NAM

Assen, juli 2016

TOELICHTING RESULTATEN M_{MAX}-WORKSHOP

In maart van dit jaar kwamen in Amsterdam 36 deskundigen uit de hele wereld bij elkaar voor een workshop om, op basis van alle aanwezige data uit de Groninger ondergrond, van gedachten te wisselen over de maximale magnitude van aardbevingen in Groningen. De workshop heeft geresulteerd in een kansverdeling van mogelijke maximale magnitudes van geïnduceerde en tektonische aardbevingen in Groningen. De resultaten van de workshop zijn vastgelegd in het uitgebreide *Report on M_{max} Expert Workshop*, met daarin zowel de hoofdconclusies als alle individuele bijdragen van de workshopdeelnemers.[1] De door de experts overeengekomen kans op zwaardere aardbevingen, met een magnitude van 5.0 of hoger, is ten opzichte van eerdere inschattingen significant afgenomen.
De verwachtingswaarde van de maximale magnitude bedraagt nu 5.0 op de schaal van Richter. Dat is lager dan de inschatting van 5.75 die tot dusver in de dreigingsberekeningen zijn gebruikt. Deze nieuwe verwachtingswaarde komt overigens sterk overeen met eerdere inschattingen door kennisinstellingen TNO en KNMI. De workshop past binnen het bredere onderzoeksprogramma naar de dreiging van aardbevingen in het Groningen gasveld en de risico's die daaruit voortvloeien. Dit onderzoeksprogramma loopt sinds 2013.

Achtergrond van de workshop

In december 2015 heeft de Commissie Meijdam in haar advies *Omgaan met risico's van geïnduceerde aardbevingen*[2] om duidelijkheid gevraagd over de maximaal te verwachten aardbevingsmagnitude. Deze duidelijkheid is onder meer nodig voor het opstellen van aardbevingsbestendige bouwnormen voor zeeweringen, chemische installaties en andere bouwwerken.

Op dit moment is er geen vanzelfsprekende partij die over de kennis beschikt om de maximale aardbevingsmagnitude op gezaghebbende wijze vast te stellen. Daarom is besloten om, bij wijze van alternatief, een speciale expert workshop te organiseren volgens de wereldwijd geaccepteerde standaard van de *Senior Seismic Hazard Analysis Committee* (SSHAC, zie onder voor details). Deze workshop vond plaats van 8 tot en met 10 maart 2016 in het World Trade Centre in Amsterdam (Schiphol). Onder leiding van Dr. Kevin J. Coppersmith, een van de grondleggers van de SSHAC methode, heeft een onafhankelijk, door hem geselecteerd, team van acht internationale deskundigen de bijdragen van de verschillende aardbevingsexperts beoordeeld en op basis hiervan een uiteindelijke inschatting gemaakt van de maximaal te verwachten aardbevingssterkte.[3] Het team van Dr. Coppersmith werd in de workshop ondersteund door 19 aardbevingsexperts. Daarnaast waren er negen waarnemers, namens het Staatstoezicht op de Mijnen, EBN, ExxonMobil, NAM en TNO.

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[1] Report on Mmax Expert Workshop, 8-10 March 2016, World Trade Centre, Schiphol Airport, the Netherlands.
[2] Advies van de Commissie Meijdam: https://www.rijksoverheid.nl/binaries/rijksoverheid/documenten/rapporten/2015/12/18/eindadvies-commissie-meijdam-bijlage-7/eindadvies-commissie-meijdam-bijlage-7.pdf
[3] Het panel is door Dr. Copperwith samengesteld en bestond naast hemzelf uit de volgende personen: Dr. Jon P. Ake (US Nculear Regulatory Commission), Dr. Hilmar Bungum (consultant, oud-NORSAR), Prof. dr. Torsten Dahm (GFZ, Potsdam), Prof. Ian Main (university of Edinburgh), Dr. Art McGarr (US Geological Survey), Dr. Ivan Wong (AECOM) en Dr. Bob Youngs (EMEC Foster Wheeler).

De workshop volgde de Level 3-richtlijnen van de *Senior Seismic Hazard Analysis Committee* (SSHAC). SSHAC geldt wereldwijd als de standaard voor het beoordelen van de benodigde aardbevingsmaatregelen bij de bouw van stuwdammen en nucleaire installaties.

De workshop en de bijbehorende rapportage zijn onderdeel van het lopende studiewerk over de aardbevingen als gevolg van gaswinning in Groningen. De kansverdeling zoals voorgesteld was nog geen onderdeel van bestaande dreigings- en risicoanalyse, zoals opgenomen in het Winningsplan 2016 dat door NAM afgelopen april is ingediend bij de minister van Economische Zaken. Op het moment dat de analyses voor het Winningsplan 2016 werden gedaan, waren de resultaten van de workshop nog niet beschikbaar. Bij een volgende update van de risicoberekeningen zal de uitkomst, samen met de bijdrage uit de andere studietrajecten, meegenomen worden.

Dreigingsanalyse en maximale magnitude

Het door NAM in 2013 ingediende Winningsplan ging vergezeld van een dreigingsanalyse, welke op latere tijdstippen enkele malen is geactualiseerd.

Het berekende dreigingsniveau – en daarmee de grondversnelling – rust onder andere op (zie box) een onderliggende kansverdeling van de verwachte maximale magnitude van aardbevingen. Tot dusver ontbrak voor dit laatste een wetenschappelijk onderbouwde beschrijving. In plaats daarvan werd gerekend met een op inhoudelijke gronden beredeneerde verdeling. Dit was ook de procedure voor het Winningsplan 2016.

Tot dusver is in de dreigingsanalyses steeds gewerkt met een onderliggende verdeling van de maximale magnitude die loopt van 5.0 tot en met 6.5 op de schaal van Richter, met een verwachtingswaarde van 5.75. De verwachtingswaarde is gedefinieerd als de waarde die de maximale magnitude ‘gemiddeld genomen’ zal aannemen.

De Gutenberg-Richterrelatie

De relatie tussen de magnitude (sterkte) van een aardbeving en de kans dat deze daadwerkelijk optreedt wordt de *Gutenberg-Richter relatie* genoemd. Deze relatie houdt grofweg[1] in dat de kans op een aardbeving van een bepaalde magnitude een factor 10 afneemt als de aardbeving één eenheid op de schaal van Richter toeneemt. Een aardbeving van 4 op de schaal van Richter komt volgens die relatie 10 keer minder vaak voor dan een aardbeving van 3 op de schaal van Richter.

Hoewel de kans op een aardbeving per eenheid hogere magnitude steeds met een factor 10 afneemt, wordt deze volgens de Gutenberg-Richterrelatie nooit helemaal nul – de relatie is asymptotisch. Omdat het niet realistisch is om te veronderstellen dat bepaalde extreem hoge magnitudes daadwerkelijk kunnen plaatsvinden, wordt naast de Gutenberg-Richterrelatie tevens gebruik gemaakt van de maximale sterkte van aardbevingen. Dat betekent dat aardbevingen met een nog grotere magnitude worden uitgesloten, terwijl deze nog wel met een heel kleine kans worden voorspeld op basis van de Gutenberg-Richter relatie.

[1] In de Gutenberg-Richterrelatie komt ook een b-waarde voor. Strikt genomen heeft het bovenstaande betrekking op een b-waarde van 1. Waarnemingen in Groningen ondersteunen een b-waarde rond 1.

Uitkomst M_{max} expert workshop
De workshopexperts hebben besloten om deze range zowel naar onder als naar boven op te rekken, wat heeft geresulteerd in een aangepaste bandbreedte van 3.8 tot 7.25, met een verwachtingswaarde van 5.0. De verlenging naar boven is een direct gevolg van het besluit van de experts om ook tektonische aardbevingen in ogenschouw te nemen. Dit type aardbevingen is potentieel zwaarder zijn dan geïnduceerde aardbevingen. Zo kent de krachtigste tektonische aardbeving die zich ooit in Nederland voordeed, die van 13 april 1992 in Roermond, een magnitude van 5.8.

De door de experts overeengekomen kans op zwaardere aardbevingen, met een magnitude van 5.0 of hoger, is ten opzichte van eerdere inschattingen echter significant afgenomen. De verwachtingswaarde van de maximale magnitude bedraagt nu 5.0 op de schaal van Richter. Dat is lager dan de inschatting van 5.75 die tot dusver in de dreigingsberekeningen zijn gebruikt. Deze nieuwe verwachtingswaarde komt overigens sterk overeen met eerdere inschattingen door kennisinstellingen TNO en KNMI.

Onafhankelijke kennisontwikkeling
NAM onderkent het belang van onafhankelijke kennisontwikkeling en is groot voorstander van de vorming van een nieuw kennisnetwerk, onder toezicht van een onafhankelijke wetenschappelijke adviesraad. Wetenschappelijke workshops als deze zouden in de toekomst onder regie van een dergelijke adviesraad kunnen plaatsvinden. NAM blijft, als verantwoordelijke operator, ook zelf actief onderzoek doen naar de Groningse ondergrond en de effecten van gaswinning.

Groningen Seismic Hazard and Risk Assessment

Report on Mmax Expert Workshop

8-10 March 2016

World Trade Centre, Schiphol Airport, The Netherlands

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1. Introduction

In response to induced earthquakes caused by gas production in the Groningen field in the northernmost region of the Netherlands, NAM is developing a probabilistic assessment of the consequent seismic hazard and risk.

One of the key elements of this seismic hazard and risk, namely the largest earthquake that could possibly occur, generally referred to as the maximum magnitude, or Mmax. In order to address the estimation of Mmax for the Groningen field, NAM engaged a panel of external and independent experts and convened an international workshop focused exclusively on this issue. This report summarises the background to the exercise and the organization of the workshop, as an introduction to the report by the expert panel on their conclusions regarding the distribution of possible Mmax values for the Groningen gas field.

2. Induced Seismic Hazard and Risk Assessment for Groningen

NAM has been engaged in developing a seismic hazard and risk model for the Groningen gas field, since the M_L 3.6 Huizinge earthquake that occurred on 16 August 2012, the largest induced event to date. The first stage of the model was to develop a seismological model to explain the occurrence of induced earthquakes in response to the reservoir compaction (Bourne *et al*., 2014). In order to correctly model the risk to the distributed exposure of close to 250,000 buildings across the gas field and in a surrounding 5 km buffer zone, the hazard is calculated using a Monte Carlo simulation approach (Bourne *et al*., 2015). A first version of the hazard and risk model was issued in May 2015, the purpose of which was to demonstrate the ability to produce useful and insightful hazard and risk estimates over the entire field. The most recent version of the complete risk model, now calibrated more accurately to conditions in the Groningen field, was released in November 2015 and includes a seismological model, ground-motion prediction equations (GMPEs), an exposure database with fragility functions assigned to each building class, and casualty functions to estimate loss of life resulting from building damage. The full documentation of this risk model is available for download from the NAM platform at www.namplatform.nl.

Inevitably, several elements of such a risk model are associated with considerable epistemic uncertainty, which prompts the deployment of a logic-tree formulation in order to capture the influence of such uncertainties in the hazard and risk estimates. Logic trees were first introduced for use in probabilistic seismic hazard analysis (PSHA) more than 30 years ago (Kulkarni *et al*., 1984), and they have become a standard tool in seismic hazard assessment. For each input to the hazard and risk model associated with epistemic uncertainty, a node is established with branches that carry either alternative models or alternative parameter values. Weights are assigned to each branch that reflect the relative degree-of-belief of the analyst in each branch being the most likely representation of the physical phenomenon. These weights are subsequently treated as probabilities, as the hazard and risk is calculated using all possibly branch combinations, the total probability associated to each hazard and risk estimate being obtained from the product of the participating branch weights.

In view of the scale of the risk calculations to cover the entire study area (about 60 x 50 km) and to obtain risk estimates to all building types down to low annual probabilities, the logic-tree formulation to date has been kept rather simple in order to facilitate computations in the short timescales required and to enable multiple sensitivity analyses to be performed. The logic-tree established for the November 2015 risk model is shown in Figure 2.1, in which branches were included only for the factors exerting greatest influence on the risk estimates, namely Mmax, the choice of GMPE, the fragility functions and the consequences function that defines the likelihood of fatal injuries to a building occupant as a function of the damage.

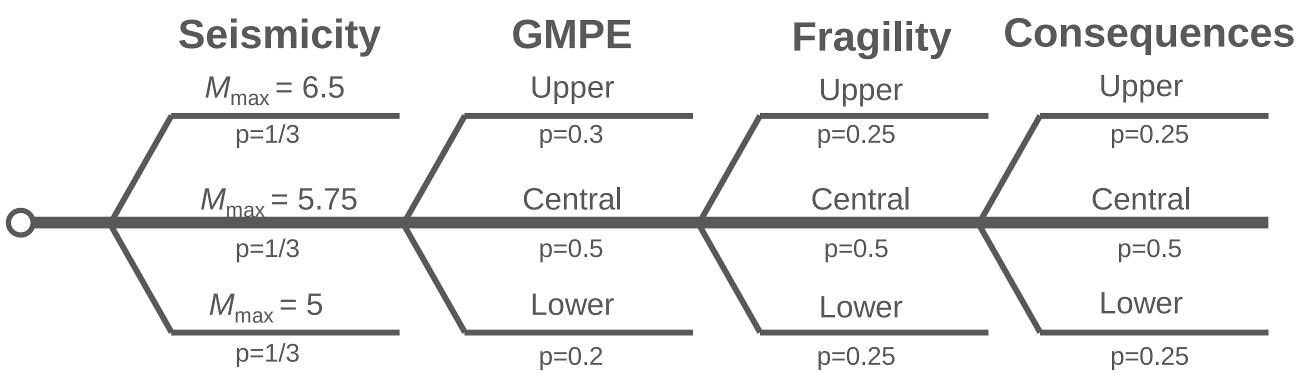

Figure 2.1. Logic-tree for the November 2015 (V2) risk model

The ranges of uncertainty on the GMPE, fragility and consequences, as expressed by the combinations of branch models and weights, were determined by the members of the NAM hazard and risk team. However, these decisions were subject to extensive review and feedback by international panels of experts, who were convened to appraise the models at workshops held in London in October 2015.

As can be seen from Figure 2.1, the V2 logic-tree included branches for Mmax, with equally weighted values of 5, 5.75 and 6.5 for induced earthquakes. The value of 6.5 was used in earlier versions of the hazard and risk model, the value being the result of all the reservoir compaction at the end of production being released seismically in a single earthquake event. The branches depicted in Figure 2.1 reflect the recognition of there being large uncertainty associated with this parameter and at the same time the ignorance of the hazard and risk team regarding what the distribution of possible values might be. The fullest expression of ignorance would be a range from 3.6 to 6.5, since it is conceivable that the 2012 Huizinge event actually represents the largest earthquake that could occur in the field. However, in view of the very strong influence that such a distribution would exert on the hazard and risk estimates, it was decided to use a lower limit of 5—loosely inferred from analogy with other gas fields in Europe—pending the outcome of the exercise reported herein. This choice was in line with the strategy to be conservative while the hazard and risk assessment is being developed, while seeking to remove uncertainty in the process to achieve a balanced assessment before Winningsplan 2016.

3. The Issue of Maximum Magnitude

In the societal and regulatory response to the Huizinge earthquake, there was considerable attention given to the question of the largest magnitude of event that could occur as a result of gas production in the Groningen field. However, this question was posed primarily in the context of deterministic—or scenario-based—approaches to hazard and risk assessment. In the initial probabilistic analyses carried out by NAM's hazard and risk team, it was found that the Mmax of 6.5 had almost no impact on the results (Figure 3.1). However, subsequent analyses—such as the site-specific seismic hazard assessment for the Groninger Forum[1] site in the city of Groningen, a long-period structure that is required to comply with the stringent performance targets in the new NPR seismic design code for the northern Netherlands (Figure 3.2)—showed that the influence of Mmax may be important and that careful consideration of the upper limit on the magnitude-frequency distribution was warranted.

In PSHA studies for natural (tectonic) seismicity, Mmax is routinely included in the logic-tree formulation but it generally exerts a relatively modest influence on the hazard estimates except for very low annual exceedance frequencies—such as are applicable to critical facilities like nuclear power plants—and longer response periods. However, for induced seismicity in the Groningen field, it became apparent that the choice of Mmax was a critically important element of the hazard and risk assessment. Faced with this realization, NAM opted to convene a panel of suitably qualified and experienced panel of independent experts to evaluate the available evidence and develop a logic-tree formulation to represent the distribution of possible Mmax values in the Groningen field.

The reasons NAM opted this approach of charging an independent expert panel with the task of estimating Mmax are as follows:

- The maximum magnitude has previously been estimated by other bodies, and these estimates have since then been questioned and revised. This has made the topic of the maximum magnitude controversial.
- The estimation of the maximum magnitude requires bringing together knowledge from different areas of knowledge, various disciplines and areas of expertise, and weighting

[1] The Groninger Forum is a large building under construction in the centre of the city of Groningen. with a planned completion in 2019. The building will be a cultural centre with libraries and museums.

up the results from these areas of expertise. An expert panel is the best way to achieve this given the absence of specific expertise on those topic within the NAM hazard and risk assessment team.

- Placing the assessment of the maximum magnitude in the hands of an international team of experts separate from NAM, should increase acceptance of the resulting hazard assessment by the local community.

Once it was resolved to engage such a panel of experts for the assessment of Mmax, two key decisions needed to be taken: who to appoint to the panel and how to organise the work of the panel most effectively and transparently within the limited timeframe available. The membership of the expert panel is discussed below in Section 5. In order to facilitate the assessment by the expert panel, it was decided to follow the principles of the so-called SSHAC process, which is explained in the following section.

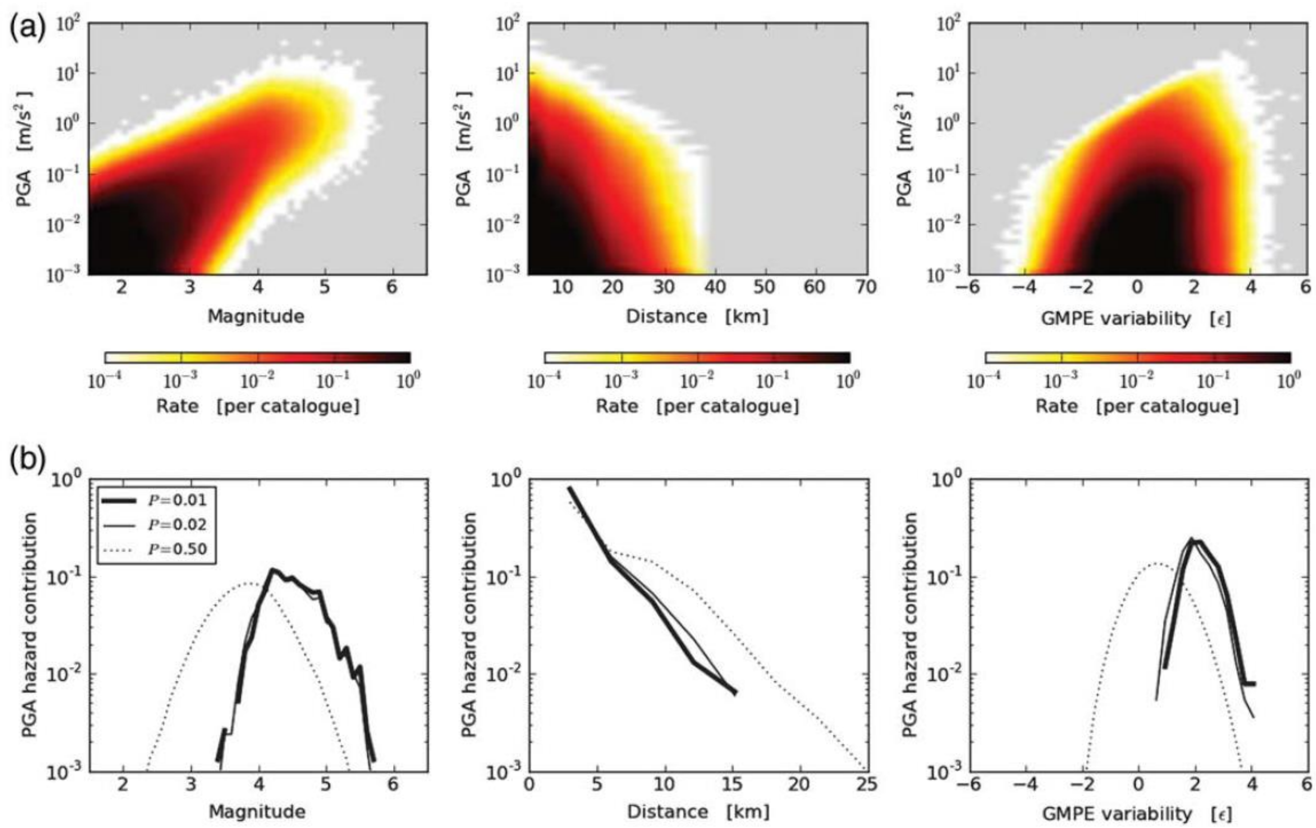

Figure 3.1. (a) Occurrence rates for PGA as a function of magnitude, distance and GMPE epsilon (the number of standard deviations relative to the mean prediction) for a single surface location directly above the region of maximum reservoir compact. (b) The fractional contribution to the ground motion with a probability of exceedance of 0.01, 0.02 and 0.5 from 2013 to 2023. These results correspond to the 2013 version of the hazard model (Bourne *et al.,* 2015).

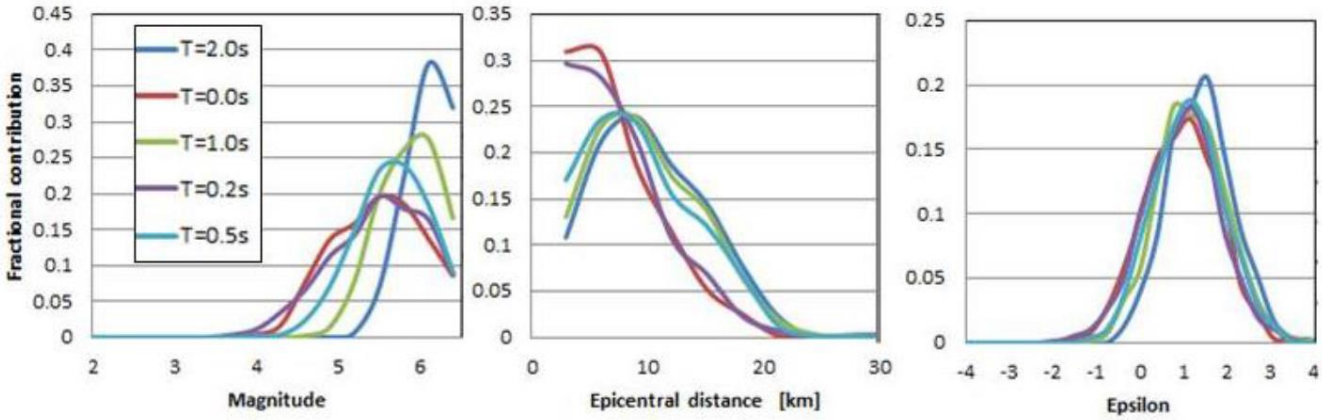

Figure 3.2. Disaggregation of the seismic hazard at the baserock horizon for the Groninger Forum site for a return period of 8,500 years in terms of fractional contributions by magnitude, distance and GMPE epsilon.

4. The SSHAC Process for Hazard Assessments

The SSHAC process was originally developed for the conduct of multiple-expert assessments of seismic hazard for safety-critical and locally-controversial infrastructure projects (*e.g.*, nuclear facilities), and it is now widely viewed as the gold standard for performing such studies. Although the time available for the conduct of the Mmax assessment to be included in the 2016 Winningsplan was insufficient to allow the full Level 3 process to be applied, the intention was to comply with as many of the specifications and requirements as possible. This section briefly describes the SSHAC process and notes the features adopted for the Groningen Mmax assessment.

4.1. History and development of the SSHAC process

Epistemic uncertainty in seismic hazard analyses reflects lack of knowledge in earthquake processes and ground-motion generation both in general and in the specific region under consideration. By definition, the quantification of epistemic uncertainty requires expert judgement and it is widely accepted that an adequate characterisation of epistemic uncertainty if the logic-tree reflects the judgements of multiple experts. This view was behind two major PSHA projects performed in the 1980s for nuclear power plant sites in central and eastern United States, conducted by EPRI (Electric Power Research Institute) and LLNL (Lawrence Livermore National Laboratory). The results from the two projects for individual sites were in many cases markedly different and there were also significant differences in the expert-to-expert variations in two projects. This prompted EPRI, the US Department of Energy (DOE) and the US Nuclear Regulatory Commission (USNRC) to form the Senior Seismic Hazard Analysis Committee, or SSHAC. This august group of experts in seismic hazard analysis, risk assessment and decision analysis were charged with investigating—and, if possible, resolving—the large differences between the two PSHA studies. In their final report, the SSHAC stated the following important finding from their work: "*In the course of our review, we concluded that many of the major potential pitfalls in executing a successful PSHA are procedural rather than technical in character. ….. This conclusion, in turn, explains our heavy emphasis on procedural guidance*" (Budnitz *et al*., 1997). Although the second volume of the 1997 SSHAC report does include numerous appendices discussing technical details of executing a PSHA, the main focus of the report is defining procedures for the conduct of multiple-expert hazard assessments. The guidelines defined four levels at which such studies could be conducted, increasing in complexity, duration and cost as one progresses from Level 1 to Level 4.

The purpose of the higher study levels, and in particular Level 4, was to provide greater likelihood of regulatory assurance in studies performed for critical facilities such as nuclear power plants. The SSHAC Level 4 framework has only been used twice for full PSHA studies, for the Yucca Mountain waste repository in Nevada (Stepp *et al*., 2001) and in the PEGASOS Project for the assessment of seismic hazard at NPP sites in Switzerland (Abrahamson *et al*., 2002). A review of the lessons learned from 15 years of experience in implementation of the original SSHAC guidelines (Hanks *et al.,* 2009) prompted the drafting of more detailed guidelines for both Level 3 and 4 studies, especially since the former was given relatively attention in Budnitz *et al*. (1997). These guidelines were issued as NUREG-2117 (USNRC, 2012) and provide clear specification of the steps required to execute SSHAC Level 3 and 4 studies. Significantly, in NUREG-2117 USNRC makes no distinction between the two study levels in terms of regulatory assurance, viewing them as simply alternative rather than approaches to achieving the same goals. This was reflected in the requirement that all US nuclear power plant operators re-assess the seismic hazard at their sites through SSHAC Level 3 PSHAs as the first stage of the USNRC's response to the 2011 Fukushima accident.

The SSHAC Level 3 process has also been adopted in countries other than the United States, and has been applied to nuclear sites in South Africa, Spain, Taiwan and Turkey, and now also in Japan. A SSHAC Level 3 PSHA was also carried out for hydroelectric dams in British Columbia, Canada.

4.2. Essential elements of the SSHAC process

The basic objective of a SSHAC study, at any level, is to develop a distribution for each element of the hazard model that represents the best estimate, the uncertainty around this estimate in terms of alternative models, and the limits on the distribution. This is expressed in NUREG-2117 as the centre, the body and the range of technically-defensible interpretations of the available data, methods and models that may be applicable to the site and region under study. More succinctly, this is referred to as the CBR of the TDI.

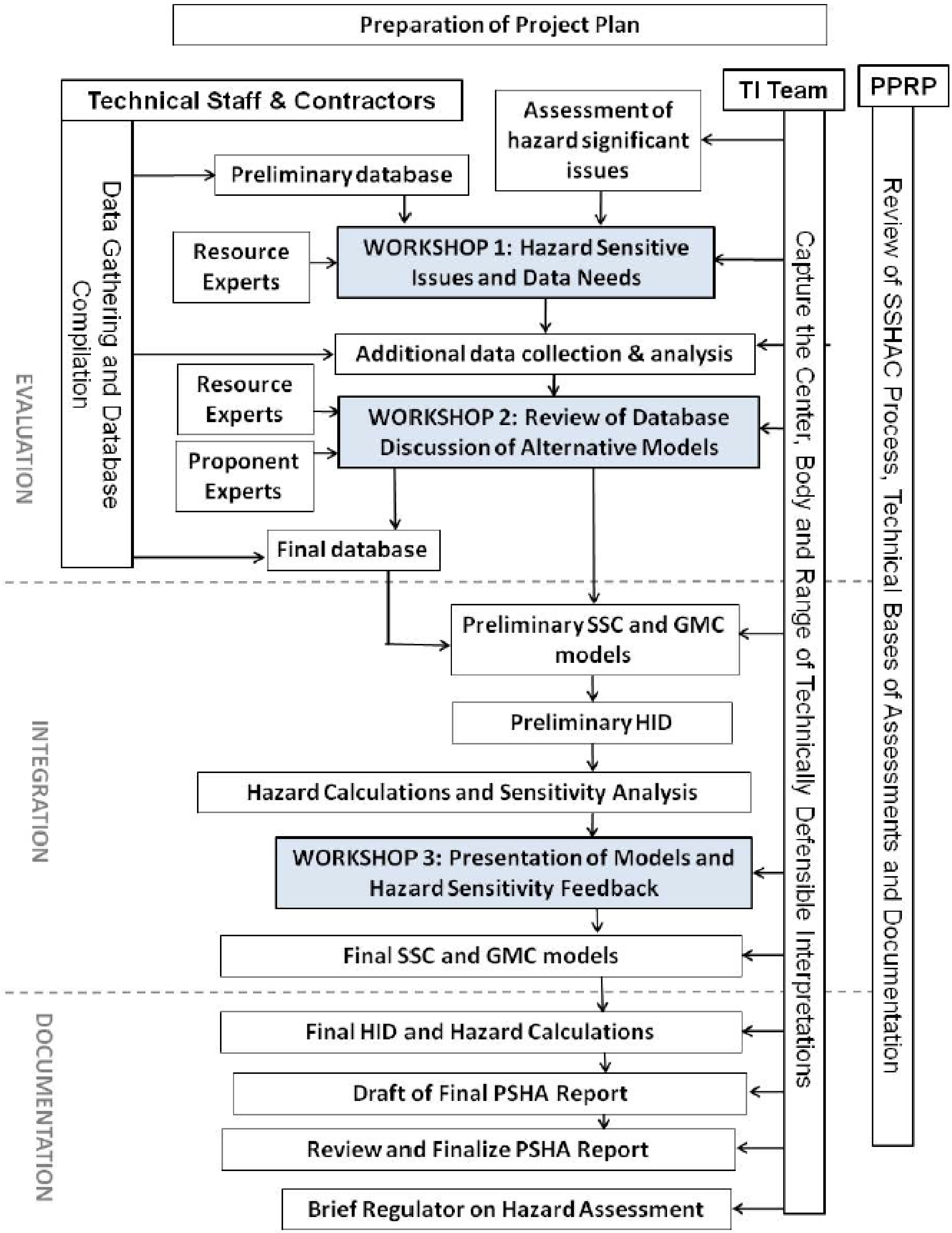

Figure 4.1. Overview of the activities and participants in a SSHAC Level 3 PSHA, with time running from top to bottom (USNRC, 2012)

This objective is met through a two-stage process of evaluation and integration. Those responsible for the assessment first assemble all available data, methods and models that are potentially applicable to the issue under consideration; this should include compilation of existing data and where feasible and appropriate the collection of new data. These data, together with existing models, are evaluated in terms of their general quality and specifically their applicability to the region and site being studied. Informed by this evaluation phase, those responsible for the assessment then enter the integration phase in which a distribution that captures the CBR of the TDI is developed. The final stage of the process is then to document the technical bases for all of the decisions taken and justification for how the final logic-tree represents the CBD of the TDI. For SSHAC Level 3 studies, the process is built around three formal workshops, as illustrated in Figure 4.1.

The execution of the complete process shown in Figure 4.1 for a PSHA would generally be between two and three years. In this application, however, the focus was not on the full inputs a PSHA but rather to a single component of the PSHA input. This is not inconsistent with the original intentions of the SSHAC process: Budnitz *et al*. (1997) noted that the higher study levels might be invoked to address individual topics—such as, for example, the activity of a particular geological fault—characterised by high uncertainty and/or considerable controversy. Even if applied to a single topic, however, to qualify as a SSHAC Level 3 process all of the steps illustrated in Figure 4.1 would still need to be followed, and in the available timeframe this was clearly not feasible for the estimation of Mmax for the Groningen gas field. Nonetheless, the intention was to follow the spirit of the SSHAC process as far as possible.

In addition to access to a common and comprehensive database for the participants, and the sequence of activities illustrated in Figure 4.1, another key element of the SSHAC process is clearly defined roles, each has specific attributes and responsibilities. The key roles are discussed in the next section.

4.3. Roles and responsibilities in a SSHAC process

The process of evaluation and integration is undertaken by a group referred to as the Technical Integration (TI) Team, which is generally coordinated by a nominated TI Lead. The TI Team must have appropriate subject matter expertise and be willing to put aside individual views on a topic in order to act as impartial evaluators. The TI Lead, at least, should have direct experience of the SSHAC process and the TI Team collectively should have a good appreciation of the workings of PSHA. The TI Team assumes exclusive and total intellectual ownership of the resulting distribution.

In order to inform the evaluations of the TI Team, Resource Experts are invited to present information, models, methods or data sets of which they have particular knowledge. The presentation by a Resource Expert should be impartial and explain the technical bases for any models presented and also clearly expound on assumptions, caveats and limitations.

Another group of invited individuals are Proponent Experts, being individuals who advocate the use of a particular method or model. There is no requirement for a Proponent Expert to be impartial since they are expected to follow the standard scientific approach of presenting a model and subjecting it to the usual process of technical challenge and defence. A Proponent Expert must be willing to explain the technical bases for their model when questioned by the TI Team.

A vitally important role in the SSHAC process is independent peer review and in SSHAC Level 3 and 4 studies this role is assigned to a Participatory Peer Review Panel (PPRP). The name implies that this panel is engaged throughout the process—as indicated in Figure 4.1—rather than only conducting late-stage review, so that concerns and questions can be raised at an early stage and addressed before the model is complete. The PPRP is charged with both process and technical review, to ensure that the requirements of the SSHAC process were complied with in the project, and the adequate justification is provided for all technical decisions. The issue of a final concurrence letter by the PPRP is considered to be the mark of success for a SSHAC Level 3 or 4 project.

5. Expert Panel for Mmax in Groningen

In order to apply the key principles of a SSHAC Level 3 process to the evaluation of Mmax in the Groningen gas field, the first step was to appoint a TI Team. The first step was to identify and engage a suitably-qualified TI Lead and then to charge that individual with the task of identifying suitable candidates for the TI Team.

5.1. TI Lead

The role of the Technical Integration Lead was assigned to **Dr Kevin J Coppersmith**, who is eminently qualified for this role. Dr Coppersmith was a member of the original SSHAC and a co-author of the Budnitz *et al.* (1997) report and the Hanks *et al.* (2009) review report, as well as being a major contributor to NUREG-2117. He also has unparalleled experience in terms of practical application of the SSHAC process, having led the Level 4 probabilistic assessment of volcanic hazard for the Yucca Mountain nuclear waste repository in Nevada and the seismic source characterisation (SSC) component of the Level 4 PSHA for the same facility. Dr Coppersmith was also SSC lead on the Level 4 PEGASOS project for PSHA at nuclear power plant sites in Switzerland. He was TI Lead on the regional SSC project for nuclear sites in central and eastern United States (CEUS-SSC) and both overall lead and TI Lead for SSC on SSHAC Level 3 PSHA studies for the US Department of Energy Hanford site in Washington state and for nuclear power plants throughout Spain. He also served as SSC TI Lead in the SSHAC Level 3 PSHA for the Thyspunt nuclear site in South Africa. Dr Coppersmith has also served on the PPRP for the SSHAC Level 3 PSHA for hydroelectric dams in British Columbia and he chaired the PPRP for the SSHAC Level 3 SSC study for the Diablo Canyon nuclear power plant in California. He is currently advising on the application of the SSHAC Level 3 process to a PSHA for a nuclear power plant site in Japan and he is also engaged in the updating of NUREG-2117.

In addition to these impeccable credentials in terms of the SSHAC process, Dr Coppersmith has extensive experience in addressing the question of defining Mmax for PSHA, including in several of the projects listed above. Additionally, he was a co-author on the major EPRI-sponsored report devoted to the issue of Mmax in stable continental regions (Johnston *et al.,* 1994).

5.2. TI Team

Once appointed as TI Lead, Dr Coppersmith was invited to propose candidates for membership of the TI Team, who were then invited to join the expert panel. Dr Coppersmith specifically sought a mixture of individuals from different backgrounds and regions who would collectively bring experience of the SSHAC process, PSHA and the estimation of Mmax, as well as specific expertise in the field of induced seismicity. In all cases, these had to be individuals willing to forego any proponent position and assume the role of an independent and impartial evaluator, in accordance with the SSHAC requirements. Following these selection criteria, seven individuals were added to the TI Team:

1. **Dr Jon P Ake** (US Nuclear Regulatory Commission). A co-author of NUREG-2117 and coordinating the updating of these guidelines for SSHAC processes. Dr Ake served as an expert panel member in the Level 4 PSHA for Yucca Mountain and as a PPRP member in the CEUS-SSC and NGA-East SSHAC Level 3 projects. Dr Ake has multiple publications on injection-induced seismicity and on mining-induced seismicity including, for the latter, the estimation of Mmax. He also served as a reviewer for US National Academy of Sciences report on Induced Seismicity.
2. **Dr Hilmar Bungum** (consultant, formerly at NORSAR). Dr Bungum has very extensive experience in seismic hazard assessment worldwide and has published extensively on topics related to this field. Dr Bungum was an expert panel member in the SSHAC Level 4 PEGASOS project. He served as chairman of the PPRP in the SSHAC Level 3 PSHA for Thyspunt and currently fulfils the same role for the SSHAC Level 3 for Spanish nuclear power plant sites. He serves as an advisor to regulatory authorities in Sweden and Finland on issues related to permanent underground storage of nuclear waste. For the Groningen project, Dr Bungum has also served as a peer reviewer for the GMPE development work.

3. **Professor Torsten Dahm** (GFZ, Potsdam). Distinguished academic in the field of earthquake seismology, fluid-filled fractures, induced seismicity and seismic discrimination. Former editor of *Geophysical Journal International* and Editor-in-Chief of *Journal of Seismology*. Professor Dahm is the chair of the German FKPE advisory group on the induced seismicity discrimination and has also served as an independent reviewer for induced seismicity in gas storage projects in The Netherlands and Spain.
4. **Professor Ian Main** (University of Edinburgh, UK). Another distinguished academic with extensive experience in statistical seismology, earthquake population dynamics, natural and induced seismicity and hazard, and the underpinning rock physics. In 2014 Professor Main was awarded the Louis Neel medal of the European Union of Geosciences for "sustained and exceptional contributions" in seismology and rock physics "including earthquake scaling, hazard and fluid movements in hydrocarbon reservoirs". He has previously served as an independent reviewer on NAM's seismological model and for the Dutch State Supervision of Mines (SodM) on statistical analyses of the Groningen seismicity. He has recently been appointed to the Expert Panel on Seismic Hazard of the UK Office for Nuclear Regulations.
5. **Dr Art McGarr** (US Geological Survey). Dr McGarr is widely considered one of the foremost pioneers in the study of induced seismicity and has published extensively on earthquakes caused by mining, hydrocarbon production and waste water injection. Specific engagements by Dr McGarr in the field of induced seismicity have included the development of ground-motion prediction equations for coal-mining induced earthquakes in central Utah, which were used in the risk assessment for Joe's Valley Dam. He also developed a seismic hazard assessment for the Sudbury Neutrino Observatory where there was concerns regarding ground motions from events indiuced in the nearby Creighton Mine. For the Groningen field, Dr McGarr also serves as an advisor to SodM, together with USGS colleagues Dr Bill Ellsworth.
6. **Ivan Wong** (AECOM). Ivan Wong is seismologist with several decades of experiences in seismic hazard studies for critical facilities around the world. He was project manager for the SSHAC Level 4 PSHA at Yucca Mountain and a member of the SSC TI Team in the SSHAC Level 3 PSHA for hydroelectric dams in British Columbia. In recent years, Ivan Wong has been extensively involved in projects related to induced seismicity and is co-author of the US DOE protocol and best practices for geothermal-induced seismicity. He is also co-author of StatesFirst primer on induced seismicity associated with oil and gas activities. Mr Wong is currently engaged in seismic hazard assessments for induced earthquakes in the United States and Canada. For the Groningen project, Mr Wong has also served as a peer reviewer for the GMPE development work.
7. **Dr Bob Youngs** (AMEC Foster Wheeler). Dr Youngs has several decades of experience in the field of seismic hazard assessments, including a role in the SSC Team for the EPRI study conducted in the 1980s for nuclear power plant sites in CEUS. He was a contributor to the Johnston *et al*. (1994) EPRI study on Mmax and developed updated Mmax approaches as part of the TI Team for the SSHAC Level 3 CEUS-SSC

project. Dr Youngs was part of the Technical Facilitation Integration (TFI) teams for the SSC components of the SSHAC Level 4 Yucca Mountain and PEGASOS PSHA projects. He contributed to the SSHAC Level 3 PSHA for Thyspunt, South Africam, as a Resource Expert on Mmax. For the Groningen project, Dr Youngs has also served as a peer reviewer for the GMPE development work.

6. Workshop on Groningen Mmax

As noted previously, the timescale of the current phase of the Groningen hazard and risk assessment for the 2016 Winningsplan (license application for gas production) prohibited the adoption of the complete SSHAC Level 3 process to address the Mmax issue. In effect, the process was reduced to a single workshop, which would most closely correspond to Workshop 2 in the normal Level 3 project as depicted in Figure 4.1. As can be appreciated from that diagram, there are four groups of participants in such a workshop, namely the TI Team, the Resource and Proponent Experts, and the peer review panel (as well as observers). The full list of workshop participants and their roles are presented in Appendix 1.

The purpose of the workshop was to provide the TI Team (expert panel) with as much information as possible regarding the geology and history of the Groningen field, and the patterns of production and induced seismicity to date, with the opportunity to ask questions regarding details on any of these topics. Similarly, the workshop was design to provide the TI Team with an opportunity to listen to various proposals for Mmax values or distributions, and to be able to interrogate the authors of these proposals. In summary, the objective was to facilitate in the most efficient and effective manner possible, the process of evaluation by the expert panel.

6.1. Resource experts

Several presentations were scheduled to provide the expert panel with background information, both on the Groningen field and also on key topics related to the brief of the panel. The topics covered included the geology of the Groningen field, the history and future perspectives for gas production, and an overview of geomechanical studies of the field, particularly with regards to the reservoir compaction. All these topics were presented by speakers from NAM. Dr Bernard Dost from KNMI presented the history of seismic instrumentation and observed seismicity in the region. Within this presentation, Dr Dost also presented very recent work on the relationship between local and moment magnitudes in the Groningen field. Summarising a report that had been completed and circulated to the expert panel and all Resource and Proponent Experts shortly before the workshop, Dr Dost presented the conclusion that for local magnitudes of 2.5 and greater, moment magnitudes (**M**) are on average 0.2 units smaller than local magnitude (M_L) reported by KNMI (Dost *et al*., 2016).

Two other presentations not directly related to the Groningen field given by resource experts to provide background and contextual information. The first of these was an overview of the different approaches that are used in PSHA practice to estimate Mmax for natural (tectonic) seismicity. This presentation was given by Dr Bob Youngs, a member of expert panel who adopted the role of Resource Expert for the presentation, which is entirely consistent with the SSHAC process (it would be less likely for a member of the TI Team to assume a Proponent Expert role, but it is common that evaluator experts serve as Resource Experts during the workshops). The second presentation was given by Professor Gillian Foulger, who gave an overview of largest earthquakes known or believed to have been caused by anthropogenic activities, including those related to hydrocarbon production. This was based on an update and extension of the database presented by Davies *et al.* (2013).

6.2. Proponent experts

Several individuals and teams were invited to present their models for estimating Mmax in the Groningen field. Some of these Proponent Experts were from NAM, Shell and ExxonMobil, who have been working on the problem for some time, and others were external experts invited because of their work and publications in this area. All the external Proponent Experts were provided with a common data package—assembled in response to identifying their individual data requirements but ensuring that the same information was provided to all modellers—regarding the gas field, production history, pressure depletion, compaction and subsidence, and observed seismicity. The explanatory notes provided to the Proponent Experts with this data package are reproduced in Appendix II.

Researchers from TNO have issued a number of reports that address the question of Mmax for the Groningen field and in adherence to the principles and requirements of the SSHAC process, it was essential that these were also presented to the TI Team. Regrettably, a decision was taken within TNO not to participate actively in the workshop (although two TNO researchers did attend as observers), for which reason Dr Steve Oates from Shell provided an overview and summary of the TNO models. Dr Oates therefore served as a Resource Expert in presenting models to the expert panel on behalf of Proponent Experts from TNO.

6.3. Workshop format

The workshop was conducted at the World Trade Centre in Schiphol airport over a period of two-and-a-half days from 8th to 10th March 2016. The meeting agenda is reproduced in Appendix III. The expert panel held a closed meeting on the morning of 8th March in order to discuss their objectives and *modus operandi*.

The meeting begun with a general welcome and a round of presentations, followed by a brief presentation given by Jan van Elk from NAM that provided an overview of the history of the Groningen field and the response—by NAM, the Dutch government and society—to the induced seismicity, particularly following the M_L 3.6 Huizinge earthquake in August 2012. Mr van Elk's presentation also reminded the workshop participants that for this activity NAM had made no confidentiality requirements. This was followed by a presentation given by Dr Julian Bommer on the SSHAC process and the way it was being applied to the estimation of Mmax for the Groningen hazard and risk assessment through the workshop and subsequent deliberations of the expert panel.

The main body of the workshop was then initiated with a presentation by Dr Coppersmith on the objectives and scope of the TI Team, including clarification regarding the definition and interpretation of Mmax in the context of the Groningen field. This was followed by the Resource Expert presentations through to the middle of the second day, after which the remaining day-and-a-half were devoted to Proponent Expert presentations, There were extensive discussions prompted by questions from both the TI Team and other Proponent and Resource Experts present, giving rise to lively debates. In order to provide a continuous narrative, the second and third days of the workshop both began with brief presentations by Dr Coppersmith giving an overview of the presentations and discussions up to that point, and the questions and issues that had arisen for the expert panel's consideration.

As was explained in Section 4.3, independent peer review is an indispensable element of the SSHAC process. In a SSHAC Level 3 study, the PPRP is charged with both process and technical review. In view of the relatively short timescale available for the Mmax assessment, coupled with the fact that a large portion of the appropriate technical communities had already been engaged either to serve on the expert panel or to participate as Resource and Proponent Experts, it was decided not to additionally engage a formal review panel for workshop. In terms of process review, the main criteria are that the expert panel act independently and impartially, and that they duly consider a wide range of models in their evaluation. NAM assumed that this role could be informally fulfilled by observers from both SodM and from the Scientific Advisory Committee (SAC) who were invited to attend the workshop as observers. Regrettably, the SAC declined the invitation and was not represented at the workshop. SodM initially also declined the invitation but did request that Dr Dirk Kraaijpoel from TNO attend on behalf of the regulator. Dr Rafael Steenbergen from TNO also attended as an observer, as did Marc Hettema and Bastiaan Jaarsma from the Dutch state oil company EBN. Therefore, there were independent observers present at the workshop and in the introductory presentation on the SSHAC, Dr Bommer explained the expectation that these individuals would effectively play the role of process peer reviewers for the conduct of the workshop, which was accepted by the observers.

Immediately following the closure of the workshop, the expert panel spent a full day on Friday 11th March in a closed meeting to discuss the outcomes of the workshop. In effect, this meeting represented the final stage of the expert panel's evaluation of the available data, methods and models, and the start of their integration of the CBR of the TDI.

7. Concluding Remarks

NAM has appointed an independent panel of highly-qualified experts to estimate the distribution of Mmax values to be used in induced seismic hazard and risk assessments for the Groningen gas field. Since this is an issue with appreciable associated uncertainty, and also one that has become controversial, NAM decided that the most appropriate course of action was to engage such a panel and to charge them with making their assessment following the guidelines for a SSHAC Level 3 process. This approach is widely viewed as the gold standard for multiple-expert assessments of natural hazards. Within the timeframe of the Groningen hazard and risk assessment, it was not possible to conform with all of the requirements of a SSHAC Level 3 process and it is important to emphasise that no claim is being made by NAM that this assessment was conducted as a SSHAC Level 3 project. However, there was a clear commitment to benefit from as many features of such a process as possible and in this regard the Mmax assessment project did conform with the following requirements of a SSHAC Level 3 process:

- A Technical Integration (TI) Team composed of suitably qualified and experienced subject matter experts led by an individual with extensive first-hand experience of the SSHAC process
- Agreement by the TI Team members, collectively and individually, to forsake any proponent positions and to undertake the assessment as impartial evaluators
- Exposure of the TI Team to a comprehensive database related to the issue under consideration and to a wide range of proponent models
- A formal workshop in which the TI Team members were able to question both the Resource and the Proponent Experts and engage in open discussion of the issues in an atmosphere of scientific challenge and defence
- Independent observers present at the workshop to observe the conduct of the discussions and the nature of the interactions
- A final output in terms of a fully documented logic-tree intended to capture the centre, the body, and the range of technically-defensible interpretations, for which the TI Team take complete responsibility in terms of intellectual ownership

The workshop was judged to be a success by all participants in terms of a series of clear presentations covering a very wide range of directly relevant topics, followed by question and answer sessions conducted in an open and constructive atmosphere.

This report has summarised the reasons behind the organisation of the Groningen Mmax workshop and also documented the main features of the workshop. The independent report from the expert panel is attached as an Annex to this report. An important point to stress in closing is that NAM openly committed to be bound to the proposed logic-tree presented by the expert panel and this distribution of Mmax values will be deployed in future hazard and risk assessments.

8. References

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Appendix 1

List of Workshop Participants

No.	Name	Affiliation	Workshop Role
1	Jon Ake	US Nuclear Regulatory Commission	TI Team
2	Julian Bommer	Consultant to NAM	Facilitator
3	Stephen Bourne	Shell	Proponent Expert
4	Emily Brodsky	University of California Santa Cruz	Proponent Expert
5	Hilmar Bungum	NORSAR (retired)	TI Team
6	Kevin Coppersmith	Coppersmith Consulting Inc.	TI Lead
7	Helen Crowley	Consultant to NAM	Observer
8	Torsten Dahm	GFZ Potsdam	TI Team
9	Nora Dedontney	ExxonMobil	Proponent Expert
10	Carsten Dinske	Free University Berlin	Proponent Expert
11	Dirk Doornhof	NAM	Observer
12	Bernard Dost	KNMI	Resource Expert
13	Gillian Foulger	Durham University	Resource Expert
14	Leendert Geurtsen[1]	NAM	Resource Expert
15	Chris Harris[2]	Shell	Proponent Expert
16	Marc Hettema	EBN	Observer
17	Matthias Holschneider	Potsdam University	Proponent Expert
18	Bastiaan Jaarsma	EBN	Observer
19	Dirk Kraaijpoel	TNO	Observer
20	Ian Main	University of Edinburgh	TI Team
21	Art McGarr	USGS	TI Team
22	Steve Oates	Shell	Resource Expert
23	Rui Pinho	Consultant to NAM	Observer
24	Pablo Sanz-Reherman	ExxonMobil	Proponent Expert
25	Serge Shapiro	Free University Berlin	Proponent Expert
26	Raphael Steenbergen[2]	TNO	Observer
27	Jenny Suckale[3]	Stanford University	Proponent Expert
28	Martin J Terrell	ExxonMobil	Observer
29	Peter van den Bogert	Shell	Proponent Expert
30	Rob van Eijs	NAM	Resource Expert
31	Jan van Elk	NAM	Observer
32	Clemens Visser	NAM	Resource Expert
33	Rick Wentinck	NAM	Proponent Expert
34	Ivan Wong	AECOM	TI Team
35	Bob Youngs	AMEC Foster Wheeler	TI Team / Resource Expert
36	Gert Zöller	Potsdam University	Proponent Expert

Notes: 1 – attended only 8th March; 2 – only 9th and 10th March; 3 – only 10th March

Appendix 2

Data Package Provided to Proponent Experts

Almost 1 GB of data related to the Groningen field was provided to all of the external participants invited as Proponent Experts; the accompanying data sheet was prepared by Dr Steve Oates to explain the datasets

Summary and brief description of the content of the NAM Groningen data package for analysis in preparation for the Mmax workshop

Overview

A data package has been prepared as input to the various data analysis workflows which will generate input to the Groningen Mmax Workshop on 9th and 10th March 2016. The scope and content of this data package, summarised in the table below, reflects the specific requests made by the invited experts and the need for background information to support these requested items.

The data falls into the following main categories: general background information; seismological data; reservoir engineering output and production data; geomechanical data. Data files should be self-explanatory but in some cases read-me files have been bundled with the data where it was felt to be of use or necessary. The two greyed out items in the table correspond to specific requests made but for which the data has not yet been obtained.

The figure below shows an approximate overlay of the earthquake and monitoring station locations on a GoogleMaps display of the region – it is important to be aware that this map has been produced for the purpose of summarizing some of the data discussed here, it is not a topographically precise composite map. An interactive map, showing earthquake locations and monitoring stations and supported by NAM, is available at http://feitenencijfers.namplatform.nl/geotool/nam.html?layer=beving.

Other notes

For spatial coordinates NAM uses the standard system for The Netherlands – RDS, the Rijksdriehoekstelsel (see definition at https://nl.wikipedia.org/wiki/Rijksdriehoeksco%C3%B6rdinaten). Locations of the KNMI seismic stations have been converted from latitude and longitude to RDS by NAM Geodetics.

Note that the KNMI earthquake monitoring network is currently undergoing a major upgrade, bringing on-line a factor of 10 more stations over the Groningen Field than previously. The event locations in the catalogue provided have however been obtained with the earlier sparse network as described in Dost et al (2012).

Earthquake catalogue magnitude of completeness (Mc) is considered to be 1.5, since 1995. Epicentral locations have been determined by KNMI using conventional arrival time inversion techniques. In almost all cases, a depth of 3km (approximate average reservoir depth) has been assumed as the array was too sparse to enable depths to be reliably determined. Recent deep borehole monitoring data supports this assumption.

Further background information concerning KNMI's monitoring activities can be found at http://www.knmi.nl/nederland-nu/seismologie/aardbevingen.

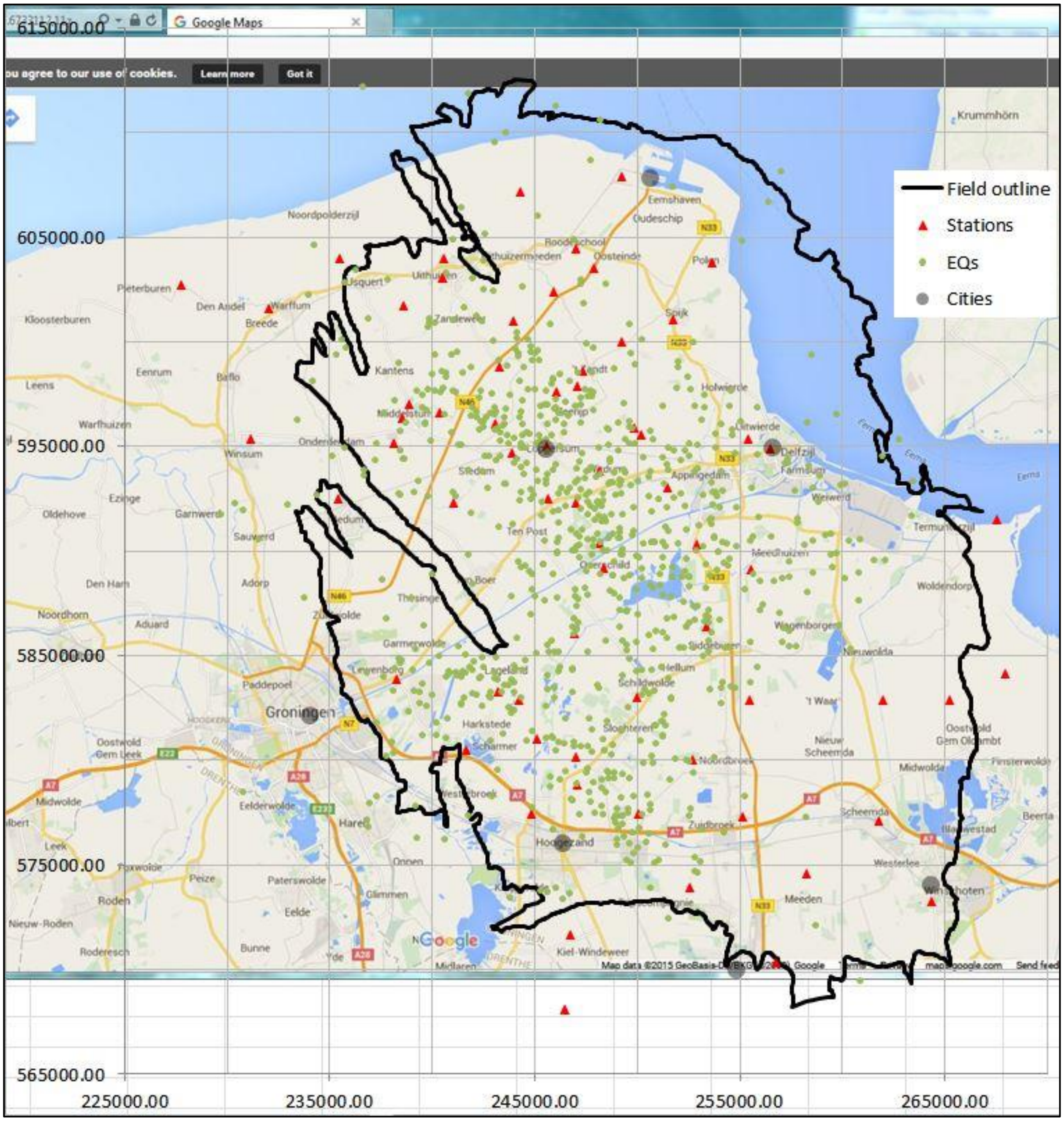

Figure 1: approximate overlay of earthquake and monitoring station locations on map display from GoogleMaps. It is important to be aware that this map has been produced for the purpose of summarizing some of the data discussed here, it is not a topographically precise composite map. An interactive composite map supported by NAM is available on-line at http://feitenencijfers.namplatform.nl/geotool/nam.html?layer=beving.

Dataset name	Dataset description
General	
Geological summary	Report ***Groningen Field Review 2012*** details geology of the field including characteristics of faults
Field outline and major cities	ASCII files give field outline and major cities in RDS coordinates
Hazard and Risk report 7th Nov 2015	***Hazard and Risk Assessment for Induced Seismicity Groningen – Interim Update 7th November 2015***. Provides useful background including details of production scenarios
Seismology	
Earthquake catalogue	Event origin times, epicentral coordinates in RDS, focal depths and magnitudes. Some details of methods used for location and magnitude determination are given in KNMI monitoring report.
Network configuration	Coordinates and types of seismometers (surface and boreholes). Downloaded from KNMI website & converted to RDS
Magnitude of completeness	Mc is taken as 1.5 since 1995. See KNMI monitoring report
KNMI monitoring report	Dost et al (2012) ***Monitoring induced seismicity in the North of the Netherlands: status report 2010***
Stress drops	Stress drop estimates are given in Figure 4 of Bommer et al (2015) ***Developing an Application-Specific Ground-Motion Model for Induced Seismicity***
Broadband seismic records for key global earthquakes	Broadband records in the field from 2004 Sumatra, 2011 Tohoku and 2012 Indian Ocean earthquakes
Reservoir Engineering	
Gas production	Gas production volume per cluster per month for production scenarios described on pages 41-46 of the Hazard and Risk report. Overview of production by month/year; history (1956 up to Aug 2015) and forecast (Sep 2015 up to 1/1/2025).
Reservoir pressures	3D extract of simulator pressures by grid block, at the end of each year, for History Match (HM) and Forecast (FC). 2D extract of simulator pressures averaged over the Z-direction gives single averaged pressure per X,Y-location at the end of each year
Well locations	Surface locations of production wells/clusters (reasonable proxy for subsurface location)
Geomechanics	
Subsidence	INSAR, GPS and levelling data
Compaction	Reservoir compaction derived from subsidence data - forecasts for 33, 27 & 21bcm scenarios.
Pressure	Reservoir pressure (in bar) used in deriving compaction for 33, 27 & 21bcm scenarios. Equivalent to the pressure data described above under Reservoir Engineering but given on the compaction grid.
Further geomechanical data	Additional geomechanical data at NAM's discretion/recommendation

Table 1: summary and description of datasets provided.

Appendix 3

Workshop Agenda

Workshop on Maximum Magnitude Estimates for Probabilistic Seismic Hazard and Risk Modelling in Groningen Gas Field

8-10 March 2016

World Trade Centre, Schiphol Airport, Amsterdam, NL

Purpose and Outline

A two-day workshop, conducted following the guidelines for a SSHAC Level 3 process, in which an expert panel will evaluate the distribution of Mmax values for the Groningen field to best represent the current state of knowledge and uncertainty. During the two-day workshop, in presence of invited observers, the panel will listen to presentations on geological, geophysical, seismological and production data for the Groningen field, as well as proponent model for the estimation of Mmax and specific values of this parameter for Groningen. The panel will address questions to all presenters to obtain greater insights into the information and models put forward.

Following the two-day workshop, the panel will conduct a closed meeting to discuss their impressions and evaluations, and then to formulate their proposal for an Mmax distribution (to be documented after the workshop).

Panel Members and Invited Participants and Observers

The workshop will be hosted by the NAM hazard and risk team led by Jan van Elk and consisting of Dirk Doornhof, Julian Bommer, Stephen Bourne, Helen Crowley, Steve Oates and Rui Pinho.

The expert evaluation panel consists of the following members:

- Dr Kevin Coppersmith (chair)
- Dr Jon Ake
- Dr Hilmar Bungum
- Professor Torsten Dahm
- Dr Art McGarr
- Professor Ian Main
- Dr Ivan Wong
- Dr Bob Youngs

Dr Coppersmith will facilitate the workshop following a brief introduction by the NAM hazard and risk team. Representatives of SSM (SodM) and the SAC have been invited to attend as observers. Other individuals are invited in their capacity as resource or proponent experts, as indicated in the draft agenda below. The purpose of the presentations is to provide the panel with a full overview of the available data and models, and to be able to interrogate the presenters regarding the assumptions, limitations and caveats related to the information put forward. Each presentation will therefore be followed by a Q&A period; *the times indicated in the agenda for each topic include both the presentation and its discussion by the panel*. Members of NAM hazard and risk team, as well as members of the SodM and SAC delegations, may also make presentations, as either resource or proponent experts, suspending their observer status for the period of their presentation and its discussion by the panel. Before closing the sessions each day, the floor will be opened to provide an opportunity for observers to ask questions and make comments on the proceedings and the discussions.

Agenda: Day 1 (Tuesday 8th March 2016)

10:00-11:30 am: Closed meeting of Expert Panel, Room G3.02

Start	End	Topic	Speaker
11:45	13:00	*Lunch and coffee*	
13:00	13:30	Welcome. Overview of Groningen hazard & risk project	Jan van Elk
13:00	14:00	The SSHAC process and application to this project	Julian Bommer
14:00	14:30	Objectives of the workshop: definition of Mmax	Kevin Coppersmith
14:30	15:15	Geology of the Groningen field	Clemens Visser
15:15	15:30	*Coffee*	
15:30	16:00	History and future perspective of gas production	Leendert Geurtsen
16:00	16:45	History of geomechanics for the Groningen field	Rob van Eijs
16:45	17:30	History of earthquakes in the Groningen field	Bernard Dost
17:30	18:00	Comments from observers	SAC /SodM
18:00	18:30	Closing comments from expert panel	Kevin Coppersmith

Agenda: Day 2 (Wednesday 9th March 2016)

Start	End	Topic	Speaker
08:30	09:00	*Coffee*	
09:00	09:30	Re-cap of Day 1	Kevin Coppersmith
09:30	10:30	Overview of Mmax estimation for natural earthquakes	Bob Youngs
10:30	10:45	*Coffee*	
10:45	11:15	History of KNMI Mmax estimates for Groningen	Bernard Dost
11:15	12:15	Overview of triggering large EQs	Emily Brodsky
12:15	13:15	*Lunch*	
13:15	14:15	Overview of largest induced/triggered events	Gillian Foulger
14:15	15:15	Mmax distribution for Groningen	Dinske, Shapiro
15:15	15:30	*Coffee*	
15:30	17:30	Mmax distribution for Groningen	Nora Dedontney/ Pablo Sainz
17:30	18:00	Comments from observers	SAC /SodM
18:00	18:30	Closing comments from expert panel	Kevin Coppersmith

Agenda: Day 3 (Thursday 10th March 2016)

Start	End	Topic	Speaker
08:30	09:00	*Coffee*	
09:00	10:00	Re-cap of Days 1 and 2	Kevin Coppersmith
10:00	11:00	Mmax distribution for Groningen	Stephen Bourne
11:00	11:15	*Coffee*	
11:15	12:15	Mmax distribution for Groningen	Gert Zöller / M. Holschneider
12:15	13:15	*Lunch*	
13:15	14:15	TNO Mmax models for Groningen	Steve Oates*
14:15	15:15	Mmax distribution for Groningen	Jenny Suckale
15:15	15:30	*Coffee*	
15:30	16:30	Mmax distribution for Groningen	Rick Wentinck / Peter van den B.
16:30	17:30	General discussion	All participants
17:30	18:00	Comments from observers	SAC /SodM
18:00	18:30	Closing comments from expert panel	Kevin Coppersmith

* The TNO reports will be summarised by Dr Steve Oates because authors of TNO report declined to present

Agenda: Friday 11th March: All Day

Closed meeting of Expert Panel (all day) at Sheraton Hotel (Mercury boardroom), Schiphol Airport

Report from the Expert Panel on Maximum Magnitude Estimates for Probabilistic Seismic Hazard and Risk Modelling in Groningen Gas Field

25 April 2016

Framework for the Assessment

The Groningen Mmax Panel is charged with developing a distribution of the maximum magnitude (Mmax) for the Groningen natural gas field that is appropriate for use in a probabilistic seismic hazard analysis (PSHA) and subsequent probabilistic risk analyses (PRA). The definition of Mmax is in the context of its common use in seismic source characterization for PSHA (probabilistic seismic hazard analysis). For example, as defined in USNRC (2012a, Chapter 11): Mmax is "the largest earthquake that a seismic source is assessed to be capable of generating. The maximum magnitude is the upper bound to recurrence curves." Mmax, as it is defined for PSHA and used here, is a time-independent upper bound. In general, it cannot be defined from an earthquake catalogue alone or statistical analyses of the catalogue. This is a well-known observation and has been documented for decades. In some cases where a large number of earthquakes have been recorded, it has been suggested that point estimates of Mmax can be made from the catalogue data (e.g. Kijko, 2004). However, assessment of the uncertainty distribution for Mmax from the catalogue data remains problematic without imposing some additional constraints (USNRC, 2012a). As a result, the assessment of Mmax requires expert judgment and the application of physical principles beyond just the earthquake catalogue. The assessment of Mmax is a common assessment and is a required part of all PSHAs. Such assessments are done routinely for purposes of engineering hazard analyses, risk analyses, and safety assessments. For example, regulatory agencies worldwide for nuclear facilities and other critical facilities require PSHAs and deterministic seismic hazard analyses, and they all require Mmax assessments.

This assessment of Mmax for the Groningen field is intended to capture the center, body, and range of technically defensible interpretations (see Section 3.1 of USNRC 2012b for explanation of this concept). This means that the Panel has focused on developing an Mmax distribution that includes epistemic uncertainties and is based on a consideration of factors relating to the Groningen field, earthquake physics, analogues, and experience in developing Mmax for PSHAs in other studies. We view our charge as not requiring statistical proof that our Mmax distribution is correct; rather, we are providing a technically-defensible distribution whose shape and limits reflect the Panel's knowledge and our assessment of the uncertainties after due consideration of the pertinent information. Following the SSHAC process of providing assessments that are based on expert-judgments, the Panel has considered the Groningen field-specific data, analogies to other induced seismicity cases, analogies to cases of triggered seismicity, models of physics of earthquake generation processes, and experience in the Mmax estimation process.

The Panel assumes that this analysis is related to earthquakes that are either induced by withdrawal activities associated with the Groningen field or triggered by such activities. In turn, the hazard associated with earthquakes induced or triggered by the field production is assumed to occur in addition to a “background” hazard from tectonic earthquakes defined by regional hazard mapping or assessments. Therefore, the Mmax distribution relates to events purely induced by the field and possible triggered seismicity that is related to the activities in the field[1].

The assessment made for this study is the Mmax that can be used for PSHA and risk assessment at the Groningen field. The assessment is specific to the Groningen source of seismicity and is not applicable to any other location or seismic source. This is because the characteristics of earthquake sources for PSHA are always based on as much source-specific information as possible. Further, it is apparent to the Panel that the characteristics of sources of induced seismicity differ significantly from place to place, such that drawing analogies among induced seismicity case histories must be done with care. Further, the incorporation of site-specific information—particularly when it is available in abundance as it is at Groningen—means that conclusions drawn for the Groningen field do not necessarily apply to any other gas field, even those within the Netherlands.

As is the case for most assessments of Mmax, the epistemic uncertainties include both conceptual model as well as parametric uncertainties. Logic trees are particularly well-suited to incorporating both conceptual model and parametric uncertainties and have been used in the Groningen Mmax assessment. In particular the assessment includes uncertainties in alternative approaches to assessing Mmax at Groningen and uncertainties in whether or not ruptures will nucleate or propagate significantly outside of the reservoir. The structure of the logic tree allows for the assessment of Mmax to be a function of the alternative models in the tree. These “conditional” Mmax assessments are more readily made by the Expert Panel, and they are then combined according to the relative weights provided by the Panel for the alternative conceptual models.

Process followed by the Mmax Panel

Because the assessments of Mmax for Groningen are difficult, require expert judgement, and are associated with large uncertainties, they are suited to using the SSHAC process (see process implementation in USNRC, 2012b). This Mmax assessment process is not a full SSHAC Level 3 process. Such a process requires that all pertinent data, models, and methods be assembled and distributed to the Technical Integration (TI) Team (in this case the “Panel”), and that a minimum of three workshops be conducted. The first two are devoted to the discussion of the data, models, and methods, and the third to feedback associated with the

[1] The Panel adopts the terminology given in McGarr et al. (2002): “As used here, the adjective "induced" describes seismicity resulting from an activity that causes a stress change that is comparable in magnitude to the ambient shear stress acting on a fault to cause slip, whereas "triggered" is used if the stress change is only a small fraction of the ambient level (e.g., Bossu, 1996; McGarr and Simpson, 1997).”

assessments of models developed by the TI Team. In essence, the Mmax workshop was conducted in the spirit of the typical SSHAC Level 3 Workshop #2, which is devoted to presentations by Proponent Experts who advocate their particular models and methods. The workshop provides an opportunity for the TI Team to understand alternative models and methods, their technical bases, and their uncertainties. The discussions that occur at the workshop put the TI Team in a strong position to subsequently make their assessments and build their models.

This is the case for the Groningen Mmax assessment. The “database” provided to the Panel included a suite of papers on the topic and presentations made during the workshop. As in all SSHAC processes, the assessments made by the Panel do not come merely from the data provided, they require the exercise of judgment by the evaluator experts. The Panel is required not only to define the central or favoured parts of the distribution of Mmax, but also to define the body or shape of the distribution as well as the range. The SSHAC process assists in developing this product, which was the focus and aim of the Mmax Panel.

Information Considered by the Panel

Although a sampling of publications and reports were provided to the panel before the workshop related to induced seismicity at the Groningen field and elsewhere, the fundamental information considered by the Panel was provided in the presentations made by the Resource and Proponent Experts at the workshop. PowerPoint presentations were provided to the Panel each day after their oral presentation by the presenters, including materials assembled at the request of the Panel. For example, the Panel requested that the presenters summarize any evidence for the location and extent of faults beneath the reservoir, and Quaternary faults within or near the reservoir. The presenters assembled applicable data related to these topics and provided a summary to the Panel the following day. The Panel is particularly appreciative of the extra effort and responsiveness by all presenters to focus their presentations on the topics of interest and for assembling additional pertinent information on short notice. In addition to the materials provided to the panel, the panel relied on their own experience and a wealth of comparable studies related to induced seismicity and to assessments of Mmax.

Assessments Leading to Mmax

This section of the report provides a summary of the elements of the Mmax assessment, including the values and weights given in the logic tree. Also given is a brief summary of the technical justification for the assessments made. In many cases, this summary draws upon the information provided to the Panel by making reference to particular presentations from the workshop. Although the Panel has drawn heavily on the work presented during the workshop, it should be emphasized that the assessed Mmax distribution is owned intellectually solely by the Panel. They are the only group who was responsible for its construction and they are the group that will defend it.

The assessment of Mmax for the Groningen field is summarized in the logic tree shown in Figure 1. The first node of the logic tree captures the uncertainty in approaches to assessing Mmax at Groningen. The first approach is to consider the field-specific information related to observed seismicity and physical properties to assess Mmax. The second approach is to consider analogues to other locations of known or suspected induced seismicity to help constrain the Mmax at Groningen. Unlike most other gas extraction fields, the amount and quality of data of potential use in assessing Mmax at Groningen is exemplary. In particular, the seismicity record has been carefully compiled and a host of geomechanical models have been developed and exercised with the specific purpose of evaluating issues related to the seismic potential of the field. This suggests that the field-specific approach is one that is well-supported. Additionally, the Panel also looked closely into the use of analogues to assist in the assessment of the largest earthquakes that might be possible at Groningen. The current state of compilations of case histories of induced seismicity is uneven in terms of their quality and reliability. In particular, instances of induced seismicity for gas extraction fields do not always provide a justification for their categorization of earthquakes as being induced or a full reporting of whether or not injection activities were conducted during field operations

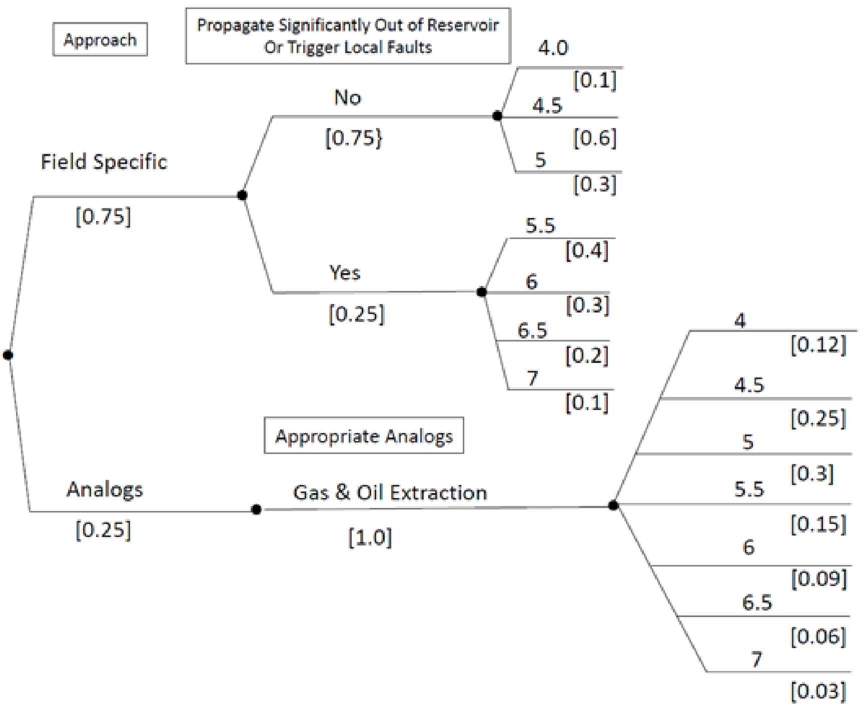

Figure 1. Logic tree showing the major elements of the assessment of Mmax for the Groningen field. Alternative branches are identified at each node and weights are assigned to each branch. The end point for each branch is the estimated maximum magnitude to the nearest half unit and its probability (in brackets).

Given the scope and timeframe of this study, the Panel concluded that it was not possible or appropriate to review in detail each case history of gas extraction given in the dataset provided by Gillian Foulger (updated database of Davies et al. [2013], including now 389 examples, 190 papers), so we have considered all of the cases identified as related to gas extraction to be appropriate analogues for consideration. We have also considered the cases noted in the database of oil extraction, but only if no injection activities were reported as having been conducted at any time during the life of the operation. The Panel also considered the possibility of developing a formal Bayesian consideration of the analogues for use in this assessment. It was concluded that the number of case studies for gas extraction was not of sufficient quality without further analysis and not of sufficient number to provide a confident basis in the timeframe of this study for establishing a Bayesian estimate of Mmax for Groningen.

Based on a consideration of the field-specific data, which are high-quality but limited for the purpose of providing an estimate of a rare event such as Mmax, and the analogue database, it was concluded by the Panel that the field-specific approach is preferred by a three-to-one margin. Therefore, the weight assigned to the field-specific approach is 0.75 and the weight of 0.25 is assigned to the analogue approach (Figure 1).

The next node of the logic tree is a conditional assessment assuming that the field-specific approach is exercised. A key uncertainty identified by the Panel as important to the assessment is whether or not it is assumed that the induced stresses in the reservoir are capable of generating fault ruptures that propagate significantly out of the reservoir or that might trigger rupture on nearby faults outside of the reservoir. "Significant" propagation out of the reservoir, which might occur downward beneath the reservoir or laterally, is defined by the Panel as having dimensions of more than one reservoir thickness, or more than about 0.5 km. Based on the presentations and discussions at the workshops, it is clear that the uncertainty of whether or not such propagation or triggering can occur is not resolved based on the available data and geomechanical modelling. A key observation though is that the vast majority of well-located seismicity appears to be confined to the reservoir (see, for example, DeDontney presentation Day 2). After due consideration of the information, the Panel assigns a higher weight by a ratio of three to one (weights of 0.75 and 0.25) to the logic tree branch signifying no significant rupture out of the reservoir will occur. Nearly all of the modelling results presented for the field concluded that the induced compaction stresses were not sufficient for significant rupture propagation out of the field. A significant uncertainty in these models is the state of tectonic stresses and how tectonic stresses might assist in the propagation of ruptures or allow for the relatively small induced stresses to trigger tectonic stress release along faults in the vicinity of the reservoir, such as the faults that are mapped beneath the reservoir as being present to depths of at least 6 km.

As shown in the logic tree, the assessed Mmax is dependent on the conceptual model shown along the particular branch. Thus, the Mmax distributions shown are "conditional" distributions that are based on the assumption that the weight on the particular branch is 1.0. The conditional Mmax distribution assuming that no significant propagation out of the reservoir occurs is the following: moment magnitude (**M)** 4 (0.1), 4.5 (0.6), 5 (0.3), where conditional probabilities are given in brackets in Figure 1. The largest observed magnitude within the field to date is approximately **M** 3.4, but this is assessed to not provide a meaningful constraint on

Mmax, other than to provide a lower bound. Very few of the field-specific analyses presented at the workshop provided expected maximum magnitude estimates as low as **M** 4, but Suckale's numerical simulations resulted in magnitudes of **M 3**.8 to 4.6, depending on various assumptions, and Shapiro reported an **M** 4.2 from a bounded frequency-magnitude distribution. The Panel assigns a low weight of 0.1 to the Mmax value of **M** 4 (Figure 1). The Mmax value of **M** 4.5 is consistent with several of the field-specific assessments discussed by researchers at the workshop. For example, DeDontney (Exxon) concluded that ruptures lying entirely within the reservoir could result in a magnitude as high as **M** 4.5. TNO researchers reported an **M** 4.7, based on a maximum length of 12 km for those faults that have cumulative displacements of 200m or more. A similar magnitude was reported by Van d. Bogen based on dynamic rupture models using the faults with the largest offsets. Zöller reported a range of **M** 3.6 – 4.7 when the 90% confidence level is used to constrain the uncertainties in b-value. Dost estimated a maximum magnitude of **M** 5 based on a rupture having length of 20km and width of 1 km, which assumes a small amount of rupture outside of the reservoir. The Panel's evaluation considered the field-specific results (particularly the fault lengths and reservoir thickness) and was informed by consideration of empirical relationships (Wells and Coppersmith, 1994; Leonard, 2014; Somerville, 2014; etc.) to arrive at the magnitude values cited in the logic tree. The Panel also notes that length-to-width aspect ratios of 20:1 to 50:1 for dip-slip fault implied by the rupture scenarios presented at the workshop are considered to be very unusual, based on consideration of observed earthquake ruptures. After due consideration of the field-specific results and assuming no significant rupture propagation out of the reservoir, the Panel assigns a weight of 0.6 to **M** 4.5 and a weight of 0.3 to **M** 5 (Figure 1).

Following the logic branch specifying that ruptures propagate out of the reservoir, the conditional probability distribution for Mmax is the following: **M** 5.5 (0.4), 6 (0.3), 6.5 (0.2), 7 (0.1) (Figure 1). Field-specific analyses presented at the workshop provided the Panel with insights into the magnitudes that would be associated with various scenarios. For example, Dost indicated that a magnitude of about **M** 5.8 results from a fault having dimensions of length 60 km and width of 3 km, which would require significant rupture propagation outside of the reservoir. DeDontney (Exxon-Mobil) reported that magnitudes in the range of **M** 5.5 to 6.5 could result from rupture downdip into the Carboniferous rocks and assuming realistic rupture geometries. Bourne reported that a **M** 6.5 would result from applying a cumulative strain model to the reservoir assuming all strain is released in a single event and that the strain partitioning factor is assumed to be 1.0, meaning that all strain energy is released seismically. This is considered to be a highly unlikely bounding assumption. Brodsky reported that earthquakes in the range of **M** 6.5 to 7 have occurred due to triggering faults from induced seismicity. In a model where the induced seismicity at the field is assumed to be capable of triggering tectonic faults, it is noted that the maximum magnitude for the seismic source zone that contains all of the Netherlands in the SHARE (Woessner et al. 2013) hazard model is **M** 6.5 to 7.1.

Following the logic tree branch for the analogue approach, the assessment was informed by a consideration of the case histories for induced seismicity due to gas extraction and from oil extraction (with no injection). No other analogues were considered to be appropriate, such as those due to dam impoundment, fluid injection, or mining. Therefore, the single branch of the logic tree that represents gas and oil extraction (without injection) is assigned a weight of 1.0. The dataset provided by Foulger during the workshop, which has very recently been updated from the dataset given in Davies et al. (2013), was used without additional refinement or review due to the time constraints of the project. The earthquake occurrences identified as being related to “Gas Extraction” were considered to be analogous to Groningen, as were three earthquake case histories identified as related to “Oil Extraction” without reported injection. This is based on the discussion during the workshop indicating that injection has not occurred within the Groningen field and that there are no plans for injection during the remaining lifetime of the field. The Panel also considered the presentation by Brodsky drawing analogy to the Gazli earthquakes, which reached **M** 7 and have been interpreted to be associated with gas extraction. The maximum observed magnitudes for the selected data set are shown in Figure 2. The conditional Mmax distribution assessed using the analogue approach is the following: **M** 4 (0.12), 4.5 (0.25), 5 (0.3), 5.5 (0.15), 6 (0.09), 6.5 (0.06), 7 (0.03).

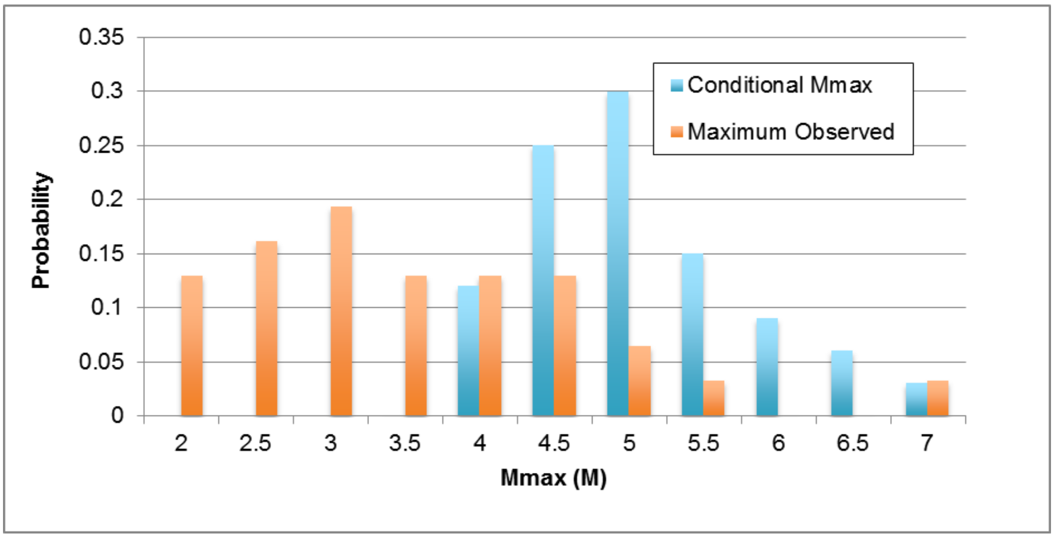

Figure 2. Histograms showing the Mmax maximum observed earthquakes within the analogue database (orange) and the assessed Mmax distribution conditional on using the analogue approach to Mmax estimation.

The approach used to develop the Mmax distribution for the analogue branch is very similar to the approach used to develop Mmax distributions for the U.S. National Seismic Hazard Maps (Wheeler, 2009), which is based on a direct expert assessment and unlike a more formalized Bayesian approach conducted for regional seismic hazard studies (Johnston et al., 1994; USNRC 2012a). The direct assessment is made by considering the maximum observed magnitudes associated with the case histories (Figure 2) and considering subjectively the range of magnitudes that should define the Mmax for Groningen in light of the observations.

The lower magnitudes are either eliminated or given low weight as being representative of the Mmax for Groningen, the magnitudes in the range of **M** 4.5 to 5.5 are judged to be the central part of the Mmax distribution and the upper tail extends to **M** 7 reflect the very low probability that such magnitudes could occur in association with the Groningen field as they have been interpreted at the Gazli field.

Unconditional Mmax Distribution

The unconditional Mmax distribution for the Groningen field is assessed by multiplying the weights associated with the branches leading to the conditional Mmax distributions (Figure 1). The distribution is shown in Figure 3 and is listed in Table 1. As can be seen, it extends from **M** 4 to 7. The weighted mean of the distribution is about **M** 5. For reference, the Mmax distribution is plotted with the observed maximum magnitudes for the analogue dataset.

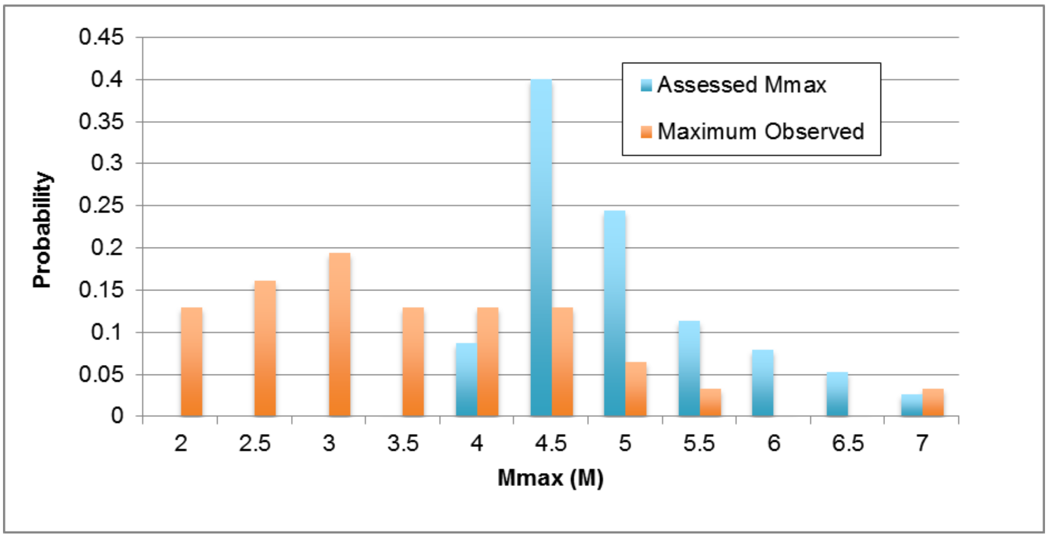

Figure 3. PMF of the assessed discrete Mmax distribution.

Table 1 Assessed discrete Mmax distribution shown in Figure 3.

Moment Magnitude	Weight
4	0.08625
4.5	0.4
5	0.24375
5.5	0.1125
6	0.07875
6.5	0.0525
7	0.02625

The assessed Mmax distribution is represented discretely by the probability mass function (PMF) shown above with values centred in 0.5 magnitude unit bins. In addition, a continuous cumulative distribution function (CDF) is provided in Table 2. The CDF is constructed by assigning the probability mass in each discrete magnitude bin uniformly over the 0.5 magnitude unit bin width centred on the magnitudes shown in Figure 3 and listed in Table 1. The resulting CDF is shown in Figure 4.

Table 2. CDF of Mmax distribution shown in Figure .

