significantly low intensities at greater distances. High near-field intensities can be explained as a source-depth effect. Low regional intensities suggest a depletion of energy between roughly 1-8 Hz, which could conceivably reflect a path or source-depth effect, but can be explained readily by low stress drop. The observations bear out a suggestion made by Hanks and Johnston (1992), that intensity data provide a robust reflection of stress drop. I define an effective intensity magnitude, M_IE, as the magnitude that best fits a set of observed intensity data, given a regional intensity-prediction equation determined from tectonic earthquakes. The difference between instrumentally determined Mw and M_IE then provides an indication of stress drop relative to a regional average. Analyzing moderate events in California as well as the CEUS, I characterize the variability of Mw - M_IE, and implied variability of stress drop, for tectonic events. These results can be compared to the degree of stress drop variability estimated from conventional analysis of waveform data, and suggest the variability of conventional stress drop estimates has been overestimated significantly due to epistemic uncertainty. I further suggest that consideration of well-constrained intensities can be useful as a discriminant to identify induced events. Analysis of 17 felt CEUS events that occurred between 2013 and Jan. 2015 identifies only two events that were likely tectonic.

Induced - Part2: Understanding and quantifying induced seismicity

Time: Tuesday, 16/Jun/2015: 3:50pm - 5:10pm · *Location:* Arcona Hotel, Havelpavillon
Session Chair: Morgan Page

Induced Aftershock Sequences and Swarms in Geothermal Systems

Robert Shcherbakov[1], Donald L. Turcotte[2], M. Burak Yikilmaz[2], Louise H. Kellogg[2], John B. Rundle[2]
[1]Western University, Canada; [2]University of California, Davis, U.S.A.; rshcherb@uwo.ca

Many natural geothermal systems are associated with high seismic activity. This can be related to large scale injection of fluids to enhance geothermal recovery. Other factors, such as changes in the stress field and pore pressure, can also stimulate the occurrence of earthquakes. These systems are also prone to triggering of seismicity by the passage of seismic waves generated by large distant main shocks. In this particular study, we analyse clustering and triggering of seismicity at the Geysers geothermal field, California, due to the occurrence of relatively large local events as well as due to the occurrence of significant long distant main shocks. For the analysis we use the Northern California Earthquake Data Center Earthquake Catalog. The recent Mw 6.0 South Napa main shock triggered a ml 4.5 event and a subsequent swarm of seismic activity at The Geysers. We compare this sequence of events to several other earthquake sequences generated by local large events with magnitudes greater than 4.5 and sequences generated by several other long distant main shocks. We show that the rate of decay of the aftershock sequences generated by local large events in the first day after the main event follows the modified Omori law reasonably well. On the other hand, the swarms of activity triggered by large distant earthquakes cannot be described by the simple modified Omori law. In almost all cases the frequency-magnitude statistics of triggered sequences follow Gutenberg-Richter scaling to a good approximation with relatively large b-values. The analysis indicates that the seismicity triggered by relatively large local events can initiate sequences similar to regular aftershock sequences. In contrast, the distant main shocks trigger swarm like activity with faster decaying rates.

Seismogenic Index, Bounds of Magnitude Probability and Triggered versus Induced Earthquakes

Serge A. Shapiro, Oliver Krüger O., Carsten Dinske C, Cornelius Langenbruch
Freie Universität Berlin, Germany; shapiro@geophysik.fu-berlin.de

Induced seismic hazard is a topic of significance in the shale-oil and gas industry. Its understanding is of a considerable importance for mining of deep geothermic energy. It is of significance for CO2 underground storage and possibly also for other types of geo-technological activities. Identifying parameters that control magnitudes and their statistics is a

key point for evaluating the seismic hazard of fluid injections.

Similarly to the tectonic seismicity, statistics of the induced seismicity can be rather well described by the Gutenberg-Richter frequency-magnitude distribution. We start with a model of point-like independent seismic events. This model describes well the statistics of numerous small-magnitude earthquakes. The model allows to formulate a simple description of the seismicity rate and to introduce parameters quantifying the seismo-tectonic state of a fluid-injection site in the frame of the Gutenberg-Richter distribution. One of such useful parameters is the seismogenic index. It helps to predict the probability of given-magnitude events.

However, the model of point-like events tends to overestimate the probability of significant magnitudes. Fluid-induced seismicity results from an activation of finite rock volumes. The finiteness of perturbed volumes influences frequency-magnitude statistics. We observe that induced large-magnitude events at geothermal and hydrocarbon reservoirs are frequently underrepresented in comparison with the Gutenberg-Richter law. This is an indication that the events are more probable on rupture surfaces contained within the stimulated volume.

We theoretically and numerically analyze this effect. We consider different possible scenarios of event triggering: rupture surfaces located completely within or intersecting only the stimulated volume, and derive lower and upper bounds of the probability to induce a given-magnitude event. The bounds depend strongly on the minimum principal size of the stimulated volume. We compare the bounds with data on seismicity induced by fluid injections in boreholes. Fitting the bounds to the frequency-magnitude distribution provides estimates of a largest expected induced magnitude and a characteristic stress drop, in addition to improved estimates of the Gutenberg-Richter a and b parameters.

The observed frequency-magnitude curves seem to follow mainly the lower bound. However, in some case studies there are individual large-magnitude events clearly deviating from this statistics. We propose that such events can be interpreted as triggered ones, in contrast to the absolute majority of the induced events following the lower bound.

Examples of induced/triggered seismicity in Italy: state of the art and perspectives

Thomas Braun[1,2], Buttinelli Mauro[2], Caciagli Marco[1,3], Improta Luigi[2], Piccinini Davide[4], Saccorotti Gilberto[4], Scrocca Davide[5]
[1]Istituto Nazionale di Geofisica e Vulcanologia, Arezzo, Italy; [2]Istituto Nazionale di Geofisica e Vulcanologia, Roma, Italy; [3]Istituto Nazionale di Geofisica e Vulcanologia, Bologna, Italy; [4]Istituto Nazionale di Geofisica e Vulcanologia, Pisa, Italy; [5]CNR-IGAG, Roma, Italy; thomas.braun@ingv.it

The relationship between anthropic operations and seismic events has increasingly drawn the attention of the international scientific community during the last decades.

Especially in Italy and after the Emilia seismic sequence of May 2012, this topic sparked a new particular interest. Several round tables and ad-hoc commissions were set up in order to define the state-of-the-art of induced/triggered seismicity (ITS), in association with the publication of guidelines for its discrimination and monitoring. According to this, the following human activities have been defined as relevant for the generation of ITS: reservoir impoundments, geothermal production, hydrocarbons exploitation and mining.

Unfortunately a review of historical ITS-related earthquakes seems to be a difficult task due to the poor data quality from historical records. Despite this, some promising results were obtained by a re-evaluation of several hypothesized historical ITS-

related events.

Considering the high seismicity of the Italian peninsula, the evaluation of actual ITS requires new discrimination approaches and high resolution seismic monitoring facilities for a reliable distinction between anthropogenic and natural seismicity. In this context a close cooperation with the industrial companies for accessing the production data would be desirable, if not necessary.

This contribution presents an overview of the recent researches performed in the framework of INGV-projects and other ongoing activities.

Performance evaluation of models to forecast fluid-induced seismicity

Flaminia Catalli, Sebastian Hainzl, Torsten Dahm

GFZ - Potsdam, Germany; flaminia.catalli@gfz-potsdam.de

A major challenge in geothermal projects is to model induced seismicity and forecast inacceptable levels of seismic hazard before harmful events occur. Understanding the behavior of induced seismicity in space, time and magnitude might also favor the acceptance of such alternative source of energy by local populations.

Some forecasting models, based on the assumption that earthquake triggering for fluid-induced seismicity is based on pore pressure diffusion, have already been applied and reproduced the main features of observed seismicity in different cases (e.g. Shapiro et al., 2010; Goertz-Allmann and Wiemer, 2012; Gishig and Wiemer, 2013; Hakimashemi et al., 2014).

Here we propose a comparative test of some of these models for induced seismicity, taking also into account for the possible influence of mutual earthquake interactions during and after the injection of fluids (e.g. Catalli et al., 2013). We use a set of common injection scenarios to model expected induced seismicity by using: 1) a geomechanical stochastic seed model (GSSM, Gishig and Wiemer, 2013); 2) an ETAS model (e.g. Bachmann et al., 2012), and 3) a rate-and-state model (Dieterich, 1994) based on Coulomb triggering. We aim to explain similarities and differences and to assess pro and contra of the examined approaches. The three methodologies are independent from the geomechanical model used for the reservoir and it allows also testing different kind of pore pressure models (e.g. fully coupled or not; in 2 or 3D; linear and non-linear).

The final task of our study is evaluating the performance of each model under different initial assumptions on the fluid flow trend and relative pressure diffusion; we aim to understand which model might be more robust and reliable in terms of predicting: 1) the number of events; 2) the spatio-temporal growth and pattern of the seismic event density around the well and at further distances; 3) the magnitudes distribution of triggered events.

Forcasting - Part1: New Perspectives in Probabilistic Earthquake Forecasting and Testing

Time: Wednesday, 17/Jun/2015: 8:30am - 10:10am · *Location:* Arcona Hotel, Havelpavillon
Session Chair: Matthew Gerstenberger

Anomalous hiatus of California paleo-earthquakes?

David Diether Jackson

UCLA, United States of America; david.d.jackson@ucla.edu

Many seismic hazard projects use earthquake rates estimated from paleoseismic data as a mainstay for estimating future earthquake probabilities. A prime example is the third Uniform California Earthquake Rupture Forecast (UCERF3), which relies on reported dates of observed paleo-seismic displacements at 31 sites on 13 named faults in California. However, there is a problem: recorded paleoseismic events ceased at about the beginning of the instrumental seismic era.

The reported event rates for the ensemble of 31 sites sums to about 0.1 per year. Allowing generously for occurrences of earthquakes that rupture multiple sites simultaneously, the event rate is on the order of 0.04 per year. Yet the most recent paleo-event date is 1910. Such a long open interval would be extremely unlikely for a Poisson process with that rate, which might be expected statewide even if individual faults ruptured in quasi-period events. Quasi-periodic behavior for the whole ensemble would make the discrepancy worse.

Possible explanations for the discrepancy include (1) extreme luck, (2) unexplained regional collaboration amongst faults, or (3) mistaken identification of near-surface displacements as evidence of large earthquakes. The first can be rejected with 99% confidence. There is no evidence for the second in the pre-1910 paleoseismic history nor in any theoretical models yet published. The third could explain the observed quiescence because mistaken identity would be prevented by instrumental seismic data.

Adaptive smoothing of seismicity in time, space and magnitude for long-term and short-term earthquake forecasts

Agnès Helmstetter[1], Maximilian Werner[2]

[1]Institut des Sciences de la Terre, CNRS, University of Grenoble, France; [2]University of Bristol; agnes.helmstetter@ujf-grenoble.fr

We present new methods for long-term and short-term earthquake forecasting that employ space, time, and magnitude kernels to smooth seismicity. These forecasts are applied to Californian seismicity and compared with other models. Our models are purely statistical and rely on very few assumptions about seismicity. In particular, we do not use Omori–Utsu law. The magnitude distribution is either assumed to follow the Gutenberg–Richter law or is estimated non-parametrically with kernels. We employ adaptive kernels of variable bandwidths to estimate seismicity in space, time, and magnitude bins. For long-term forecasts, the long-term rate in each spatial cell is defined as the median value of the temporal history of the smoothed seismicity rate in this cell, circumventing the relatively subjective choice of a declustering algorithm. For short-term forecasts, we simply assume persistence, that is, a constant rate over short time windows. Our long-term forecast performs slightly better than our previous forecast based on spatially smoothing a declustered catalog. Our short-term forecasts are compared with those of the epidemic-type aftershock sequence (ETAS) model. Although our new methods are simpler and require fewer parameters than ETAS, the obtained probability gains are surprisingly close. Nonetheless, ETAS performs significantly better in most comparisons, and the kernel model with a Gutenberg–Richter law attains larger gains than the kernel model that nonparametrically estimates the magnitude distribution. Finally, we show that combining ETAS and kernel model forecasts, by simply averaging the expected rate in each bin, can provide greater predictive skill than ETAS or the kernel models can achieve individually.

