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Nr.

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 CL3/Veld/wingpl/onsh/Groningen  
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**Datum**  
4 april 2016

**Onze referentie**  
AGE 16-10.024

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**Onderwerp**

Literatuurstudie seismologisch model Groningen

Geachte heer van der Meijden,

In antwoord op uw vraag per e-mail d.d. 26 januari 2016 om een korte literatuurstudie met als onderwerp het seismologisch model Groningen bijgaand onze resultaten.

De resultaten bestaan uit enerzijds een literatuurlijst met geraadpleegde literatuur (bijlage A) en een korte samenvatting per artikel (bijlage B). Deze literatuurstudie richt zich specifiek op die artikelen en andere literatuur, welke (inter)nationaal beschikbaar zijn in het publieke domein en inzicht geven in mogelijke alternatieven voor het huidige seismologisch model van het Groningen veld.

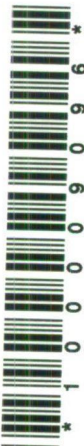
Hopend u hiermee van dienst te zijn geweest.

Hoogachtend,

 Dr. I.C. Kroon  
Hoofd Adviesgroep Economische Zaken

Op opdrachten aan TNO zijn de Algemene Voorwaarden voor opdrachten aan TNO, zoals gedeponeerd bij de Griffie van de Rechtbank Den Haag en de Kamer van Koophandel Den Haag van toepassing. Deze algemene voorwaarden kunt u tevens vinden op [www.tno.nl](http://www.tno.nl).  
Op verzoek zenden wij u deze toe.

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## Bijlage A

Authors	Subject
Allmann, B.P. and Wiener S. (2014)	The authors have simulate induced seismicity (within an application for geothermal reservoir) using pressure-driven stress changes and seismicity triggering based on Coulomb friction.
Bachmann C.E., S Wiemer, Goertz □ Allmann B.P. (2012).	The authors report a geomechanical model with random distribution of stress and seeds that was able to model spatiotemporal evolution of effective stress based on a linear diffusion model in a hydraulically homogenous and isotropic medium with a linearly increasing pressure source.
Gaucher E. et al. (2015)	Review paper regarding different modelling approaches in forecasting induced seismicity in geothermal reservoirs
Hazzard, J.F. and Young, P.R. (2002)	In this paper a numerical modelling approach that simulates cracking and failure in rock and the associated seismicity is presented. A technique is described for quantifying the seismic source mechanisms of the modelled events.
Holliday et al. (2005)	In this paper the authors discuss an approach to earthquake forecasting based on a pattern informatics (PI) method which quantifies temporal variations in seismicity.
Holliday J.R., Turcotte D.L. and Rundle J.B. (2008)	A review of statistical models based on observed seismicity. The ETAS (epidemic type aftershock sequence) model and BASS (branching aftershock sequence) model.
Hori H. and Oike K. (1996)	Authors investigated the temporal variation of seismicity in Japan using a statistical model based on Ogata and Katsura (1985)
Jiménez A., K.F. Tiampo and Posadas A.M. (2007)	This paper focuses on extracting the information contained in seismic space-time patterns and their dynamics.
Jiménez, A. (2013)	The author models each part of the lithosphere as a cell that is constantly communicating its state to the environment. In this study this approach is used to the quantify this communication, with the aid of the Information Theory, and model seismicity as a complex network.
Lahaie, F and Grasso J.R. (1999)	Authors analyzed fracturing patterns in a gas reservoir in correlation with gas production rate. The authors hypothesize that the loading rate on the reservoir due to production has an effect on b an D parameters.
Langenbruch C.	Authors investigate the impact of elastic heterogeneity