Moment Magnitude	Cumulative Probability
3.75	0.0
4.25	0.08625
4.75	0.48625
5.25	0.73
5.75	0.8425
6.25	0.92125
6.75	0.97375
7.25	1.0

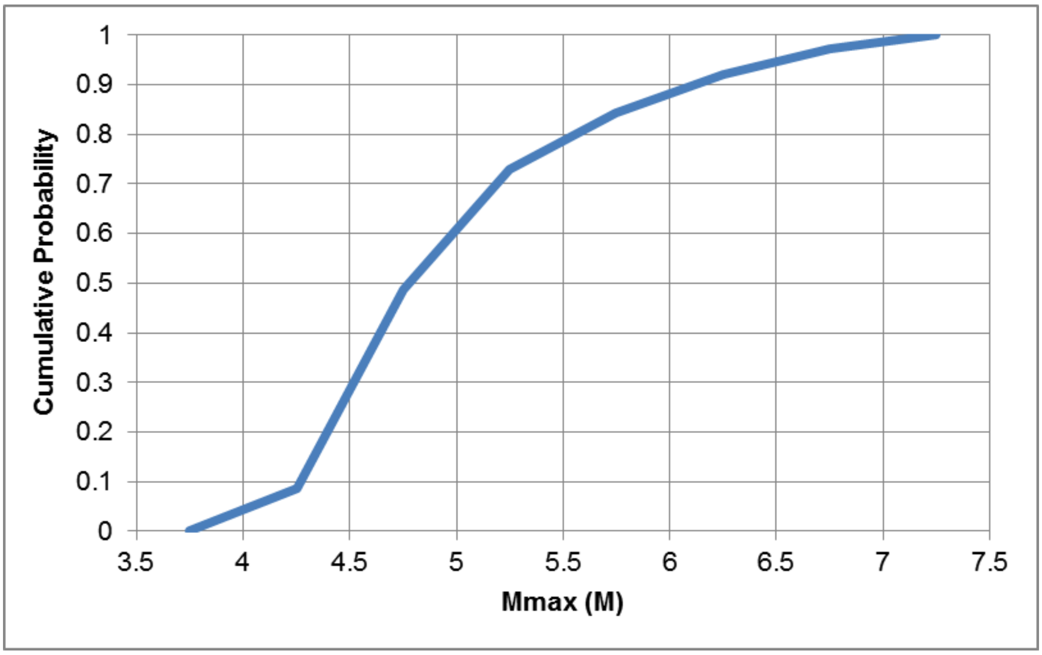

Figure 4: Assessed Mmax CDF.

Comments on the Use of the Mmax Distribution for Groningen

As it was presented and discussed during the workshop, induced seismicity and observed maximum magnitudes in Groningen are time-dependent and controlled by the production and compaction history. However, the Groningen Mmax distribution given above is judged by the Panel to be appropriate for use in a PSHA that considers the next ten years or the entire lifetime of the conventional gas recovery in the field which is estimated to extend to about 2060. In other words, the distribution is not judged to have a significant time dependency. The reasons for this are twofold. First, the only potentially time-dependent constraints on Mmax are those related to the compaction process associated with the gas extraction process. As discussed in the work by Bourne and his colleagues, compaction volume would be expected to increase with time and releases more gravitational energy. However, as reported to the Panel, the field is about ¾ produced and an additional ¼ volume would be expected to increase the moment magnitude by a relatively small fraction. Second, most of the constraints on Mmax are associated with the maximum dimensions of fault ruptures, either those that would be essentially confined to the reservoir or those that could propagate significantly out of the reservoir, including the triggering of tectonic faults. Those physical constraints on rupture dimensions are time-independent in the sense that the distribution of Mmax is considered to be stationary for tectonic faults in a PSHA. For these reasons, the Panel concludes that the Mmax distribution for the Groningen field provided in this document is essentially the same for hazard assessment conducted currently, ten years from now, or at the conclusion of production activities in 2060. However, as is true for all gas field case histories, the distribution is subject to updating in the future if significant new findings occur, such as the occurrence of larger earthquakes at the field, or a change in production or operation mode.

It is suggested that the use of this Mmax distribution in the PSHA be carefully done, given the plans to attach it to the recurrence distributions presented by Bourne. In particular, it is suggested that the development of the earthquake recurrence distributions takes into account that a value of Mmax exists (i.e. the size of the largest event is not unbounded), and that the uncertainty distribution for Mmax is defined by the distribution developed in this document. For purposes of the ground motion model for the PSHA, the Panel notes that the magnitudes at **M** 5 and smaller should be assumed to nucleate at the reservoir depth; magnitudes larger than **M** 5 can nucleate at any depth within the seismogenic crust. This reflects the assessment that a triggered earthquake can also nucleate outside, e.g below, the reservoir layer. The stress perturbation from depletion also affects the region outside the depleted layer.

Recommendations for Reducing Uncertainties

With permission from the project, we offer our suggestions for activities that we conclude would reduce uncertainties in Mmax for the Groningen field. The activities identified are either part of the existing studies being conducted for the field, or utilize the information that is being developed from those studies.

1. Review and analyse the analogue case histories of induced seismicity associated with gas extraction, especially the earthquakes that are given in the database presented by Gillian Foulger. The case history of the Gazli earthquake region and gas extraction should be given high priority, given the large magnitude earthquakes that have been observed. The case histories should be examined using all available information in the literature and production information that can be identified. Potentially important information includes the history of seismicity prior to, during, and following field operations; the production history and associated characteristics could be helpful. Any information related to injection at the site should be identified.

2. It is apparent that a high quality seismic network has recently been installed in the Groningen field and that this network will provide valuable information including high-resolution hypocentral locations, focal mechanisms, moment tensors, stress drops, and ground motion parameters. Incorporation of detailed crustal velocity structure into the analysis of seismicity should be encouraged, as well as inversions based on combined use of data from surface and borehole instruments. Attention should be given to obtaining accurate estimates of moment magnitudes for all events.

3. Conduct in situ stress measurements to characterize the magnitudes and orientations of the principal stresses in the region of the reservoir with particular emphasis in the Carboniferous. Such measurements can provide input information to rock-mechanical (2D or 3D) modelling studies (at different scales) regarding the propagation of ruptures into the rocks beneath the reservoir and/or triggering of events that nucleate outside the producing horizon.

4. Compile and analyse all regional geodetic data that can serve to better define the large-scale crustal deformation as well as to provide longer baselines for more local measurements. Regional deformation rates can help to provide regional constraints on seismic moment rates and place limits on the moment balance that is possible across the reservoir.

5. If not already done, encourage studies aimed at confirming (or not) the dominance of normal faulting within the reservoir, as well as larger-scale studies aimed at resolving the stress field in the Carboniferous, and in deeper strata.

6. Continue analyses that address the issue of propagation of ruptures out of the field, including dynamic modelling and geomechanical analyses. Incorporate information developed on stress state and magnitudes from in situ measurements.

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Respectfully submitted,

Members of the Expert Panel on Maximum Magnitude Estimates for Probabilistic Seismic Hazard and Risk Modelling in Groningen Gas Field

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Jon Ake

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Bob Youngs

Groningen Induced Seismic Hazard and Risk Assessment Project

Workshop on Maximum Magnitudes for the Groningen Field

Time: 8th to 10th March 2016

Location: World Trade Centre, Schiphol Airport, Amsterdam

Agenda: Day 1 (Tuesday 8th March 2016)

10:00-11:30 am: Closed meeting of Expert Panel, Room G3.02

Start	End	Topic	Speaker
11:45	13:00	*Lunch and coffee*	
13:00	13:30	Welcome. Overview of Groningen hazard & risk project	Jan van Elk
13:00	14:00	The SSHAC process and application to this project	Julian Bommer
14:00	14:30	Objectives of the workshop: definition of Mmax	Kevin Coppersmith
14:30	15:15	Geology of the Groningen field	Clemens Visser
15:15	15:30	*Coffee*	
15:30	16:00	History and future perspective of gas production	Leendert Geurtsen
16:00	16:45	History of geomechanics for the Groningen field	Rob van Eijs
16:45	17:30	History of earthquakes in the Groningen field	Bernard Dost
17:30	18:00	Comments from observers	SAC /SodM
18:00	18:30	Closing comments from expert panel	Kevin Coppersmith

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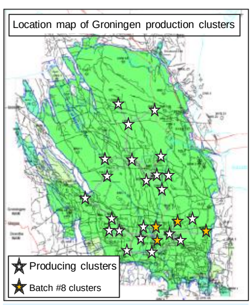
Introduction

Workshop on Maximum Magnitude Earthquakes in Groningen

BRON VAN ONZE ENERGIE

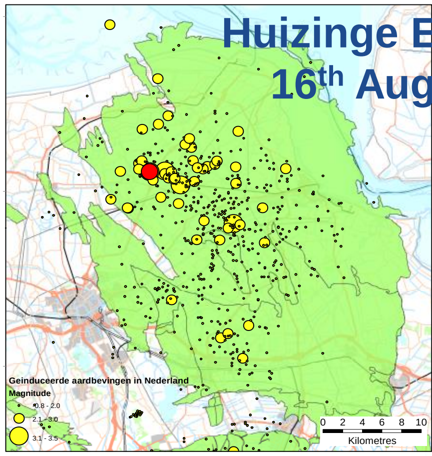
Groningen Gas Field

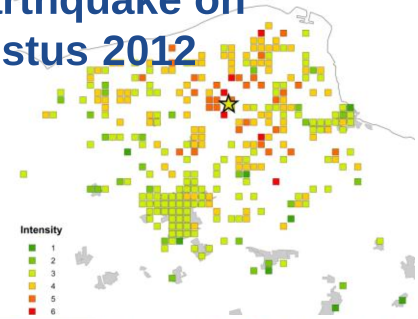


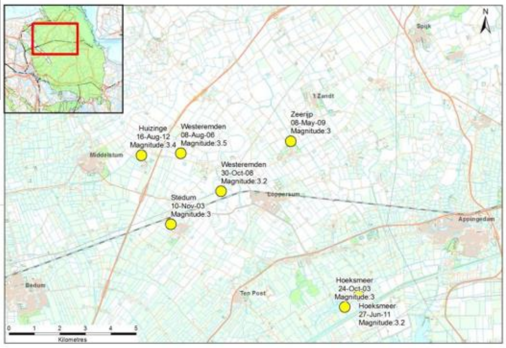
- The Groningen gas field is the 7th largest gasfield in the world, based on initial reserves. Some 70% of the gas has already been produced, but based on current reserves it is still 13th in the world ranking,
- The field was discovered in 1959 and taken into production in 1963,
- The field is located in rural the north-eastern part of the country (Groningen province), close to the city of Groningen,
- The gas contains 14% nitrogen and has a lower calorific content than gas from other fields,
- The field is operated by NAM (a joint venture of Shell and Exxonmobil),
- Some 93% of the gross revenue of gas sales is paid in taxes to the Dutch state. If the tax income had been put into a bank account, it would now contain some 1 trillion Euro.

Workshop on M_{max} Groningen

Huizinge Earthquake on 16th Augustus 2012







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Workshop on M_{max} Groningen

SCHOKKEND GRONI

Groninger Bodem Beweging

NAM

March 2016

Workshop on M_{max} Groningen

Societal Events

Several Debates in House of Commons

Reimbursement Declining House Prices

FORUM and other infra-structure project

Criminal Case against NAM

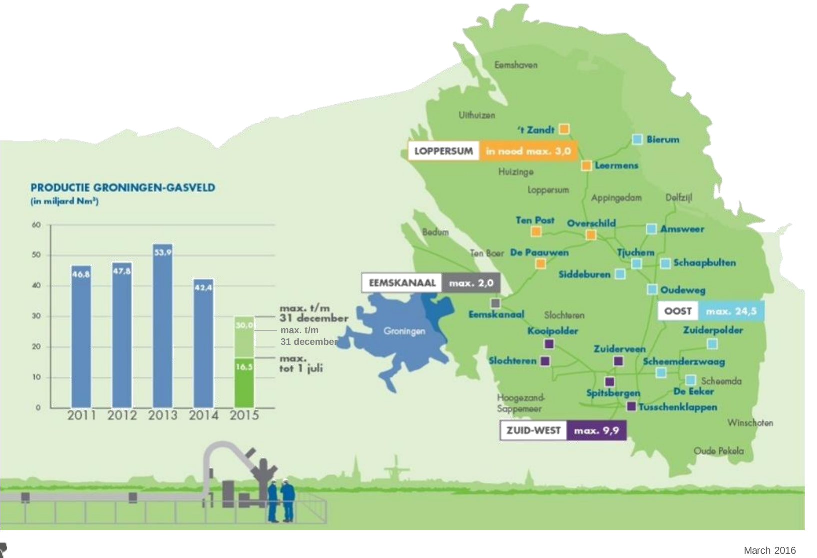
Committee Meijdam

National Coordinator Groningen (NCG)

Raad van State Ministerial Decision

Workshop on M_{max} Groningen

Gas Production Restrictions



Workshop on M_{max} Groningen

Context Studies and Data Acquisition

NAM

- Hazard
- Norm
- Impact
- Action Plan

Koninklijk Nederlands Meteorologisch Instituut
Ministerie van Infrastructuur en Milieu

Commissie Meijdam

Stuurgroep NEN-NPR

Staatstoezicht op de Mijnen
Ministerie van Economische Zaken

Nationaal Coördinator Groningen

NAM
Requirement for Production license
Responsibility for Safe Operation
→ Earthquake Studies & Data Acquisition

Workshop on M_{max} Groningen

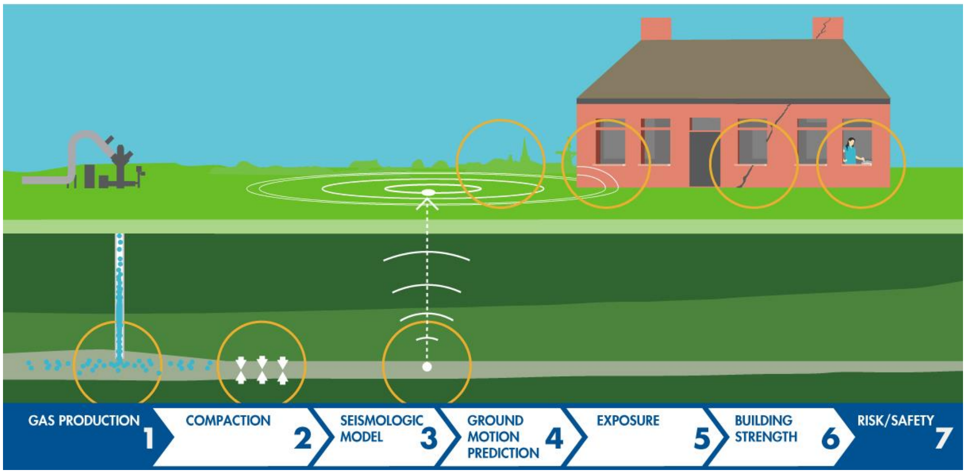
Study and Data Acquisition Plan

- Scientific research into the risks and measures.
- Commenced in 2012. Current program runs until 2016 (new Winningsplan).
- Scope is some 100 million euros over three year period.
- Cooperation with some 25 universities and research institutions.
- Supervision by an independent scientific committee.

Workshop on M_{max} Groningen

Study and Data Acquisition Plan

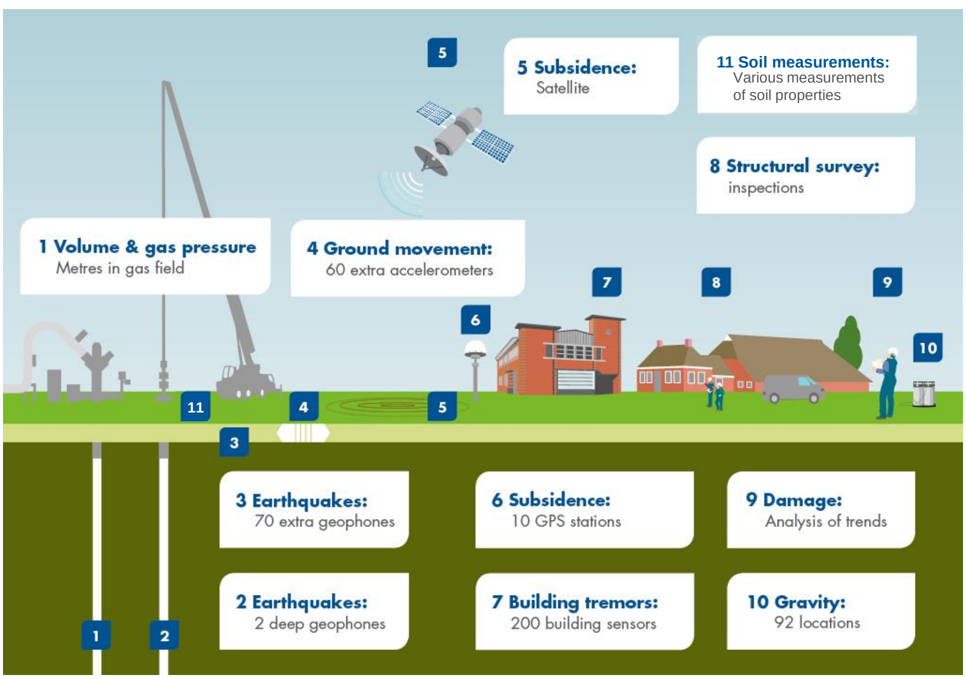
SCOPE OF THE RESEARCH



NAM

March 2016

Workshop on M_{max} Groningen



Study and Data Acquisition Plan

COOPERATION AND ASSURANCE

Assurance and Supervision of Studies:

1. Voluntary: by independent international experts and publication in scientific journals
2. Government: Scientific Advisory Committee, SodM, KNMI en Tcbb
3. Public Review: Sharing reports on NAMplatform.nl

Confidentiality

- No Confidentiality Arrangement in Place for the M_{max} Workshop.
- Panel will prepare report with their conclusions.

NAM

Groningen Induced Seismic Hazard and Risk Assessment Project
Workshop on Maximum Magnitudes for the Groningen Field
8th to 10th March 2016, World Trade Centre, Schiphol Airport, Amsterdam

The SSHAC Process and its Application to the Estimation of Maximum Magnitude in the Groningen Gas Field

Julian J Bommer

Overview of Presentation

- **Epistemic uncertainty in seismic hazard analysis**
- **Expert judgements and logic-trees**
- **The origin of the SSHAC guidelines**
- **Elements of the SSHAC process**
- **Mmax in Groningen: An epistemic uncertainty**
- **Applying the SSHAC process to the Mmax issue**

Overview of Presentation

- **Epistemic uncertainty in seismic hazard analysis**
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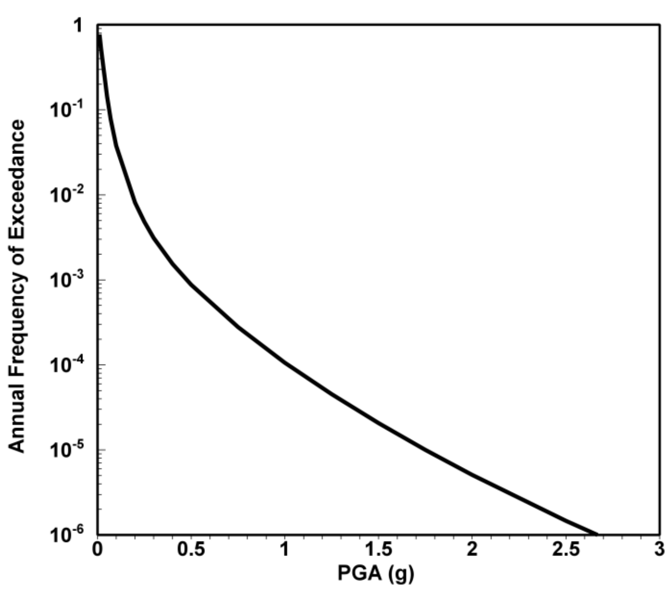
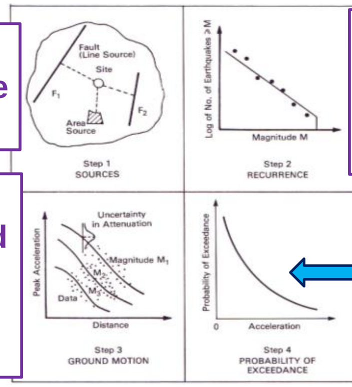
Seismic Hazard Curve



Best model for locations of future earthquakes?

Best model for predicting ground motion levels from future earthquakes?



Best model for rates of future earthquakes? Largest EQ?

Accurate hazard estimation of fundamental importance

Models generally not uniquely defined because:

- **Scenarios considered in PSHA calculations include events not represented in the data**
- **The data are usually of such quality and completeness that there will be multiple interpretations (all defensible)**

Epistemic Uncertainty

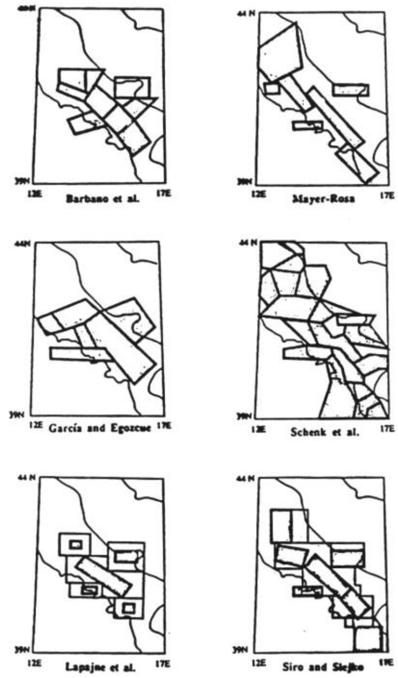
EPISTEMIC uncertainty reflects our lack of knowledge regarding earthquake source processes and seismic wave propagation in general and in the region under study

(From *epistêmê* Greek for "knowledge")

Celsus Library, Ephesus

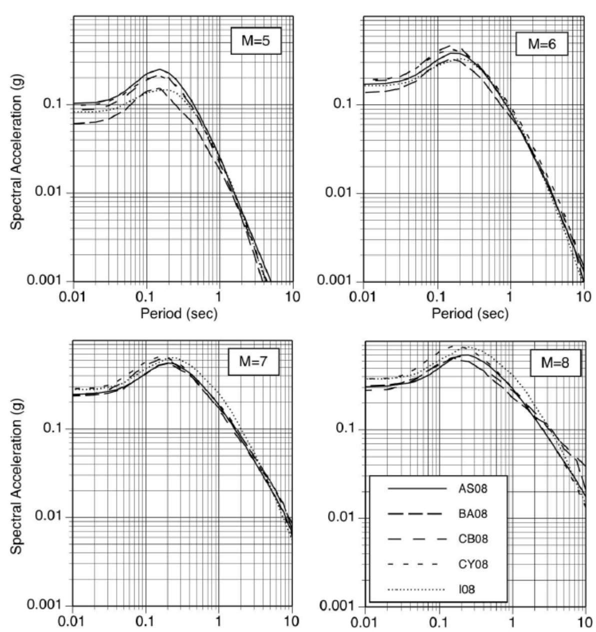
Divergent views on appropriate source zonation models among seismologists and hazard analysts are not uncommon

Six source zonation models for the Sannio-Matese region of Italy proposed by six eminent groups of experts......



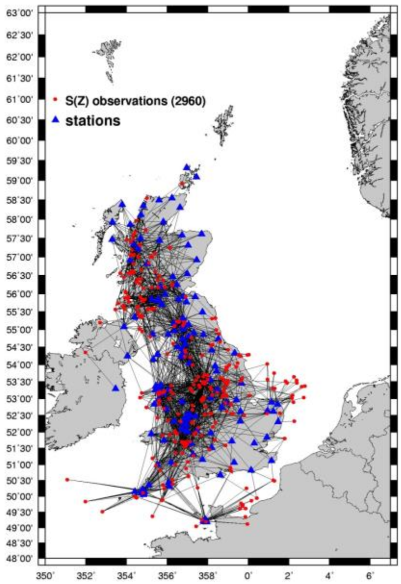
Barbano *et al.* (1989)

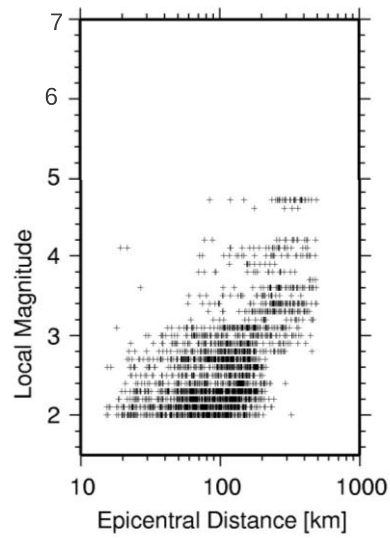
Median spectra for strike-slip earthquakes recorded on rock sites at 10 km, from NGA models for California



Abrahamson *et al.* (2008)

Epistemic Uncertainty Larger in Low Seismicity Regions





Edwards *et al.* (2007)

Overview of Presentation

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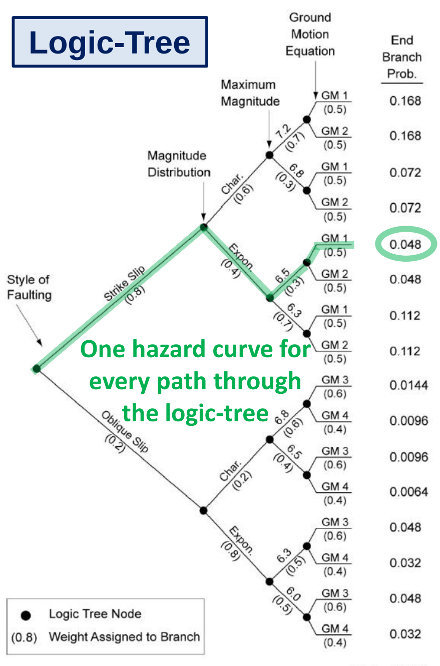
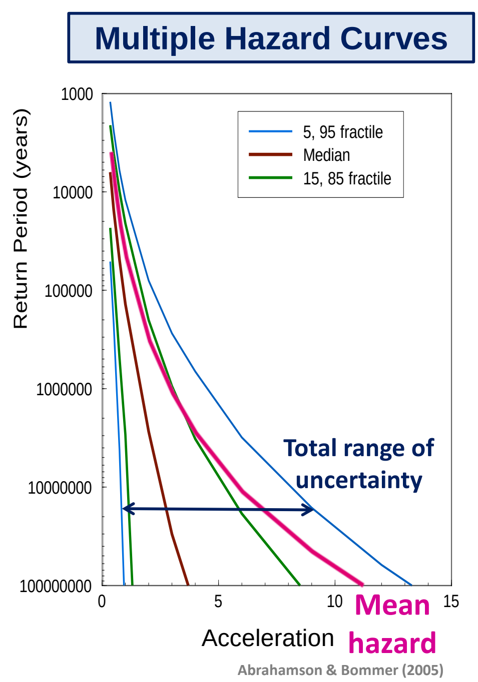
Epistemic Uncertainty and Logic-Trees

The existence of epistemic uncertainty means that for nearly every model and parameter value there is a range of alternatives that warrant consideration

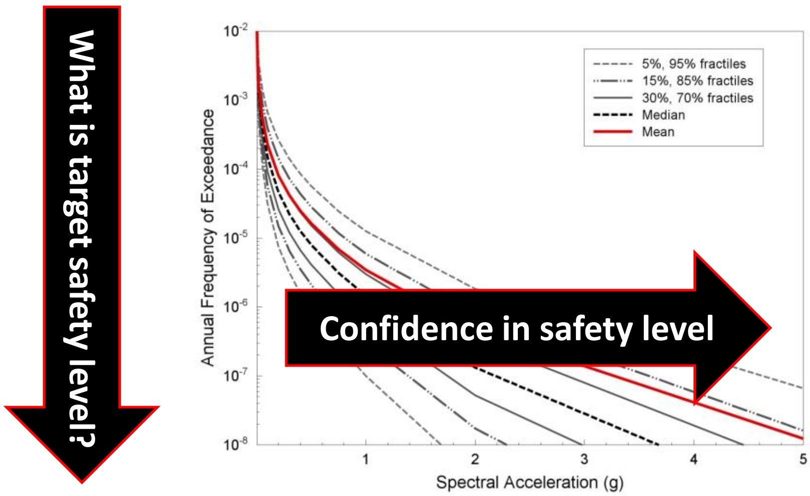
A LOGIC-TREE allows all of the alternative options to be considered and assigned a weight that reflect the relative confidence of the analyst in each model or parameter value being the most appropriate

Whereas aleatory variability influences the shape of the seismic hazard curve, epistemic uncertainty leads to multiple hazard curves

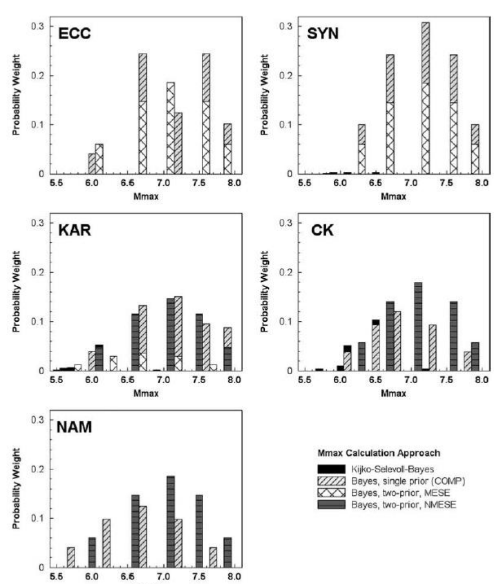




Identification, quantification and incorporation of epistemic uncertainties is fundamental to regulatory assurance



Common practice to include logic-tree branches for Mmax in PSHA studies



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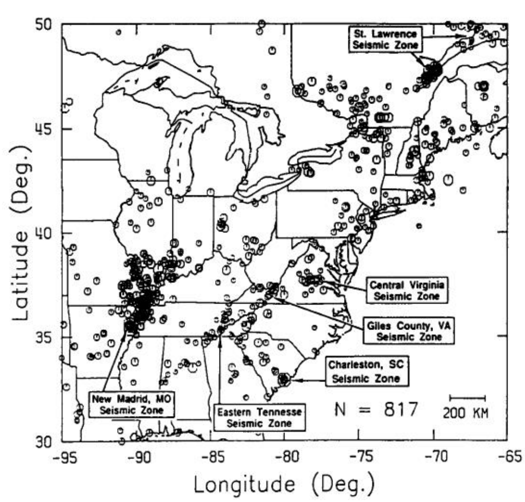
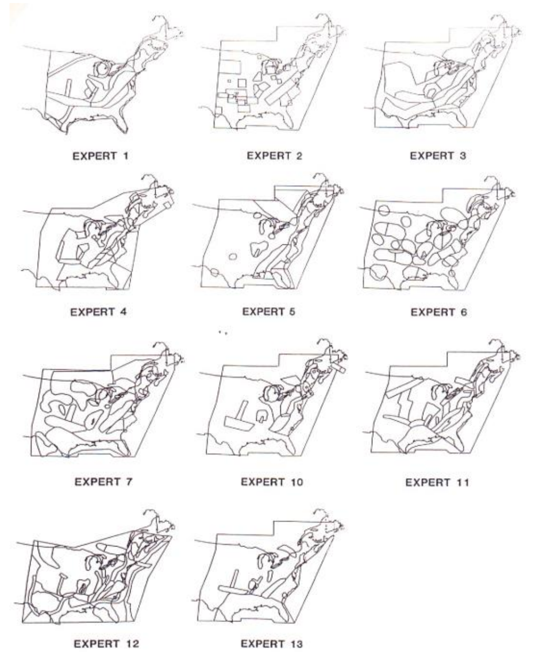
Why was SSHAC formed?

In the 1980s, two major PSHA studies were conducted (by LLNL and EPRI) for nuclear power plant sites in Central and Eastern USA

Because of the high degree of uncertainty regarding seismicity and ground motions in CEUS both projects employed multiple experts (to obtain multiple expert judgements)

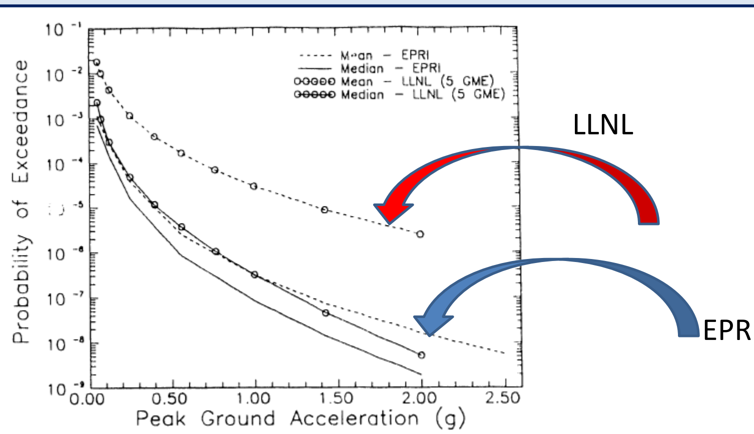


Source models from multiple-expert PSHA study by for NPPs in Central and Eastern USA



Bernreuter *et al.* (1989)

Large systematic differences between the mean hazard estimates from the two projects



This prompted US Department of Energy, EPRI and the US Nuclear Regulatory Commission to form the Senior Seismic Hazard Analysis Committee (SSHAC)

The SSHAC Report was issued in 1997, after an extensive review of the EPRI and LLNL seismic hazard studies

NUREG/CR–6372
UCRL–ID–122160
Vol. 1

Recommendations for Probabilistic Seismic Hazard Analysis: Guidance on Uncertainty and Use of Experts

Main Report

Prepared by
Senior Seismic Hazard Analysis Committee (SSHAC)
R. J. Budnitz (Chairman), G. Apostolakis, D. M. Boore, L. S. Cluff, K. J. Coppersmith, C. A. Cornell, P. A. Morris

Lawrence Livermore National Laboratory

"In the course of our review, we concluded that many of the major potential pitfalls in executing a successful PSHA are <u>procedural</u> rather than technical in character. ….. This conclusion, in turn, explains our heavy emphasis on procedural guidance."

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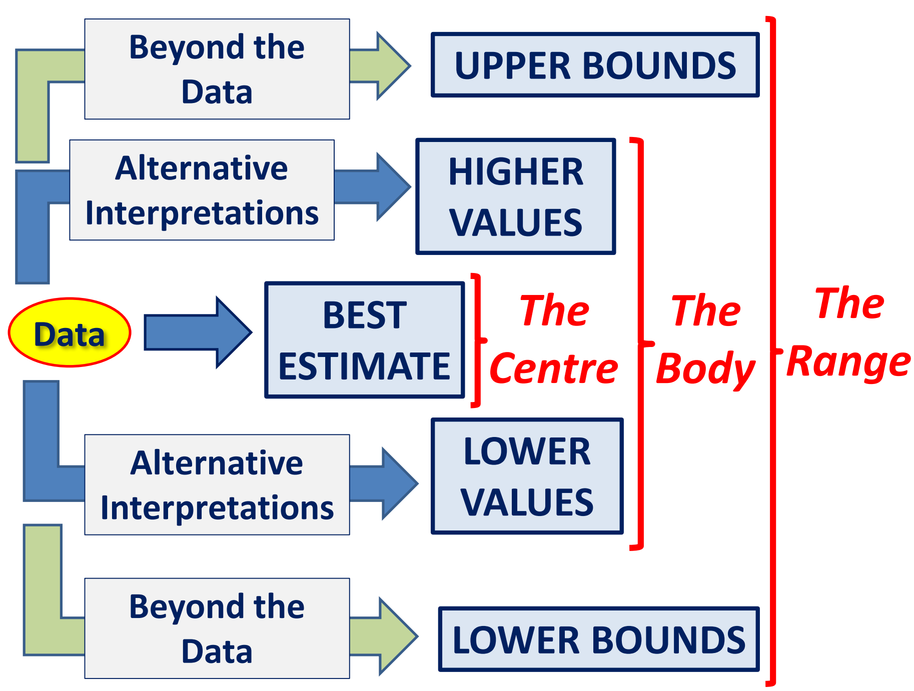
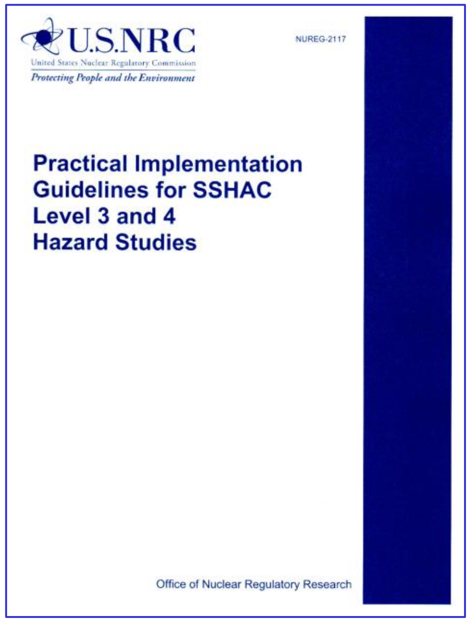
Fundamental Features of the SSHAC Process

- Comprehensive databases available to all participants
- Clearly defined roles and responsibilities
- Ownership of hazard model by evaluator/integrator
- Structured interactions among participants
- Clear sequence of tasks and events
- Peer review (preferably continuous not late-stage)
- Complete documentation

The basic objective is to identify the centre, the body and the range of technically-defensible interpretations (CBR of the TDI) of the available data, methods and models relevant to the assessment of seismic hazard at the site




U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

NUREG-2117

Practical Implementation Guidelines for SSHAC Level 3 and 4 Hazard Studies

Office of Nuclear Regulatory Research

NUREG-2117 (NRC, 2012)

Roles in a SSHAC Level 3 Process

TI Team

EVALUATOR EXPERT	Impartial and objective assessor of potentially applicable models
INTEGRATOR	Ensures that the logic-tree captures the full range of legitimate models
RESOURCE EXPERT	Has particular knowledge of a relevant data set, method or models
SPECIALTY CONTRACTOR	Retrieves new data or undertakes new analyses to inform evaluators
PROPONENT EXPERT	Advocates a particular hypothesis or technical position; will often promote a model that they have developed
PARTICIPATORY REVIEWER	Provides procedural and technical review; ensures capture of full range of views and robust technical justifications of logic-tree

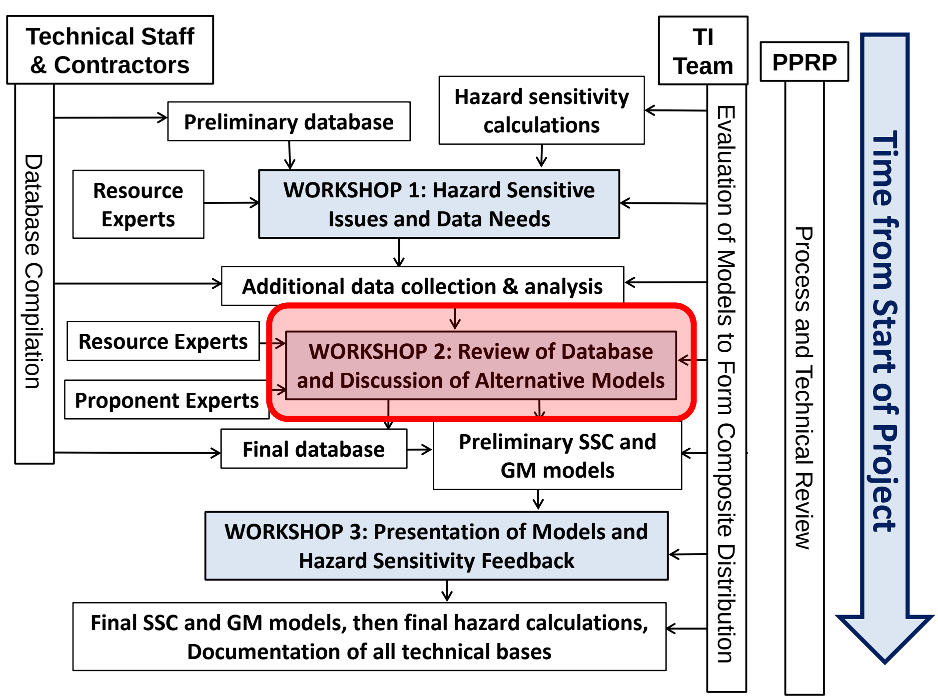
The Two-stage SSHAC Process

1. **Evaluation**

The TI Team examines all available data, methods and models in order to impartially assess their rigour and reliability, and their potential applicability to the situation under study

2. **Integration**

Informed by the process of evaluation, the TI Team develops a logic-tree representing the distribution of their best estimate and its associated uncertainty, representing the centre, the body and the range of the technically-defensible interpretations (CBR of the TDI)



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Initial responses to the Huizinge earthquake of August 2012 focused on the maximum magnitude but from the perspective of scenario-based analysis of hazard and risk

Reassessment of the probability of higher magnitude earthquakes in the Groningen gas field

Including a position statement by KNMI

by

Mevr. Dr. A.G. Muntendam-Bos and Dr. J.A. de Waal

16 January 2013
State Supervision of Mines

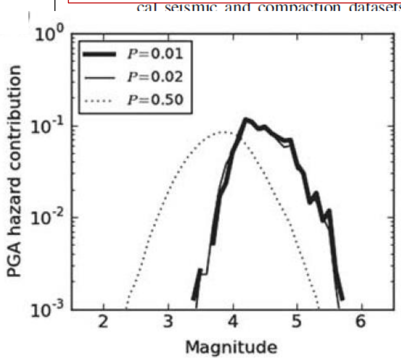
Bulletin of the Seismological Society of America, Vol. 105, No. 3, pp. –, June 2015, doi: 10.1785/0120140302

A Monte Carlo Method for Probabilistic Hazard Assessment of Induced Seismicity due to Conventional Natural Gas Production

by S. J. Bourne, S. J. Oates, J. J. Bommer, B. Dost, J. van Elk, and D. Doornhof

"An alternative estimate of the maximum magnitude based on releasing all induced strain within a single event yields a value of 6.5."

cal seismic and compaction datasets by sampling probability distributions for total



Early disaggregations of hazard (and risk) at short return periods and high-frequency accelerations indicated relative insensitivity to the choice of Mmax

Subsequent analyses have shown that the choice of Mmax is important

For the current hazard and risk analyses, a holding position was adopted reflecting a broad interval of uncertainty (but erring on the conservative side*)

- **5.00**
- **5.75**
- **6.50**

Equal weighting

***** Our current state of knowledge (ignorance) is a value in the interval from 3.6 to 6.5 for induced earthquakes

[All values based on assumption **M** = M_L]

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Roles in a SSHAC Level 3 Process

EVALUATOR EXPERT

TI Team

INTEGRATOR

Expert Panel chaired by Dr Kevin Coppersmith

RESOURCE EXPERT

PROPONENT EXPERT

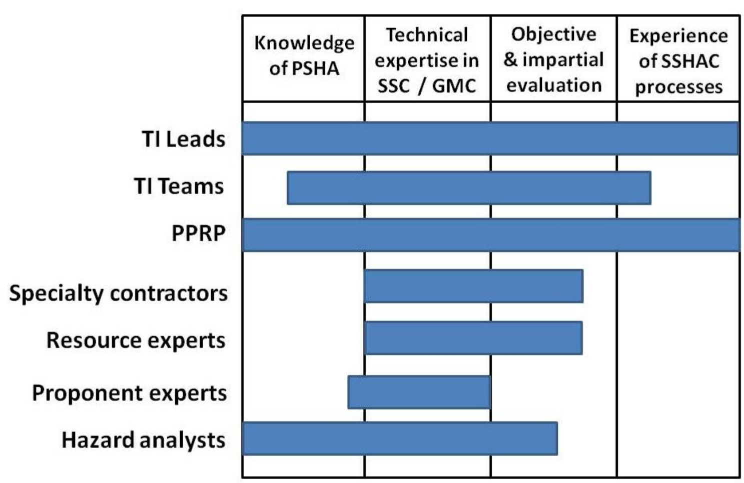
PARTICIPATORY REVIEWER

Dr. Kevin J Coppersmith

Coppersmith Consulting, Inc., California, USA

- **Member of the original Senior Seismic Hazard Analysis Committee (SSHAC) and co-author of SSHAC guidelines**
- **Co-author of EPRI 1994 study on Mmax estimation in stable continental regions**
- **Seismic Source Characterisation Technical Integration (TI) I Lead in SSHAC Level 3 PSHA studies for nuclear sites at Thyspunt (South Africa), Hanford (Washington, USA) and throughout Spain**
- **Project Technical Integrator (PTI) on SSHAC Level 3 PSHA studies in USA and Spain**
- **TFI for Level 4 studies in Switzerland and at Yucca Mountain**
- **Chair of PPRP in Diablo Canyon SSHAC Level 3 PSHA**
- **Member of PPRP in BC Hydro SSHAC Level 3 PSHA**
- **SSHAC Adviser to NRRC at CRIEPI, Japan**
- **Contributor to NUREG-2117 SSHAC implementation guidelines**

Suggested Selection Criteria for SSHAC Participants

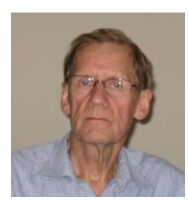


Bommer, J.J. and Coppersmith, K.J., 2013, SMiRT-22, *Lessons Learned from Application of the NUREG-2117 Guidelines for SSHAC Level 3 Probabilistic Seismic Hazard Studies for Nuclear Sites*

Dr. Jon P Ake

US Nuclear Regulatory Commission, USA

- Publications on fluid injection-induced seismicity
- Publications on mining-induced seismicity (including Mmax)
- Co-Author of NUREG-2117 practical implementation guidelines for SSHAC Level 3 and 4 hazard studies
- Expert Panel Member for Yucca Mountain SSHAC Level 4 study
- Member of PPRP for the Central and Eastern United States Seismic Source Characterization (CEUS-SSC) Project
- Member of PPRP for the Next-Generation Attenuation-Central and Eastern North America (NGA-East) Project
- Peer reviewer for U.S. National Academy of Sciences report on Induced Seismicity
- Seismic hazard assessments (including Mmax) for critical facilities throughout U.S.



Dr. Hilmar Bungum

Consultant (Retired NORSAR), Norway

- Formerly Adjunct Professor of Geophysics, Universities of Bergen and Oslo, Norway
- Publications: Thomson Reuter's Web of Knowledge h-index = 27
- Ground-motion panel member in SSHAC Level 4 PSHA studies in Switzerland (Pegasos and Pegasos Refinement)
- Chairman of the PPRP in SSHAC Level 3 PSHA studies of nuclear power plant sites in South Africa and Spain
- Chair of Independent Review Panel for two nuclear power plant PSHA studies in the UK
- Adviser to regulatory authorities in Sweden and Finland on issues related to permanent underground storage of nuclear waste

Professor Dr. Torsten Dahm

GFZ, Potsdam, Germany

- **Extensive experience in earthquake seismology, fluid-filled fractures, induced seismicity and seismic discrimination**
- **Former editor of *Geophysical Journal International* and Editor-in-Chief of *Journal of Seismology***
- **Independent reviewer for induced seismicity in gas storage projects in The Netherlands and Spain**
- **Member of international the commission on the Volcano programme 2007-2009 in Italy for DPC/INGV**
- **Chair of german (FKPE) advisory group on the induced seismicity discrimination problem**
- **Topic speaker for Natural Hazard and Risk within the Earth and Environment POFIII programme of Helmholtz**

Professor Ian Main FRSE

University of Edinburgh, UK

- **Extensive experience in statistical seismology, earthquake population dynamics, natural and induced seismicity and hazard, and underpinning rock physics**
- **Moderator of the 1999 *Nature* debate on Earthquake Prediction**
- **Member of the International Commission on Operational Earthquake Forecasting for Civil Protection, 2009-10.**
- **Awarded the 2014 Louis Neel medal of the European Union of Geosciences for 'Sustained and exceptional contributions' in seismology and rock physics 'including earthquake scaling, hazard and fluid movements in hydrocarbons reservoirs'**
- **Member of the Independent Review Group for decommissioning of the Brent oilfield 2013-2015, reporting to DECC and Shell UK**
- **Independent reviewer for Shell and SodM on induced seismicity in the Groningen field, 2012-present**

Dr. Art McGarr

US Geological Survey

- **Internationally recognized expert on induced seismicity with numerous publications on earthquakes induced by mining, oil production and waste water injection**
- **Developed ground motion prediction equations for coal-mining induced earthquakes in central Utah that were key to assessing the seismic risk to the Joe's Valley Dam, which is in close proximity to extensive coal mining.**
- **Developed a seismic hazard assessment for the Sudbury Neutrino Observatory, which was at an early stage of development in 1990. There was concern that ground motion from earthquakes induced in the Creighton Mine might damage the neutrino detection facility. The hazard assessment provided the design engineers with the information they needed to proceed.**

Mr. Ivan Wong

AECOM (for now), California, USA

- **Extensive experience in seismic hazard studies for critical facilities around the world**
- **Project Manager for the SSHAC Level 4 Yucca Mountain PSHA and PFDHA**
- **Member of SSC TI Team in SSHAC Level 3 PSHA for hydroelectric dams in British Columbia, Canada**
- **Currently engaged in seismic hazard assessments related to induced earthquakes in the U.S. and Canada**
- **Coauthor of the U.S. Department of Energy Protocol and Best Practices for geothermal-induced seismicity**
- **Coauthor of the StatesFirst (U.S.) primer on induced seismicity associated with oil and gas activities**

Dr Robert R Youngs

AMEC Foster Wheeler (Geomatrix)

- **Pre SSHAC SSC TIF Team member for EPRI-SOG CEUS PSHA**
- **Contributor to EPRI 1994 study on Mmax estimation in stable continental regions**
- **Updated Mmax estimation approaches as part of TI Team for SSHAC Level 3 CEUS-SSC project**
- **SSC TFI Team member for Level 4 studies in Switzerland and at Yucca Mountain**
- **Resource Expert on Mmax for SSHAC Level 3 PSHA study for nuclear site at Thyspunt (South Africa)**
- **Jesuit Seismological Association Award for Observational Seismology from the Eastern Section of Seismological Society of America**

Roles in a SSHAC Level 3 Process

EVALUATOR EXPERT

TI Team

INTEGRATOR

Expert Panel chaired by Dr Kevin Coppersmith

RESOURCE EXPERT

PROPONENT EXPERT

Presentations to follow in the next three days

PARTICIPATORY REVIEWER

Agenda: Day 1 (Tuesday 8th March 2016)

10:00-11:30 am: Closed meeting of Expert Panel, Room G3.02

Start	End	Topic	Speaker
11:45	13:00	*Lunch and coffee*	
13:00	13:30	Welcome. Overview of Groningen hazard & risk project	Jan van Elk
13:00	14:00	The SSHAC process and application to this project	Julian Bommer
14:00	14:30	Objectives of the workshop: definition of Mmax	Kevin Coppersmith
14:30	15:15	Geology of the Groningen field	Clemens Visser
15:15	15:30	*Coffee*	
15:30	16:00	History and future perspective of gas production	Leendert Geurtsen
16:00	16:45	History of geomechanics for the Groningen field	Rob van Eijs
16:45	17:30	History of earthquakes in the Groningen field	Bernard Dost
17:30	18:00	Comments from observers	SAC /SodM
18:00	18:30	Closing comments from expert panel	Kevin Coppersmith

Agenda: Day 2 (Wednesday 9th March 2016)

Start	End	Topic	Speaker
08:30	09:00	*Coffee*	
09:00	09:30	Re-cap of Day 1	Kevin Coppersmith
09:30	10:30	Overview of Mmax estimation for natural earthquakes	Bob Youngs
10:30	10:45	*Coffee*	
10:45	11:15	History of KNMI Mmax estimates for Groningen	Bernard Dost
11:15	12:15	Overview of triggering large EQs	Emily Brodsky
12:15	13:15	*Lunch*	
13:15	14:15	Overview of largest induced/triggered events	Gillian Foulger
14:15	15:15	Mmax distribution for Groningen	Dinske, Shapiro
15:15	15:30	*Coffee*	
15:30	17:30	Mmax distribution for Groningen	Nora Dedontney/ Pablo Sainz
17:30	18:00	Comments from observers	SAC /SodM
18:00	18:30	Closing comments from expert panel	Kevin Coppersmith

Agenda: Day 3 (Thursday 10th March 2016)

Start	End	Topic	Speaker
08:30	09:00	*Coffee*	
09:00	10:00	Re-cap of Days 1 and 2	Kevin Coppersmith
10:00	11:00	Mmax distribution for Groningen	Stephen Bourne
11:00	11:15	*Coffee*	
11:15	12:15	Mmax distribution for Groningen	Gert Zöller / M. Holschneider
12:15	13:15	*Lunch*	
13:15	14:15	TNO Mmax models for Groningen	Steve Oates*
14:15	15:15	Mmax distribution for Groningen	Jenny Suckale
15:15	15:30	*Coffee*	
15:30	16:30	Mmax distribution for Groningen	Rick Wentinck / Peter van den B.
16:30	17:30	General discussion	All participants
17:30	18:00	Comments from observers	SAC /SodM
18:00	18:30	Closing comments from expert panel	Kevin Coppersmith

* The TNO reports will be summarised by Dr Steve Oates because authors of TNO report declined to present

Roles in a SSHAC Level 3 Process

TI Team
- EVALUATOR EXPERT
- INTEGRATOR

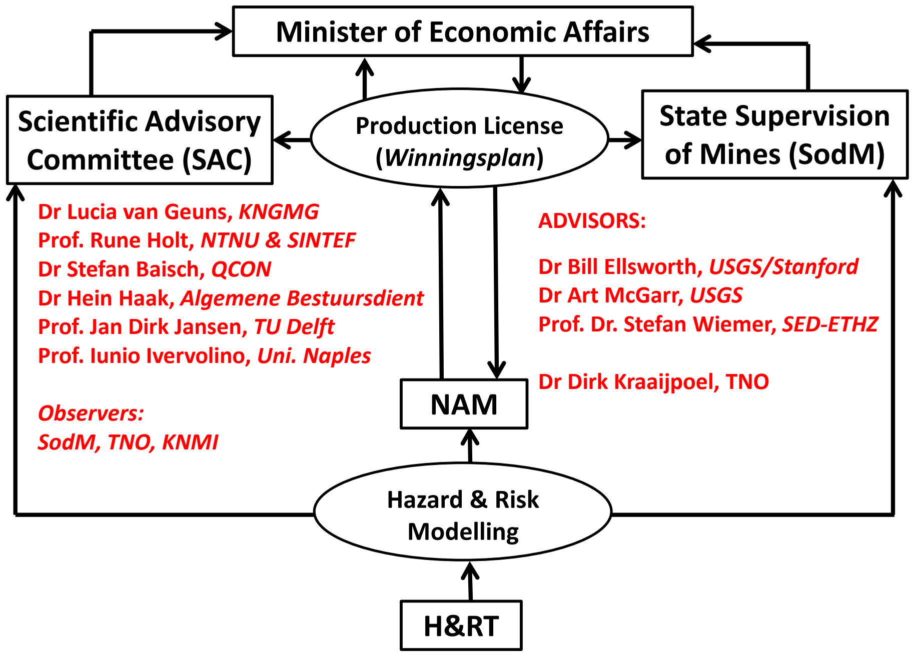
Expert Panel chaired by Dr Kevin Coppersmith

- RESOURCE EXPERT
- PROPONENT EXPERT

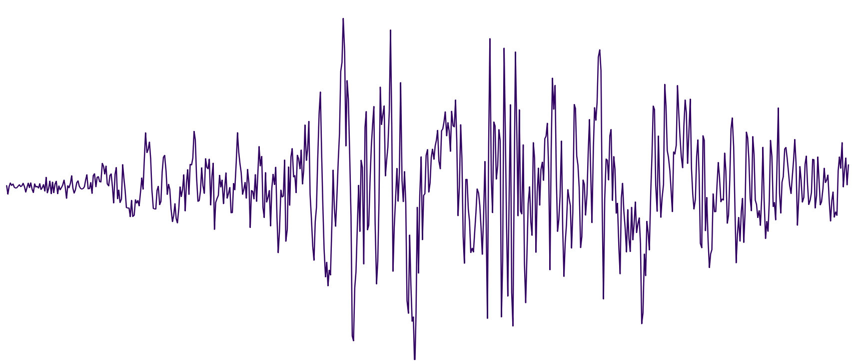
Presentations to follow in the next three days

- PARTICIPATORY REVIEWER

SAC and SodM plus expert advisors, EBN



Wishing you all an enjoyable and interesting workshop!



Objectives of the Workshop
Definition of Mmax

Kevin J. Coppersmith

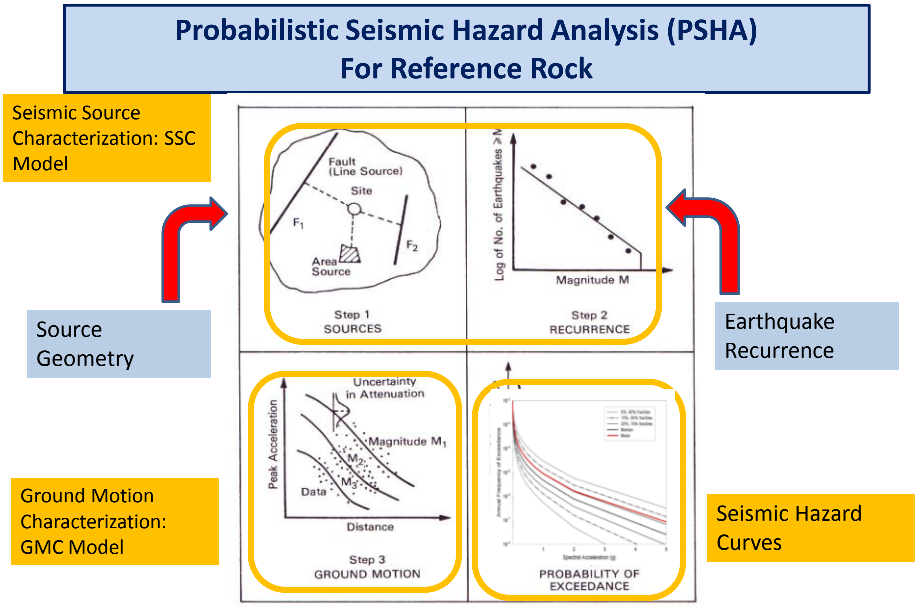
Workshop on Maximum Magnitude Estimates for Probabilistic Seismic Hazard and Risk Modelling in Groningen Gas Field

8-10 March 2016

World Trade Centre, Schiphol Airport, Amsterdam,

Objective of Workshop

- To develop an estimate of Mmax for the Groningen field that can be used in a PSHA
  - Based on the evaluation of applicable data, models, and methods by the Mmax Panel
  - Captures the center, body, and range of technically defensible interpretations
  - Seismic source-specific estimate



Modified from Reiter (1990)

3

Definition of Mmax

- Largest earthquake that a seismic source can generate within the present tectonic regime
  - Upper bound to the magnitude-frequency relationship
  - Seismic source-specific
  - Independent of time as long as within present tectonic regime
  - Commonly associated with considerable epistemic uncertainty

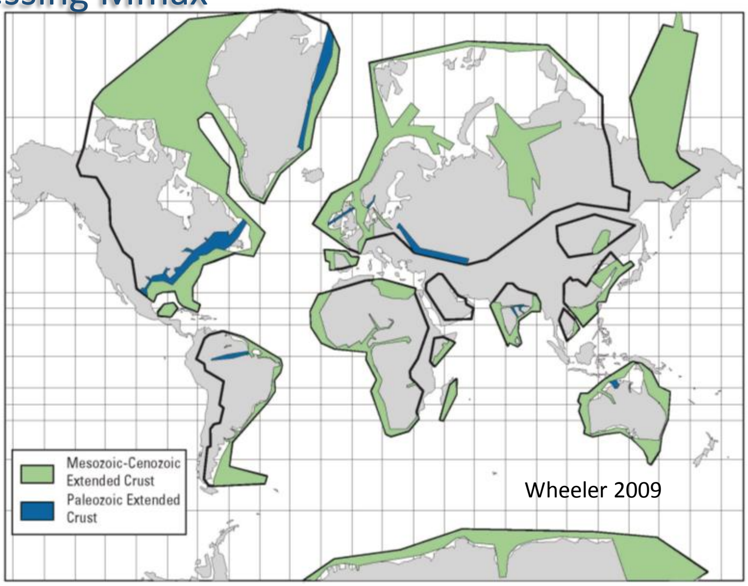
Ergodicity

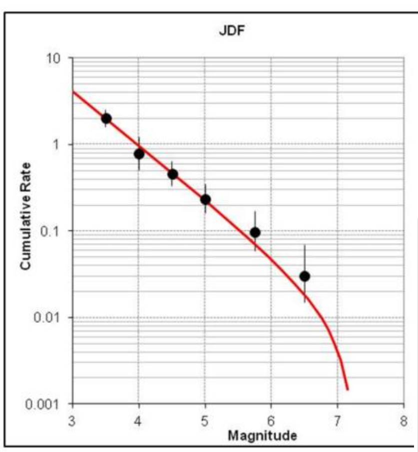
- The concepts of ergodicity and the ergodic hypothesis: The underlying idea is that for certain systems the time average of their properties is equal to the average over the entire space.
- Space-for-time substitution: increase the length of the record at one location by considering other, analogous, locations
- Common application in assessing rare events such as large earthquakes, large ground motions
- Plus: Often provides more statistically significant numbers of events
- Minus: Often glosses over differences to increase the sample size

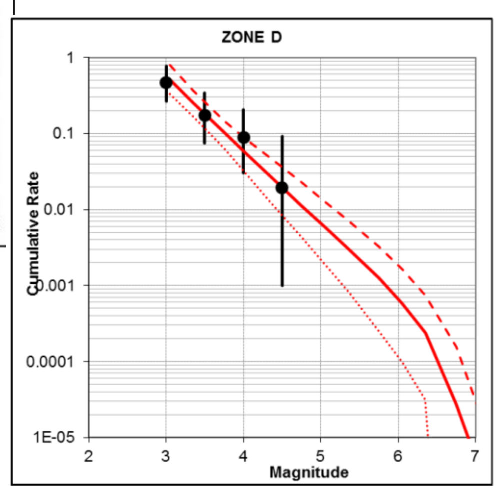
Short History of Mmax for Tectonic Seismic Sources

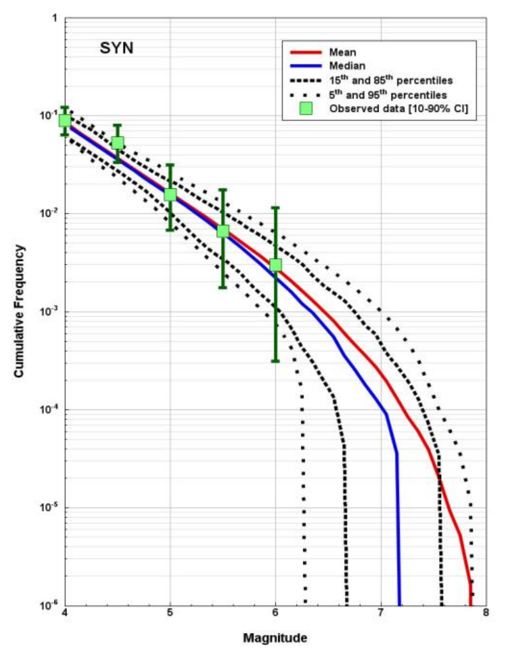
- First Mmax assessments were for source zones
  - Max observed (if large)
  - M_{obs} + increment
  - Source-specific recurrence, arbitrary return period
- Ergodicity imposed: Consider the largest magnitude in tectonically analogous regions
  - What are tectonic analogues?
  - Listings of largest earthquakes globally: up to ~M8
  - Attempts to subdivide: ACR, intraplate, SCR
  - Make source-specific: types and ages of structures, correlations with magnitude
  - Because few things are statistically correlated with magnitude, Mmax distributions remain wide

Stable Continental Regions: Analogues to CEUS for Assessing Mmax



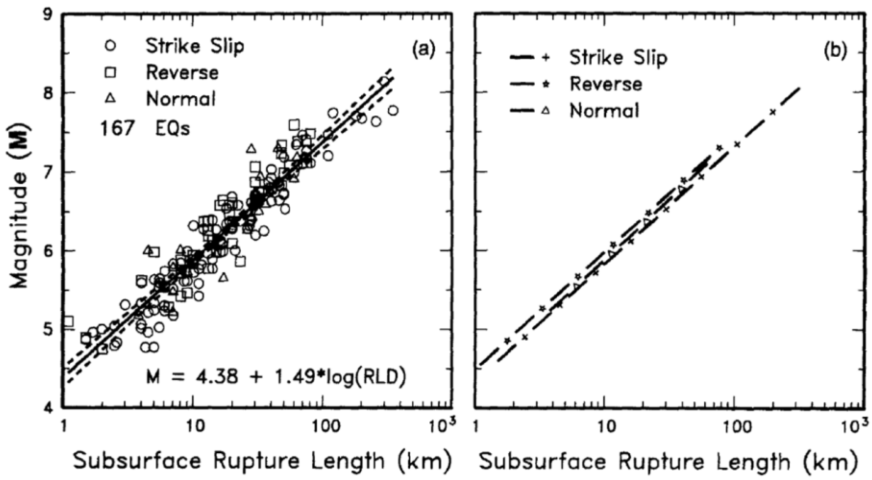






Short History of Mmax for Tectonic Seismic Sources (cont'd)

- Fault sources
  - Paleoseismic recurrence not statistically significant (just like observed catalogue) for Mmax
  - Never fully ergodic: largest fault-related earthquake defines Mmax for a given fault
  - Partially ergodic:
    - Rupture dimensions relate to magnitude
    - Estimates of dimensions for large magnitudes come from analogues
    - Uncertainties in rupture dimensions associated with a fault-specific Mmax
    - Logic trees and fault-specific Mmax distributions



Wells & Coppersmith 1994

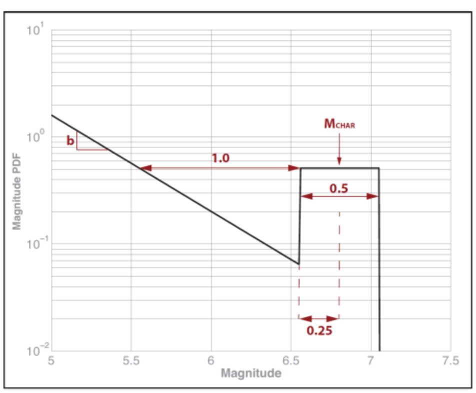


Figure 2. General form and parameters of the Youngs and Coppersmith (1985) MFD.

Youngs & Coppersmith, 1985

Fault-Specific Constraints

- Slip rate/seismic moment rate
- Observed seismicity
- COV of repeated displacements

Wooddell et al. 2014

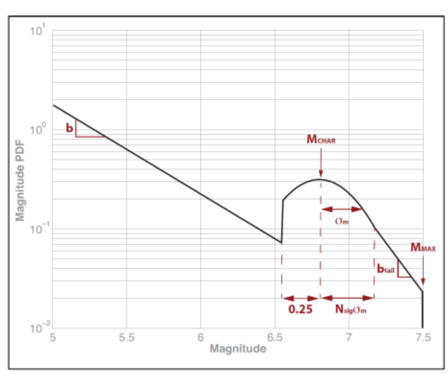


Figure 3. General form and parameters of the WAACY model.

Assessing Mmax for Sources of Induced Seismicity

- McGarr and Simpson (1997): “induced” events are those where man-made stress changes account for most of the stress perturbation and “triggered” events are those where the man-made stress changes are minor
  - Implies different Mmax
  - Distinction is difficult to make for most sources
- Ergodicity: assemble all (potentially) triggered and induced earthquakes as analogues
  - Subdivide: Mechanism for stress perturbation (injection, withdrawal, hydraulic frac, reservoir)
  - Results in large uncertainty in Mmax up to largest analogous earthquakes

Assessing Mmax for Sources of Induced Seismicity (cont’d.)

- Physical approaches: partially ergodic
  - Consider physical mechanisms for stress perturbations at analogous fields
  - Progressively more field specific:
    - Total injected volumes; time dependence
    - Field production history
    - Presence of faults, fault density, dimensions
    - Pre-production seismicity
    - Spatial extent of seismicity relative to the field
    - Seismic moment rate and cumulative moment
    - Timing of observed magnitudes relative to production
    - Ambient stress state (tectonic stresses)
    - Strain partitioning/ seismic efficiency

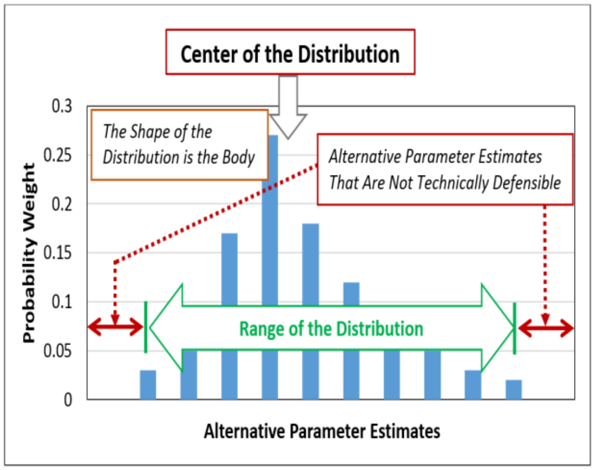
Implications to Groningen Mmax Assessment

- Mmax definition is still valid and a distribution can be used in PSHA
- Assessment should be as source-specific as possible
  - Ergodic estimates should be used with caution
    - Provide collections of earthquakes deemed to be analogous, but glosses over distinctions
    - Can provide insights into physical processes
    - Use to develop models, approaches that then use source-specific information
  - Use of the assessed Mmax will be source-specific

Implications to Groningen Mmax Assessment (cont'd.)

- Uncertainties in Mmax are important
  - Treated as an epistemic uncertainty: there is a true Mmax for the field and we don't know what it is
  - Will include both conceptual model and parameter uncertainties; logic trees handle this well
  - If have different alternative models or methods, can have alternative branches
- SSHAC process is well-suited to this assessment
  - Will hear from Resource and Proponent Experts
  - We are acting as a TI Team, responsible for the assessment
  - We will capture the center, body, and range of technically defensible interpretations

Center, Body and Range - Illustrated



Center, Body, and Range of Technically Defensible Interpretations = CBR-TDI USNRC, 2014

Our Deliverables

- A Groningen field-specific Mmax distribution for use in PSHA
- Summary of technical justification for distribution
- We are not attempting to address other sources, source types, mechanisms, etc.
- Our results apply to the Groningen field only and they are a snapshot of our current knowledge and uncertainties

References

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- Wooddell KE, NA Abrahamson, AL Acevedo-Cabrera, and RR Youngs. 2014. Hazard implementation of simplified seismic source characterization allowing for linked faults. *Seismological Research Letters* 85(2):471.
- Youngs, R.R., and Coppersmith, K.J., 1985, Implications of fault slip rates and earthquake recurrence models to probabilistic hazard estimates: *Bulletin of the Seismological Society of America*, v. 75, pp. 939-964.

INTRODUCTION TO THE GEOLOGY OF THE GRONINGEN FIELD

NAM

Mmax WORKSHOP
March 2016

BRON VAN ONZE ENERGIE

PRESENTATION OUTLINE

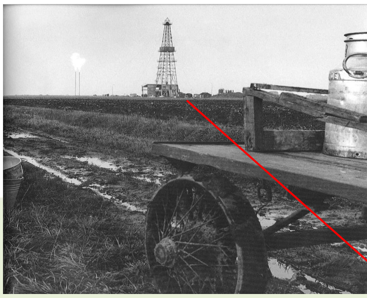
- Introduction to Groningen
- Tectonic setting
- Structural model framework
- Depositional setting
- Property models
- Earthquakes in Groningen

2

GENERAL INTRODUCTION

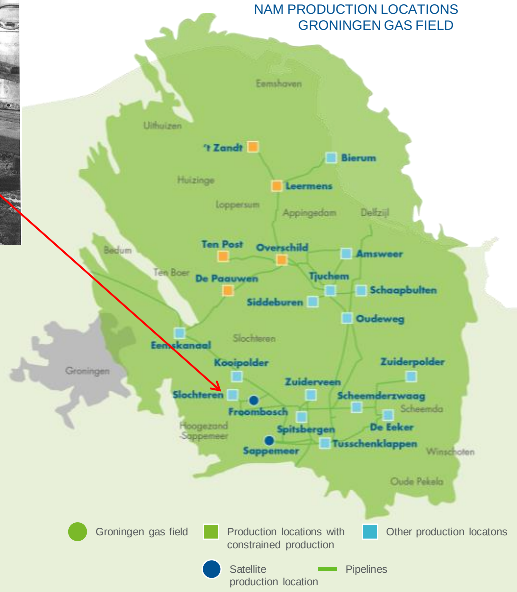
Groningen area

Discovery well Slochteren-1, 1959



Field Characteristics	
Area	862 km²
Discovered	1959
Wells drilled	333
Producing wells	253
Observ. wells	32
Water inj. Wells	2
GIIP	~2900 mrd Nm³

Main Reservoir Properties	
Net / Gross	0.88 – 0.98
Porosity	0.11 – 0.18
Permeability	1 – 1000 mD
Gas Saturation	0 – 0.83

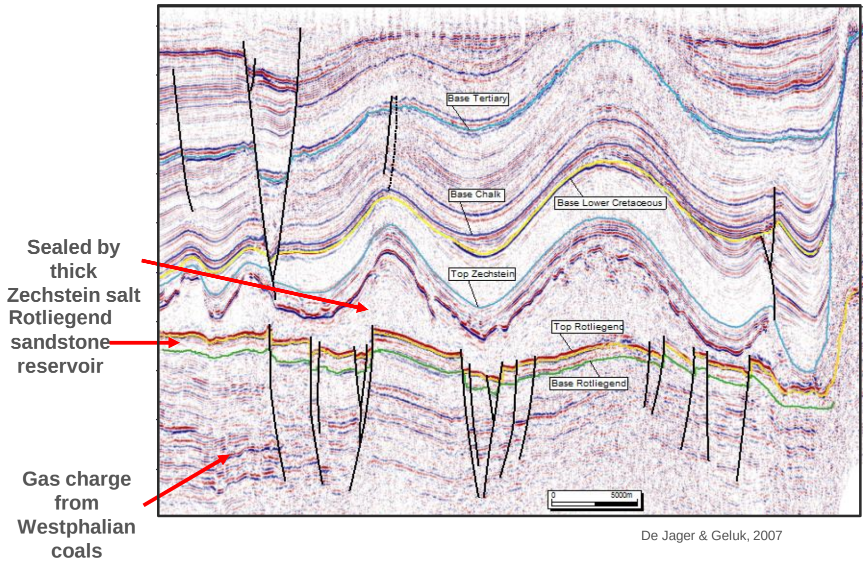


A FEW NUMBERS (as per January 1st 2015)*

- Total cumulative production in the Netherlands 3345 x 10^9 m^3 gas
- Remaining proven reserves 883 x 10^9 m^3
- 95% contained in Rotliegend reservoirs
- 3/4 contained in the Groningen field alone (671 x 10^9 m^3 gas)
- 255 producing fields
- Total production in 2014 was 66 x 10^9 m^3 gas (42.4 from Groningen)
- Yearly Dutch consumption ~42 x 10^9 m^3 gas

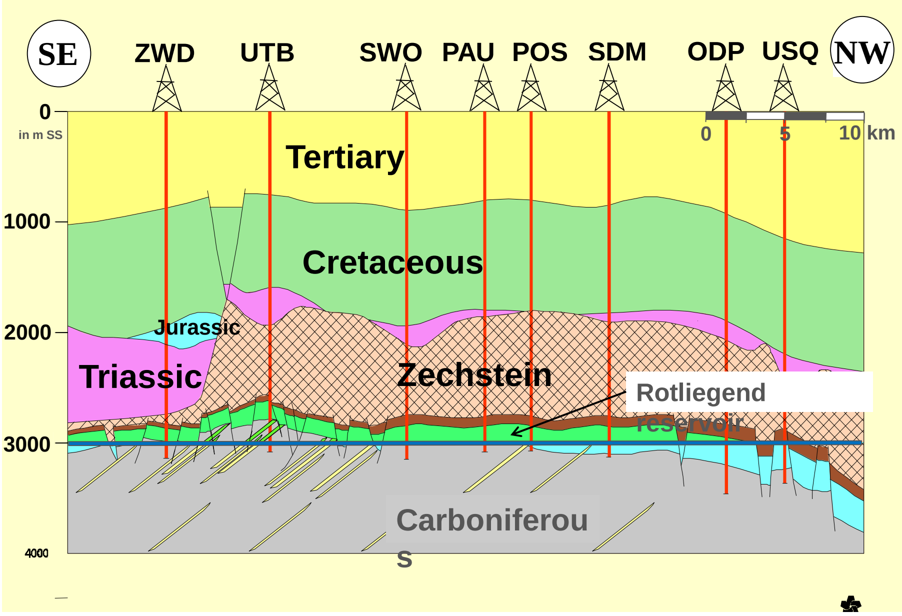
* Data Ministry of Economic Affairs

Rotliegend play - seismic line



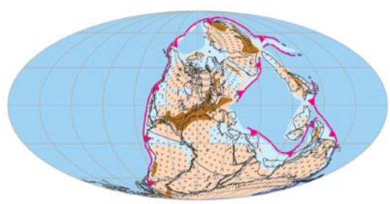
De Jager & Geluk, 2007

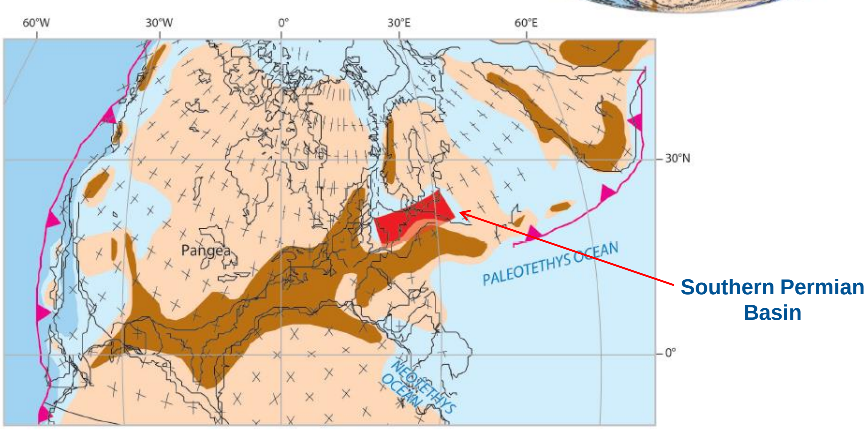
Schematic cross-section

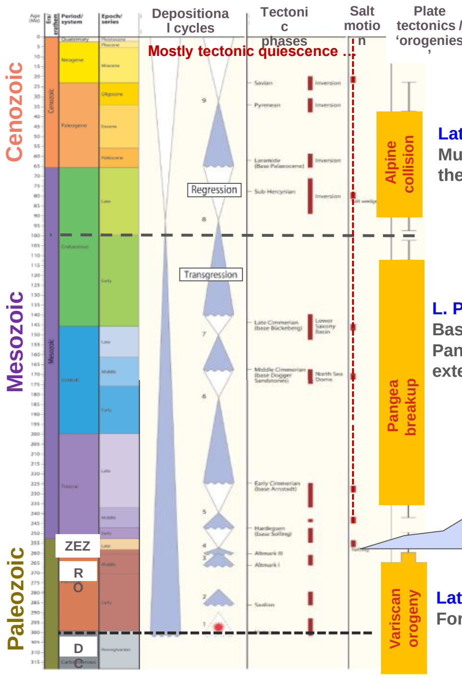


TECTONIC SETTING

Late Carboniferous Pangea Supercontinent





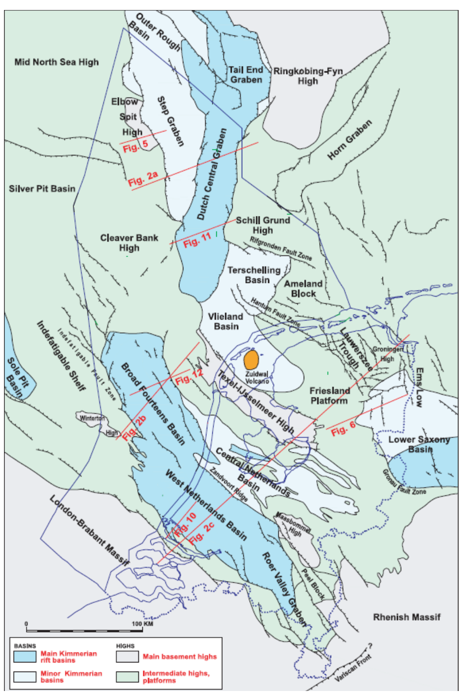


Main tectonic phases

Late Cretaceous to Cenozoic:
Multiple pulses of intra-plate compression related to the Alpine Orogeny. Widespread basin inversion.

L. Permian to Early Cretaceous: progressive rifting
Basin development associated with breakup of the Pangea Supercontinent. Multiple phases of crustal extension, subsidence, uplift.