On the earthquake predictability of fault interaction models

Warner Marzocchi, Daniele Melini

Istituto Nazionale di Geofisica e Vulcanologia, Italy; warner.marzocchi@ingv.it

Space-time clustering is the most striking departure of large earthquakes occurrence process from randomness. These clusters are usually described ex-post by a physics-based model in which earthquakes are triggered by Coulomb stress changes induced by other surrounding earthquakes. Notwithstanding the popularity of this kind of modeling, its ex-ante skill in terms of earthquake predictability gain is still unknown. In this presentation we show that even in synthetic systems that are rooted on the physics of fault interaction using the Coulomb stress changes, such a kind of modeling often does not increase significantly earthquake predictability. Earthquake predictability of a fault may increase only when the Coulomb stress change induced by a nearby earthquake is much larger than the stress changes caused by earthquakes on other faults and by the intrinsic variability of the earthquake occurrence process.

Reviews on the pre- and post-seismicity of the Tohoku-Oki mega-earthquake, and future long-term forecasts

Yosihiko Ogata

Earthquake Research Institute / The University of Tokyo, Japan; ogata@ism.ac.jp

It has been four years since the 2011 Tohoku-Oki earthquake of M9.0 occurred. The impact of this giant event is still very large on the current and future seismicity in and around Japan.

In this occasion, I would like to review my series of agendas related to this event reported at the Coordinating Committee of Earthquake Prediction (CCEP) of Japan that was held quarterly for every year. These agendas included the observed and analyzed characteristics of (1) seismicity anomalies before the event, (2) foreshock activity, (3) induced activities in the inland, (4) aftershock activity at some stages, and (5) future long-term forecasts in Japan.

If the time allows, these will be discussed in comparison with some global seismicity including 2006 Sumatra, 2010 Chili, and the NZ Darfield-Christchurch earthquakes

Toward automatic 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 Tokyo, Japan; [2]The Institute of Statistical Mathematics, Japan; [3]National Research Institute for Earth Science and Disaster Prevention, Japan; [4]University of Tsukuba, Japan; omi@sat.t.u-tokyo.ac.jp

Early aftershock forecasting is particularly difficult since a significant number of events that occur at short times after larger mainshocks are missing in earthquake catalogs. To overcome this difficulty, we have recently developed a statistical model of incompletely detected aftershocks and found that the model can be successfully applied to retrospective forecasting tests. At present, the forecasting method uses a revised catalog, which contains many manually reviewed events that are not available in real-time. For practical situations, it is desirable to undertake forecasts based on data available only in real-time. However, the forecasting based on the real-time records is challenging, since they are even more incomplete than the revised catalog data.

Here we address the predictability of aftershocks based on the Hi-net automatic hypocenter catalog by the National Research Institute for Earth Science and Disaster Prevention, Japan. We first retrospectively compare the early aftershock data between the Hi-net automatic catalog and the JMA compiled catalog to examine the relative incompleteness of real-time data. We then show aftershock forecasting results based on the Hi-net catalog and discuss the current possibilities and challenges of real-time aftershock forecasting.

Forcasting - Part2: New Perspectives in Probabilistic Earthquake Forecasting and Testing

Time: Wednesday, 17/Jun/2015: 10:40am - 12:00pm · *Location:* Arcona Hotel, Havelpavillon
Session Chair: Warner Marzocchi

GLOBAL EARTHQUAKE FORECAST

Yan Y. Kagan
University of California Los Angeles (UCLA), United States of America; kagan@moho.ess.ucla.edu

STOCHASTIC MODELS:

Earthquake processes are inherently multidimensional: in addition to the origin time, 3-D locations, and the measures of size for each earthquake, the orientation of the rupture surface and its displacement requires for its representation either second-rank symmetric tensors or quaternions. Models based on the theory of stochastic multidimensional point processes were employed to approximate the earthquake occurrence pattern and evaluate its parameters. Even cursory inspection of seismological datasets suggests that earthquake occurrence as well as earthquake fault geometry are scale-invariant or fractal. Thus, the statistical distributions that control earthquake occurrence are power-law or stable (Levy-stable) distributions. These distributions, which, with the exception of the Gaussian law, have a power-law (heavy) tail, have recently become an object of intense mathematical investigation. Adequate mathematical and statistical techniques have only recently become available for analyzing fractal temporal, spatial, and tensor patterns of point process data generally and earthquake data in particular. The application of stable distributions to the analysis of seismicity and other geophysical phenomena would significantly increase our quantitative understanding of their fractal patterns.

STATISTICS:

Earthquake occurrence exhibits scale-invariant statistical properties:

(a) We derived a negative-binomial distribution for earthquake numbers, which approximates observations much better than the Poisson distribution.

(b) Earthquake size distribution is a power-law (the Gutenberg-Richter relation for magnitudes or the Pareto distribution for seismic moment). Preservation of energy principle requires that the distribution should be limited on the high side; thus we use the generalized gamma or tapered Pareto distribution. The observational value of the distribution index is about 0.65. However, it can be shown that empirical evaluation is upward biased, and the index of 1/2, predicted by theoretical arguments, is likely to be its proper value. The corner (maximum) moment has a universal value for shallow earthquakes occurring in subduction zones. We also determined the corner moment values for 5 or 8 other global tectonic zones.

(c) Earthquake occurrence has a power-law temporal decay of the rate of the aftershock and foreshock occurrence (Omori's law), with the index 0.5 for shallow earthquakes. The short-term clustering of large earthquakes is followed by a transition to the Poisson occurrence rate. In the subduction zones this transition occurs (depending on the deformation rate) after 7-15 years, whereas in active continents or plate-interiors the transition occurs after decades or even centuries.

(d) The spatial distribution of earthquakes is fractal: the correlation dimension of earthquake hypocenters is equal to about 2.2 for shallow earthquakes.

(e) The stochastic 3-D disorientation of earthquake focal mechanisms is well approximated by the rotational Cauchy distribution.

FORECASTS:

Since 1977 on the basis of our studies, we have developed statistical short- and long-term earthquake forecasts to predict earthquake activity rate per unit area, time, magnitude and focal mechanism orientation. The forecasts are based on smoothed maps of past seismicity and assume spatial and temporal clustering. Our program forecasts earthquakes on a 0.1 degree grid for a global region 90N--90S latitude. For the long-term forecast we test two types of smoothing kernels based on the power-law and on the spherical Fisher distribution. We employ adaptive kernel smoothing which improves our forecast in seismically quiet areas. The forecast efficiency can be measured by likelihood scores expressed as the average probability gains per earthquake compared to the spatially or temporally uniform Poisson distribution. The other method uses the error diagram to display the forecasted point density and the point events. In our recent development we combined two forecasts from smoothed seismicity and geodetic strain rates into a hybrid forecast called GEAR1: a "Global Earthquake Activity Rate" model. GEAR1 gives the rate of shallow earthquakes of magnitudes 6 through 9 everywhere on Earth on 0.1 degree grid. It was constructed through a uniform and reproducible process to make testable earthquake forecasts. The log-linear mixing method with 60% weight on the Seismicity component and 40% weight on the Tectonics component produced the most successful hybrid predicting earthquakes for 2005-2012 period. GEAR1 was also retrospectively tested against the independent ISC-GEM seismic catalog (m>= 6.8 during

1918-1976) with similar success.

Correlation-based evaluation for earthquake forecast

Ken'ichiro Yamashina[1], Hiroshi Tsuruoka[2], Tetsuto Himeno[3]

[1]Ex University of Tokyo, Japan; [2]University of Tokyo, Japan; [3]Seikei University, Japan; yama_3823@76.alumni.u-tokyo.ac.jp

The CSEP (Collaboratory for the Study of Earthquake Predictability) tests for earthquake forecasts will be useful to find effective forecast models. Here, L-, N- or S-test, for example, is currently applied to evaluate the performance of the models, assuming the Poisson distribution. However, considering the occurrence of fore- and aftershocks or earthquake swarms, it is evident that earthquakes do not necessarily occur independently with each other. Consequently, the Poisson-based evaluation may be unreasonable as long as all the correlated earthquakes are not excluded from forecast targets.

In fact, a distribution function of the numbers of earthquakes which occurred at a certain area over a certain time period can never be approximated by the Poisson distribution. Although the distribution has sometimes been fitted by the negative binomial distribution, it is questionable especially in the case that a rate of the occurrence is small. Accordingly, it is necessary to prove a reasonable distribution function which is applicable to the wide range of the rate and available to evaluate the forecast models.

In the case that the occurrence rate r is small, i.e. r<<1, an inverse power law seems to be dominant. Considering this, a discrete function f(x) = c (x^-a) exp(-bx), i.e. the Gamma distribution if it is defined continuously for x=0 or greater, was proposed before (Yamashina et. al, JPGU annual meeting, 2012). Here, x=1, 2, 3, ..., and f(0) is determined as 1-(total of f(x)). Alternatively, a function f(x) = c (x^-a) exp(-b/x) is proposed to fit the distribution of the number of earthquakes. Here, x=1, 2, 3, …, and f(0)=1-(total of f(x)), simultaneously.

It is interesting and fortunate that the parameters of the function are strongly correlated with the occurrence rate, i.e. the average of the distribution. Consequently, referring to empirical relations between the average and values of parameters, it will be possible to obtain correlation-based likelihoods or evaluation of correlation-based L-, N-, or S-tests, if only several lines of the current computer program will be replaced.

Testing by hybridisation - a practical approach to testing earthquake forecasting models

David A. Rhoades, Annemarie Christophersen, Matthew C. Gerstenberger

GNS Science, New Zealand; d.rhoades@gns.cri.nz

Statistical tests of earthquake forecasting models within the Collaboratory for the Study of Earthquake Predictability (CSEP) are predominantly of two types: consistency tests - which compare the distribution of target earthquakes with the distribution implied by the forecast; and ranking tests – which measure the extent to which one model outperforms another (i.e. the information or probability gain). Systematic fitting and ranking of hybrids offers a different, and we would argue, more practical approach to testing.

Given that presently available forecasting models on all time scales have low information value, consistency tests seem less relevant than ranking tests. Ranking tests also have limited relevance when the models to be compared are based on different data or ideas, but more relevant when one model is an elaboration of the other. For operational forecasting, it is desirable to bring all pertinent information together into a “best” current forecast. Systematic fitting and ranking of hybrid models provides a means of identifying the pertinent information and of combining it in an optimal way. Multiplicative hybrid models are easily fitted to gridded models of CSEP type. More importantly, they can also be used to incorporate the information from any gridded data correlated with earthquake occurrence, including alarm functions from proposed precursors, into an existing forecasting model. The key question when considering any new proposed type of forecasting information is: is the best current hybrid improved by including the new information in it? Recent experience with multiplicative hybrids in New Zealand and California will be used as illustrations.