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and Shapiro S.A , 2013	of the Earth's crust on Coulomb stress distribution and earthquake magnitude scaling. They propose that the Gutenberg-Richter relation originates from Coulomb stress fluctuations caused by elastic rock heterogeneity
McGarr A. (2014)	Review paper regarding the maximum possible magnitude of induced earthquake caused by fluid injection.
Miller, S.A. and Olgaard D. L. (1997)	The authors propose an earthquake model that couples shear stress and zones of high pore pressure produces many features of observed seismicity patterns and geodetic observations.
Nanjo K.Z. (2011)	The author developed an algorithm based on number of earthquakes (relative intensity) in the past to predict future intensity of earthquakes.
Narteau C. (2007)	Author models seismicity in hierarchical model, modelling rupture from microscale to fault scale.
Papazachos et al (2006)	Authors try to predict seismicity in California based on an algorithm that identifies regions with increasing or decreasing seismic deformation.
Segall P. and Lu S. (2015)	The authors model injection-induced seismicity using full poroelastic coupling of stress and pore pressure, and time-dependent earthquake nucleation. Authors propose that the seismicity rate at a given magnitude depends on the nucleation rate, the size distribution of fault segments, and if the background shear stress is low, the time-varying volume of perturbed crust.
Saltykov V.A., Patonin A.V. (2009)	Authors conducted experiments on sandstone destruction in combination with acoustic emission in order to reproduce the influence of Earth tide on seismicity under controlled laboratory conditions.
Shapiro S. A., Dinske C., and Kummerow J. (2007)	Shapiro et al. formulates a way to estimate expected magnitudes distribution depending on injection pressure and pore pressure distribution, assuming pre-existing fracture system.
Shapiro S. A., Krüger S. and C. Dinske (2013)	The authors study the underrepresentation of large magnitude events induced in geothermal and hydrocarbon reservoirs compared to the Gutenberg-Richter law.
Shan-Ming Ke, Hoa-Ding GU and Wen-Jie Zhai (1999)	Making use of nonlinear physics theory and earthquake focus theory, combined with seismicity characteristics, the percolation model of earthquake activity is given in this paper
Stock, C., 2008	The goal of this study is to develop new methodologies for the generation of an earthquake occurrence model for New Zealand that is consistent with both historical earthquake catalogues and compilations of mapped, active faults. Author reports in this study that large dip-slip and strike-slip earthquakes scale differently.

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Toda S., Stein R.S. and Sagiya, T. (2002)	Authors study abrupt changes in seismicity related to magma intrusion that occur at a distance far from the intrusion so that they cannot be associated with diffusion of pore fluids or heat. They find a proportional relation in seismicity rate to increase in stressing rate related by dyke intrusions.
Troiana A. et al. (2013)	In this study, the authors provide an interpretation of induced seismicity based on computation of Coulomb stress changes that result from fluid injection or withdrawal at depth, mainly focused on the interpretation of induced seismicity due to stimulation of a geothermal reservoir
Wang, W-H. and Huang, S-H. (2006)	The authors studied the effect of spatial distribution of stress drop ratios on the seismicity. The authors find a relation between the distribution of stress ratio and the likelihood to generate larger magnitude earthquakes.
Ward S.N. and Goes S.D.B. (1993)	Authors tried to improve estimates of long term earthquake recurrence probabilities by means of synthetic seismicity calculations.
Zechar J.D. and Jordan T.H. (2007)	Authors study the success of different alarm-based earthquake prediction. They find that the relatively simple Relative Intensity model has an seismicity prediction equal or better than more complicated statistical earthquake prediction models when tested for the prediction of large $M_L$ in California, USA.

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## Bijlage B

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Allmann B.P. and Wiener S., 2014, Geomechanical modeling of induced seismicity source parameters and implications for seismic hazard assessment, *Geophysics*, **78**, pp. 25-39

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The authors have simulated induced seismicity (within an application for geothermal reservoir) using pressure-driven stress changes and seismicity triggering based on Coulomb friction.

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Bachmann C.E., Wiemer S. and Goertz-Allmann B.P. (2012). Influence of pore-pressure on the event-size distribution of induced earthquakes. *Geophysical Research Letters*, **39** (9).

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The authors report a geomechanical model with random distribution of stress and seeds that was able to model spatiotemporal evolution of effective stress based on a linear diffusion model in a hydraulically homogenous and isotropic medium with a linearly increasing pressure source.

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Gaucher, E., Schoenball, M., Heidbach, O., Zang, A., Fokker, P.A., van Wees, J-D and Kohl T., 2015, Induced seismicity in geothermal reservoirs: A review of forecasting approaches, *Renewable and Sustainable Energy Reviews*, **52**, 1493-1490

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Review paper regarding different modelling approaches in forecasting induced seismicity in geothermal reservoirs.

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Hazzard, J.F. and Young, P.R., 2002, Moment tensors and micromechanical models, *Tectonophysics*, **356**, -. 181-197.

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A numerical modelling approach that simulates cracking and failure in rock and the associated seismicity is presented and a technique is described for quantifying the seismic source mechanisms of the modelled events.

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Holliday, J.R., Nanjo K.Z., Tiampo, K.F., Rundle, J.B. and Turcotte, D.L., 2005, Earthquake forecasting and its verification, *Nonlinear Processes in Geophysics*, **12**, pp. 965-977

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The authors introduce in this paper a different approach in predicting earthquakes from previous observed seismicity. They propose an earthquake forecasting model based on a pattern informatics (PI) method which quantifies temporal variations in seismicity. The result, which is based on an association of small earthquakes with future large earthquakes, is a map of areas in a seismogenic region ("hotspots") where earthquakes are forecast to occur in a future 10-year time span. The authors test their PI method against the standard RI -forecasting method and report that the PI method out performs the RI method under most circumstances.