Late Carboniferous:
Formation of the Pangea Supercontinent



Main structural elements

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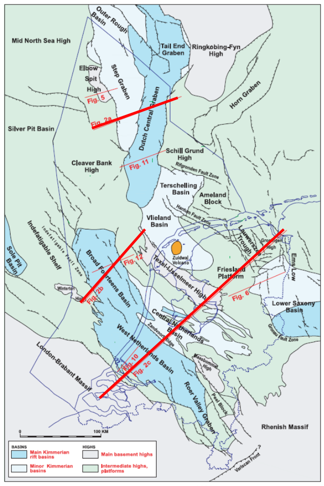
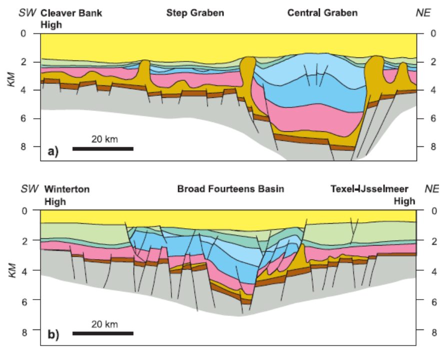
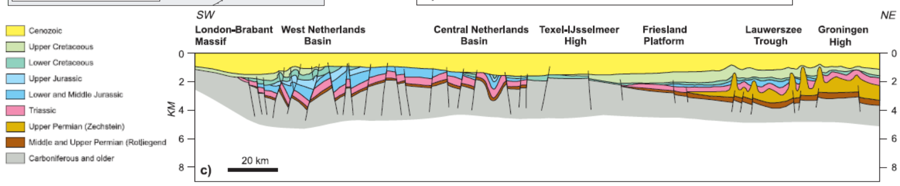
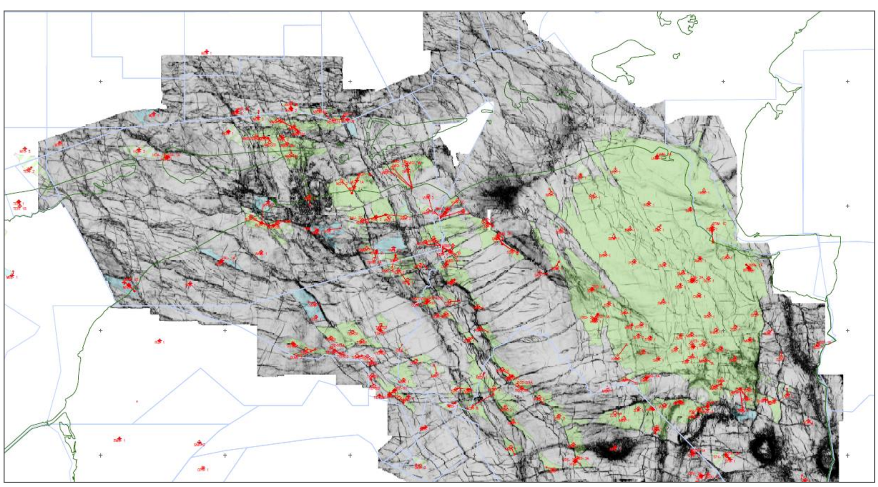
Regional geological overview



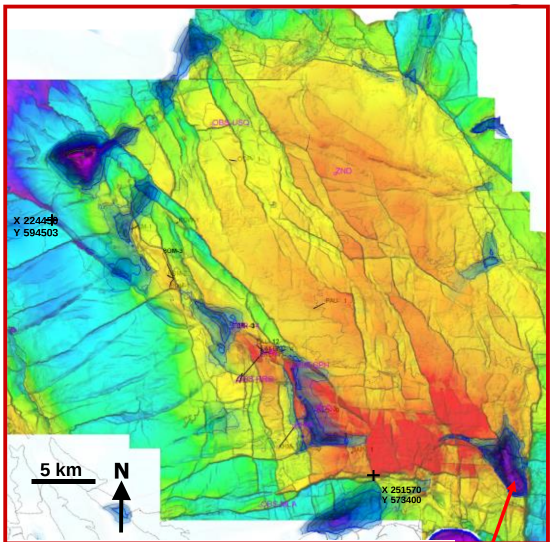




Regional Top_Rotliegend semblance map

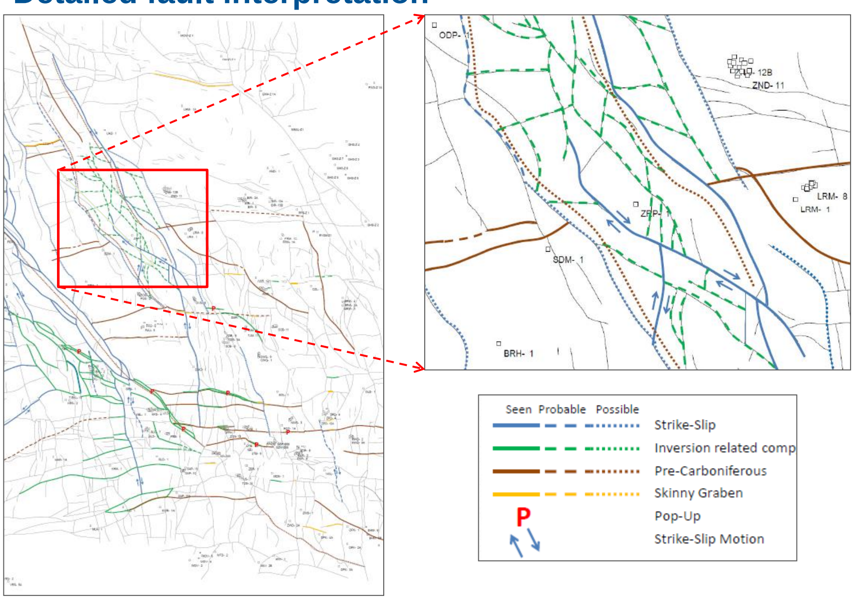


Top_Rotliegend structural map

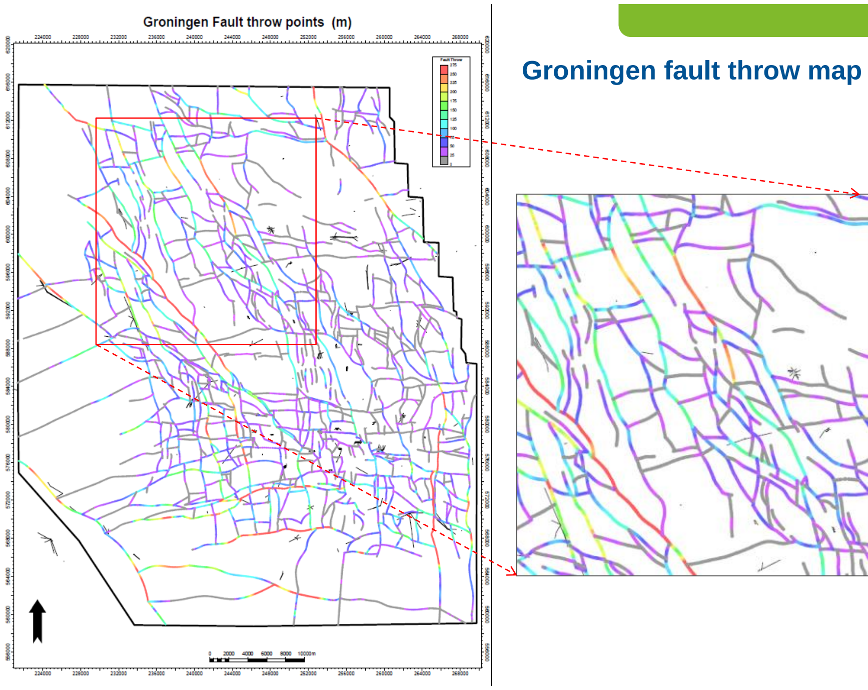


Zechstein isochores >1000m

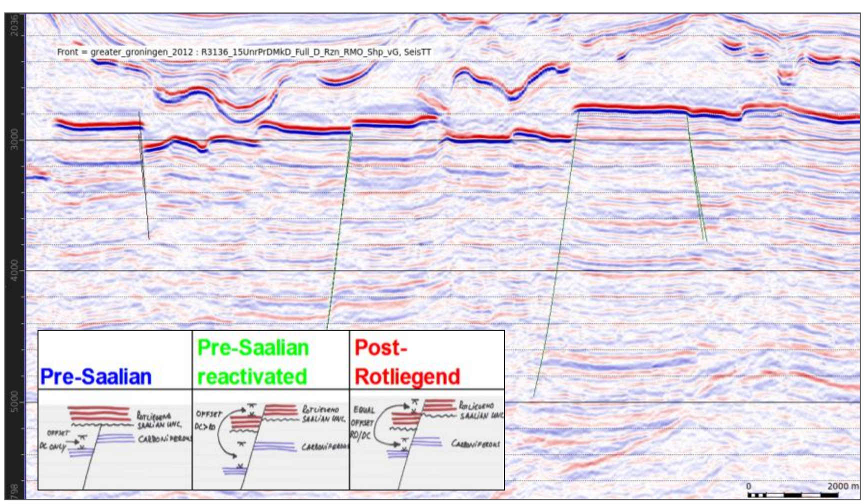
Detailed fault interpretation



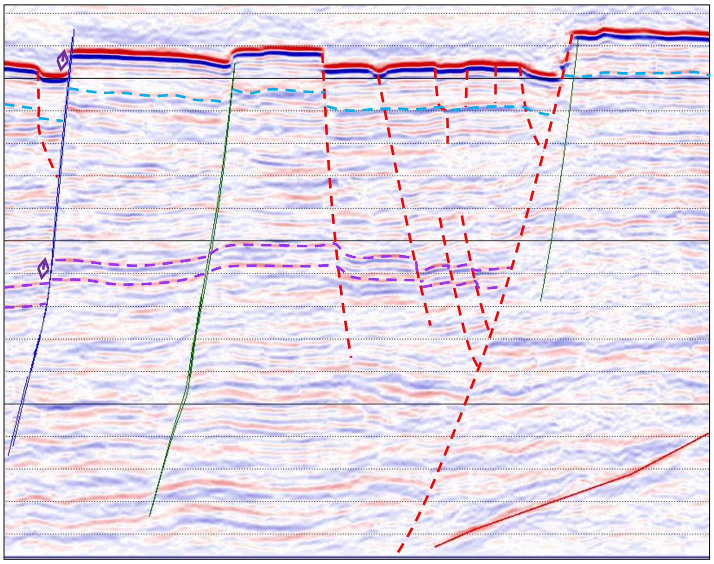
Groningen fault throw map



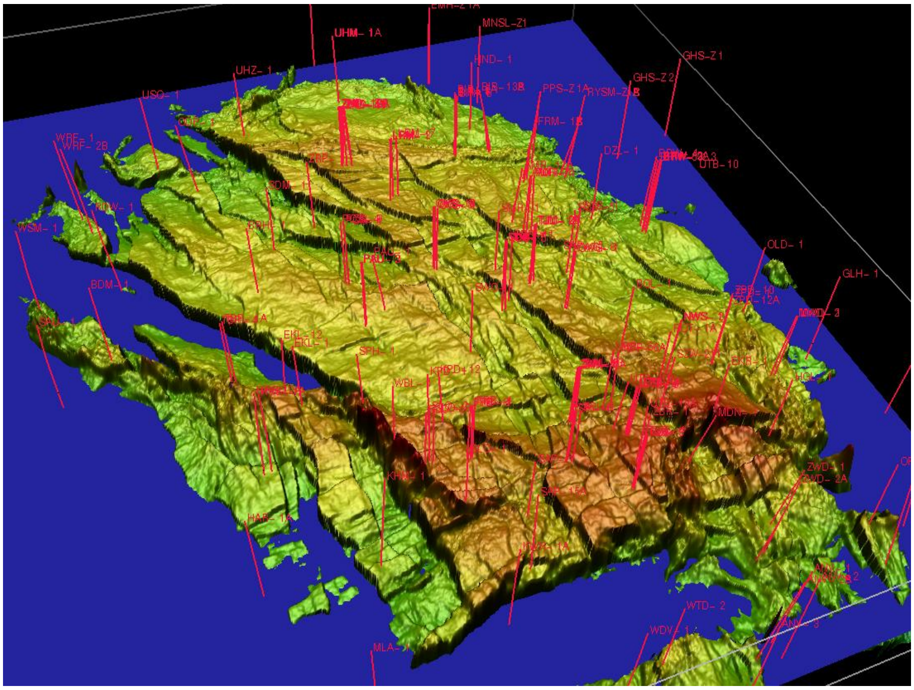
Newly reprocessed seismic now available



Newly reprocessed seismic now available

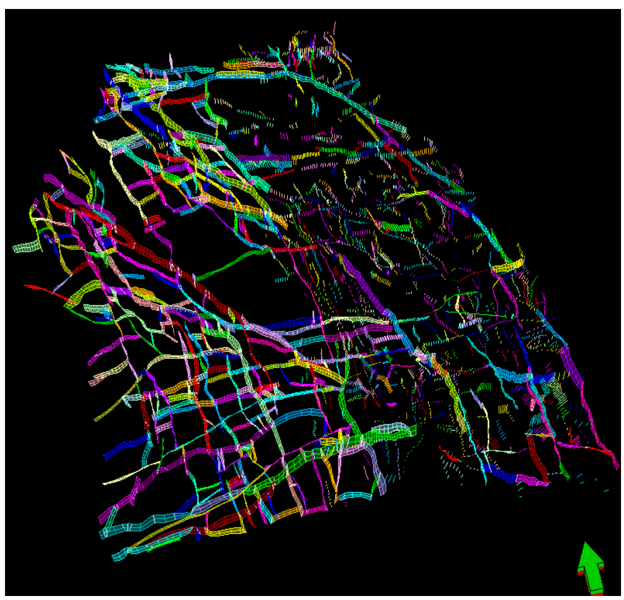


MODEL FRAMEWORK

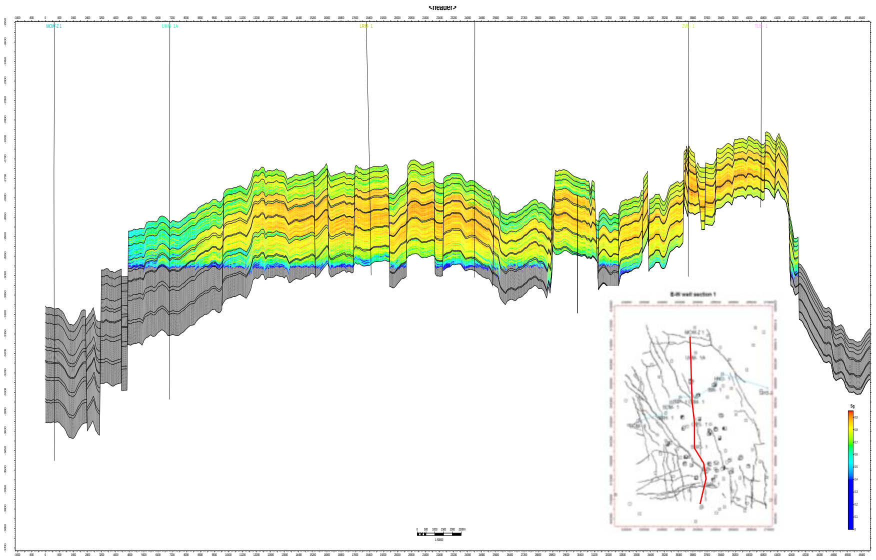


Groningen fault model

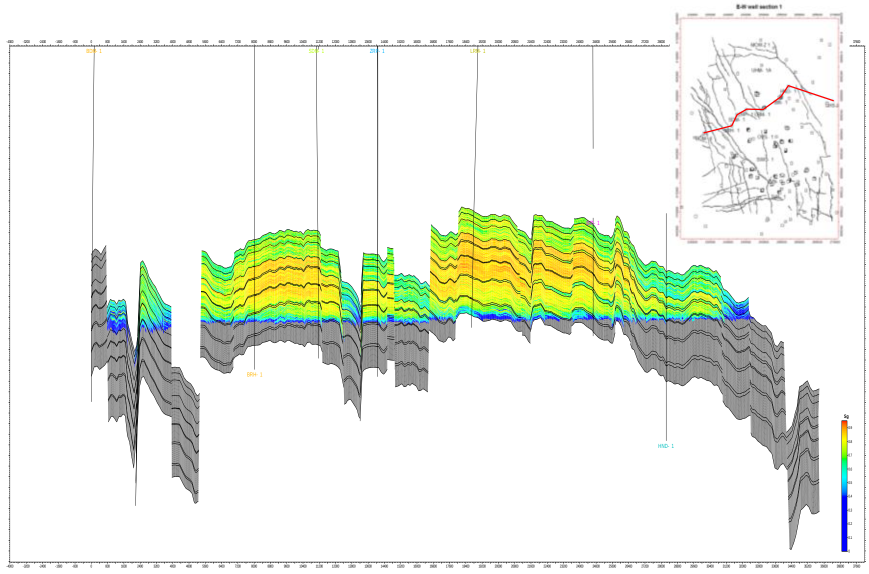
- 1700 faults interpreted
- 1100 faults in Petrel model
- 700 faults used for gridding
- Hand-picked inclined faults
- 100 x 100 m grid



N-S section through saturation model

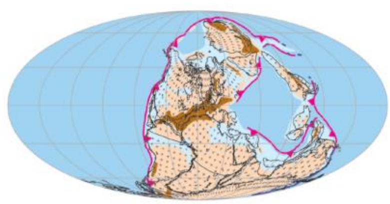


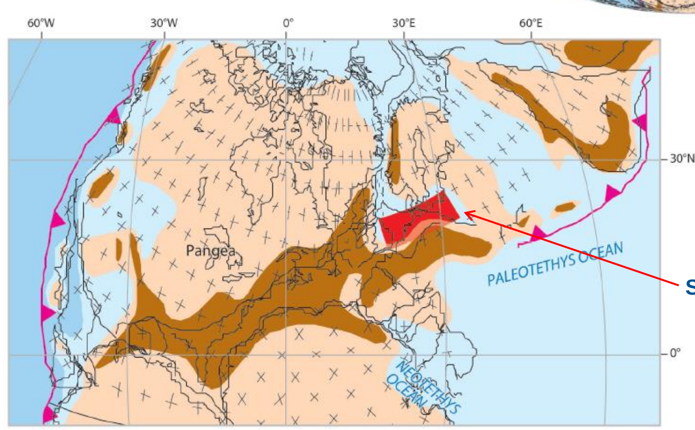
E-W section through saturation model



DEPOSITIONAL SETTING

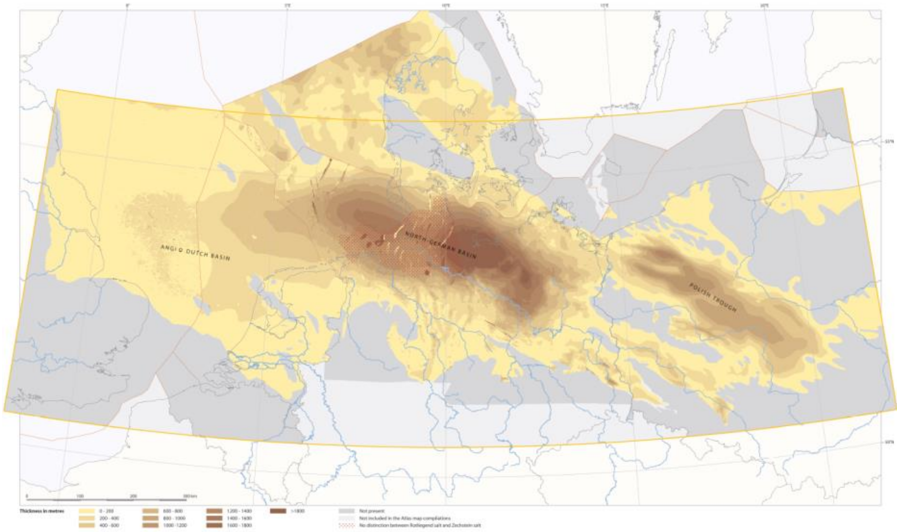
Late Carboniferous Pangea Supercontinent



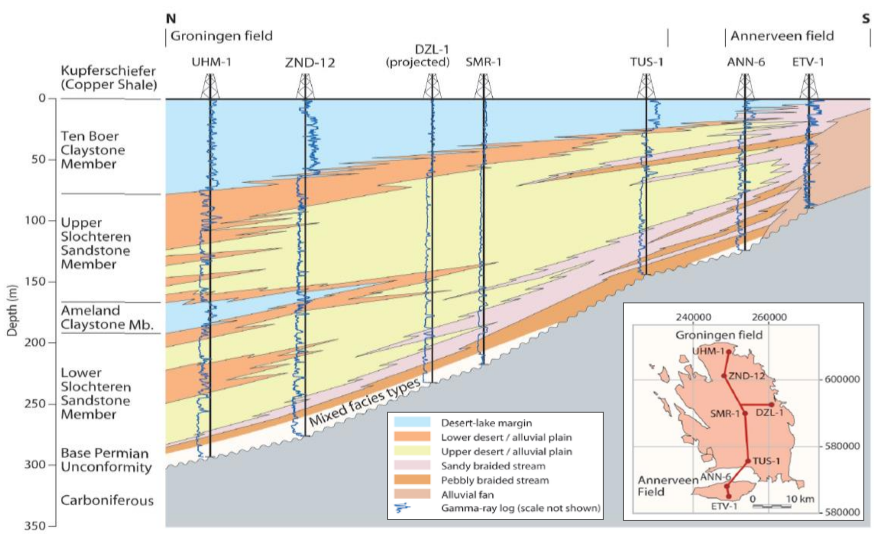


Southern Permian Basin

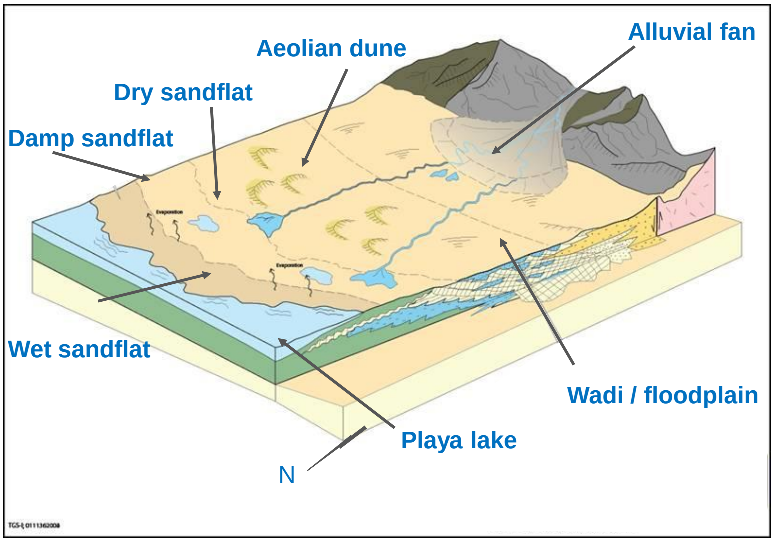
Rotliegend thickness map



N-S section through Groningen field



Depositional setting



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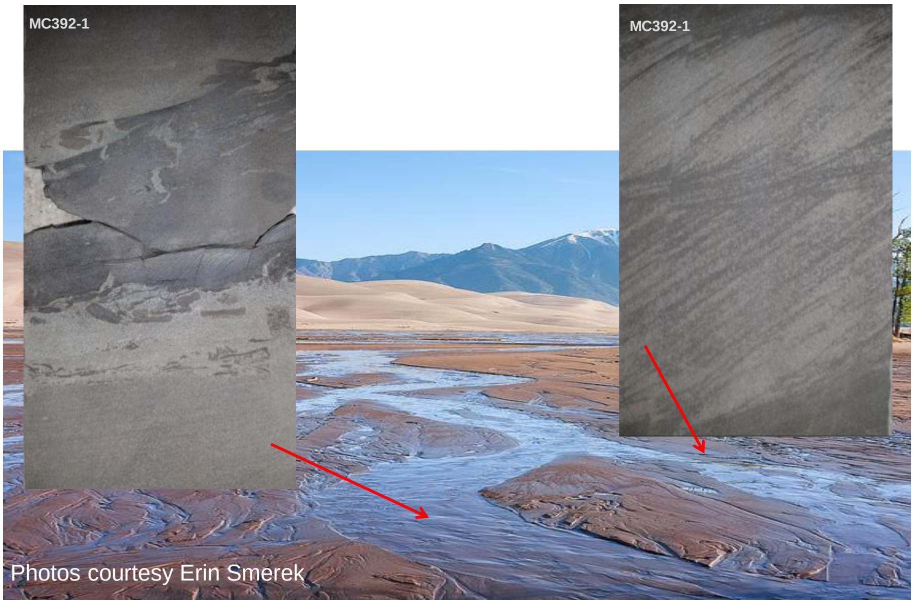
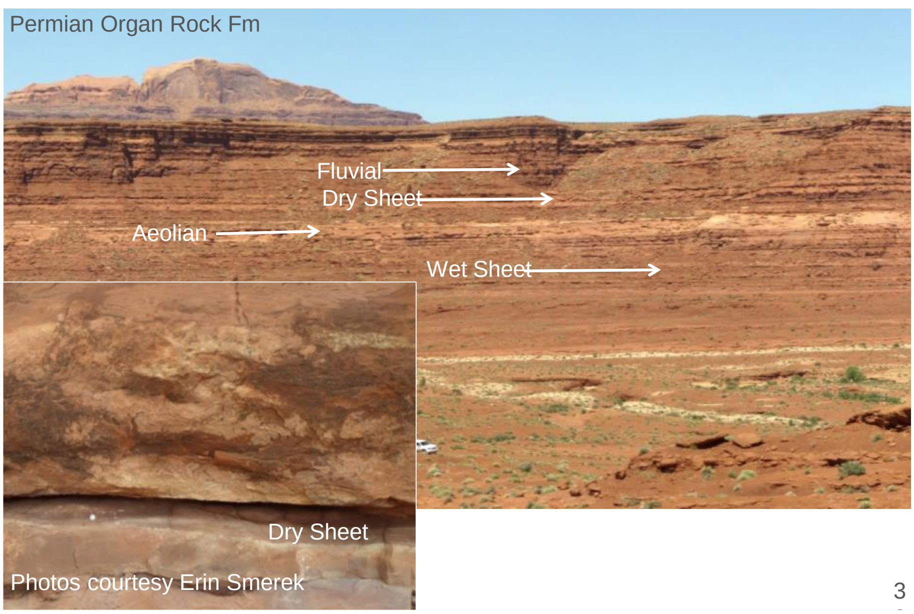
Ephemeral fluvial facies

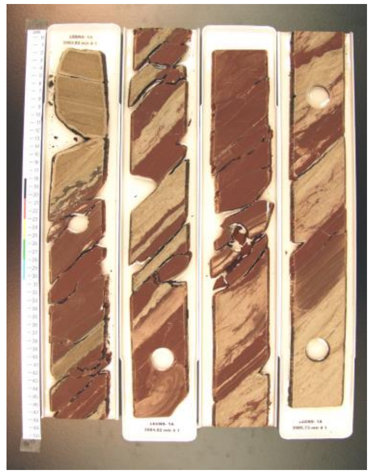


Sandflat facies



3

Rotliegend core samples



- medium-fine grained, well-sorted
- dune slip-face dipping laminae
- porosity 20 – 25 %
- Kh 300 – 1000 mD

- adhesion ripples, fluvial and/or aeolian reworking
- muddy to silty to fine sandy;
- porosity in sandy beds 3 - 8%;
- permeability 0.01 - 1 mD

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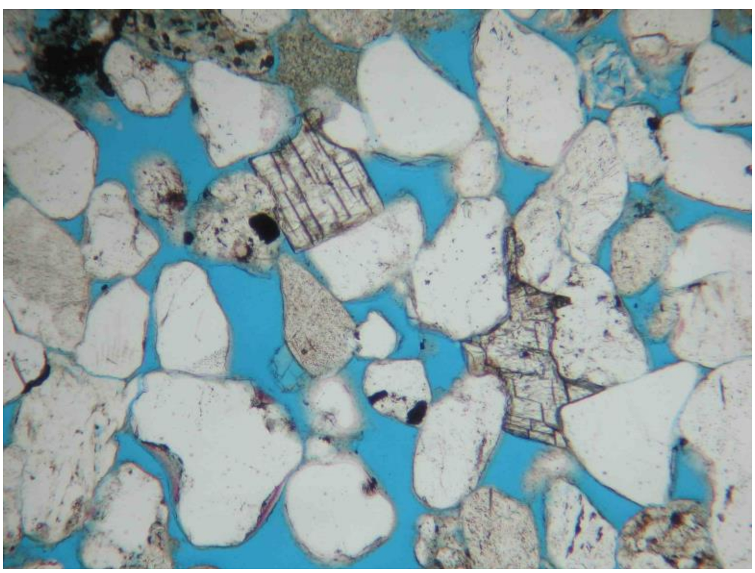
Rotliegend microscope samples



250 µm

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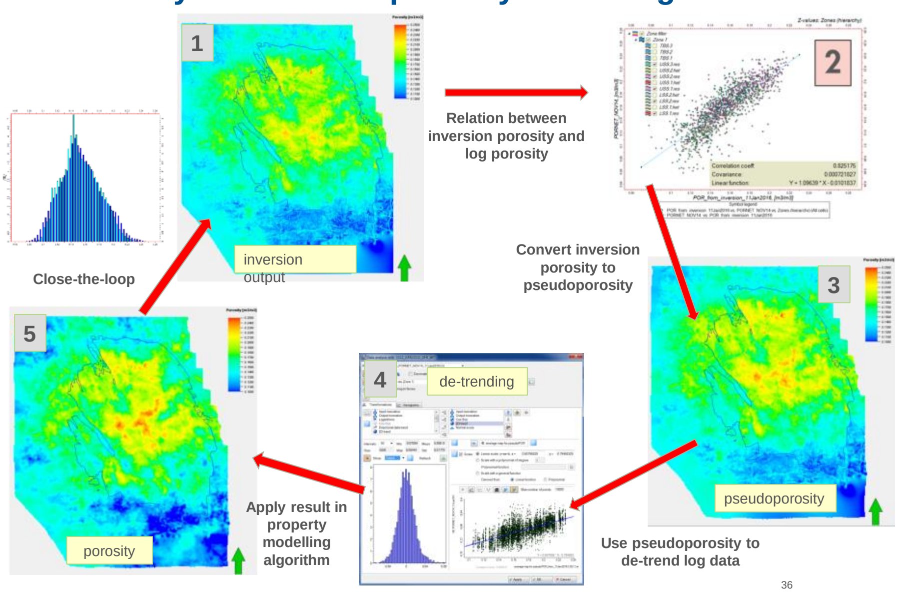
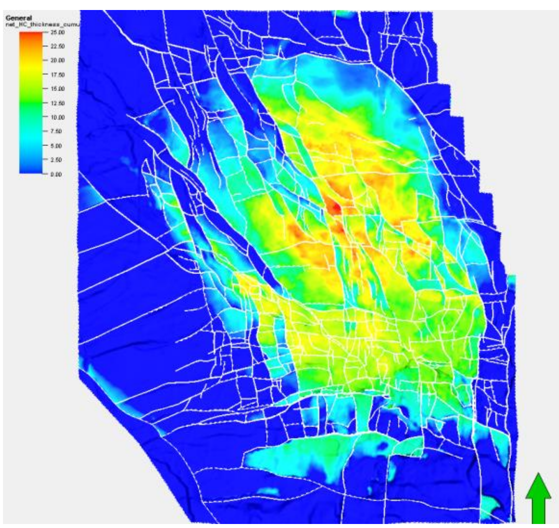
PROPERTY MODELS

Seismically constrained porosity modelling



EARTHQUAKES IN GRONINGEN

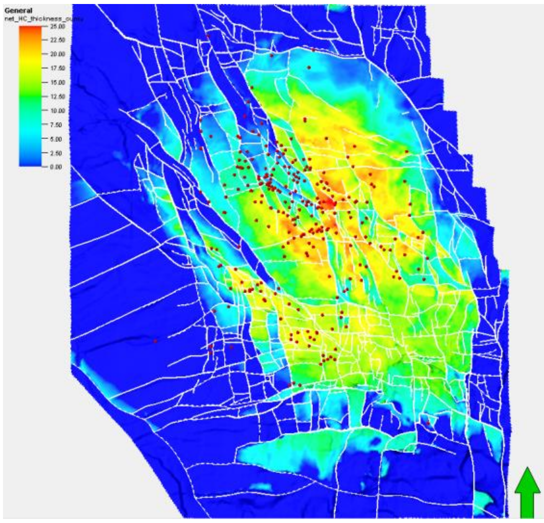
NAM



Property shown is net hydrocarbon thickness, calculated as:

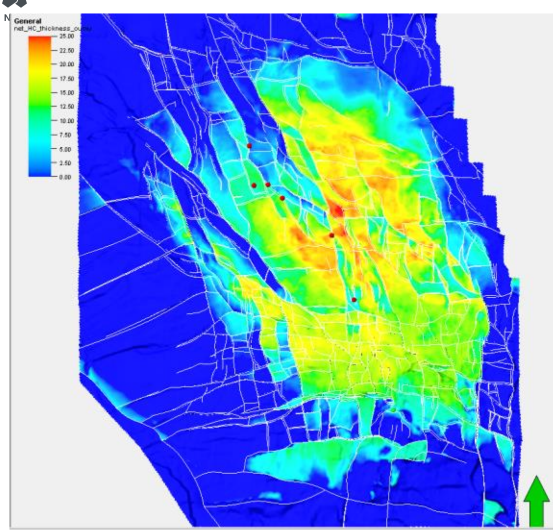
POR * Sg * Thickness

All events > 1.5, period 1995 – 2015 (n=258)



Property shown is net hydrocarbon thickness, calculated as:

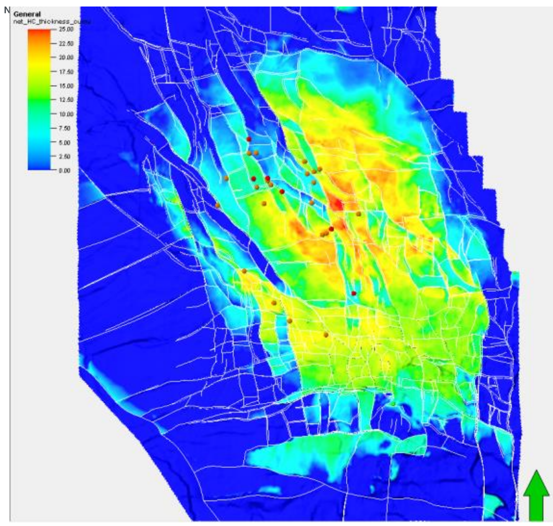
POR * Sg * Thickness



Property shown is net hydrocarbon thickness, calculated as:

POR * Sg * Thickness

Magnitude
- > 3
- 2.5 - 3
- 2 - 2.5
- 1.5 - 2
- 1 – 1.5

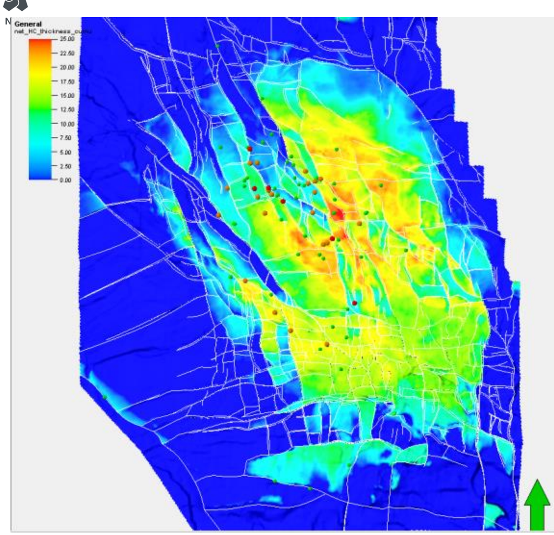


Property shown is net hydrocarbon thickness, calculated as:

POR * Sg * Thickness

Magnitude

- > 3
- 2.5 - 3
- 2 - 2.5
- 1.5 - 2
- 1 – 1.5



Property shown is net hydrocarbon thickness, calculated as:

POR * Sg * Thickness

Magnitude

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- 2.5 - 3
- 2 - 2.5
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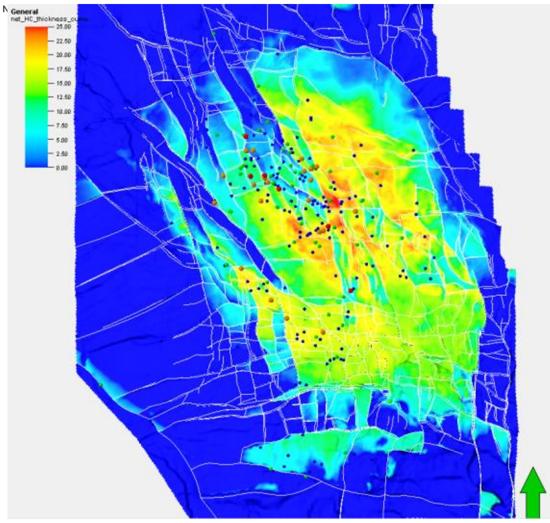
- 1 – 1.5



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Magnitude

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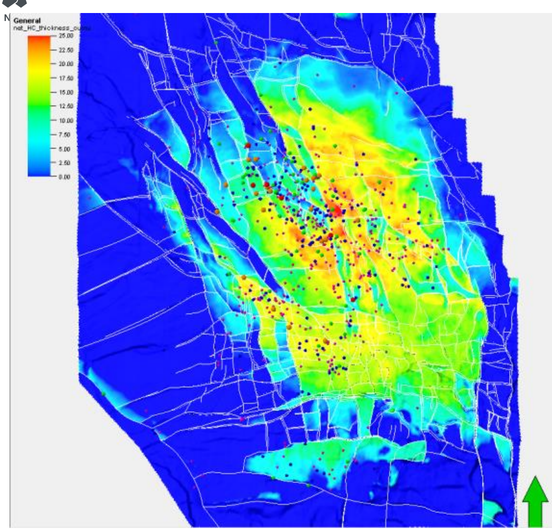
- 1 – 1.5



Property shown is net hydrocarbon thickness, calculated as:

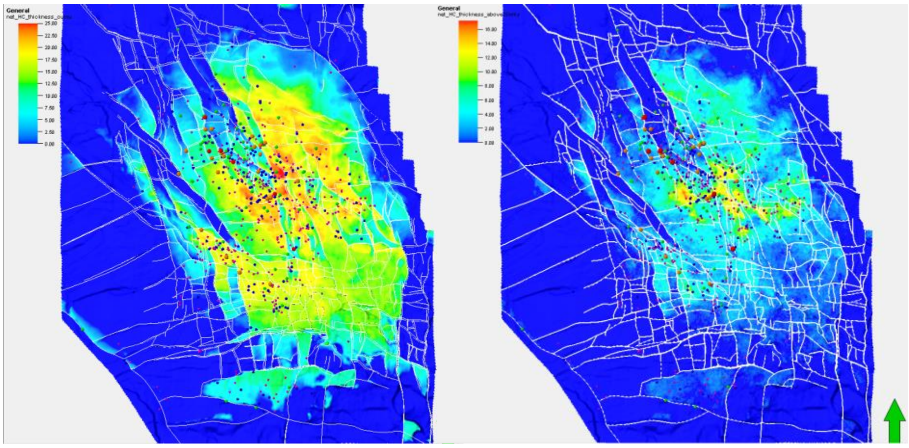
POR * Sg * Thickness

Magnitude

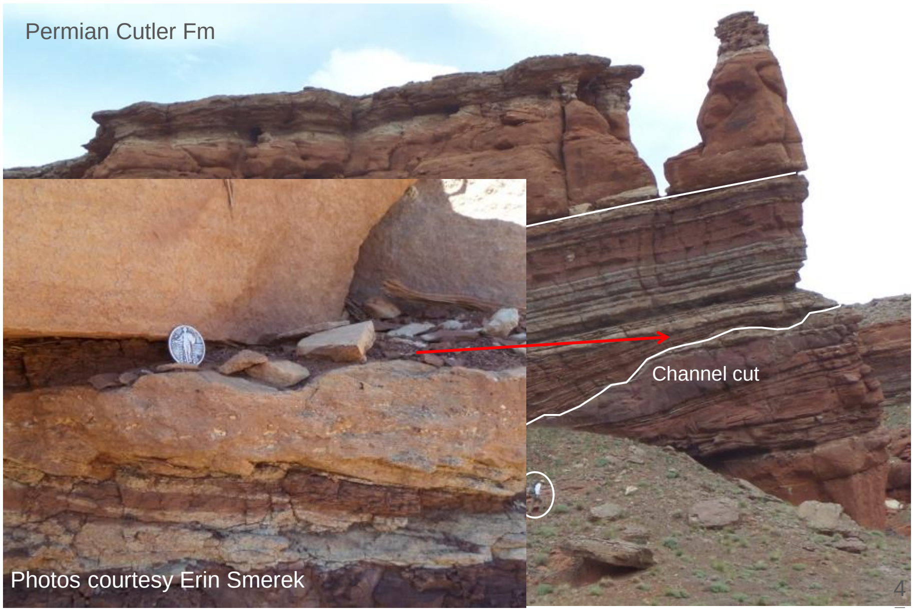
- > 3
- 2.5 - 3
- 2 - 2.5
- 1.5 - 2
- 1 – 1.5

Full porosity range

Porosity > 20% only

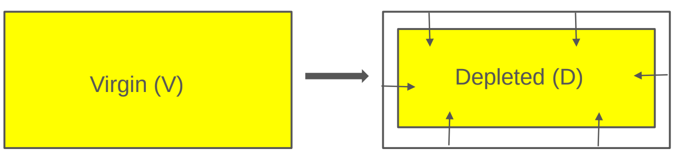


Ephemeral fluvial facies

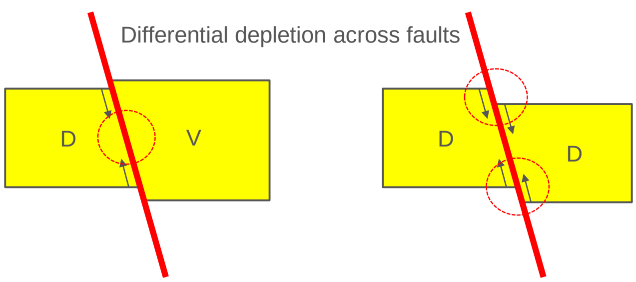


Faults, depletion, compaction (1)

Depletion causes volume reduction - compaction

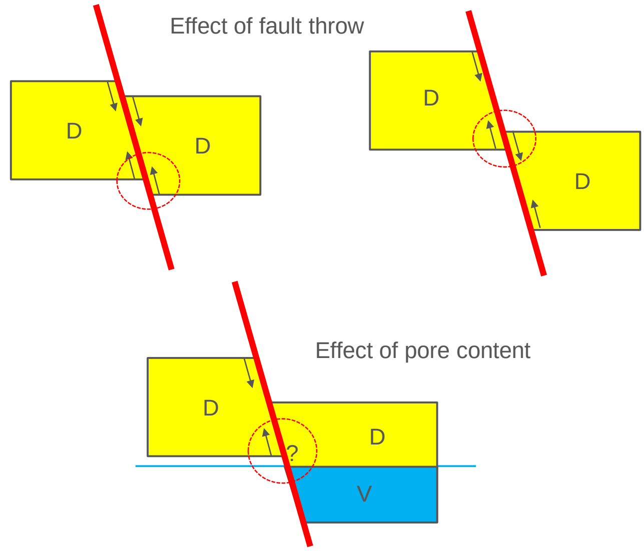


Differential depletion across faults

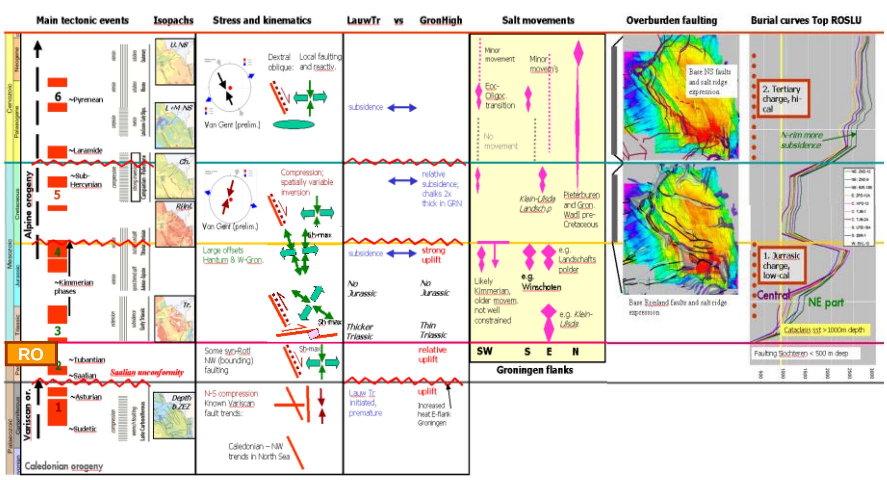


48

Faults, depletion, compaction (2)



Detailed kinematics of tectonic phases

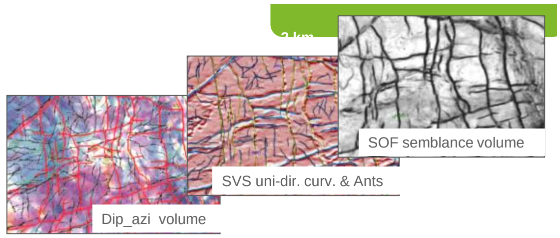


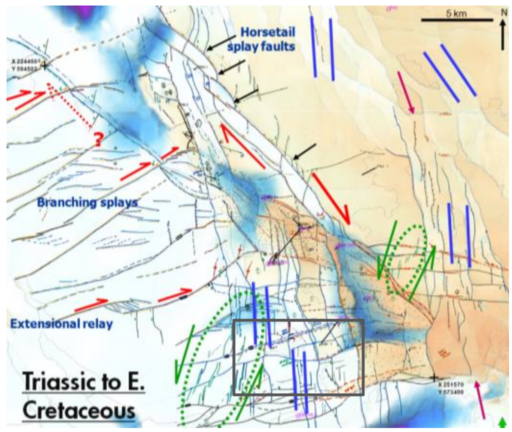
Fault relative ages & kin's

- Abutting relations
- 3D offset relations
- Characteristic fault styles

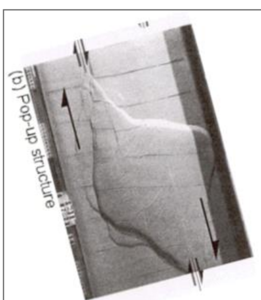
Other constraints e.g.

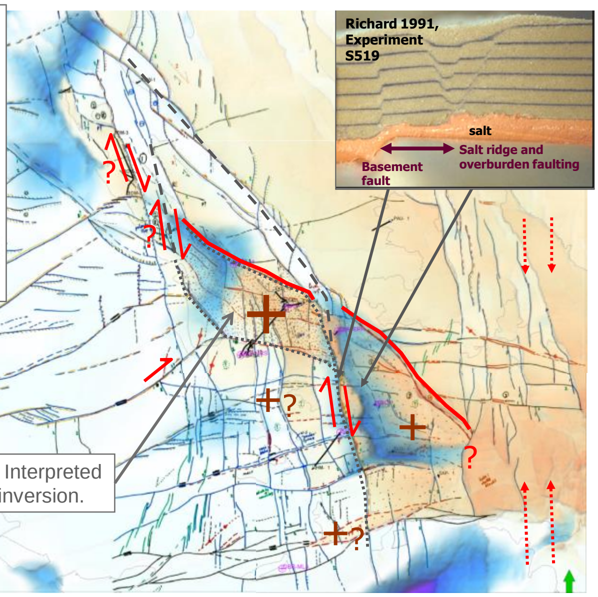
- Regional tectonic framework
- Scale (e.g. 'old' basement trends)
- Analogues (e.g. Germany, sandbox)
- Overburden deformation, halokinesis





L. Cretaceous-Paleogene activity





Eemskanaal-Ten Boer block: Interpreted as a restraining bend during inversion.

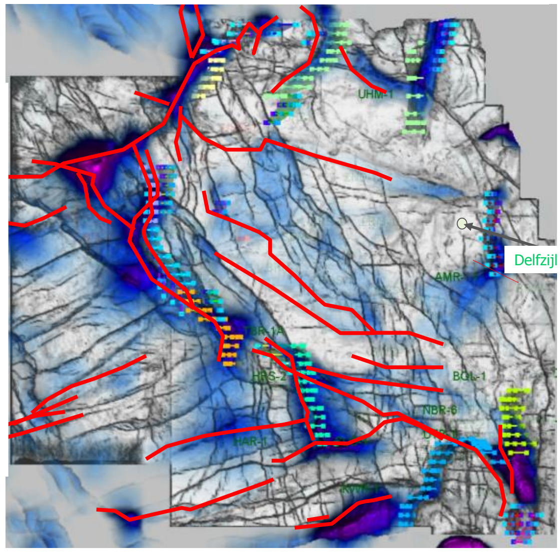
L. Cretaceous-Paleogene activity

Grey base map:
RO SOF-semblance

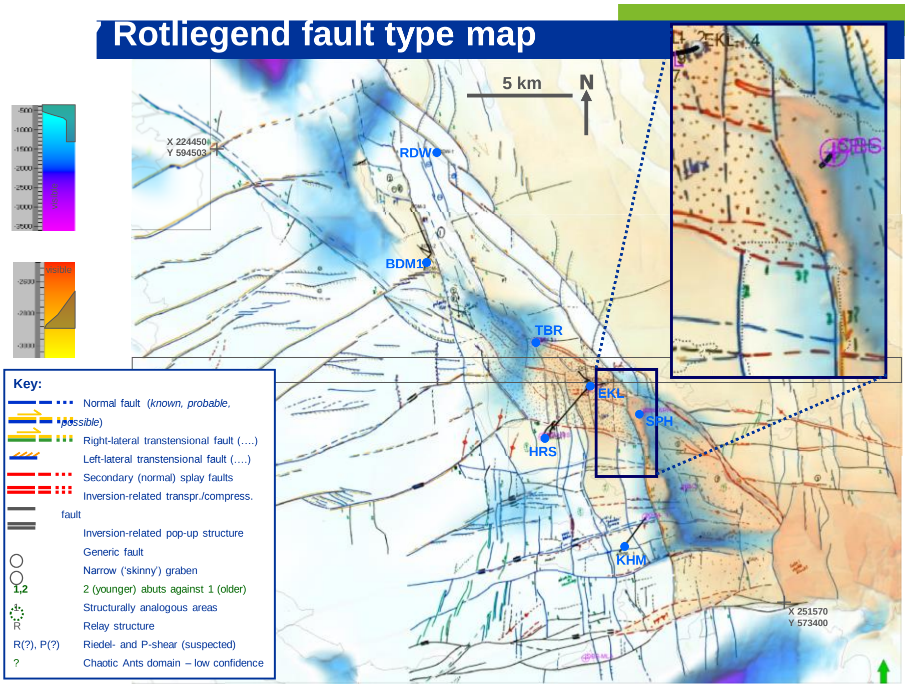
Blue shades:
Zechstein isochore
(>1000 m)

Fault sticks in various colours:
Quick overburden fault interpreted by J. Steenbrink

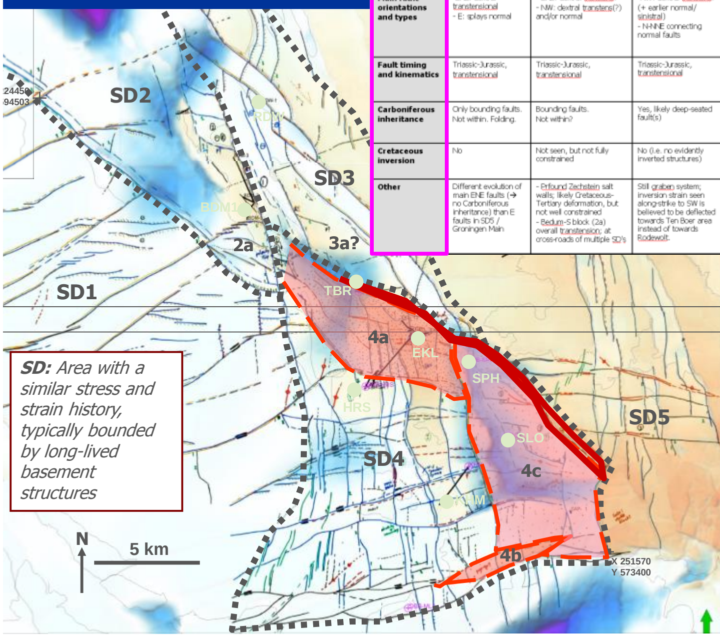
Red lines:
I. van der Molen
Base Rijnland fault mapping 2001 (i.e. Lower Cretaceous)



Rotliegend fault type map



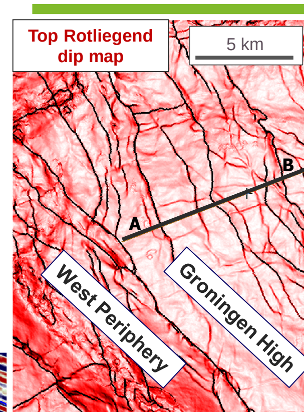
Structural domains

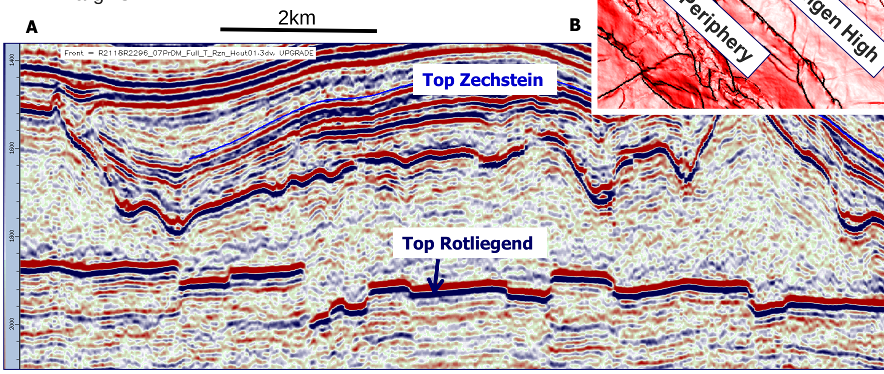


Rotliegend W-periphery:	SD1 Lauwerszee Trough	SD2 W-Groningen fault zone west	SD3 W-Groningen fault zone east	SD4 SW periphery	SD5 South-central Groningen Main
Main fault orientations and types	-ENE: dextral transtensional - E: splays normal	- ENE: dextral transtens. - NW: dextral transtens(?) and/or normal	-NW: dextral transtens. (+ earlier normal/ sinistral) - N-NNE connecting normal faults	-E to ENE: normal and/or (early) wrench; some inverted (see below) -N: normal, some strike-slip component	-E to ENE: normal and/or (early) wrench; some inverted (see below) -N and NW: normal, some possibly a small strike-slip component
Fault timing and kinematics	Triassic-Jurassic, transtensional	Triassic-Jurassic, transtensional	Triassic-Jurassic, transtensional	-Triassic-Jurassic, transtensional - Late Cretaceous, transpressional	-Triassic-Jurassic, transtensional - Some Late Cret. transpressional
Carboniferous inheritance	Only bounding faults. Not within. Folding.	Bounding faults. Not within?	Yes, likely deep-seated fault(s)	Yes, bounding faults and some E and N faults internal	Yes, bounding faults and some internal, especially E faults
Cretaceous inversion	No	Not seen, but not fully constrained	No (i.e. no evidently inverted structures)	Yes, most prominent within study area; variable intensity e.g. 4a, 4b, 4c	Yes, localised along some E faults; overall less than in SD4a, b, c
Other	Different evolution of main ENE faults (→ no Carboniferous inheritance) than E faults in SD5 / Groningen Main	- Prfound Zechstein salt walls; likely Cretaceous-Tertiary deformation, but not well constrained - Bedum-S block (2a) overall transtension; at cross-roads of multiple SD's	Still graben system; inversion strain seen along-strike to SW is believed to be deflected towards Ten Boer area instead of towards Rodewolt.	Some other blocks may have seen inversion as well, less constrained	Not investigated in as much detail as W-periphery. Origin of large E systems with Carboniferous inheritance still poorly constrained;

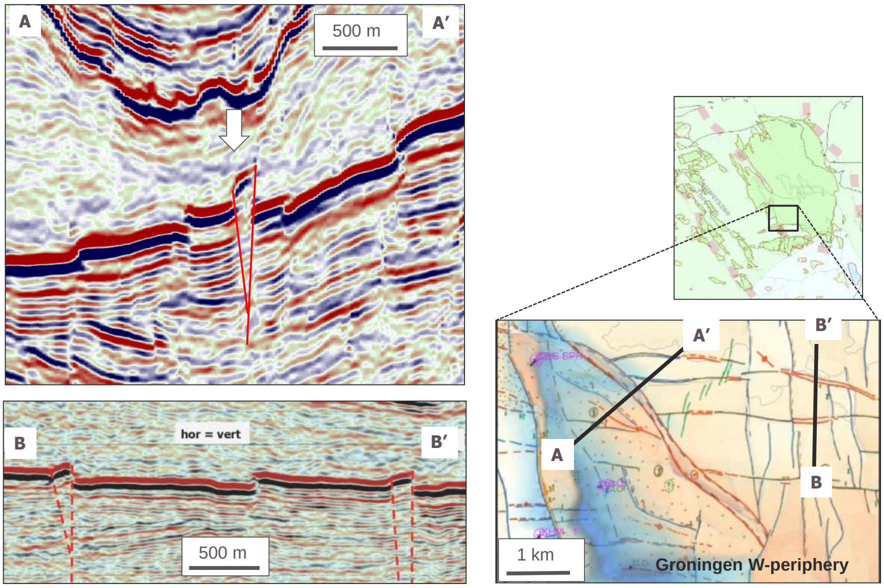
Groningen High internal faults

- Relatively simple system of normal faults
- More wrenching through time along its margins

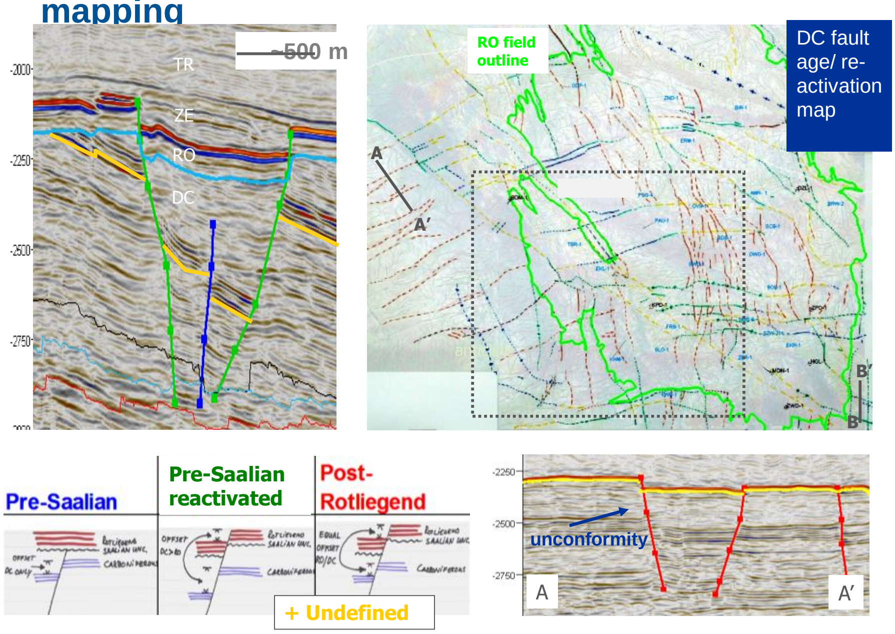




Late Cretaceous to Paleogene inversion – Pop-ups

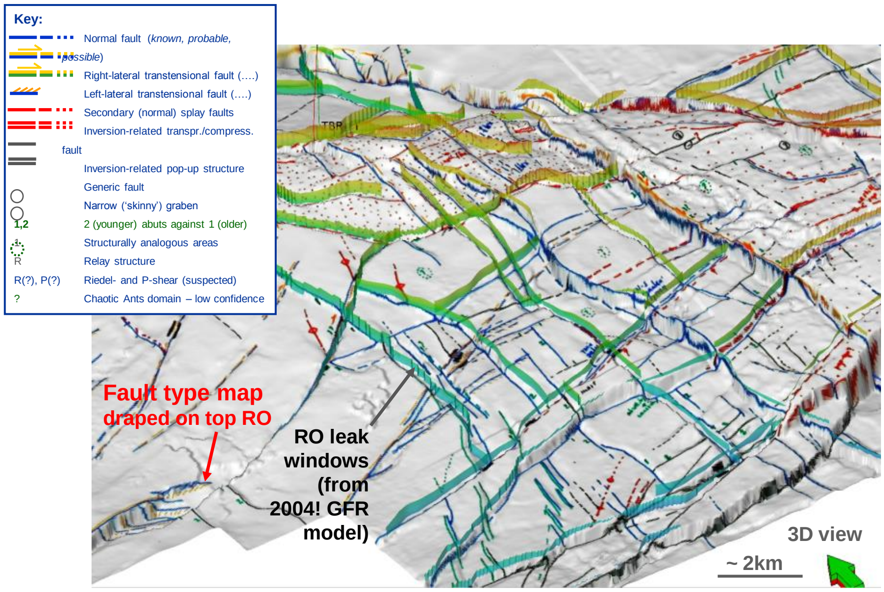


Carboniferous – Previous structural mapping

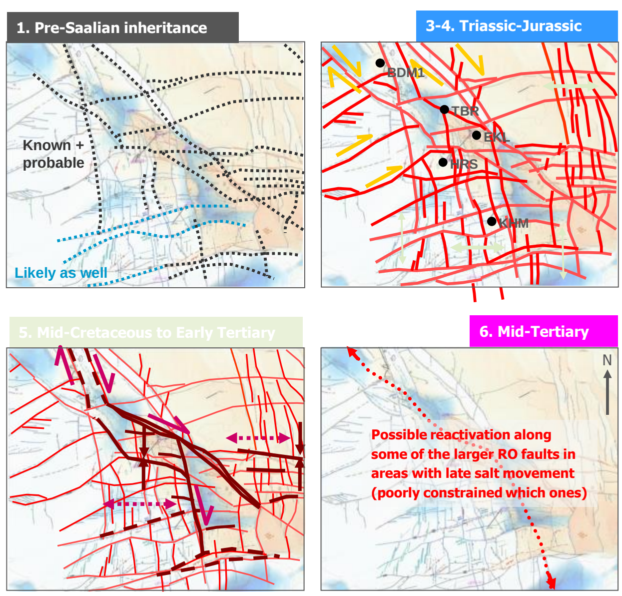


uctural

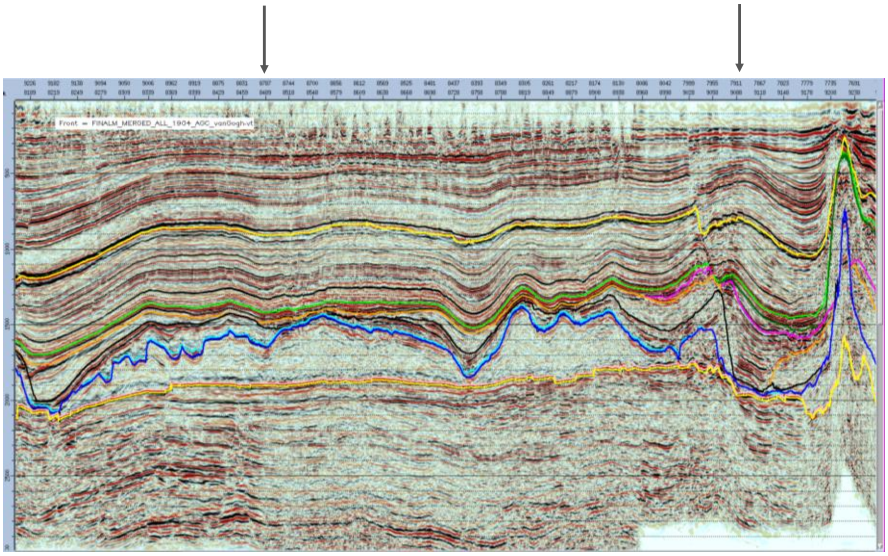
3


Key:
Normal fault (known, probable, possible)
Right-lateral transtensional fault (….)
Left-lateral transtensional fault (….)
Secondary (normal) splay faults
Inversion-related transpr./compress. fault
Inversion-related pop-up structure
Generic fault
Narrow ('skinny') graben
1,2
2 (younger) abuts against 1 (older)
Structurally analogous areas
R
Relay structure
R(?), P(?)
Riedel- and P-shear (suspected)
?
Chaotic Ants domain – low confidence
TBR
Fault type map draped on top RO
RO leak windows (from 2004! GFR model)
3D view
~ 2km

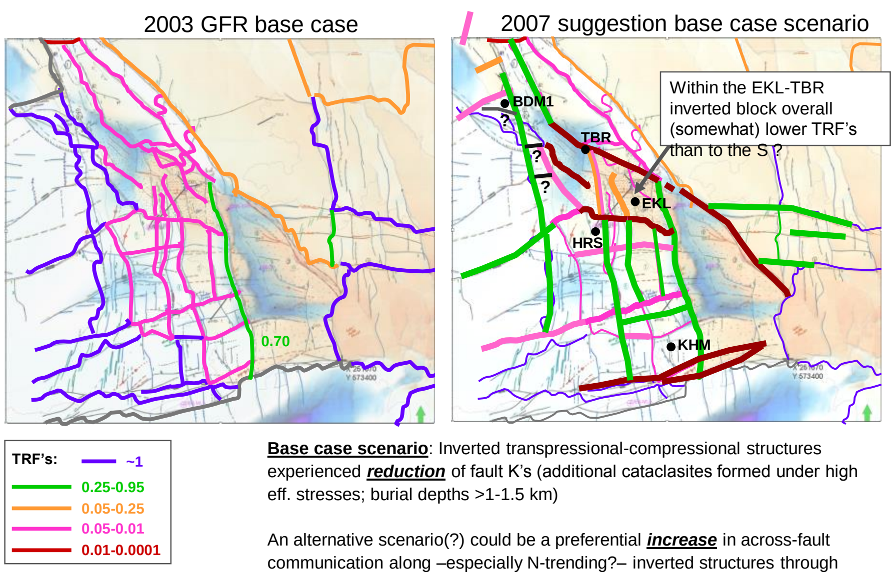
on


1. Pre-Saalian inheritance
Known + probable
Likely as well
3-4. Triassic-Jurassic
BDM1
TBR
EKL
NRS
KNM
5. Mid-Cretaceous to Early Tertiary
6. Mid-Tertiary
N
Possible reactivation along some of the larger RO faults in areas with late salt movement (poorly constrained which ones)

Example line NW- SE through merged dataset

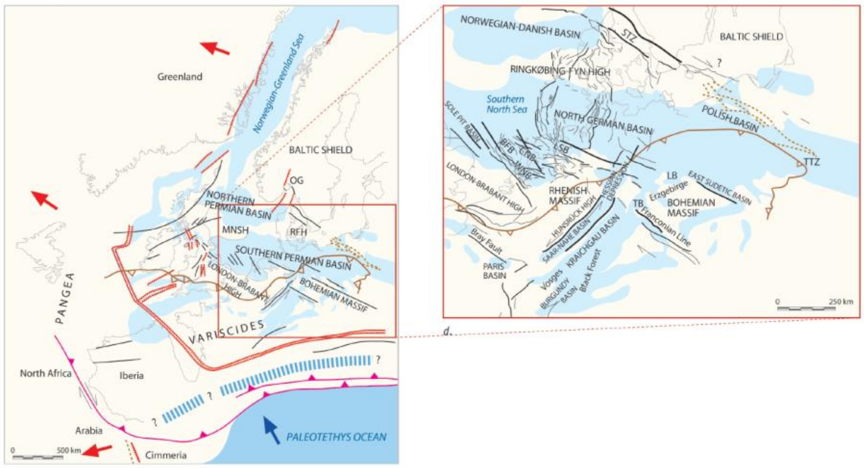


GFR - Transmissibility Reduction Factors (TRF's)



Base case scenario: Inverted transpressional-compressional structures experienced ***reduction*** of fault K's (additional cataclasites formed under high eff. stresses; burial depths >1-1.5 km)

An alternative scenario(?) could be a preferential ***increase*** in across-fault communication along –especially N-trending?– inverted structures through increased fracturing and/or late-stage re-opening


Greenland
Norwegian-Greenland Sea
BALTIC SHIELD
OG
NORTHERN PERMIAN BASIN
MNSH
RFH
SOUTHERN PERMIAN BASIN
LONDON-BRABANT HIGH
BOHEMIAN MASSIF
PANGEA
VARISCIDES
North Africa
Iberia
Arabia
Cimmeria
PALEOTETHYS OCEAN
0 500 km
NORWEGIAN-DANISH BASIN
STZ
BALTIC SHIELD
RINGKØBING-FYN HIGH
Southern North Sea
NORTH GERMAN BASIN
POLISH BASIN
SOLE PIT BASIN
BFB
GNB
LSB
WNB
TTZ
LONDON-BRABANT HIGH
RHENISH MASSIF
HESSIAN DEPRESSION
LB
Erzgebirge
EAST SUDETIC BASIN
TB
BOHEMIAN MASSIF
HUNSRÜCK HIGH
SAAR-NAHE BASIN
KRAICHGAU BASIN
Franconian Line
Bray Fault
PARIS BASIN
Vosges
Black Forest
BURGUNDY BASIN
0 250 km
d.

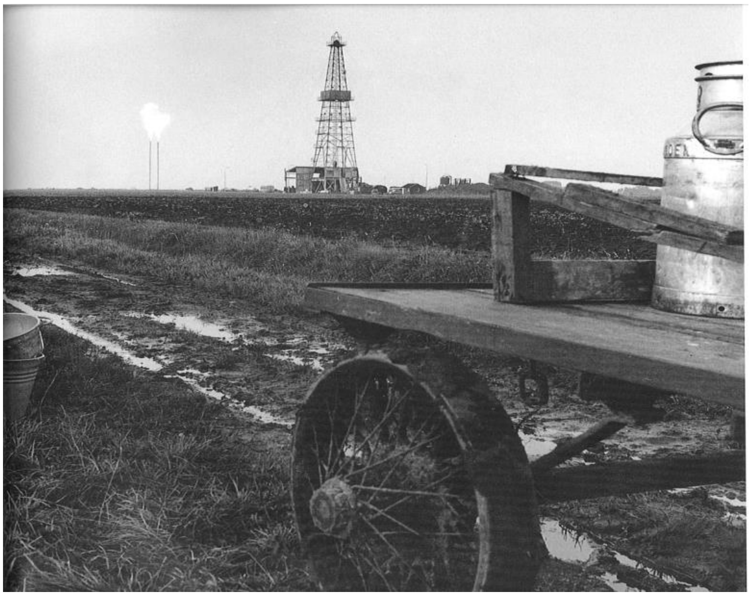
History and future perspective of gas production

08/03/2016

Leendert Geurtsen
Groningen Development Team

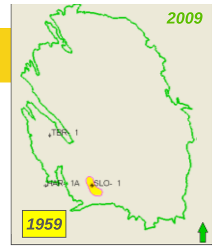
1

1959 : Well test Slochteren-1

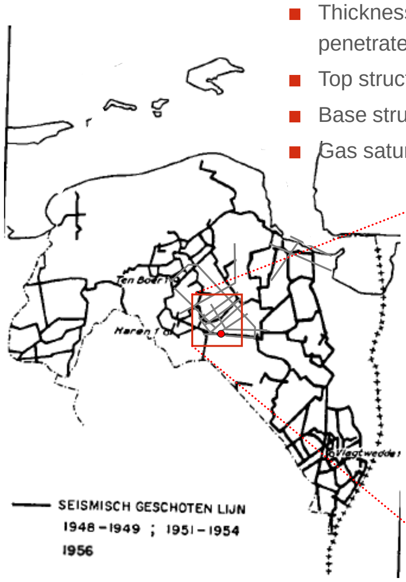


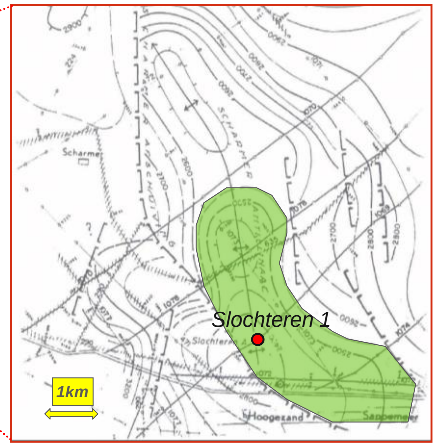
NAM

1959: ~5 Bcm

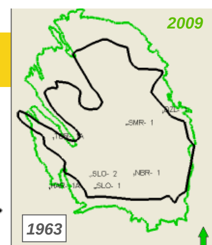


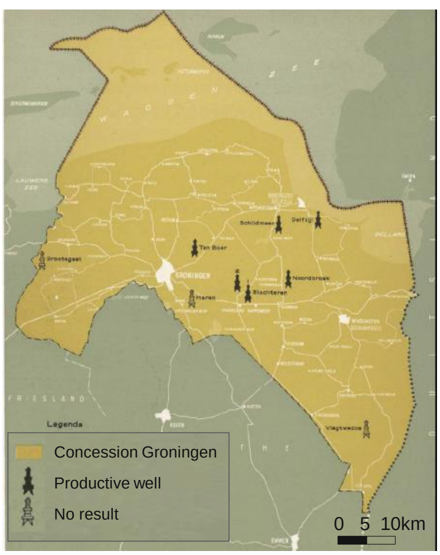
- Thickness: 25m (Base not penetrated)
- Top structure: 2.25km^2
- Base structure: 6.45km^2
- Gas saturation: 70%



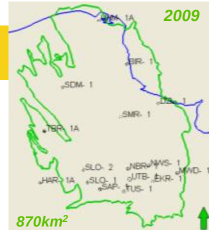


1963: ~1000 Bcm

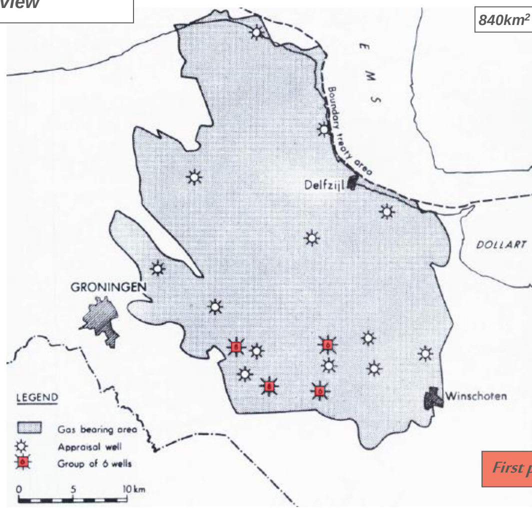




1966: ~1850 Bcm

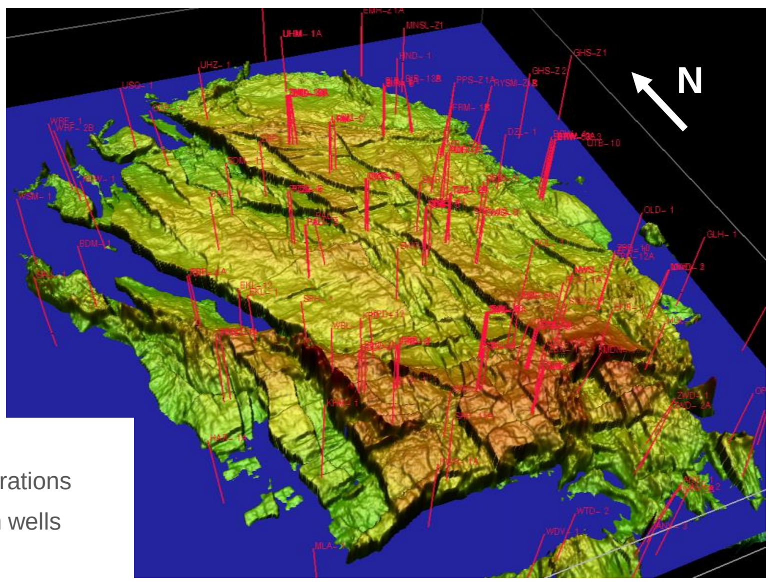


Northern and Southeastern Appraisal
1st Southern clusters
New seismic (2 x 3km grid, 430km)
Full petrophysical review



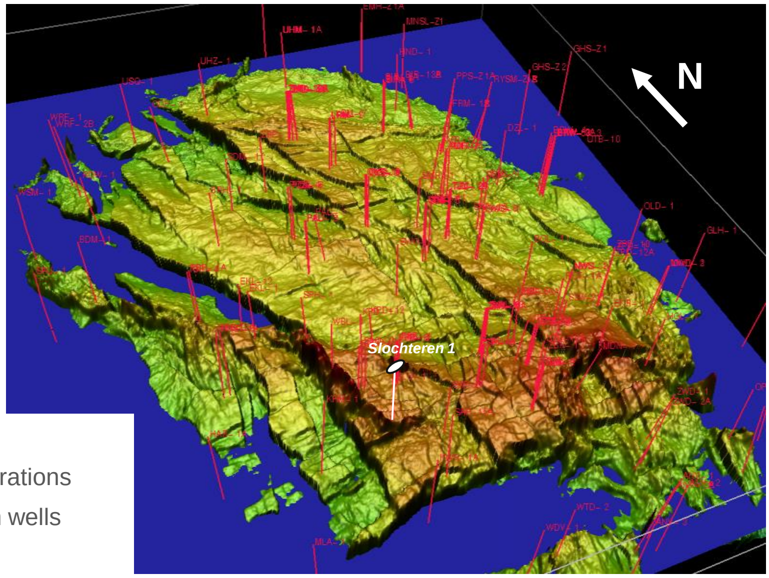
First production: 1963

2016: ~3000 Bcm



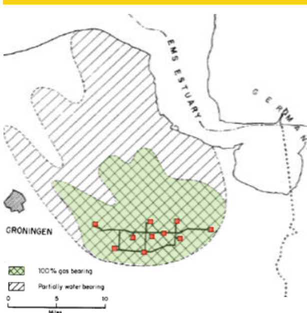
- 300 well penetrations
- 30 observation wells

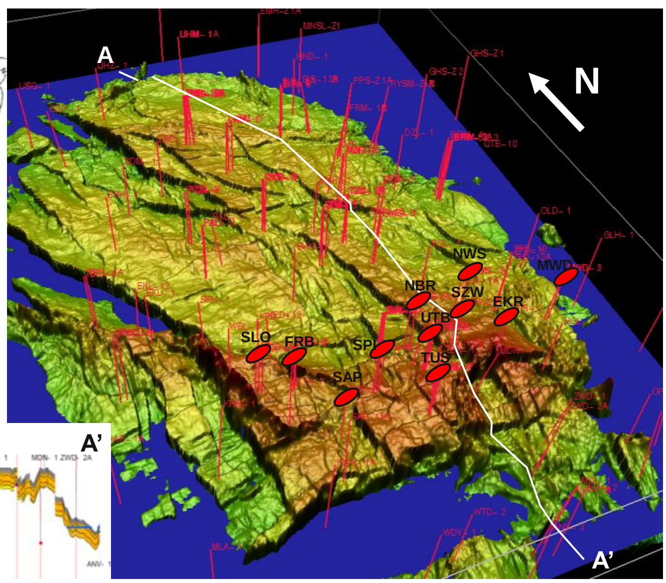
2016: ~3000 Bcm

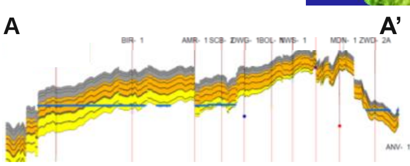


- 300 well penetrations
- 30 observation wells

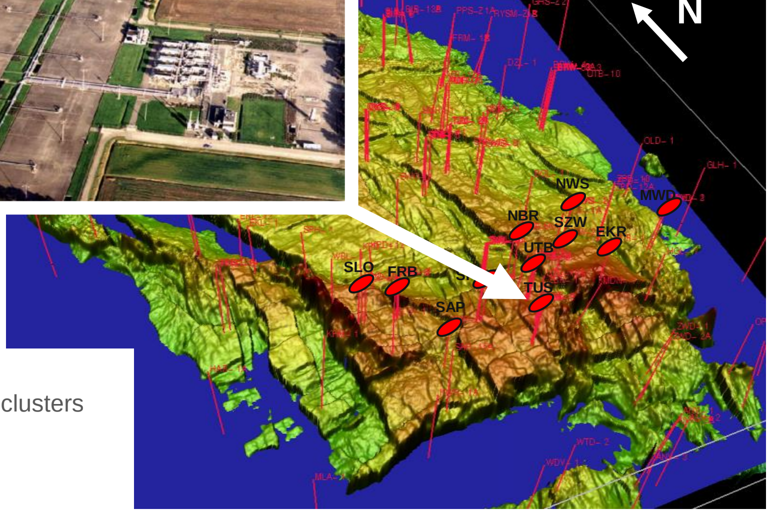
Development 1963-1970





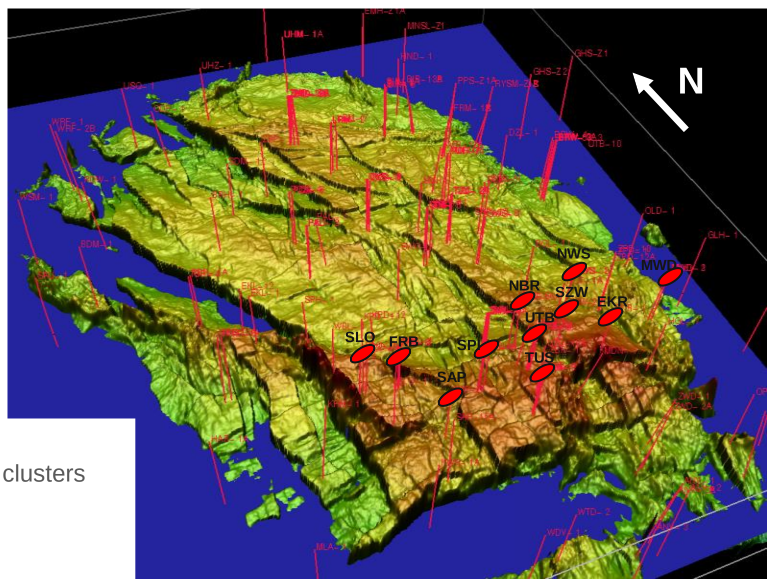


Development 1963-1970



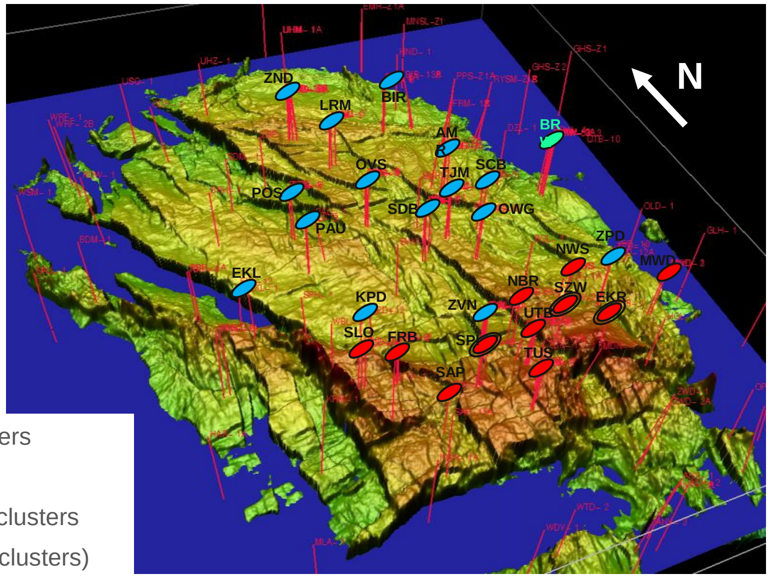
- Standard Size clusters (8 wells)

Development 1963-1970



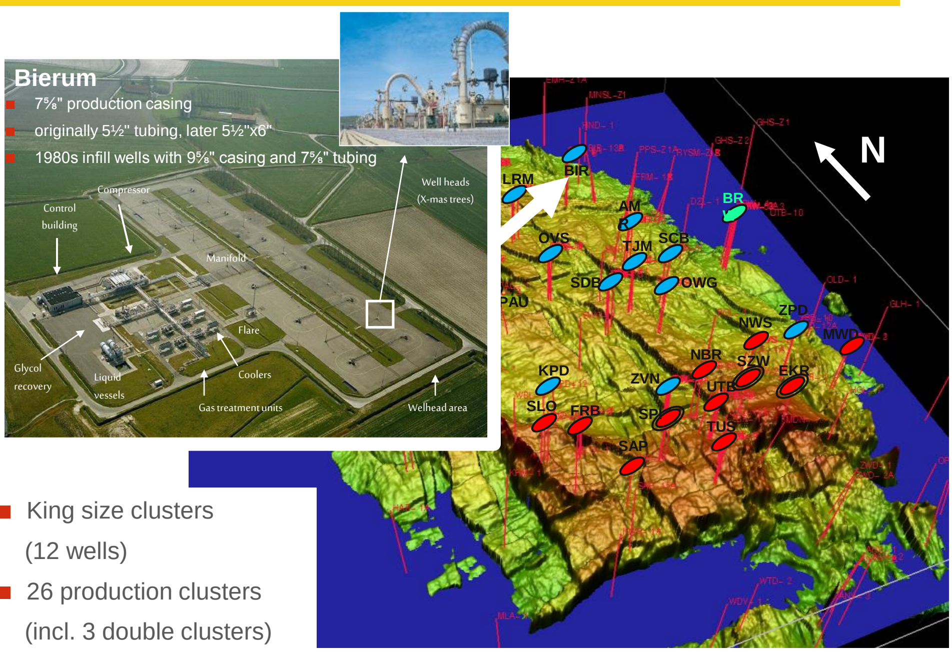
- Standard Size clusters (8 wells)

Development 1970+



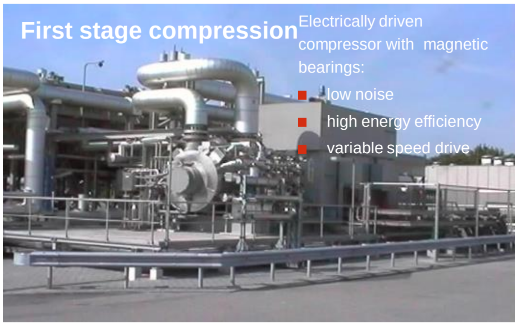
- King size clusters (12 wells)
- 26 production clusters (incl. 3 double clusters)

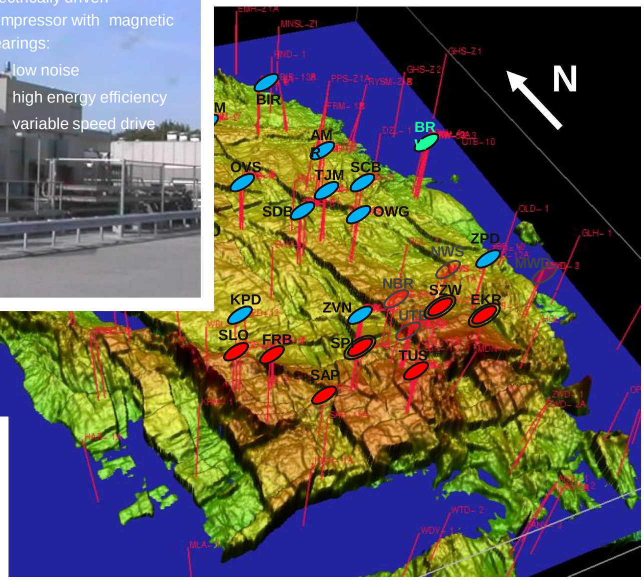
Development 1970+



- King size clusters (12 wells)
- 26 production clusters (incl. 3 double clusters)

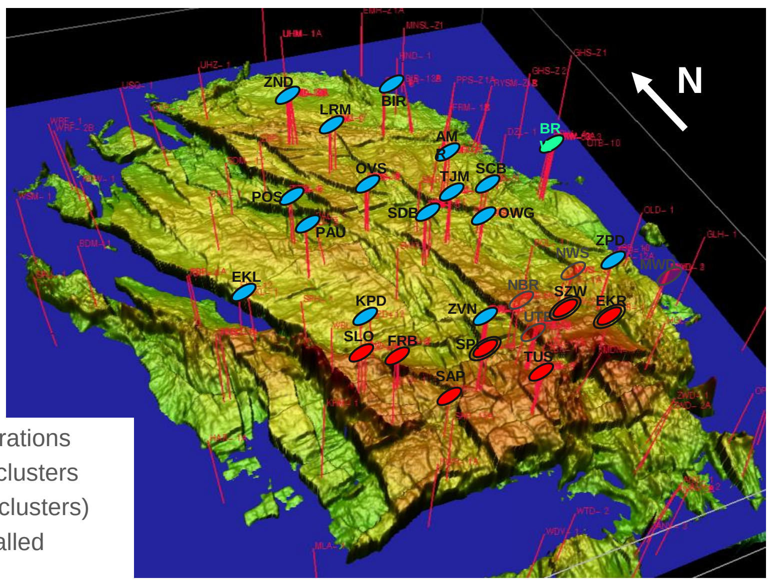
Development 1997-2009: Groningen Long Term





- All clusters on 1st stage compression, except:
  - —EKL
  - —SCB (2nd stage)

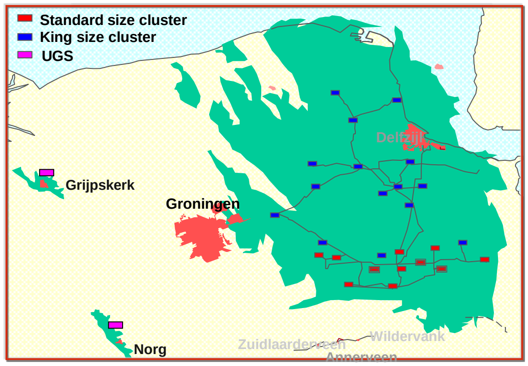
Current overview



- 300 well penetrations
- 22 production clusters
  (incl. 3 double clusters)
  (excl. 4 mothballed clusters)

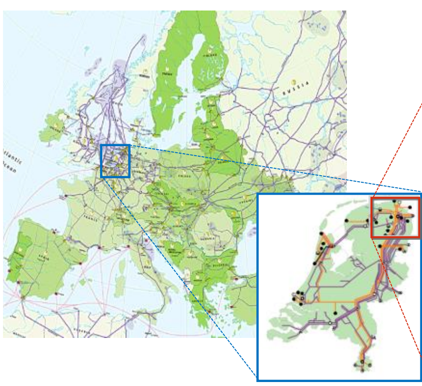
Groningen gas field

- 20 production clusters, 2 satellites
- gas pipeline grid consists of 136 valves and 59 different sections of pipeline (total 162 km)
- 7 custody transfer stations (Overslagen) to Gasunie network

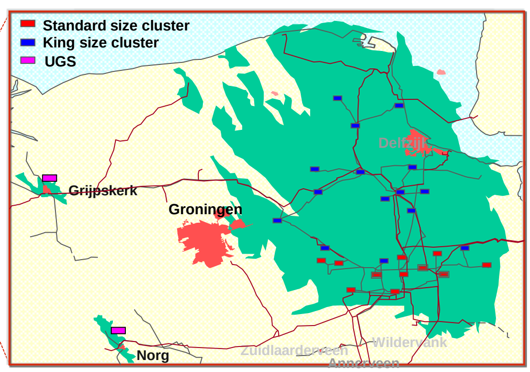


Groningen gas field

- Groningen is one of largest gas fields in the world (top 20)
- Crucial role in Dutch and European security of gas supply: balancing supply from small fields and market demand
  - —97% of Dutch domestic households use natural gas
  - —Natural gas supplies 45% of the Dutch energy demand
  - —Some 56% of the total European Union Gas Reserves are in the Netherlands



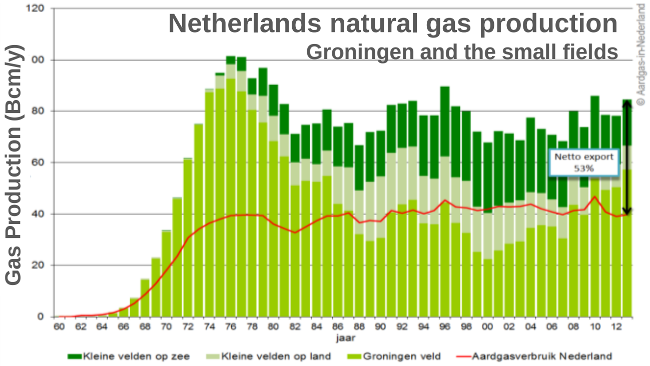
Gasunie network



Small fields policy

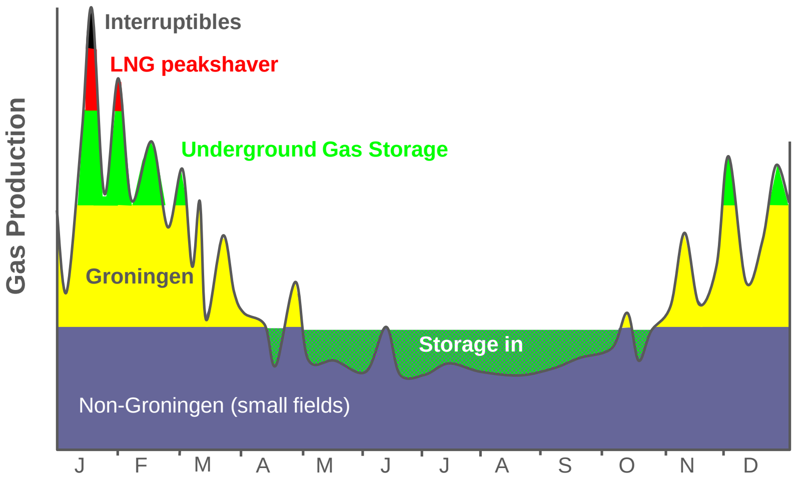
"Gasgebouw" :

- Priority for the exploration and development of small fields
- Conservation of the Groningen field as national strategic gas reserve

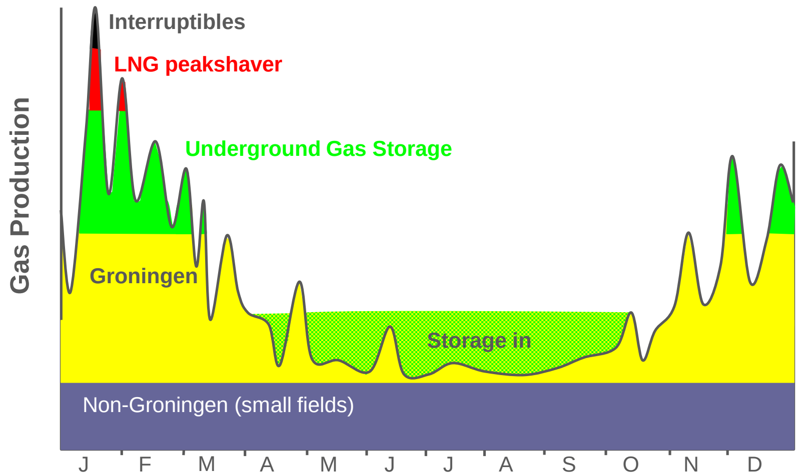


100 Bcm/y
= 275 mln m³/d
= 1.7 MMboe/d

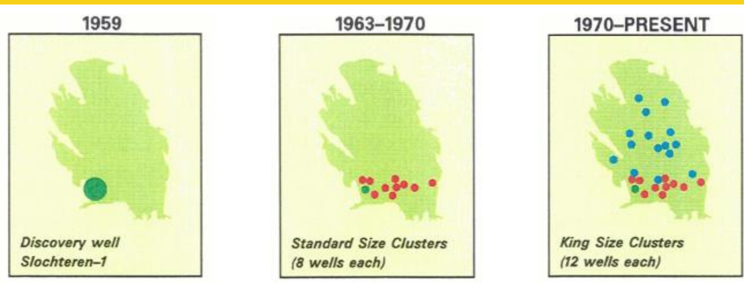
Gas seasonal demand

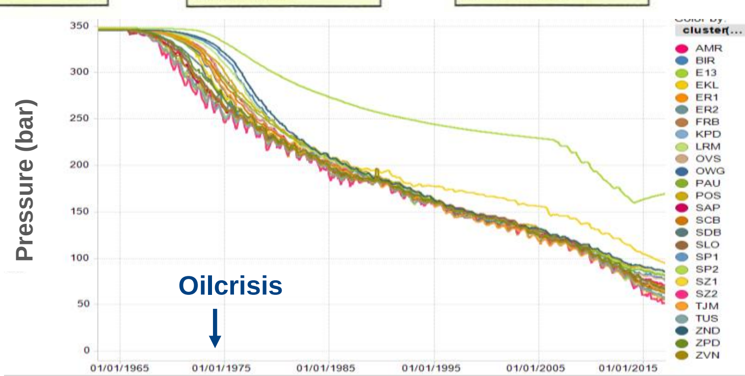


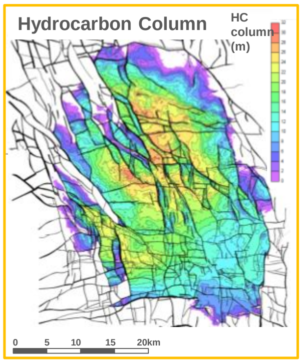
Gas seasonal demand

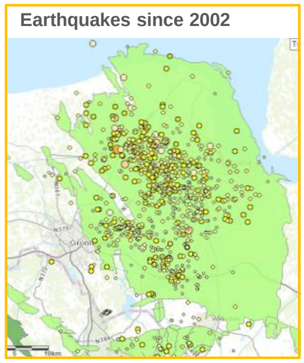


Reservoir pressure







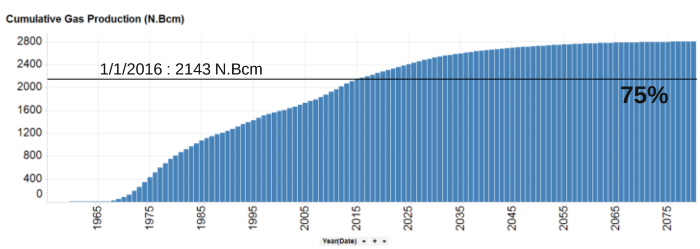


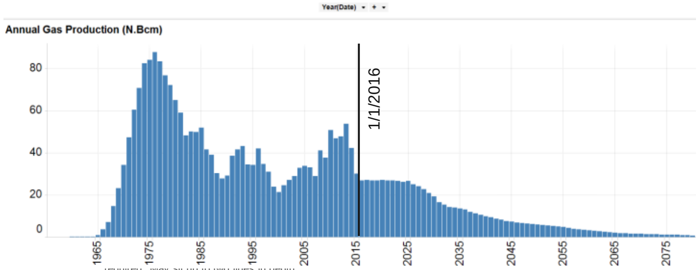
Date	Description	2015	2016	2017	onwards	comments
29/11/2013	Winningsplan 2013	42.5	42.5	42.5	42.5	Gaswet applies (425Bcm over a 10y period)
17/01/2014	Kamerbrief	42.5	40			Regional cap on LOPPZ clusters of 3.0 N.Bcm/y
Jan-15	Besluit	39.4	39.4			Regional caps (in N.Bcm per year): LOPPZ: 3.0 EKL: 2.0 SouthWest: 9.9 East: 24.5
15/04/2015	Kamerbrief	39.4	39.4			Maintain regional caps as per previous, but can only produce LOPPZ for security of supply, don't produce full cap unless cold winter.
29/06/2015	Besluit	30	33			Maintain regional caps as per previous. Can only produce 33Bcm in gas year 2015/2016
07/10/2015	Kamerbrief	30*	31*			Maintain regional caps as per previous. * Can only produce 31Bcm in gas year 2015/2016
18/11/2015	Raad van State		27*			Besluit Jan-15 and 29/6/2015 annihilated. Until new Besluit: 27Bcm in gas year 2015/2016 . Maintain regional caps as per previous.