Operational Earthquake Forecasting in New Zealand: Advances and challenges

Annemarie Christophersen, David A. Rhoades, David Harte, Matthew C. Gerstenberger

GNS Science, New Zealand; a.christophersen@gns.cri.nz

New Zealand straddles the plate boundary between the Pacific and the Australian plates and expects, as a rule of thumb, about one magnitude 7 or larger earthquake every 2.5 years. Prior to the Canterbury earthquake sequence that began with the Darfield event in September 2010, there had been no large and severely damaging earthquakes close to a major population centre for several decades. An active research community has developed earthquake forecast models for several decades and recently has tested them within the framework of the global Collaboratory for the Study of Earthquake Predictability (CSEP). However, there was no regular public dissemination of earthquake forecasting information, nor did the public show any particular interest in aftershock information. This changed with the occurrence of the Darfield earthquake and even more so with the M6.1 February 2011 Christchurch earthquake that occurred underneath Christchurch City and was classified as an aftershock of the Darfield earthquake. Since the Canterbury earthquake sequence a number of magnitude 6 and larger earthquakes occurred near the capital city, Wellington, in July and August 2013 and January 2014, as well as the Wilberforce earthquake in the South Island in January 2015. We briefly review the advances in operational forecasting in response to these events over the past few years. We highlight the challenges presented by uncertainty of earthquake catalogue data. In 2012, the data acquisition system to locate earthquakes and calculate magnitudes changed. We discuss our efforts to understand the effect of changes in earthquake magnitudes on our earthquake forecast models.

Forcasting - Part3: New Perspectives in Probabilistic Earthquake Forecasting and Testing

Time: Wednesday, 17/Jun/2015: 2:00pm - 3:00pm · *Location:* Arcona Hotel, Havelpavillon
Session Chair: Stefan Wiemer

Retrospective Evaluation of Time-Dependent Earthquake Forecast Models during the 2010-12 Canterbury, New Zealand, Earthquake Sequence

Maximilian Werner[1], Matthew Gerstenberger[2], Maria Liukis[3], Warner Marzocchi[4], David Rhoades[2], Matteo Taroni[4], Jeremy Zechar[5], Camilla Cattania[6], Annemarie Christophersen[2], Sebastian Hainzl[6], Agnes Helmstetter[7], Abigail Jimenez[8], Sandy Steacy[9], Thomas Jordan[3]

[1]University of Bristol, UK; [2]GNS Science, New Zealand; [3]SCEC, USC, USA; [4]INGV Rome, Italy; [5]ETH Zurich, Switzerland; [6]GFZ Potsdam, Germany; [7]ISTerre Grenoble, France; [8]University of Ulster, UK; [9]University of Adelaide, Australia;
max.werner@bristol.ac.uk

With efforts underway in New Zealand, Italy and the US to deploy and improve Operational Earthquake Forecasting (OEF) systems, an objective evaluation of the predictive skills of candidate OEF models is crucial for transparent model choices as well as the credibility of disseminated information. For this purpose, the Collaboratory for the Study of Earthquake Predictability (CSEP) is conducting a retrospective evaluation of time-dependent forecast models during the complex and fatal 2010-12 Canterbury, New Zealand, earthquake cascade that provided a wealth of new data to assess progress in recent model development.

Fourteen models were developed by groups in New Zealand, Europe and the US. The models comprised statistical, physics-based and hybrid models, presenting the opportunity to compare purely empirical models against those with a physical basis. The statistical group includes non-parametric kernel smoothing models and variants of the Epidemic-Type Aftershock Sequence (ETAS) model. The physics-based model group includes versions of the static Coulomb stress model together with Dieterich's rate-and-state friction formulation. Several newly developed hybrid models use components of the Coulomb model (e.g., the spatial pattern) within a statistical Omori-Utsu clustering formulation such as ETAS or STEP (Short-Term Earthquake Probabilities model).

We evaluated the forecasting prowess of the models from the time just after the Mw7.1 Darfield earthquake until February 2012 with several likelihood-based measures. To probe the relation between forecast skill and time horizon, we analyzed forecasts of three durations (1-year, 1-month and 1-day). Forecasts were updated immediately after the four strong earthquakes of the sequence (including the devastating February 2011 Christchurch quake) to mimic likely real-time scenarios.

To evaluate the effect of real-time input data on the quality of forecasts, CSEP collected two data sets as model input data for this experiment: a best-available data set comprising 394 target earthquakes greater than magnitude 3.95 from GeoNet as well as recent fault slip models from GNS scientists; and a near-real-time data set comprising the preliminary GeoNet earthquake catalog as captured by CSEP during the sequence and rapid fault slip models available within 10 days.

In stark contrast to previous rigorous comparisons between Coulomb stress models and statistical models, the information content of physical and hybrid model forecasts is greater or comparable to that of statistical model forecasts at all forecast horizons. Differences are greatest for 1-yr horizons, where three variants of the Coulomb model and a Coulomb/STEP hybrid model outperform a reference ETAS model by a probability gain per earthquake of about 7. The influence of near-real-time data on forecast skill is complex and model-dependent: the effect varies from insignificant to substantial but does not necessarily degrade quality. Our results offer some encouragement for a physical basis in OEF and suggest that some of the recent physics-based and hybrid model development has added informative components.

Five-year Japanese earthquake predictability experiment with multiple runs since 2009 including the 2011 Tohoku-oki earthquake

Naoshi Hirata[1], Hiroshi Tsuruoka[1], Danijel Schorlemmer[2]

[1]Earthquake Research Institute, The University of Tokyo, Japan; [2]German Research Centre for Geosciences, GFZ, German;
hirata@eri.u-tokyo.ac.jp, tsuru@eri.u-tokyo.ac.jp, ds@gfz-potsdam.de

It is 5 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 and seismic activity changed very much in entire part of Japanese Islands.

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." Starting from 91 models in September 2009, a total of 160 models, as of January 2015, are currently under testing in the CSEP Japan official suite with collaboration of CSEP Testing Center at the Southern California Earthquake Center (SCEC) (Nanjo et al., 2011; Tsuruoka et al., 2012). For 3-month and one-year testing experiments, more than 15 runs of fully prospective experiments have been completed. Probability gains of tested models with respective to a spatially uniform probability model show that some models have always better performances in regions of AllJapan and Kanto, but the best model varies runs by runs for the region of Mainland.

In the testing period including the 2011 Tohoku-oki earthquake, a model which has wider spatial smoothing radius of 100km shows larger probability gain than those with a narrow smoothing while in other periods a small smoothing radius of 10 km shows better performance. Probability gains of models for 3-month and 1-year test class for each model are almost same although a magnitude of target events is different: M>=4 for 3-month, M>=5 for 1-year. A model of HISTETAS5PA (Ogata, 2011) shows best performance for one-day class and a region of AllJapan before the 2011 Tohoku-oki event but after the event ETAS (Zhuang, 2011) is better than HISTETAS5PA.

UCERF3-ETAS: Including Spatiotemporal Clustering for a California Operational Earthquake Forecast

Edward H. Field & other WGCEP participants
USGS, Golden, United States of America; field@usgs.gov

The Working Group on California Earthquake Probabilities (WGCEP) has been developing the third Uniform California Earthquake Rupture Forecast (UCERF3). With the long-term, time-dependent model published, which relaxes segmentation, includes multi-fault ruptures, and incorporates elastic rebound, we have now turned our attention to including spatiotemporal clustering. Recongnizing that triggered events can be large and damaging, the ultimate goal is to deploy an Operational Earthquake Forecast (OEF) for California, now listed as one of the USGS's strategic-action priorities (http://pubs.usgs.gov/of/2012/1088; page 32). This presentation will demonstrate progress thus far, wherein we have added an Epidemic Type Aftershock Sequence (ETAS) component to UCERF3 (UCERF3-ETAS). Notably, our model represents a merging of ETAS with finite-fault based forecasts, as well as the inclusion of elastic rebound (both firsts, as far as we are aware). In fact, inclusion of elastic-rebound turns out to be critical in terms of replicating spatiotemporal clustering statistics (otherwise ~85% of large triggered events re-rupture the same fault, which we don't see in nature). This presentation will also outline efficient loss calculations and additional steps needed for taking UCERF3-ETAS operational.

Poster 2: Poster session B (& Coffee)

Time: Wednesday, 17/Jun/2015: 3:00pm - 5:00pm · *Location:* Arcona Hotel, Havelpavillon
Session Chair: Sebastian Hainzl

A parimutuel gambling perspective to compare probabilistic seismicity forecasts and deterministic eartquake predictions

J. Douglas Zechar[1], Marc Rierola[1], Jiancang Zhuang[2]

[1]Swiss Seismological Service, Zürich, Switzerland; [2]Institute of Statistical Mathematics, Tokyo, Japan; jeremy.zechar@sed.ethz.ch

Using analogies to gaming, we consider the problem of comparing multiple probabilistic seismicity forecasts and the problem of assessing binary earthquake predictions. To measure relative model performance, we suggest a parimutuel gambling perspective which addresses shortcomings of other methods such as likelihood ratio, information gain and Molchan diagrams. We describe two variants of the parimutuel approach for a set of forecasts: head-to-head, in which forecasts are compared in pairs, and round table, in which all forecasts are compared simultaneously. For illustration, we compare the 5-yr forecasts of the Regional Earthquake Likelihood Models experiment for M4.95+ seismicity in California, and we present a retrospective assessment of the M8 earthquake predictions at the global scale.

A Potential Promising Approach to Extract Ionospheric Anomaly Related to Earthquake from DEMETER Satellite Data

Yongxian Zhang[1], Caiyun Xia[2], Turson Nilupar[3], Xiaotao Zhang[1], Yongjia Wu[1]

[1]China Earthquake Networks Center, China, People's Republic of; [2]Institute of Earthquake Science, China Earthquake Administration, China, People's Republic of; [3]Earthquake Administration of Xinjiang Uygur Autonomous Region, China, People's Republic of; yxzh@seis.ac.cn

There has been a lot of research work on the ionospheric anomaly related to earthquake from the DEMETER satellite data, including the fatal destructive Wenchuan M8.0 earthquake. Due to the large spatial dispersion and long revisiting period of the observation data, most of the research results by direct-vision method showed that the obvious ionospheric anomaly often occurred several days before the coming earthquake, which is profitless for earthquake preparedness. In addition, ionospheric contents fluctuate violently with space weather, hence the difficulty to extract the ionospheric anomaly related to earthquake. In order to overcome the shortcomings of large spatial dispersion and long revisiting period due to the single satellite observation, the continuous simulated spatial and temporal variation of the ionospheric contents were constructed by smoothing interpolation on the original data. Then the PI (Pattern Informatics) Method (Rundle et al., 2002) that has been successfully applied to extract seismic anomaly was modified and applied to extract the ionospheric anomaly from the simulated spatial and temporal data before Wenchuan M8.0 and some other strong earthquakes. The results by MPI (Modified Pattern Informatics) method show that the abnormal disturbance of the ionosphere usually occurred about a month before the forth coming large earthquakes. The comparison among MPI method and other methods shows that MPI method is more practical for earthquake forecasting because the abnormal disturbance detected by other methods appears only a few hours to a few days before an earthquake and leaves very short time for response. The preliminary research results show that the MPI method might be a potential promising approach to extract the ionospheric anomaly related to earthquake from satellite observation data.

Aftershock Statistics of Injection-Induced Earthquakes in the Central U.S.

Morgan Page, Susan Hough

U.S. Geological Survey, United States of America; pagem@caltech.edu

In the last decade, deep injection of wastewater from oil and natural gas production has led to a dramatic increase in earthquakes in the central U.S. Oklahoma in particular has a rate of M≥3 earthquakes that currently exceeds that of California. Like tectonic earthquakes, injection-induced earthquakes can produce vigorous aftershock sequences. We examine the statistics of aftershock sequences for both induced and tectonic earthquakes. Our analysis provides evidence that, at short distances (<20 km) from the mainshock, induced earthquakes have enhanced aftershock triggering relative to tectonic earthquakes.