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Holliday, J.R., Turcotte, D.L. and Rundle, J.B., 2008, A review of Earthquake Statistics: Fault and Seismicity-Based Models, ETAS and BASS, *Pure and Applied Geophysics*, pp. 1003-1024

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In this paper the authors review the available seismological models that are based on faults or on previous seismicity. In the first type of models the statistical occurrence of earthquakes is determined for mapped faults, where as in the second type of model the risk on future earthquakes is based on the past seismicity of the region. After reviewing different fault and seismicity based models the authors introduce a new seismicity based model, the branching aftershock sequence (BASS). In the BASS model an initial, or seed, earthquake is specified. The subsequent earthquakes are obtained from statistical distributions of magnitude, time, and location. The authors conclude that the main advantage of this model compared to previous seismicity based models is that the BASS model is fully self-similar and is not sensitive to the low magnitude cutoff.

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Hori H. and Oike K., 1996, A statistical Model of Temporal Variation of Seismicity in the Inner Zone of Southwest Japan related to the Great Interplate earthquakes along the Nankai Trough, *Journal of Physics of the Earth*. Phys. Earth, **44**, 349-356

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The authors studied the variation in seismicity in the Inner Zone of Southwest Japan with the ultimate aim of establishing the reoccurrence time of an event in the Nankai trough. Authors used historical data in there estimate of the relative intensity of seismicity in the different regions in the Inner Zone of Southwest Japan. The relative intensities for the different regions was calculated using a statistical model introduced by Ogata and Katsura (1985). Furthermore the authors estimate the reoccurrence time of the next large event in the Nankai through in the 2030's.

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Jiménez, A. Tiampo, K.F and Posadas A.M., 2007, An Ising model for earthquake dynamics, *Nonlinear Processes in Geophysics*, 14, 5-15

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This paper focuses on extracting the information contained in seismic space-time patterns and their dynamics.

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Jiménez, A., 2013, A complex network for seismicity based on mutual information, *Physica A*, 392, 2498-2506.

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The author models each part of the lithosphere as a cell that is constantly communicating its state (e.g. stress state) to the environment. In this study this approach is used to the quantify this communication, with the aid of the Information Theory, and model seismicity as a complex network.

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Lahaie, F and Grasso J.R., 1999, Loading rate impact on fracturing pattern: Lessons from hydrocarbon recovery, Lacq gas field, France, *Journal of Geophysical Research*, Vol 104, No. B8, 17941-17954

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Authors analyzed fracturing patterns in a gas reservoir, Lacq, in correlation with the production rate of this reservoir. They observed among others a significant decrease in size of activated fractures. These changes were interpreted in terms of a change in the deformation mode of the stressed rocks from a more brittle to a more ductile behavior as the stress state was decreased. Based on these observations the authors hypothesize that the loading rate has an effect on b and D parameters.

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Langenbruch C. and Shapiro S.A., 2013, Gutenberg-Richter relation originates from Coulomb stress fluctuations caused by elastic rock heterogeneity, *Journal of Geophysical Research*, **119**, pp. 1220-1234

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Authors investigate the impact of elastic heterogeneity of the Earth's crust on Coulomb stress distribution and earthquake magnitude scaling. They hypothesize that the Gutenberg-Richter relation originates from Coulomb stress fluctuations caused by elastic rock heterogeneity.

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McGarr, A. (2014), Maximum magnitude earthquakes induced by fluid injection, *J. Geophys. Res. Solid Earth*, **119**, pp. 1008–1019

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This a literature review regarding the maximum magnitude earthquake possible by fluid injection. The main conclusions are that the maximum seismic moment is bounded by the volume of injected fluid and that the maximum seismic moments are generally caused by deep injection of wastewater.

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Miller S.A. and Olgaard D. L., 1997, Modelling Seismicity Clustering and Fault Weakness due to High Pore Pressures, *Phys. Chem. Earth*, **22**, pp.43-48.

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In this paper an earthquake model is introduced that couples shear stress and zones of high pore pressure produces many features of observed seismicity patterns and geodetic observations. The model shows earthquake clustering, repeated events, large spatial and temporal variations in stress drop, complex slip distributions, and a power law distribution of size frequency.