*) Gas Year

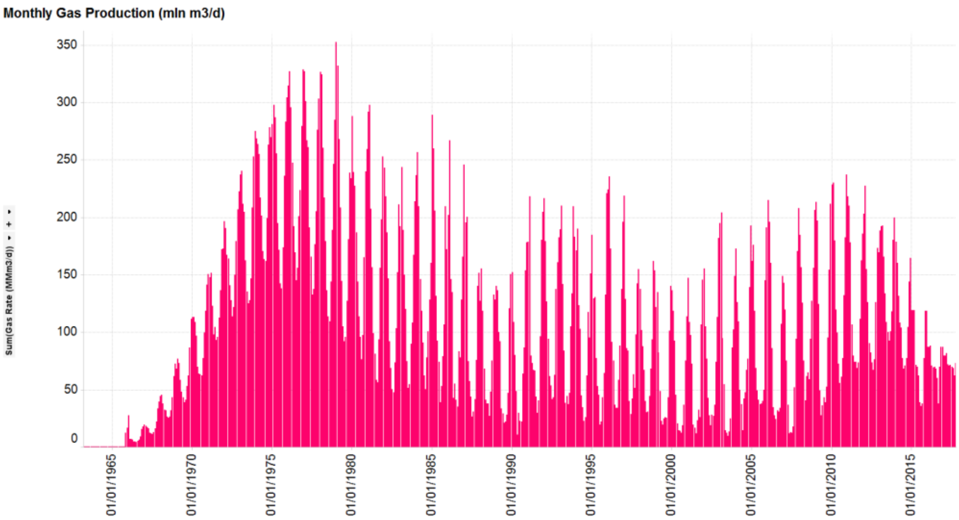
Groningen field production overview

- 2nd + 3rd stage (no further development)



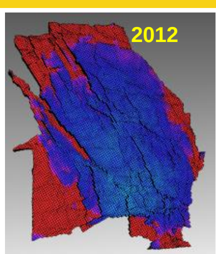


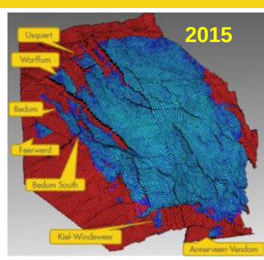
Historic monthly production

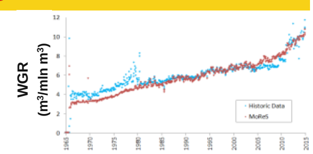


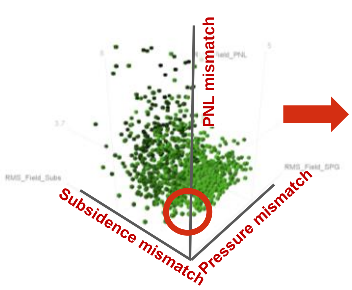
Footer: Title may be placed here or disclaimer if required. May sit up to two lines in depth.

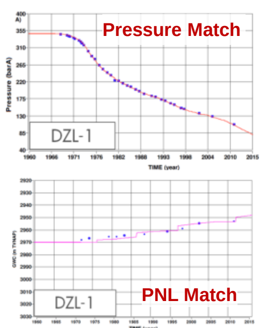
Full Field Model update – Groningen

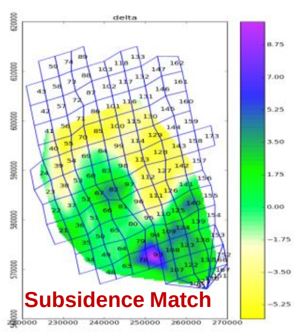






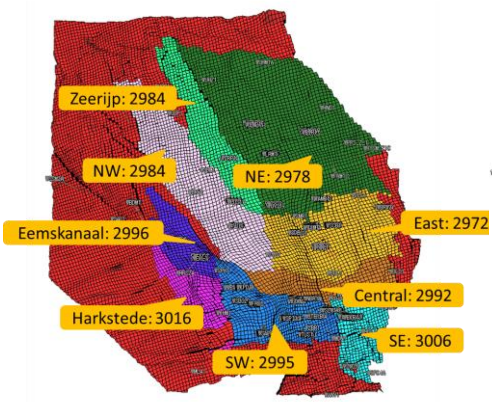


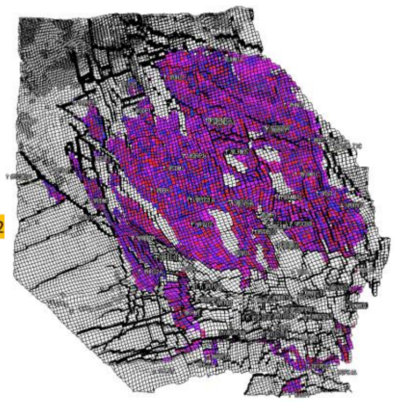




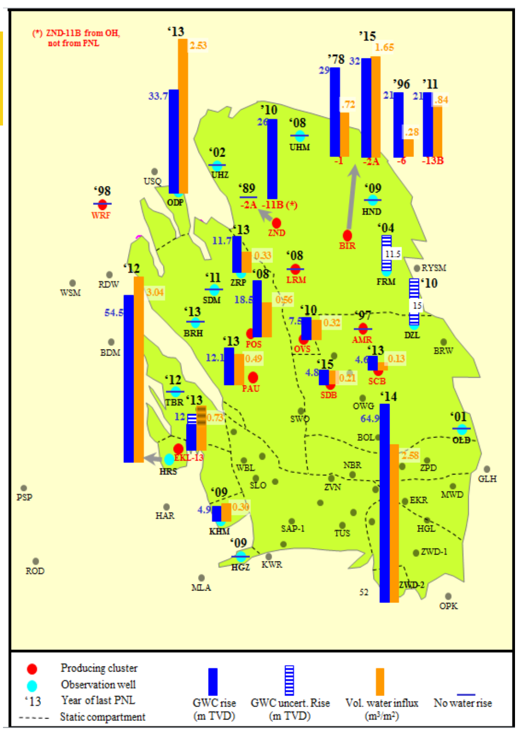
Initialization

- Initial Gas Water Contact is varying in the field
  - In the south it's typically located in the Carboniferous
- Stability of the contacts have been investigated

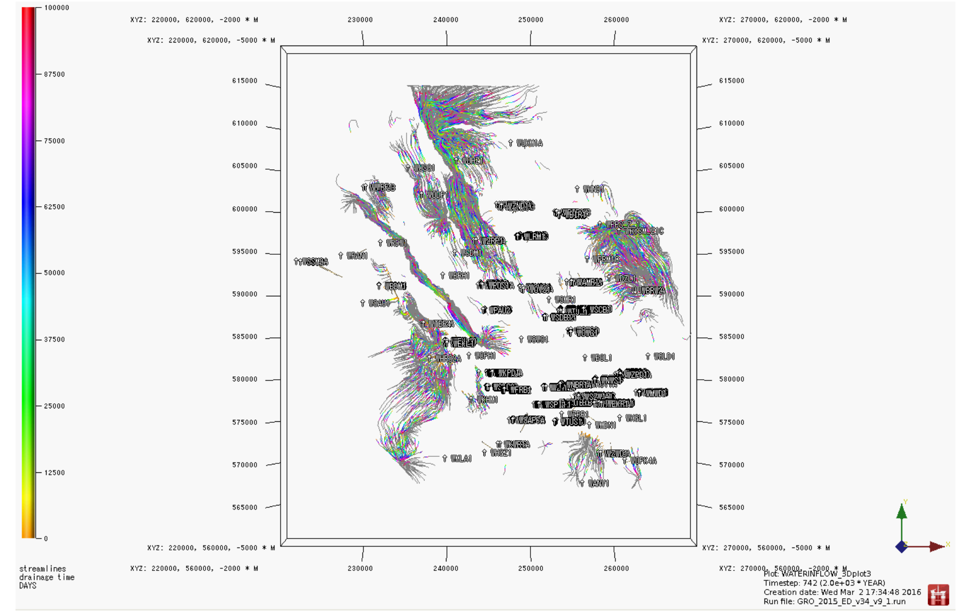




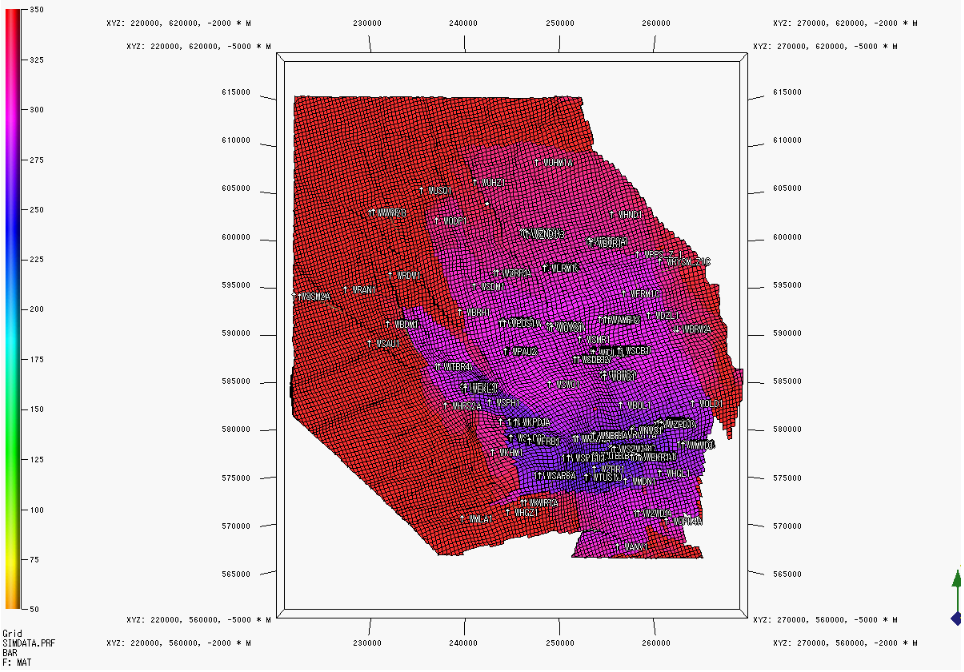
Historic PNL measurements



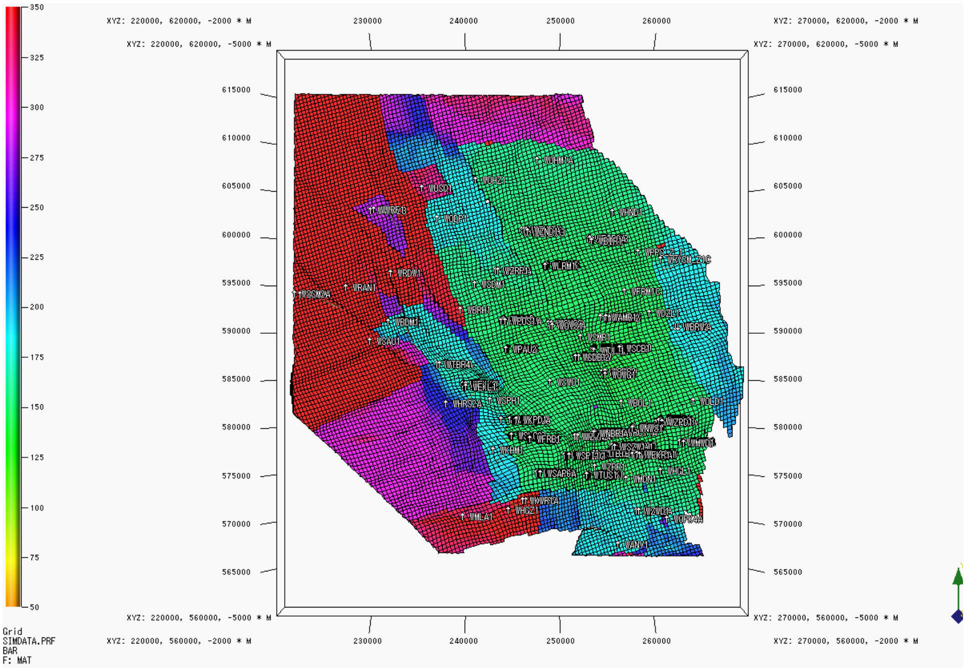
Water phase streamlines



Water phase streamlines (drainage time), indicative for where the water flows in the



1/1/1975



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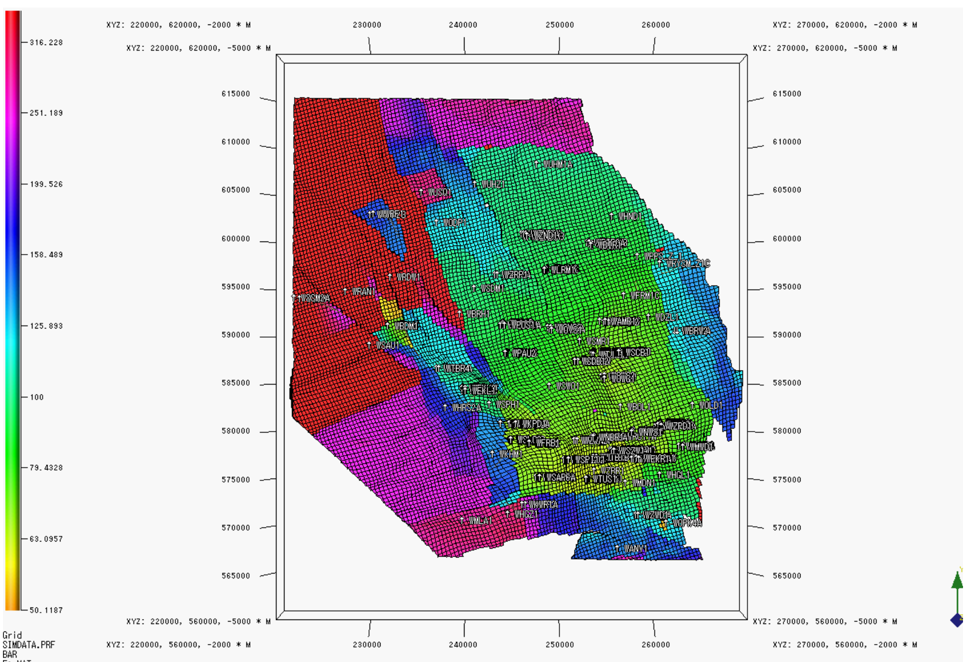
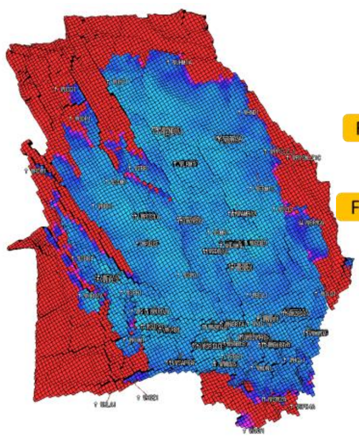


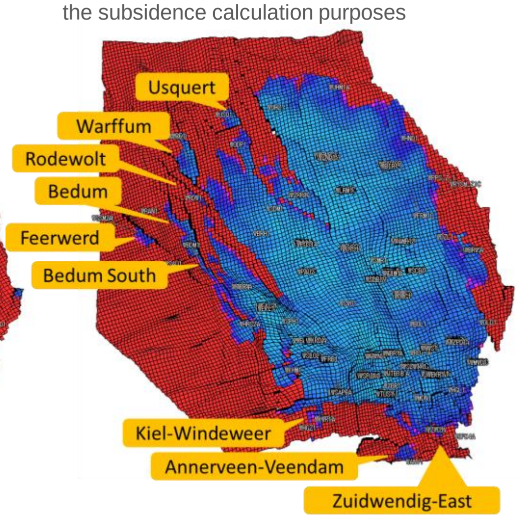
1/1/2016

EXTENDED GRID WITH LAND FIELDS

"Base case grid" - GFR 2015 initial static model



"Extended grid" - GFR 2015 static model with additional cells in the aquifers and land fields for the subsidence calculation purposes



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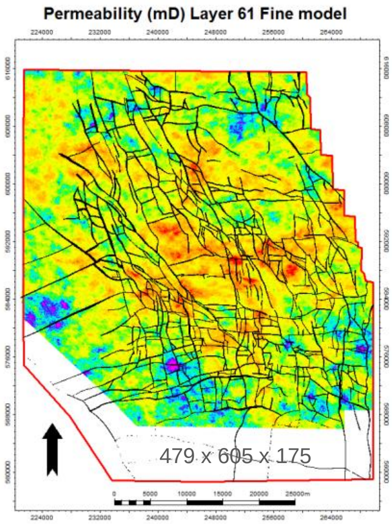
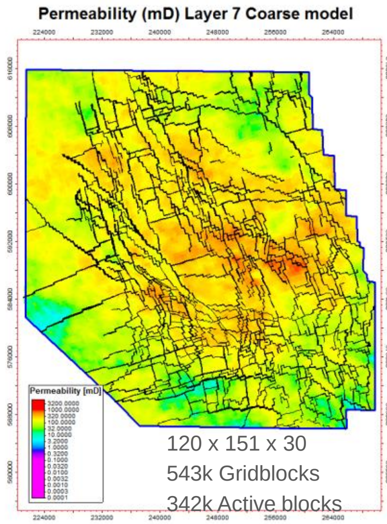
UPSCALING (PERMEABILITY)





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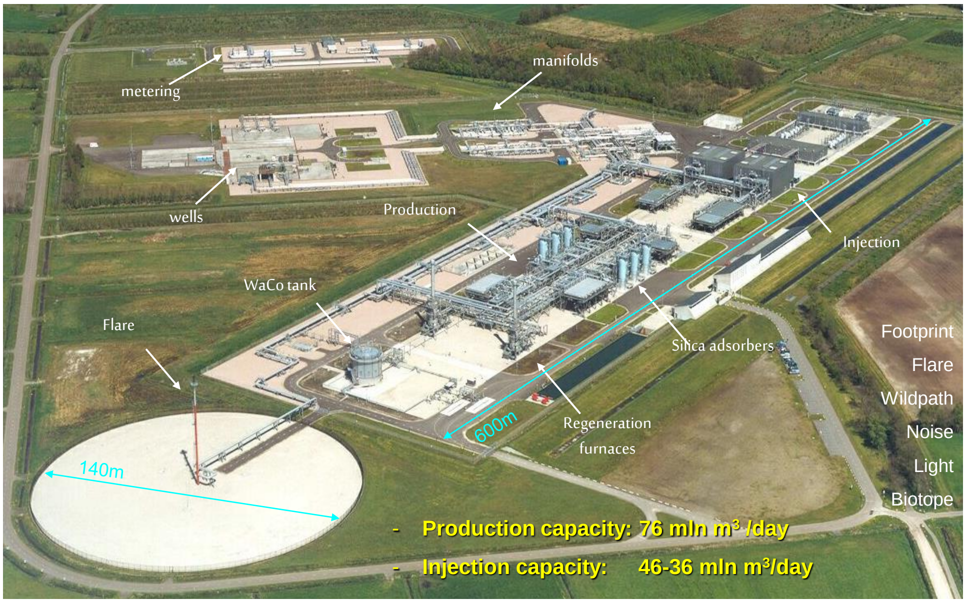
Production Coordination Centre (PCC) – Hoogezand

- Manning: 2 Supervisors, 24 hours per day.
- 4-5 Operators in the field

Norg (UGS)



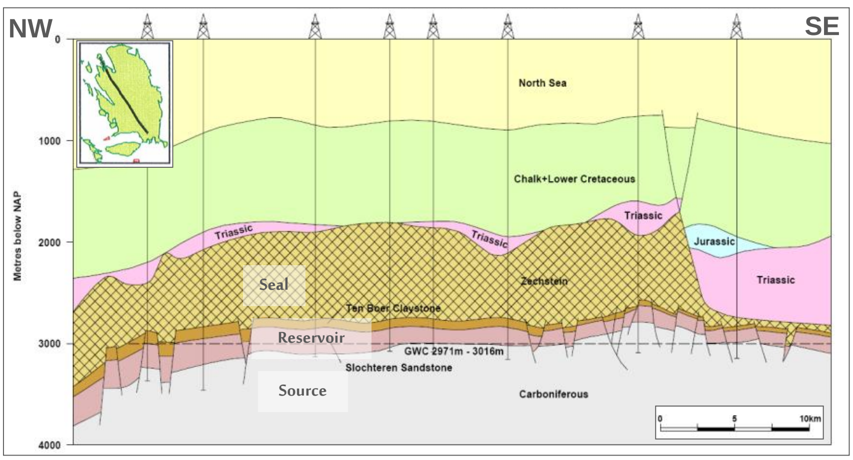
Grijpskerk (UGS)

Delfzijl water and condensate treatment plant

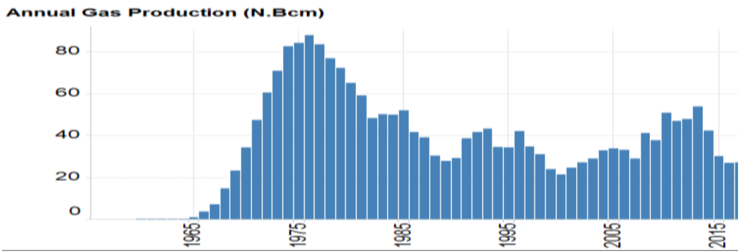
- Max handling capacity: 5800 m^3 condensate per day
- Max handling capacity: 5000 m^3 water per day

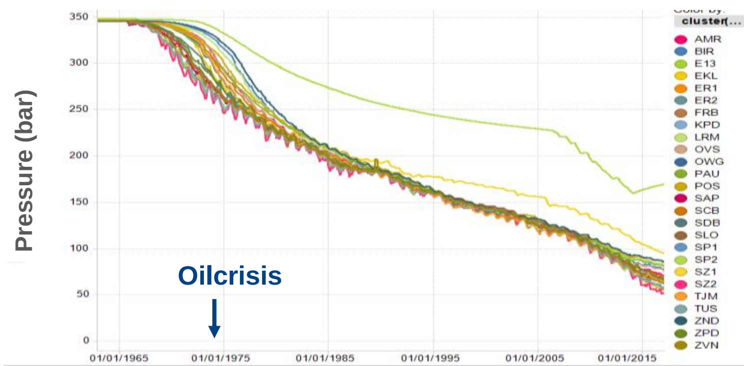
Groningen Gas Field

- Structure: Culmination of regional North Netherlands High
- Seal: Zechstein salts, anhydrites and carbonates
- Reservoir: Rotliegend Slochteren Formation
- Source: Carboniferous Coals



Historic Field Development



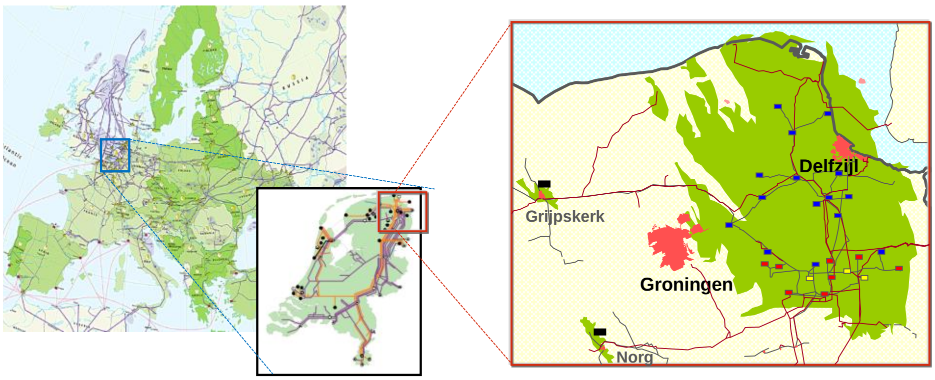


The Groningen production system – “the ring”

- 20 production clusters, 2 satellites
- 7 custody transfer stations (Overslagen)
- gas pipeline grid consists of 136 valves and 59 different sections of pipeline (total 162 km)
- Directly connected to Norg UGS via NorGron pipeline, indirectly via GasUnie network

Groningen gas field

- One of largest gas fields in the world (top 20)
- Discovered 1959 – start production 1963
- Original reserves: 2,700 billion m3 (~ 17,000 mboe)
- Crucial role in Dutch and European security of gas supply: balancing supply from small fields and market demand



Small fields policy

"Gasgebouw" :

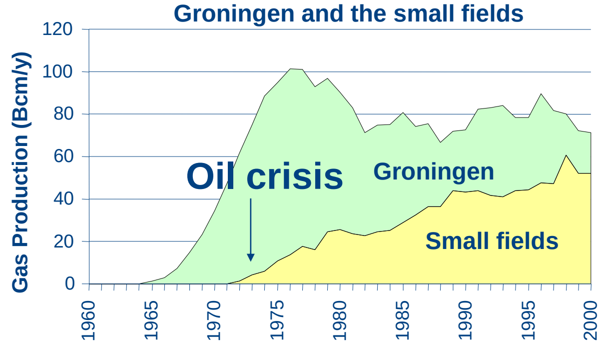
- Priority for the exploration and development of small fields
- Conservation of the Groningen field as national strategic gas reserve

100 Bcm/y

= 275 mln m^3/d

= 1.7 MMboe/d

Netherlands natural gas production
Groningen and the small fields



Source to consumer

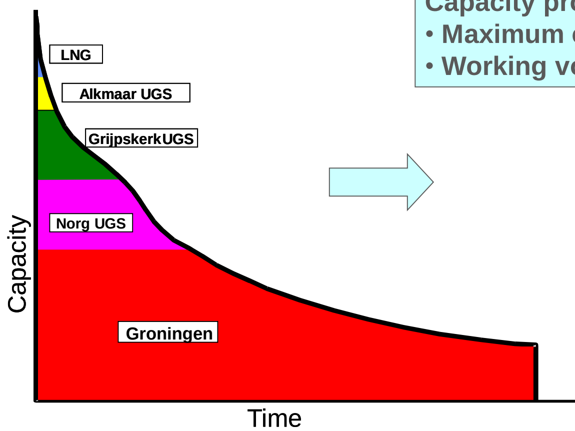
Exploration Development → *Sales* → *Transport* → *Distribution* → *Consumer*

NAM | GasTerra | gasunie | essent, NUON, ENECO energie

King size cluster (Overschild)

- Production capacity: 25 million m3 gas per day

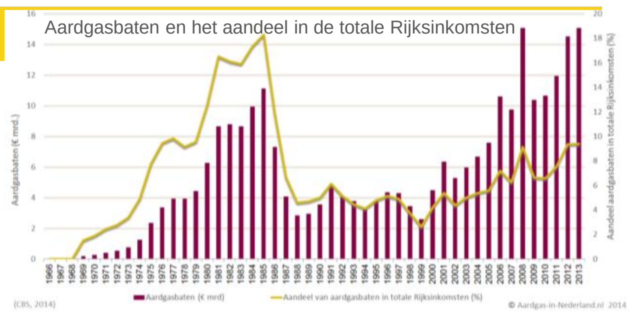
Load vs. Duration

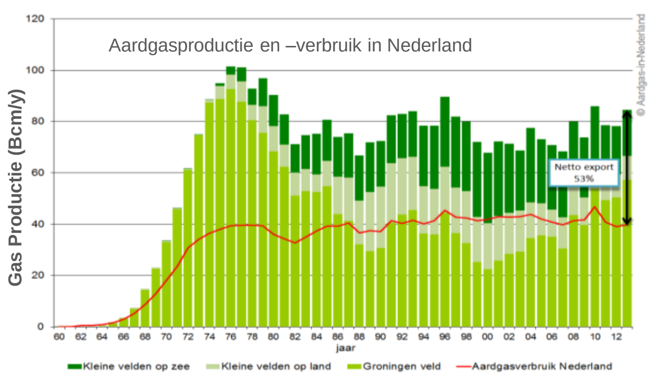


Capacity provision:
- **Maximum capacity;**
- **Working volume.**

23/01/0

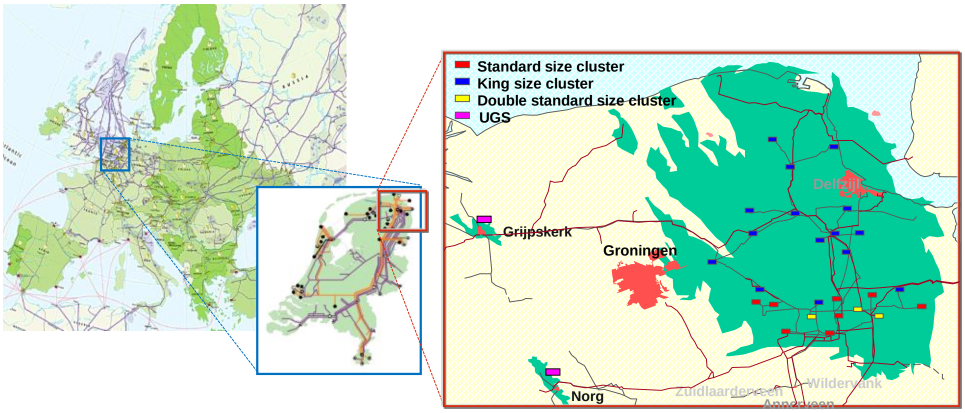
100 Bcm/y
= 275 mln m3/d
= 1.7 MMboe/d





Groningen gas field

- One of largest gas fields in the world (top 20)
- Crucial role in Dutch and European security of gas supply: balancing supply from small fields and market demand
  - —97% of Dutch domestic households use natural gas
  - —Natural gas supplies 45% of the Dutch energy demand
  - —Some 56% of the total European Union Gas Reserves are in the Netherlands



1959: ~5 Bcm

DISCOVERY WELL SLOCHTEREN-1

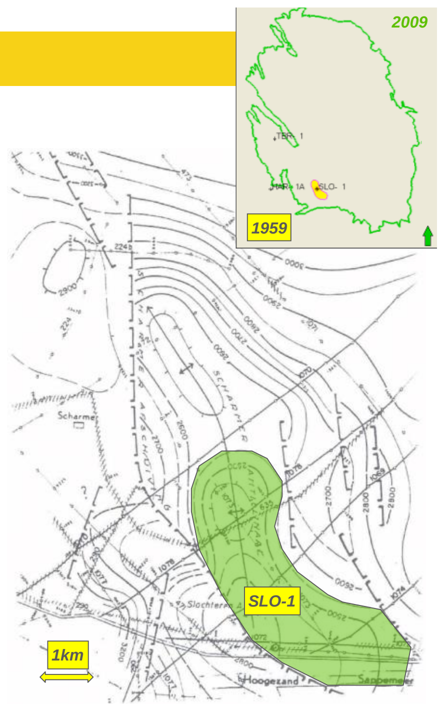
Notitie voor de heer Stheeman

Betreft: Reservoirinhoud van Slochteren

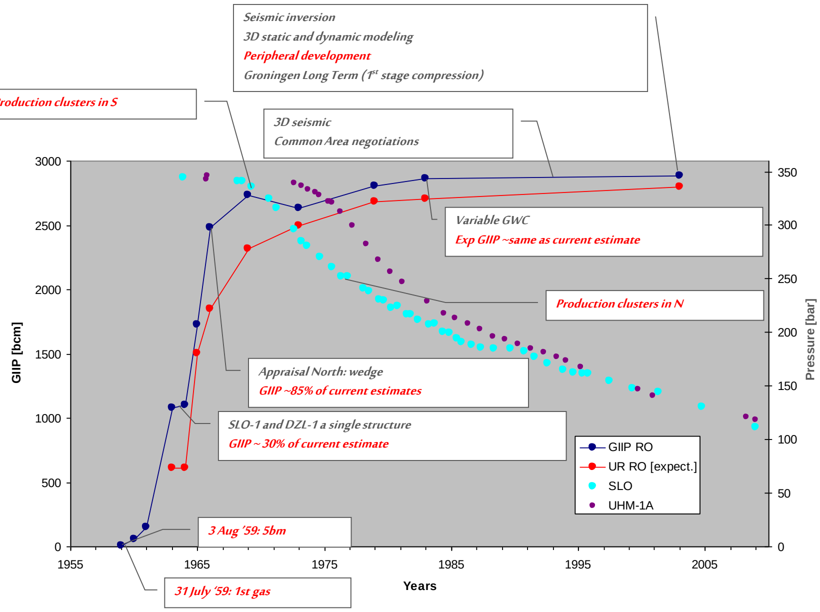
Bij een grondwatervlak dat voor de berekening is aangenomen op 2710 meter, een totale poreuze laagdikte van 25 meter, een gemiddeld connate water gehalte van 30%, een basis oppervlakte van 6,45 km2, een top oppervlakte van 2,25 km2 en een reservoirdruk van 357 at, bedraagt de reservoirinhoud van de Slochteren structuur 5 miljard m3 gas. Hierbij is de inhoud van de dolomieten, die niet te berekenen is, buiten beschouwing gelaten.

Oldenzaal, 3 augustus 1959
C.W.B.

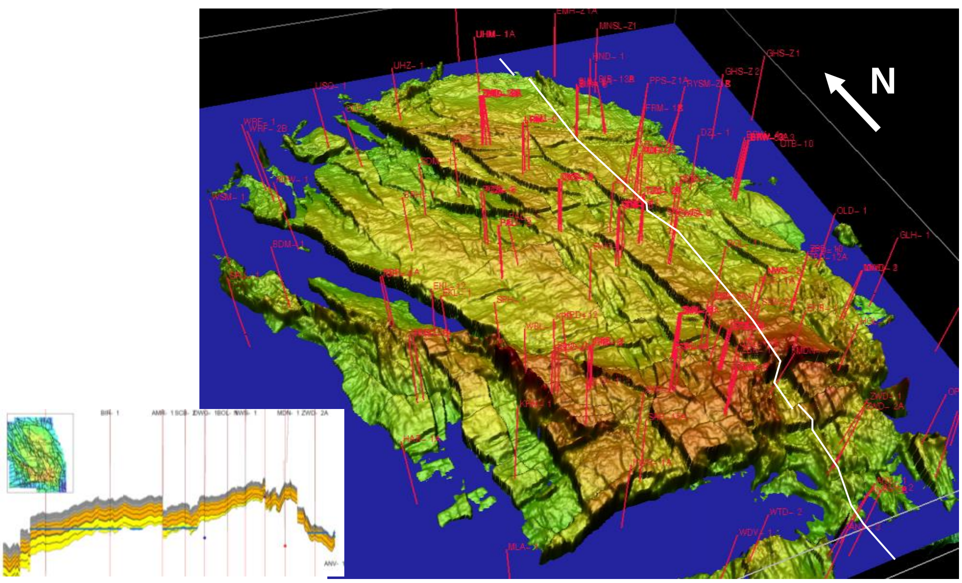
Thickness: *25m*	
	(Base not penetrated yet)
Top structure:	*$2.25 km^2$*
Base structure:	*$6.45 km^2$*
Gas saturation:	*70%*



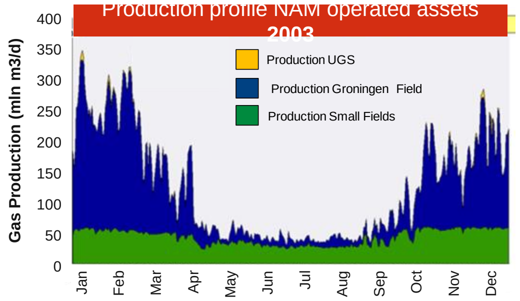
50 Years of Volumes and Pressure

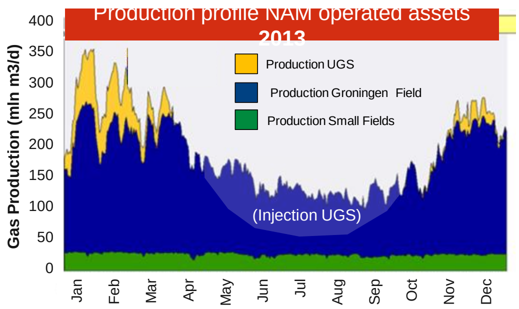


Current overview



Annual production swing





Up to 2003

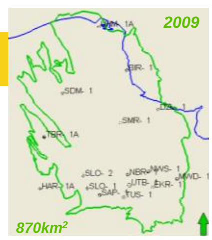
- Low Groningen production (< 10 mln m^3/d) in Summer (Mar-Oct)
- Occasional utilization of UGS capacity in Winter

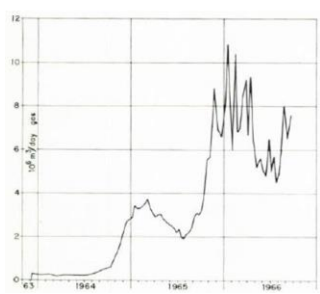
2013

- Declining Small Fields Production
- Higher Groningen production (> 50 mln m^3/day) during shorter summer (May –Aug)
- Sustained utilization of UGS capacity in Winter

- Declining Groningen capacity
- Market demand for high Working volume Norg UGS (7Bcm)
  - Norg expansion project

1966: Appraisal and Development



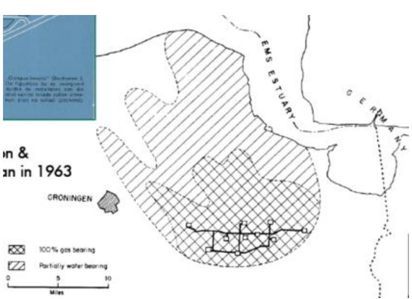


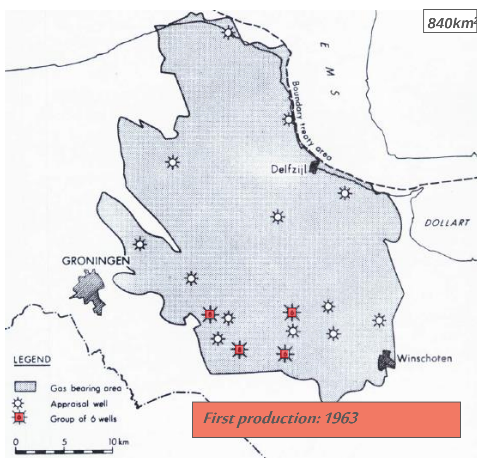
Northern and Southeastern Appraisal

1st Southern clusters

New seismic (2 x 3km grid, 430km)

Full petrophysical review





Mmax workshop March 2016

NAM

History of geomechanics for the Groningen field

Rob van Eijs

NAM BRON VAN ONZE ENERGIE

Mmax workshop March 2016

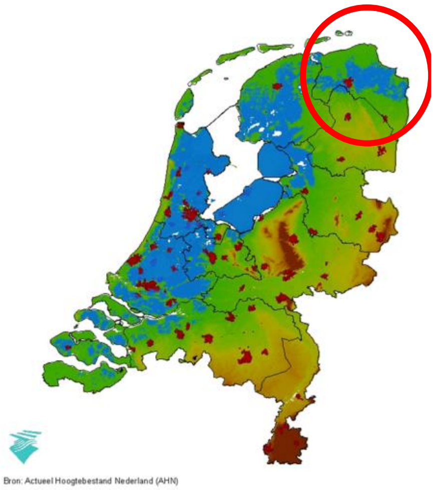
contents

- Geomechanical threats linked to Groningen gas production
- Data to constrain compaction and subsidence uncertainty in Groningen
- Subsidence predictions – a historical overview
- Inversion of subsidence data to compaction
- Data on stress values and directions

NAM

Geomechanical threats

- Main Issue: **land subsidence**
  - Parts of Groningen below sea level
  - Considered to be an issue already before start of production
- Less important issues:
  - Sand production
  - Until 2012: induced seismicity



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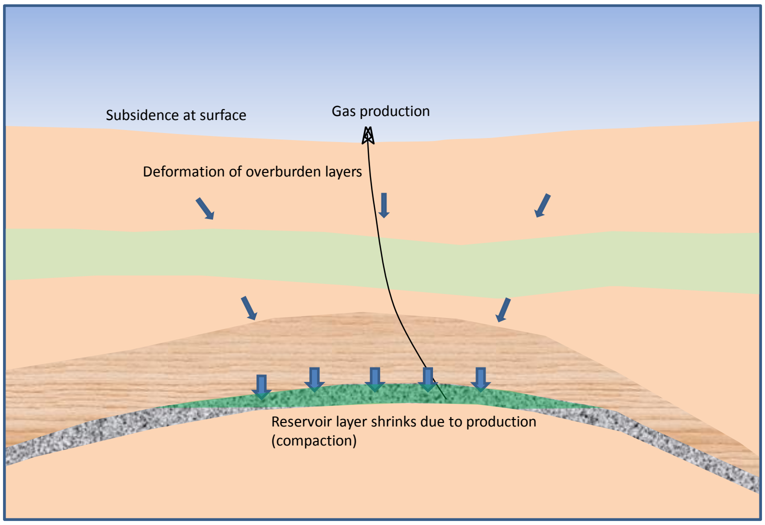
Compaction and subsidence



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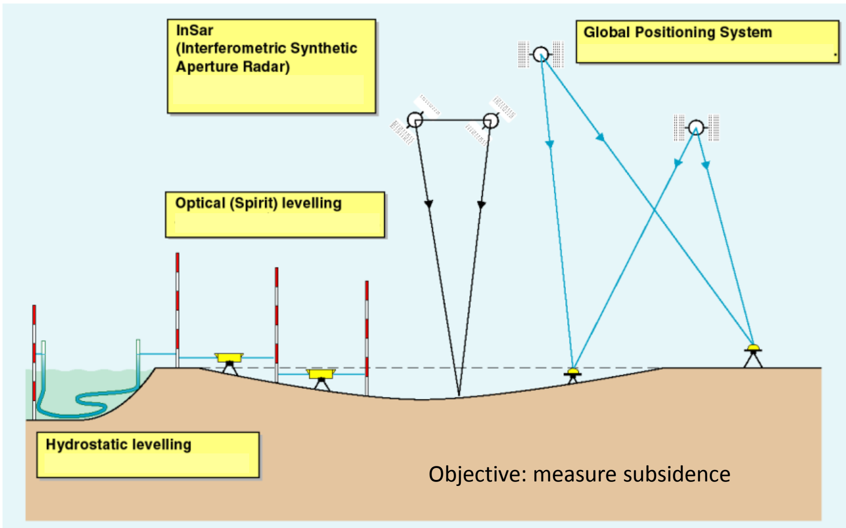
Data to constrain compaction and subsidence uncertainty in Groningen - Geodetics



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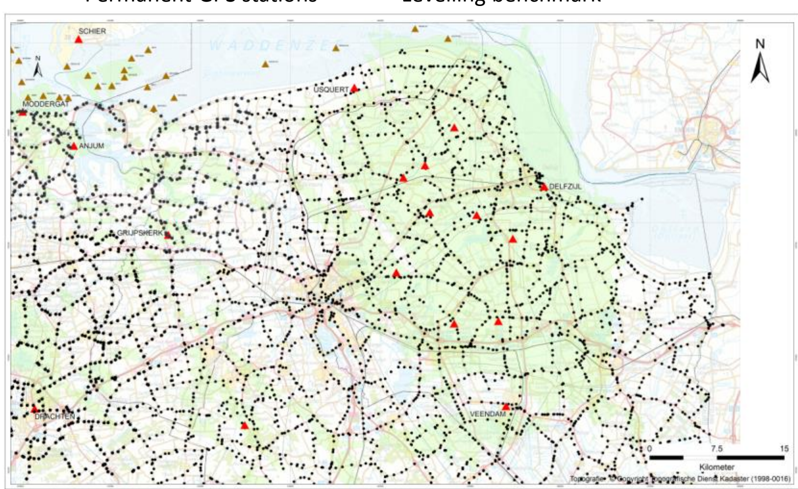
levelling network in the northern part of the Netherlands data since 1964

▲ Permanent GPS stations • Levelling benchmark



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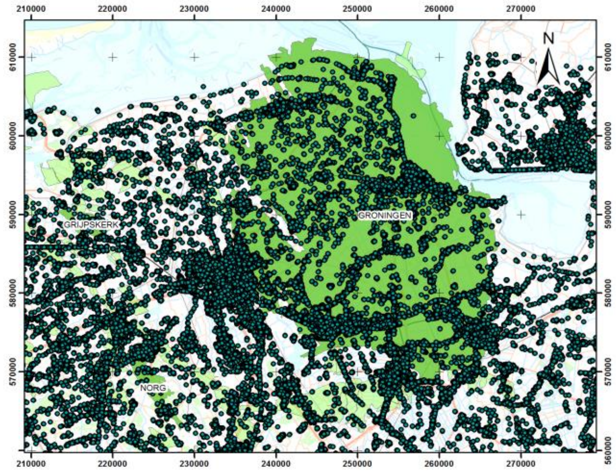
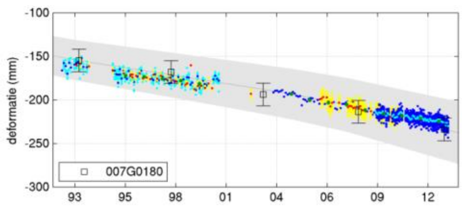
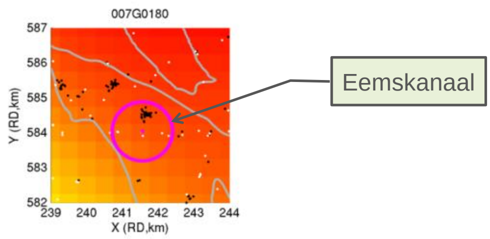
PS-InSAR scatterers data since 1993

- Persistent scatterer

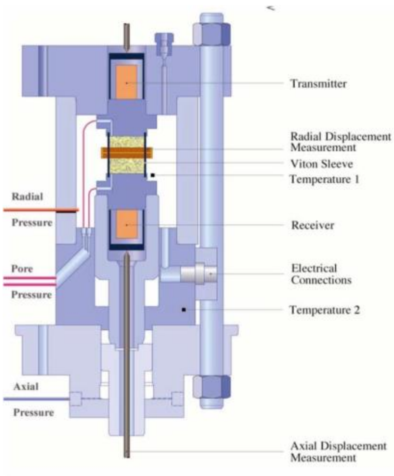


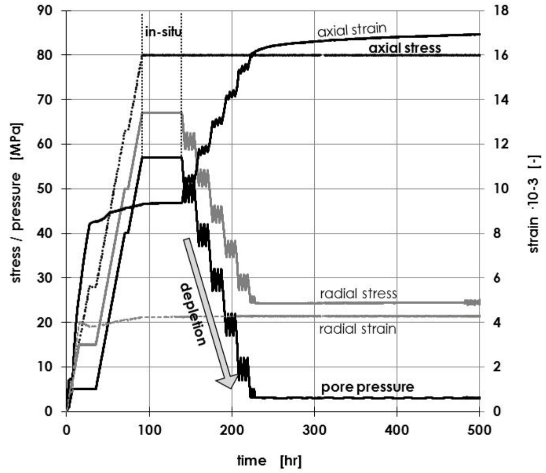
Integration of InSar and levelling





Data to constrain compaction and subsidence uncertainty in Groningen – laboratory measurements





Hol et al. (2015)

Objective: measure compressibility (Cm) of the rock

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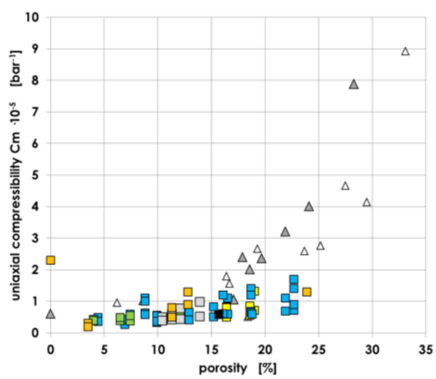
Data to constrain compaction and subsidence uncertainty in Groningen – laboratory measurement



Some observations:

- Cm increases with porosity
- Inelastic strain increases with porosity,
  typically 50% for a 20% porosity sample
- 80% of the strain
  time independent;
  20% time dependent

Hol et al. (2015)

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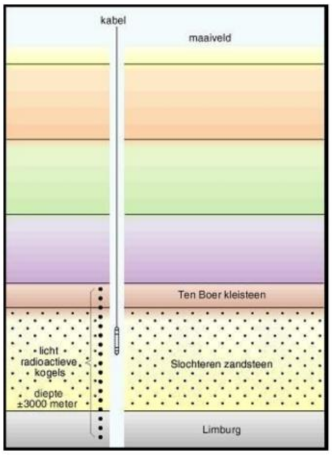
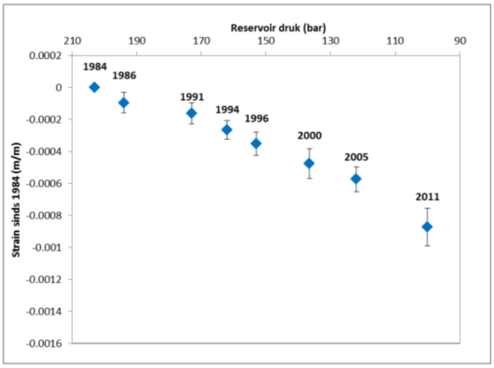
Data to constrain compaction and subsidence uncertainty in Groningen –In-situ compaction

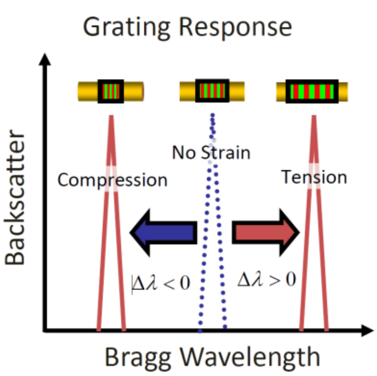


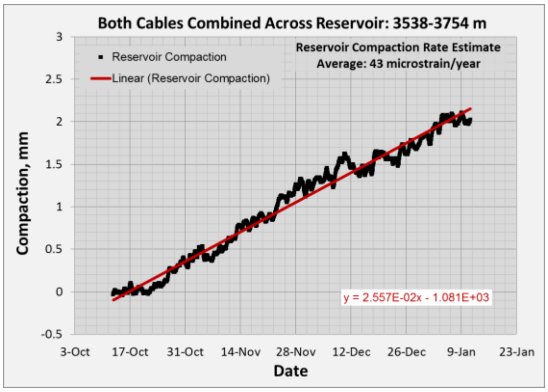
$$\Delta h = h_{ref} * \Delta P_p * C_m$$



Objective: measure compaction in the field

Data to constrain compaction and subsidence uncertainty in Groningen – In-situ compaction. Real Time Compaction Measurement ZRP-3



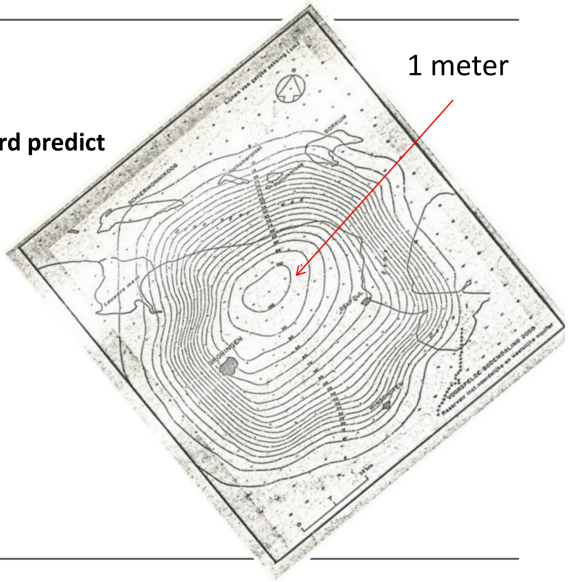


Objective: measure compaction in the field

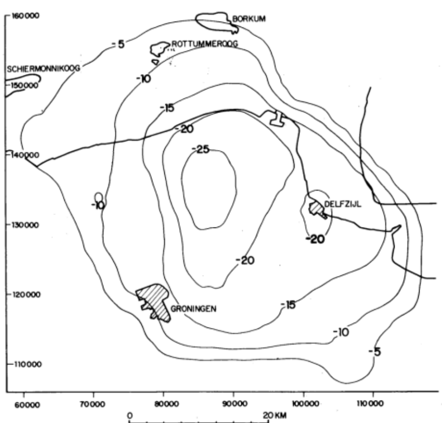
Subsidence – prognosis end of field life 1971

Only based on first lab results

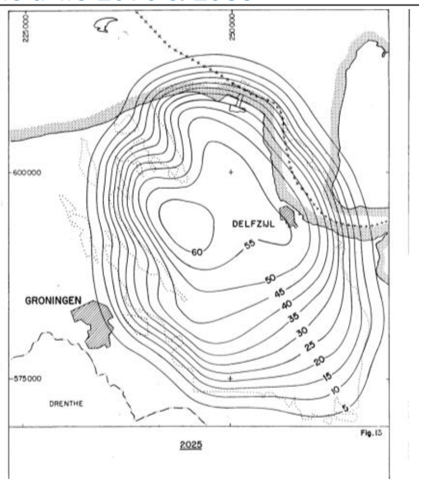
- **Cm from core**
- **Analytical equations to forward predict subsidence (Geertsma, 1973)**



Subsidence – prognosis end of field life 1976 & 1985

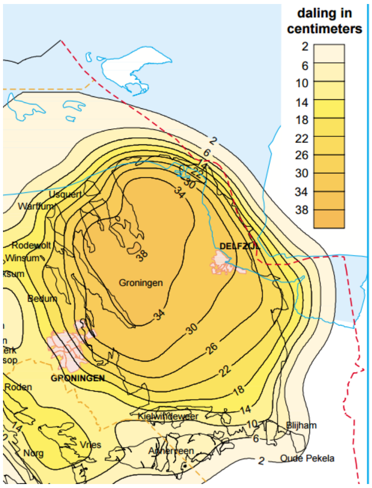


1976 Prediction based on first geodetic measurement

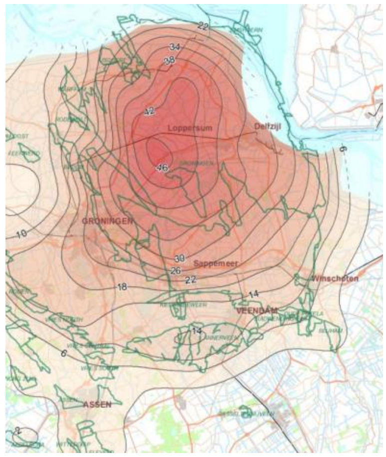


1985 Prediction based on RTCM compaction model

Subsidence – prognosis end of field life 2000 & 2015

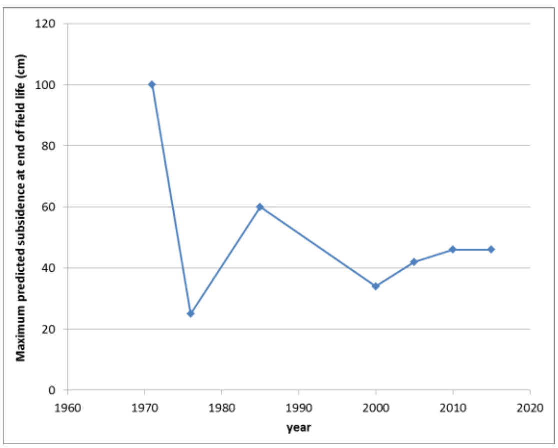


Prediction 2000 linear compaction model



Prediction 2015 time-decay model

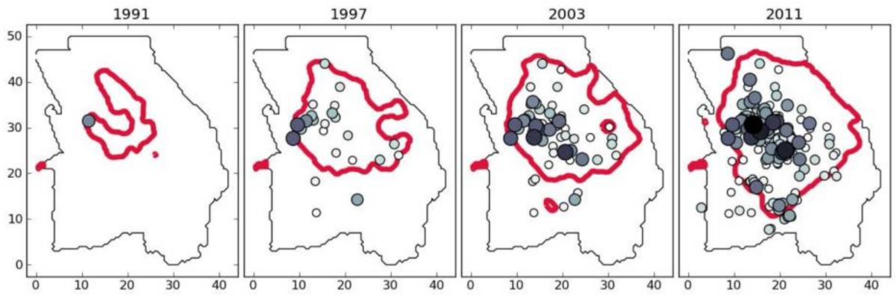
Subsidence – Maximum predicted subsidence at end of field life through time



Convergence of predictions

- **More geodetic available to constrain uncertainty**
- **Guidance from observations above other fields (Ameland)**
- **Analytical and numerical models**

Short term compaction forecasts for seismic risk

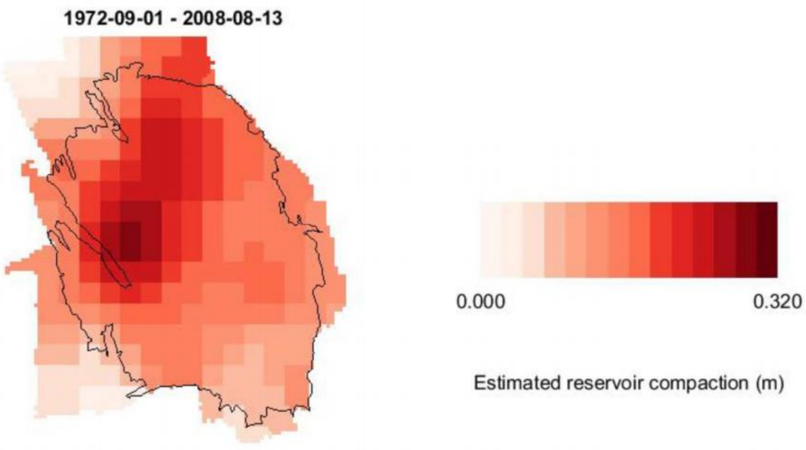


The observed earthquakes plotted on the map of the field together with the 18 cm compaction contour for four years (1991, 1997, 2003 and 2011)

NAM (2013)

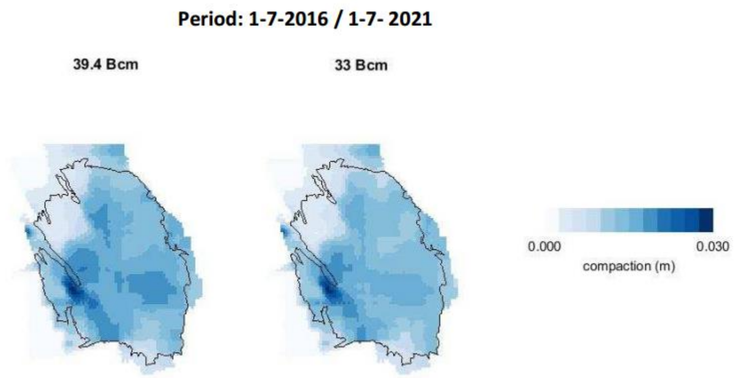
NAM

Compaction based on inversion of subsidence data



NAM

Short term compaction forecast based on compaction model from inversion



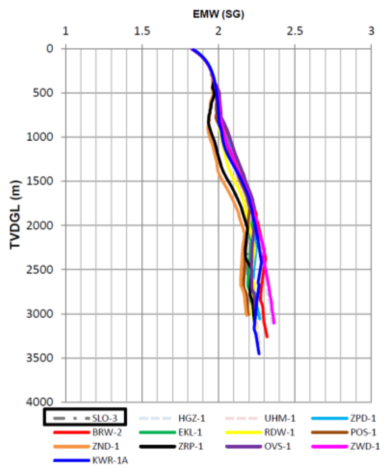
Compaction for the period 1-7-2016 to 1-7-2021 for both production scenarios using the linear compaction model (NAM, 2015)

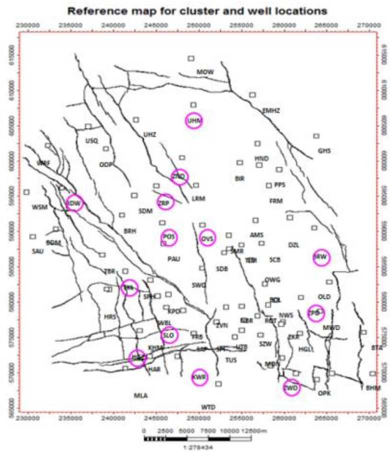
Stress measurements in the Groningen field

- Data from:
  - Density logs → Sv value
  - Minifrac data → Sh value
  - Loss circulation events → Sh value
  - Oriented Caliper log → SH direction
  - Image logs → SH direction, SH/Sh ratio
  - Sonic Scanner – circumferential dipole sonic →SH direction, SH/Sh ratio
  - Differential strain analysis → SH direction, SH/Sh ratio
  - Strain recovery analysis → SH direction, SH/Sh ratio

Remember 'stress gradient' = Stress / depth → units bar/10m, SG

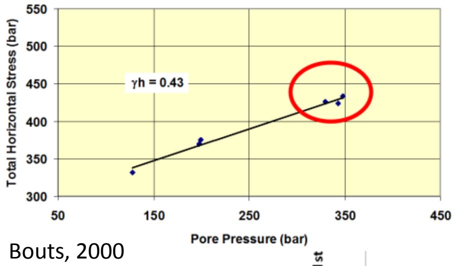
Vertical stress from density logs





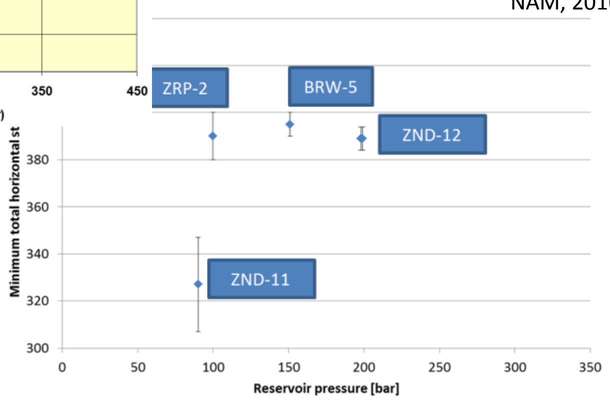
NAM

Minimum stress values and the depletion constant



Bouts, 2000

NAM, 2016



NAM

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Values for SH/Sh ratio (average values)

Well	Well spud [year]	test type	Formation	pore pressure [bar]	SH/Sh
BRW-5	2013	circumferential sonic	RO	151	1.07
KWR-1a	1997	image log	RO/DC	382	1.12
RDW-1	1998	image log	RO/DC	352	1.12
t Zandt-9	1976	DSA	ROSL	240	1.07
ZRP-2	2014	circumferential sonic	RO	100	1.03
ZRP-3	2015	circumferential sonic	RO/DC	93	1.03

NAM

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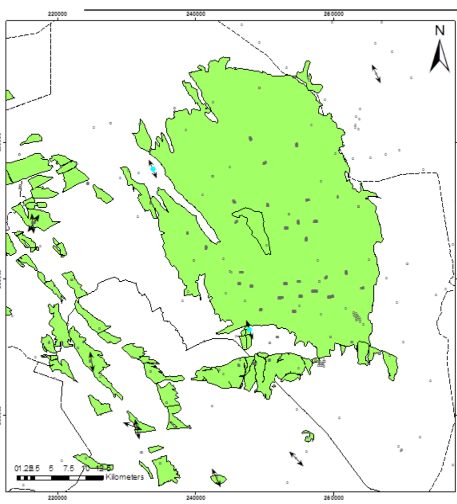
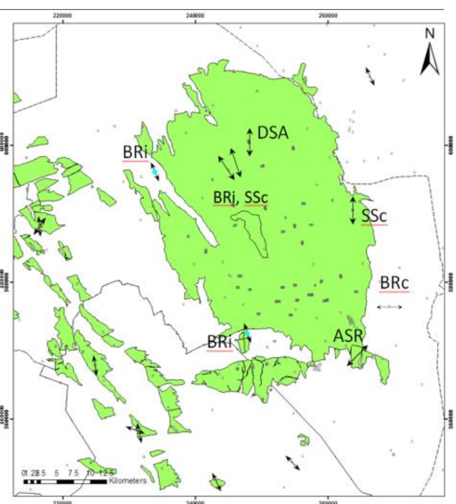
SH direction



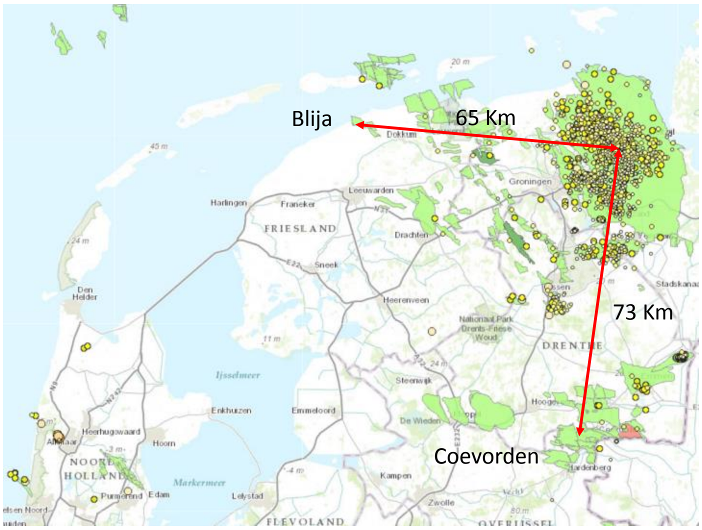
Status 2012



Status 2016

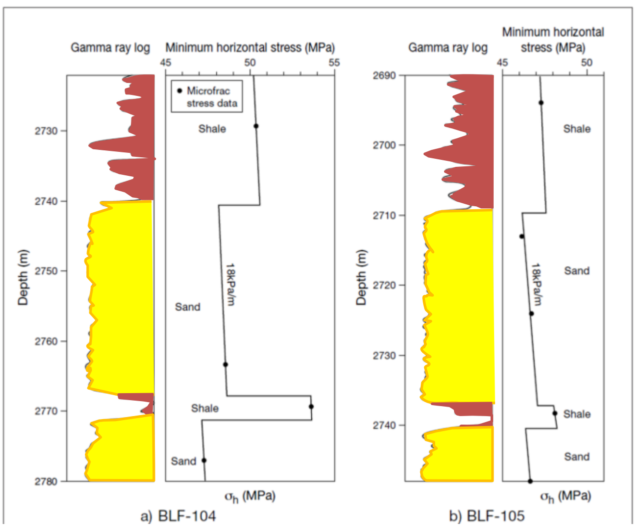
NAM

Stress measurements outside Groningen field



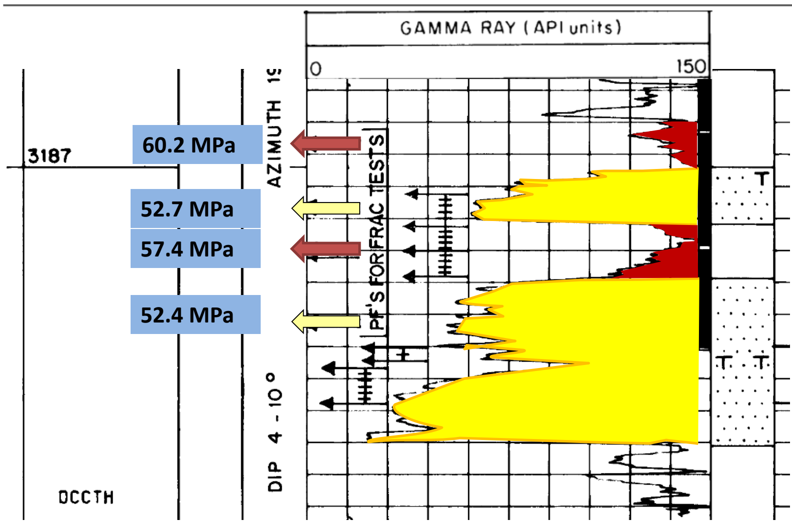
NAM

Stress contrast in Rotliegendes sand-shale sequence (Blija field) 65 km from Groningen field centre



NAM

Coevorden microfrac experiments in Carboniferous sand-shale sequence



Conclusions

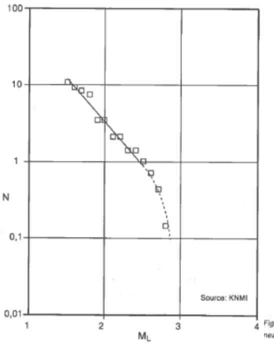
- Good temporal and spatial coverage of geodetic data. Both subsidence and compaction uncertainty is well constrained.
- New data on stress direction reveals more variation
- No value for the virgin min. total stress could be retrieved from legacy data → no determination of a depletion constant possible at present
- This makes the calibration of explicit (stress based) geomechanical models more cumbersome

History of earthquakes in the Groningen field

Bernard Dost
KNMI

Koninklijk Nederlands Meteorologisch Instituut
Ministerie van Infrastructuur en Milieu

Early history (1986-1995)



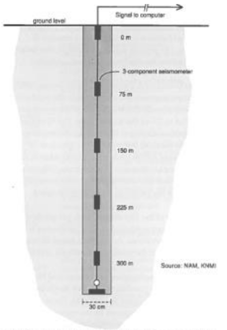


Figure 10: Diagrammatic summary of the borehole seismometers near Finsterwolde.

24 events 1986-08.1993; 1.4<ML<2.8

- Final report on a multidisciplinary study of the relationship between Gas production and earthquakes in the northern part of the Netherlands (1993)
- First network around Assen (1989-1993) and installation of a 300m deep borehole (FIN) in 1992.

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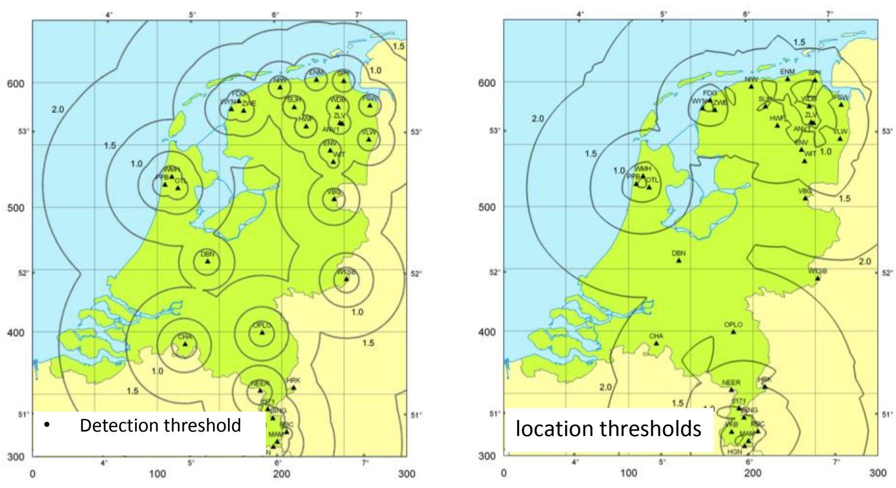
- 1986: First event near Assen
- 1988/89: Network of vertical component short period sensors around Assen
- 1991: First event in Groningen (Middelstum)
- 1995: installation of borehole network covering the North of the Netherlands (20km spacing)
- 2010: extension of the borehole network to the west
- 2014-2016: Lowering monitoring treshold by improving station coverage for Groningen (3-5 km spacing).

Network design: detection (left) and location (right) treshold



- Our event catalogue (1996 – 2014) is complete from M = 1.5
- Events are generally not felt for M < 1.8

Network development:

January 2015:
18 accelerometers in real-time
6 boreholes near the Groningen field

New network in development

63 200m deep borehole arrays
63 surface accelerometers
4 borehole broad-band sensors
2 deep downhole arrays (3 km)

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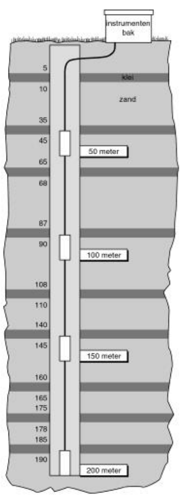
Instrumentation



- Borehole strings, 4 levels, distance between sensors 30, 50 or 75m (120, 200, 300m). No casing
- SM6 4.5 Hz geophone
- Old network: response electronically modified to 1 Hz
- Accelerometers, SIG & Episensor
- Communication:
  - Boreholes: real-time DSL connections (100Hz sampling) with wireless backup
  - Accelerometers: real-time DSL
  - Old system: GPRS, call on demand
- Although investments in instrumentation and maintenance are financed by industry, data ownership is at KNMI.

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Magnitude calibration

Assen network: ML calibration based on the vertical component
(no hor. comp. available) and checked with South Netherlands network.

An attenuation curve was constructed of the form:

$$A_0(r) = c\,R^{-1}\,e^{-\alpha R} \qquad (1)$$

with c= 5500 counts, α= 0,005 km^{-1}

Borehole network: ML calibration based on hor. comp. at 200m depth
1996: 8 events, 157 recordings

$$\log_{10} A_0 = -1.33 \log(R) - 0.00139\,R - 0.424 \qquad (14)$$

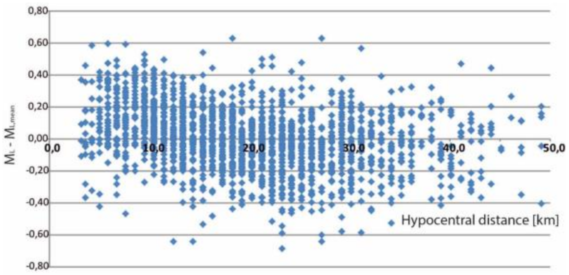
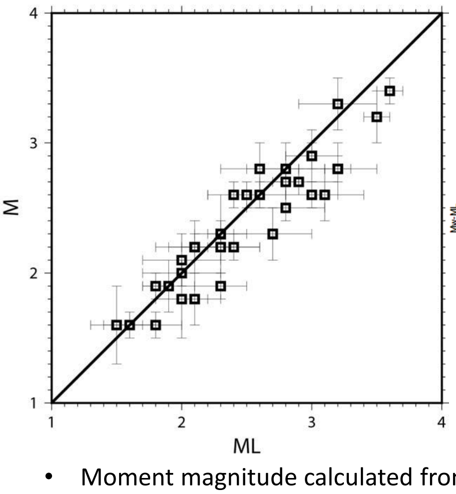
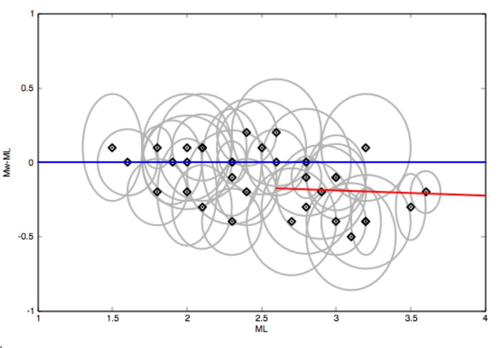


Figure 11. M_{Lj} - M_L for events recorded in the period 2010-2015 as a function of distance.

Relation between Moment magnitude and local magnitude



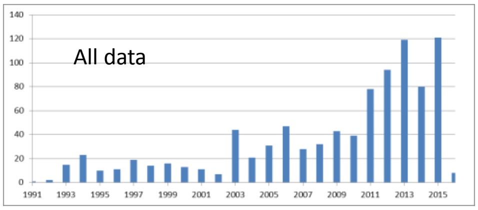


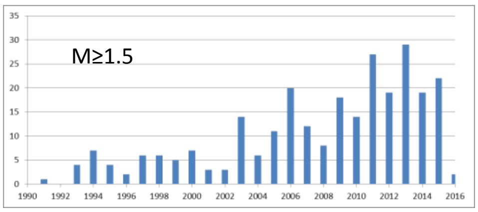
- Moment magnitude calculated from surface accelerometer data (2006-2015)
- For M_L>2.5: **M**= M_L- 0.2

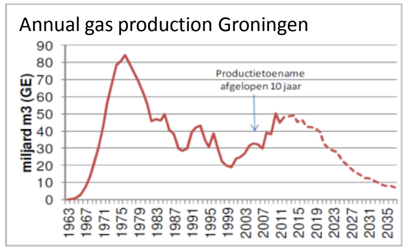
Dost, B., B. Edwards and J.J. Bommer, 2016, Local and Moment magnitudes in the Groningen field, 34pp

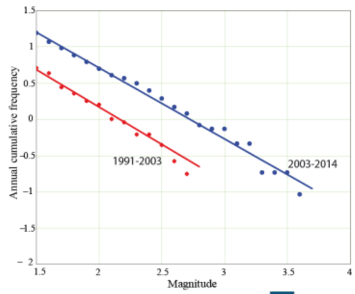
Groningen seismicity, development in time

- Large variability in annual number of earthquakes M>1.4
- Since 2003 increase in activity rate, no significant change in b-value
- Magnitude completeness M= 1,5; Clearly non-stationary process
- Increase in activity rate coincides with an increasing trend in production









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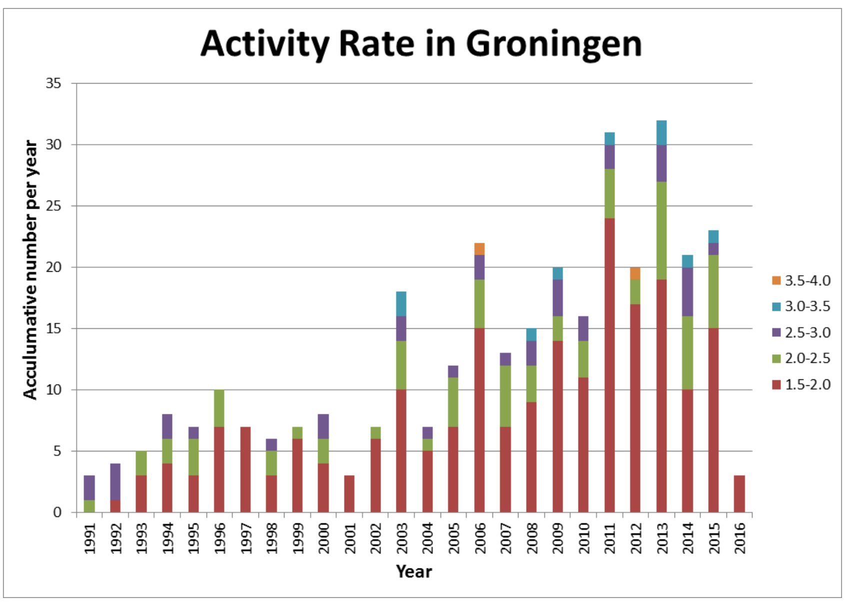

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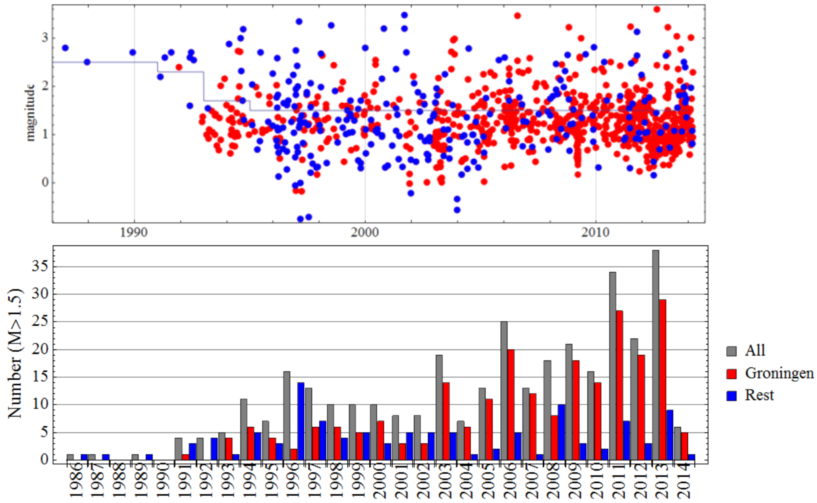
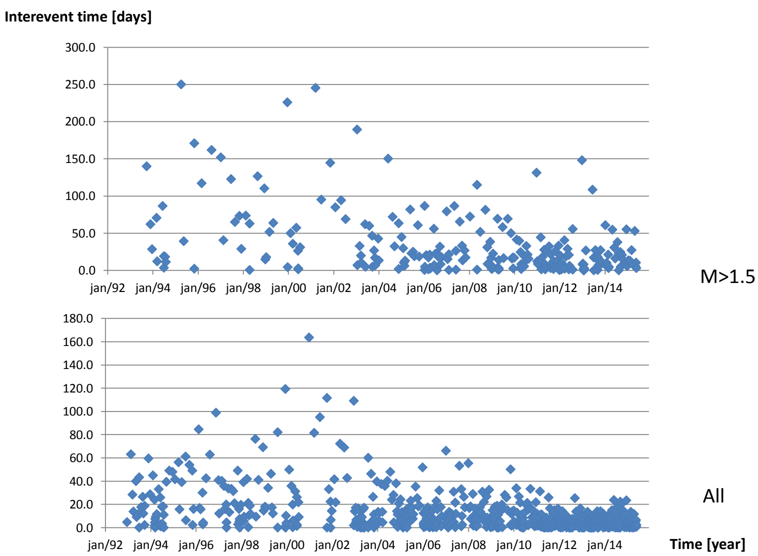
Induced seismic catalogue

	All	Groningen
Total	1037	731
M>1.5	314	219
M>3.0	18	10





- Inter-event time shows a decrease over the period 1991-2015
- This concerns all data, not only M>1.5 (complete magnitude range)
- Statistically significant seasonal variation and correlation with production, only for M<1.3

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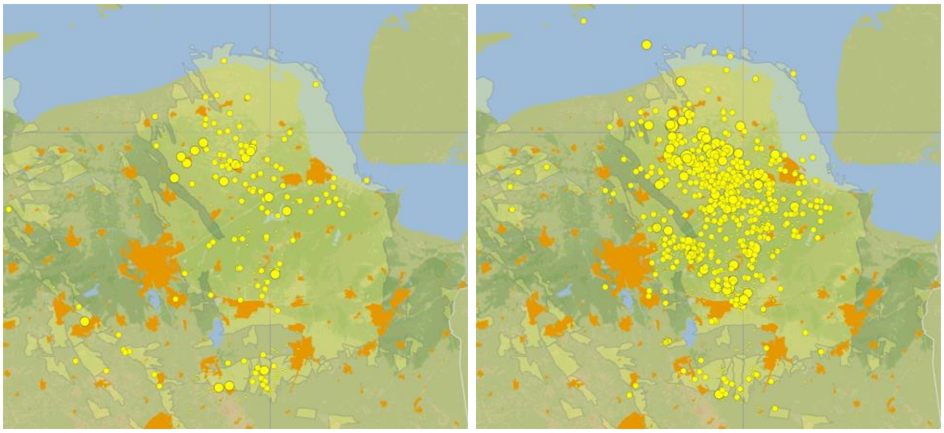
Earthquakes in the Groningen field; spatial distribution



- Seismicity 1986-2003 (left) compared to 2003-2016 (right)

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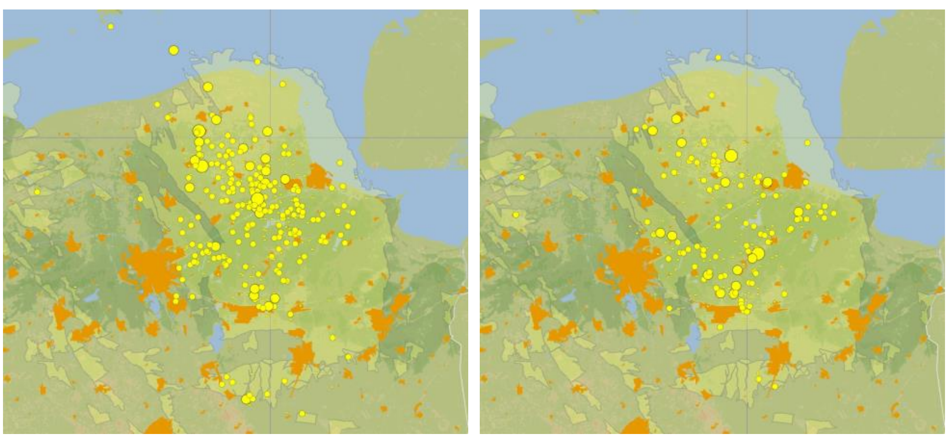
Spatial distribution of seismicity in Groningen



- Seismicity 2010-2014 (left) compared to 2014-2016 (right)

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Location accuracy

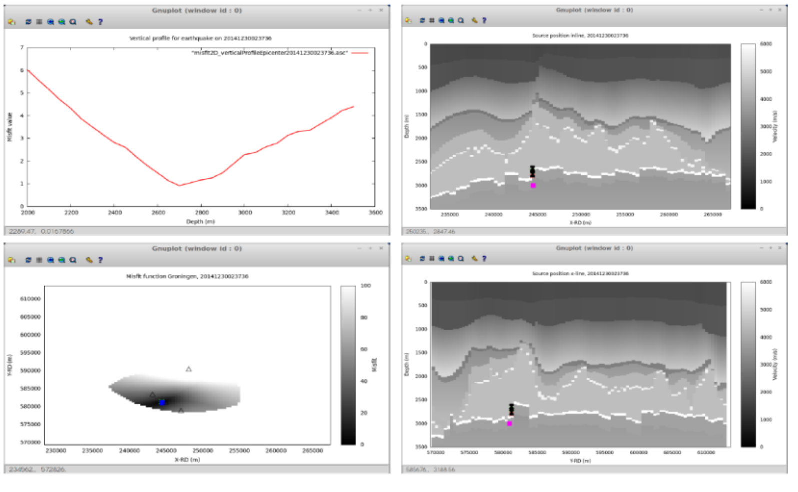
- The sparse borehole network (20km station separation) covered a heterogeneous shallow structure
- An average velocity model was used in the hypocenter calculation
- Average location accuracy was 0,5-1km in the horizontal plane and at least 1-2 km in depth.
- The new Groningen network (2014-now) allows the use of a detailed velocity model for Groningen and the use of new location methods (e.g. EDT, Lomax, 2005)
- Location accuracy improved to 0,1-0,2 km in all coordinates.
- This method will be implemented in the automatic locations

Improvement of event locations (100-200m resolution); J. Spetzler

Event: 20141230023736

Magnitude: 2.8

Event type: Top reservoir, fault

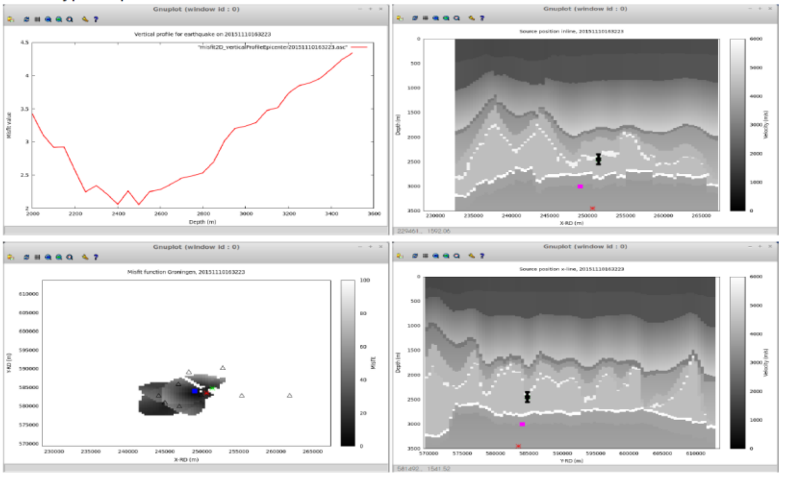


Example of a source above the reservoir

Event: 20151110163223

Magnitude: 0.6

Event type: Top floater



Events above the reservoir are of small magnitude

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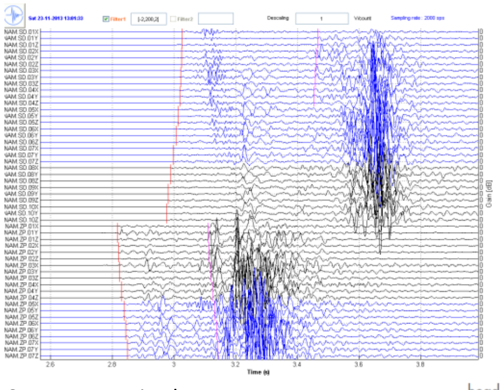
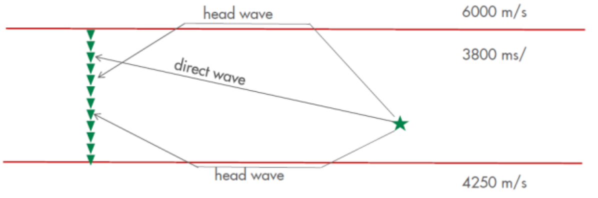


Data example, recorded in STD and ZRP Boreholes at 3 km depth

Complex pattern of arrivals

Source: magnitude



Head waves traveling through the higher velocity layers may arrive earlier than the direct waves traveling through the lower velocity layer

Source NAM

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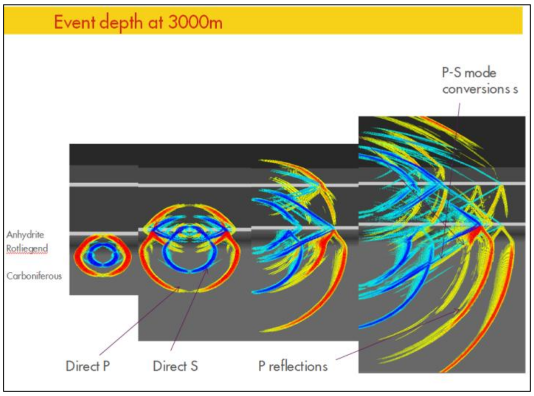
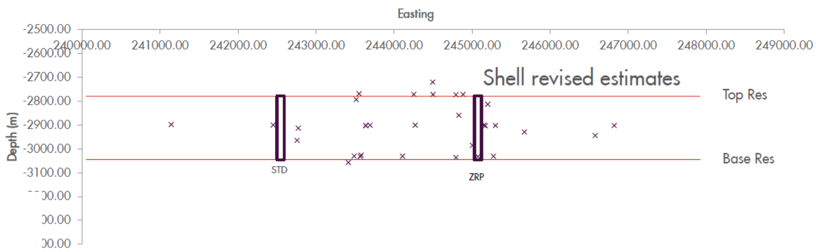


Steve Oates et al., 2014



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New KNMI website: development of new products

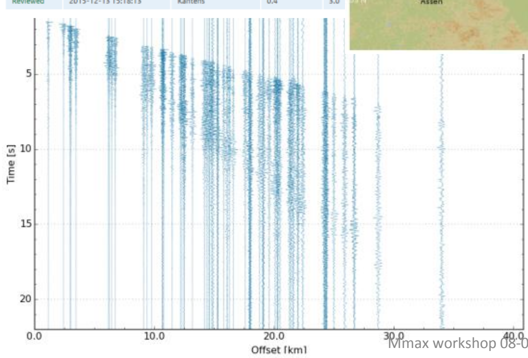
Analyse	Datum en tijd (UTC)	Plaats	Magnitude	Diepte (km)	Type aardbeving	Details
Reviewed	2016-01-26 22:22:33	Harkstede	1.5	3.0	Geinduceerd	Detail page
Reviewed	2016-01-20 03:57:08	Woltersum	0.6	3.0	Geinduceerd	Detail page
Reviewed	2016-01-19 13:19:07	't Zandt	0.6	3.0	Geinduceerd	Detail page
Reviewed	2016-01-17 11:57:33	Siddeburen	1.5	3.0		
Reviewed	2016-01-14 14:03:58	Sandkrug	2.9	3.0		
Reviewed	2016-01-13 06:41:42	Siddeburen	1.3	3.0		
Reviewed	2016-01-11 05:31:35	Froombosch	0.6	3.0		
Reviewed	2016-01-07 05:25:55	Zuidbroek	1.6	3.0		
Reviewed	2016-01-02 00:04:28	Sint-Annen	0.5	3.0		
Reviewed	2015-12-25 04:19:36	Ten Post	1.3	3.0		
Reviewed	2015-12-22 06:00:13	Bergheim	2.4	1.0		
Reviewed	2015-12-15 07:43:55	Noordwolde (Gr.)	1.7	3.0		
Reviewed	2015-12-15 00:01:50	Delfzijl	1.6	3.0		
Reviewed	2015-12-14 02:47:45	Emmen	1.4	3.0		
Reviewed	2015-12-13 15:18:13	Kantens	0.4	3.0		

Aardbeving van 2016-01-26 22:22:33 (UTC)

Datum en tijd (UTC): 2016-01-26 22:22:33
Latitude: 53.203 °
Longitude: 6.720 °
Diepte: 3.0 km
Type aardbeving: Geinduceerd
Plaats: Harkstede
Magnitude: 1.5

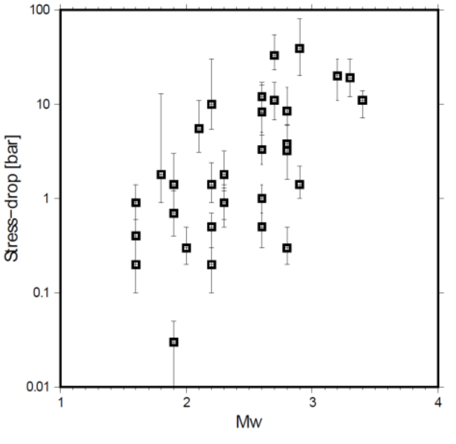
Link naar event data: FDSN web services *(beta)*

2016-01-27 08:35 (UTC)



Station	Network	Distance (km)	Phase	Tijd (UTC)	Residual (s)	Pha Weight	Magnitude	Mag Weight
WDB4	NL	1.2	P	22:22:34.47	-0.03	1.0	1.32	1.0
G444	NL	2.4	P	22:22:34.60	-0.10	1.0	1.77	1.0
G454	NL	3.0	P	22:22:34.73	-0.07	1.0	-	-
G494	NL	3.0	P	22:22:34.76	-0.05	1.0	-	-
BFB2	NL	3.5	P	22:22:34.93	0.03	1.0	-	-
G334	NL	6.2	P	22:22:35.33	-0.10	1.0	1.52	1.0
G344	NL	6.3	P	22:22:35.47	0.02	1.0	1.36	1.0
G404	NL	6.5	P	22:22:35.48	-0.01	1.0	1.48	1.0
G504	NL	6.7	P	22:22:35.55	-0.01	1.0	-	-
G544	NL	9.1	P	22:22:36.07	0.05	1.0	1.62	1.0
G664	NL	9.3	P	22:22:36.06	-0.02	1.0	1.61	1.0
G294	NL	9.8	P	22:22:36.12	-0.03	1.0	-	-
G554	NL	10.7	P	22:22:36.32	-0.02	1.0	1.30	1.0
G324	NL	10.7	P	22:22:36.41	0.05	1.0	-	-
G274	NL	10.8	P	22:22:36.29	-0.08	1.0	-	-
G514	NL	11.5	P	22:22:36.49	-0.01	1.0	-	-
G234	NL	12.2	P	22:22:36.61	-0.04	1.0	-	-
G224	NL	12.3	P	22:22:36.59	-0.07	1.0	-	-
ZL24	NL	12.5	P	22:22:36.66	-0.05	1.0	1.55	1.0
ZLV4	NL	12.5	P	22:22:36.66	-0.05	1.0	1.53	1.0
G244	NL	13.2	P	22:22:36.82	-0.04	1.0	-	-

Stress-drop



Mmax workshop 08-03-16

Groningen Induced Seismic Hazard and Risk Assessment Project

Workshop on Maximum Magnitudes for the Groningen Field

Time: 8th to 10th March 2016

Location: World Trade Centre, Schiphol Airport, Amsterdam

Agenda: Day 2 (Wednesday 9th March 2016)

Start	End	Topic	Speaker
08:30	09:00	*Coffee*	
09:00	09:30	Re-cap of Day 1	Kevin Coppersmith
09:30	10:30	Overview of Mmax estimation for natural earthquakes	Bob Youngs
10:30	10:45	*Coffee*	
10:45	11:15	History of KNMI Mmax estimates for Groningen	Bernard Dost
11:15	12:15	Overview of triggering large EQs	Emily Brodsky
12:15	13:15	*Lunch*	
13:15	14:15	Overview of largest induced/triggered events	Gillian Foulger
14:15	15:15	Mmax distribution for Groningen	Dinske, Shapiro
15:15	15:30	*Coffee*	
15:30	17:30	Mmax distribution for Groningen	Nora Dedontney/ Pablo Sainz
17:30	18:00	Comments from observers	SAC /SodM
18:00	18:30	Closing comments from expert panel	Kevin Coppersmith

Day 1 Panel Questions and Day 2 Areas of Focus

- Anisotropy of the stress field; how much variability in the Sh (minimum horizontal stress); important for the potential for fault reactivation
- Want to look more closely at the focal mechanisms: Is the whole field in an extensional stress state?
- Have any calculations been made of stress drop?
- Will be watching closely the issue of events occurring outside of the reservoir horizon; can they propagate outside (down or laterally)
- Can these faults be traced down into the basement?
- What is the evidence for Quaternary faulting in the region?
- Where are the holes where waste water was injected; depth and volume; is there some likelihood that the injection will be done in the field?
- In discussions of Mmax, what is the time period for which the estimates are appropriate?