Applying clustering model and Gutenberg-Richter's Law to Forecast Large Aftershocks

Peter Shebalin[1], Sergey Baranov[2]

[1]International Institute of Earthquake Prediction Theory and Mathematical Geophysics of RAS, Russia; [2]Geophysical Survey of RAS, Russian Federation; p.n.shebalin@gmail.com, bars.vl@gmail.com

Forecasting aftershock activity is an important task of seismology. In contrast to mainshock, genesis of aftershocks is more determinate process which is similar to microfracturing in brittle rock. Due to the progress of fracture mechanics and statistical seismology many clustering models for short-term forecasting were suggested. However, correct forecasting of large aftershocks in an operational mode is rarely achieved.

The problem of aftershock forecasting consists of two subtasks: 1) applying the Reasenberg-Jones approach to combine aftershock clustering models with Gutenberg-Richter law; 2) forecasting an area where large aftershocks will occur.

For the specific task of forecasting aftershocks we estimate parameters of clustering model and transfer the estimated values to the future time for estimating the number of aftershocks with different magnitudes using Gutenberg-Richter's law. To take into account the power-law temporal decay of aftershocks with an exponent being close to 1 a geometric progression of the forecast time intervals with the beginning and the end multiplied by a factor at each step was used. We try different schemes of the “learning” intervals after the main shocks to achieve better results. At each step the model was corrected to take into account well-known change of the b-value, lower catalog completeness right after the main shock and other factors. For measuring the forecast quality we apply slightly modified L-test and S-test, which had been used in the CSEP experiment. L- and S- tests were also used for the optimization of the forecasting schemes (the choice of the operational learning intervals). In this research we use the simplest clustering model of Omori-Utsu.

Another subtask is to forecast the large aftershocks area. As far as we know this subtask was never considered in terms of

operational forecasting. There are some different declustering methodologies for separating aftershocks from "independent" events based on retrospective processing catalog of seismicity. The distribution of the aftershocks distances from the mainshock fault was discussed in many previous studies. In this research we study an effect of spatial spreading of the aftershock area in terms of operational aftershock forecasting. Here we present results we achieved during the study.

We suggest simple mnemonic rules to forecast the number of large aftershocks using the number of aftershocks that occurred during first hours after the main shock.

This research was supported by Russian Foundation of Basic Research (Projects 13-05-00158 and 13-05-00541).

Communicating time-varying seismic risk during an earthquake sequence

Marcus Herrmann, **J. Douglas Zechar, Stefan Wiemer**

ETH Zürich, Switzerland; marcus.herrmann@sed.ethz.ch

When an earthquake occurs, people suddenly want advice on how to cope with the situation. The 2009 L'Aquila sequence highlighted the importance of public communication and pushed the use of scientific methods to drive alternative risk mitigation strategies. For instance, van Stiphout et al. (2010) suggested a new approach for objective short-term evacuation decisions: probabilistic risk forecasting combined with a cost-benefit analysis. In the present work, we apply this approach to a scenario earthquake sequence that simulated a repeat of the 1356 Basel earthquake, one of the most damaging events in central Europe. We translate probabilistic aftershock forecasts into seismic hazard and subsequently into time-varying seismic risk, which provides an indication of the socio-economic impact. Compared with van Stiphout et al. (2010), we use an advanced aftershock forecasting model and more detailed settlement data to allow us spatial forecasts and district-wise decision-making; we also consider a different vulnerability method, which correlates hazard levels with expected damage states based on a mechanical approach. We quantify the risk forecast in terms of human loss: one minute after the M6.6 mainshock, for instance, the probability for an individual to die within the next 24 is 4 orders of magnitude higher than the long-term average; but the absolute value remains far below one per mille. The final cost-benefit analysis adds value beyond making probabilistic forecasts: it provides objective statements that justify evacuation decisions. To deliver supportive information in a simple form, we propose a warning approach in terms of alarm levels. Our results do not justify evacuations prior to the M6.6 mainshock, but in certain districts afterwards. The ability to forecast the short-term seismic risk at any time—and with sufficient data anywhere—is the first step of personal decision-making and raising risk awareness among the public.

References

van Stiphout, T., S. Wiemer, and W. Marzocchi (2010), Are short-term evacuations warranted? Case of the 2009 L'Aquila earthquake, Geophys. Res. Lett., 37, L06306, doi:10.1029/2009GL042352.

Computationally Efficient Earthquake Detection with Continuous Seismic Waveform Data

Clara Yoon, **Ossian O'Reilly, Karianne Bergen, Gregory Beroza**

Department of Geophysics, Stanford University, United States of America; ceyoon@stanford.edu

Cross-correlating continuous seismic data streams with waveform templates has proven to be a sensitive, discriminating detector of similar seismic signals; however, template matching requires a priori knowledge of the signals we wish to detect. Detection of unknown repeating sources is possible with autocorrelation, which searches for similar waveforms within all pairs of short overlapping windows from continuous data. Unfortunately, naïve application of autocorrelation scales quadratically with time, which limits its use to short duration time series.

We developed an efficient approach to find similar seismic waveforms that avoids comparing most dissimilar signals by first developing compact, discriminative "fingerprints" of waveforms, and then assigning signals to sub-groups (buckets) using locality-sensitive hash functions (LSH). The probability that two signals enter the same bucket increases monotonically with similarity. LSH trades space for speed, requiring near-linear storage, yet yielding near-constant query time - thus avoiding nearly all of the unproductive pair-wise computation of autocorrelation. To improve detection sensitivity and reduce the likelihood of false detections, our method incorporates multiple channels of continuous data from stations in a distributed seismic network.

Our computationally efficient approach detects uncataloged earthquakes 40 times faster than autocorrelation when applied to one day of continuous data from five stations in the Northern California Seismic Network, while finding about the same total number of events. This increases to ~150 times faster for one week of continuous data. Based on observed scaling, we expect a speedup of ~10,000 times for one year of continuous data. This method will be especially useful as we look forward to processing months to years of continuous waveform data, because we can potentially find unknown seismic sources that repeat infrequently in time.

Continuous Time Random Walk (CTRW) approach on modeling anomalous (pore-pressure?) diffusion in the 2001 Agios Ioanis (West Corinth rift) earthquake swarm sequence.

Georgios Michas[1], **Filippos Vallianatos**[1,2], **Peter Sammonds**[1]

[1]University College London, United Kingdom; [2]Technological Educational Institute of Crete, Greece; georgios.michas.10@ucl.ac.uk

Induced seismicity is frequently observed in the Earth's crust as response to stress perturbations. Characteristic cases can be drawn from earthquake swarm sequences that have in many cases been associated to pore-pressure perturbations caused by fluid diffusion phenomena in the Earth's crust. In a critically stressed crust such phenomena are known to decrease the effective normal stress along pre-existing cracks and trigger earthquakes. Earthquake swarm sequences are typically characterized by strong variations and clustering effects in time and space and can neither be described by a dominant earthquake nor by any simple scaling relation, as the Omori scaling known for aftershock sequences. Here we study such a sequence that occurred on 2001 at the SW part of Corinth rift (central Greece) and its possible relation to pore-pressure diffusion (Agios Ioanis earthquake swarm, Pacchiani and Lyon-Caen, 2010). We consider earthquakes as a point process in time and space and study their spatiotemporal evolution in terms of Continuous Time Random Walk (CTRW) theory that presents joint probability density functions of inter-event times and jumps between the successive earthquakes. The spatiotemporal analysis of seismicity indicates a correlated anomalous diffusion process that migrates slowly with time. Inter-event times exhibit a broad probability distribution while jump lengths a finite variance, properties that correspond to the subdiffusive regime in terms of CTRW theory (Metzler and Klafter, 2000). In normal (Brownian) diffusion the mean squared displacement of seismicity, in regard to an initial point in time and space, will be linearly time dependent. In our case we get a power-law time dependency of the mean squared displacement that grows slower than time, indicating the anomalous (subdiffusive) process. In addition, we show that the fractional diffusion equation can be used to model the propagation of the earthquake activity with time. While other mechanisms may be plausible, the results are accordant to the hypothesis of a slow pore-pressure diffusion process as the triggering mechanism of the earthquake swarm sequence.

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CSEP-based Test Bench for Assessing Induced Seismicity Models

Eszter Kiraly[1], J. Douglas Zechar[1], Valentin Gischig[2], Dimitrios Karvounis[1], Joseph Doetsch[2], Stefan Wiemer[1]

[1]Swiss Seismological Service, Switzerland; [2]Swiss Competence Center on Supply of Electricity, Switzerland; eszter.kiraly@sed.ethz.ch

Monitoring and controlling induced seismicity in deep geothermal systems are important elements of reservoir creation and circulation phases. We propose near real-time induced seismicity modeling and forecasting to improve existing traffic light systems. A CSEP-based test bench environment for induced seismicity is being built to find the most suitable model (or model combination) for forecasting induced micro-seismicity and unexpected events in geothermal reservoirs.

In this study, we consider the Basel 2006 dataset and generate forecasts with two types of models: (1) a hydro-geomechanical stochastic seed model based on pore pressure diffusion with irreversible permeability enhancement (HySei model); and (2) four variants of a 3D "Shapiro" model which combine estimates of the seismogenic index with a spatial forecast based on kernel-smoothed seismicity and temporal weighting (SiS model). For both model groups, hydraulic and seismic parameters are calibrated against data from a learning period (starting at the beginning of injection) every six hours. We examine three different forecast time horizons: 6-hour, 1-day and 3-day intervals. We explore the forecast skills of the models using metrics developed by the CSEP community: consistency tests and pairwise ranking of the models.

Development of Seismicity Analysis software: TSEIS – ETAS module implementation -

Hiroshi Tsuruoka, Yoshihiko Ogata

Univ. Tokyo, Japan; tsuru@eri.u-tokyo.ac.jp

We usually discuss on seismic activity by selecting with region, time, depth and magnitude etc. to earthquake catalogues. So, there are many seismicity analysis tools to search, filter or analyze earthquake catalogues by using graphical user interfaces. We are developing such a tool named TSEIS on running multi platforms for 10-years. TSEIS software has many functions such as focal mechanism plotting or error plotting. In this report, we implemented ETAS analysis function to this software. In japan, earthquake predictability study of CSEP started on November 1st, 2009. It is very important to compare with real seismicity with ETAS forecasted results.

ETAS algorithm implemented to TSEIS according to the package of SASeis2006 (Ogata, 2006). ETAS analysis is non-linear inversion method. It is very important to set initial parameter values in order to start analysis. We set proper values of parameters and run a process until a solution converges automatically. Especially, we can set a time parameters by using GUI plotting M-T diagram, we can run ETAS analysis with very simple and easy procedure. In the future, we are continuing to develop TSEIS and ETAS soft wares.

Ensemble Model Earthquake Forecasts during the 2010-12 Canterbury, New Zealand, Earthquake Sequence

Matteo Taroni[1], Warner Marzocchi[1], Maximilian Werner[2], Jeremy D. Zechar[3]

[1]INGV, Italy; [2]University of Bristol, UK; [3]ETH, Zurich, Switzerland; matteo.taroni@ingv.it

Ensemble models provide at least two advantages for earthquake forecasting. Firstly, they circumvent the question of which model to choose for operational purposes by objectively and transparently merging all available ones. And secondly, the optimally merged model may provide better forecasts than any single model. In addition, complimentary or inconsistent models, hypotheses and input data sets can easily be combined according to defined rules. Our purpose here is to investigate ensemble modeling techniques in the context of the 2010-12 Canterbury, New Zealand, earthquake sequence, for which over a dozen time-dependent earthquake forecast models have been developed that are currently under evaluation by the Collaboratory for the Study of Earthquake Predictability (CSEP). The models include recently refined and developed physics-based Coulomb stress models as well as new statistical models and hybrid models that employ physics-based components within a statistical framework. Here, we explore ensemble modeling techniques to create optimal forecasts by merging all available model forecasts. The mixing of the models is determined by a dynamic, weighted average over all forecasts, where the weights are determined according to a continually updated measure of past predictive skill. The ensemble model thus changes from day to day, giving greater weight to more informative models. We compare several methods for assembling ensemble models in terms of their predictive skills during the sequence and compare the optimal models with the individual best models.