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Narteau C., Classification of seismic patterns in a hierarchical model of rupture: a new phase diagram for seismicity, *Geophys. J. Int.* (2007) **168**, pp.710–722

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The author models seismicity in a hierarchical model, modelling rupture from microscale to fault scale. At the microscopic scale, a stochastic process controls transitions between a solid and a broken state with respect to the local stress. From the distribution of broken elements, geometric rules of interaction determine the state of fracturing of domains of larger dimensions and the shape of the stress redistribution. Then any point in space evolves with respect to its state of stress and its state of fracturing measured at different length scales. Applied to a single fault zone under a constant loading rate, this model of seismicity reproduces the main characteristics of the seismic catalogues: Gutenberg– Richter law for the magnitude–frequency relationship, Omori law for the aftershock decay rate,

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clustering of major events, swarms of earthquakes, seismicity of creeping segment and seismic noise.

From this model the author concludes that the control on seismic behaviour is given by the dimensionless parameter  $A$ , the ratio between the healing time and loading time of a fault. If  $A = 1$  the system is critical, if  $A < 1$  the system is subcritical and controlled by faulting and lastly if  $A > 1$  the system is subcritical but controlled by healing or creep. Based on these observation on the parameter  $A$  the author proposes a new phase diagram of seismicity to incorporate these results.

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Nanjo K.Z., 2011, Earthquake forecast for the CSEP Japan Experiment based on the RI algorithm,

*Earth Planets Space*, **63**, pp. 261-274

The author developed an algorithm based on number of earthquakes, the so called relative intensity, in the past to predict future intensity of earthquakes. The premise of this model is simply that large earthquakes are more likely to occur in the future where historical seismicity is higher than elsewhere. This kind of model was previously used a background reference against which to test more sophisticated forecast models. In this paper the RI-algorithm is improved by among others spatial smoothing and it is found that it performs equal or better than other available forecast models.

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Saltykov V.A., Patonin A.V., 2009, Staging of Acoustic Emission in Laboratory Modeling of Tidal effects in Seismicity, *Doklady Earth Sciences*, 2010, Vol. 430, Part 2, pp. 235–238 Original Russian Text © V.A. Saltykov, A.V. Patonin, 2010, published in *Doklady Akademii Nauk*, 2010, Vol. 430, No. 5, pp. 693–696

In this paper the authors want to study the effects of the Earth's tide on seismicity. They report that: "a large volume of data has been accumulated concerning the effects of Earth's tide on seismicity in general and on its low energy level, in particular, with high-frequency seismic noise." Loading experiments on sandstones were carried out in order to reproduce the influence of Earth tide on seismicity under controlled laboratory conditions in compliment with measurements on acoustic emissions. The authors report that the staging in acoustic response of destruction of a specimen to an external weak periodic effect is decided as the main result of the experiments. Moreover, the different stages are related to the different conditions of the specimen during the destruction process.

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Segall P. and Lu S., 2015, Injection-induced seismicity: Poroelastic and earthquake nucleation effects, *Journal of Geophysical Research: Solid Earth*, **120**, pp. 5083-5013

The standard model of injection-induced seismicity considers changes in Coulomb strength solely due to changes in pore pressure. The authors additionally considered in this paper the full poroelastic coupling of stress and pore pressure, as well as time-dependent earthquake nucleation. They modeled stress and pore pressure due to specified injection rate in a homogeneous, poroelastic medium. The results of Segall and Lu suggest the seismicity rate at a given magnitude



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depends on the nucleation rate, the size distribution of fault segments, and if the background shear stress is low, the time-varying volume of perturbed crust.

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Shan-Ming Ke, Hoa-Ding, GU and Wen-Jie Zhal, 1999, Research on percolation model and criticality of seismicity, *Acta seismologica Sinica*, **12**, pp. 419-427

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Authors introduces model for earthquake activity based on percolation theory (percolation threshold). Although it has an interesting premise, the quality of the paper is not great, among others a lot of spelling mistakes.

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Shapiro S. A., Krüger O. S., and C. Dinske (2013), Probability of inducing given-magnitude earthquakes by perturbing finite volumes of rocks, *Journal of Geophysical Research Solid Earth*, **118**, pp. 3557–3575,

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The authors study the underrepresentation of large magnitude events induced in geothermal and hydrocarbon reservoirs compared to the Gutenberg-Richter law. This underrepresentation of large magnitude events stems from the fact that fluid induced seismicity is the result of an activation of a finite volume of rock. The authors approximate the stimulated volume by an ellipsoid or cuboid and derive the statistics of induced events from the statistics of random thin flat discs modeling rupture surfaces. Lower and upper bounds of the probability to induce a given-magnitude event are drawn. The authors propose that events near the upper bound can be interpreted as triggered ones, in contrast to the absolute majority of the induced events following the lower bound.