Overview of Mmax Estimation for Natural Earthquakes in PSHA

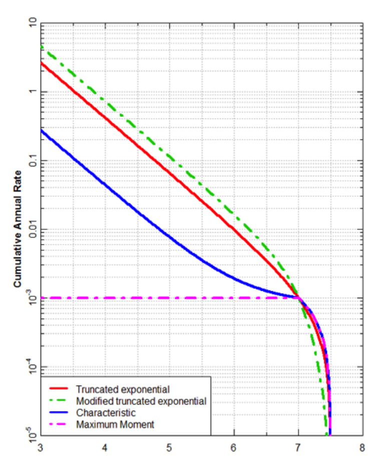
Robert Youngs
Amec Foster Wheeler

Workshop on Maximum Magnitude Estimates for Probabilistic Seismic Hazard and Risk Modelling in Groningen Gas Field

8-10 March, 2016

What is Mmax for a Seismic Source in a PSHA

- A seismic source describes where earthquakes occur spatially
- Earthquake recurrence relationships define the relative frequency of earthquakes of different magnitudes associated with the source
- Mmax (m^u) is the upper limit on earthquakes that can occur associated with the seismic source



Mmax Assessments for Types of Seismic Sources Used in PSHA

- Geologic structure-specific (i.e. faults and fault zones)
  - Usually assessed using an estimate of maximum rupture dimension and empirical relationships between rupture dimensions and earthquake magnitude
- Seismic Source Zones
  1. Maximum observe plus an increment
  2. Maximum observed in analog regions
  3. Assessment of maximum rupture dimensions
  4. Seismicity and geodetics

Mmax for Geological Feature-Specific Seismic Sources

Assess Maximum Dimensions for Rupture

- Maximum rupture length
  - Surface rupture length
  - Rupture length at depth
- Maximum length at depth X rupture width = maximum rupture area
- Maximum displacement
- Average displacement
- Rupture area x average displacement = seismic moment for maximum event

Relationships Between Rupture Dimensions and Magnitude

- Some of the better known for individual rupture parameters
  - Wells and Coppersmith (1994)
  - Anderson et al. (1996) (influence of slip rate)
  - Stirling et al. (2013) (compilation)
  - Leonard (2014) (self-consistent scaling, ACR and SCR)
  - Somerville (2014) (CEUS area-moment)
- Moment magnitude scale, **M**
  - Hanks and and Kanamori (1979)

Addressing Statistical Variability in Empirical Relationships

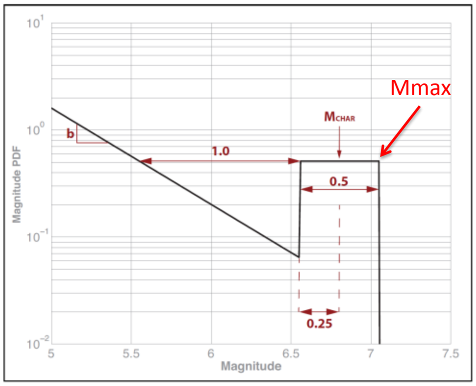


Figure 2. General form and parameters of the Youngs and Coppersmith (1985) MFD.

Youngs & Coppersmith, 1985

- Empirical relationships give expected **M** as a function of fault dimensions
- Statistical variability addressed by incorporating aleatory variability about this estimate in recurrence model

Epistemic Uncertainty in Mmax for Structure-Specific Sources

- Uncertainty in assessing maximum rupture dimensions (perhaps larger component)
- Uncertainty in selection of appropriate empirical relationships

Mmax for Seismic Source Zones

1. Maximum observe plus an increment
2. Maximum observed in analog regions
3. Assessment of maximum rupture dimensions
4. Seismicity and geodetics

1. Maximum Observed Plus Δ

- Maximum possible should be at least as large as largest observed (within uncertainty in assessing magnitude of past earthquakes)
- Assessment of Δ
  - Scientific judgment – typically use a wide range (e.g. 0, 0.3, 0.6, EPRI-SOG, 1988) with perhaps minimum value of Mmax
  - Statistical based on observed seismicity (e.g. Kijko and Sellevoli, 1989; Kijko, 2004)

Statistical Assessment of Δ

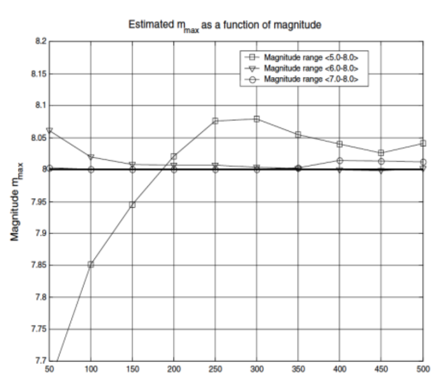
- From Kijko (2004)

$$m^u = E(M_{\max-obs}) + \int_{m_0}^{m^u} F_{m_{\max-obs}}(m)\mathrm{d}m$$

- Additive term provided in three forms
  - Based on truncated exponential model (Kijko and Sellevoli, 1989), the K-S estimator
  - Based on truncated exponential model with uncertain b-value (Kijko and Graham, 1998), the K-S-B estimator
  - Based on arbitrary magnitude distribution, Kijko et al. (2001), the N-P-G estimator

Statistical Estimates of Δ Require Large Samples

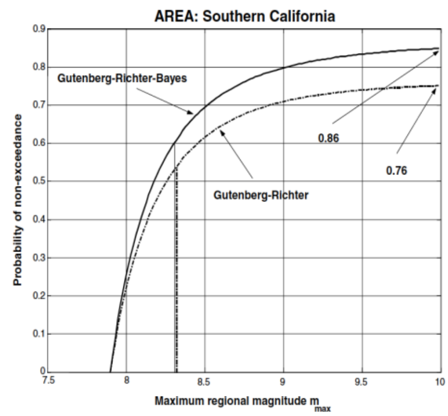
- Performance of K-S estimator as a function of sample size, N, and magnitude range of sample.
- Based on average value from 1000 simulated catalogs (Kijko, 2004)



Uncertainty in Mmax

$$P(m^u < z) = F(m^u) = 1 - F_{m_{max-obs}}(m_{max-obs}|z)$$

- Variance in Mmax estimate is of the order of $\Delta^2 + \sigma^2(M_{max\text{-}obs})$
- Distribution for Mmax is unbounded $P(m^u < \infty) = 1 - \alpha$ with α function of sample size
- Possible to use an external constraint on upper limit in order to apply method (EPRI/DOE/NRC, 2012)



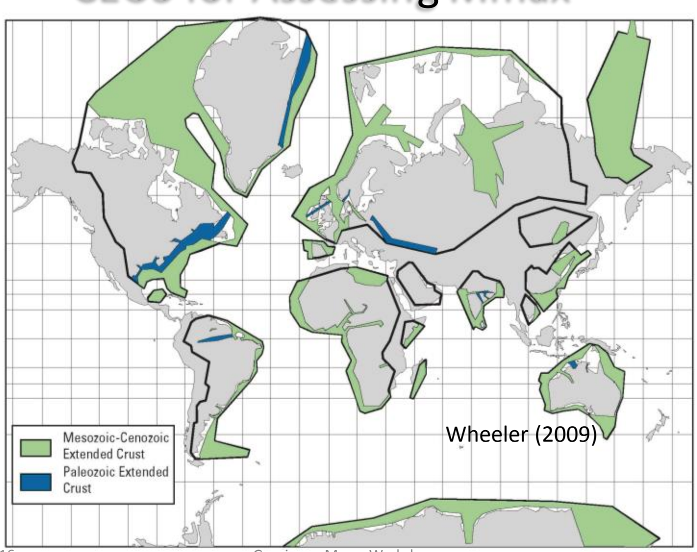
2. Maximum Observed in Analog Regions

- Define regions considered to be analogs for seismic source
- Assemble catalog of larger earthquakes that have occurred in the analog regions
- Use a representation of the distribution of earthquakes in this catalog for the uncertainty in Mmax

Example from Petersen et al. (2014) for CEUS (USGS Seismic Hazard Maps

- Analog regions – global stable continental regions (SCR) separated into extended margins and cratons
- Assembled catalog for each type of region (Wheeler, 2014a, 2014b)
- Using histogram of magnitudes in each catalog along with estimates of the $M_{max\text{-}obs}$ for past CEUS earthquakes, define epistemic uncertainty distribution for Mmax

Stable Continental Regions SCR: Analogues to CEUS for Assessing Mmax



Petersen et al. (2014) SCR – Extended Margins

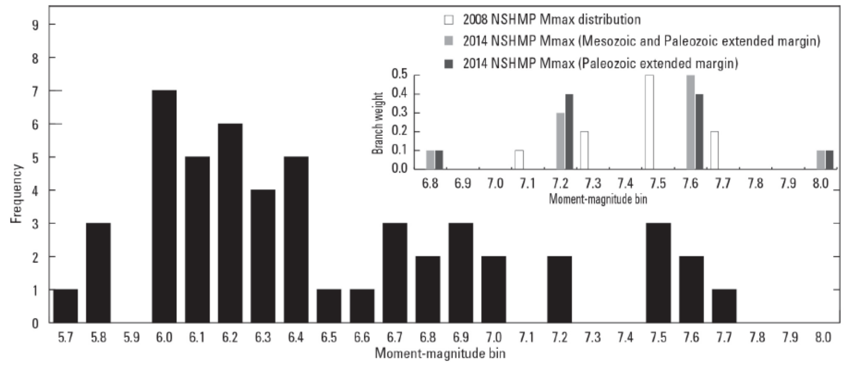


Figure 19. Distribution of large earthquake magnitudes (51 earthquakes) for extended margins in stable continental regions, worldwide. Mmax distributions used in the 2008 and 2014 updates shown in inset.

Petersen et al. (2014) SCR – Cratons

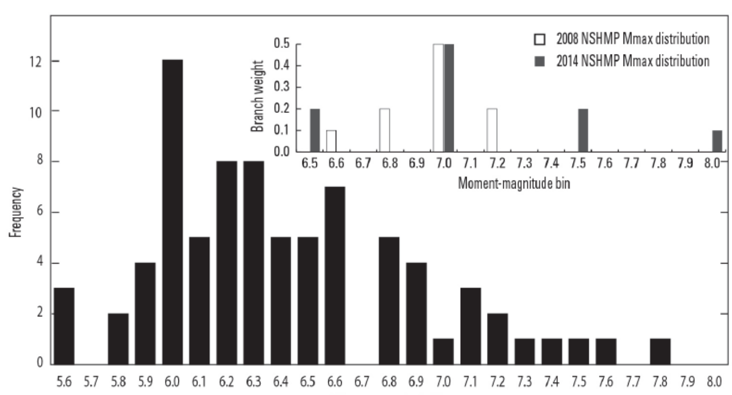


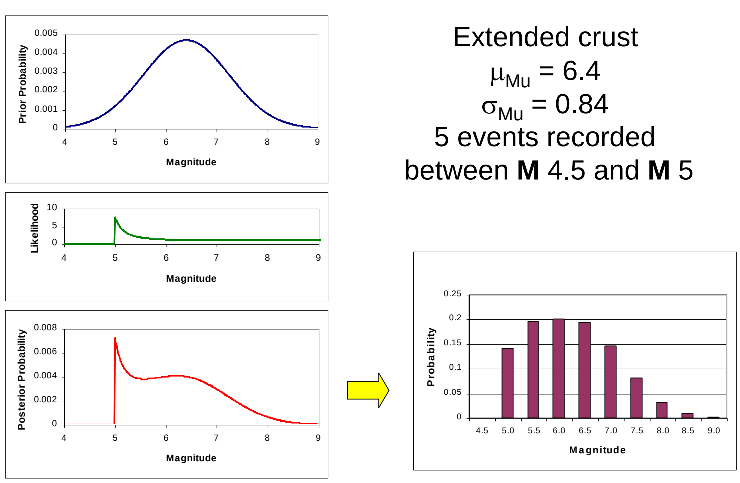
Figure 20. Distribution of large earthquake magnitudes (79 earthquakes) for cratons in stable continental regions, worldwide. Mmax distributions used in the 2008 and 2014 updates shown in the inset.

Johnston et al. (1994) Bayesian Approach

- Subdivide SCR into domains on the basis of
  - Crustal type (extended or not extended)
  - Crustal age
  - State of stress
  - Orientation of structure with respect to stress (favorably or not favorably oriented)
- Using a catalog of SCR earthquakes, assess $M_{max\text{-}obs}$ for each domain
- Use distribution of $M_{max\text{-}obs}$ (adjusted for bias) as a prior distribution for Mmax – Used normal priors
- Update prior with likelihood function based on observed earthquake catalog in seismic source to produce posterior distribution for Mmax

Example Application Using Johnston et al. (1994) Prior for Extended Crust

Extended crust
μ_{Mu} = 6.4
σ_{Mu} = 0.84
5 events recorded between **M** 4.5 and **M** 5

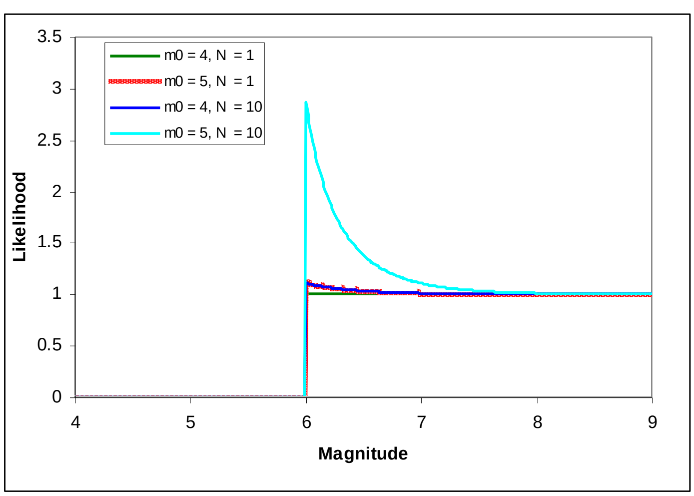


Likelihood Function for m^u (M_{max})

- Assumption - earthquake size distribution in a source zone conforms to a truncated exponential distribution between m_0 and m^u
- Likelihood of m^u given observation of N earthquakes between m_0 and maximum observed, $m_{max\text{-}obs}$

$$L[m^u] = \begin{cases} 0 & \text{for } m^u < m_{\max-obs} \\ \left[1-\exp\left\{-b\ln(10)(m^u-m_0)\right\}\right]^{-N} & \text{for } m^u \geq m_{\max-obs} \end{cases}$$

Plots of Likelihood Function for $m_{max\text{-}obs}$ = 6



Results of Likelihood Function

- $m_{max\text{-}obs}$ is the most likely value of m^u
- Relative likelihood of values larger than $m_{max\text{-}obs}$ is a function of sample size *and* the difference $m_{max\text{-}obs} - m_0$
- Likelihood function integrates to infinity and cannot be used by it self to define a distribution for m^u (e.g. Zöller, G., and M. Holschneider, 2016)
- Hence the need to combine likelihood with a some form of prior to produce a posterior distribution

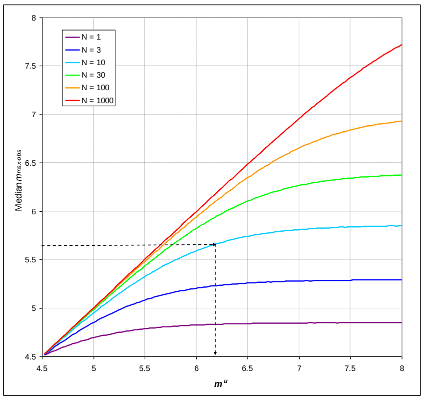
Johnston et al. (1994) Bias Adjustment (1 of 3)

- "bias correction" from $m_{max\text{-}obs}$ to m^u based on distribution for $m_{max\text{-}obs}$ given m^u
- For a given value of m^u and *N* estimate the median value of $m_{max\text{-}obs}$, $\hat{m}_{\max-obs}$

$$F[m_{\max-obs}] = \left[\frac{1-\exp(-b\ln(10)(m_{\max-obs}-m_0)}{1-\exp(-b\ln(10)(m^u-m_0)}\right]^N \quad \text{for } m_0 \le m_{\max-obs} \le m^u$$

- Use $m^u - \hat{m}_{\max-obs}$ to adjust from mean $m_{max\text{-}obs}$ to mean m^u

Bias Adjustment (2 of 3)



Example:

$m_{max\text{-}obs}$ = 5.7

$N(m \leq 4.5)$ = 10

m^u = 6.3 produces

$\hat{m}_{\max - obs}$ = 5.7

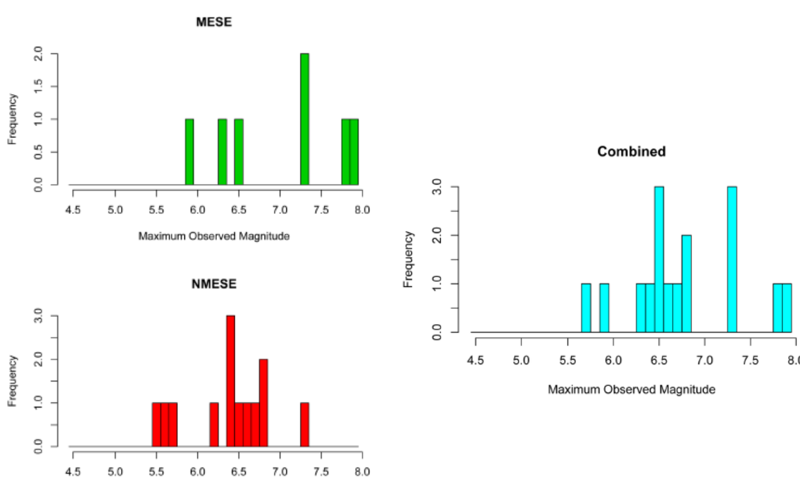
Bias Adjustment (3 of 3)

- Obtaining usable estimates of bias adjustment necessitated pooling “like” domains (trading space for time)
- “Super Domains” created by combining domains with the same characteristics
- Average of event counts in super domains used to adjust mean $M_{max\text{-}obs}$ to mean Mmax

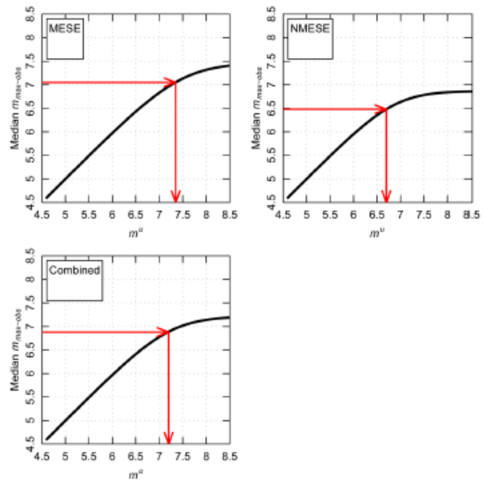
EPRI/DOE/NRC (2012) Update to Johnston et al. (1994) Mmax Priors

- Updated SCR earthquake catalog to using Schulte and Mooney (2005) and GMT catalog
- Reassessed significance of separation into extended and non-extended crust
  - Found that “significant” separation was between Mesozoic and younger extension (MESE) and combined older extension and non-extended (NMESE)
  - Significance of difference only marginal, included and alternate single prior for all SCR

Distributions of $M_{max\text{-}obs}$ in Super Domains



Bias Adjustments to Mean Mmax



EPRI/DOE/NRC (2012) Updated Priors

Prior*	Mean Mmax	Sigma Mmax
Mesozoic and younger extended crust	7.35	0.75
Pre-Mesozoic extension and non-extended crust	6.70	0.61
Composite SCR crust	7.2	0.64

* Prior distributions limited to magnitude range **M** 5.5 to **M** 8.25

3. Use of Maximum Rupture Dimensions

- Estimate the maximum dimensions of ruptures
  - Limits based on size of source
  - Limits based on size of geologic structures
- Use empirical relationships between magnitude and rupture dimensions

4. Seismicity and Geodetics

- Finite rate of moment release requires finite Mmax or at least a decay in the relative frequency of earthquakes that it greater than in increase in seismic moment with magnitude
- After fitting an appropriate magnitude distribution relationship (e.g. G-R) to the observed seismicity, the resulting recurrence relationship can be used to assess seismic moment rate as a function of Mmax
- Applying constrains on the seismic moment rate from geodetic data provides constrains on Mmax (e.g. Main et al., 1999).

Recent Applications for SCR Regions

- SHARE (European Seismic Hazard Model) – SCR regions based on Bayesian approach
- US seismic hazard model (USGS) – Global Analogs
- Canada seismic hazard model (GSC) – Global Analogs
- PEGASOS (Switzerland) – Bayesian (EPRI and band limited uniform priors), Kijko, with some dimensional limits
- Australia – Maximum rupture dimensions
- CEUS SSC (NUREG-2115) – Bayesian (updated priors) and Kijko

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History of Mmax estimates for Groningen

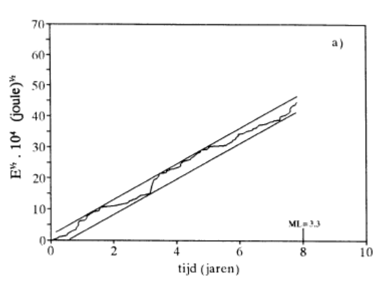
Bernard Dost
KNMI

Mmax developments

- 1995: 56 events, 39 in Groningen
- 3 methods to determine M_{max} from data
  – Trend in cumulative energy (Mmax= 3.3)
  – Monte Carlo modelling of the cum. frequency-magnitude relation using a bounded Gutenberg-Richter relation (too small dataset for Groningen)
  – Maximum credible earthquake based on geological parameters (dePolo and Slemmons, 1990)
  Groningen: Fault length 0.8 km, width 0.4 km: Mmax= 3.5 ± 0.5
  (moment magnitude; shear modulus 8 Gpa for shallow events)

$$M_0 = \mu.A.d$$

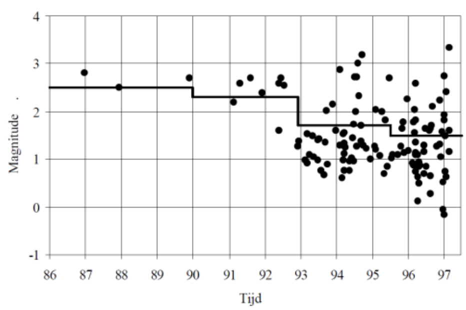
Crook, Th. de, B. Dost and H.W. Haak, 1995, Analyse van het seismische risico in Noord-Nederland, KNMI report TR-168, 30pp.

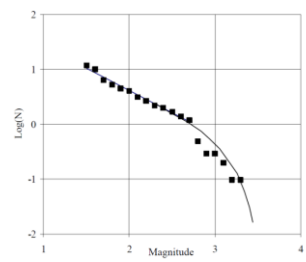


Mmax developments

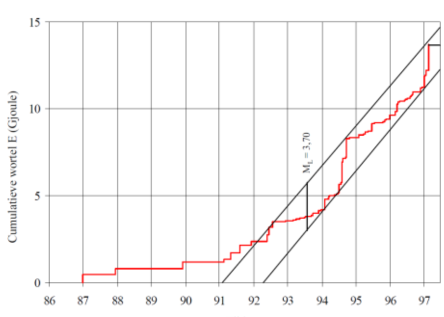
- 1998: 125 events in the North of the Netherlands
- 3 methods to determine Mmax
  - Trend in cumulative energy (Mmax= 3.7)
  - Monte Carlo modelling of the cum. frequency-magnitude relation using a bounded Gutenberg-Richter relation (Mmax=3,8 (mean + 1 std))
  - Maximum credible earthquake based on geological parameters
    Fault length 0.8 km, width 0.4 km: Mmax= 3.5 ± 0.5 (same as 1995)

Crook, Th. de, H.W. Haak and B. Dost, 1995, Seismisch risico in Noord-Nederland, KNMI report TR-205, 24pp.

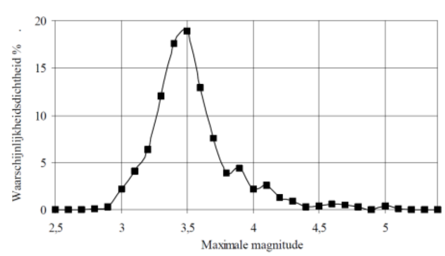




Mmax developments-1998 cont.



Cumulative square root of the Energy



Probability density as a function of Mmax for a Monte Carlo calculation. Results are for 1000 experiments

Mmax= 3.8 (mean + 1 sigma)

- Results apply to all gas fields in the region
- Monte Carlo calculation assumes a truncated exponential distribution to model the finite frequency-magnitude distribution

Mmax developments 2004

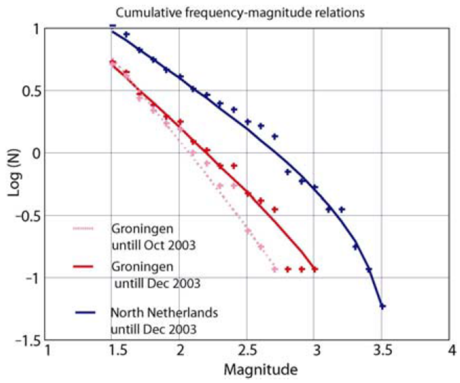


Figure 4. *Cumulative annual frequency-magnitude relation obtained for all induced seismicity in the north of The Netherlands for the period 1986 - 2003 (blue curve) and observations (blue crosses). Also is shown the same frequency-magnitude relation for all earthquakes in the Groningen field. However, for this selection we have shown the relation excluding (purple broken curve) and including (red curve) the three 2.7 < M < 3.0 events that occurred October-November 2003. This shows that the slope (b-value) of the frequency-magnitude relation for a subset of 179 events has a tendency to approach the b-value of the frequency-magnitude relation for all earthquakes (340 events).*

Van Eck, F. Goutbeek, H. Haak and B. Dost, 2004, Seismic hazard due to small shallow induced earthquakes, KNMI Scientific report; WR-2004-01, 52pp.
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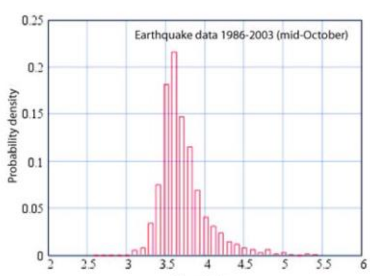
Mmax developments-2004 cont.

Table 1*. Estimated M_{max} using a Bayesian approach.*

mean	median	84%	Comments
3.5	3.5	3.8	Earthquake data 1986-1997
3.7	3.6	3.9	Earthquake data 1986-2003



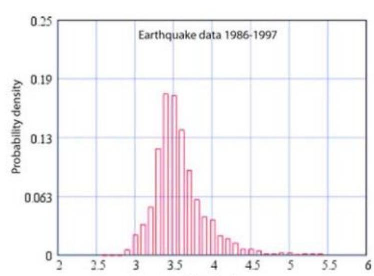
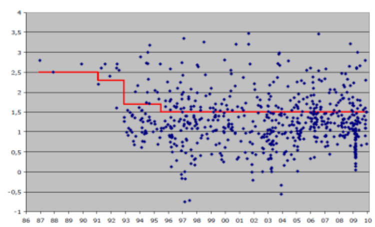


Figure 6. *Estimating the maximum possible magnitude based on the observed seismicity using a Bayesian approach. The left figure shows the most recent estimate based on earthquake data up to October 2003. Right figure shows an estimate based on the data up to 1997 and is consequently similar to that obtained by De Crook et al. (1998). The results of this analysis are summarized in Table 1.*

Mmax developments

- 1.1.2010: 640 events in the North of the Netherlands; 341 in Groningen
- 3 methods to determine Mmax
  - Trend in cumulative energy (Mmax= 3.7)
  - Monte Carlo modelling of the cum. frequency-magnitude relation using a bounded Gutenberg-Richter relation (Mmax=3,9 (mean + 1 std))
  - Maximum credible earthquake based on geological parameters
    Fault length 0.8 km, width 0.4 km: Mmax= 3.5 ± 0.5

Dost, B., F. Goutbeek, T. van Eck and D. Kraaijpoel, 2012, Monitoring induced seismicity in the North of the Netherlands: status report 2010, KNMI report WR-2012-03, 39pp.



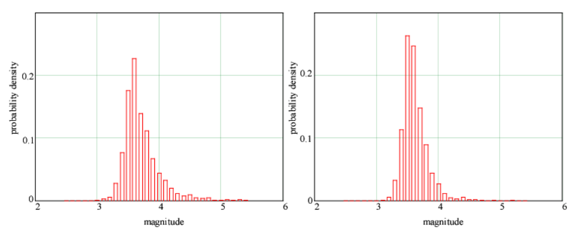
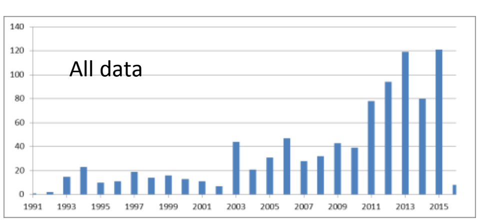
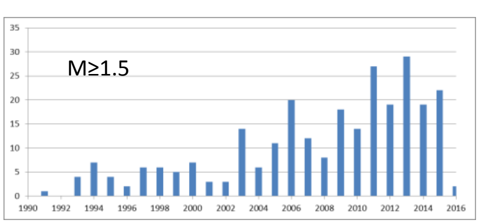


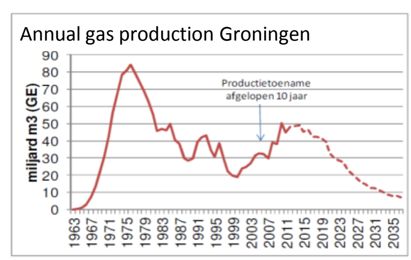
Figure 7. Comparison of the estimation of the maximum possible magnitude for all induced earthquakes in the period 1986-2003, left figure (Van Eck et al., 2004), and the update 1986-2010.

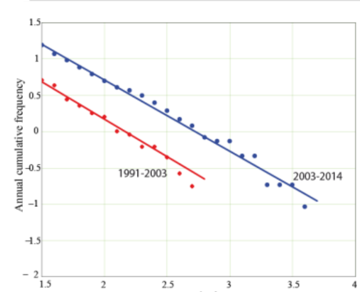
Groningen seismicity, development in time

- Large variability in annual number of earthquakes M>1.4
- Since 2003 increase in activity rate, no significant change in b-value
- Magnitude completeness M= 1,5; Clearly non-stationary process
- Increase in activity rate coincides with an increasing trend in production









Koninklijk Nederlands Meteorologisch Instituut
Ministerie van Infrastructuur en Milieu

Developments 2013

To conclude, the magnitudes of the largest induced events in hydrocarbon reservoirs, as reported in the scientific literature, remain, if rounded upwards, below ML = 5.0. One has to keep in mind, however, that the comparison is made for hydrocarbon fields in different geological settings and tectonic regions. Also, enough existing fault surface should be available to accommodate the movement of a larger event.

Based on statistics only, no reliable estimate could be obtained of a maximum probable earthquake for the Groningen field. Further research using additional information from geology and geomechanical modeling is expected to provide additional constraints on the possible value of the Mmax. Until this information is available, we estimate an conservative upper limit for Mmax at magnitude 5.0.

Dost, B. and D. Kraaijpoel, 2013, The August 16, 2012 earthquake near Huizinge (Groningen)

Developments 2013-2

Arguments based on a finite fault size provides an estimate of M=5.8 as a maximum value. However, this value corresponds to a slip of 0.3 m over a fault dimension of 3 km width and 60 km length. Since the part of the fault directly influenced by compaction is only 0.3 km, a more realistic estimate is a fault width of 1 km and a fault length of 20 km assuming a similar high aspect ratio of 20. This provides a M= 4.9 and a slip of 0.1 m. In all calculations a stress drop of 1 MPa is assumed.

Dost, B., M. Caccavale, T. van Eck and D. Kraaijpoel, 2013. Report on the expected PGV and PGA values for induced earthquakes in the Groningen area, KNMI report, 26pp.

Estimating maximum possible earthquake (M_{max})

- **Finite strain**

All strain accumulated over the life cycle of the field released in one event at the end of production: M_{max}=6.5. Highly unlikely hazard scenario.

- **Finite fault length** (fault width = W; fault length = L)
  a) 0.3m slip over a fault dimension W=3 km and L=60 km: M_{max} 5.8. This assumes full release over lifetime of production field
  b) 0.1m slip over W=1 km and L=20 km: M_{max} = 4.9

NPR: Considered likely hazard scenario for the next five years → M_{max} = 5.0.

- **Finite mass**
  - A mass shift of 2-2.5 Gt results in M_{max} ~ 4.5 (Klose, 2013)

  Unlikely hazard scenario as it does not consider specific local mechanism constraints.

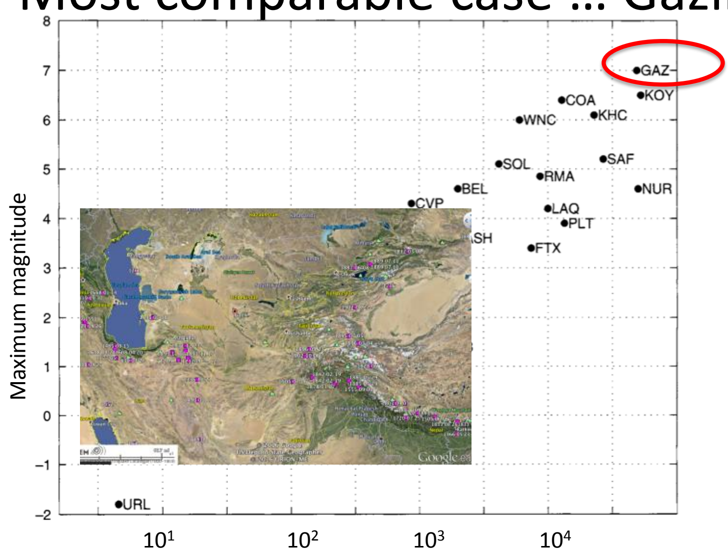
Conclusions

- M max estimates based on modelling of a GR relation for Groningen do not provide reliable results due to the non-stationary character of the development of seismicity
- Finite fault length considerations and results from geomechanical modelling may provide constraints on Mmax
- A Mmax=5.0 is currently assumed in KNMI hazard calculations.

Making a large earthquake:
What is physically possible?

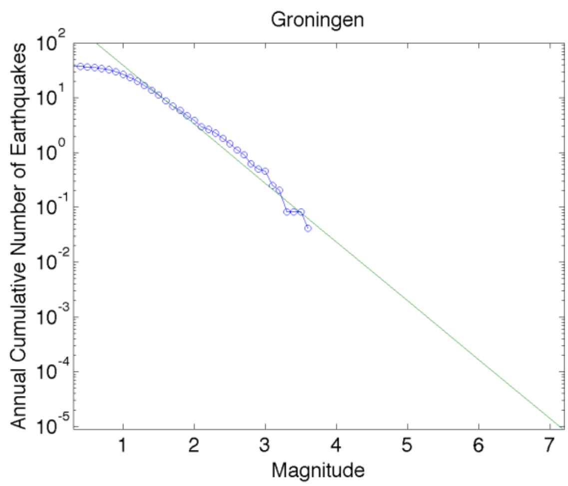
Emily E. Brodsky
University of California, Santa Cruz

Most comparable case … Gazli



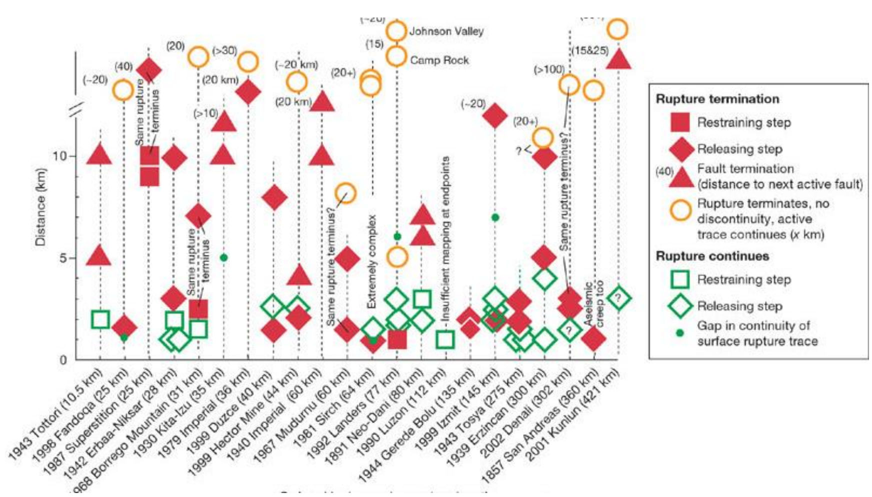
Scale of volume change (m) McGarr et al., 2002

A naïve extrapolation



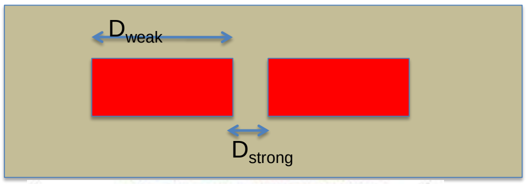
A very rare event

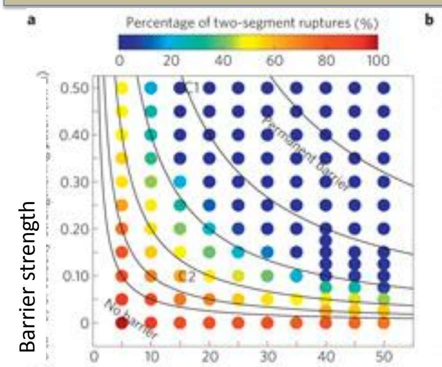
Are the faults big enough (or is this a limit)?



Wesnousky, *Nature*, 2006

Numerical simulations of connecting faults

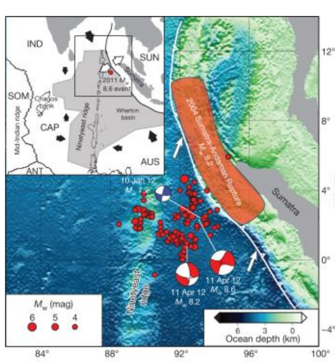




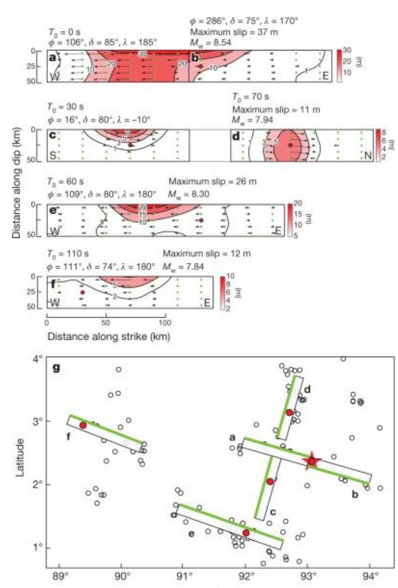
Probability of earthquakes overcoming barriers

Kaneko, Avouac and Lapusta, *Nat. Geosci*., 2010

Multiple fault ruptures

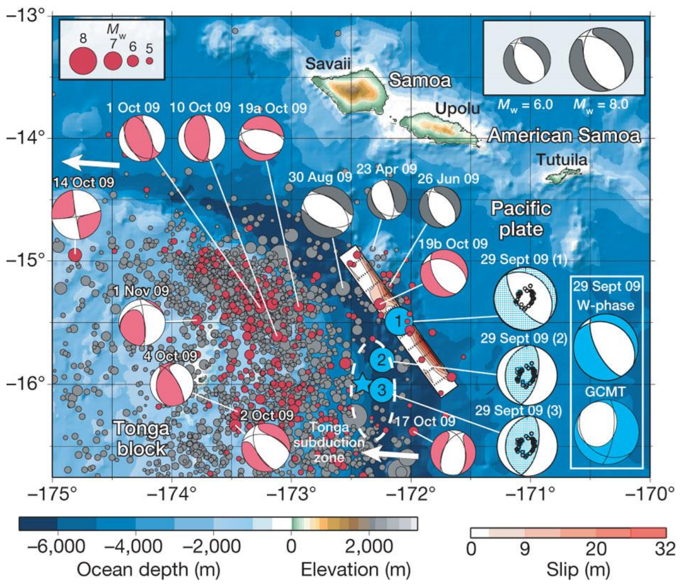


Complex, multiple fault rupture of the April 11, 2012 M8.7 earthquake



Yue et al., *Nature*, 2012

M8.1 Samoa Earthquake

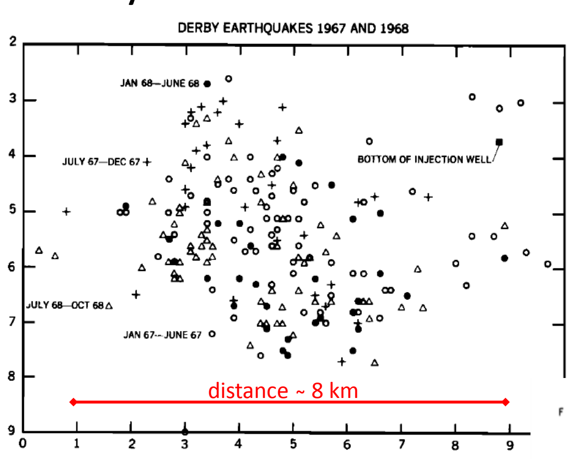


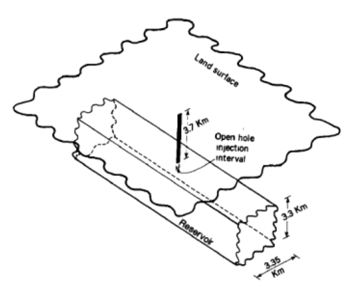
T Lay *et al.* *Nature* **466**, 964-968 (2010) doi:10.1038/nature09214

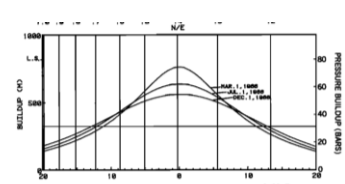
Earthquakes limited by available faults in region

How far away can faults be stressed?

Rocky mountain Arsenal



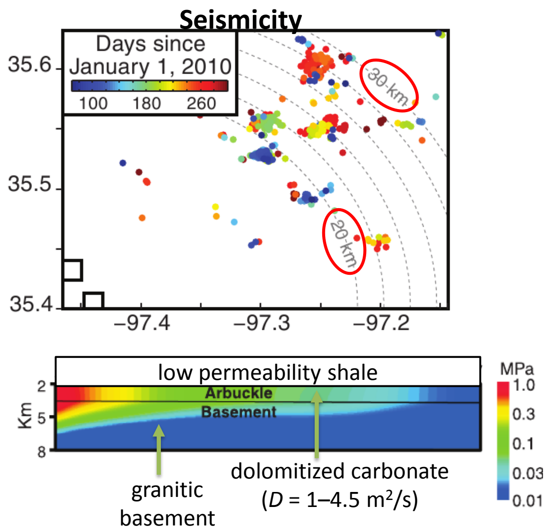




Hsieh & Bredehoeft, 1981
Rocky mountain Arsenal

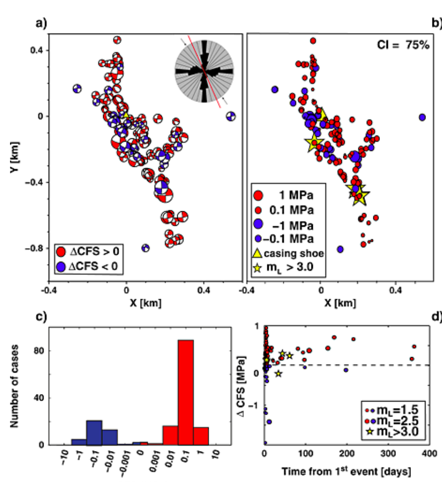
How far away can faults be stressed?

Oklahoma pore pressure diffusion to 20-35 km



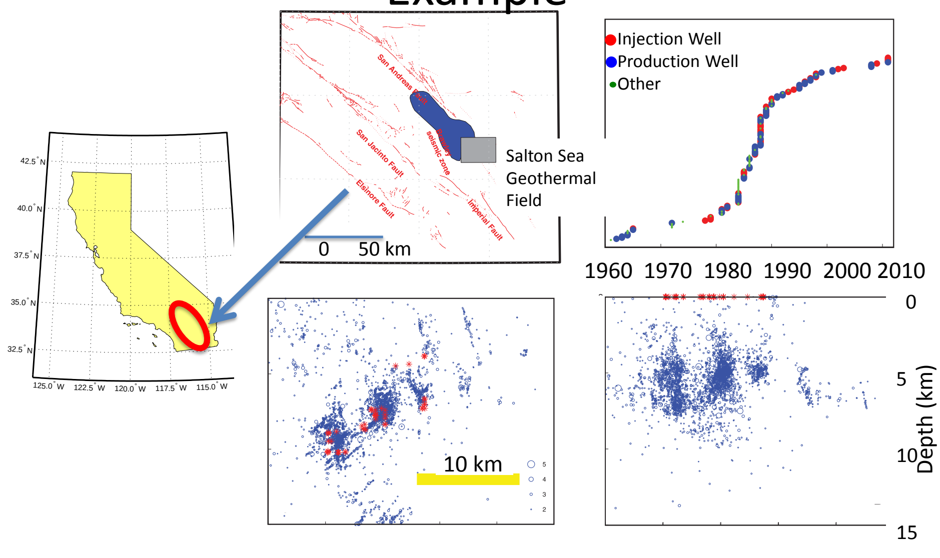
Keranen et al., 2014

Another means of fault interactions: Earthquake-earthquake interactions



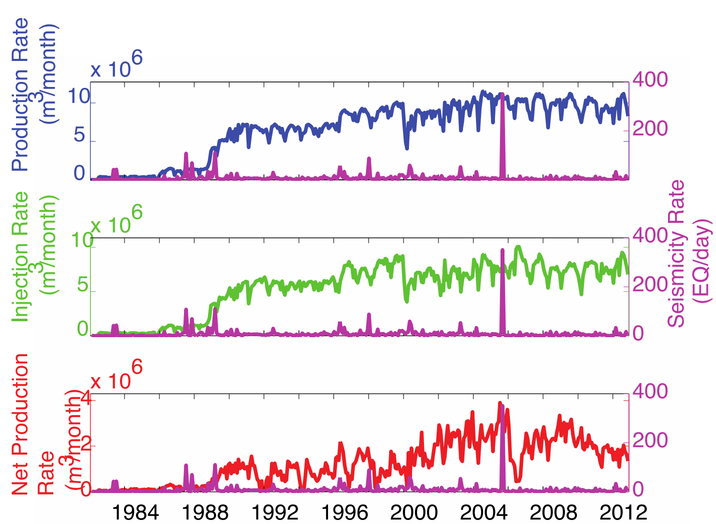
Catalli et al., *GRL, 2013*

Compaction Induced Seismicity Example

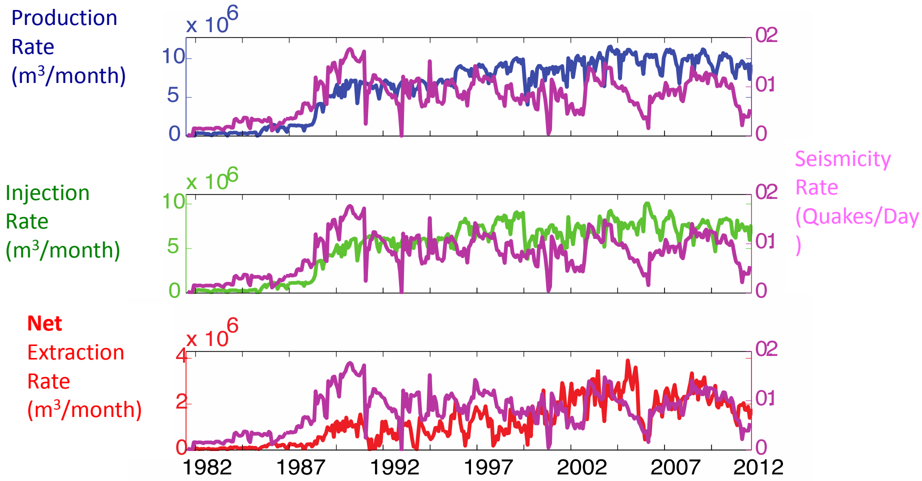


Brodsky & Lajoie, *Science*, 2013

Raw Earthquake & Operational Data

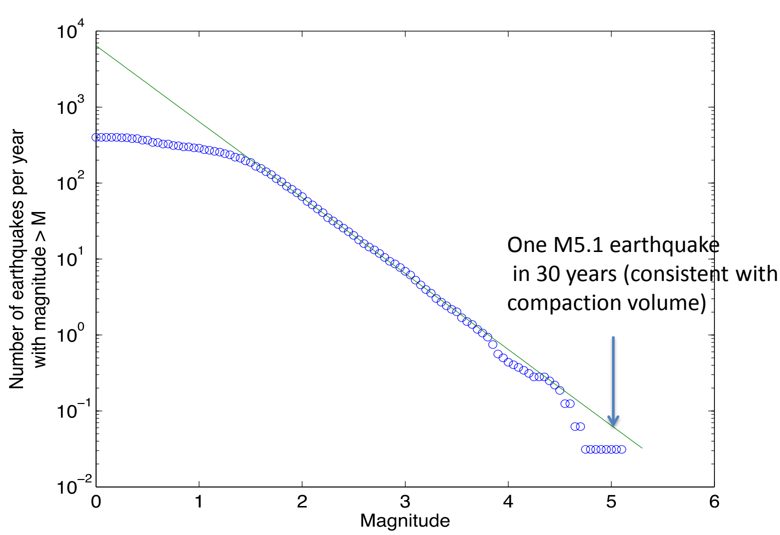


Aftershock-removed rate and operations



Brodsky & Lajoie, *Science,* 2013

Magnitude Distribution



We we are so far…

- A Gazli-like event (M~7 in the field and adjoining area) is physically possible
  – Has precedent
  – Faults can connect
  – Affected volume includes 10's of km around field
    - Hydrologically connected or 1 source length (static stress)
  – Sufficient energy exists

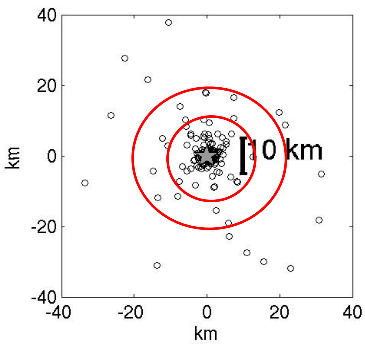
- …..What about something further? Or bigger?

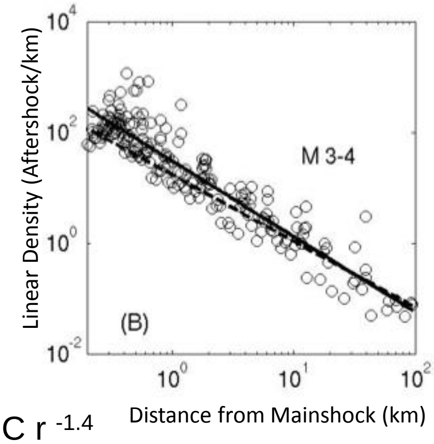
Two scenarios

- Remote triggering following a local event

- Contribution of pre-existing tectonics to the energy

Aftershock spatial decay

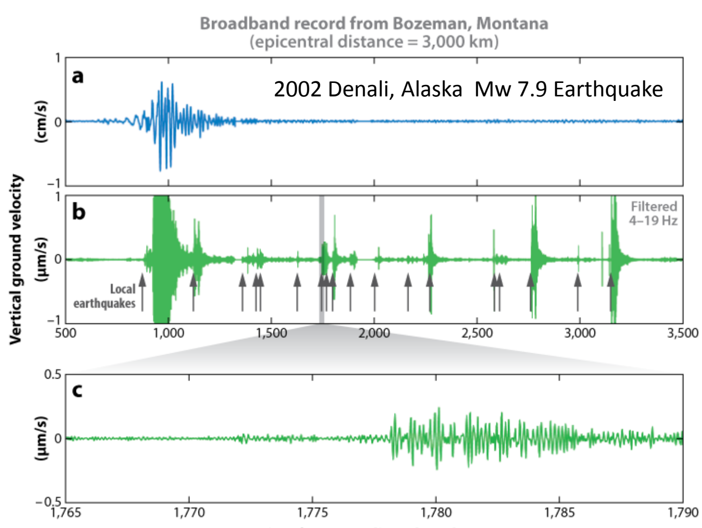




Αφτερσηοχκ Δενσιτψ ~ C r $^{-1.4}$

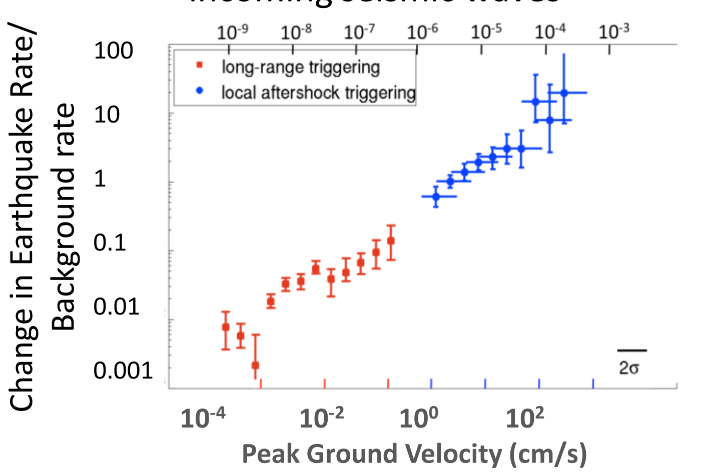
Felzer and Brodsky, *Nature*, *2006*

Extending the reach of earthquakes



Brodsky EE, van der Elst NJ. 2014.
Annu. Rev. Earth Planet. Sci. 42:317–39

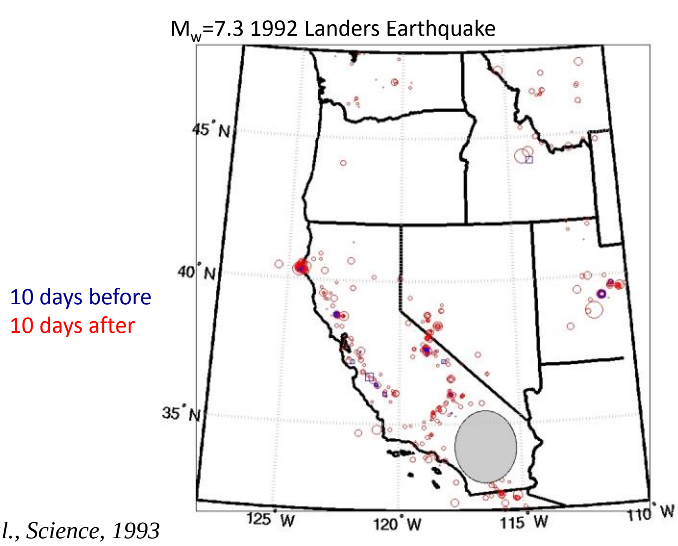
Triggering rate as a function of causative strain



California
1984-2008

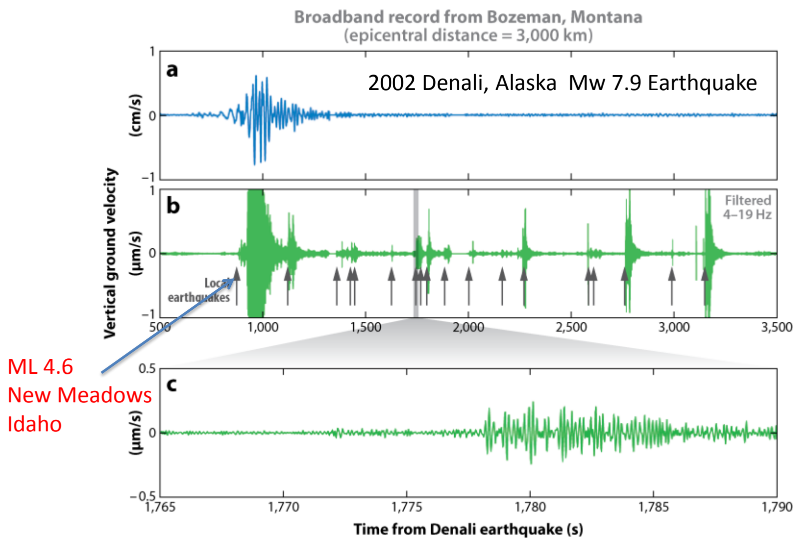
Van der Elst and Brodsky, *J. Geophysical Research* 2010

Seismic Waves Trigger Earthquakes



Hill et al., Science, 1993

Extending the reach of earthquakes



Brodsky EE, van der Elst NJ. 2014.
Annu. Rev. Earth Planet. Sci. 42:317–39

Scenario 2

- Releasing tectonic stress locally to extend the rupture (example: 2008 Mw7.9 Wenchuan?)

How do earthquake rupture?

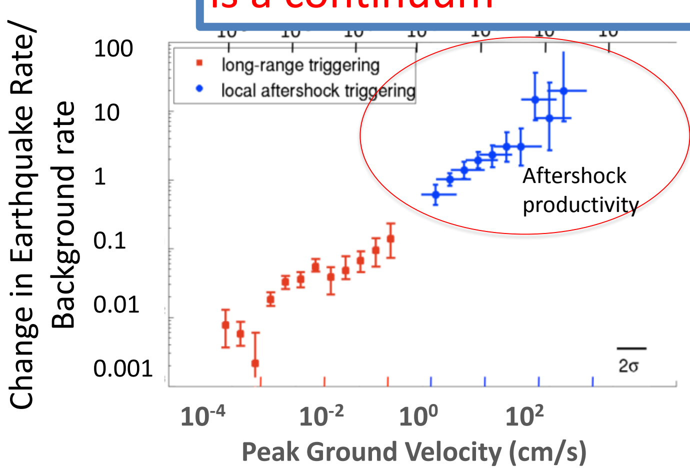
Movie of 2004 Mw 9.15 Sumatra earthquake from Ishii et al., 2005

How do w c stress?

P

i

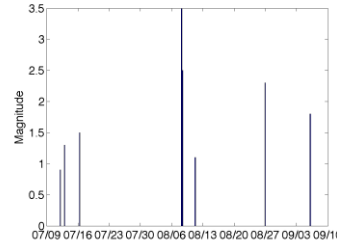
The distinction between "induced" and "triggered" is a continuum

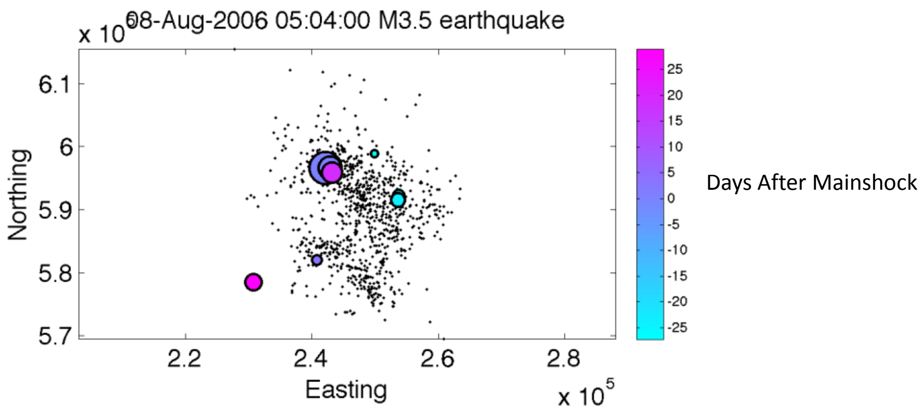


California 1984-2008

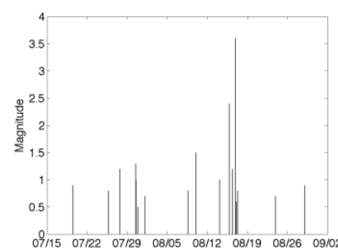
Van der Elst and Brodsky, *J. Geophysical Research* 2010

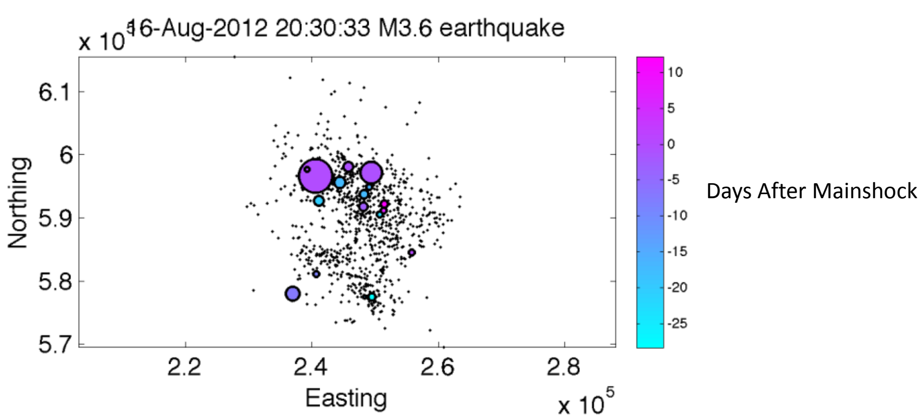
What about Groningen?



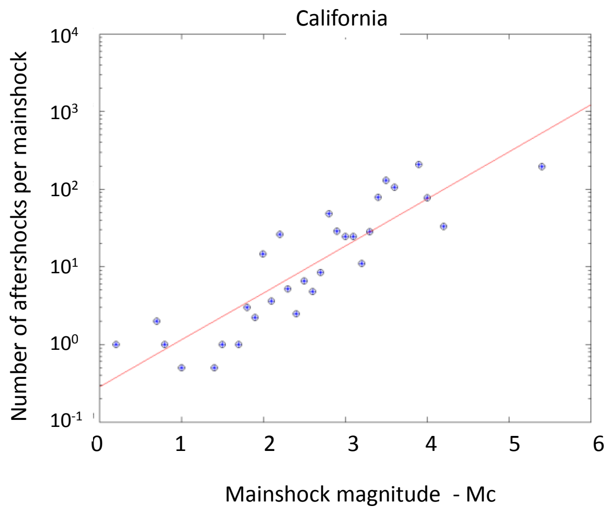


What about Groningen?

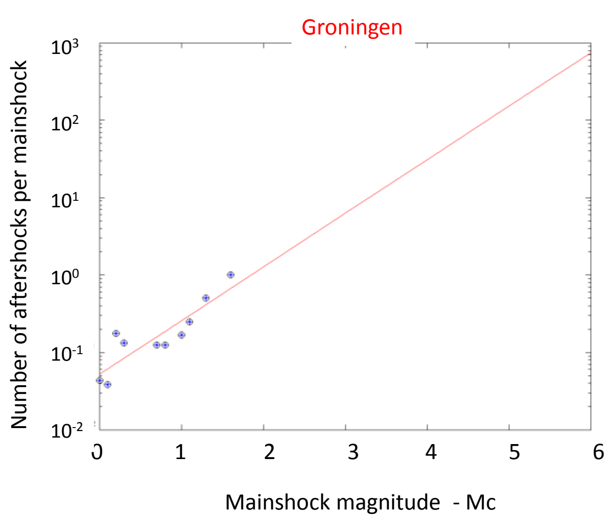




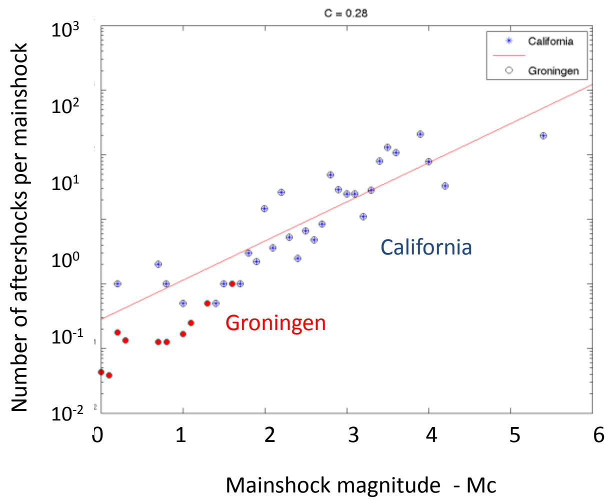
Combining Earthquakes



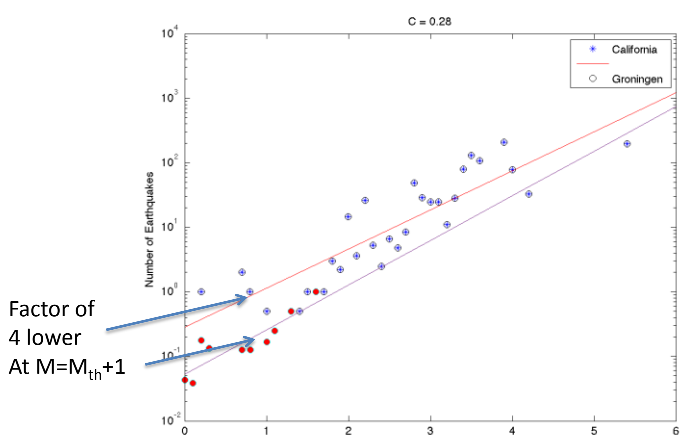
Combining Earthquakes



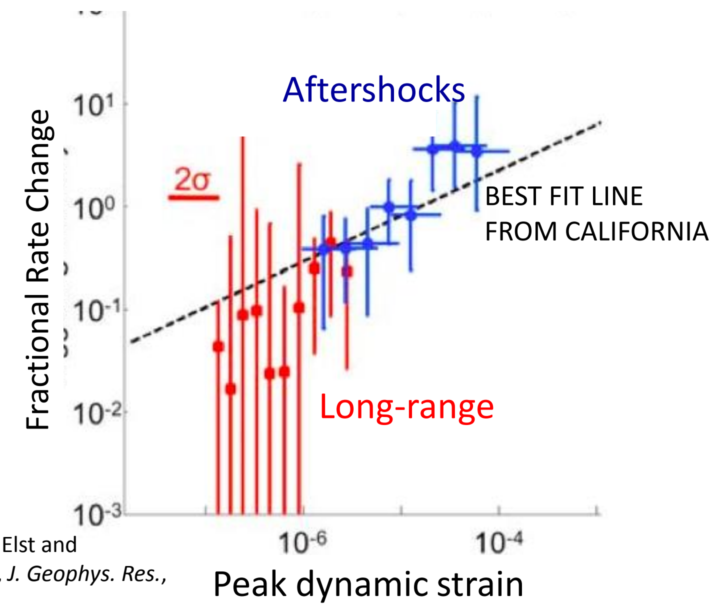
Productivity Comparison



Productivity Comparison



Crustal Japan



JMA
1997-2006

>25,000
earthquakes

Van der Elst and Brodsky, *J. Geophys. Res.*, 2010

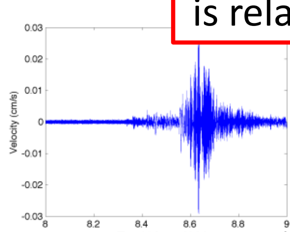
Consistent with the lack of dynamic triggering onsite

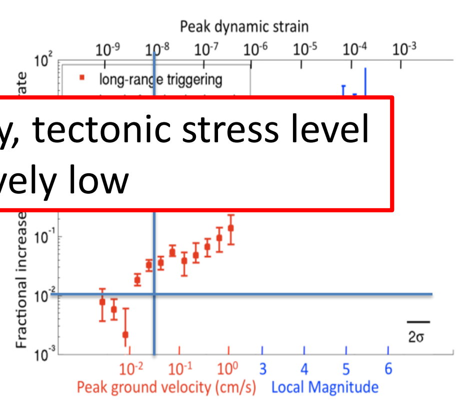
- Sept 16, 2015 Chile Mw8.3

Peak vertical

Ground velocity

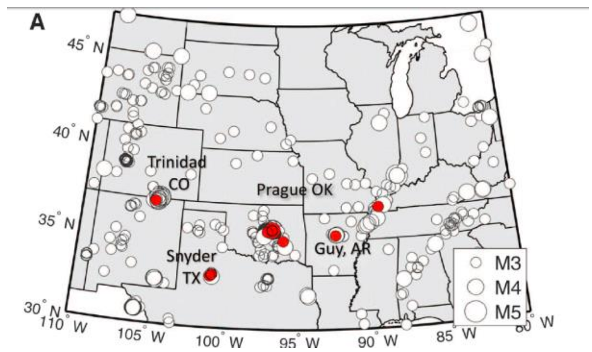
0.3 mm/s





Currently, tectonic stress level is relatively low

Recommendation: Continued monitoring of long-range triggering

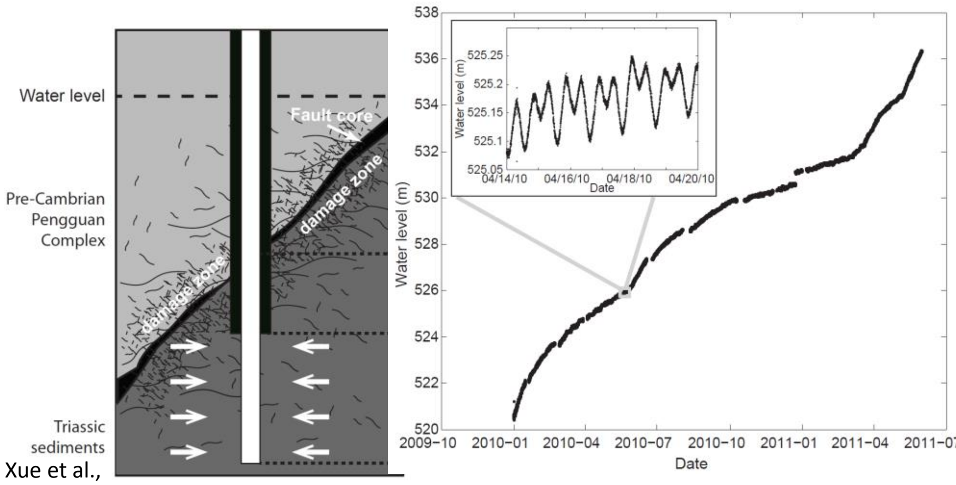


Van der Elst et al., Science, 2013

Conclusions

- A M~7 earthquake is possible based on
  - Historical precedent
  - Size of field and affected region
  - Examples of ruptures connecting faults
  - Available energy from compaction
- Two more drastic scenarios
  - Farfield triggering
    - Possible (not probable) for M~7 in Groningen to trigger Rhine Graben
      - Recommend inclusion in PSHA using ordinary GR and local aftershock productivity on affected faults (rare^2)
  - Tectonic release locally
    - Possible (not probable) given current stress state
      - Recommend continued monitoring of farfield triggering and field aftershock productivity

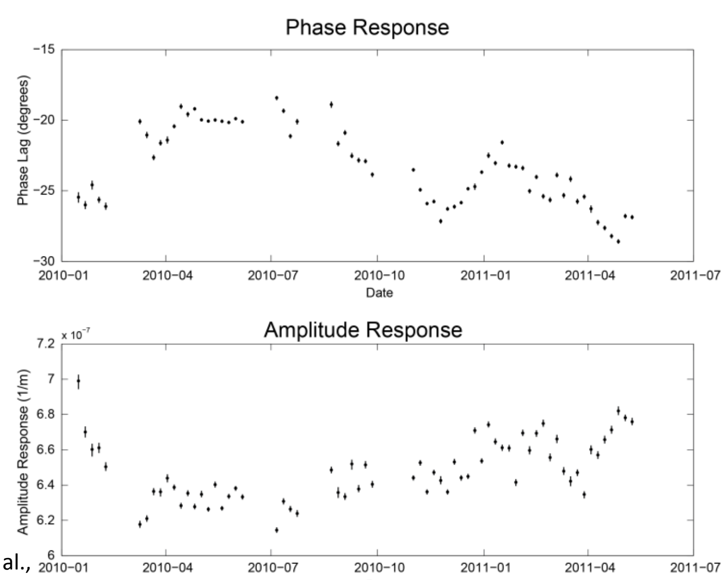
Permeability in the Fault Zone: Wenchuan Fault Zone Scientific Drilling



Xue et al., *Science*, 2013

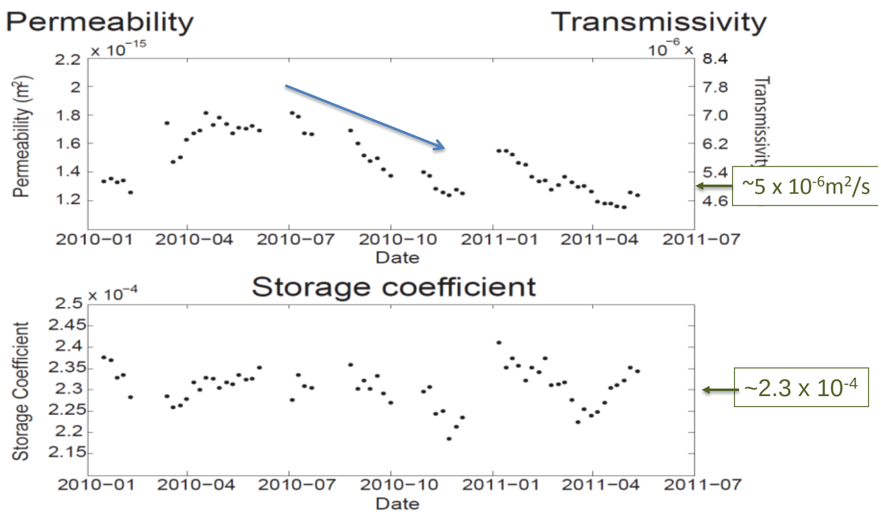
Water level from WFSD-1 borehole

Tidal Response



Xue et al., *Science*, 2013

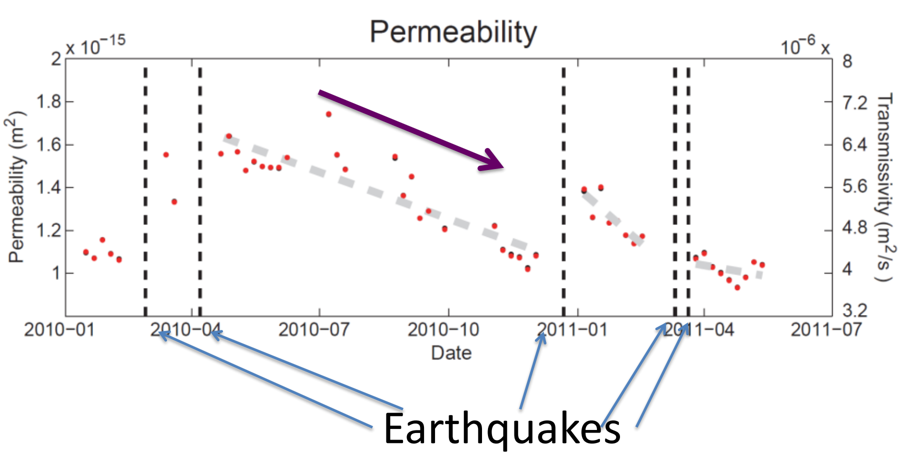
Permeability and Storage in the Wenchuan Fault



Xue et al., *Science*, 2013

Hydraulic Diffusivity = T/S ≈ 2 x 10^{-2} m^2/s

Temporal Changes



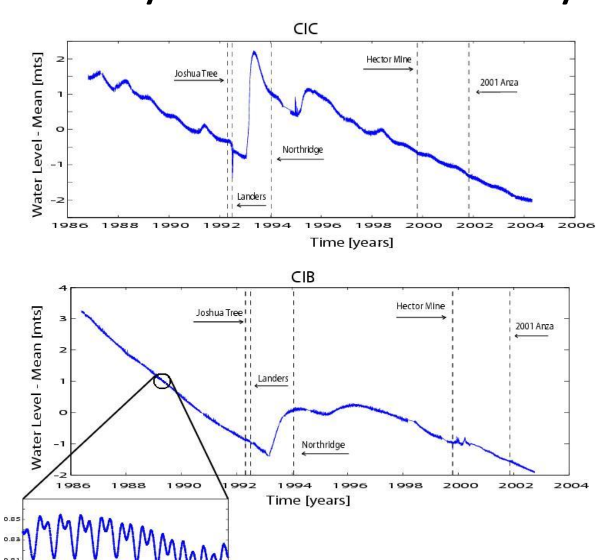
Xue et al., *Science*, 2013

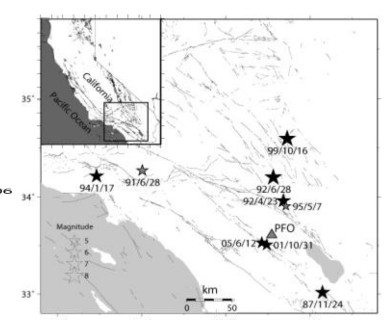
Permeability changes indicate fast, episodic healing in the fault following a major earthquake

Conclusions

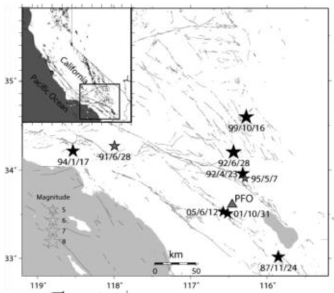
- **Permeability varies over time**
  - Seismic waves can increase permeability by factors up to 3-4
    - In some cases, permeability change correlated to amplitude of dynamic strain
      - Reproduced in the lab
    - Possibly due to opening (unclogging) of fractures
  - Over years, permeability can decrease by similar amounts
    - May be the fingerprint of fault zone healing
- **IMPLICATION FOR HYDROGEOLOGY:**
  Permeability is a dynamically controlled and its steady-state value is governed by the competition of processes.

Part III: Dynamic Permeability Enhancement



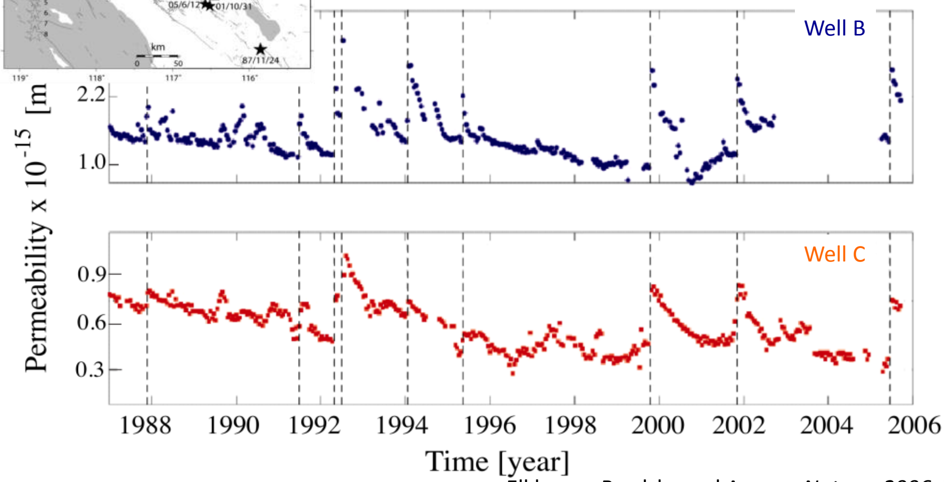


Elkhoury, Brodsky and Agnew, *Nature*, 2006



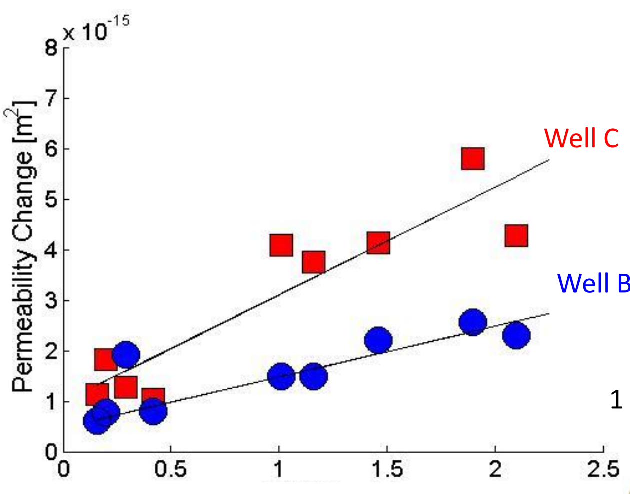
Permeability Records: Permeability increases at the Time of Earthquakes

Assuming a homogenous, isotropic flow following Hsieh et al., 1987



Elkhoury, Brodsky and Agnew, *Nature*, *2006*

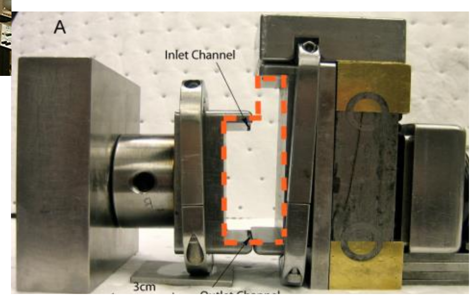
Permeability Increases with Shaking



1 cm/s ~0.1 MPa

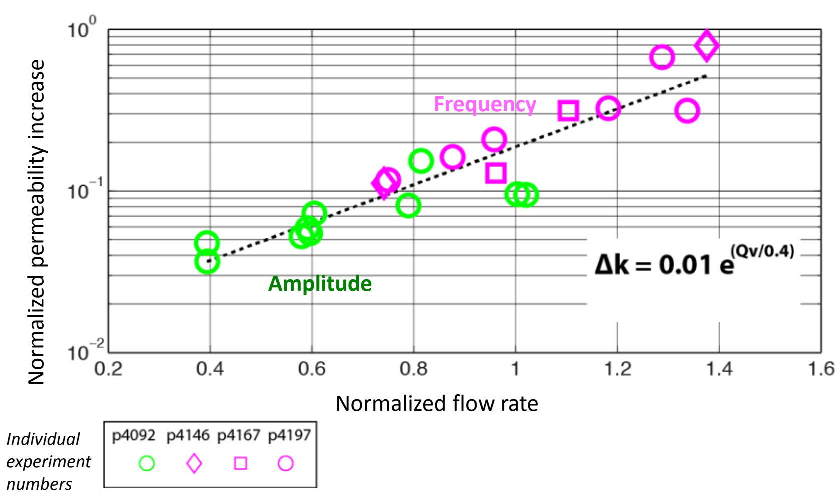
Elkhoury, Brodsky and Agnew, *Nature*, *2006*

Laboratory Experiment



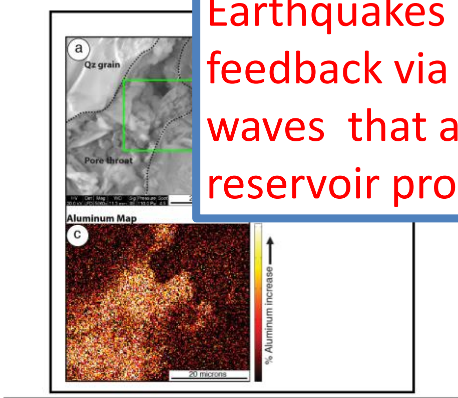
Elkhoury et al., *J. Geophys. Res.*, 2011
Candela et al., *Earth & Planet. Sci. Let,* 2014
Candela et al., *J. Geophys. Res.*, 2015

Permeability Increases Generated in the Lab

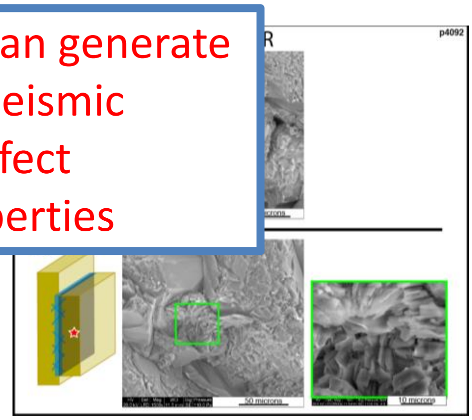


Candela et al., *J. Geophys. Res.*, 2015

Imagery of throat clearing

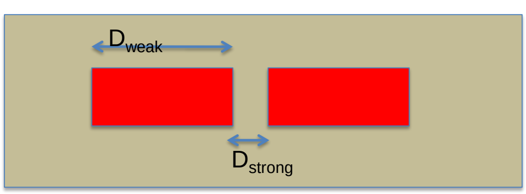


Earthquakes can generate feedback via seismic waves that affect reservoir properties

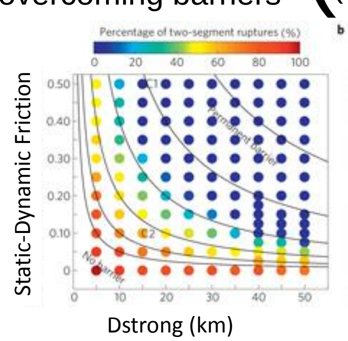


Candela et al., *EPSL*, 2014.