Forward Induced Seismic Hazard Assessment – FISHA Application to the seismicity catalogue generated by a discrete element hydromechanical model

Amir Hossein Hakimhashemi, Jeoung Seok Yoon, Arno Zang, Oliver Heidbach, Gottfried Grünthal

GFZ German Research Centre for Geosciences, Germany; hakim@gfz-potsdam.de

The Forward Induced Seismic Hazard Assessment – FISHA (Hakimhashemi et al. 2014a,b) is a general workflow which links the output of geomechanical-numerical models, either in terms of seismicity catalogue (Hakimhashemi et al. 2014a) or in the form of spatiotemporal changes in the stress field (Hakimhashemi et al. 2014b), to a time-dependent probabilistic seismic hazard assessment in terms of the potential time-dependent occurrence rate of the Seismic Events of Economic Concern – SEECo. SEECo refer to the seismic events of low to moderate magnitudes which may not be destructive but can cause economic losses due to damage to the infrastructure (Grünthal, 2014).

In this study FISHA is applied to a synthetic seismicity catalogue that results from a fluid injection model (Yoon et al. 2013). The model uses the Particle Flow Code 2D (PFC2D, Itasca) to simulate fluid injection in a granitic geothermal reservoir with an inclined through-going fault zone and subjected to different stress regimes (Yoon et al. poster presented in the workshop). The resulting synthetic induced seismicity catalogues include the occurrence time, the coordinated hypocenter as well as the moment magnitude for the events. These are used to calibrate the magnitude completeness Mc, as well as the parameters of the frequency-magnitude relation, i.e. a and b. Using these parameters, time-dependent occurrence rate of SEECo is computed for different stages of the injection and the potential hazard associated with occurrence of SEECo are addressed. Finally the results according to different stages of the injection are analyzed and compared in order to assess the risks associated with SEECo for different stages of the fluid injection.

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Improvement of aftershock models based on Coulomb stress interactions and rate-state dependent friction�

Camilla Cattania[1], Sebastian Hainzl[1], Lifeng Wang[2], Frank Roth[1], Bogdan Enescu[3,4]

[1]GFZ, Germany; [2]China Earthquake Networks Center, Beijing, China; [3]Earth Evolution Sciences Department, Faculty of Life and Environmental Sciences, University of Tsukuba, Tsukuba, Japan; [4]Institute of Statistical Mathematics, Tokyo, Japan; camcat@gfz-potsdam.de

The clustering properties of earthquakes have proved the most effective tool to forecast seismicity in the short and medium term (hours to months), and efforts are being made to extend the scope of these models to operational earthquake forecasting. The goal of the work presented here is to improve short/medium term physics-based earthquake forecasts.

Physical models of triggered seismicity are based on the redistribution of stresses in the crust: observations indicate a qualitatively good agreement between positive Coulomb stress changes and the location of aftershocks. Stress calculations can be coupled with the rate-and-state constitutive law proposed by Dieterich, which considers the frictional response of a population of faults and allows to calculate changes in seismicity rate. These models are known as Coulomb-Rate-and-State (CRS) models. In spite of the success of the Coulomb hypothesis, in the past CRS models performed poorly in comparison to statistical ones. In this work, we address some of the issues of CRS models, and in particular these questions: (1) how can we realistically model the uncertainties and heterogeneity of the mainshock stress field, and how does heterogeneity affect the distribution of aftershocks in space and time? (2) what is the role of time dependent stresses in the postseismic phase (afterslip and stresses from previous aftershocks)?

We focus on the aftershock sequences following the Mw 6.0 Parkfield and the Mw 9.0 Tohoku earthquakes, and quantify model performance using the log-likelihood fit to the seismic catalog. We find that a dramatic improvement in model performance is obtained by accounting for aleatoric and epistemic uncertainties in the stress field. Including stresses from aftershocks also leads to a performance improvement, while the effect of afterslip is more subtle and difficult to assess, especially in the near field region where slip model uncertainties are largest.

Insights from applying a statistical medium-term forecast model to physics based synthetic catalogues

Annemarie Christophersen[1], David A. Rhoades[1], Harmony V. Colella[2]

[1]GNS Science, New Zealand; [2]Arizona State University, School of Earth and Space Exploration; a.christophersen@gns.cri.nz

The EEPAS (Every earthquake a precursor according to scale) model is a medium-term earthquake forecasting model and currently the only model that fills the gap between long-term renewal earthquake models and short-term clustering models. The EEPAS model is based on the precursory scale increase phenomenon Ψ, which manifests itself as an increase in the magnitude and rate of minor earthquakes before most major earthquakes. The onset of the Ψ –phenomenon occurs with a precursor time that, in active seismic regions, ranges from months to decades before the major event. The precursory time seems to depend on the earthquake magnitude, and perhaps on other factors, such as strain rate.

The 2010 M7.1 Darfield, New Zealand earthquake occurred in a region of low geodetic strain rate, and without an observable precursory scale increase. Is the Darfield earthquake a rare exception to the Ψ-phenomenon, or is the historical earthquake catalogue is not long enough to detect it?

To investigate this question we use the earthquake simulator, RSQSim, in which the strain rate is represented by the slip rate on faults. A fault network representative of the crustal faults in the Wellington region was employed to generate seismicity catalogues, where the slip rates are systematically reduced by ¼ . Initial results, where the EEPAS model is fit to simulated catalogues, indicate that the precursor time is inversely proportional to the slip rate. Results support the hypothesis that the New Zealand earthquake catalogue is not sufficiently long to observe the Ψ-phenomenon for the Darfield earthquake.

Italian and Japanese Ground Motion Prediction Equations (GMPEs): Accounting for epistemic uncertainty through ensemble modeling

Pamela Roselli[1], Warner Marzocchi[1], Licia Faenza[2]

[1]Istituto Nazionale di Geofisicae Vulcanologia, Rome, Italy; [2]Istituto Nazionale di Geofisicae Vulcanologia, Bologna, Italy; pamela.roselli@ingv.it

The Ground Motion Prediction Equations (GMPEs) are meant to describe source-site propagation of seismic waves and contribute to Probabilistic Seismic Hazard Analysis (PSHA). GMPEs are presently the largest sources of aleatory variability and epistemic uncertainty. So, it is essential for PSHA a proper definition of the 'right' model in order to minimize this source of uncertainty. In this work, we describe a probabilistic method to rank GMPEs according to their forecasting performances. This ranking is useful to assign objective weights to GMPEs, and to build an ensemble model (EGMPE). We analyze in detail the probabilistic procedure for building EGMPE and we evaluate and compare the EGMPE forecasting performances with respect to the performances of each single GMPE and we quantify the impact of EGMPEs in the hazard analysis. Finally this procedure is applied to two quite different datasets, in terms of quality of data and tectonic environments (Italy and Japan), in order to explore the stability of the results as a function of these components.

Lessons from the establishment of the Operational Earthquake Forecast System in Italy

Anna Maria Lombardi

Istituto Nazionale di Geofisica e Vulcanologia, Italy; annamaria.lombardi@ingv.it

The first official Operational Earthquake Forecast (OEF) system has been developed in Italy by the new-born Hazard Seismic Center of the Istituto Nazionale di Geofisica e Vulcanologia. The establishment of this system was a unique opportunity to broaden and partially revise the knowledge about the earthquake occurrence modeling, the forecast strategies and the integration of seismic attenuation laws. The main goal of this talk is to share the key lessons learned from this experience and to discuss the potential implications for the interpretation of the system outputs.

Modelling of induced seismicity and frequency-magnitude relation in multi-stage hydraulic stimulation of crystalline geothermal reservoir

Jeoung Seok Yoon[1], Arno Zang[1], Günter Zimmermann[2], Ove Stephansson[1]

[1]Section 2.6 Seismic Hazard and Stress Field, GFZ German Research Centre for Geosciences, Germany; [2]Section 4.1 Reservoir Technologies, GFZ German Research Centre for Geosciences, Germany; jsyoon@gfz-potsdam.de

We present a numerical tool that is capable of modelling multi-stage hydraulic stimulation experiments including the process of seismic energy release as a failure process in the model formulation. The migration of viscous fluid is pressure driven and the failure of discontinuities (joints and faults) radiates seismic energy which is then converted to seismicity with magnitudes and fault plane solutions. The modelled rock mass is granitic with permeability ranging between 0.1 and 0.001 mD and the initial stress conditions represents depths of 5 km. We present the model results of five stages of hydraulic stimulation with a focus on the generated seismicity catalogue rather than the details of the hydro-mechanical implications of the results. In particular, we investigate the evolution of the frequency-magnitude distribution of the induced seismicity, i.e. Gutenberg-Richter a and b values. Preliminary results show that later stage stimulation tends to produce more induced seismicity with larger magnitude which attributes to accumulated effect of stress shadowing. Spatio-temporal variations of the a and b values are investigated to see their correlations to occurrence of large magnitude seismicity. Statistical interpretation of the Gutenberg-Richter parameters changing in time and space from this study is addressed in terms of occurrence probability of large magnitude seismicity in the paper by Hakimhashemi et al. in this workshop.

Multivariate Poisson hidden Markov Models: The case study of the North Aegean Sea, Western Greece

Katerina Orfanogiannaki[1,2], Dimitris Karlis[2], Gerassimos Papadopoulos[1]

[1]Institute of Geodynamics, National Observatory of Athens, Greece; [2]Department of Statistics, Athens University of Economics and Business; kath_orf@noa.gr

Discrete valued hidden Markov Models (HMMs) are used to model time series of event counts in several scientific fields like genetics, engineering, seismology and finance. In its general form the model consists of two parts: the observation sequence and an unobserved sequence of hidden states that underlies the data and consist a Markov chain. Each state is characterized by a specific distribution and the progress of the hidden process from state to state is controlled by a transition probability matrix. We extend the theory of HMMs to the multivariate case by assuming different multivariate distributions to describe each state of the model. At first the known multivariate Poisson distribution (MPHMMs) is considered and then copula based multivariate distributions are used to allow for full flexibility. Two copula families have been selected the Frank (HMMC-Frank) with 1 copula parameter and hence assuming similar correlation for each pair and the FGM (HMMC-FGM) that has 3 parameters allowing for more flexible structure. An EM type algorithm has been constructed to estimate the parameters of both models.

Using the extended models we monitor the development of earthquake occurrences in time, in 3 seismogenic regions of North Aegean Sea, Greece simultaneously and we estimate the correlation between the time series having a measure of the

interaction between them. It is evident that the 3 regions interact with a time difference of a few months. In most cases though it's only from one time point to the next. This migration of seismic activity from one region to the other is captured by the model as jump to states of increased seismicity. The active states are also associated with intense seismic activity individually to the 3 regions. So the model captures not only the interactions between the 3 regions but also the individual features of the 3 time series. Comparisons with different models are also considered.

On the convolution of stochastic processes for modelling strong earthquake occurrences: a multi-rupture model driven by a self-correcting model

Renata Rotondi, Elisa Varini

CNR - Institute of Applied Mathematics and Information Technology, Italy; reni@mi.imati.cnr.it

Two widely noted features of earthquake generation are the following:

- earthquakes tend to occur in clusters, sometimes, but not only, referred to as “swarms”, “foreshocks activity” and “aftershocks activity";
- the fault ruptures that generate earthquakes decrease the amount of strain present at the locations along the fault where rupture occurs.

Two different classes of models: self-exciting models and self-correcting models correspond respectively to the two features and have been widely studied separately in the literature.