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Shapiro, S. A., C. Dinske, and J. Kummerow (2007), Probability of a given magnitude earthquake induced by a fluid injection, *Geophys. Res. Lett.*, **34**

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Shapiro et al follow hypothesis that seismicity is induced by pore pressure perturbations which reduce the effective normal stress on the fractures. They propose that the relaxation of pore pressure perturbations created at the injection source controls the spatio-temporal triggering of seismicity. Hereby it is assumed the crust is critically stressed, and only small perturbations are required for failure. Nonlinear diffusional phenomena is assumed responsible for seismicity triggering. Shapiro formulates a way to estimate expected magnitudes distribution depending on injection pressure and pore pressure distribution, assuming a pre-existing fracture system.

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Stock C., 2008, A consistent Geological-Seismological Model for Earthquake Occurrence in New Zealand, Doctoral Thesis, School of Geography, Environment and Earth Sciences, Victoria University.

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The goal of this study is to develop new methodologies for the generation of an earthquake occurrence model for New Zealand that is consistent with both historical earthquake catalogues and compilations of mapped, active faults. The author reports in this study that large dip-slip and strike-slip earthquakes scale differently.

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Toda S., Stein R.S. and Sagiya, T., 2002, Evidence from the AD 2000 Izu islands earthquake swarm that stressing rate governs seismicity, *Nature*, **419**, pp. 58-61

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Authors study abrupt changes in seismicity related to magma intrusion that occur at such a distance that they cannot be associated with diffusion of pore fluids or heat. They find a proportional relation in seismicity rate to increase in stressing rate related by the dyke intrusion. Any sustained increase in stressing, e.g. creep event of intrusion should in principle produce a similar seismological (swarm) behavior.

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Troiana A., di Giuseppe, M.G., Troise, C., Tramelli A. and de Natale G., 2013, A Coulomb stress model for induced seismicity distribution due to fluid injection and withdrawal in deep boreholes, *Geophys. J. Int.*, **195**, pp. 504-512

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In this study the authors provide an interpretation of induced seismicity based on computation of Coulomb stress changes that result from fluid injection or withdrawal at depth. For modeling purposes they simulate the thermodynamic evolution of a system after fluid injection or withdrawal. The associated changes in pressure and temperature are subsequently considered as sources of incremental stress changes, which are then converted to Coulomb stress changes on favourably oriented faults, taking into account the background regional stress. The numerical model results are then applied to the enhanced-geothermal-system site, Soultz-sous-Forets (France). The authors concluded that their approach describes the observed seismicity, and provides an explanation for the different behaviors of a system when fluids are injected or withdrawn.

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Ward S.N. and S.D.B. Goes, 1993, How regularly do earthquakes recur? A synthetic seismicity model for the San Andreas fault, *Geophysical Research Letters*, **20**, pp. 2131-2134

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Authors tried to improve estimates of long term earthquake recurrence probabilities by means of synthetic seismicity calculations. These calculations are based on the concept of fault segmentation and incorporated the physics of static dislocation.

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Wang, W-H. and Huang, S-H., 2006, Seismicity and stress evolution in heterogeneous faults with various degrees of roughness, *Tectonophysics*, 424, 307-318

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The authors studied the effect of spatial distribution of stress drop ratios (SDR) on the seismicity. In order to investigate the effect of different distributions of SDRs they test four different fault models, with different SDRs. These models have the same first order similarity and mean value, but the wavelength of the SDR is different for each model. The authors assume rupture processes are quasistatic and fluid-controlled. They report that the locations of large earthquakes are more sensitive to distribution than to the values of the SDRs. Furthermore a relation between the distribution of stress ratio and the likelihood to generate larger magnitude earthquakes is reported.

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Zechar, J.D. and Jordan, T.H., 2007, Testing alarm-based earthquake predictions, *Geophys. J. Int.*, **172**, pp. 715-724.

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In this paper the authors test different proposed earthquake forecasting methods based on statistics of previous seismicity. This is done using a method based on the Molchan diagram—a plot of miss rate and fraction of space–time occupied by alarm. We test forecasts from three models: relative intensity (RI), a simple spatial clustering model constructed using only smoothed historical seismicity; pattern informatics (PI), a model that aims to capture seismicity dynamics by pattern recognition; and the U. S. Geological Survey National Seismic Hazard Map (NSHM), a model that comprises smoothed historical seismicity, zones of ‘background’ seismicity, and explicit fault information. Results show that neither PI nor NSHM provide significant performance gain relative to the RI reference model.