Numerical simulations of connecting faults



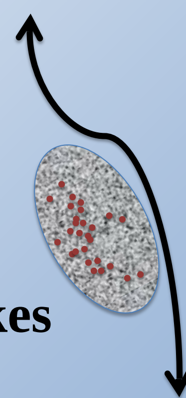
Probability of earthquakes overcoming barriers $= f\left(\frac{(\text{Peak Stress} - \text{Static Friction})\, D_{strong}}{(\text{Static Friction} - \text{Dynamic Friction})\, D_{weak}}\right)$



Kaneko, Avouac and Lapusta, *Nat. Geosci*., 2010

Mmax Workshop, 8-10 March 2016
World Trade Centre, Schiphol Airport, Amsterdam, NL

Overview of the Largest Induced/Triggered Earthquakes



Gillian R. Foulger

Durham University, U.K.

1

Database

Marine and Petroleum Geology 45 (2013) 171–185

Contents lists available at SciVerse ScienceDirect

Marine and Petroleum Geology

journal homepage: www.elsevier.com/locate/marpetgeo

Review article

Induced seismicity and hydraulic fracturing for the recovery of hydrocarbons

Richard Davies [a,*], Gillian Foulger [a], Annette Bindley [a,1], Peter Styles [b]

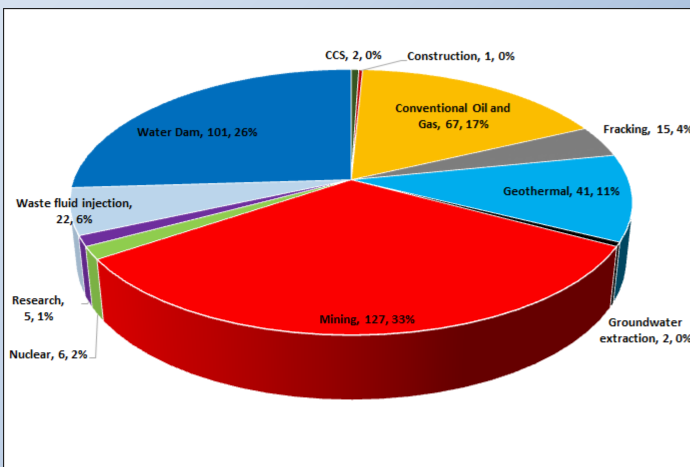
[a] Durham Energy Institute, Department of Earth Sciences, Durham University, Science Labs, Durham DH1 3LE, UK
[b] School of Physical and Geographical Sciences, Keele University, Keele, Staffordshire ST5 5BG, UK

- The task: Update the 2013 database

2

Database

- 2013 paper:
  - 198 examples
  - 66 papers
- The new 2016 database:
  - 389 examples
  - 190 papers



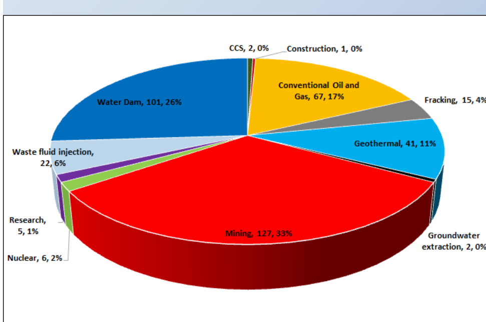
3

Database

- Excel spreadsheet
- PDF collection
- EndNote reference library

Excel spreadsheet columns:

- Location
- Cause, sub-cause
- Project name
- Dates of project & seismicity
- Delay time
- # earthquakes
- Mmax
- Magnitude scale
- Earthquake depth
- Mmax date
- Distance from project
- Lithology
- Depth interval of project
- Tectonic setting
- Prior earthquake history
- Dam height
- Extraction/injection rate
- Volume extracted/injected
- Pressure
- Area
- Fluid viscosity
- Temperature
- Notes
- References



4

Database Issues

- Only cases documented in published papers
- If Mmax not given, case not included
- Often information not provided
- Sometimes conflicting data, *e.g.*, different earthquake magnitudes
- Some projects hybrid, *e.g.*, both production and reinjection simultaneously
- Classification of tectonic setting judgmental
- Whether event induced may be questionable

5

Presentation of Results

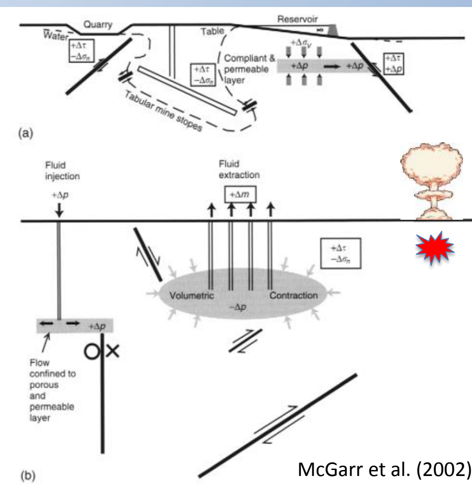
6

Environments of induced seismicity

- Surface operations
  - Adding mass
  - Removing mass
- Extraction from the subsurface
  - Groundwater extraction
  - Mining
  - Hydrocarbons
  - Geothermal production (heat/fluids)
- Injection into the subsurface
  - Liquid
  - Gas
- Explosions
  - Nuclear
  - Chemical

Individual cases:

Established → Speculative



McGarr et al. (2002)

Surface Operations

9

Surface Operations

Adding mass

10

Surface Operations

Adding mass

Water impoundment behind dams

11

Water Reservoirs

- Up to 100 m ~ 10% seismogenic
- Up to 140 m ~ 20% seismogenic
- 5 cases with M > 6

12

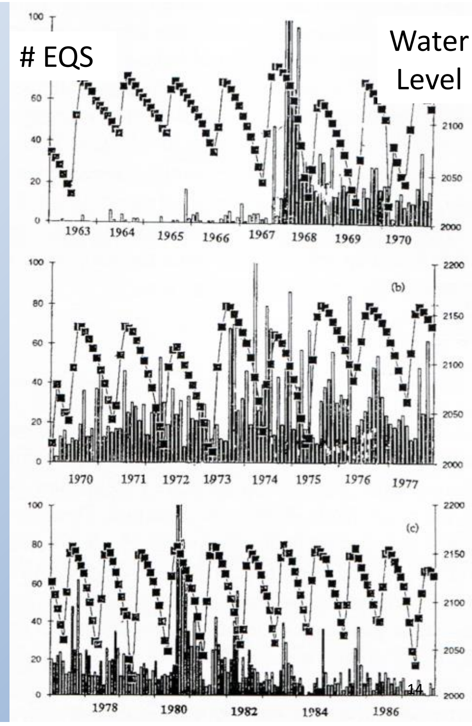
Koyna Dam, India

- Created 1962
- Dam 103 m high, reservoir 75 m deep & 52 km long
- 1967 M 6.3, ~ 200 deaths & dam damaged
- Depth < 5 km, < 10 km distance from dam
- M > 5 ~ once every 4 years

Koyna, India

Eqs M > 2 and reservoir water levels (feet) 1963 - 1986

Talwani (1995)



Other notable examples

- Highest dam @ 300 m – Nurek, Tadjikistan, M 4.6 (1972). Reservoir 10 km^3
- Largest volume reservoir @169 km^3 – Aswan, Egypt, M 5.6 (1981). Dam 111 m high
- Largest (pop.) state in USA – Oroville, California, M 5.7 (1975). 11 km from reservoir


Aswan Dam

Surface Operations

Adding mass

Erecting tall buildings

16

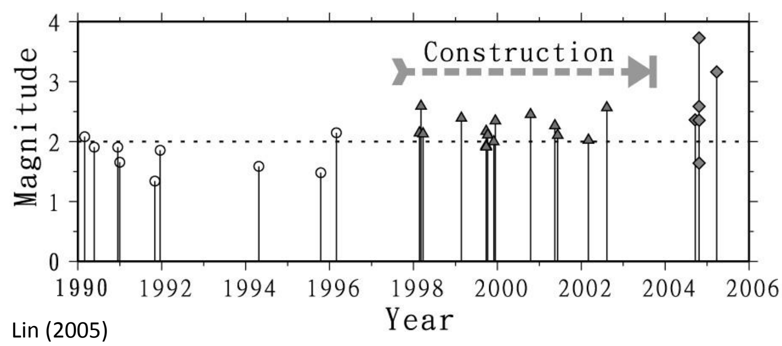
Taipei 101, Taiwan

- Weight of building ~ 700,000 tonnes
- Increase in stress at base: ~ 0.47 MPa

17

Taipei 101, Taiwan

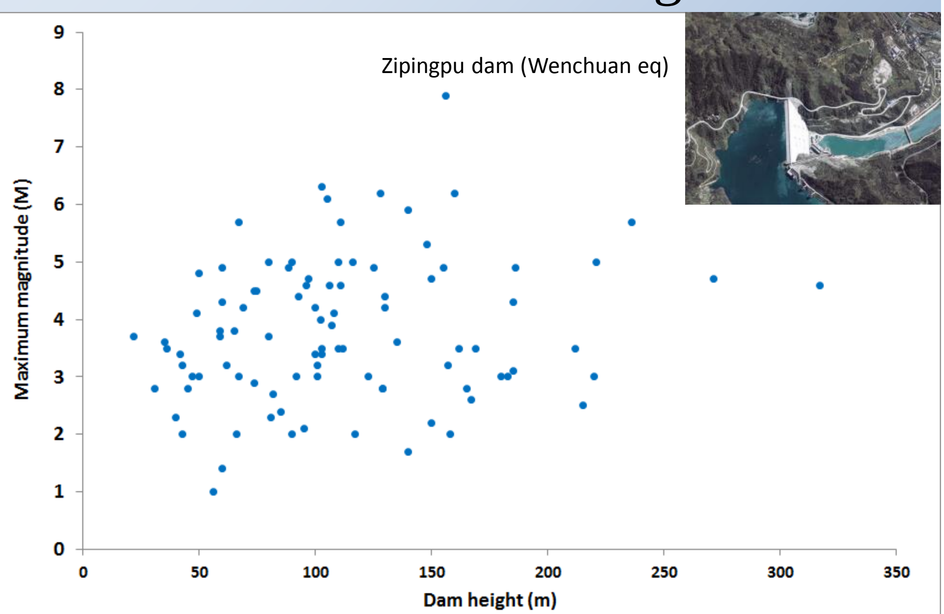
- Unusual earthquakes after construction: M 3.8, M 3.2
- On blind thrust under building ~ 10 km depth



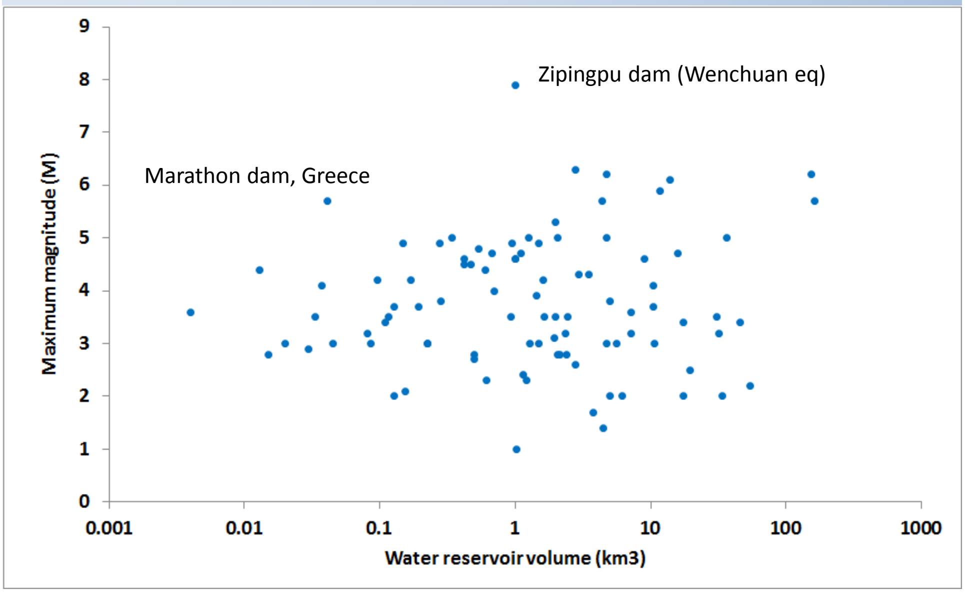
Lin (2005)

8

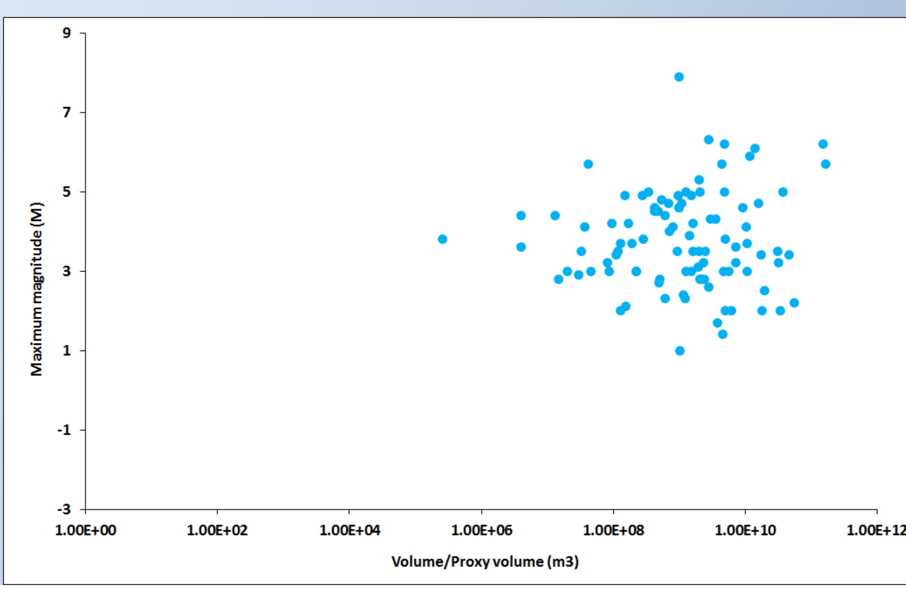
Database: Dam Height



Database: Water Reservoir Volume



Database: Surface Operations Volume vs. Mmax



Extraction From the Subsurface

25

Extraction From the Subsurface

Groundwater extraction

26

Lorca, Spain

nature geoscience LETTERS
PUBLISHED ONLINE: 21 OCTOBER 2012 | DOI: 10.1038/NGEO1610

The 2011 Lorca earthquake slip distribution controlled by groundwater crustal unloading

Pablo J. González[1]*, Kristy F. Tiampo[1], Mimmo Palano[2], Flavio Cannavó[2] and José Fernández[3]

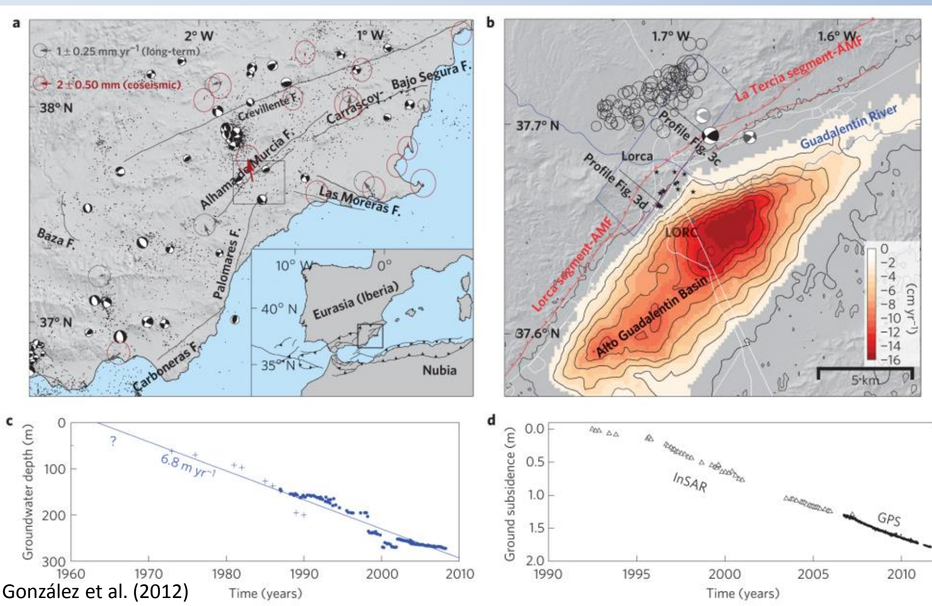
Earthquake initiation, propagation and arrest are influenced by fault frictional properties[1,2] and preseismic stress[3,4]. Studies of triggered and induced seismicity[5–7] can provide unique insights into this influence. However, measurements of near-

Methods). Two different ENVISAT descending satellite tracks (I2 and I6) imaged the area before and after the event, providing estimates of the displacement field from two different look angles (Fig. 2a,c). Differential interferograms were processed in time

González et al. (2012)

27

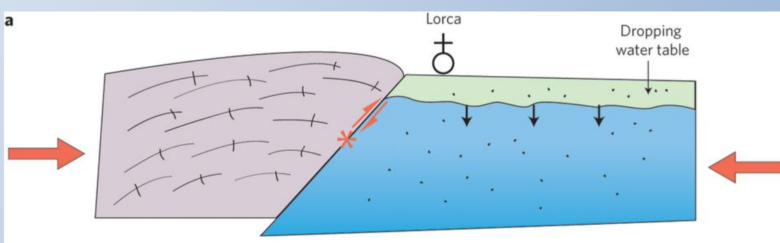
Lorca, Spain



González et al. (2012)

Lorca, Spain

- 2011 M_W 5.1
- Shallow, ~ 3 km depth, Alhama de Murcia Fault
- ~ 10 x 10 km fault area



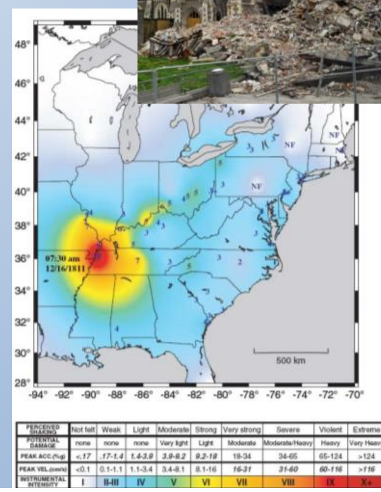
29

Lorca, Spain
9 people killed, 100s injured

30

Other very shallow earthquakes

- 2010 Canterbury earthquake, M 7.1, depth ~ 10 km (damage ~ NZ$3 billion)
- 1812 New Madrid earthquakes? M ~7.5



Other places where water table lowered

- The Netherlands

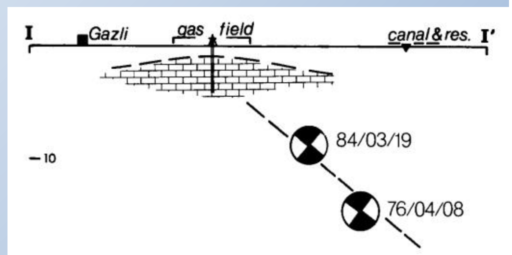
Extraction From the Subsurface

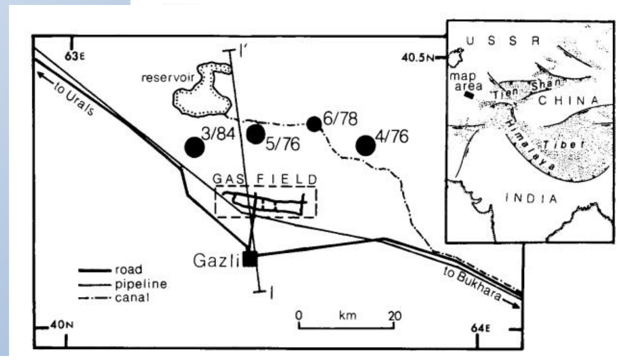
Hydrocarbons

36

Gazli, Uzbekistan

- 1966 – Large-scale gas production
- 1976, 1984 – 3 x M ~ 7
- 1 death, 100 injuries
- Pressure reduction ~ 5 MPa

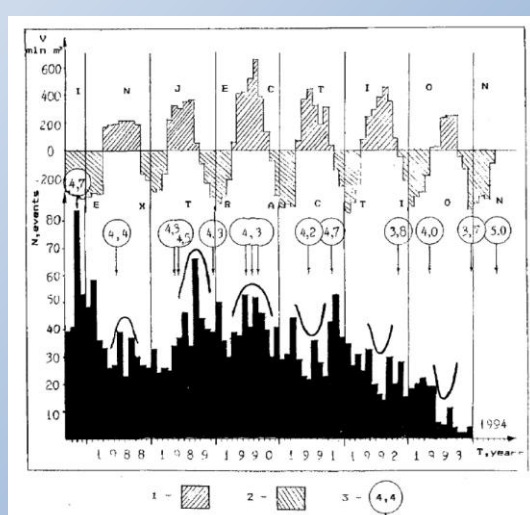




Simpson & Leith (1985)

Gazli, Uzbekistan

- Since 1988 – used for underground storage
- Gas cycled in & out seasonally



Plotnikova et al. (1996)

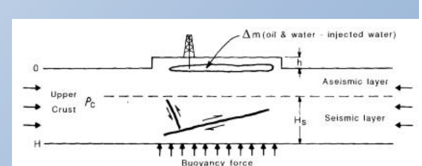
Reporting Inhomogenous

- No seismicity reported in most fields (but is it observed?)
- Eats, shoots, and leaves
- Eats shoots and leaves
- No seismicity is observed
- No. Seismicity is observed
- Seismicity is not reported
- No seismicity is reported



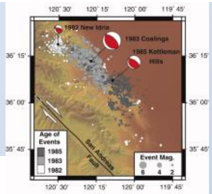
Possible large anthropogenic earthquakes under oil/gas reservoirs

- 1983 M 6.2 Coalinga earthquake, California
- 1985 M 6.1 Kettleman North Dome, California
- 1987 M 6.0 Whittier Narrows, California
- All:
  - ~ 10 km deep
  - under producing oil fields
  - uplifting anticlines
  - seismic deformation = required to restore isostatic equilibrium if backflow of water ignored



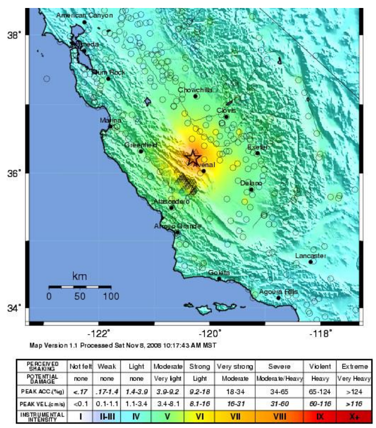
McGarr (1991)

41

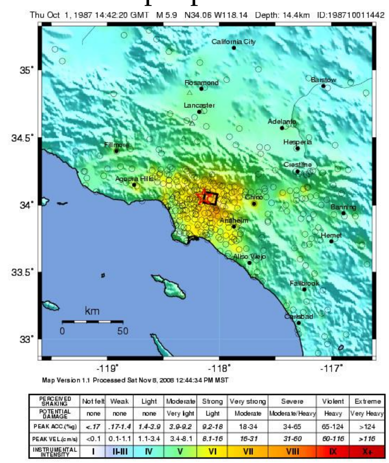


The term "blind thrust" comes up a lot

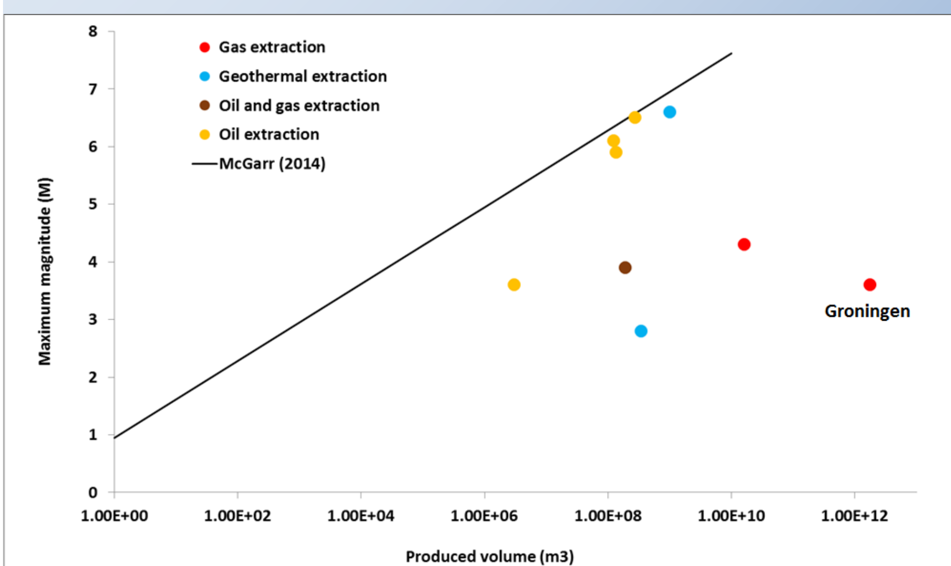
Coalinga
94 injured, felt throughout half the State



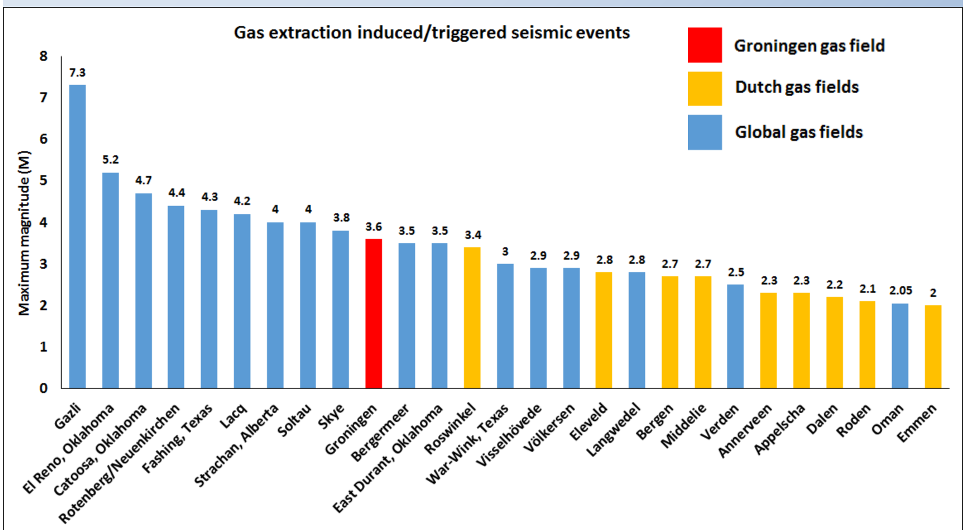
Whittier Narrows
6 people killed



Database: Extraction – Subsurface Volume vs. Mmax



Database: Mmax Gas Fields Only



46

Injection Into the Subsurface

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Injection Into the Subsurface

Liquid

48

Injection Into the Subsurface

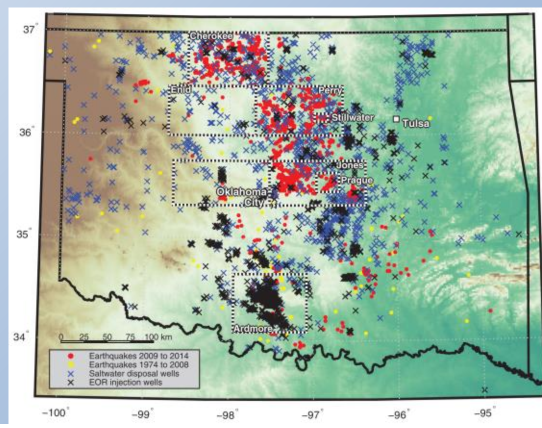
Liquid

Wastewater disposal & enhanced oil recovery

49

Oklahoma: Injection wells & earthquakes

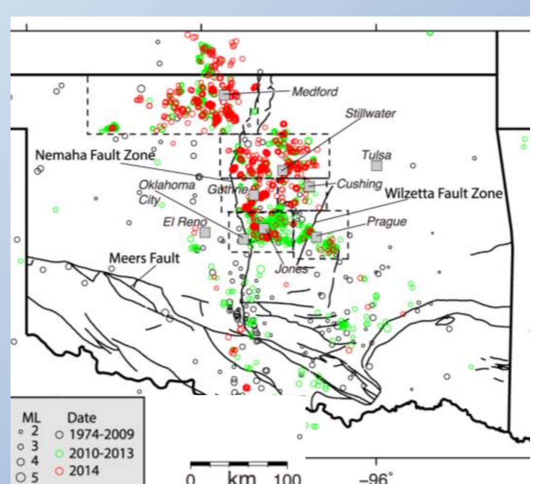
- ~ 7,000 injection wells
  - Disposal of produced brine (dominant)
  - Enhanced oil recovery
  - Disposal of frack fluid
- Most injected in Arbuckle Group: carbonates/sandstones close to Precambrian crystalline basement



Walsh & Zoback (2015)

Oklahoma seismicity

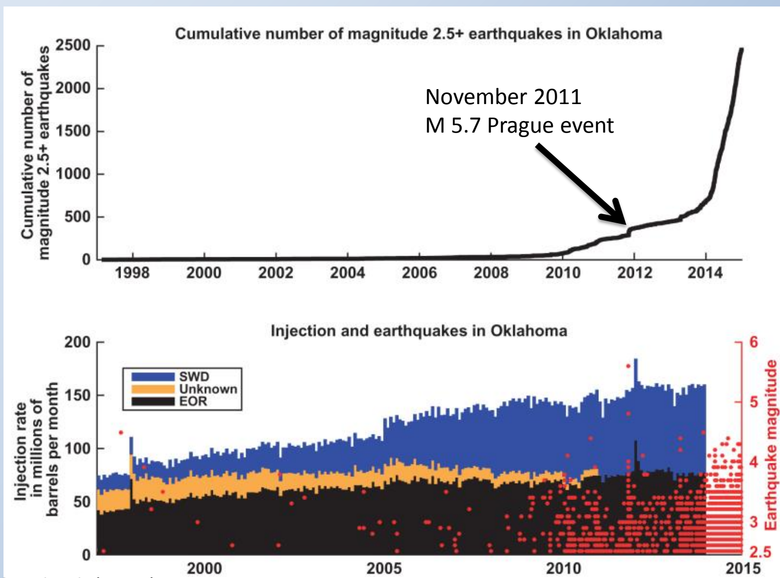
- Injected volume doubled over last 17 years
- Seismicity suddenly increased 2009
- Correlations between eqs & injection/production are rare
- Meers Fault – M 6.5-7 events last 3,500 years



McNamara et al. (2015)

51

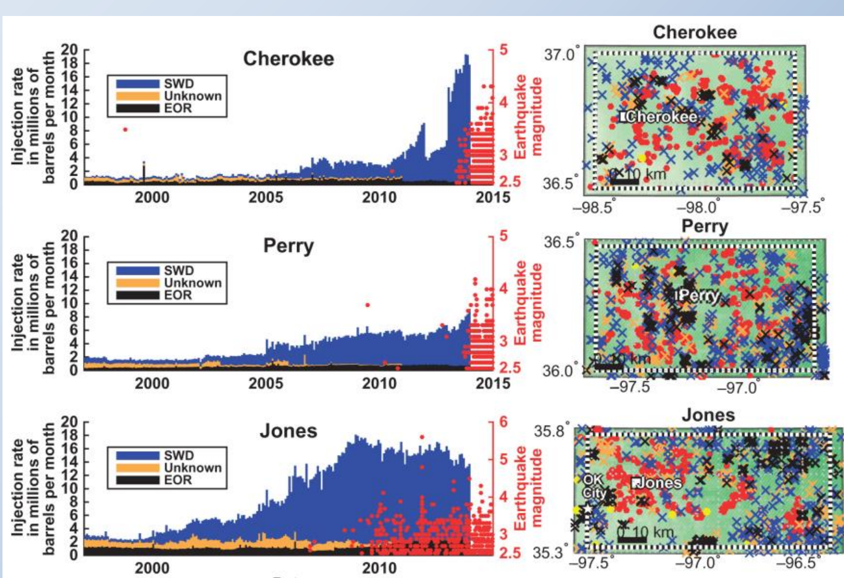
Oklahoma: Earthquakes and injection



Walsh & Zoback (2015)

52

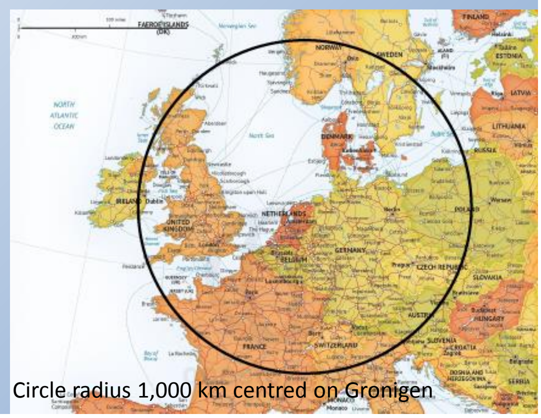
Oklahoma: Individual wells



Walsh & Zoback (2015)

Oklahoma

- 2011 – M_W 4.8, 4.8, 5.7 due to wastewater injection in depleted oilfield (Prague sequence)
- Felt 1,000 km away in Chicago
- 2014, M 4.0, 4.3,
  - felt 200 km away
  - items thrown from shelves
  - broken windows
- Can spill into next jurisdiction



Circle radius 1,000 km centred on Gronigen

Injection Into the Subsurface

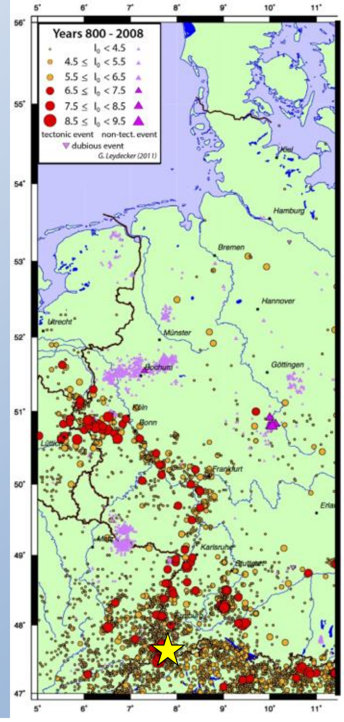
Liquid

Enhanced Geothermal Systems (EGS)

55

Example: Basel, Switzerland

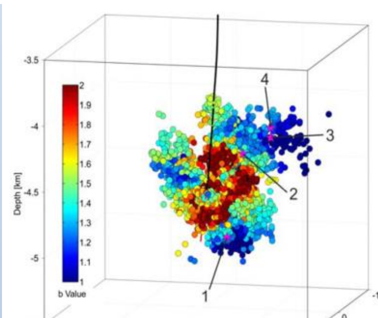
- EGS project
- Where Upper Rhine Graben meets Jura Mountains fold/thrust belt
- 1356: M ~ 6.5 earthquake destroyed city



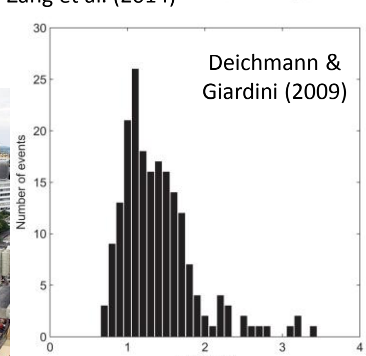
☆ Basel

Basel, Switzerland

- Mmax 3.4 (2006) + 3 M > 3 events weeks after shut-in
- Depth: 4.6-5.0 km
- Volume: 11,570 m^3
- Project status: Abandoned



Zang et al. (2014)

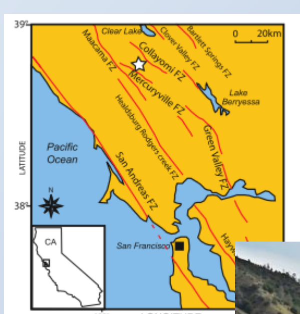


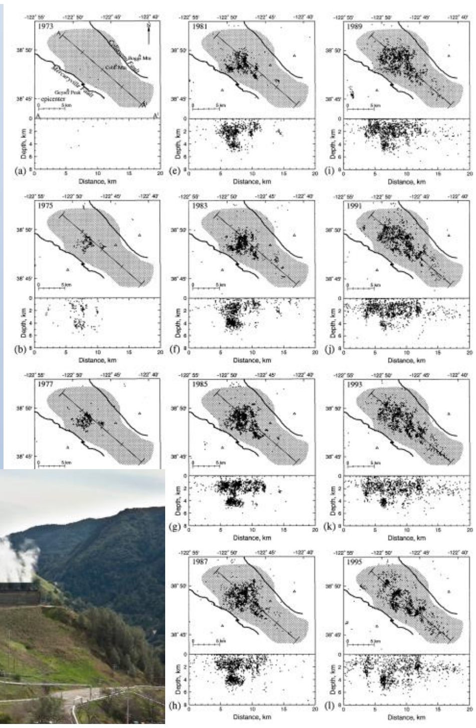
Injection Into the Subsurface

Liquid

Geothermal reinjection

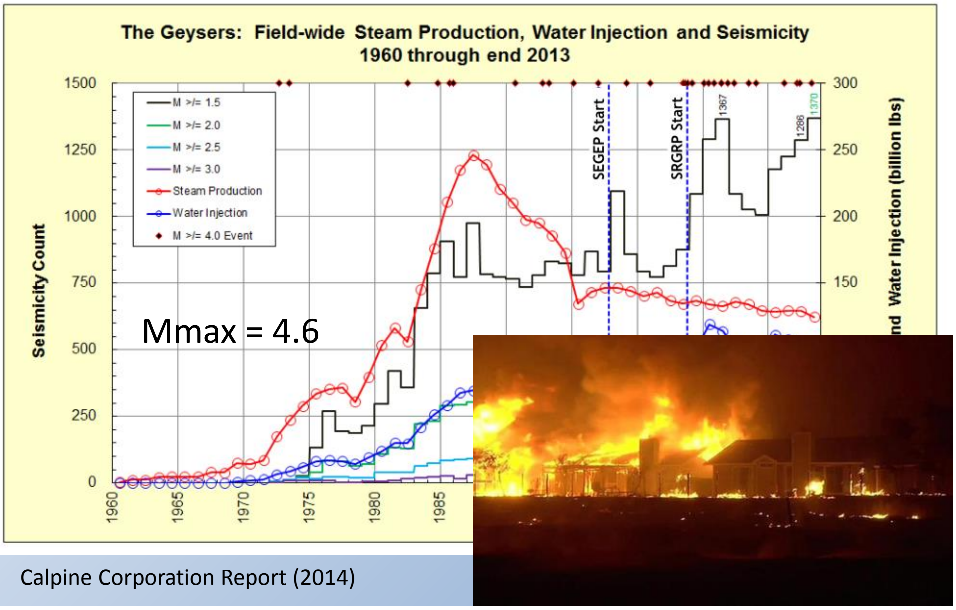
The Geysers Geothermal Field, California





Ross et al. (1999)

The Geysers, California



Calpine Corporation Report (2014)

Injection Into the Subsurface

Gas

66

Injection Into the Subsurface

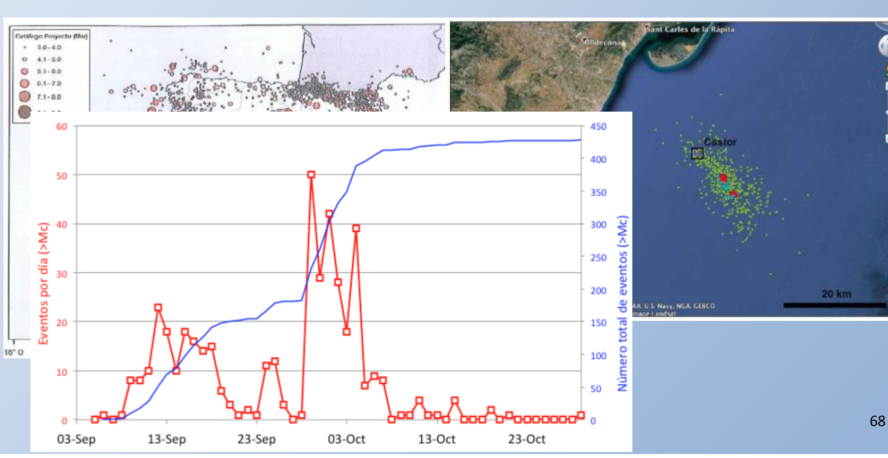
Gas

Natural gas storage

67

Amposta Depleted Oil Field, Spain

- Injection of cushion gas for storage
- Oct 2013 > 1,000 earthquakes up to M 4.3



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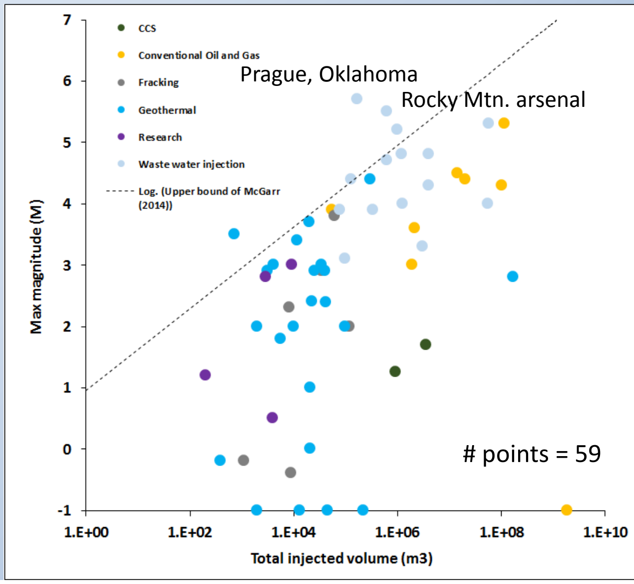
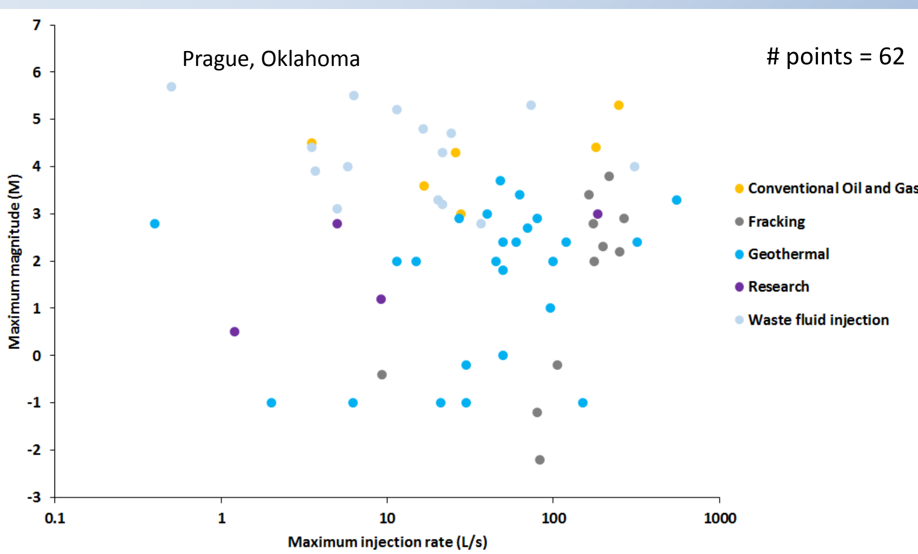
Database: Injection – Subsurface Volume vs. Mmax

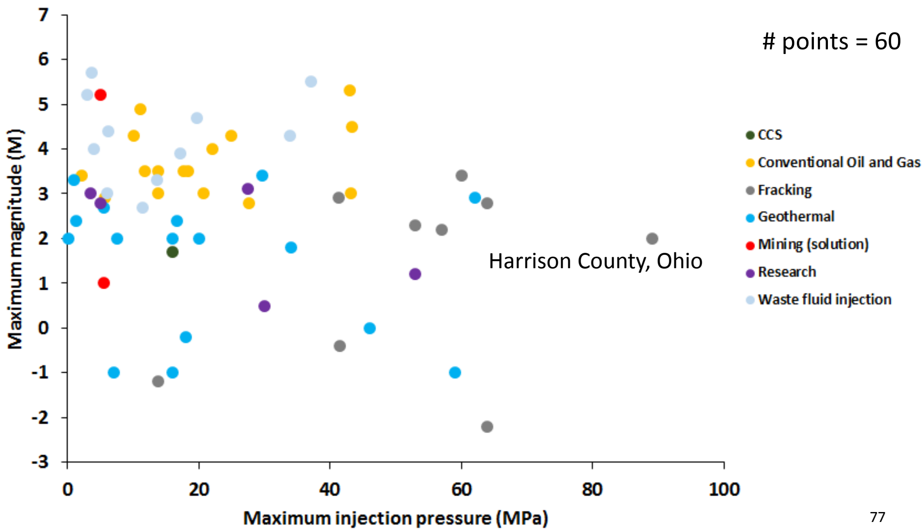


75

Database: Injection – Subsurface Maximum Injection Rate vs. Mmax



Database: Injection – Subsurface Maximum Injection Pressure vs. Mmax



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Nuclear Explosions

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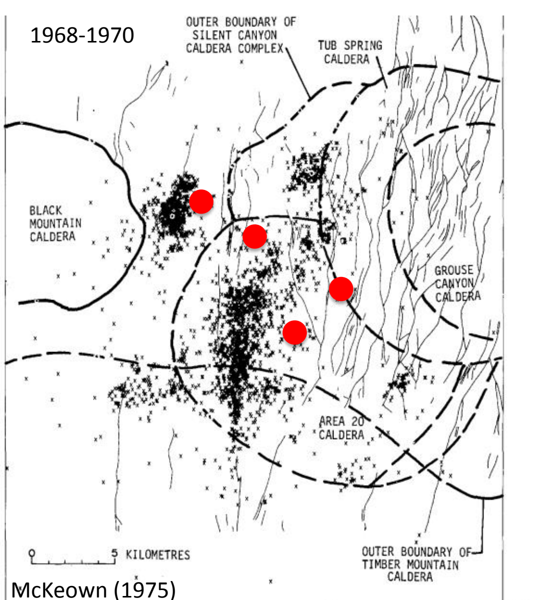
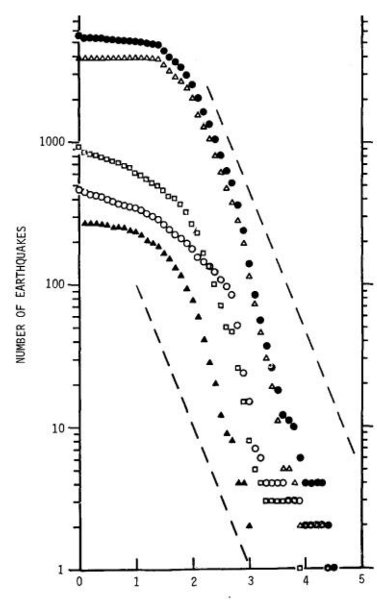
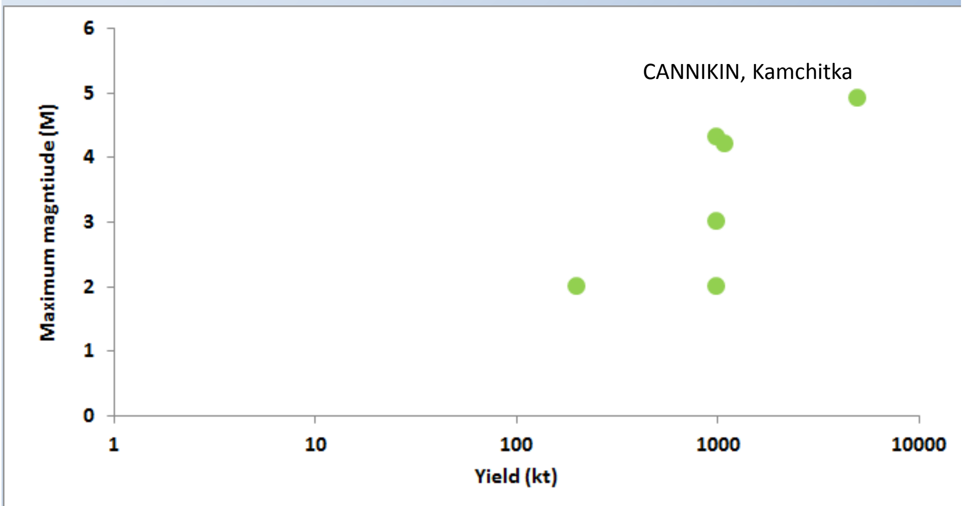
Nevada test site

BENHAM, PURSE, JORUM & HANDLEY





Nuclear Test Yield vs. Mmax



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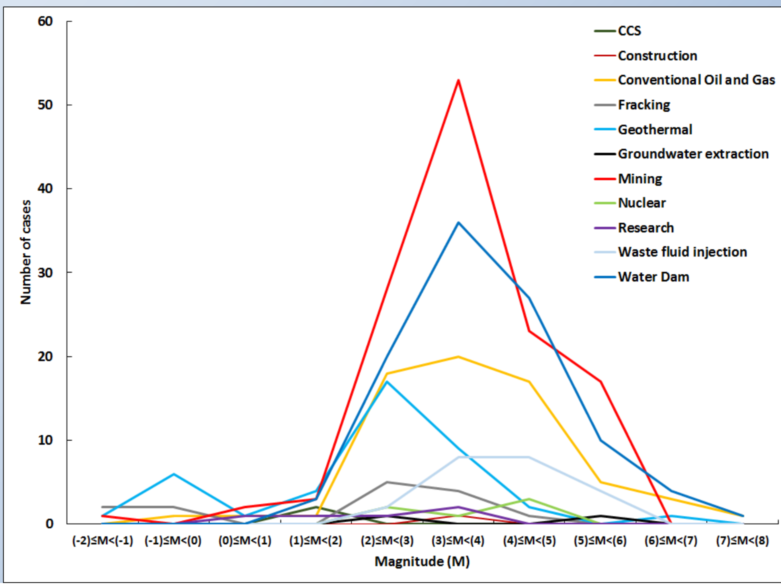
Total Database

82

All Projects
Mmax Broken Down by Project Type



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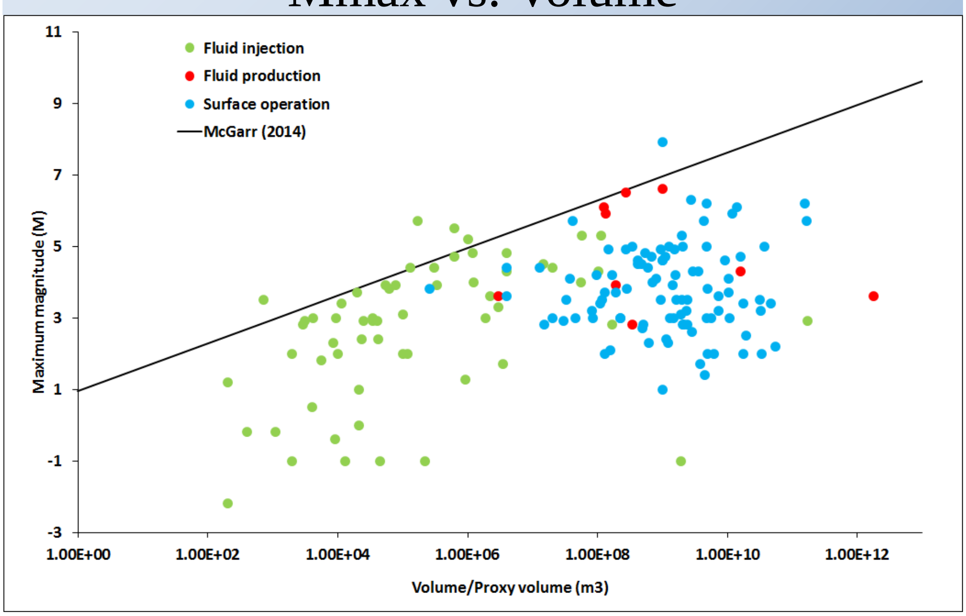
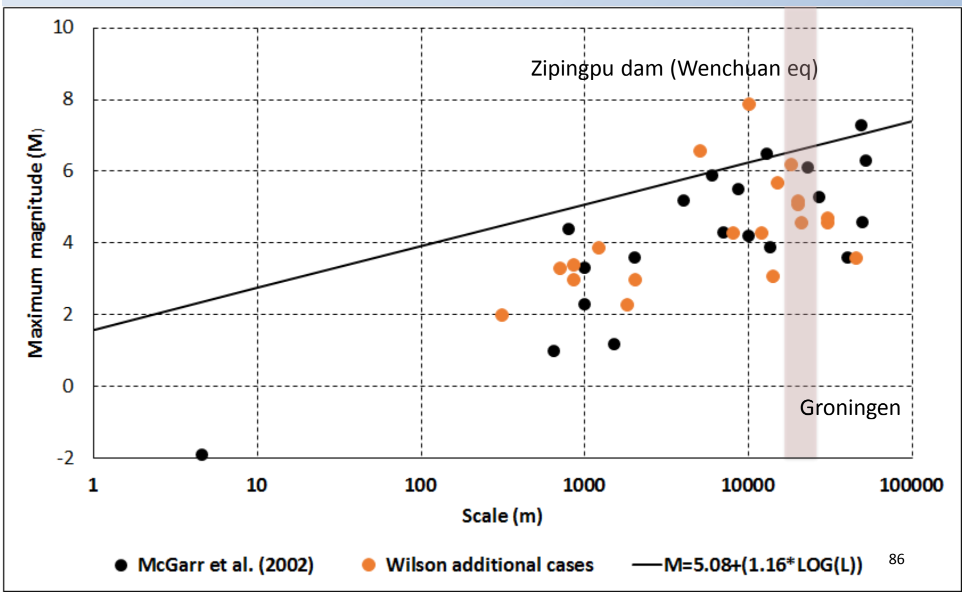
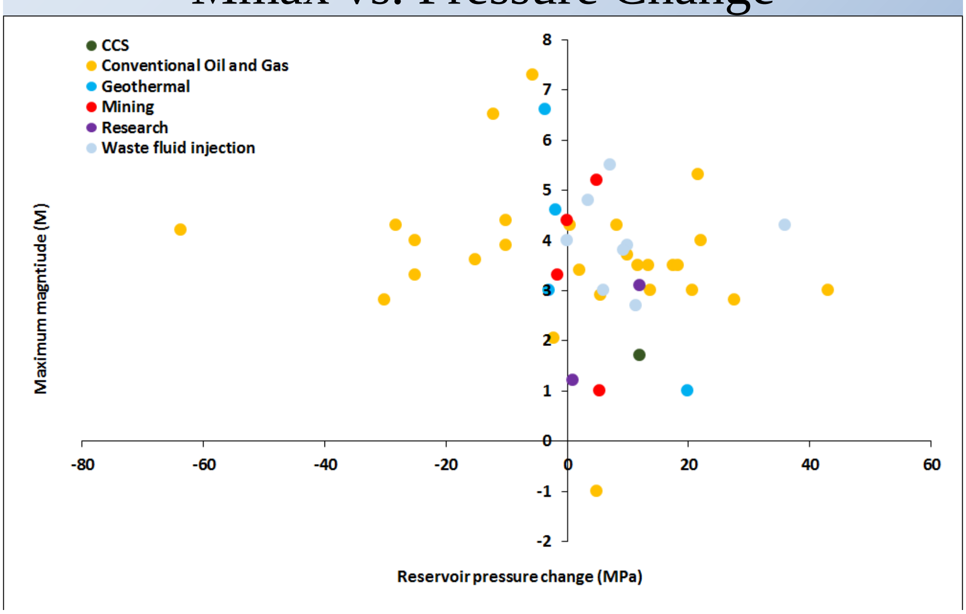
All Projects
Mmax vs. Volume



All Projects
Mmax vs. Scale



All Projects
Mmax vs. Pressure Change



Last Comments

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Some considerations

- Systematic patterns rare – maybe we are looking in the wrong place
- We need a model for why earthquakes don't occur
- Fundamental nature of earthquakes
  - Earthquakes occur whether or not human operations
  - "Firing squad problem": Which, of many contributory effects, was "responsible" for an earthquake?
- Public perception
  - If a large earthquake occurs in a project area, the project may be blamed regardless

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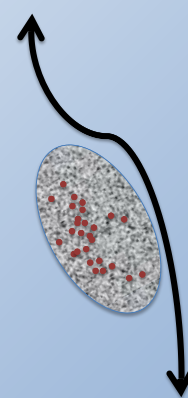
Future Work With Database

Future Work

- Interpret results in detail
- Expand to grey literature (*e.g.*, conference abstracts)
- Assemble more data, *e.g.*, volumes, where the data are available but require organizing
- Revisit hard-to-estimate parameters *e.g.*, project scale
- Place database on public website & openly solicit more cases

That’s all folks



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Freie Universität Berlin

Mmax estimation for Groningen

S. A. Shapiro, C. Dinske, O. S. Krüger.

Freie Universität Berlin

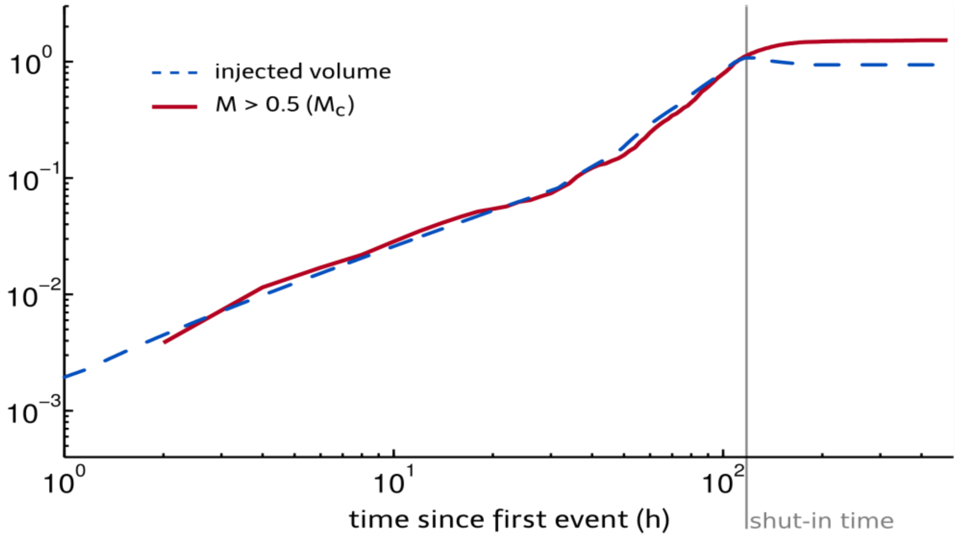
The Gutenberg-Richter law for fluid injections

$$\log N_M = a - bM$$

$$\log N_M(t) = \Sigma + \log Q_{inject}(t) - bM$$

Freie Universität Berlin

Basel: normalized cumulative seismicity and injected volume



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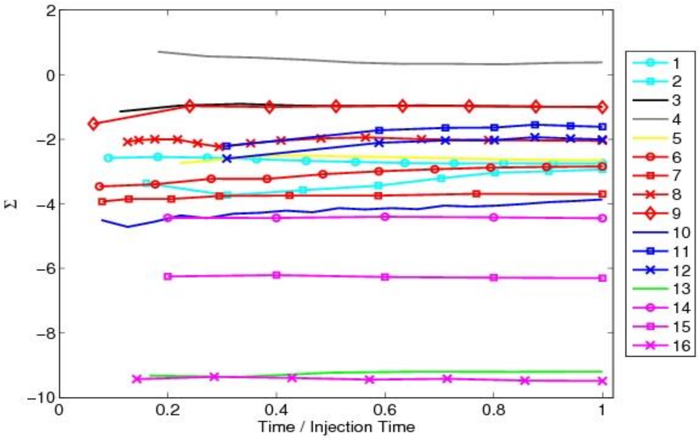
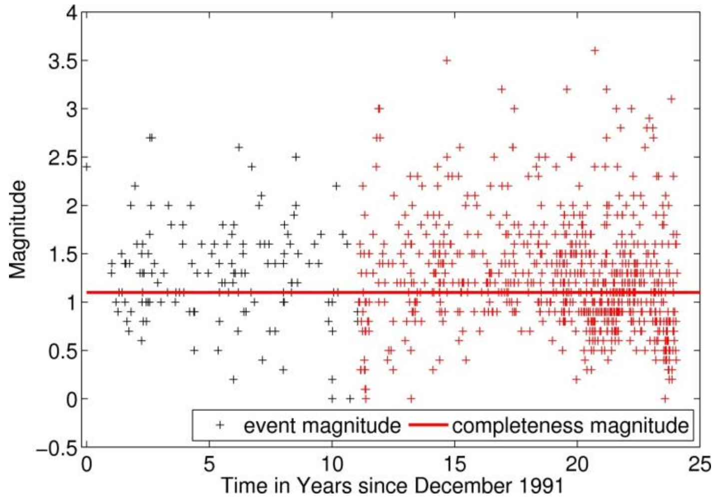
Seismogenic index, Σ



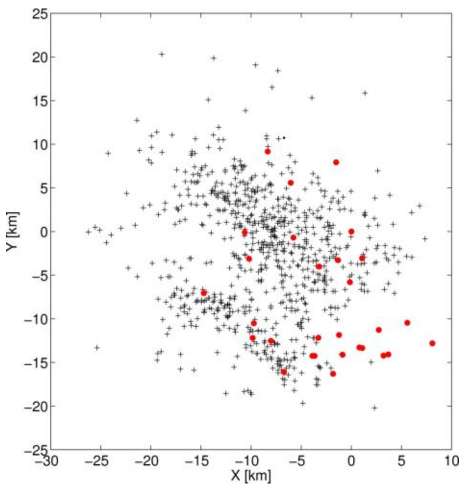
1-2: Ogachi 1991/93, **3**: Cooper Basin 2003, 4: Basel 2006, 5: Paradox Valley, **6-9**: Soultz 1996/95/93/00. **10-12**: KTB 2005/94.13: Barnett Shale, 14-16: Cotton Valley stages A, B,C.

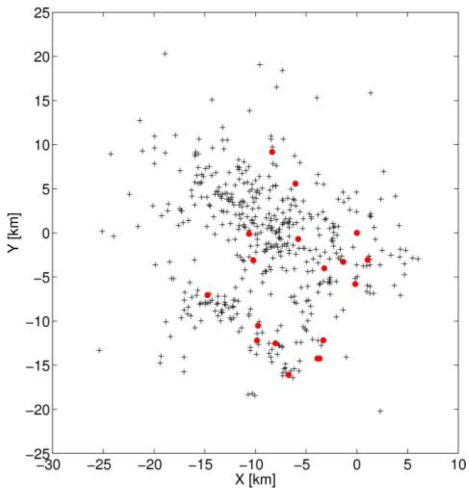
Magnitudes vs time
What had happened in 2002 with the observation system?
With the production?



Production wells and events (2003-15)

Why are there 10 boreholes producing reduced seismicity?
What is in the geologic/tectonic difference between SE and NW ?
Why is the seismicity shifted to the North West?





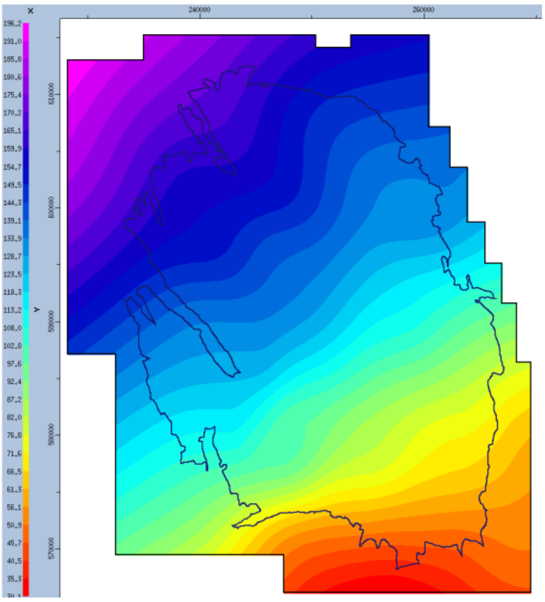
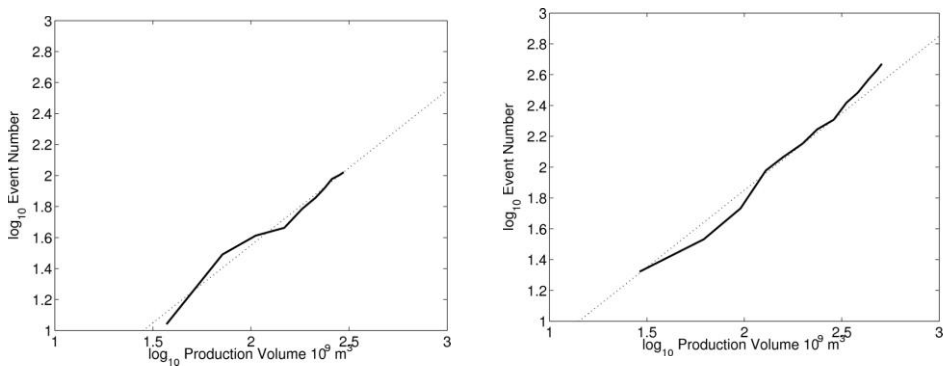
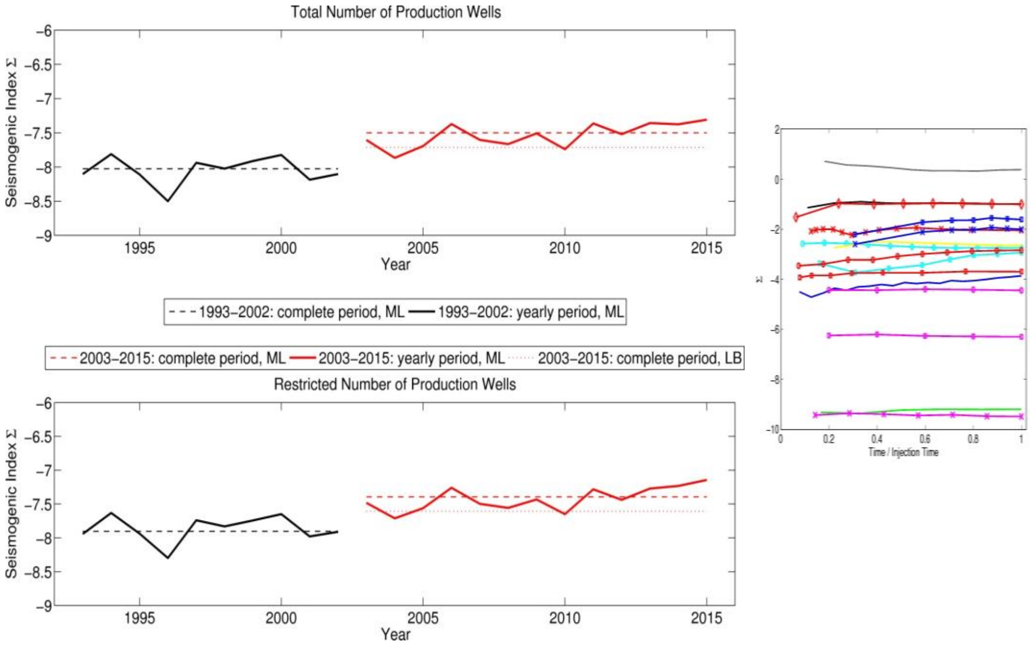


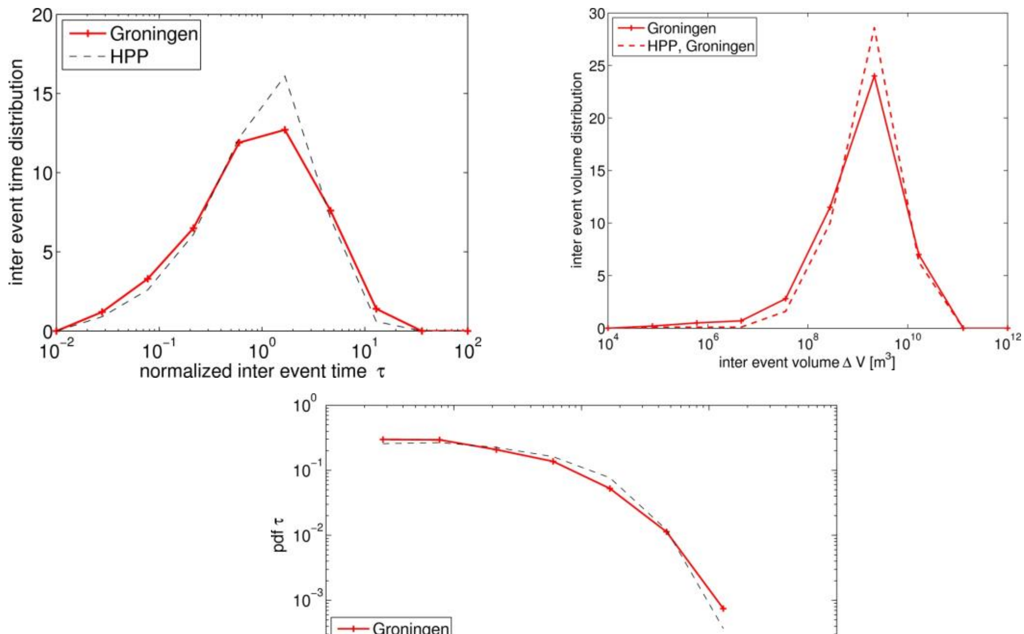
Fig. 2.23 Rotliegend time thickness, derived from well sonics and used to construct a DC_T time event (Field Review, Shell)

Seismicity vs Production 1993-2002 and 2003-2015

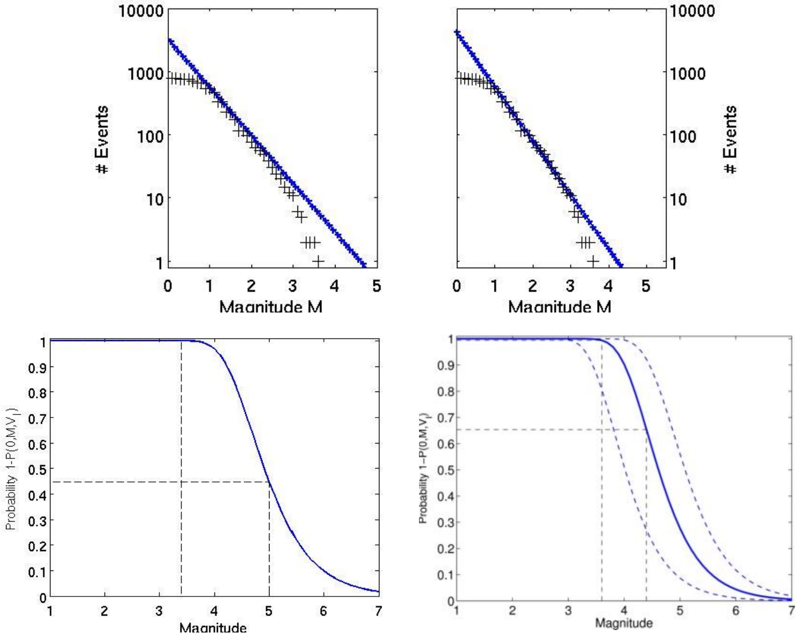


$$\log N_M(t) = \Sigma + \log Q_{prod}(t) - bM$$

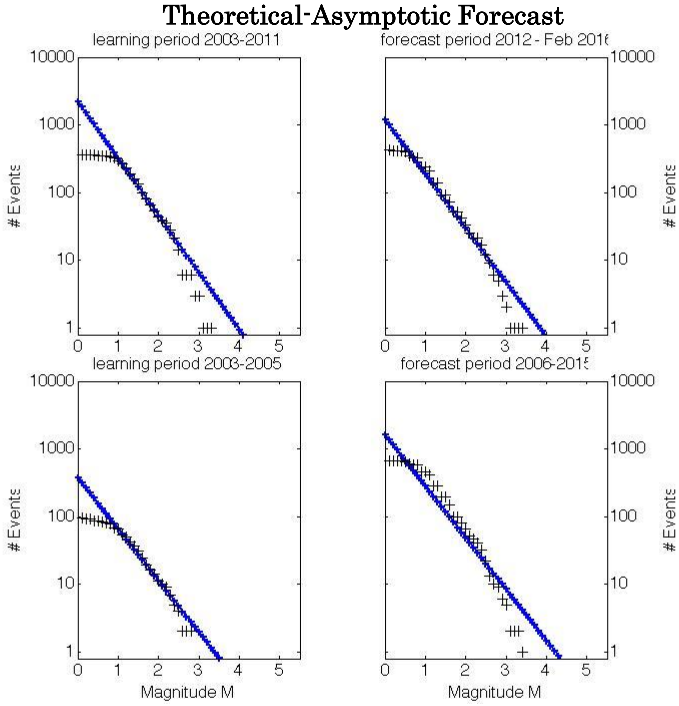

Total Number of Production Wells
Seismogenic Index Σ
Year
1993−2002: complete period, ML
1993−2002: yearly period, ML
2003−2015: complete period, ML
2003−2015: yearly period, ML
2003−2015: complete period, LB
Restricted Number of Production Wells
Seismogenic Index Σ
Year
Σ
Time / Injection Time


Groningen
HPP
inter event time distribution
normalized inter event time τ
Groningen
HPP, Groningen
inter event volume distribution
inter event volume Δ V [m³]
pdf τ
Groningen
HPP
normalized inter event time τ

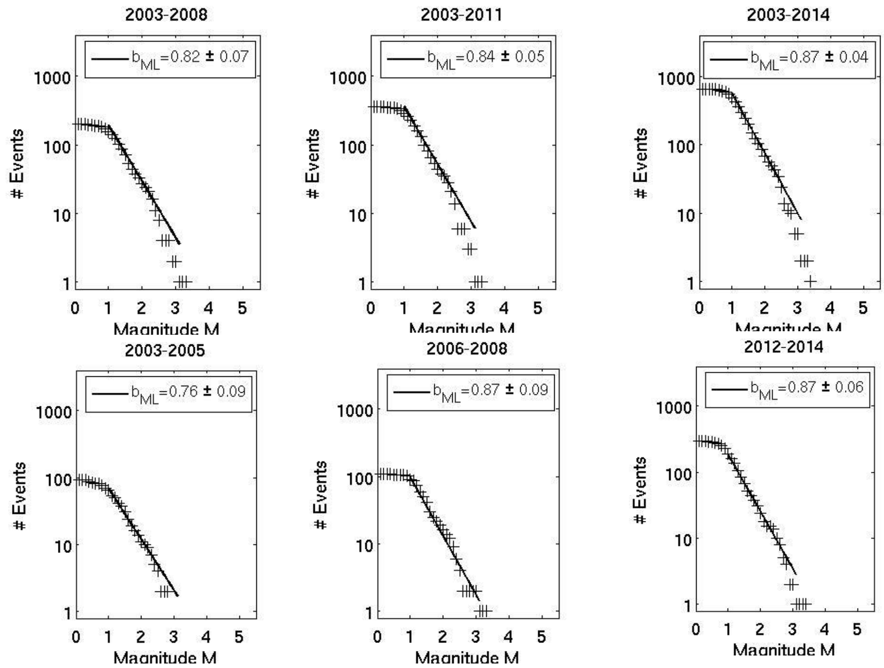
Theoretical Asymptotic: infinite medium + maximum-production rate until 2024



Theoretical-Asymptotic Forecast



b-value time dependence



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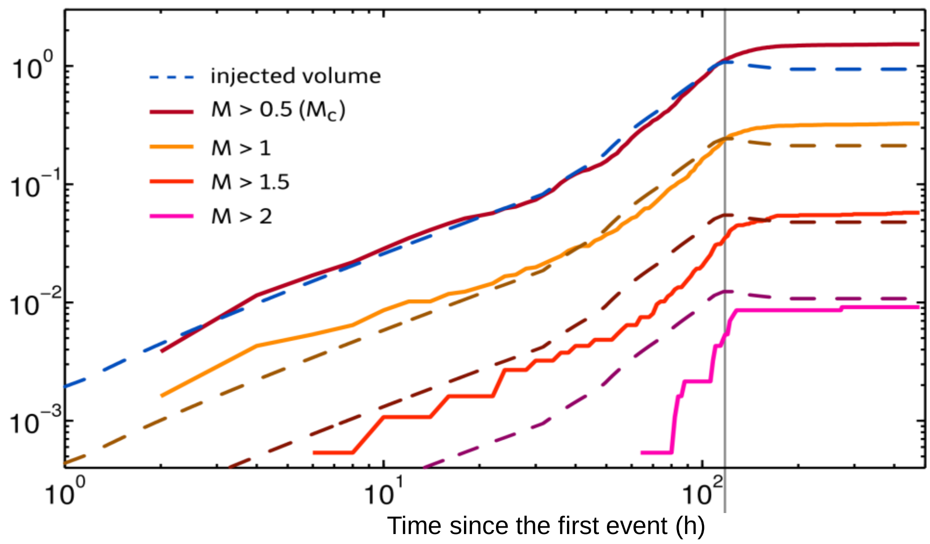
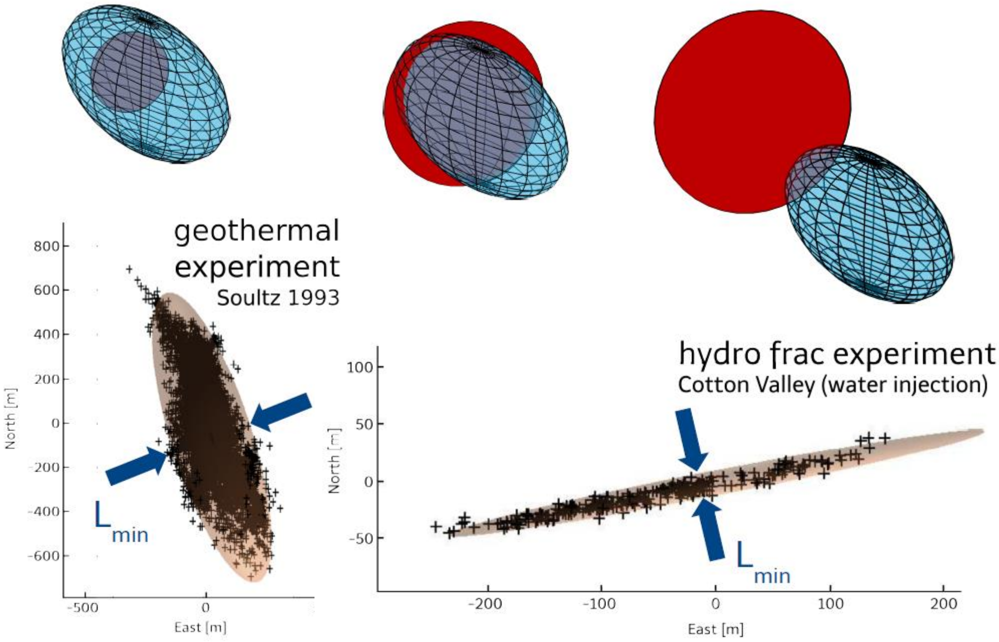
Basel: normalized cumulative seismicity and injected volume



Finite stimulated volume

Shapiro et al, 2011, Geophysics, v. 76, #6.



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Effect of the geometry

A power-law probability of a rupture size L produces the Gutenberg-Richter magnitude law

$$W_F \propto L^{-2b-1}\delta L$$

Effects of the geometry are accounted by

$$W_F(L)W_{geometry}(L)$$

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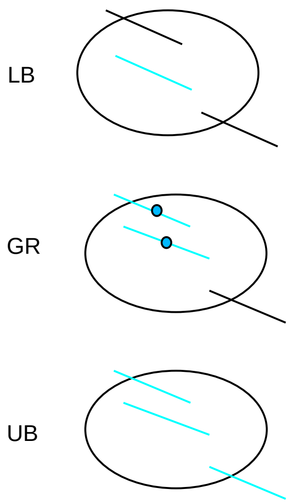
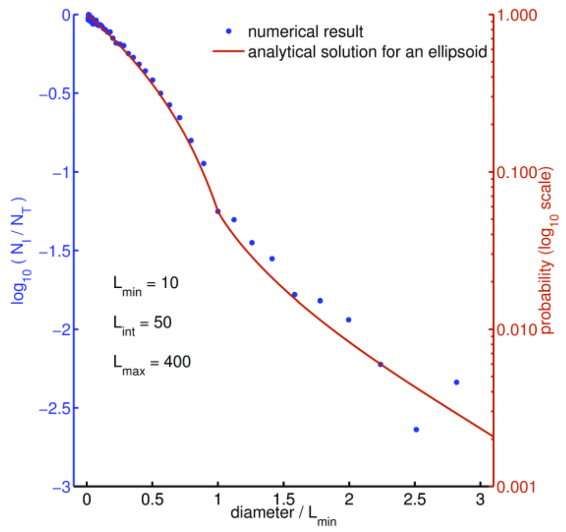
$$W_{sphere}(x) = (1 + x^2/2)\sqrt{1 - x^2} - 3\pi x/4 + (3x/2)\arcsin(x)$$

$$x = rupture\_length / sphere\_diameter$$

The geometry of the lower- and upper bounds





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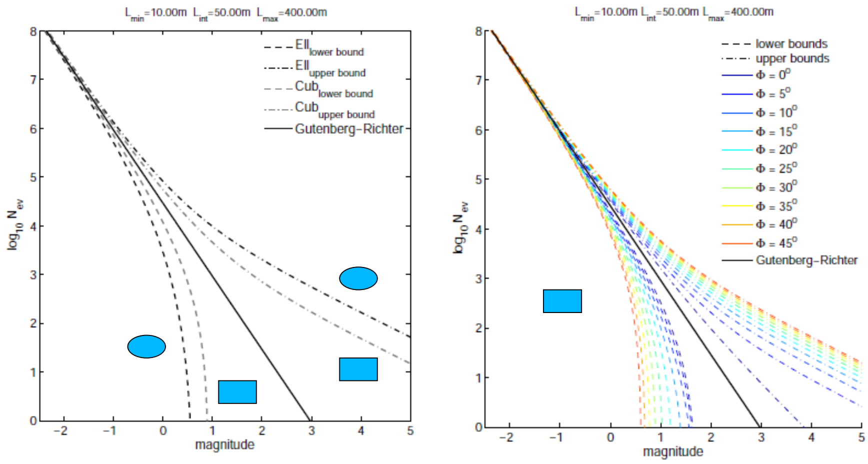
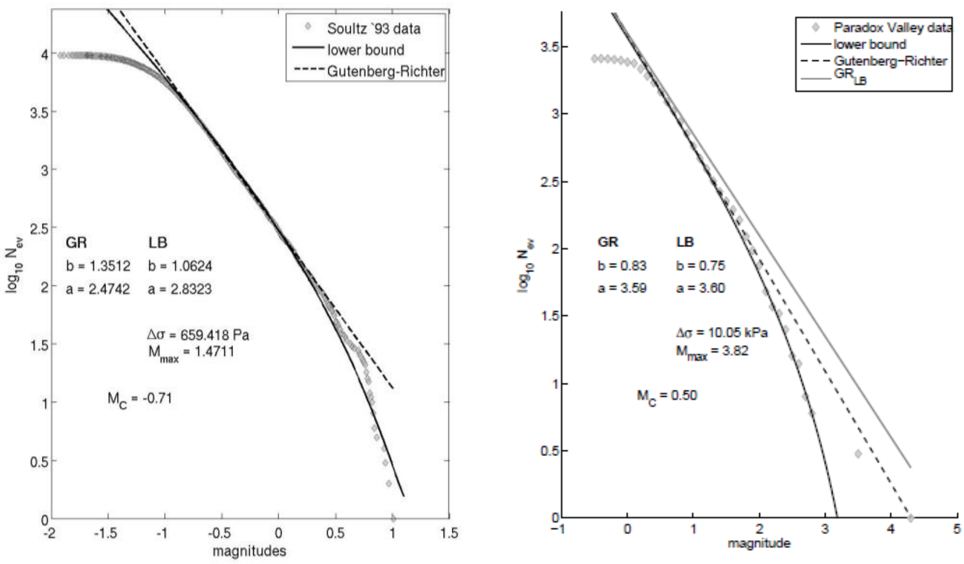
The lower- and upper bounds for magnitude distributions



The lower bound seems to be preferred!



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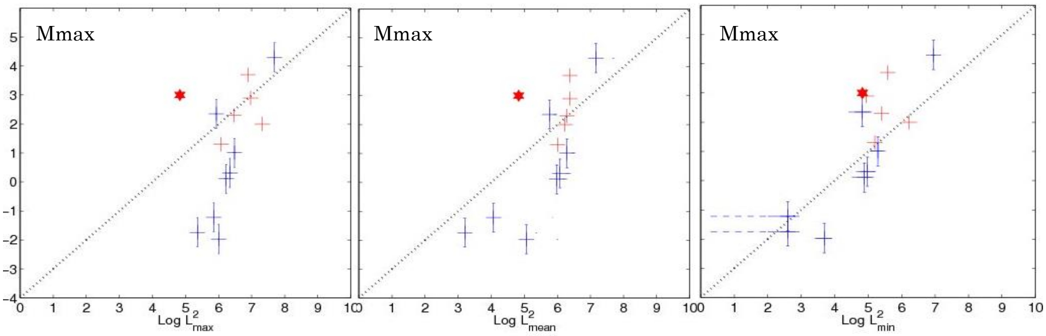
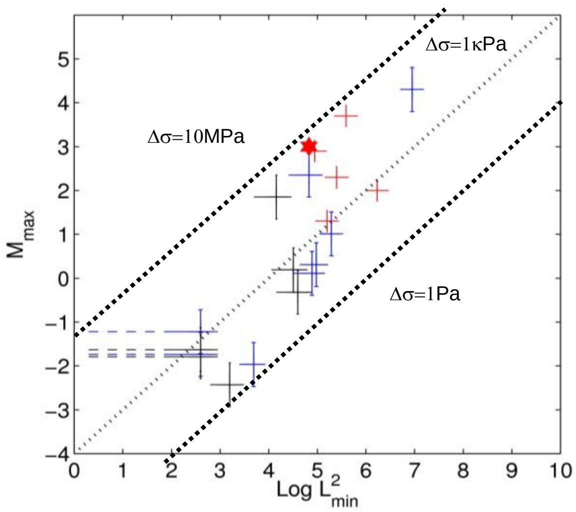
The scale controlling maximum magnitudes



Shapiro et al, 2011, Geophysics, v. 76, #6.

$$M_L = \log L^2 + [\log \Delta\sigma - \log C]/1.5 - 6.07$$

Maximum magnitude vs minimum axis



$$\mathrm{MAX}\{M_{max}\} \approx 2 \log L_{min} - 1$$

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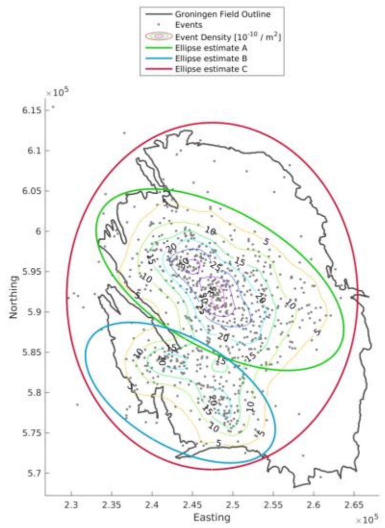

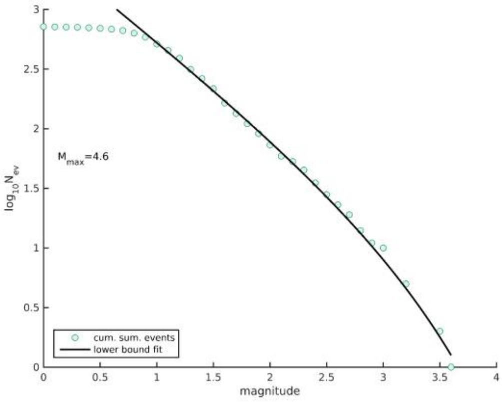

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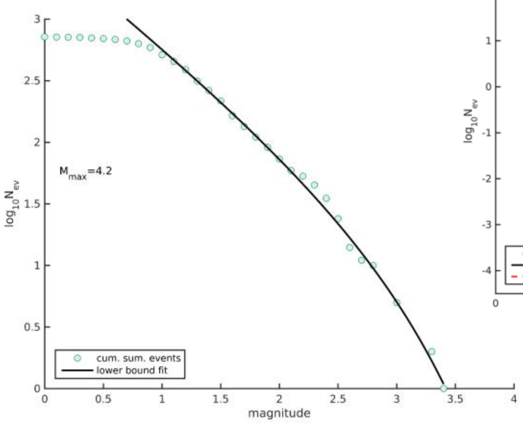
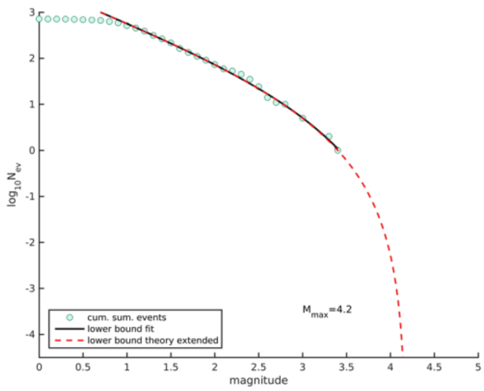
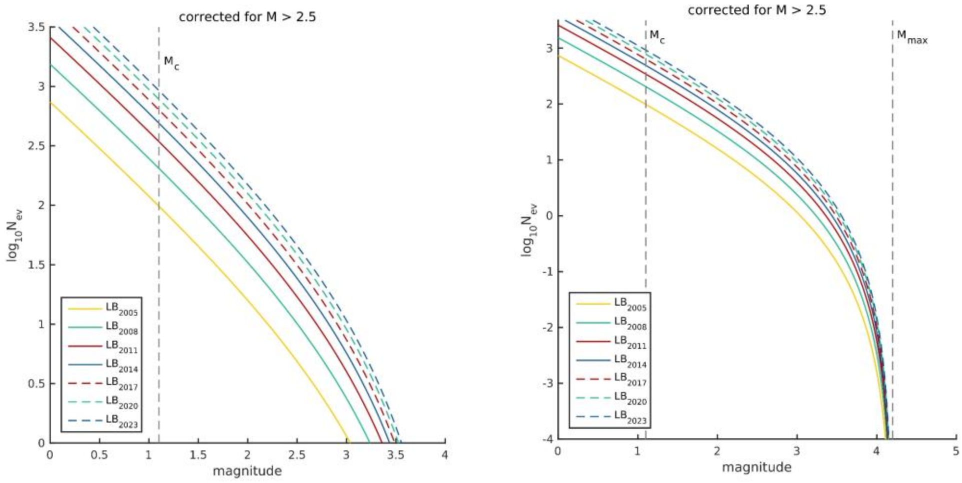
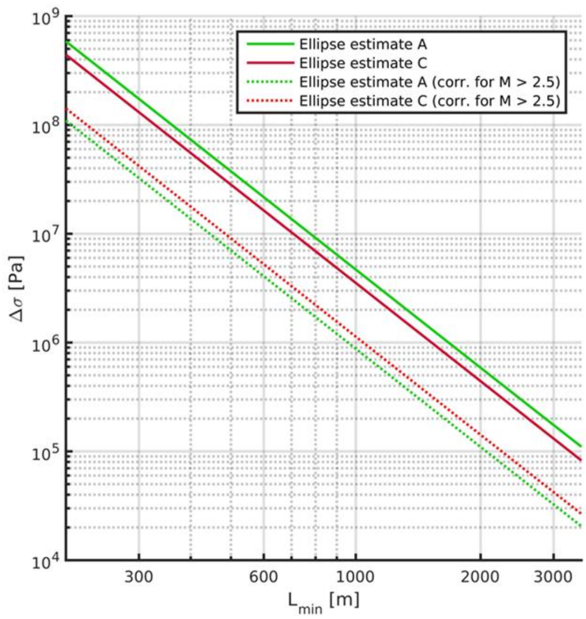





corrected for M > 2.5
M_c
log10 N_ev
magnitude
LB2005
LB2008
LB2011
LB2014
LB2017
LB2020
LB2023
corrected for M > 2.5
M_c
M_max
log10 N_ev
magnitude


Ellipse estimate A
Ellipse estimate C
Ellipse estimate A (corr. for M > 2.5)
Ellipse estimate C (corr. for M > 2.5)
Δσ [Pa]
L_min [m]

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Conclusions

- The seismogenic index in Groningen seems to be quite low.
- However, it increases slightly with the production.
- Most probable Mmax is around 4.2 (uncorrected: 4.6-4.7).
- Probably, Lmin is > 300m. It seems to be in the range 400-1100m.
- Alternatively, the stress drop must be very high (> 10 MPa).
- The geometry-uninfluenced b-value is close to 0.76-0.77 (in contrast to ML:0.86)
- A good depth resolution of event locations is necessary.