Models that try to capture both these diametrically opposed features should reconcile contrasting trends. The simplest solution would be to mix stochastic models of the two classes: trigger and strain-release models (Schoenberg and Bolt, 2000); in this way, since it is unknown who belongs to what (which events are triggered and which trigger), each event is meant to be generated by both models and the normalized estimate of the conditional intensities $\lambda i/(\lambda 1+\lambda 2)$, i=1,2, indicates the percentage of events belonging to each class. The large difference between the scales, at which the triggering and strain-release mechanisms appear to operate, may be a misleading element. To overcome this issue we can assume that the different behaviours correspond to different phases of the seismic activity and the dynamics of their activation times is driven by an unobserved pure jump Markov process; in this perspective a seismic sequence can be considered as a realization of a series of three marked point processes: Poisson, stress release and trigger models (Varini, 2005, Varini and Rotondi, 2006). The comparison on simulated datasets shows that about 70% of the events are correctly classified but the model is hardly able to fit the abrupt changes of state.

This leads to think that it is more reasonable to assume that the different behavioural trends (models) are superimposed rather than consecutive. In this perspective we consider a sequence of strong earthquakes {ti, Mi}, i=1,…,n, where ti indicates the occurrence time and Mi the magnitude. Among these events we distinguish the leaders, with higher magnitude (exceeding a fixed threshold) from the subordinates, with lower magnitude. The leaders follow a stress release model; conditioned on their occurrence, the remaining events constitute a set of ordered times of minor ruptures occurring in the time interval between two consecutive leader-events. In other words, the events of I level (leaders) match the elastic rebound theory, while the events of II level (subordinates) depend on the previous ones and take charge of the other trends.

A preliminary application to data from an Italian seismogenic source is shown.

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Optimal short-term earthquake forecasts based on ULF seismo-magnetic data

Peng Han[1], Katsumi Hattori[1], Jiancang Zhuang[2]

[1]Chiba University, Japan; [2]Institute of Statistical Mathematics, Tokyo, Japan; hanpeng407@gmail.com

Our previous statistical studies have indicated that the ULF seismo-magnetic phenomena contain precursory information and can be useful in short-term forecasting of sizable earthquakes. In practice, for given series of precursory signals and related earthquake events, the efficiency of forecast is a function of the leading time of alarms (Δ) and the length of alarm window (L). To find out the best prediction strategies, Molchan’s error diagram has been employed. The same as our previous study, we utilized geomagnetic data and earthquake events registered in Kakioka (KAK), Japan during 2001-2010. Ratios of observed energy to modeled background are applied to indentify precursory signals. A modified area skill score, which measures the area between actual prediction curve and random prediction line, is introduced to assess the efficiency of different prediction strategies. The results indicate that ULF magnetic data of KAK contains higher precursory information when Δ is around 1 or 2 weeks and L is less than 2 weeks; the optimal strategy of short-term forecasts is: Δ =8 days, L =1 day. The methodology proposed in this study could help to evaluate and find the optimal policy of other different measurements for short-term earthquake forecasting. The best combination of all available observations may provide better forecasting results and is worth further study.

Probabilistic, non-linear relocation of the 1980-2014 Southern Californian seismicity

Yavor Kamer[1], Guy Ouillon[2], Edi Kissling[1], Didier Sornette[1]

[1]ETHZ, Switzerland; [2]Lithophyse, France; yaver.kamer@gmail.com

Earthquake catalogs are the single most essential element in the study of earthquake phenomena within seismology. They provide the origin time, location and magnitude information that constitute the basis for earthquake interaction analysis as well as for earthquake forecasting models based on physics and statistics. The information quality of earthquake catalogs has been improving together with the detection capabilities of the seismic networks. Smaller and smaller earthquakes are being detected and the location accuracy continues to improve as the coverage and density of seismic stations increases. Additionally, new relocation techniques, such as the double difference methods, have been introduced to further constrain the initially determined hypocenters. These techniques work under the assumption that waveform similarity is an indicator of a common source point. Cross-correlation coefficients of individual waveforms and proximity of initial hypocenters are used to cluster events that are then relocated jointly to reduce the arrival time residuals. The resulting catalogs feature linear structures (streaks) of tightly grouped hypocenters that are often associated with fault geometries.

Apart from being dependent on several parameter choices, studies have demonstrated that double-difference methods result in biased relocations in the presence of velocity model errors. In our analysis of the Southern Californian seismicity catalog (relocated with a double difference method), we observe that the majority of events are displaced far beyond their initially reported location error margins. Furthermore, multifractal analysis of the relocated catalog indicates the presence of a scaling break at 2.5km that coincides with the minimum distance criterion used in the initial clustering of events.

These observations, together with the inevitable need for a consistent catalog, have motivated us to locate the Southern Californian seismicity using the state of the art probabilistic and non-linear method NonLinLoc. For this purpose, we obtained all individual waveforms from the Southern California Earthquake Data Center (SCEDC). We use only the P picks in order not to introduce the velocity model errors of the S phase, which is harder to detect and thus less constrained. To assess the picking time uncertainty associated with each pick and to detect possible biases, we re-pick all the ~20 million waveforms using an automatic broadband picker (FilterPicker). This automatic picker is trained for each station to account for the different site conditions. Using a subset of the best quality picks and the most well recorded earthquakes, we then conduct a joint inversion using the Velest software to obtain a minimum 1D velocity model and station corrections. With this 1D velocity model and the obtained picks, we use the NonLinLoc software to obtain realistic location distributions for each event. To account for the velocity model error, we repeat the location procedure several times by perturbing the velocity values. We compare the resulting catalog with the current state of the art catalogs obtained using double difference methods.

Relationship between skewness and kurtosis for characterizing seismic excitations in Corinth Gulf (Greece)

Maria Mesimeri[1], Vassilios Karakostas[1], Eleftheria Papadimitriou[1], George Tsaklidis[2]
[1]Geophysics Department,Aristotle University of Thessaloniki, Greece; [2]Department of Statistics and Operational Research, Aristotle University of Thessaloniki,Greece; mmesimer@geo.auth.gr

Seismic excitations occur as mainshock-aftershock sequences (MS-AS) associated with a strong event called mainshock, or as earthquake swarms when a distinctive main event is absent. In regions, as our study area, where seismicity is manifested with a large number of small in magnitude events is important to distinguish MS-AS from earthquake swarms for providing information on the physical process of earthquake generation and seismic hazard assessment. For this purpose, a highly accurate local earthquake catalog was compiled and an effort was made for clusters identification after establishing certain criteria on spatio-temporal properties of seismicity. The skewness and kurtosis of moment release history were calculated for each cluster considering the normalized time of every event in a cluster since the starting time of the cluster and its seismic moment. For MS-AS we found large positive values for skewness and kurtosis contrary to earthquake swarms that exhibit negative to lower positive values of skenweness and lower positive values of kurtosis. The parabolic relationship that is derived between skewness and kurtosis is examined along with its symmetry as an additional indication for distinguishing MS-AS from earthquake swarms.

Retrospective forecast of ETAS model with daily parameters estimate

Giuseppe Falcone[1], Maura Murru[1], Rodolfo Console[1,2], Warner Marzocchi[1], Jiancang Zhuang[3]
[1]Istituto Nazionale di Geofisica e Vulcanologia, Italy; [2]Center of Integrated Geomorphology for the Mediterranean Area, Italy; [3]The Institute of Statistical Mathematics, Japan; giuseppe.falcone@ingv.it

After the 2011 Tohoku-Oki earthquake the Collaboratory for the Study of Earthquake Predictability in Japan provided an appropriate test for the five 1-day models submitted. Of all the models only one was able to predict the number of events that really happened. This result was verified using both the catalog in real time and the revised one.

The main cause of the underestimation of the forecasted events was due to fixed model parameters during the test. The absence in the learning catalog of an event similar to the Tohoku-Oki and the magnitude of the mainshock, which drastically changed the seismicity in the area, make the learning parameters not suitable to describe the real seismicity. In this work we present a retrospective ETAS (Epidemic Type of Aftershock Sequence) model based on the daily updated parameters before and during the sequence. We present the evolution of the parameters during the last two seismic sequences in Italy: the 2009 L'Aquila and the 2012 Reggio Emilia. The performance of this model is compared with that of similar models where the parameters remain fixed during the test time.

Seismic Hazard Assessment in Corinth Gulf (Greece) via a Moment Release Model

Ourania Mangira, Georgios Tsaklidis, Eleftheria Papadimitriou, Irene Votsi
Aristotle University of Thessaloniki (AUTH), Greece; ouraniamg@gmail.com

The linked stress release model is based on the deterministic increase of stress within a region and its stochastic dissipation due to earthquakes. Stress transfer and interaction are observed between different regions. In order to study the long-term probabilistic seismic hazard of the Corinth Gulf, an area that accommodates high seismicity, the whole area is divided into two distinct subregions, namely Western Gulf of Corinth and Eastern Gulf of Corinth, based on their seismotectonic features. We review the genesis of the simple and the linked stress release model and we propose a new version of the linked stress release model, where interaction between the two subregions is studied through moment transfer. Point process theory is applied by means of the conditional intensity function. In the model proposed, the conditional intensity function has the form of the exponential distribution. The results demonstrate that the moment release model fits adequately the dataset and evidence the existence of interaction between the two subregions. We then apply the "original" linked stress release model and compare the results between the two models. Finally, we examine the application of a moment release model where the hazard function for the interevent times between successive events is that of Weibull function.

Seismic Parameters Variations for Iran and Its Vicinity

Mona Salamat, Mehdi Zare

International Institute of Earthquake Engineering and Seismology, Iran, Islamic Republic of; salamat.mona@gmail.com

This article concerning the spatial evaluation of seismic parameters along Iran and its vicinity. For this purpose, the composite earthquake catalogue has been collected from different national and international earthquake banks which data set spanned nearly 213 years (1800-2013). The seismicity of the whole area and its neighboring region were divided into 87 nodes at equal square area of 2° lat. × 2° long. Seismicity data in each square is combined to calculate seismic activity. In the first step, earthquake catalogue was de-clustered by Gardner & Knopoff (1974) method and in the next step; each sub region was evaluated for its completeness. Based on completeness test of STEPP (1972), the catalogue was separated into complete and extreme parts. Using Kijko & Sellevol (1989) which applied information in the complete and extreme parts of the catalogue, seismic parameters b-value, λ and maximum expected magnitude Mmax were estimated. Spatial variation of these hazard parameters were assembled in each region and final results were shown in the form of contours.

Seismicity properties revealed by stochastic means: Application in Corinth Gulf and Mygdonia Basin (Greece) seismic zones

Charikleia Gkarlaouni[1], Stanislaw Lasocki[2], Eleftheria Papadimitriou[1]

[1]Geophysics Department, Aristotle University of Thessaloniki, Greece; [2]Institute of Geophysics, Polish Academy of Sciences, Warszawa, Poland; hara.gkarlaouni@gmail.com

Seismicity parameters are estimated from a wide range of methodologies and techniques, and are engaged to decipher properties of seismogenesis and seismotectonics in a specific area. For revealing the hidden characteristics of the seismicity process, descriptive analysis tools are lately reinforced with the adoption of stochastic means. For this purpose the variation and distribution of parameters expressing time, space and size characteristics of the seismic process are treated as independent time series and are investigated by stochastic means. This kind of analysis is performed for two seismogenic units of the extensional back arc Aegean region, namely the Corinth rift and Mygdonian graben. The analysis revealed a significant long memory content in the seismic process, especially for the lapse time between consecutive events of recent micro seismicity and moderate earthquakes. When data sets of strong earthquakes were examined, both from historical and instrumental catalogs, a different pattern of dependence was observed. The heterogeneity and the evolution incorporating in the seismicity properties of both areas does not possess a totally random behavior, but rather exhibits a strong dependency between past and future events with a fluctuating degree through time. Temporal and spatial variations of the Hurst exponent seemed to be associated with seismicity bursts. The significance of the memory content lies in the better understanding of the way the seismogenic sources activate, interact and influence the strong events occurrence. (This work is co–financed by the European Union (European Social Fund – ESF) and Greek national funds through the Operational Program "Education and Lifelong Learning" of the National Strategic Reference Framework (NSRF) – Research Funding Program: Heracleitus II. Investing in knowledge society through the European Social Fund.

Seismicity simulation in Ordos region of China based on the fault interactions and hazard assessment

Xin Jin, Shiyong Zhou

School of Earth and Space sciences, Peking University, China, People's Republic of; jinxinkid@126.com, zsy@pku.edu.cn

Seismicity over 10000 years in Ordos region of China has been simulated based on the mechanical synthetic seismicity model we developed. There are 26 faults in Ordos region. We developed the model Zhou built in 2008, so that it can simulate a model more fault cells. So we can simulate earthquakes of lower magnitude in this region. Histogram of the inter event time of simulated strong earthquake with Ms≥6.5 for the whole region is very close to Poisson model. We illustrate the distribution of intervals for Ms≥6.5 of each fault to see the seismicity of each fault. We use some weight coefficients determined by attenuation relationship of the region to simulate the hazard of one point in the region. In this way, we can assess the seismic hazard of each city in the region and build an earthquake hazard map of this region. Our result can be used to calculate the coupons and principal payments of catastrophe bonds. I would like to express my gratitude to Shiyong Zhou, my supervisor, for his model and all the suggestion he gave me. I also wish to thank Zengping Wen for the attenuation relationship model and Gareth Peters, Lucas Tian for the CAT bond model.

Short-term earthquake risk assessment considering time-dependent b-values

Laura Gulia, Thessa Tormann, Stefan Wiemer, Marcus Herrmann

Swiss Seismological Service, ETH, Zurich, Switzerland; lgulia@ethz.ch

Laboratory experiments highlight a systematic b-value decrease during the stress increase period before the main event. Many large natural events showed a precursory decrease in the b-value. Short-term forecast models currently consider the generic probability that an event can trigger subsequent seismicity in the near field. While the probability gain of a stationary Poissonian background is substantial, selected case studies have shown through cost-benefit analysis that the absolute probability remains too low to warrant actions.

We here analyze the probability gain of estimating forecasting model parameter values in real-time and then generating forecasts calibrated on the seismicity evolution (changes in the seismicity rates and b-value). We first present the case study of L'Aquila: by translating changes in earthquake probability into time-varying hazard and risk, we show that the precursory b-value decrease in the weeks preceding the mainshock results in an additional probability increase of a M6.3 event by a factor of 30-50—surpassing the cost-benefit threshold for short-term evacuation. This case study, along with similar findings for the M2011 M9 Japan megathrust events, suggests that short term forecast models which consider temporal changes in b-values should be systematically evaluated. We are currently performing this evaluation using data from a wide range of well monitored sequences.

Spatial Analysis of Earthquake Frequency-Magnitude Distribution at Geothermal Region in the South of Bandung, West Java, Indonesia

Dicky Ahmad Zaky[1], Andri Dian Nugraha[1], Mohammad Rachmat Sule[1], Philippe Jousset[2]

[1]Faculty of Mining and Petroleum Engineering, Bandung Institute of Technology, Indonesia; [2]Helmholtz Centre Potsdam GFZ German Research Center for Geoscience, Germany; d.ahmad.zaky@gmail.com

High geothermal potential lies on the Quaternary volcanic complex in the south of Bandung. Seismic network with 48 stations in total was setup within these geothermal regions. During 8 months of recording, we manually identified more than 600 local earthquakes with more than 4752 P-wave and 4589 S-wave arrival time phases. Result from Joint hypocenter and 1D velocity inversion shows 3 seismic clusters which is correspond with Mt. Kencana, Wayang Windu and Darajat geothermal field. Local magnitude (Ml) was determined by general inverse calculation, involving simultaneous determination of magnitude, stations correction and two constant express variation of amplitude as function of distance. Automatic coda duration estimation is also performed to facilitate the calculation of duration magnitude (Md). The Ml calculation result show that the values are in the range of 0.12 to 2.9. We performed a spatial analysis of earthquake frequency-magnitude distribution for the whole data set. High b-values ~1.1+/- 0.09 and ~1.02 +/- 0.07 are associated with the Darajat and Wayang Windu seismic clusters, respectively Lower b-values (~0.838 +/- 0.08) are associated with Mt. Kencana cluster. We interpret the low b-values as a result of higher stress condition due to tectonic stresses, whereas higher b-values observed in Darajat and Wayang Windu clusters are interpreted as resulting from lower stress condition due to hot fluid in the geothermal production areas. Those results suggest that the Mt. Kencana cluster does not involve hot fluids.

Spatiotemporal variations of faulting regimes and source parameters of induced seismicity at The Geysers geothermal field

Patricia Martínez-Garzón[1], Grzegorz Kwiatek[1], Hiroki Sone[1], Marco Bohnhoff[1], Georg Dresen[1], Craig Hartline[2]

[1]GFZ Potsdam, Germany; [2]Calpine Corporation, Middletown, California; patricia@gfz-potsdam.de

Spatial, kinematical and magnitude characteristics of induced seismicity occurring at different fluid-injection rates are investigated using a high-resolution hypocenter catalog of a prominent cluster of induced seismicity at the northwestern part of The Geysers geothermal field, California.

Studying the characteristics of this seismicity cluster, we find that during peak-injections seismicity occurs at greater distances from the injection well, mainly aligned with the orientation of the maximum horizontal stress. In contrast, during lower injection rates seismicity concentrates closer to the injection well. Analysis of focal mechanisms and stress field shows that during high injection rates the percentage of strike-slip and/or thrust faulting events increases, the orientation of the principal stress axis moves aproximately 20° and the seismic moment released by the strike-slip events is higher on average than that of normal faulting events. The b value decreases during peak-injections, suggesting the increase in differential stresses at the reservoir during these periods.

It is here suggested that the observed differences in the seismicity characteristics at different injection rates could be related to variable influence of physical mechanisms inducing seismicity. Prior to peak-injections, the seismicity might be predominantly connected with the thermal fracturing of the reservoir rock given the high encountered reservoir temperatures. However, during peak injections, the limited pore pressure increase around the open hole section (~1MPa) may play a significant role. By estimating the reservoir permeability and the characteristic diffusion lengths of the heat and the pressure, we confirm that the pore pressure reaches significantly greater distances from the injection well than the heat diffusion.

Statistical properties of microearthquakes induced by hydraulic fracturing

Samira Maghsoudi[1,2], Jörn Davidsen[2], David Eaton[1]

[1]Department of Geoscience, University of Calgary, Canada; [2]Department of Physics and Astronomy; samira.maghsoudi@ucalgary.ca

Permeability-enhancing treatments such as hydraulic fracturing induce microseismic events with reported magnitudes in the range of -3.0 to -0.5 though significantly larger earthquakes up to magnitude 4.4 have been reported very recently as well. Essentially the diffusion of pore pressure is responsible for the initial activation of seismicity in hydraulic fracturing. Understanding the specific primary and secondary triggering mechanisms in hydraulic fracturing could potentially help us learn more about subsequent properties such as stress, strength of faults and rupture initiation and propagation. Knowledge of the underlying physical mechanisms behind triggering can lead to significant progress in earthquake hazard assessment and forecasting. There is a growing interest in understanding risks and hazard associated with hydraulic fracturing earthquakes, especially in the areas where earthquake large enough to be felt were rare. In order to estimate the probability of further large and potentially damaging events during and after stimulation, the seismic hazard associated with hydraulic fracturing needs to be studied. Analyzing and forecasting the seismicity during hydraulic fracturing is an important step towards time-dependent seismic hazard assessments. Here, we present results on the statistical characteristics of microseismic catalogues in order to identify more specific details about fracture mechanics during hydraulic fracturing treatments. We also investigate possible options for more reliable seismic hazard assessment in hydraulic fracturing based on statistical methods used to forecast seismic aftershock sequences such as Epidemic Type Aftershock Model. Combining statistical and physical models, the ultimate goal is to determine the evolution of microseismicity, including forecasts for seismicity rates and expected intensities.

The medium-term seismic hazard model for Italy

Licia Faenza[1], Warner Marzocchi[2], Pamela Roselli[3], Giuseppe Falcone[4], Matteo Taroni[5]

[1]INGV, Italy; [2]INGV, Italy; [3]INGV, Italy; [4]INGV, Italy; [5]INGV, Italy; licia.faenza@ingv.it

The aim of this project is the quantification of the seismic hazard in the medium-term for Italy within the INGV Seismic Hazard Center (Centro di Pericolosità Sismica – CPS). The medium-term models represent the transition between short-term models, characterized by Omori-Ustu cluster occurrence, and the long-term ones that are mainly based on time-independent processes. In the first case, the forecasting time window is of a few days / weeks, whereas in the latter case the time window is usually tens of years. The long-term model constitutes the basic ingredient for the seismic hazard estimates and it is related to the definition of the national seismic code. The medium-term models fill the gap between these two time intervals with time windows ranging

from a few months (e.g., six months) to a few years (e.g., 5 years). Besides the pure scientific aspects we also explore the needs of a wide range of potentially interested stakeholders, such as citizens, the media, decision makers of civil protection or municipalities, and the formats that may satisfy these needs.

At this early stage, we rely exclusively on models subjected to EU CSEP Testing Center. The choice to use only these models is motivated by the need to have models already reviewed and accepted by the scientific community and with homogeneous data input and output. This last aspect is crucial to be able to compare and combine the results of the various models.

Our strategy consists in the weighting different hazard models in order to create an ensemble model. Noteworthy, the ensemble model is meant to describe the aleatory variability and the epistemic uncertainty in a consistent way. In particular, we describe in detail how this ensemble model is built merging different models of earthquake rate and GMPEs. Finally, we discuss some examples showing the forecasting performances of the ensemble model with respect to each single model.

The simplest probabilistic model for spatial forecasting of earthquake locations

Álvaro González

Universidad de Zaragoza, Spain; Alvaro.Gonzalez@unizar.es

Earthquakes usually occur at, or close to, the locations of past earthquakes, reflecting the underlying geometry of the fault system which generates them.

The limits of such a fact are debated, though, particularly when just the few largest earthquakes are regarded. The largest earthquakes in slowly-deforming continental interiors might not typically occur at the same sites, and great earthquakes along plate boundaries might fill the gap between previous ones, rather than overlapping with them.

There is no agreement either about how to properly extrapolate past earthquake locations to estimate spatial probabilities of future ones (the most frequent procedures being uniform-probability seismogenic zones, and power-law or Gaussian smoothing kernels).

This work defines, and successfully tests, a probabilistic spatial forecast for earthquake locations, which is arguably the simplest, most parsimonious one (beyond a uniform probability model). It also sheds light on how many past earthquakes are required for calculating meaningful spatial probabilities of future ones.

Namely, the procedure simply assumes that the next earthquake in a series will follow the same spatial distribution of past earthquakes in the region considered. Instead of proposing a parametrized smoothing kernel, it uses the empirical distribution function of nearest-neighbour distances between earthquakes. In particular, the following statement should hold: "If a percentage p of n previous epicentres (with $n \to \infty$) have their respective nearest-neighbours at a distance ≤ d, then, conversely, with probability p the next epicentre will occur at a distance ≤ d from its nearest one."

This allows calculating, after each earthquake, a spatial probability map for the next earthquake. The map is then tested against the location of this new event. And the procedure is repeated, updating the map after each earthquake in a complete catalogue.