ExxonMobil

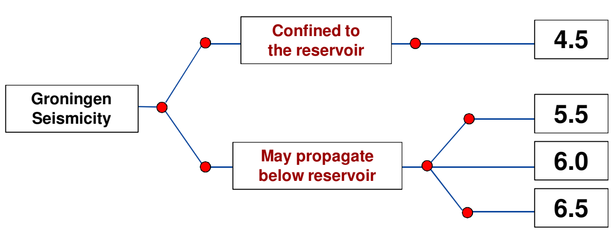
March 9, 2016

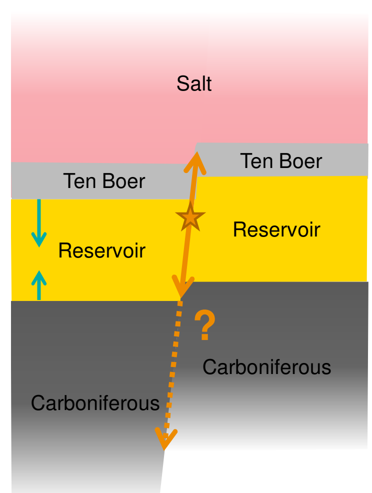
Maximum Magnitude of Events in Groningen Field

Energy lives here™

Key Messages

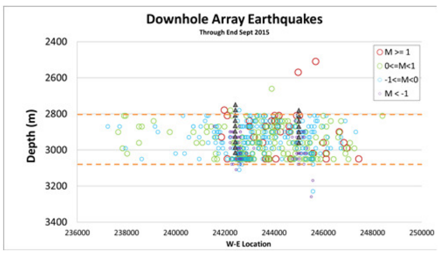
- A distribution of maximum magnitudes should be applied
- Most ruptures will be confined to the reservoir interval
- If the earthquakes are confined to the reservoir interval then a maximum magnitude of 4.5 should be applied
- If earthquakes can propagate outside of the reservoir then a larger maximum magnitude should be considered





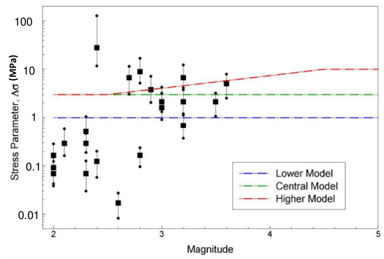
Earthquake observations provide key constraints

Earthquakes are nucleating within the reservoir interval



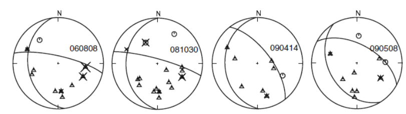
563 events recorded on downhole array, relocated by Magnitude and posted to NAM platform

Stress drop estimates range from 0.1-10 MPa (3 MPa is the best fit)



Stress drops calculated by Bommer et al, 2015, Development of V2 GMPEs…

Focal mechanisms show predominantly normal faulting



(Kraaijpoel & Dost, J Seismol 2013)

The catalog is consistent with a truncated distribution

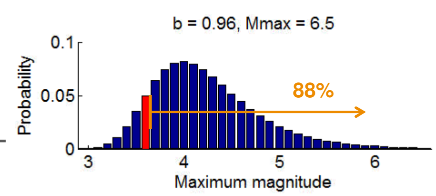
- The M 3.6 Huizinge event is the largest observed out of 271 Groningen events (M>=1.45)

Probability that we should have seen an event larger than M 3.6 by now

	Truncation Magnitude			
b value	**4.0**	**4.5**	**5.5**	**6.5**
0.85	84%	95%	97%	97%
0.96 (bf)	68%	83%	87%	88%
1.07	50%	65%	70%	70%

P < 5%
5% < P < 15%
15% < P < 35%
35% < P < 65%
65% < P < 85%
85% < P < 95%
P > 95%

Probability of a given magnitude being the observed maximum



- Catalog is more consistent with a lower magnitude truncation
- Probabilities are lower bounds due to:
  - Additional 78 Rotliegend events in nearby depleting fields
  - Not all earthquakes larger than M 1.5 have historically been recorded
  - Lower b values best characterize the seismicity where most events occur
- Extreme value analysis estimates a lower truncation magnitude

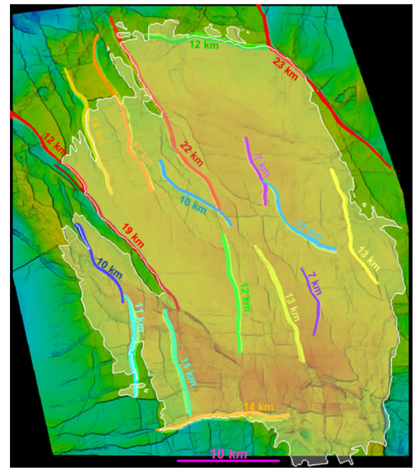
Extreme value analysis of maximum annual magnitude

Distribution	Mag
Weibull	3.8
Largest Ext. Value	4.6
Gamma	4.1

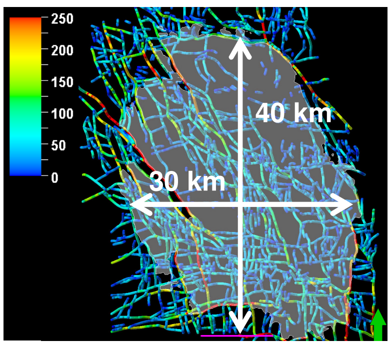
Overview of fault geometry

- Faults within the reservoir have been extensively mapped
  - ~700 faults in reservoir model
  - 43 faults > 7 km
  - Longest fault linkage is < 30 km
- No individual fault spans the horizontal dimension of the field

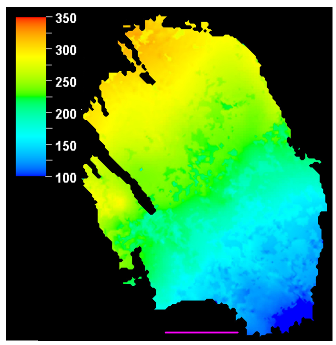
Depth of Top Rotliegend



Fault Offsets



Rotliegend Thickness



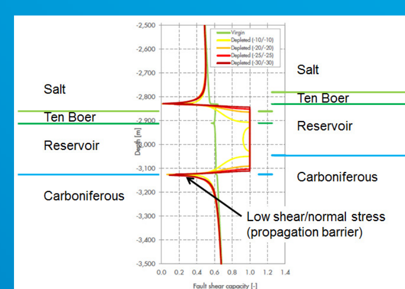
- Reservoir thickness and offset vary throughout the field
  - 270 m – representative thickness (includes Ten Boer)
  - 80 m – Average max fault throw

5

Groningen Maximum Magnitude Workshop, March 8-10, 2016

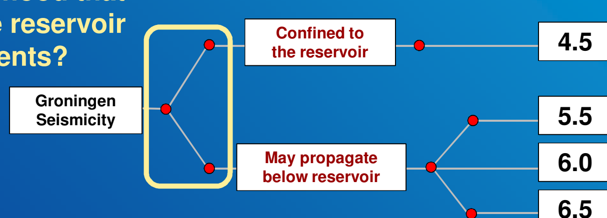
Confinement of events to the reservoir

- Ruptures can be stopped by geometric complexities, strength properties, stress barriers, or other unknown controls
- For a rupture to propagate below the reservoir there must be high enough stresses to sustain propagation
- A low shear stress environment could keep events confined to the reservoir
- Analysis of largest event is inconclusive regarding reservoir confinement



(Modified from report by P. van den Bogert 2014)

What is the likelihood that all events will be reservoir confined events?



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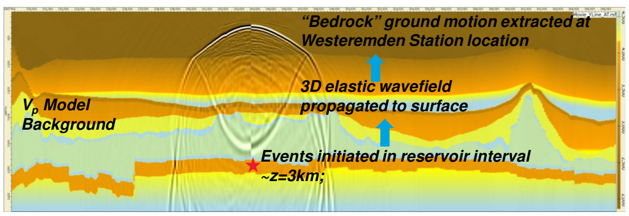
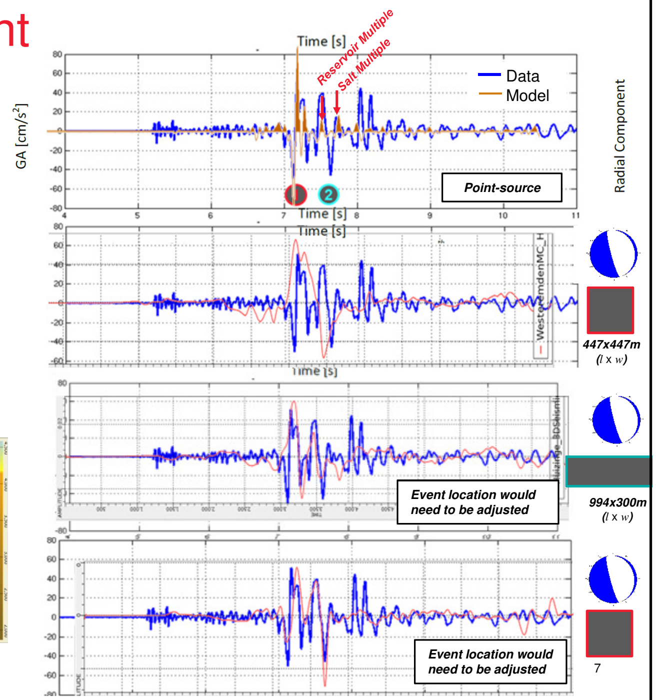
Simulations of Huizinge Event

- Finite-source (kinematic rupture) wavefield modeling through a 3D elastic model is used to simulate different Huizinge event rupture geometries and mechanisms
- Event nucleated at estimated Huizinge hypocenter with two different rupture area aspect ratios (square vs. ribbon)
- Characteristic “doublet” signature likely reflects complexities of the rupture process and the source-to-receiver path
- The doublet can be reproduced with non-unique input parameters and does not require rupture into the Carboniferous
- At this time, difficult to match all station observations





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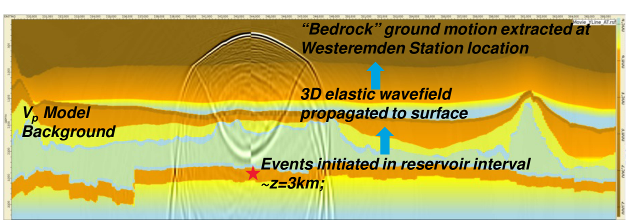

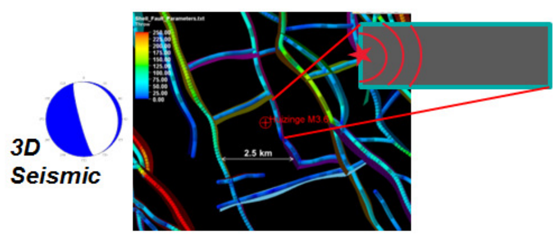

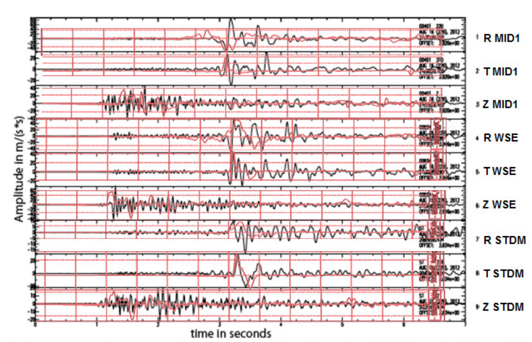

Figure 8. From top to bottom: accelerometer recording in station Middelstum-1 (1-3, radial, transverse and vertical)), Westeremden (4-6, rad, trans., vert.) and Stedum (7-9, rad, trans., vert.) for the August 16, 2012 Huizinge event.

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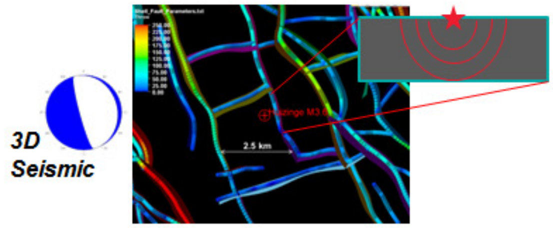

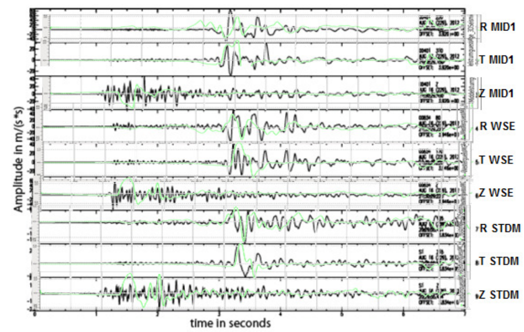

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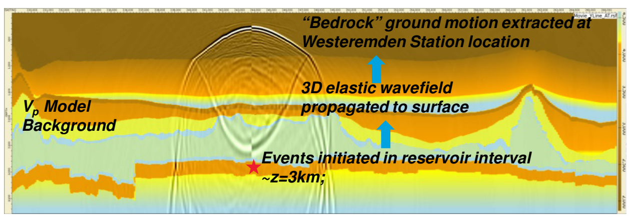
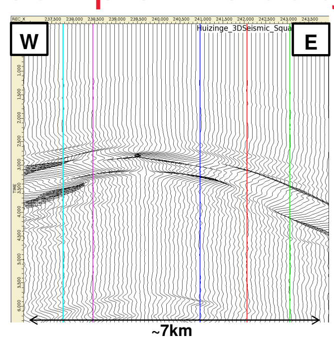
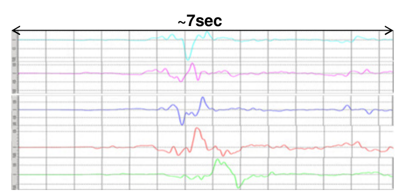


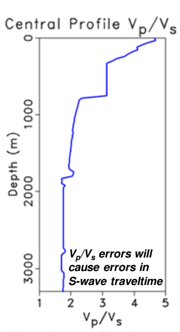
Waveforms arise from complex velocity structure

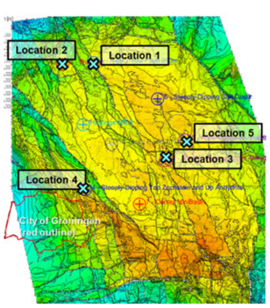
- Surface waveforms are a superposition of:
  - Complex 3D velocity structure effects
  - Focal mechanism signature
  - Rupture geometry signature
- Waveforms are extremely sensitive to station location and event location estimate
- Neighboring records can vary significantly within several kilometers of the epicenter



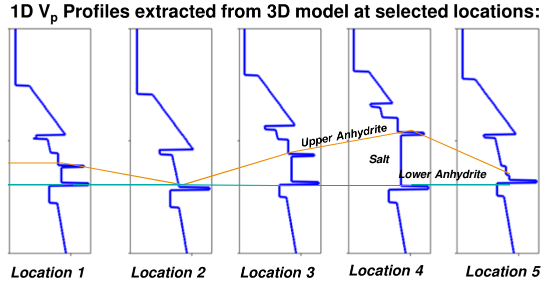


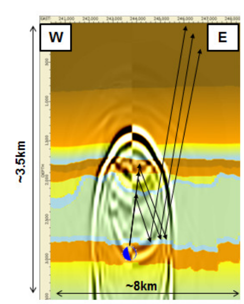
Simulated Surface Records (radial acceleration, finite rupture source)





1D V_p Profiles extracted from 3D model at selected locations:



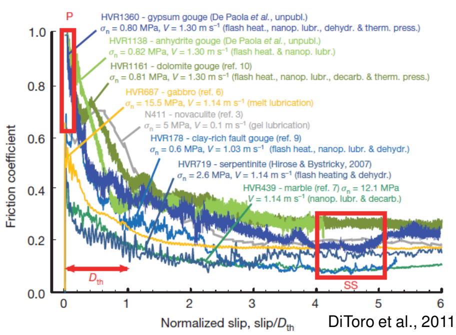


Snapshot of simulated wavefield (transverse acceleration, point source)

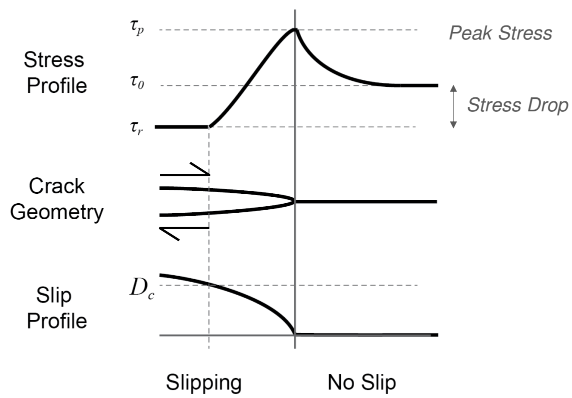
10

Earthquakes can propagate in low stress environments

- Faults start to slip when a part of the fault reaches failure stress (in the reservoir)
- Once coseismic slip starts, the fault weakens
- Faults may not reach their fully weakened state after the 1 cm of slip associated with a M 3 event



DiToro et al., 2011

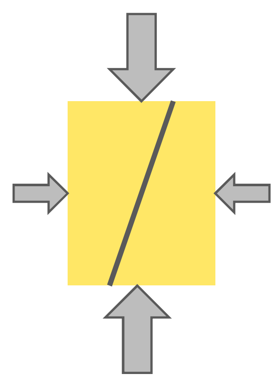


If there is a stress drop, rupture propagation is possible

Evaluate what scenarios have a stress drop

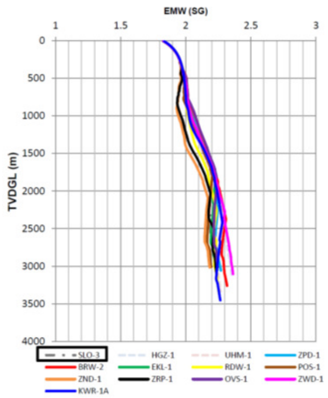
Estimate the likelihood of a rupture barrier

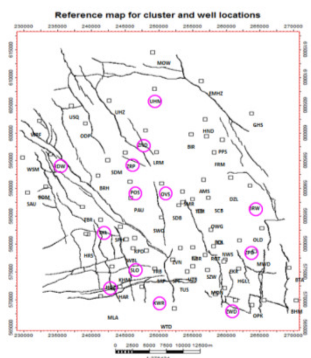
- Estimate the stress state variation and use a Monte-Carlo approach to evaluate the likelihood
- The vertical and horizontal stresses and the fault dip determine the background loading level on the fault (assume well oriented azimuth)
- The current stress state in the Carboniferous is assumed to be related (but not equal) to the initial stress state in the reservoir
- The horizontal stress should be higher in the Carboniferous due to these mechanisms/observations:
  - **Sand-shale contrast** – Horizontal stresses are generally higher in shales (Carboniferous) than in sands (the reservoir)
  - **Elevated Carboniferous measurements** – Higher horizontal stresses were measured in a Carboniferous sand 40 km to the south
  - **Stress-arching** – Reservoir contraction due to depletion can increase the horizontal stress above and below the reservoir
  - **Coal** – Coals can alter the stress state and the Carboniferous contains coal

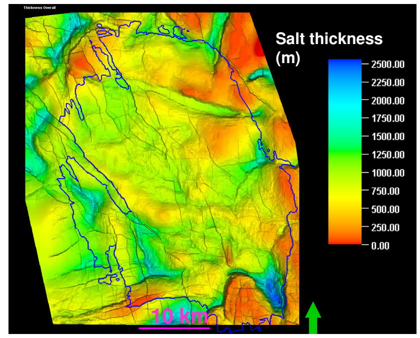


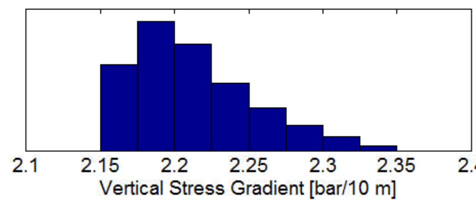
Vertical stress measurements and variation

- There is variability in the vertical stress gradient throughout the field due to sediment and salt thickness variations
- Vertical stress gradient ranges from 2.15-2.33 bar/10m

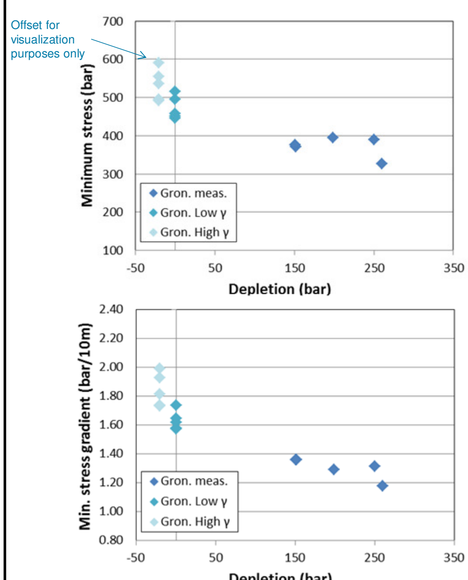








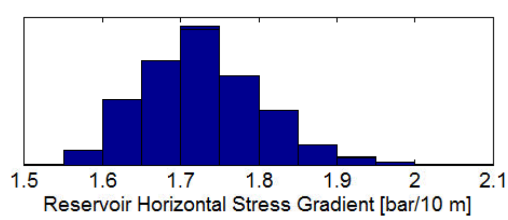
Estimate original horizontal stress state in the reservoir



- There are no reliable stress measurements of the original horizontal stress state in the Groningen reservoir
- Stress estimates made at 150+ bars of depletion are extrapolated back to virgin conditions with an assumption of the depletion constant, γ of 0.5-0.8

$$\gamma = \frac{dS_h}{dP_p} = \alpha\frac{1-2\nu}{1-\nu} \qquad \alpha = 0.7 \;\&\; \nu = 0.2 \;\Rightarrow \gamma = 0.52$$

$\gamma = 0.6 - 0.75$ measured in lab



Relative horizontal stress increase in Carboniferous

Sand-shale contrast

Blija field (65 km West)
2.0 – 5.0 MPa stress contrast
@ ~2750 m depth

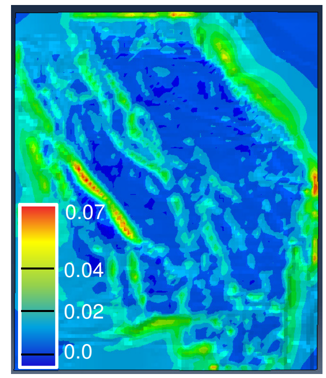
0.07 – 0.18 bar/10m increase

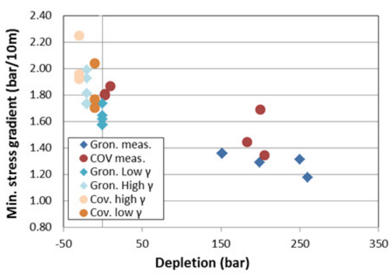
Coevorden (50 km South)
5.0 – 7.5 MPa stress contrast
@ 2825 m depth

0.18 – 0.27 bar/10m increase

Stress Arching

Most areas have a stress increase of 0-1.3 MPa (**0-0.03 bar/10m**)





Carboniferous measurements

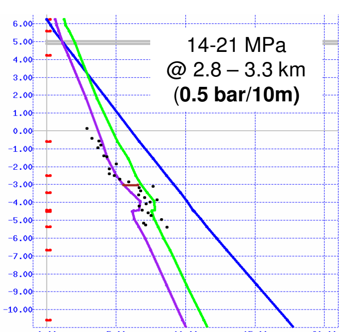
- A few Carboniferous stress measurements imply a virgin stress state higher than Groningen
- The difference is ~**0.15 bar/10 m**

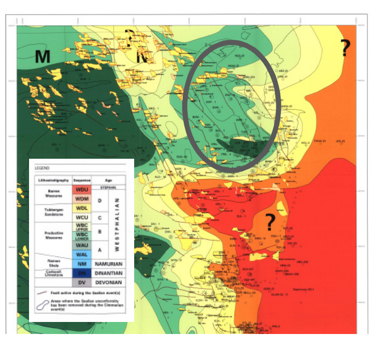
Relative horizontal stress increase in Carboniferous

Coal Rich Interval

~0.05 bar/10m

- The Rotliegend is in contact with a coal-bearing Carboniferous interval (WBCL) (~3-5% coal)
- Experience in Piceance (~25% coal) suggests high horizontal stresses in coal rich intervals





Sand-shale contrast

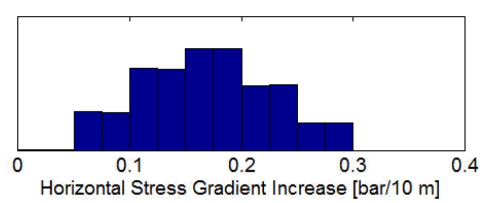
0.07-0.27 bar/10 m

Carboniferous measurements

~0.15 bar/10 m

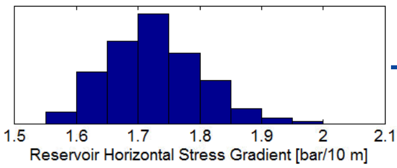
Stress Arching

0-0.03 bar/10m



Assumed input distributions to capture the uncertainty

Realizations drawn from these parameter distributions determine if there is potential for a stress drop in the Carboniferous



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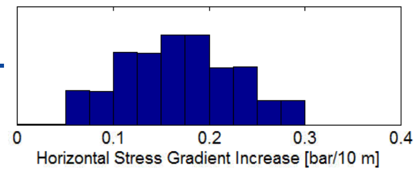

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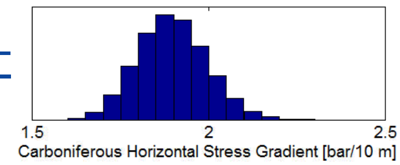

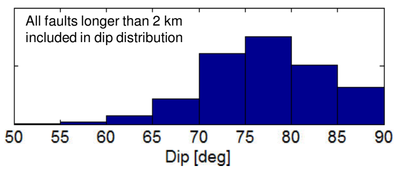

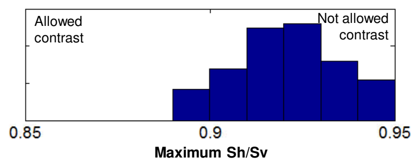

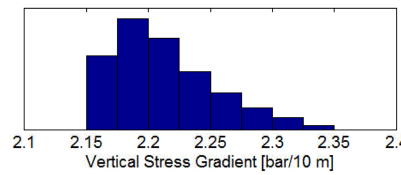

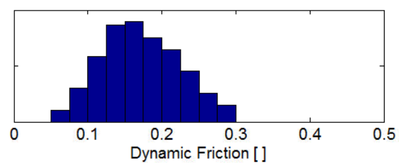

Some scenarios would result in reverse faulting, so remove scenarios with a horizontal/vertical stress ratio greater than 0.89-0.95

Assumed pore pressure gradient of 1.17 bar/10m

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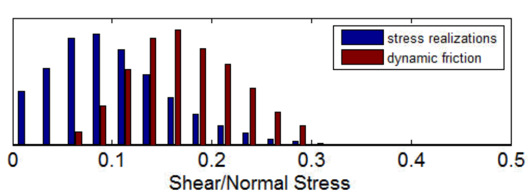
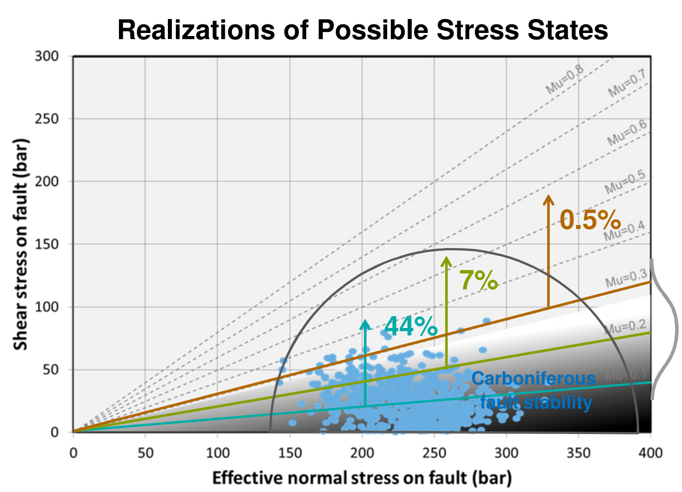
Most realizations cannot sustain rupture

- Rupture could propagate if Carboniferous background shear stress state is above the threshold for dynamic rupture
- Given the uncertainty in dynamic friction:
  - 18% of realizations have a stress drop > 0 MPa
  - 13% could host a stress drop > 0.5 MPa
  - 1% could host a stress drop > 3 MPa
  - 0% could host a stress drop > 10 MPa

  (Assume 3.5 km depth for stress drop calculations)





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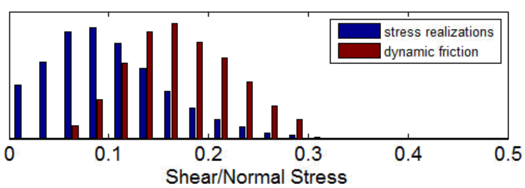

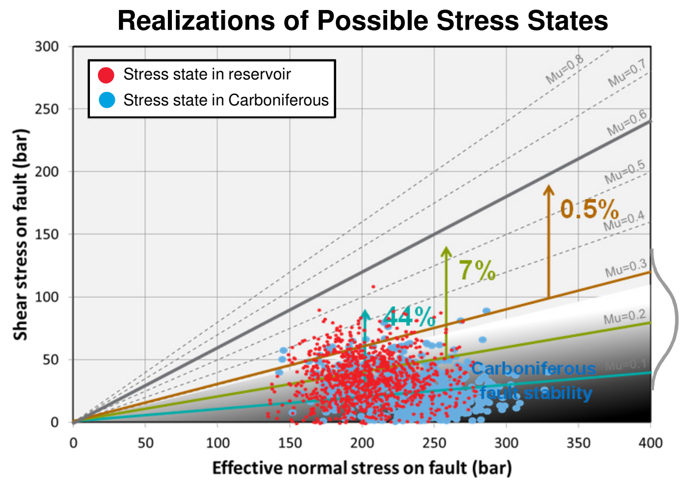

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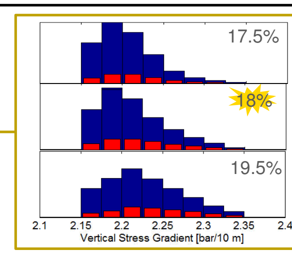
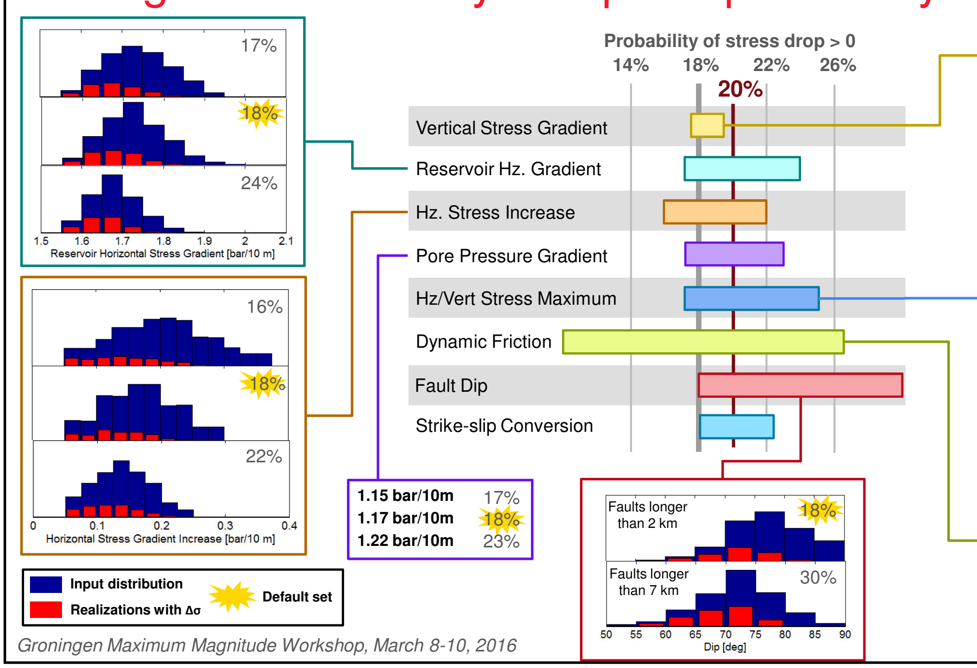
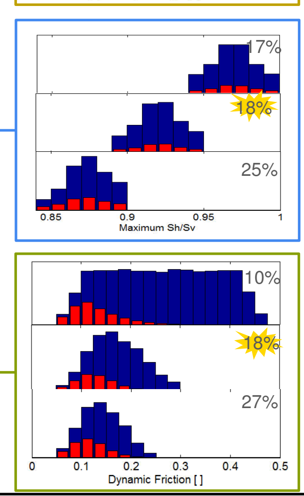
Range of uncertainty in rupture probability







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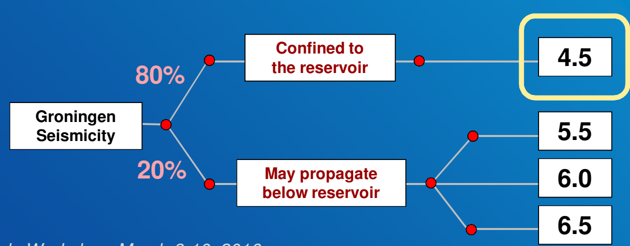
Summary of out of reservoir likelihood

- Earthquakes are nucleated in the reservoir due to the depletion-induced stress changes
  - Once nucleated, ruptures can propagate into lower loading environments
  - However, the stress state below the reservoir may be too low to sustain rupture
- The uncertainty in the stress state leads to ~20% of realizations that have the potential to allow out of reservoir rupture propagation
  - This probability could be lower because the degree of dynamic weakening reached after the slip associated with a M 3-4 event may not reach the 0.1-0.3 range
- Observed earthquake catalog is consistent with a **low truncation magnitude** Gutenberg-Richter



If a rupture is confined to the reservoir interval, how big could it be?

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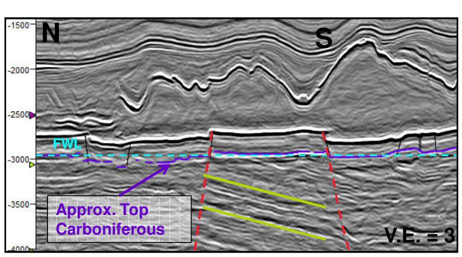
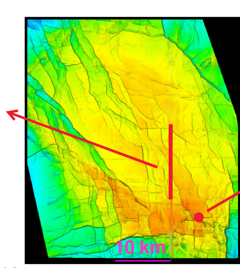
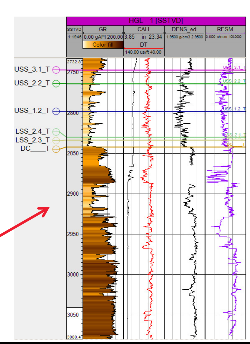
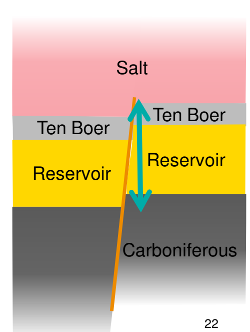
Down-dip extent of a reservoir confined rupture

- The down-dip dimension of a rupture is likely larger than the reservoir thickness
  - Even if rupture cannot be sustained in the Carboniferous, a rupture will propagate some distance before losing energy and stopping
  - Thickness + offset may be relevant
  - Isolated depleted sands exist in the Carboniferous that can increase the effective reservoir thickness
- Assume a down-dip rupture dimension of 350 m









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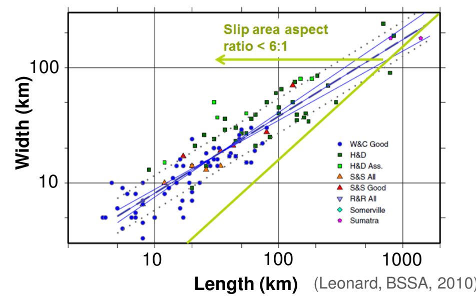
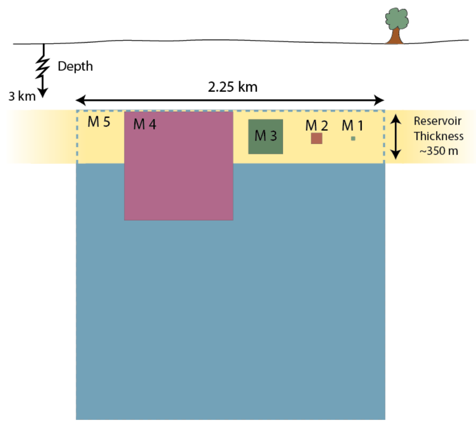
A range of earthquake magnitudes are reservoir confined events

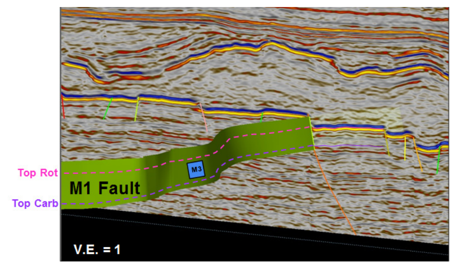
- Magnitude 1 – 3 events are easily contained within the reservoir
- Magnitude 3.5 – 4.5 events could either be confined to the reservoir or propagate out
- Magnitude 5+ events would have to propagate out of the reservoir



(Leonard, BSSA, 2010)

Slip area aspect ratios > 6:1 are not consistent with dip-slip observations





All earthquakes observed could be reservoir confined events

- For a rectangular fault, stress drop and magnitude can be related by

$$\Delta\sigma = \left(\frac{8}{3\pi}\right) * \left(\frac{G\ d}{w}\right) = \left(\frac{8}{3\pi}\right) * \left(\frac{M_o}{A\ w}\right)$$

- The down-dip dimension, w, controls the amount of slip, d

Earthquake Magnitude, M_w

Ribbon-like ruptures
Aspect ratio > 6:1

$\Delta\sigma$ / length	250 m	500 m	1 km	2 km	5 km	10 km	25 km
0.1 MPa	2.3	2.5	2.7	2.9	3.2	3.4	3.6
1.0 MPa	3.0	3.2	3.4	3.6	3.8	4.0	4.3
(bf) 3.0 MPa	3.3	3.5	3.7	3.9	4.2	4.4	4.6
10 MPa	3.6	3.8	4.0	4.2	4.5	4.7	5.0

M <= 3.0
3.0 < M < 3.6
M >= 3.6

The M 3.6 Huizinge event can be a reservoir confined event

350 m down-dip fault dimension assumed
Magnitude determination not dependent on shear modulus assumption

Unlikely Scenarios

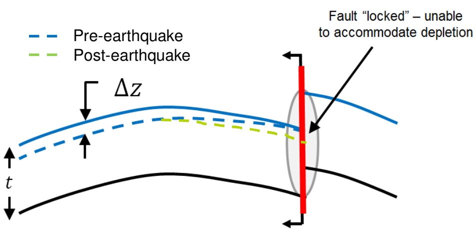
As depletion increases the compaction and slip increase

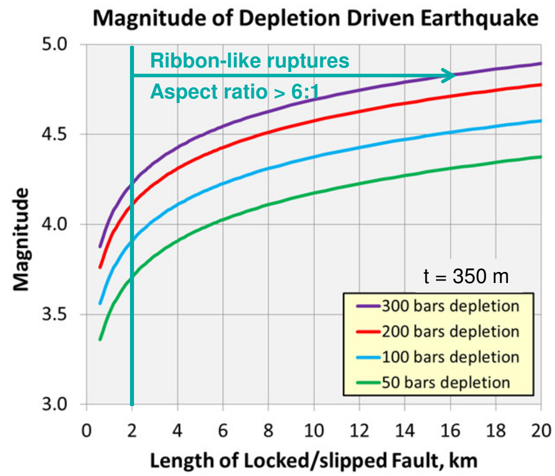
- Magnitude estimates can be made from a simple model relating depletion to compaction, equating compaction to average slip, and assuming a fault area
- At any given level of depletion, Δp, the compaction, Δz, depends on the material properties

$$\Delta z = t\frac{\Delta p}{2G}\left(\frac{1-2\nu}{1-\nu}\right)$$

- From Δz, and fault area, $t{*}L$, the maximum moment is:

$$M_o = G\cdot(tL)\cdot t\frac{\Delta p}{2G}\left(\frac{1-2\nu}{1-\nu}\right) = t^2 L\,\frac{\Delta p}{2}\left(\frac{1-2\nu}{1-\nu}\right)$$



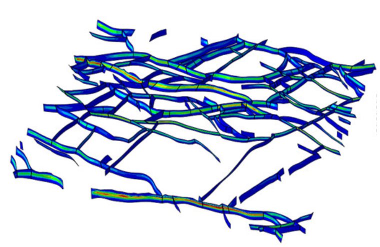


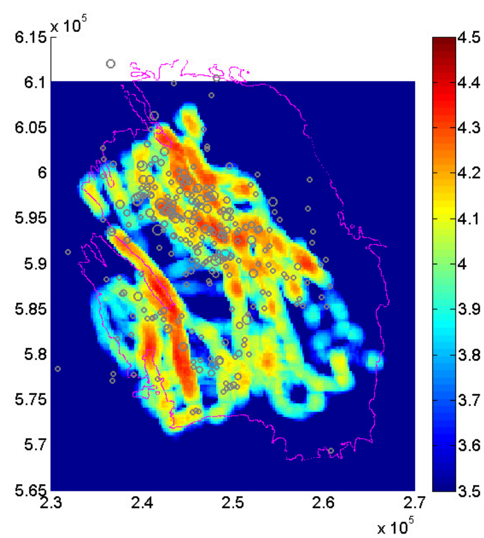
These numbers are consistent with the estimate made from the stress drop and magnitude scaling relationship

Local moment release in 3D geomechanical model

- Quasi-static model allows fault slip to evolve as a result of depletion induced stress changes and Coulomb friction
  - ~90% of mapped faults are included
  - Slip is mostly confined to the reservoir
  - Does not include dynamic effects (slip area and total slip can be larger than statically determined values)
- 3D model imposes pore pressure changes in a global model with embedded faulted submodels and porosity (location) dependent moduli
- Consider ruptures with an aspect ratio less than 6:1 by examining the moment release in a 2 km diameter circle
- If all slip accumulated by 2060 is released in one event, the maximum magnitude is 4.5 for a conservative model case
  - Conservative model uses a coefficient of friction of 0.15, a shear modulus of 20 GPa and includes slip that occurs prior to the observed onset of seismicity

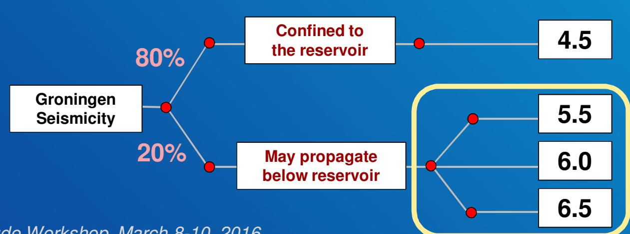
Fault slip in one of three submodels





Summary of reservoir confined events

- All events and observations to date are consistent with earthquakes that are confined to the reservoir interval
- Fault scaling relations estimate **M < 4.3** (6:1 aspect ratio implies L < 2 km)
- Limiting slip to the compaction magnitude bounds the magnitude to **M < 4.3** (L < 2 km)
- 3D geomechanical model estimates **M 4.5** as an upper bound (L < 2 km)
- Multiple lines of reasoning indicate a **Mmax = 4.5** is applicable



If a rupture is <u>not</u> confined to the reservoir interval, how big could it be and what are the weights?

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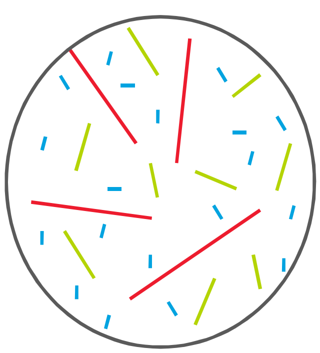
Representation in the logic tree framework

Reality



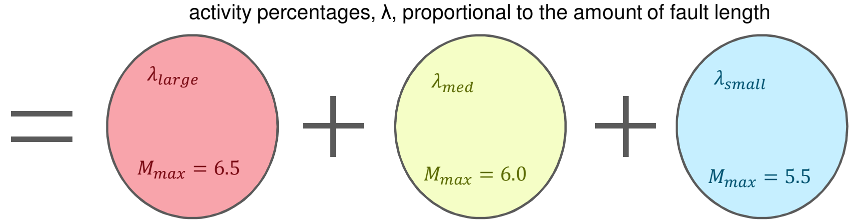
Long faults are capable of larger events than short faults

M < 6.5
M < 6.0
M < 5.5

Implementation

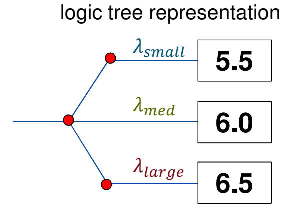
Current Groningen PSHA implementation is not fault based, but area based

Reality should be represented with area sources with different Mmax and activity percentages, λ, proportional to the amount of fault length



Representation

This is mathematically equivalent to a logic tree representation



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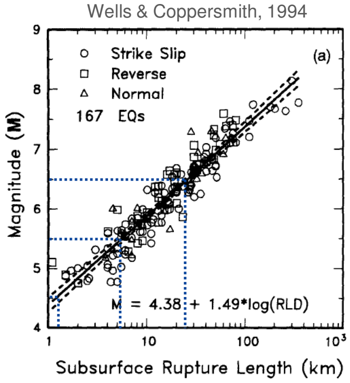
If an entire fault ruptured, larger magnitude events are possible

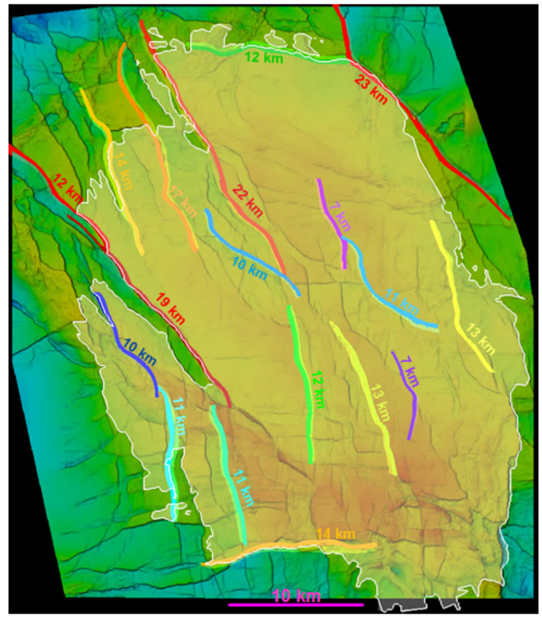
- ~88% of mapped faults are < 5 km
- Multiple fault segments would have to rupture for the entire length of the reservoir to rupture in one event

Wells & Coppersmith, 1994



Tectonic earthquakes of 25 km long rupture length are capable of a magnitude 6.5

10 km rupture lengths can host a magnitude 6.0



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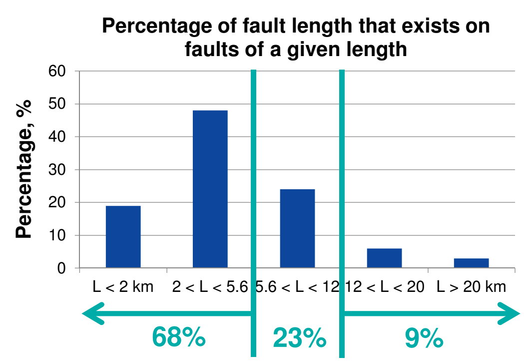
Size of out-of-reservoir events from fault length relations

- Using the Wells & Coppersmith best-fit correlation for normal faulting events
  - The longest fault (23 km) is capable of a M 6.4
  - Faults > 12 km are capable of M > 6.0
  - Faults < 5.6 km can only produce a M 5.5
- The percentage of earthquakes that start on a large fault equals the percentage of fault length that exists on long fault structures
  - 68% of fault length is on faults < 5.6 km (Mmax = 5.5)
  - 9% of fault length is on faults > 12 km (Mmax = 6.5)
  - 23% of fault length is intermediate length (Mmax = 6.0)



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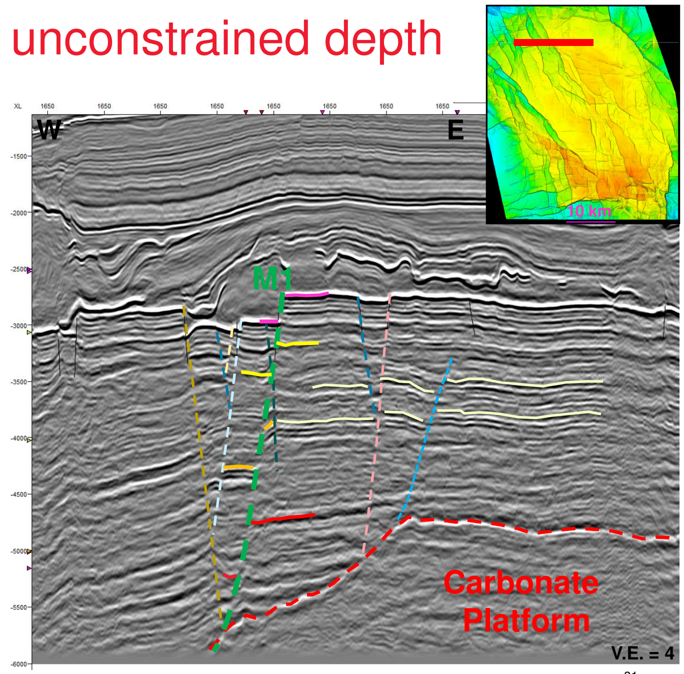
Some faults continue to an unconstrained depth

- For large earthquakes to occur, faults must rupture to a great depth
- Depth extent of largest Groningen faults is > 3 km
- If the seismogenic zone reaches a depth of 10 km, then 7 km is a maximum fault depth extent, making the down-dip dimension 8 km



Size of out-of-reservoir events from fault area relations

Earthquake Magnitude, M_w

3 km down-dip extent

$\Delta\sigma$ / *length*	2 km	5 km	10 km	25 km
0.1 MPa	4.2	4.4	4.6	4.9
1.0 MPa	4.8	5.1	5.3	5.6
(bf) 3.0 MPa	5.1	5.4	5.6	5.9
10 MPa	5.5	5.8	6.0	6.2

8 km down-dip extent

$\Delta\sigma$ / *length*	2 km	5 km	10 km	25 km
0.1 MPa	4.7	5.0	5.2	5.5
1.0 MPa	5.4	5.7	5.9	6.1
(bf) 3.0 MPa	5.7	6.0	6.2	6.4
10 MPa	6.1	6.3	6.5	6.8

Unlikely Scenarios

$M < 4.5$ | $4.5 \le M < 5.0$ | $5.0 \le M < 5.5$ | $5.5 \le M < 6.0$ | $6.0 \le M < 6.5$ | $M \ge 6.5$

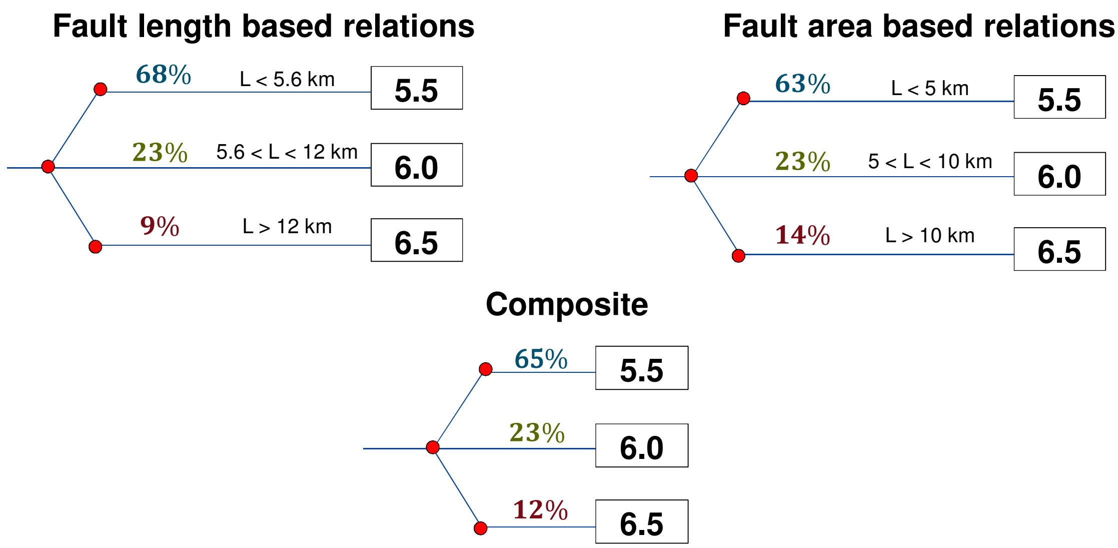
$$\Delta\sigma = \left(\frac{8}{3\pi}\right) * \left(\frac{G\ d}{w}\right) = \left(\frac{8}{3\pi}\right) * \left(\frac{M_o}{A\ w}\right)$$

- The stress-state in the Carboniferous is uncertain and the state of stress below that (~6 km depth) is less constrained
- With uncertainties, at 8 km depth:
  - 73% have 1 MPa
  - 36% have 3 MPa
  - 2.5% have 10 MPa

Percentage of realizations with a stress drop >0

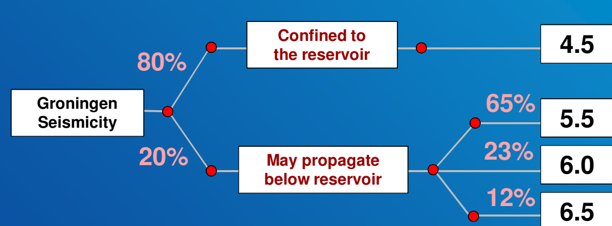
- Faults ≤ 5 km only capable of M < 5.5 (**63**%)
- Faults > 10 km are capable of M > 6.0 (M_{max} = 6.5) (**14**%)
- Intermediate length faults, M_{max} = 6.0 (**23**%)

Representation in the logic tree framework

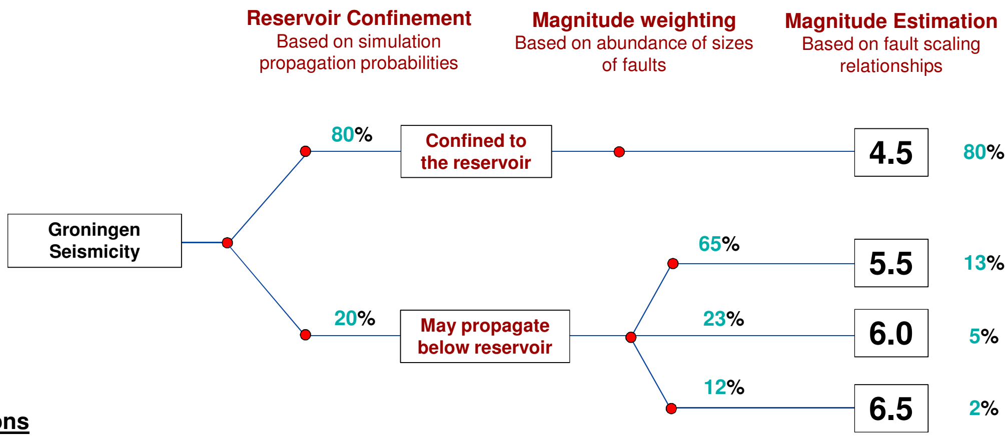


Summary of out of reservoir event magnitude

- The fault length and area scaling relationships limit the field wide maximum magnitude to M 6.5
- Some faults could produce M ≥ 6.0 events but most faults are too short and could not host an event larger than M 5.5
- Logic tree weights are determined from the percentage of fault length on a given fault size (this can represent the hazard for a distributed source representation of faults of varying sizes)



Conclusion: Logic Tree Implementation



Assumptions

Multi-segment ruptures are not likely

Earthquakes nucleate within the reservoir

Rupture area aspect ratios > 6:1 are unlikely

Very small stress drops ($\Delta\sigma < 0.1$ MPa) could sustain rupture propagation

Stress state on faults in Carboniferous is the same as the bulk stress state (no heterogeneity or stress rotation near faults) 35

Groningen Maximum Magnitude Workshop, March 8-10, 2016

Day 1 Panel Questions and Day 2 Areas of Focus

- Anisotropy of the stress field; how much variability in the Sh (minimum horizontal stress); important for the potential for fault reactivation
- Want to look more closely at the focal mechanisms: Is the whole field in an extensional stress state?
- Have any calculations been made of stress drop?
- Will be watching closely the issue of events occurring outside of the reservoir horizon; can they propagate outside (down or laterally)
- Can these faults be traced down into the basement?
- What is the evidence for Quaternary faulting in the region?
- Where are the holes where waste water was injected; depth and volume; is there some likelihood that the injection will be done in the field?
- In discussions of Mmax, what is the time period for which the estimates are appropriate?

Day 3 Panel Questions and Areas of Focus

- Day 2 was very informative and we appreciate the attention by all speakers to the topics of importance to the Panel's assessments
- Is there any direct evidence of ruptures/earthquakes occurring outside of the reservoir?
- Dynamic modeling that has the loading occur at the reservoir; loading is usually from below in tectonic processes; we do see pore pressure effects migrating downward in other places, but not the rupture per se
- In discussions of analogs, we are interested in injection versus depletion; is there a separation in the size of earthquakes?
- Are there significant faults within 5 km buffer of the field?
- Please continue to focus on the technical bases and uncertainties in your estimates of Mmax

Groningen Induced Seismic Hazard and Risk Assessment Project

Workshop on Maximum Magnitudes for the Groningen Field

Time: 8th to 10th March 2016

Location: World Trade Centre, Schiphol Airport, Amsterdam

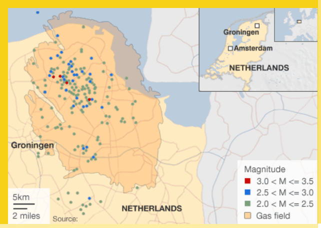
Agenda: Day 3 (Thursday 10th March 2016)

Start	End	Topic	Speaker
08:30	09:00	*Coffee*	
09:00	10:00	Re-cap of Days 1 and 2	Kevin Coppersmith
10:00	11:00	Mmax distribution for Groningen	Stephen Bourne
11:00	11:15	*Coffee*	
11:15	12:15	Mmax distribution for Groningen	Gert Zöller / M. Holschneider
12:15	13:15	*Lunch*	
13:15	14:15	TNO Mmax models for Groningen	Steve Oates*
14:15	15:15	Mmax distribution for Groningen	Jenny Suckale
15:15	15:30	*Coffee*	
15:30	16:30	Mmax distribution for Groningen	Rick Wentinck / Peter van den B.
16:30	17:30	General discussion	All participants
17:30	18:00	Comments from observers	SAC /SodM
18:00	18:30	Closing comments from expert panel	Kevin Coppersmith

* The TNO reports will be summarised by Dr Steve Oates because authors of TNO report declined to present

Groningen seismicity must have a maximum magnitude

Some constraints and uncertainties in our current knowledge



Stephen Bourne, Chris Harris, Philip Jonathan

Workshop on Maximum Magnitude Estimates for Probabilistic Seismic Hazard and Risk Modelling in Groningen Gas Field

8-10 March 2016, World Trade Centre, Schiphol Airport, Amsterdam, NL

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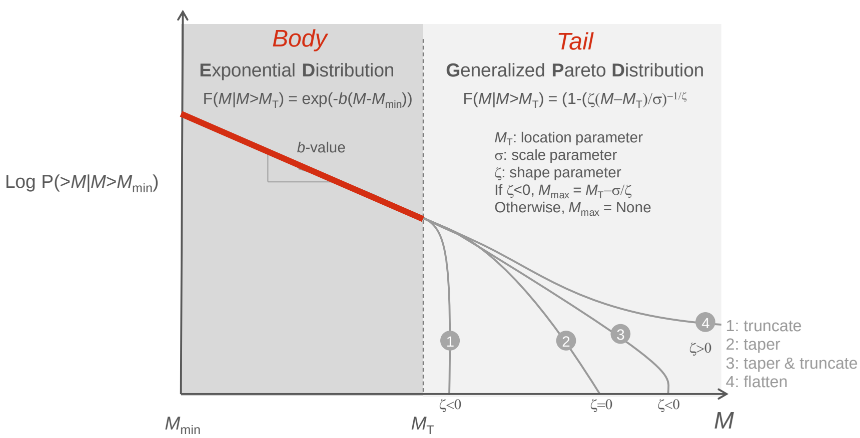
Why only maximum magnitude?

- The *body* and the *tail* of the frequency-magnitude distribution matter
- The *tail* is not necessarily defined by M_{max}
- From Extreme Value Theory, the tail of any distribution is a GPD



Sources of empirical evidence to assess the tail

- Observed frequency-magnitude distributions
  - Local events
  - Global SCR events
- Observed fault-slip geometry scaling with magnitude
  - Global empirical scaling law & local reservoir fault geometries
  - Global empirical scaling law & local basement fault geometries
- Observed maximum magnitude scaling with finite strain
  - Kostrov seismic strains and maximum induced reservoir strain
  - Global empirical scaling law & local basement strain rate
- Prior work
  - SHARE European seismic hazard assessment
  - Klose global empirical scaling with mass shift

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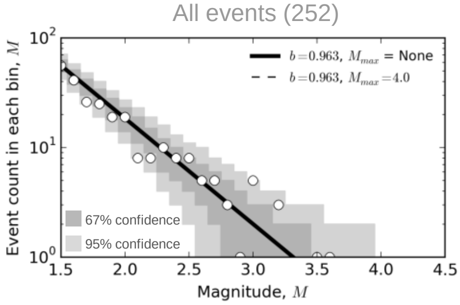
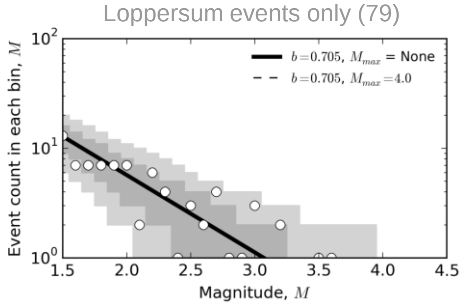
Observed frequency magnitude distributions

- Analyzed all 252 $M \geq 1.5$ events between 1 April 1995 & 1 September 2015
- Apparent under-representation of larger events is not statistically significant
- Same conclusion for the Loppersum sub-region

All events (252)



Loppersum events only (79)



Loppersum sub-region: 5 km radius from 244000, 598000

Conclusion: No simple direct evidence of M_{max}

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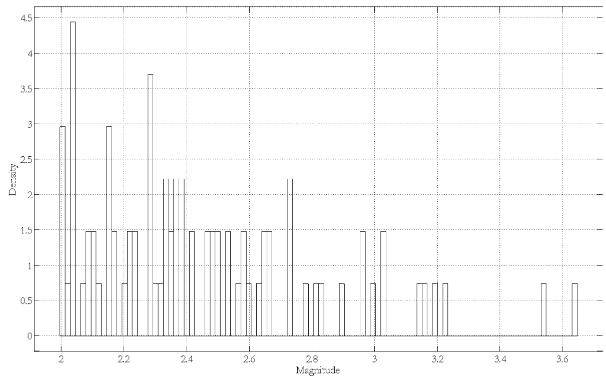
Extreme value analysis

- Sample histogram: Exceedance threshold: $M = 2$
- Data are binned at 0.1
- One realization of a perturbation distribution Uniform(-0.05, 0.05)
- Analysis based on aggregate of 100 realizations of this perturbation



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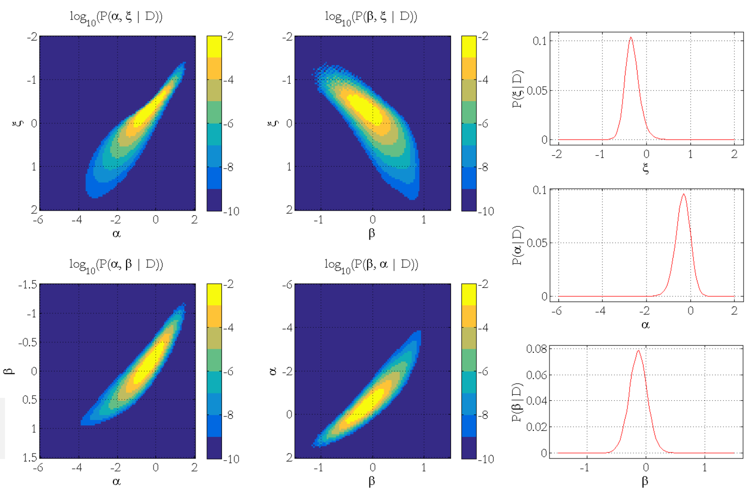
Extreme value analysis

- 2-parameter model posterior distributions: Exceedance threshold: $M = 2$
- GP model with shape ζ, scale exp(α), given data D

Issue of measurement scale



Posterior for U=2.0. Posterior predictive 1000-year event = 4.1. Probability of finite upper end point = 0.95.

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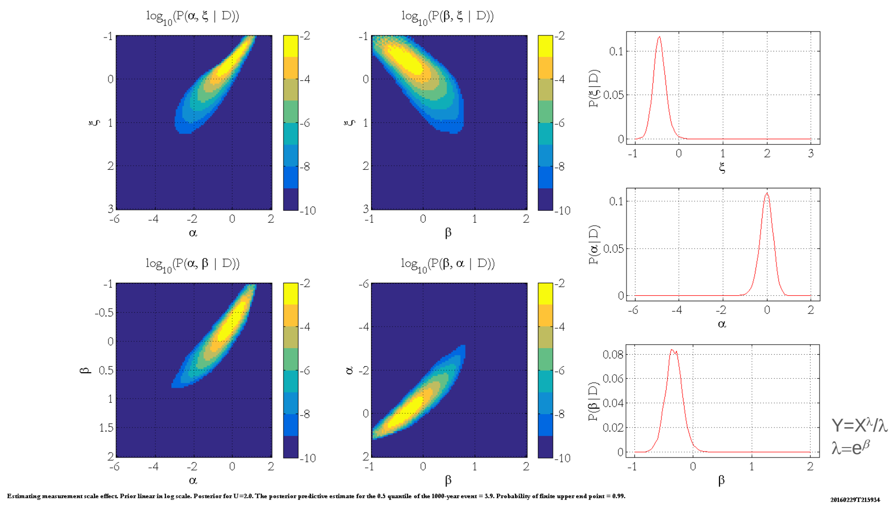
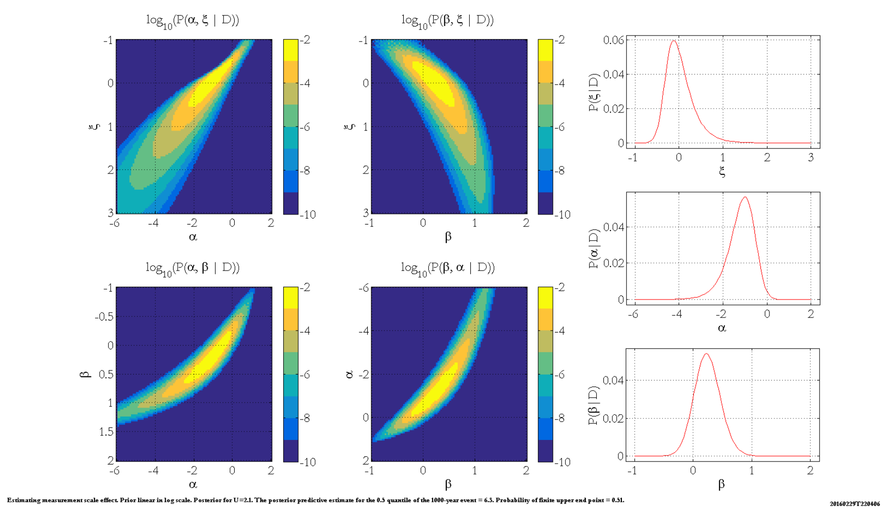
Extreme value analysis

- 3-parameter model posterior distributions: Exceedance threshold: $M = 2$
- GP model with shape ζ, scale exp(α), measurement scale exp(β) given data D



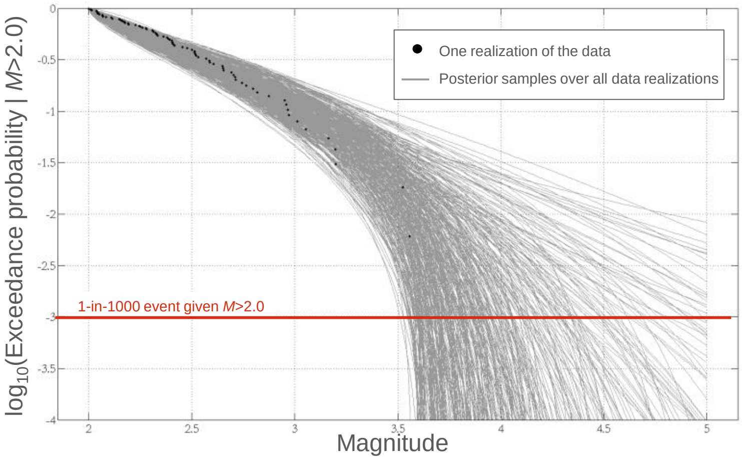
Extreme value analysis:

- Posterior distributions: Exceedance threshold: $M = 2.1$



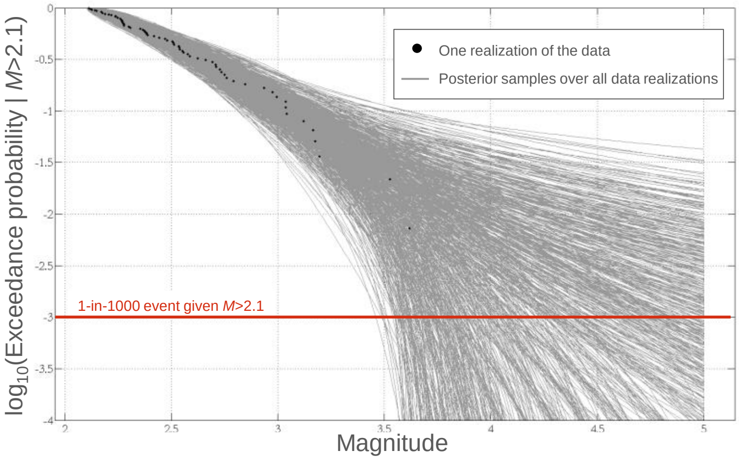
Extreme value analysis:

- Tail diagnostics, sampled from posterior: Exceedance threshold: M = 2.0
- Posterior predictive estimate, 1-in-1000 event given M>2: M = 5.9 (0.5 quantile)
- Probability of a finite upper end point: $p(M_{max})$ = 0.99



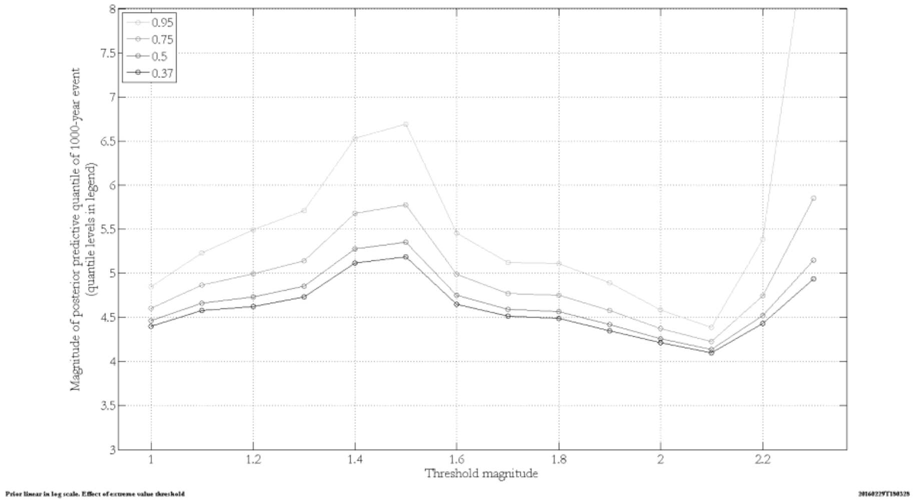
Extreme value analysis:

- Tail diagnostics, sampled from posterior: Exceedance threshold: M = 2.1
- Posterior predictive estimate, 1-in-1000 event given M>2.1: M = 6.3 (0.5 quantile)
- Probability of a finite upper end point: $p(M_{max})$ = 0.51



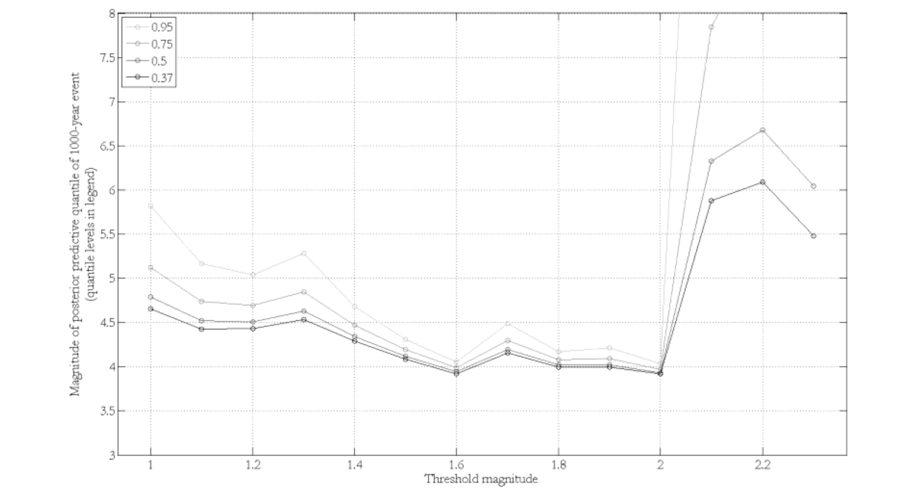
Extreme value analysis

- Effect of threshold magnitude on posterior estimates for 2-parameter model
- Magnitude of the 1-in-1000 event



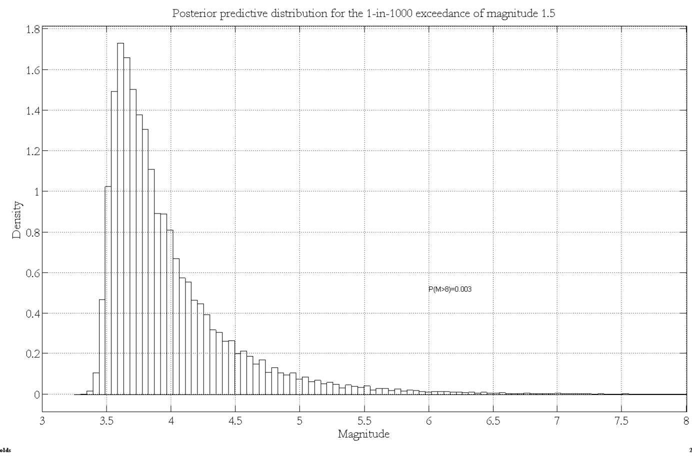
Extreme value analysis

- Effect of threshold magnitude on posterior estimates for 3-parameter model
- Magnitude of the 1-in-1000 event



Extreme value analysis

- Ensemble for all thresholds for both the 2- and 3-parameter models
- Posterior magnitude distribution for P(>*M* | *M* ≥ 1.5) =10^{-3}
- Magnitude of the 1-in-10^3 event



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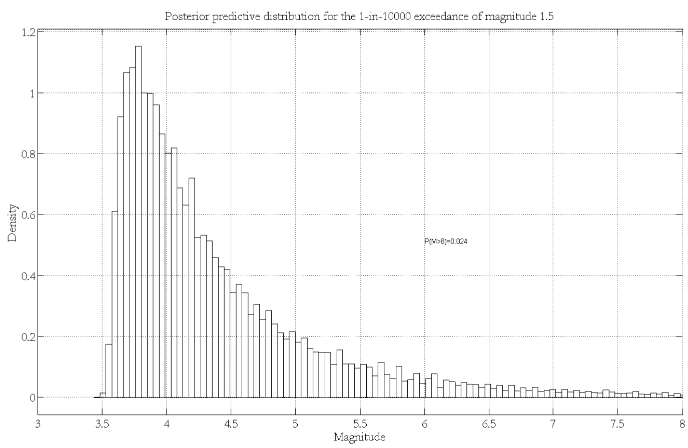
Extreme value analysis

- Ensemble for all thresholds for both the 2- and 3-parameter models
- Posterior magnitude distribution for P(>*M* | *M* ≥ 1.5) =10^{-4}
- Magnitude of the 1-in-10^4 event



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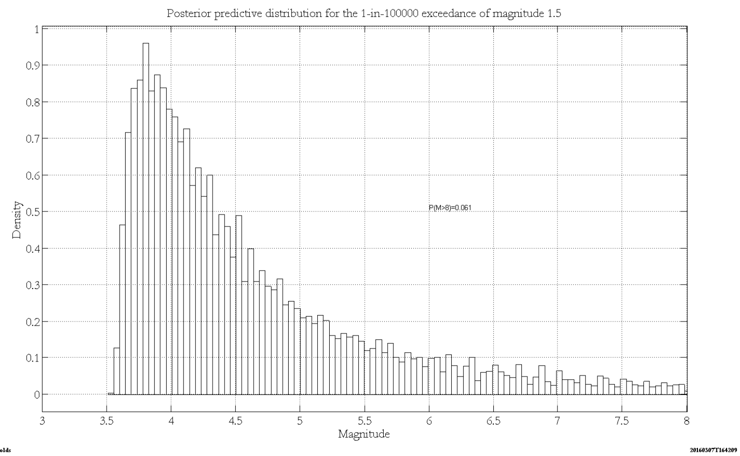
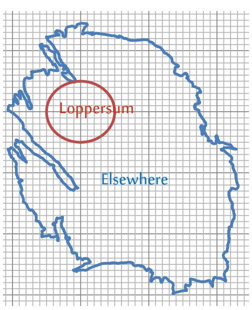
Extreme value analysis

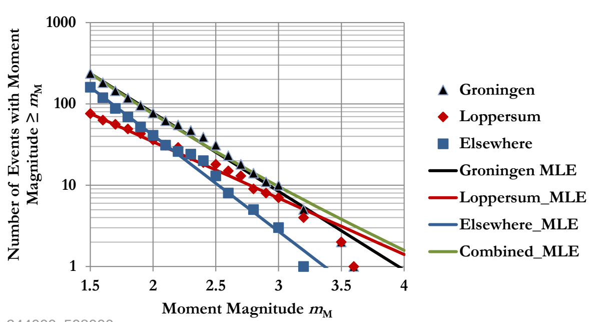
- Ensemble for all thresholds for both the 2- and 3-parameter models
- Posterior magnitude distribution for P(>*M* | *M* ≥ 1.5) =10^{-5}
- Magnitude of the 1-in-10^5 event



A mixed distribution: Spatial variation of *b*-value

- Analyzed all 236 *M* ≥ 1.5 events between 1 May 1995 & 31 December 2014
- *b*-value estimates:
  - Scenario 1: Single *b*-value b_G = 0.966
  - Scenario 2: Loppersum b_L = 0.693, elsewhere b_E =1.181





Loppersum sub-region: 5 km radius from 244000, 598000

Conclusion: Observed seismicity has mixed *b*-value distributions

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A mixed distribution: Spatial variation of *b*-value

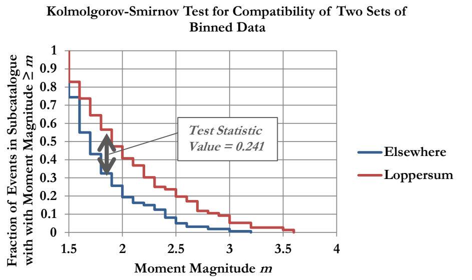
Test the hypothesis that the observed frequency versus moment magnitudes relations for the two regions arise from the same underlying distribution.