Such maps have been tested in real time during more than five years in the Southern California Earthquake Centre, under the Collaboratory for the Study of Earthquake Predictability (cseptesting.org). The maps are automatically updated daily, and tested reproducibly, for California, NW and SW Pacific, and worldwide seismicity. The procedure was also tested retrospectively, using tens of thousands of relocated earthquakes in Southern California and the whole Earth.

The tests are remarkably successful for all the regions analysed. That is, the percentage of earthquakes occurring in the areas above each probability threshold is very similar to the expected one. The maps improve with time, delineating high-probability areas with increasing precision as new earthquakes happen.

It is observed that typically at least a few hundred past earthquakes are required for the map to achieve the desired forecasting skill. Such behaviour results from the complex spatial distribution of seismicity, and can be reproduced using simulated distributions of points (fractal or multifractal). This explains why meaningless spatial probabilities may result if only the few largest earthquakes are taken into account. It is thus argued that small earthquakes should be regarded with equal weight as the larger ones for better delineating the spatial distribution of seismicity.

Understanding completeness of the New Zealand prehistorical earthquake record: Do we forecast too many events on too few faults?

Matthew Gerstenberger[1], Andy Nicol[2], Russ Van Dissen[1], Mark Stirling[1], Will Ries[1]

[1]GNS Science, New Zealand; [2]University of Canterbury, New Zealand; m.gerstenberger@gns.cri.nz

Moderate to large magnitude earthquakes in the Canterbury (2010-2011) and Cook Strait (2013) sequences caused significant damage, yet ruptured active faults that were not previously known to exist. These earthquakes fuel questions about how many unmapped active faults have the potential to generate future damaging earthquakes and how best to accommodate these in the New Zealand National Seismic Hazard Model (NSHM). Historical moderate to large magnitude earthquakes since 1840 have been analysed to estimate the likelihood of rupture occurring on hidden active faults that are not explicitly accounted for in the NSHM. We consider 105 shallow earthquakes (≤25 km focal depth) with magnitudes Mw 5-8.2 that were located onshore or ruptured faults that extend onshore (e.g., Napier 1931 Mw 7.8 earthquake). Given the relatively short duration of the historical record and the rates of seismicity over this time interval, the number of earthquakes considered is small and only permit first-order conclusions. About half of all historical earthquakes Mw ≥ 7.0 ruptured active faults that based on today's state of knowledge would have been mapped. For the most part, the remaining 50% of historical events on 'unmapped' active faults either did not displace the ground surface or were located in areas where the rates of erosion/burial exceed fault-slip rates. Incompleteness of active faults in the NSHM is greatest for earthquake sources with long recurrence intervals of ≥10 kyr. Historical earthquakes of Mw ≥ 6.5 on faults with recurrence intervals of ≥10 kyr are about 10 times more frequent than predictions based on NSHM fault sources with the same magnitude and recurrence interval ranges. Several hundred additional unmapped active faults capable of generating Mw ≥ 6.5 earthquakes with recurrence intervals of ≥10 kyr are necessary to reconcile the historical earthquake catalogue and NSHM earthquake

sources. These inferred unmapped active faults are capable of generating earthquakes up to magnitude Mw ~7.8 and, in many cases, will be located in low strain rate areas where they are expected to make an important contribution to the seismic hazard.

A pattern recognition algorithm for early characterization of seismic clusters in Italy

Stefania Gentili[1], Rita Di Giovambattista[2]

[1]Istituto Nazionale di Oceanografia e di Geofisica Sperimentale - OGS, Italy; [2]Istituto Nazionale di Geofisica e Vulcanologia - INGV, Italy; sgentili@inogs.it

In this study, we propose an analysis of the earthquake clusters occurred in Italy from 1960 to 2014. In particular, given a strong earthquake of magnitude M, we are interested to identify statistical clues to forecast whether a subsequent strong earthquake will follow. The reasons for this study are essentially two:

1. From the theoretical point of view, this information can be useful for a deeper understanding of the statistical properties of the earthquake clusters and/or to infer a physical model of the process leading or not to a swarm.

2. From the practical point of view, a large aftershock following a main shock can cause significant damages on already weakened buildings and infrastructures: a deeper knowledge of the post-main shock sequence can be important from the civil protection point of view.

Vorobieva et al. (1993) and Vorobieva (1999) proposed the subdivision of strong earthquakes into two classes: if given a main shock of magnitude M, the subsequent earthquake inside a given space and time window has magnitude ≥M-1 the strong earthquake is of type A, otherwise is of type B. We extend this concept to clusters: clusters of type A include at least one event of type A, clusters of type B otherwise.

We propose a pattern recognition approach to characterize clusters of type A or B. The analysis has been done using decision trees as classifiers and k-fold cross validation to evaluate performances. Vorobieva proposed a method to classify mainshocks as of type A or B using a time window starting 10 days after the mainshock. However, our analysis suggest that the 74% of strongest aftershocks in clusters of type A occur within 10 days from the mainshock. We propose to use some of the features of the Vorobieva method using a shorter time lapse.

In addition, we propose a set of original features to characterize a different behavior in several seismic parameters for clusters of type A or type B. In particular, we investigate the temporal evolution of the radiated energy, the spatio-temporal distribution of the immediate foreshocks including a detailed analysis of the dimension and shape of the region of preparation of the strong earthquake, the spatio-temporal evolution of the aftershocks occurring within a few days.

Finally, we examine the spatial distribution of the two types of clusters inside the Italian territory.

Spatial Variation on Earthquake Recurrence Time Distribution in Japan

Shunichi Nomura

Tokyo Institute of Technology, Japan; nomura@is.titech.ac.jp

Large earthquakes often occur repeatedly in the same region of plate boundaries or active faults. These earthquakes recur by a cyclic mechanism where stress at a hypocenter is accumulated by tectonic forces until an earthquake occurs and releases the accumulated stress to a basal level. Therefore, renewal processes, point processes in which intervals between consecutive events are independent and identically distributed, are frequently used to model this repeating earthquake mechanism and forecast the next earthquakes. However, one of the difficulties in applying recurrent earthquake models is the scarcity of the historical data. Most studied fault segments have few, or only one observed earthquake that often have poorly constrained historic and/or radiocarbon ages. The maximum likelihood estimate from such a small data set can have a large bias and error, which tends to yield high probability for the next event in a very short time span when the recurrence intervals have similar lengths.

On the other hand, recurrence intervals at a fault depend on the long-term slip rate caused by the tectonic motion in average. In addition, recurrence times are also fluctuated by nearby earthquakes or fault activities which encourage or discourage surrounding seismicity. These factors have spatial trends due to the heterogeneity of tectonic motion and seismicity. Thus, this talk introduces a spatial structure on the key parameters of renewal processes for recurrent earthquakes and estimates it by using spatial statistics. Spatial variation of mean and variance parameters of recurrence times are estimated in Bayesian framework and the next earthquakes are forecasted by the Bayesian predictive distributions. The proposal model is applied for recurrent earthquake catalog in Japan and its result is compared with the current forecast evaluated by the The Headquarters for Earthquake Research Promotion of Japan.

Forcasting - Part4: New Perspectives in Probabilistic Earthquake Forecasting and Testing

Time: Wednesday, 17/Jun/2015: 5:00pm - 6:00pm · *Location:* Arcona Hotel, Havelpavillon
Session Chair: David Diether Jackson

Testing probabilistic seismic hazard estimates against accelerometric data in two countries: France and Turkey

Hilal Tasan, Céline Beauval, Agnès Helmstetter

ISTerre, France; celine.beauval@ujf-grenoble.fr

Probabilistic seismic hazard models (PSHM) are used for quantifying the seismic hazard at a site or a grid of sites. Testing PSHA at a given site is not possible as very long observation time windows would be required (several hundreds of years at minimum). However, sampling in space can compensate short observation time windows. In the present study, a methodology is proposed to compare the distribution of the expected number of sites with exceedance with the observed number, considering an acceleration threshold at a set of recording sites. The method is applied to France and Turkey. The French accelerometric database (16 years duration) is used, as well as a synthetic dataset inferred from an instrumental catalogue (duration 34 years) combined with a ground-motion prediction equation. Results can only be drawn for very low acceleration levels (below 40 cm.s-2) or short return period (smaller than 50 years). For such levels, the two reference models for France (MEDD2002 and AFPS2006) seem to over-estimate observations. For larger acceleration levels, there are few observations, if any, and no conclusion can be drawn. In Turkey, the SHARE hazard estimates can be tested against ground-motion levels of interest in earthquake engineering. As the completeness issue is crucial, the recorded data at each station is analyzed to detect potential gaps in the recording. As most accelerometric stations are located on soil, accelerations at rock are estimated using a site-amplification model. Different minimum inter-site distances and station configurations are considered. The observed numbers of sites with exceedance are well within the bounds of the predicted distribution for accelerations between 103 and 397 cm.s-2. For higher levels, no conclusion can be drawn.

Comparing USGS NSHMs with DYFI observations

Sum Mak, Danijel Schorlemmer

GFZ German Research Centre for Geosciences, Germany; smak@gfz-potsdam.de

Verifying a nationwide seismic hazard assessment using data collected after the assessment has been made (i.e., prospective data) is a direct consistency check of the assessment. We directly compared the predicted rate of ground motion exceedance by the four available versions of the USGS national seismic hazard map (NSHM, 1996, 2002, 2008, 2014) with the actual observed rate during 2000-2013. The data were prospective to the two earlier versions of NSHM. We used three sets of somewhat independent data, namely 1) the USGS "Did You Feel It?" (DYFI) intensity reports, 2) ShakeMap gridded ground motions, and 3) instrumental ground motion records extracted from ShakeMap stations. The first two were not strictly observations but models calibrated by observations. The third was true observation but the amount of data is limited.

Our results indicated that for California, the predicted and observed hazards are very comparable. Discrepancy lied generally on the safe side (i.e., predicted hazard not lower than the observed one). The three sets of data gave consistent results, implying robustness. The consistency also encourages the use of DYFI and ShakeMap data for hazard verification in the central and eastern US (CEUS), where instrumental records are lacking. The result showed that the observed ground-motion exceedance was larger than the predicted in CEUS, implying a possible underpredicted hazard.

The primary value of this study is to demonstrate the usefulness of DYFI and ShakeMap data, originally designed for community communication instead of scientific analysis, for the purpose of hazard verification. The large discrepancy between the observed and predicted gorund-motion exceedance in CEUS implied that either the ground motions were not described correctly by DYFI and ShakeMap for the region, or the hazard was actually underestimated. Induced seismicity could be the cause of this underestimation.

How much spatio-temporal clustering should one build into a risk model?

Delphine Danielle Fitzenz

RMS, United States of America; delphine.fitzenz@rms.com

A lot of attention was given to earthquake sequences in the past few years, in particular due to the 15 loss-causing events (EQC) of the Canterbury sequence. This hinted at a need beyond the long-term view of earthquake risk in which all events are assumed to be independent provided by current models.

In this contribution 1) we aim to assess through simulation of time series the level of clustering implied by source models in current risk models of “independent” events. Then 2) we investigate how to infer joint probabilistic recurrence models for systems of nearby faults from trench and catalog data and how that might complement current forecast techniques that aim for a medium-term to long-term applicability. Indeed, if probability density functions for event dates on nearby faults always overlap, it indicates that they should be inverted jointly for the behavior of the system and also that it would have a more powerful forecasting power to do so than to consider either one or the other as an aftershock. 3) Although it is obvious how important those spatio-temporal informations would be for risk models, i.e., to assess the accessibility of a region (e.g., for lifeline-related business interruption, supply-chain studies, mobility of people and resources), optimal reconstruction strategies, etc., we show the challenging feedback loops that would be required to fully take advantage of them. Those include models for progressive damage, valuation of buildings, reconstruction and re-zoning polices and would lead to quantitative and time-varying probabilistic risk estimates, which is not a concept welcome by underwriters in general, except after a major event.