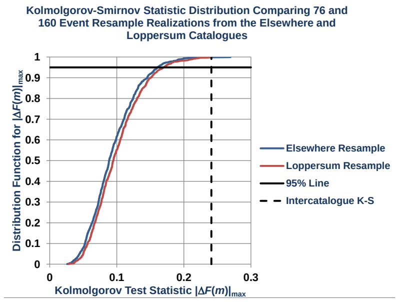
No underlying model was assumed for the distribution

- The test used was a variant of the Komolgorov-Smirnov test for binned data
- The distribution of the test statistic was computed from pairs of resampled intra-catalogue realizations using the Elsewhere and Loppersum catalogues
- One member of each pair contained 76 events and the other 160 events
- 1000 pairs of realizations were used for each resampled catalogue

Results

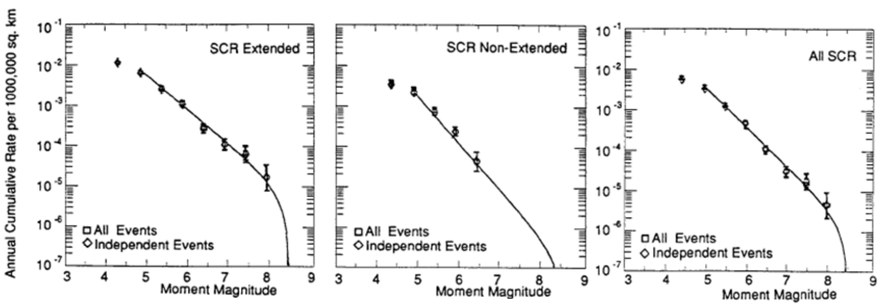
- The number of realizations (out of 1000) for which the K-S statistic was greater than the observed one was one for the Elsewhere catalogue and none for the Loppersum catalogue
- Hence we can conclude with a high level of significance that the frequency versus moment magnitude distributions underlying the seismicity in the Loppersum and Elsewhere regions are different





Stable Continental Regions: No observation of M_{max}

- Johnston *et al* 1994
- Observed *F-M* distribution within SCRs
- No observed truncation, only information is $M_{max} > \max(M_{obs})$



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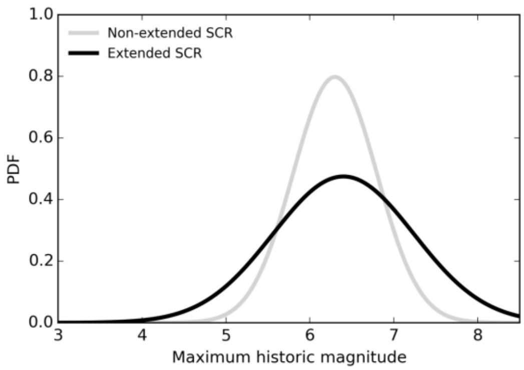
Stable Continental Regions: Max(M_{obs}) distribution

- Johnston *et al* 1994
- Distribution of max(M_{obs}) across all SCRs
  - Non-extended SCR: Normal(6.3, 0.5)
  - Extended SCR: Normal(6.4, 0.84)

Outcome sensitive to choice of each SCR and correction for differing sample sizes



M_{max} > max(M_{obs})

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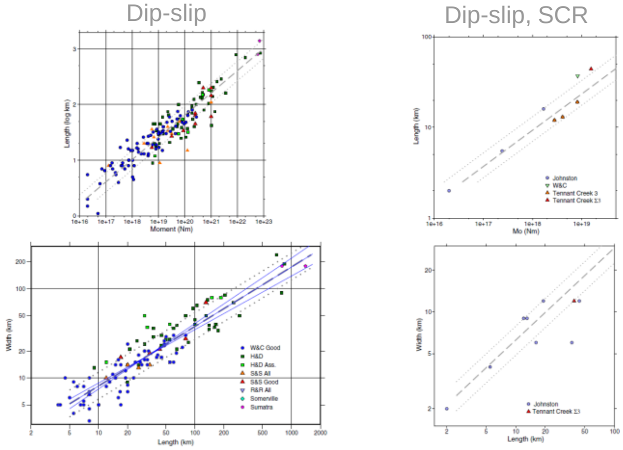
Unified earthquake scaling relationships

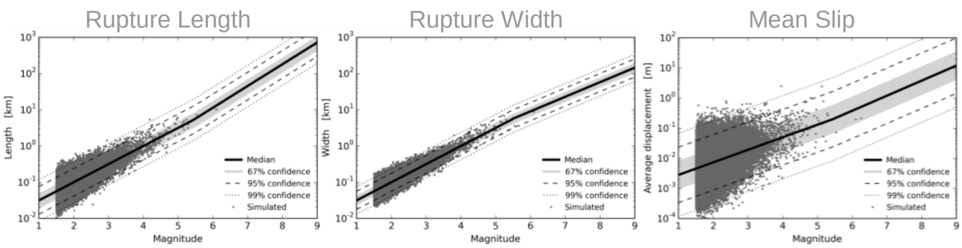
- Leonard (BSSA, 2010) for dip-slip events
  - Scaling relations inferred from global catalogue
  - Self-consistent for length, *L*, width, *W*, and slip, *D*
  - Intra-plate: *L*>5.5 km, SCR: *L*>2.5 km
  - Normal error model estimated; no evidence of truncation in Normal scatter

Dip-slip | Dip-slip, SCR



Unified earthquake scaling relationships

- Leonard (BSSA, 2010) for dip-slip events
- Reformulate as a Finite Rupture Prediction Equation, FRPE
  - Length: $\log L = F_L(M) + \varepsilon_L\ \sigma_L$
  - Width: $\log W = F_W(M) + \varepsilon_W\ \sigma_W$
  - Slip: $\log D = F_D(M) + \varepsilon_D\ \sigma_D$ where, ε is randomly sampled from Normal(0, 1)



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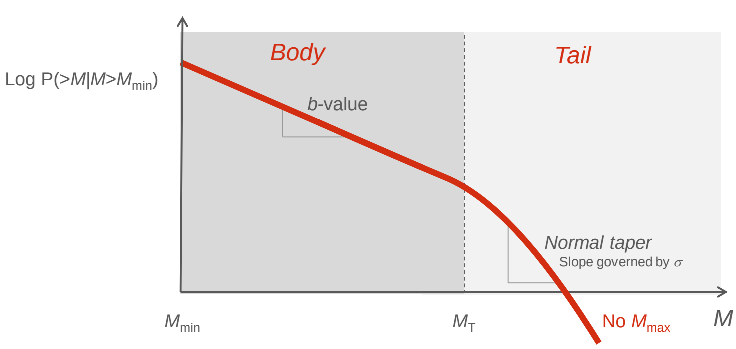
F-M distributions given upper bound on rupture geometry

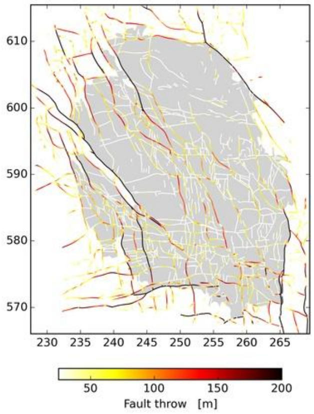
- Probability of exceeding *M* *and* not exceeding geometric upper bound
  - Length: $P(>M|M>M_{min})\ P(L<L_{max}) = \exp -b'(M-M_{min})\ (1-\Phi((\log L_{max} - F_L(M))/\sigma_L))$
  - Width: $P(>M|M>M_{min})\ P(W<W_{max}) = \exp -b'(M-M_{min})\ (1-\Phi((\log W_{max} - F_W(M))/\sigma_W))$
  - Slip: $P(>M|M>M_{min})\ P(D<D_{max}) = \exp -b'(M-M_{min})\ (1-\Phi((\log D_{max} - F_D(M))/\sigma_D))$

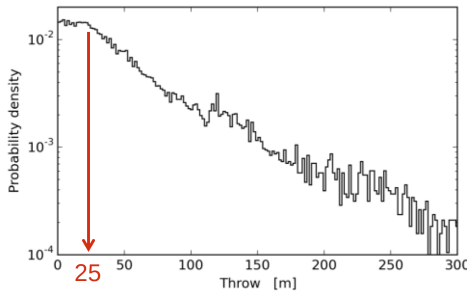
where Φ is the cumulative normal distribution



Mapped reservoir fault geometries

- Detailed, systematic interpretation of fault traces at *c.* top reservoir
- Power-law distribution of mapped fault throws
- Detection threshold = 25 m fault throw



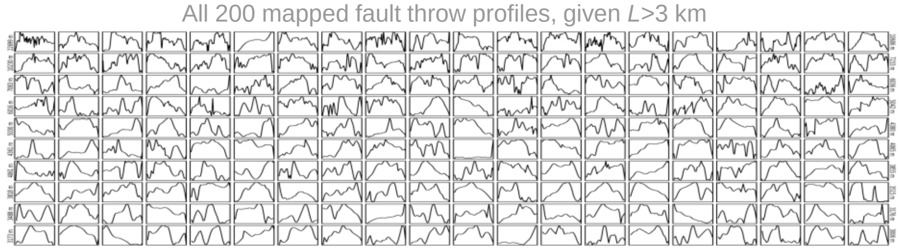


March 2016 23

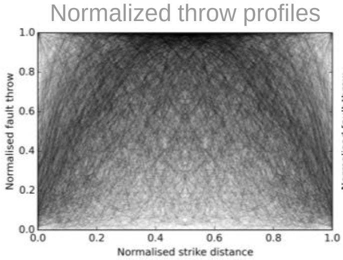
Mapped reservoir fault throw profiles

- Great variability, but typical profile is tapered towards tips
- True fault length > mapped fault length, *L*

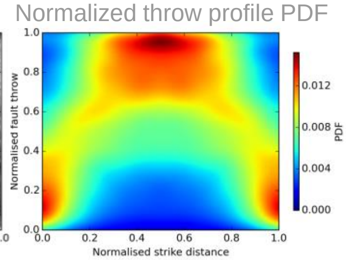
All 200 mapped fault throw profiles, given *L*>3 km

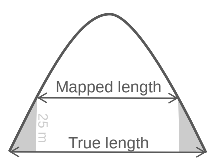


Normalized throw profiles



Normalized throw profile PDF

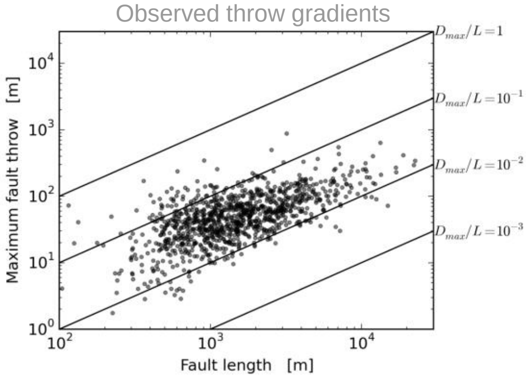




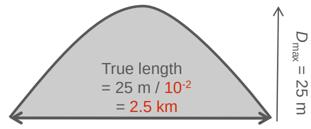
Unmapped reservoir faults

- Observed fault length–throw gradient: $D_{max}/L \sim 10^{-1}$ to 10^{-2}
- Largest faults are least biased by detection threshold: $D_{max}/L \sim 10^{-2}$
- Typical global scaling, Kim & Sanderson (2005): $D_{max}/L \sim 10^{-2}$

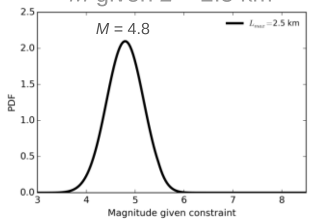
Observed throw gradients



Longest unmapped fault



M given *L* = 2.5 km



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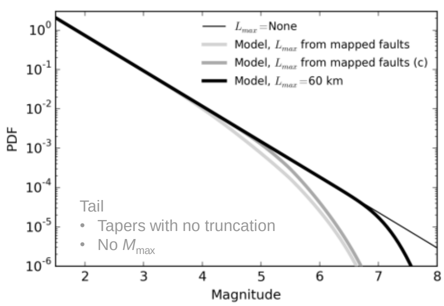
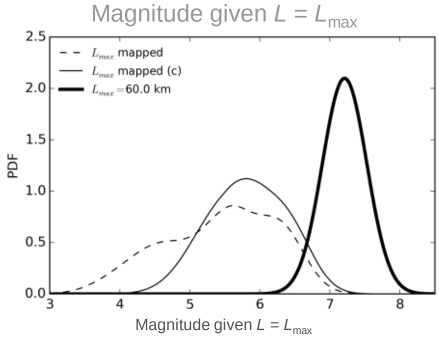
Finite reservoir fault length as constraint on tail

- Mapped fault lengths are under-estimates
- Approximately corrected mapped lengths by adding 2.5 km
- Existing unmapped fault connectivity is likely

Frequency-magnitude distribution



Magnitude given $L = L_{max}$



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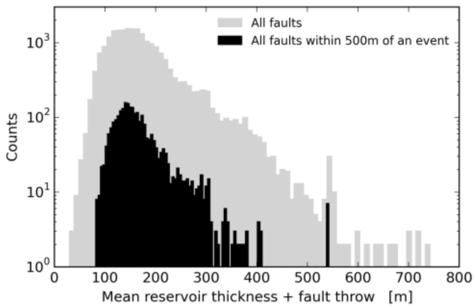
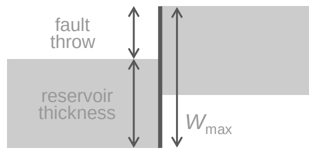
Intra-reservoir rupture height limits

- Maximum intra-reservoir rupture height, W_{max} = thickness + throw
- Modal value is 150 m
- Exponential-like distribution of W_{max} given W_{max} >150 m
- Distribution for seismogenic faults similar to distribution for all fault





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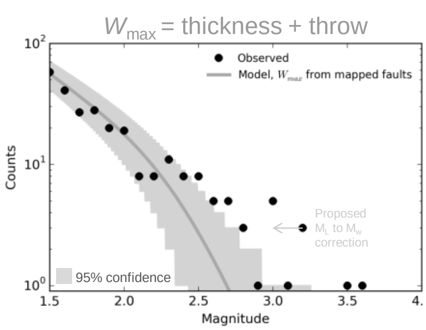
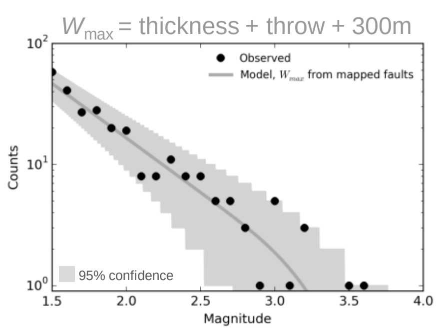
Finite reservoir fault height as constraint on tail?

- Use W_{max} distribution to construct a frequency-magnitude curve
- Relative abundance of M>3 Groningen events implies either
  - M>3 events are likely to rupture below the reservoir, or
  - Groningen events are special and do not scale like global events



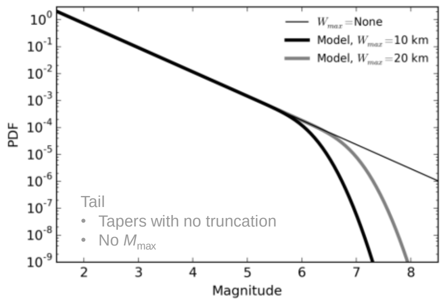


Conclusion: No reliable evidence that ruptures are always contained inside the reservoir

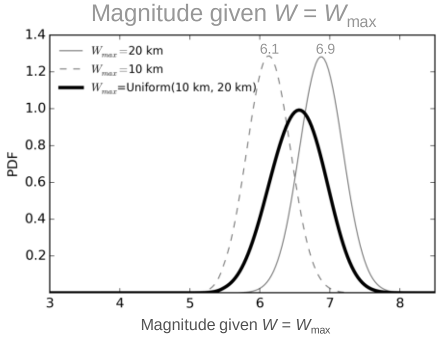
Finite seismogenic thickness constraint on tail

- Seismogenic thickness for NW-Europe: 20 km (Ward, 1998)
- Generic uncertainty: 10 – 30 km (Johnston,1994)
- Ignore upper bound as Groningen is an extended SCR

Frequency-magnitude distribution



Magnitude given $W = W_{max}$



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Finite strain limit: Kostrov estimate for induced M_{max}

- Following Kostrov (1974), McGarr (1976)
- Upper bound: All induced reservoir strain is seismogenic
- Excludes triggered seismicity
- Maximum total seismic moment, $M_{o,max} = 2\,\mu\,|\Delta V|$
- $\Delta V = 3.3 \times 10^8$ m^3, $\mu = 10$ GPa, $M_{o,max} = 7\text{x}10^{18}$Nm
- $M_{max} = 6.5$

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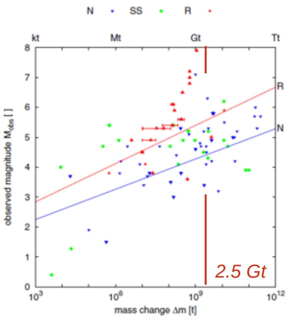
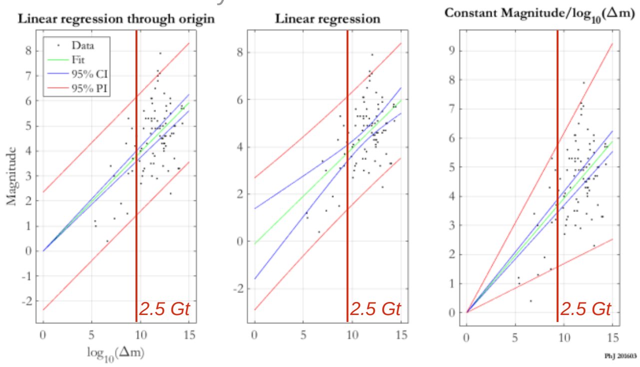
Finite mass shift limit: Klose estimate for max(M_{obs})

- From Klose (2012), global catalogue: max(M_{obs}) and mass shift, Δm
- Under-estimate: M_{max} > max(M_{obs})
  - Given Δm = 2.5 Gt, max(M_{obs}) = 1.5 – 6.0 (95% prediction interval)
  - Similar prediction band from all three simple models

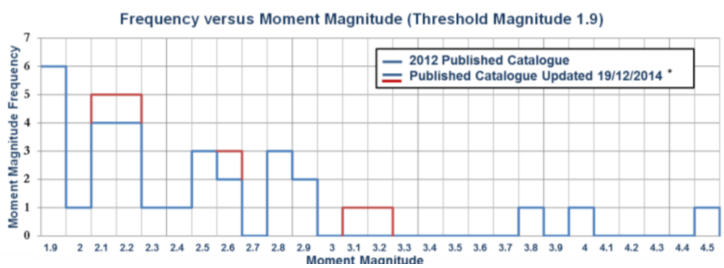
Klose Figure 3



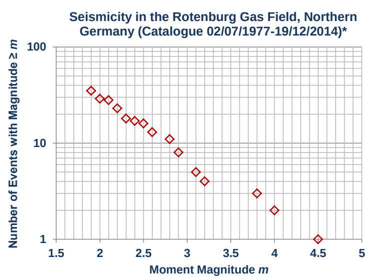
Our analysis for Prediction Interval



Seismicity in the Rotenburg Gas Field



Source: Gestermann, N., *et al* (2015) Induced Seismicity at the Natural Gas Fields in Northern Germany. Schatzalp Induced Seismicity Workshop, 10th – 13th March, 2015, Davos, Switzerland.



- Very sparse dataset (N = 35)
- MLE estimate of b-value is 0.76
- M = 4.5 event depth more likely below than within reservoir
- Unlikely for M = 4.5 rupture extent to fit inside the reservoir

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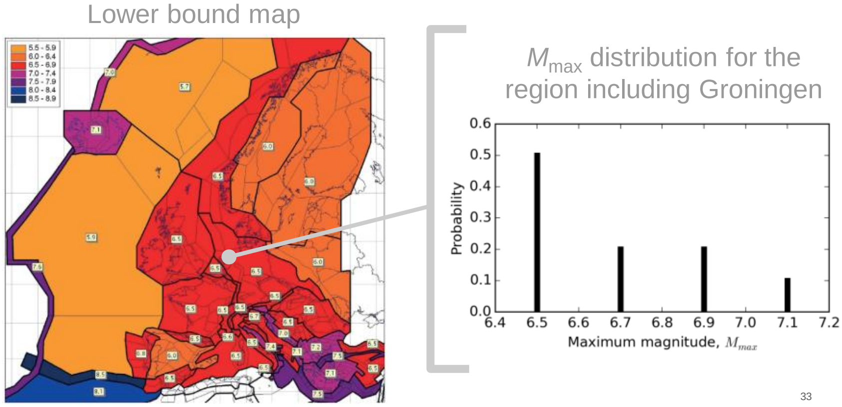
European natural seismic hazard M_{max} assessment

- SHARE Project, Woessner et al, 2015
- Uses the global analogue approach (Wheeler 2009, 2011)
- "A minimum *cautionary* value of 6.5 was assumed

Lower bound map



Summary

- There are no reliable estimates of M_{max}
  - No M_{max} observed for Groningen or SCR
  - No M_{max} from geometric bounds and the observed global rupture scaling with magnitude
  - $M_{max} \neq \max(M_{obs})$
  - Alternatively could choose to quantify extreme values of the *F-M* distribution instead
- Key uncertainty is the likelihood of reactivating basement faults
  - Abundance of $M > 3$ events *may* already indicate slip on basement faults
  - More reliable hypo-central depths will be informative
  - Imaging finite rupture extents would be informative
- Lower limit allows $M_{max} = 4.5$
  - No reliable evidence for or against this possibility
  - Groningen earthquake scaling may be special, unlike the global analogues including Rotenburg
  - Possible upper bound is only just out-of-sight
- Caution suggests $M_{max} \geq 6.5$
  - Simple finite induced strain limit implies $M_{max} = 6.5$
  - Basement rupture cannot be ruled out, perhaps already happened in Groningen and Rotenburg

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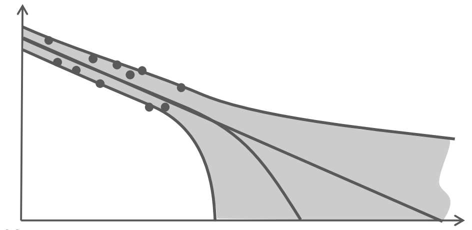
A neutral way forward

- Ensemble of *all possible F-M* models weighted by their Bayes factors
  - Posterior distribution of Generalized Pareto tails given observed magnitudes
  - Include location and reservoir deformation as covariates once sample size allows



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The largest possible and the largest expected earthquake for the Groningen gas field

Gert Zöller & Matthias Holschneider

University of Potsdam

March 10, 2016

Workshop on Maximum Magnitude Estimates for Probabilistic Seismic Hazard and Risk Modelling in Groningen Gas Field, Amsterdam

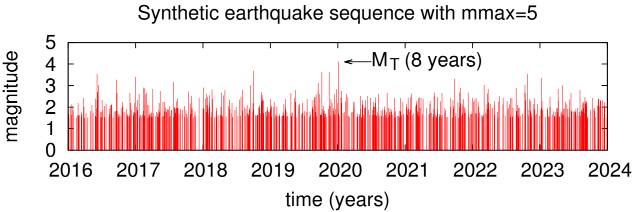
Contents

1. $m_{\max}$: The largest possible earthquake magnitude in a region
   - Estimation of $m_{\max}$: Statistical inference from rare events
   - The statistical model for magnitudes
   - The Groningen case
   - Relation to other statistical methods

2. M_T: The largest expected earthquake magnitude in time T
   - The statistical model
   - The data
   - Results for three gas production scenarios (21, 27, 33 BCM/year)

General assumptions

1. $m_{\max}$: Constant physical parameter that depends on the tectonic regime, not on the gas production.
2. The tectonic regime is constant.
3. No ergodicity assumption used. The physics of the Groningen field is encoded in the Groningen data.
4. M_T ($\leq m_{\max}$): Derived quantity that depends on $m_{\max}$ and on the gas production in the time interval T under consideration.


Synthetic earthquake sequence with mmax=5
magnitude
5
4
3
2
1
0
$\leftarrow M_T$ (8 years)
2016
2017
2018
2019
2020
2021
2022
2023
2024
time (years)

1. $m_{\max}$: The largest possible earthquake magnitude in a region

Facts on $m_{\max}$

- Earthquakes with $m \approx m_{\max}$ are rare, uncertainties of $m_{\max}$ are high!
- Only conceptual models with
  - commonly accepted physics
  - small number of parameters

  allow to calculate exactly the uncertainties of $m_{\max}$.
- For complex multi-parameter models it becomes unmanageable to quantify the uncertainties of $m_{\max}$.

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The Earthquake History in a Fault Zone Tells Us Almost Nothing about m_{max}

Gert Zöller[a] and Matthias Holschneider[a]

+ Author Affiliations

ABSTRACT

In the present study, we summarize and evaluate the endeavors from recent years to estimate the maximum possible earthquake magnitude m_{max} from observed data. In particular, we use basic and physically motivated assumptions to identify best cases and worst cases in terms of lowest and highest degree of uncertainty of m_{max}. In a general framework, we demonstrate that earthquake data and earthquake proxy data recorded in a fault zone provide almost no information about m_{max} unless reliable and homogeneous data of a long time interval, including several earthquakes with magnitude close to m_{max}, are available. Even if detailed earthquake information from some centuries including historic and paleoearthquakes are given, only very few, namely the largest events, will contribute at all to the estimation of m_{max}, and this results in unacceptably high uncertainties. As a consequence, estimators of m_{max} in a fault zone, which are based solely on earthquake-related information from this region, have to be dismissed.

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First published online November 30, 2015, doi: 10.1785/0220150176
v. 87 no. 1 p. 132-137

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What do we need (at least) to constrain $m_{\max}$?

1. A model for the distribution of earthquake magnitudes, which stems from physics and empirical knowledge.

2. A data record of earthquake magnitudes from the region under consideration (earthquake catalog).

Textbook example: Tossing a coin

Problem: What can be learned about the probability for getting “head” from observational data, e.g. is it a fair coin ($p = 0.5$)?

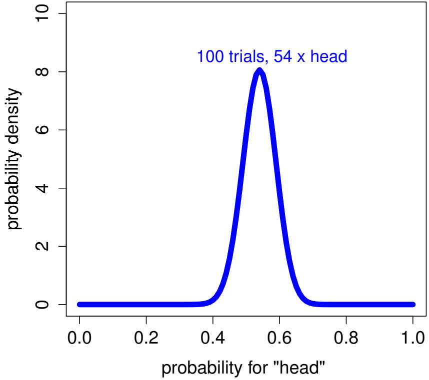
- Model: Binomial model with probability p for “head” and $1 - p$ for “tail”.
- Data: Number of observations of “head” in an experiment with N trials.
- No further information available on p.

Estimation of $m_{\max}$: Statistical inference from rare events

Posterior probability density function for p (probability for "head") after observing data (N trials, k times "head")

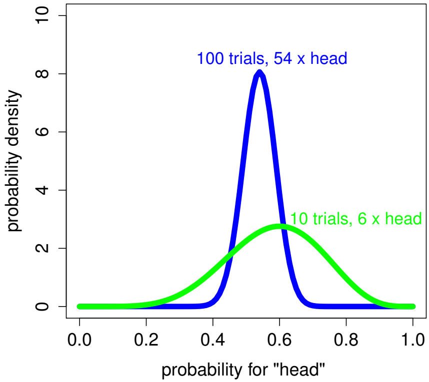
Estimation of p

"Many" trials ($N = 100, k = 54$) $\rightarrow$ high information gain



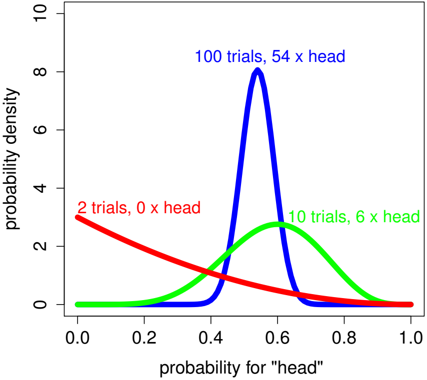
Estimation of p

"Some" trials ($N = 10, k = 6$) $\rightarrow$ moderate information gain

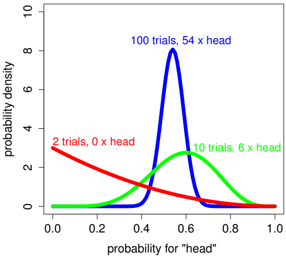


Estimation of p

"Few" trials ($N = 2, k = 0$) $\rightarrow$ low information gain

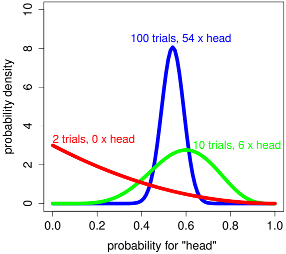


Estimation of $m_{\max}$: Statistical inference from rare events



Estimating $m_{\max}$ from an earthquake catalog is similar to the red curve, because . . .

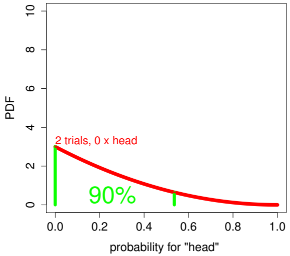
Estimation of $m_{\max}$: Statistical inference from rare events



... earthquakes with $m \approx m_{\max}$ are rare events!
Number of "trials": $0, \ldots, 1$

... point estimators of p (single numbers) are not useful!

Estimation of $m_{\max}$: Statistical inference from rare events

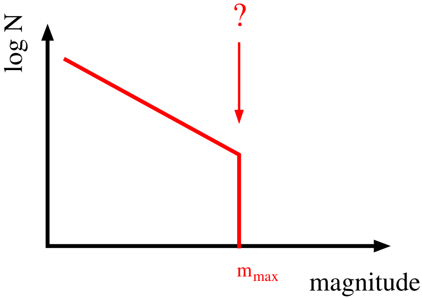


However, even from the red curve, the best (=smallest) confidence interval of p can be calculated, e.g. ...

... with 90% confidence, we have $p \in [0; 0,54]$.

The statistical model for magnitudes

Gutenberg-Richter law: $\log_{10}(N_{\geq m}) = a - bm$ for $m \leq m_{\max}$



Gutenberg-Richter probability density function

$$f_{\beta m_{\max}}(m) = \frac{b10^{-bm}}{10^{-bm_0} - 10^{-bm_{\max}}} \text{ for } m_0 \leq m \leq m_{\max}$$

The model for magnitudes

The Gutenberg-Richter (GR) law is not just an empirical finding, it is inherently related to the physics of earthquakes, see e.g.

Bulletin of the Seismological Society of America. Vol. 58, No. 1, pp. 399–415. February, 1968

THE FREQUENCY-MAGNITUDE RELATION OF MICROFRACTURING IN ROCK AND ITS RELATION TO EARTHQUAKES

BY C. H. SCHOLZ

ABSTRACT

During the deformation of rock in laboratory experiments, small cracking events, i.e., microfractures, occur which radiate elastic waves in a manner similar to earthquakes. These radiations were detected during uniaxial and triaxial compression tests and their frequency-magnitude relation studied. They were found to obey the Gutenberg and Richter relation

$$\log N = a + bM$$

where N is the number of events which occurred of magnitude M, and a and b constants. The dependence of the parameter b on rock type, stress, and confining pressure was studied. It was found to depend primarily on stress, in a characteristic way. The frequency-magnitude relation for events which accompanied frictional sliding and deformation of a ductile rock was found to have a much higher b value than that observed in brittle rock. The Gutenberg and Richter formulation of the frequency-magnitude relation was derived from a statistical model of rock and crustal deformation. This analysis demonstrates the basis of similarity between rock deformation experiments in the laboratory and deformation of the crust.

The model for magnitudes

Generations of numerical models have been studied to understand the physical meaning of the GR parameters, starting with

Bulletin of the Seismological Society of America. Vol. 57, No. 3, pp. 341–371. June, 1967

MODEL AND THEORETICAL SEISMICITY

By R. Burridge and L. Knopoff

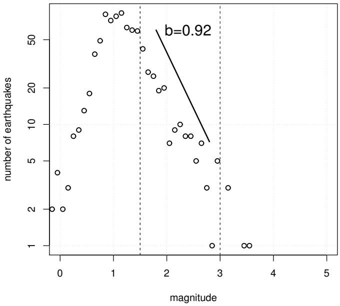
ABSTRACT

A laboratory and a numerical model have been constructed to explore the role of friction along a fault as a factor in the earthquake mechanism. The laboratory model demonstrates that small shocks are necessary to the loading of potential energy into the focal structure; a large part, but not all, of the stored potential energy is later released in a major shock, at the end of a period of loading energy into the system. By the introduction of viscosity into the numerical model, aftershocks take place following a major shock. Both models have features which describe the statistics of shocks in the main sequence, the statistics of aftershocks and the energy-magnitude scale, among others.

The earthquake catalog of Groningen

- Time: 1991 - 2015
- Magnitudes given with one decimal place
- Magnitude of completeness: $m_0 = 1.5$
- Maximum observed earthquake: $\mu = 3.6$
  (Huizinge, August 16, 2012)
- Total number of 261 earthquakes with $m \in [1.5; 3.6]$

The frequency-magnitude distribution for Groningen



ML-estimation of the $b-$value

- corrected for rounding errors
- for $m \in [1.5, 3.0]$

$$b = 0.92.$$

The confidence interval of $m_{\max}$:

Best confidence interval of $m_{\max}$

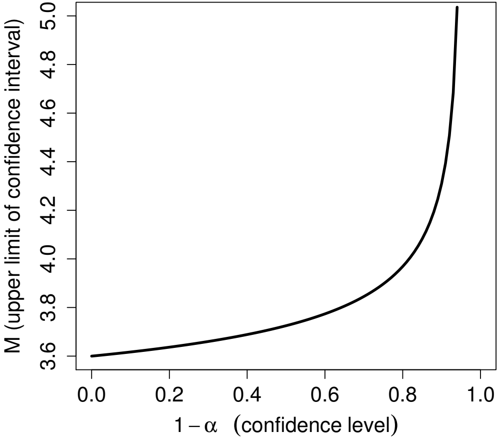
$$\mu \leq m_{\max} \leq m_0 - \frac{1}{b} \log_{10} \left[1 + \frac{10^{-b(\mu - m_0)} - 1}{\alpha^{1/n}} \right]$$

(Holschneider et al., BSSA, 101(4), 1649–1659, 2011; JGR, 119(3), 2019–2028, 2014)

with

- α: Error probability ($1 - \alpha =$ level of confidence)
- μ: Magnitude of maximum observed earthquake (=3.6 for Groningen)

The confidence interval of $m_{\max}$



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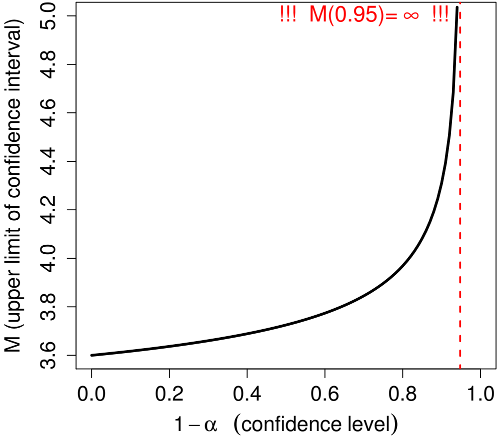
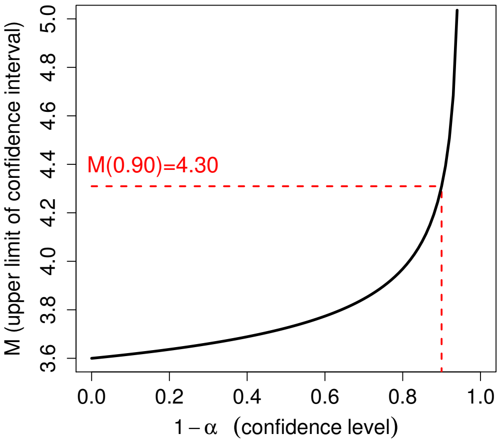


The confidence interval of $m_{\max}$



Results for $m_{\max}$

- For high levels of confidence, i.e. $1 - \alpha > 0.95$, it follows the (trivial) result

$$3.6 \leq m_{\max} < \infty$$

– no finite value of $m_{\max}$!

- For 90% confidence the upper bound of the best confidence interval is

$$M(0.9) = 4.3$$

– no improvement is possible.

- Uncertainties of b-value estimation increase the value of $M(0.9)$ to $M(0.9) = 4.7$.

Relation to other statistical methods

Pisarenko et al. (BSSA 86(3), 691–700, 1996)

- provides the best unbiased point estimator for m_{max} and shows that
- the standard deviation of the estimator cannot be used to calculate the uncertainties of m_{max}.

Relation to other statistical methods

Kijko et al. (various publications on $m_{\max}$, e.g. Kijko, Pure Appl. Geophys. 161, 1655–1681, 2004)

- provides various point estimators for $m_{\max}$.
- uncertainties are not properly calculated: Heuristic arguments and (arbitrary) approximations are used.

Relation to other statistical methods

Bayesian estimation of $m_{\max}$ from an earthquake catalog
(e.g. EPRI report, 1994)

- The Bayesian posterior distribution depends predominantly on the (arbitrarily selected!) prior distribution of $m_{\max}$.
- The earthquake catalog provides only a lower bound of $m_{\max}$ (= maximum observed magnitude).

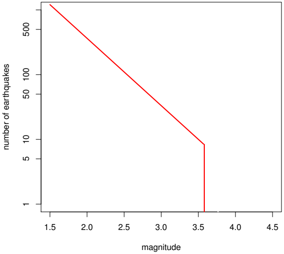
Details: Holschneider et al., BSSA, 101(4), 1649–1659, 2011
Zöller and Holschneider, SRL, 87(1), 132–137, 2016

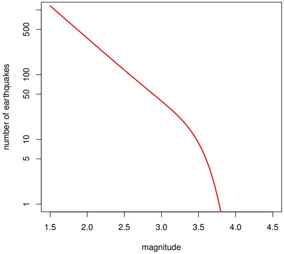
Relation to other statistical methods

Kagan et al. (various publications, e.g. Kagan and Bird, BSSA 94(6), 2380-2399, 2004):

- Magnitudes: Pareto distribution with an exponential taper (unlimited!) characterized by a corner magnitude m_c.
- $m_{\max}$: The corner magnitude m_c ($\neq m_{\max}$) is estimated from earthquake catalogs.

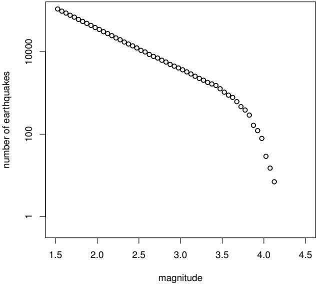
Truncated or tapered: Does it matter?





Synthetic Groningen catalog with 10^6 earthquakes

What is the underlying magnitude model?



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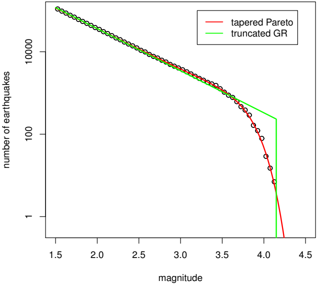

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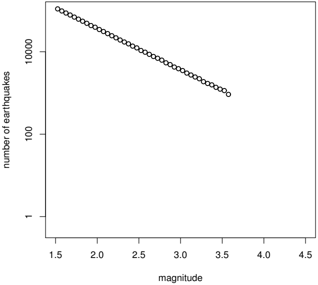
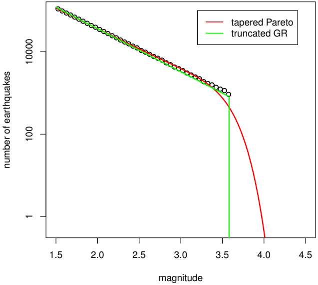


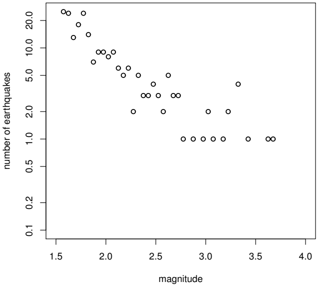
Synthetic Groningen catalog with 10^6 earthquakes

What is the underlying magnitude model?



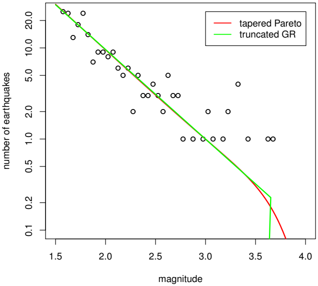
Synthetic Groningen catalog with 261 earthquakes

What is the underlying magnitude model?



Synthetic Groningen catalog with 261 earthquakes

What is the underlying magnitude model?



The tapered Pareto distribution

Probability distribution for seismic moment M

$$F(M) = 1 - \left(\frac{M_0}{M}\right)^{\beta} \exp\left(\frac{M_0 - M}{M_c}\right); \quad M_0 \leq M < \infty$$

(Kagan, GJI 148, 520–541, 2002)

with

- M_0: Minimum moment
- M_c: Corner moment (begin of roll-off), no maximum moment!
- $\beta \approx 2/3$

The tapered Pareto distribution

Confidence interval based on maximum observed earthquake

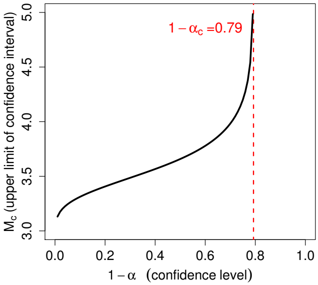
Upper bound of confidence interval for corner moment M_c

$$M_c \leq \frac{M_0 - M_{\text{max obs}}}{\log\left[\left(\frac{M_{\text{max obs}}}{M_0}\right)^{\beta}\left(1-\alpha^{1/n}\right)\right]}$$

with

- α: Error probability ($1-\alpha$ = level of confidence)
- $\beta = 0.71$ (maximum likelihood fit from data)
- $M_{\text{max obs}}$: Moment of maximum observed earthquake $=10^{\frac{3}{2}(3.6+6)}$ (in Nm) for Groningen
- M_0: Completeness moment $= 10^{\frac{3}{2}(1.5+6)}$ (in Nm) for Groningen catalog

The tapered Pareto distribution



We find:

- No finite value of $m_{\max}$ for confidence levels $1 - \alpha \geq 0.79$.
- Similar (slightly worse) performance as truncated GR law.

Findings for the truncated Gutenberg-Richter distribution

- All information on $m_{\max}$ is encoded in the *b*-value and the magnitude μ of the maximum observed earthquake.
  $\rightarrow$ The confidence interval of $m_{\max}$ is optimal!
- Preferred value of $m_{\max}$ at 90% confidence for Groningen:

$$m_{\max} = 4.3.$$

- Taking into account the uncertainties of the *b*-value estimation will even increase $m_{\max}$ to values up to $m_{\max} = 4.7$!

Summary on $m_{\max}$ II

Are other magnitude distributions more informative on $m_{\max}$?

- No. As long as the tail of the distribution has little support by data, all distributions work equally well (or poor).
- Tapered Pareto (TP) distribution:
  - The TP distribution is a priori inadequate for estimating $m_{\max}$, because it is unbounded (corner magnitude m_c can be exceeded!).
  - In terms of β (slope) and μ (maximum observed magnitude), the performance is worse: confidence intervals are larger.
- The truncated GR law is physically plausible (a magnitude limit should exist!), and allows easily to extract all information on $m_{\max}$ from an earthquake catalog.

Summary on $m_{\max}$ III

Which value of $m_{\max}$ is plausible for Groningen?

The combination of

- broadly accepted physics and
- the Groningen earthquake catalog

advocates at 90% confidence

$$m_{\max} = 4.3 \ldots 4.7$$

2. M_T: The largest expected earthquake magnitude in time T

Maximum possible versus maximum expected magnitude

- m_{max}: maximum possible magnitude, becomes visible after long observation time ($\sim$ 1000s of years).
- M_T: Maximum expected magnitude in time T can be calculated from the b-value and the earthquake rate, which are accessible from instrumental (short) earthquake catalogs.

The statistical model

1. Magnitudes: Gutenberg-Richter law (limited or unlimited? $m_{\max}$?)

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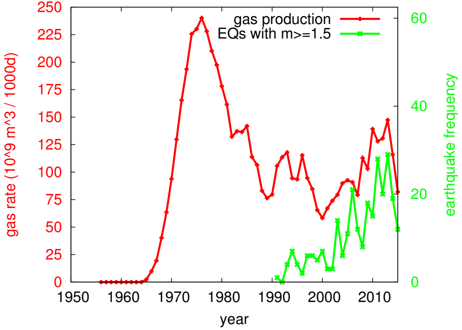
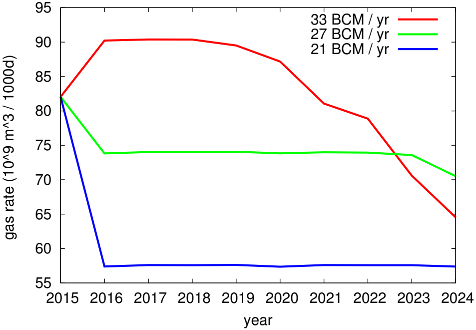
Details: Zöller and Holschneider, BSSA, 104(6), 3153–3158, 2014.
Zöller et al., BSSA, 104(2), 769-779, 2014
Zöller et al., BSSA, 103(2), 860-875, 2013.

Groningen: Gas production vs. earthquake rate



Groningen: Future scenarios for gas production (2016-2024)

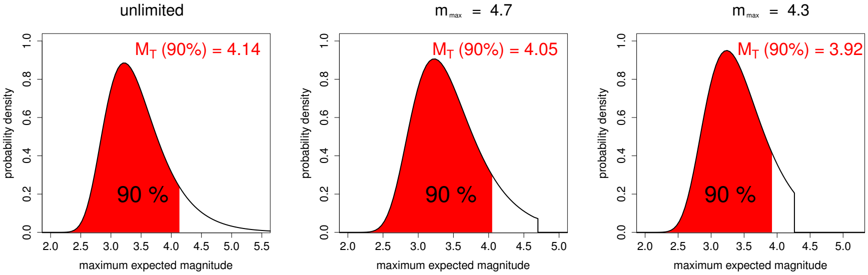


Calculation of M_T

Posterior probability density function for the maximum expected magnitude for the three future scenarios

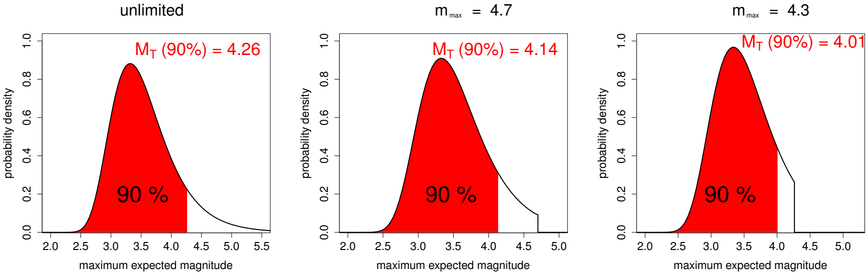
Maximum expected earthquake 2016-2024

Production scenario 21 BCM / year



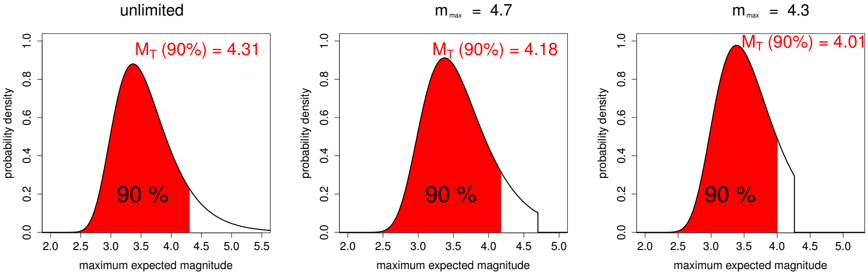
Maximum expected earthquake 2016-2024

Production scenario 27 BCM / year



Maximum expected earthquake 2016-2024

Production scenario 33 BCM / year



Summary on M_T

Findings for the largest expected magnitude M_T in the time from 2016 to 2024

- The dependence of M_T on m_{max} is moderate ($\sim 0.2 \ldots 0.3$ magnitude units).
- Depending on the production scenario, we expect the largest magnitude between 2016 and 2024 to be between

3.9 and 4.3.

Summary and conclusion

Methodology

1. Consider a family of physical models for the maximum possible and the maximum expected magnitude.

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1. Consider a family of physical models for the maximum possible and the maximum expected magnitude.
2. Select the model which is favored by the available data.
3. We obtain a straightforward description of the uncertainties, even for rare data.
4. No arbitrary selection of parameters!

Summary and conclusion

Results for Groningen (at 90% confidence)

1. Maximum possible magnitude: $m_{\max} = 4.3 \ldots 4.7$
2. Maximum expected magnitude between 2016 and 2024: $M_T = 3.9 \ldots 4.3$.

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Thank you!

Results for Groningen (at 90% confidence)

1. Maximum possible magnitude: $m_{\max} = 4.7$.

2. Maximum expected magnitude between 2016 and 2024:
   $M_T = 4.1 \ldots 4.3$.

Thank you!

Groningen fracture-mechanics seismicity model

David Dempsey, Jenny Suckale

Components:

1. Concepts
2. Stress state
3. Loading
4. Seismicity model
   a. Calibrate
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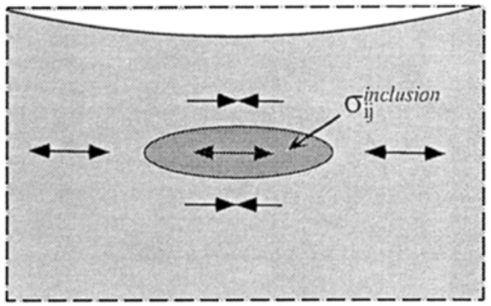
- Pressure in the Groningen reservoir is declining.
- Groningen is in an extensional stress regime.
- Seismicity occurs *inside* the delimited region of pressure decline.



- *Seismicity at Groningen caused by pressure drawdown mechanism, after Segall and Fitzgerald (1998).*

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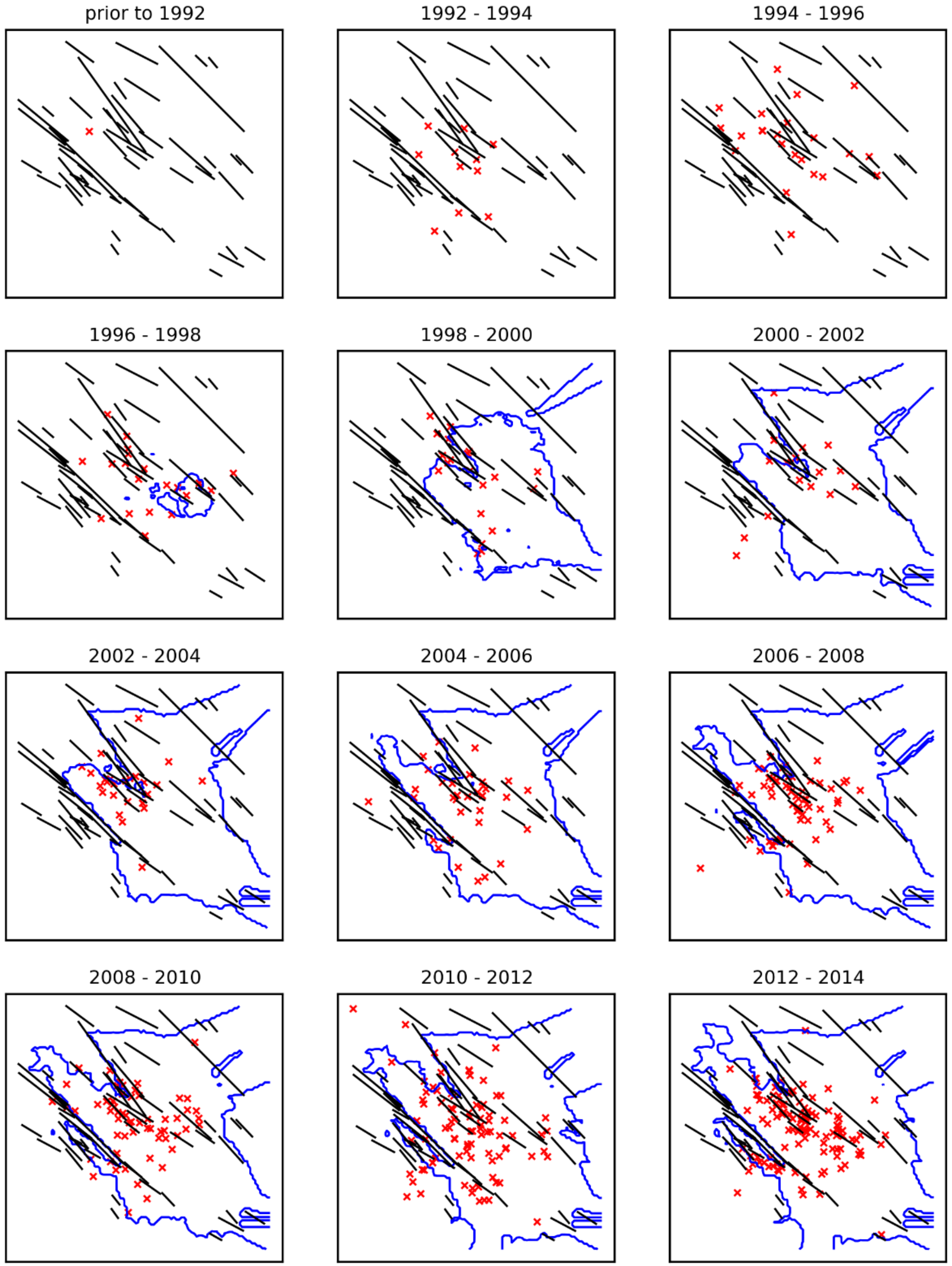

Groningen seismicity: 2 years intervals

blue contour shows 20 MPa pressure decline

Components:

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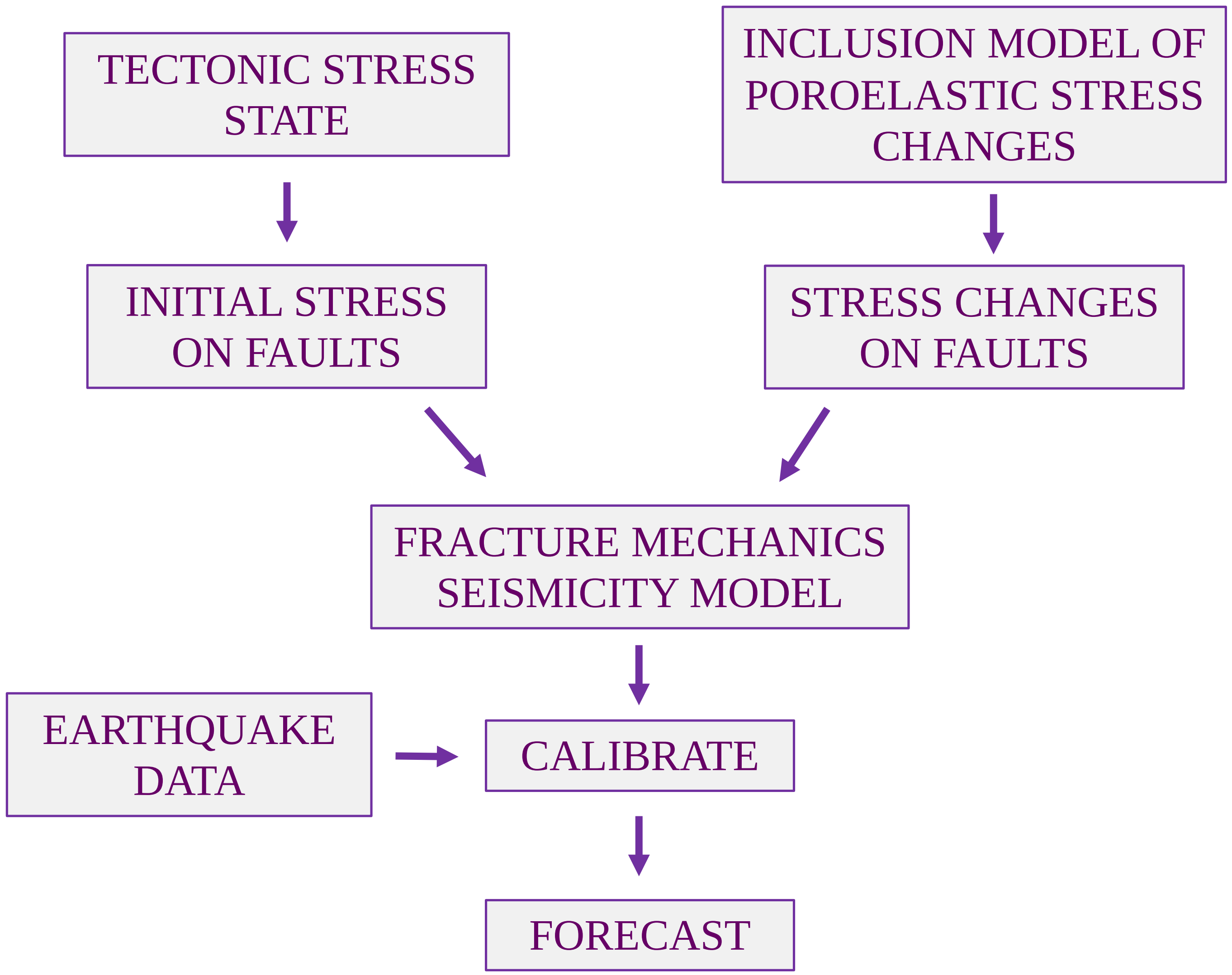

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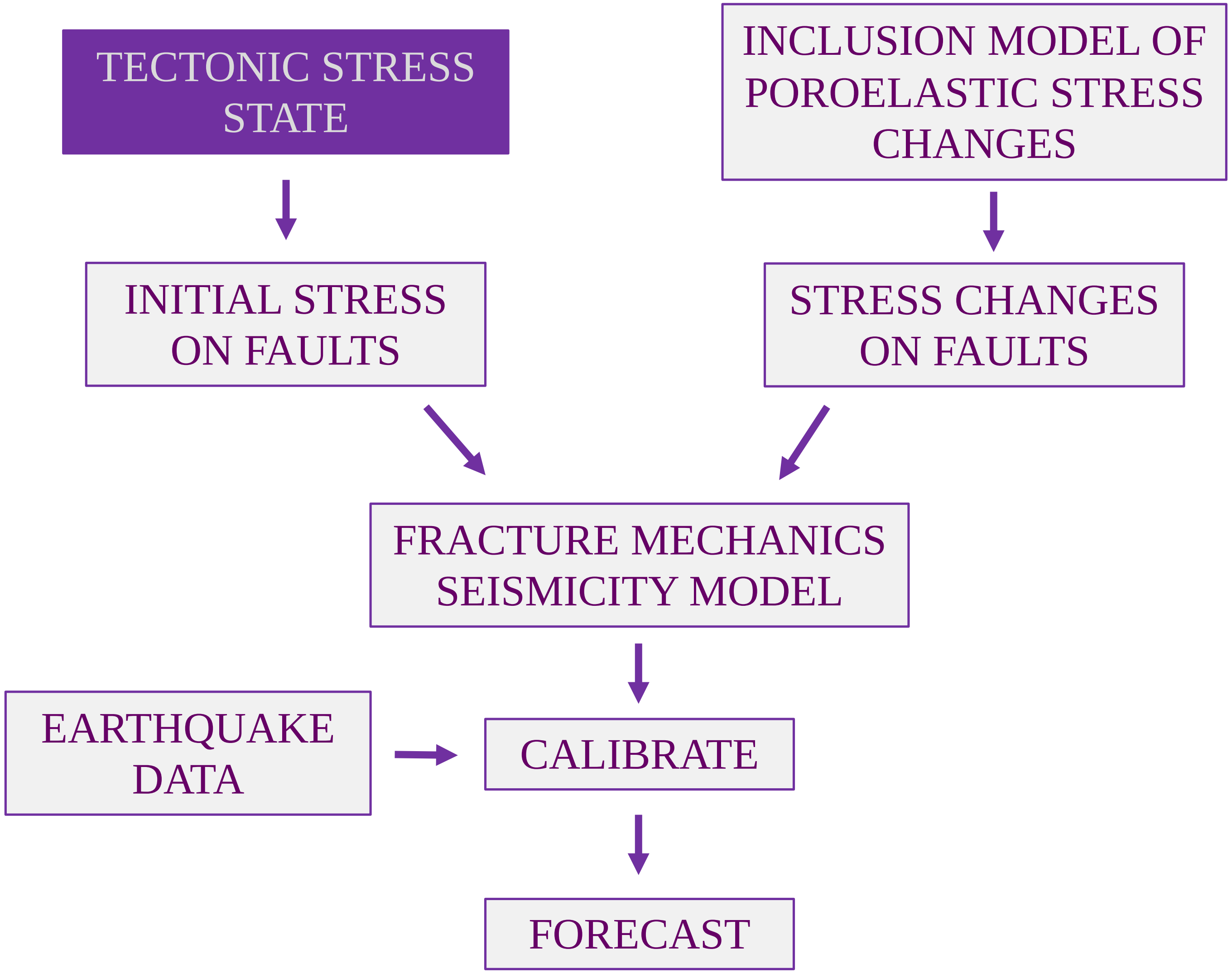

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Extensional stress regime:

- Vertical stress is maximum principal, σ_1.
  - obtain by depth integration of ρ=**2500** kg m^{-3}
  - seismicity occurs at **3** km depth
- Horizontal stress, perpendicular to rift axis, is minimum principal, σ_3
  - $\sigma_3 - P_0 = (\sigma_1 - P_0)/\left(\sqrt{f_s^2+1}+f_s\right)^2$ $\quad (f_s = 0.45)$
- P_0 is initial formation pressure.
- $\sigma_2 = \frac{1}{2}(\sigma_1 + \sigma_2)$

Components:

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Extensional stress regime:

- Stress tensor in principle component axes

$$\boldsymbol{\sigma} = \begin{bmatrix} \sigma_3 & 0 & 0 \\ 0 & \sigma_2 & 0 \\ 0 & 0 & \sigma_1 \end{bmatrix}$$

- Stress tensor in Groningen x-y coordinates

  for rift axis at angle θ=45°

$$\boldsymbol{S} = \boldsymbol{R}^T \boldsymbol{\sigma} \boldsymbol{R}, \qquad \boldsymbol{R} = \begin{bmatrix} cos(\theta) & sin(\theta) & 0 \\ -sin(\theta) & cos(\theta) & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

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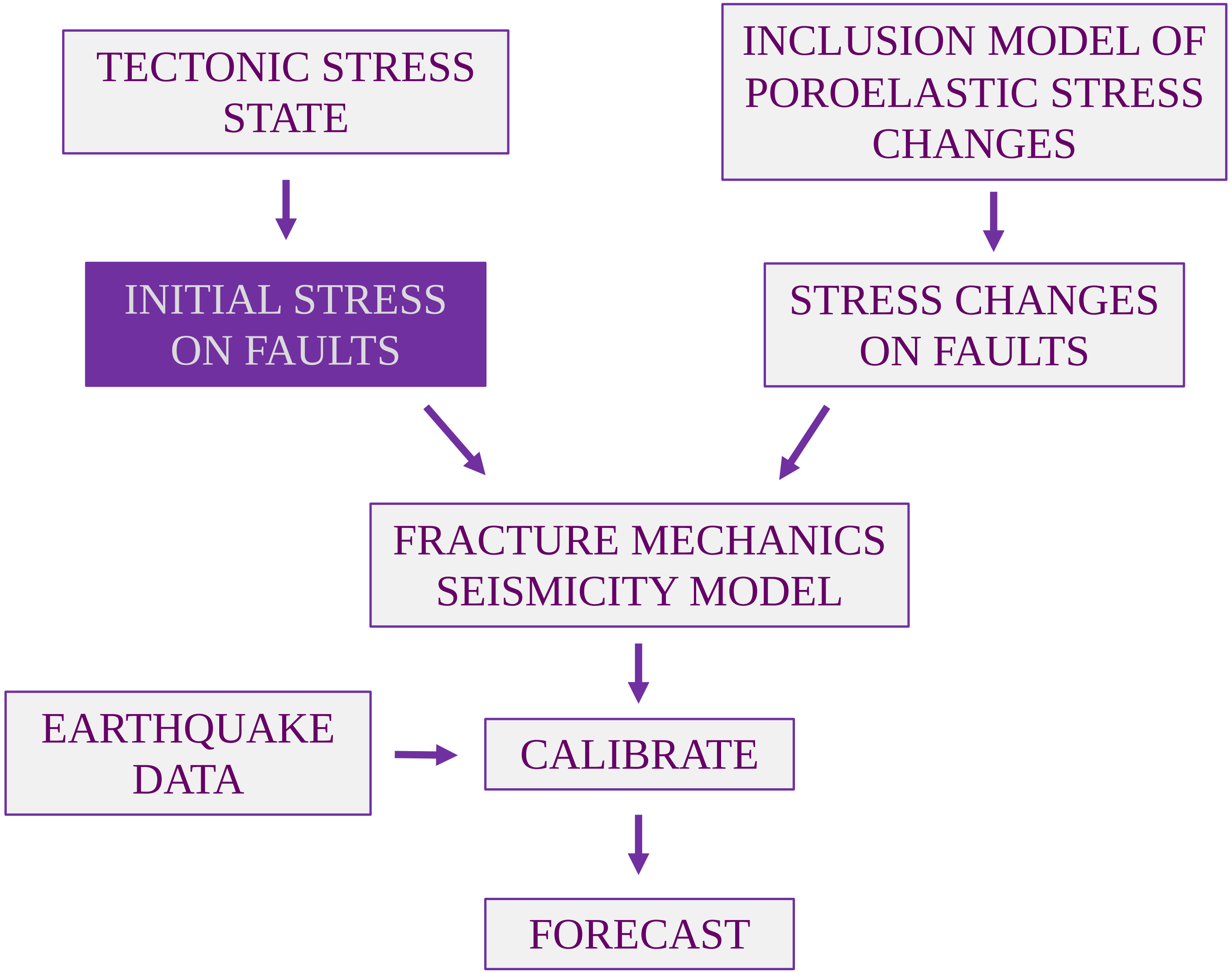

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Stress resolved on fault:

- Given a fault with normal, $\hat{\boldsymbol{n}}$.
- Resolved traction on fault is

$$\boldsymbol{t} = \boldsymbol{S} \cdot \hat{\boldsymbol{n}}$$

- Resolved normal stress on fault is

$$\sigma_n = \hat{\boldsymbol{n}} \cdot \boldsymbol{t}$$

- Resolved shear stress on fault is

$$\tau = |\boldsymbol{t} - \sigma_n \hat{\boldsymbol{n}}|$$

- *Each fault has a different $\hat{\boldsymbol{n}}$. Therefore, each fault has a different resolved shear stress.*

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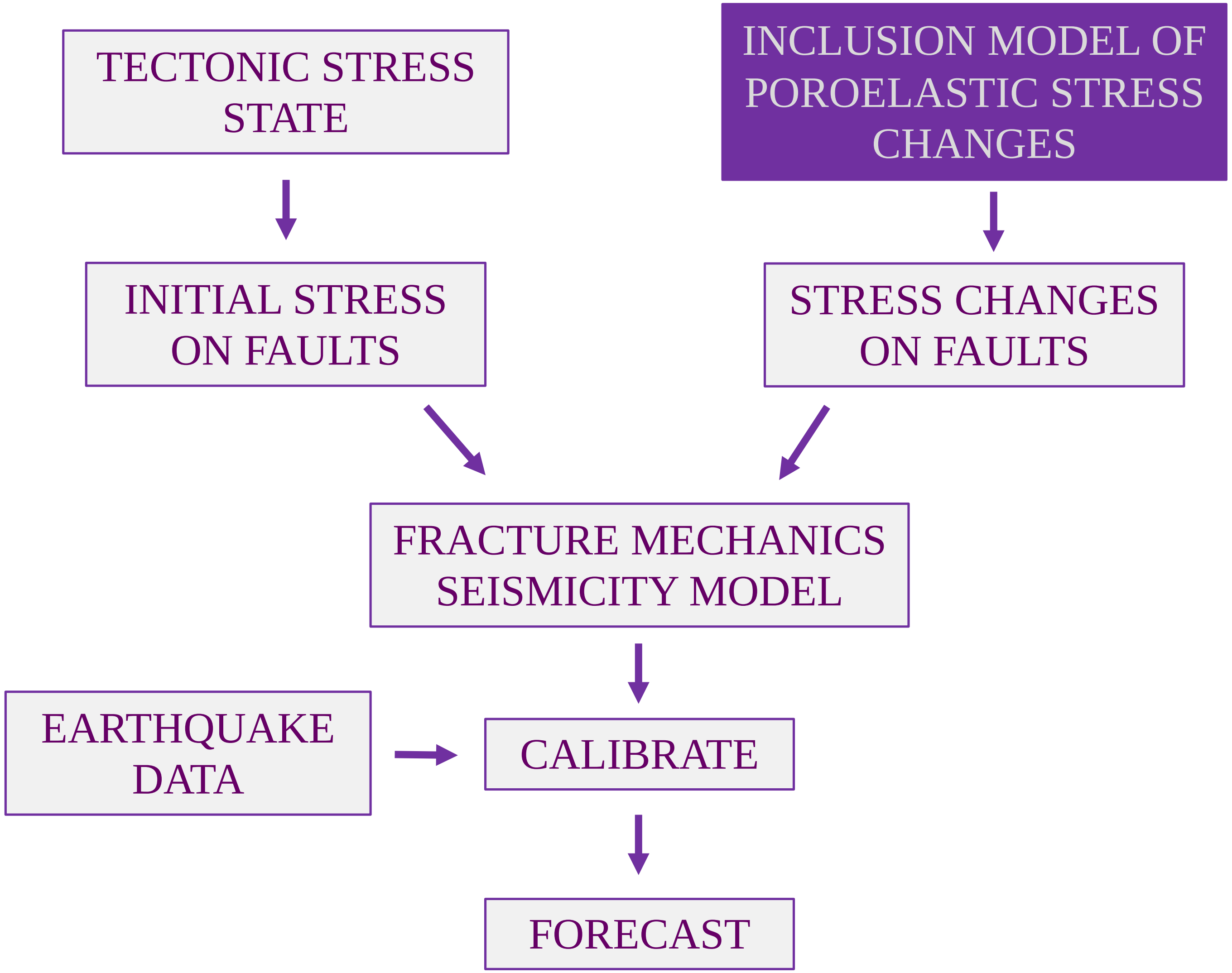

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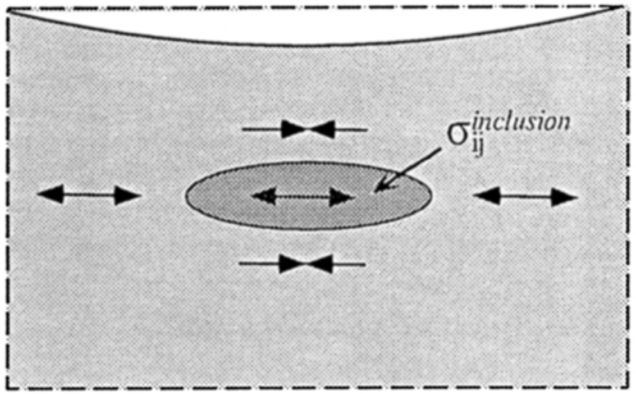
Eshelby model of production-induced seismicity:



Segall and Fitzgerald (1998)

- Compute horizontal and vertical stress changes due to pressure change within ellipse, $a_x = a_y > a_z$.

$$\Delta\sigma_{x,y} = \alpha\Delta P \frac{1-2\nu}{1-\nu}\left(1 - \frac{\pi}{4}\frac{a_z}{a_x}\right) \qquad (\alpha = 1.0)$$

$$\Delta\sigma_z = \alpha\Delta P \frac{1-2\nu}{1-\nu}\frac{\pi}{2}\frac{a_z}{a_x} \approx 0 \qquad (\nu = 0.2)$$

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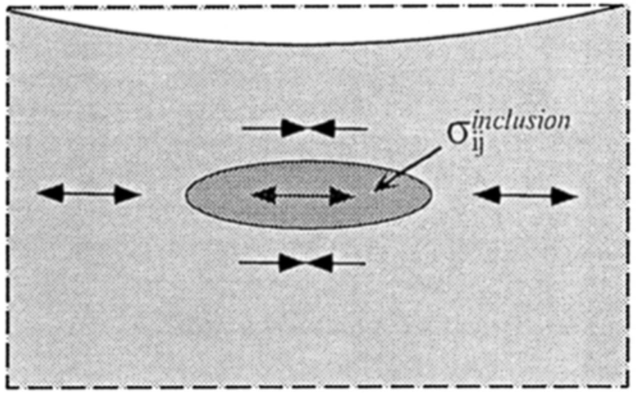

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Eshelby model of production-induced seismicity:

$$\Delta\sigma_{x,y} = \alpha \Delta P \frac{1-2\nu}{1-\nu}\left(1 - \frac{\pi}{4}\frac{a_z}{a_x}\right)$$

- Decrease in pressure induces an extensional stress, which is additive to tectonic stressing.
- To implement, we define a pressure decline "ellipse" representative of complex $\Delta P(x, y, t)$ at Groningen.

$$\Delta P(x,y,t) = \begin{matrix} 0 & : & r > r_{el}(t) \\ \Delta P(t) & : & r \leq r_{el}(t) \end{matrix}$$

$$r = \sqrt{\left(x - x_0(t)\right)^2 + \left(y - y_0(t)\right)^2}$$

Components:

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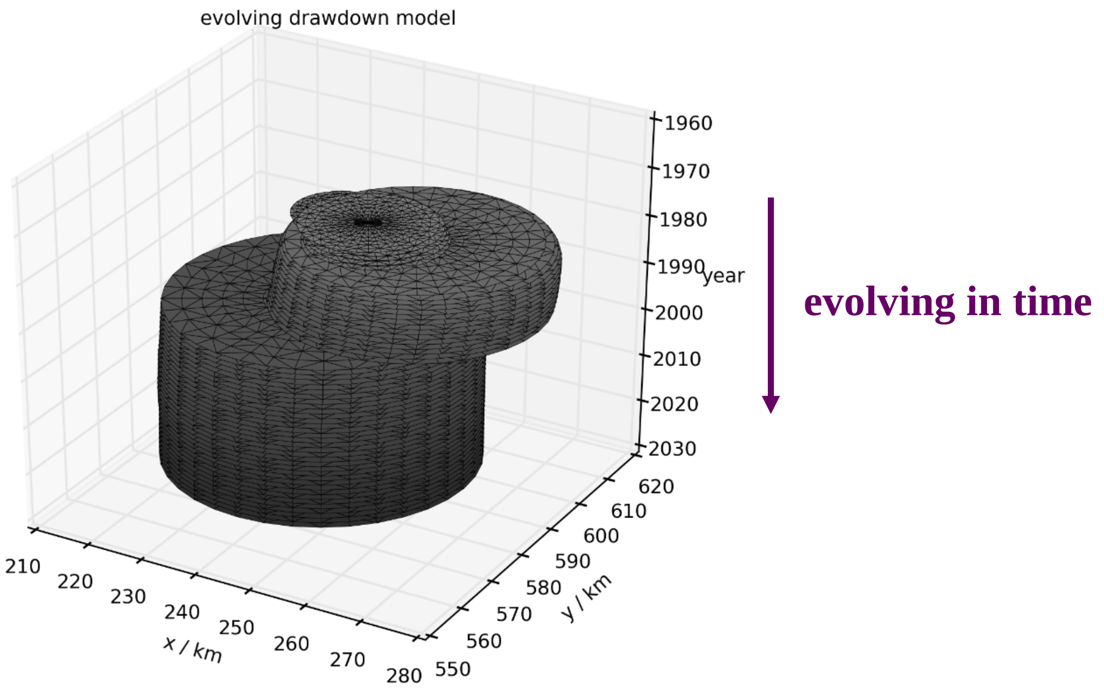
Eshelby model of production-induced seismicity:

- Determine $\Delta P(t)$ and $r_{el}(t)$ (and to a lesser extent, $x_0(t)$ and $y_0(t)$) by least-squares fit with $\Delta P(x, y, t)$ provided for Groningen.
- This yields an evolving pressure depletion ellipse.



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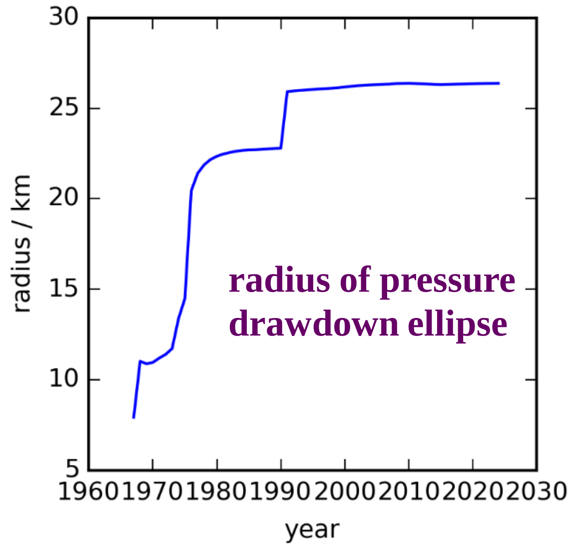

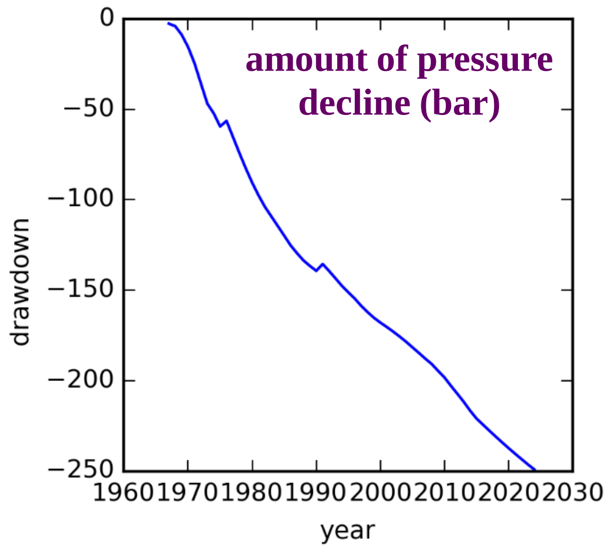

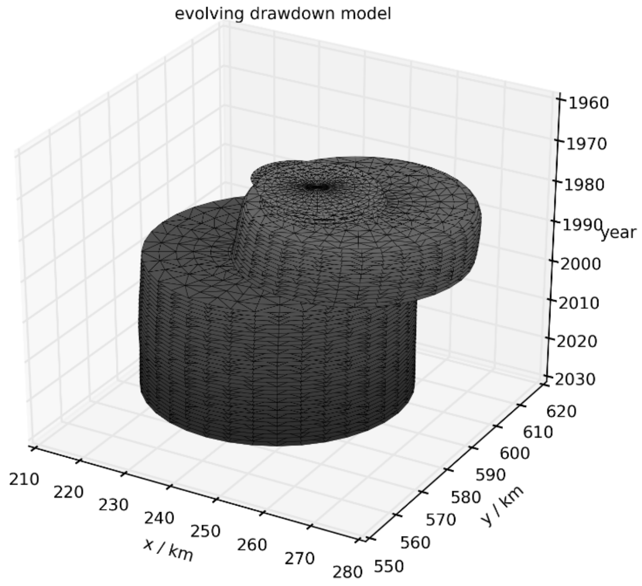

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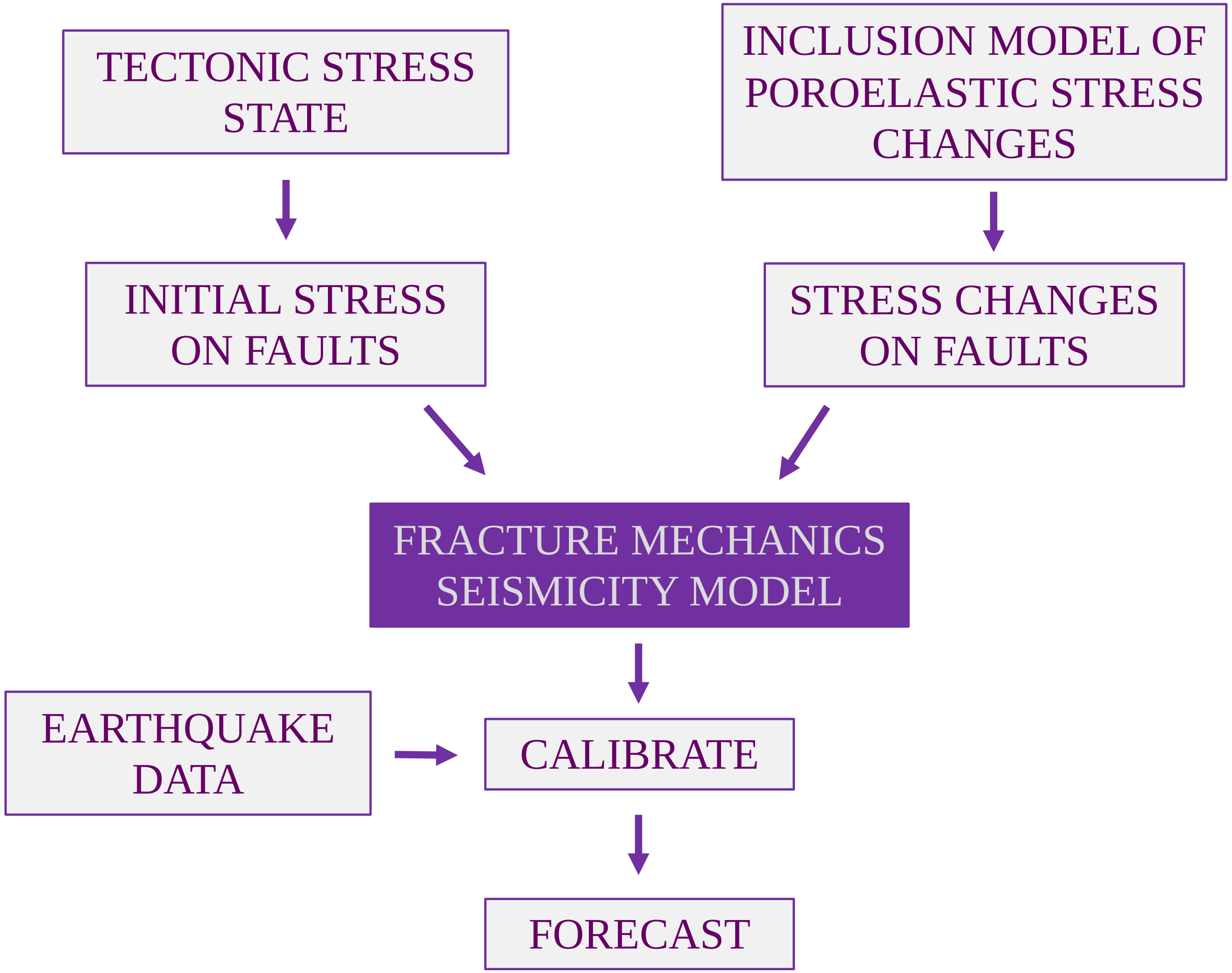

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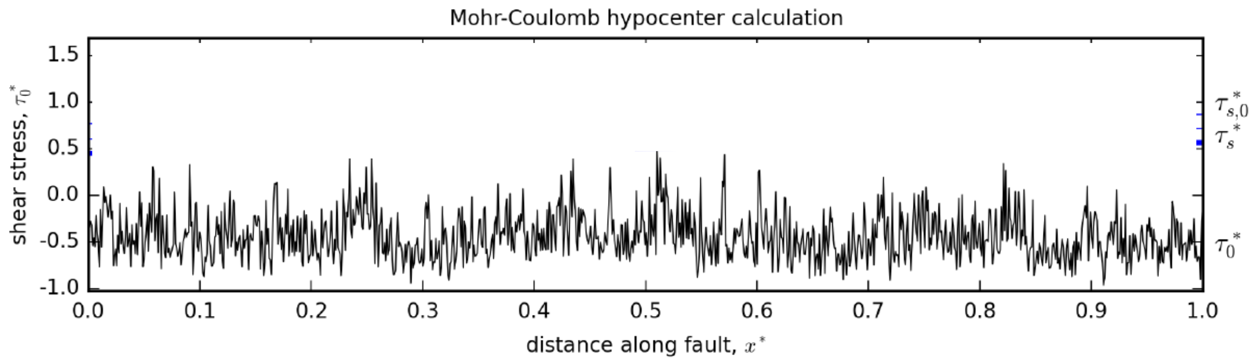
Fracture-mechanics model of seismicity:

- Represent fault as having heterogeneous stress. Many possible stress realizations for a given fault



- Our model captures two important processes:
  (1) earthquake triggering (Mohr-Coulomb)
  (2) rupture propagation and arrest (crack-energy)

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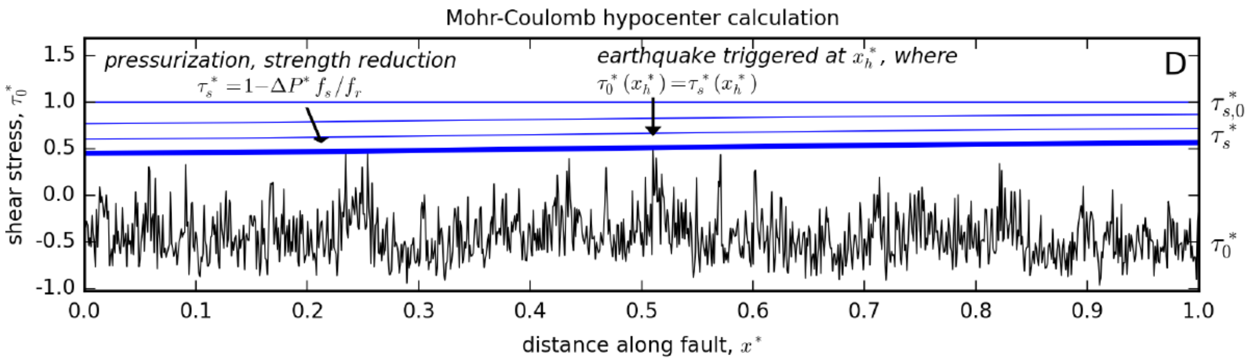

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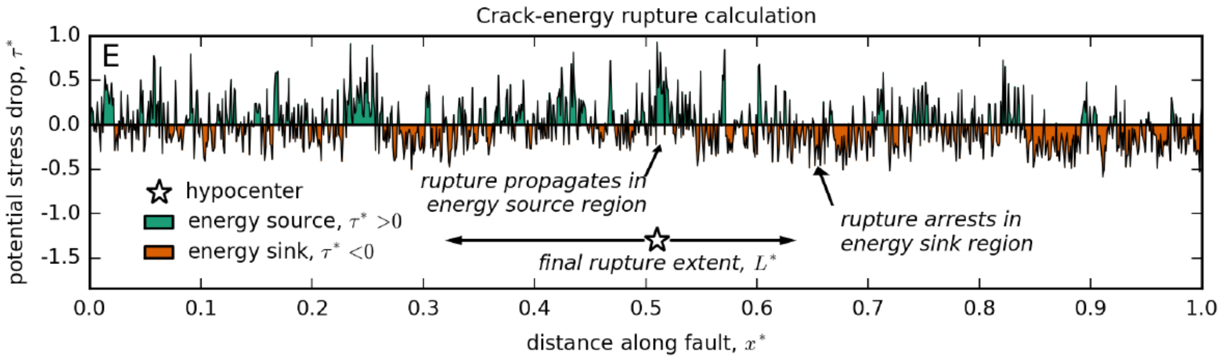

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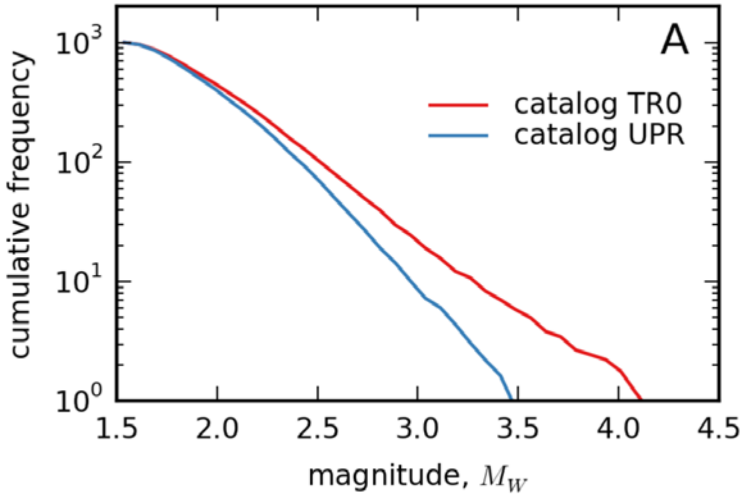
Fracture-mechanics model of seismicity:

- The model replicates Gutenberg-Richter scaling of earthquake magnitudes, changes in *b*-value



- The model is 1D in terms of rupture. However, many of the bulk seismicity features are dependent on stress and loading properties and therefore apply for 2D faults.

Components:

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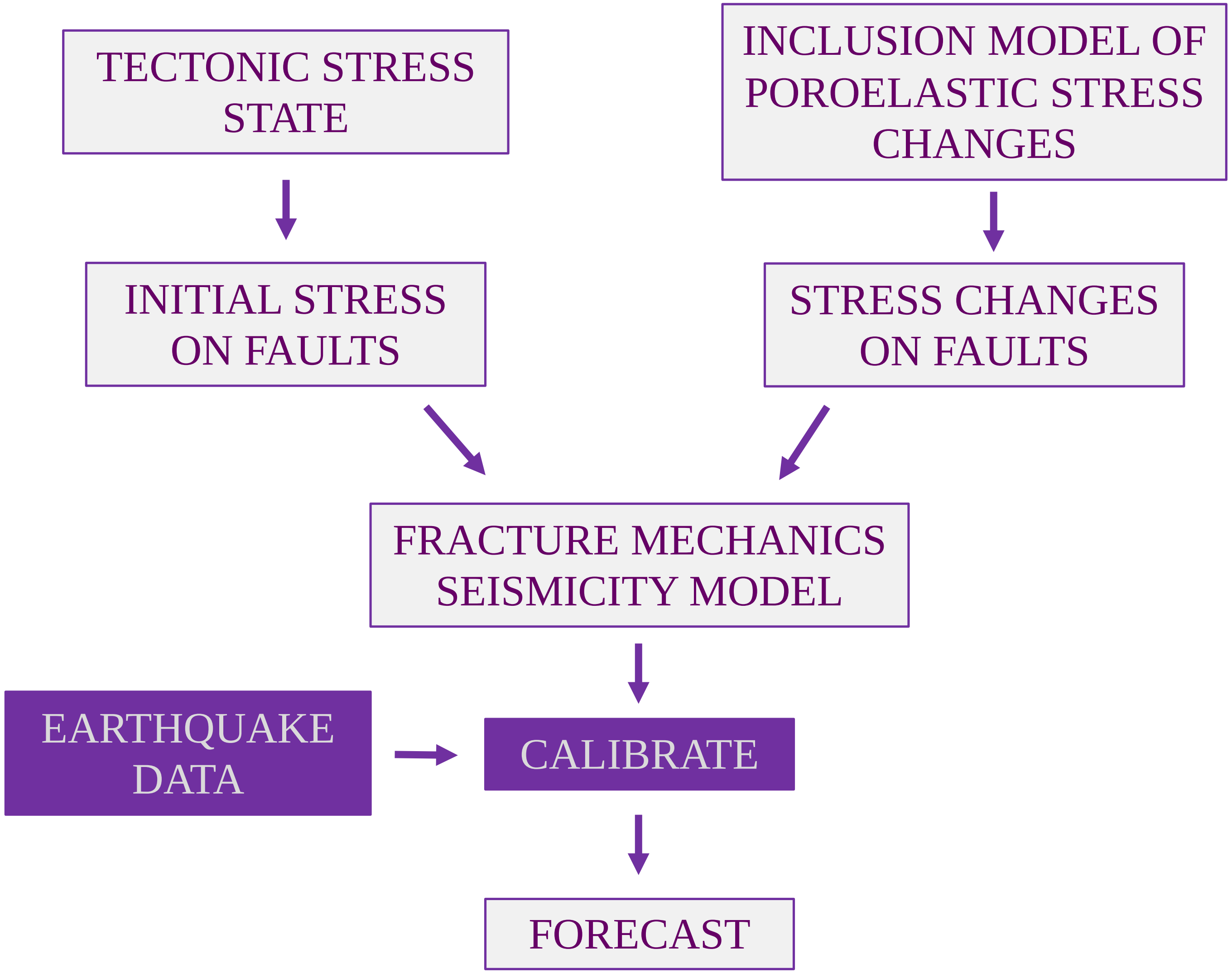

Components:

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- For each fault in the Groningen reservoir (longer than 2 km, and within 30° of optimal orientation in the stress field), an initial shear stress, τ_0, and stress change, $\Delta\tau$, are computed.
- The stress change $\Delta\tau$ operates as a nonuniform loading condition on the fault – one can imagine the "equivalent pressure" change.
- Each separate fault acts as an emitter of seismicity. Locations, rates and b-values can be assigned to different faults.
- Here, we only look at the overall seismicity rate and magnitude-frequency distribution.

Components:

1. Concepts
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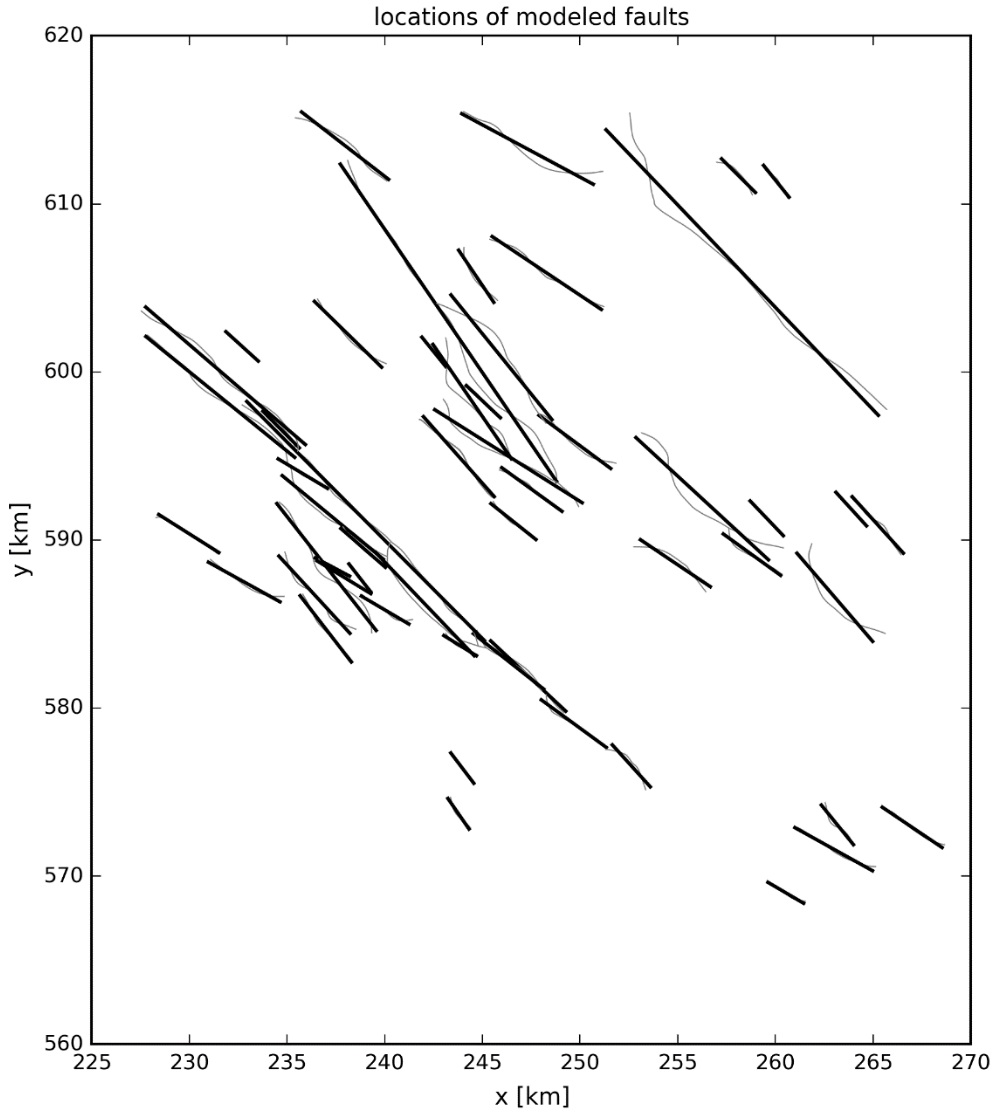

<u>Components:</u>

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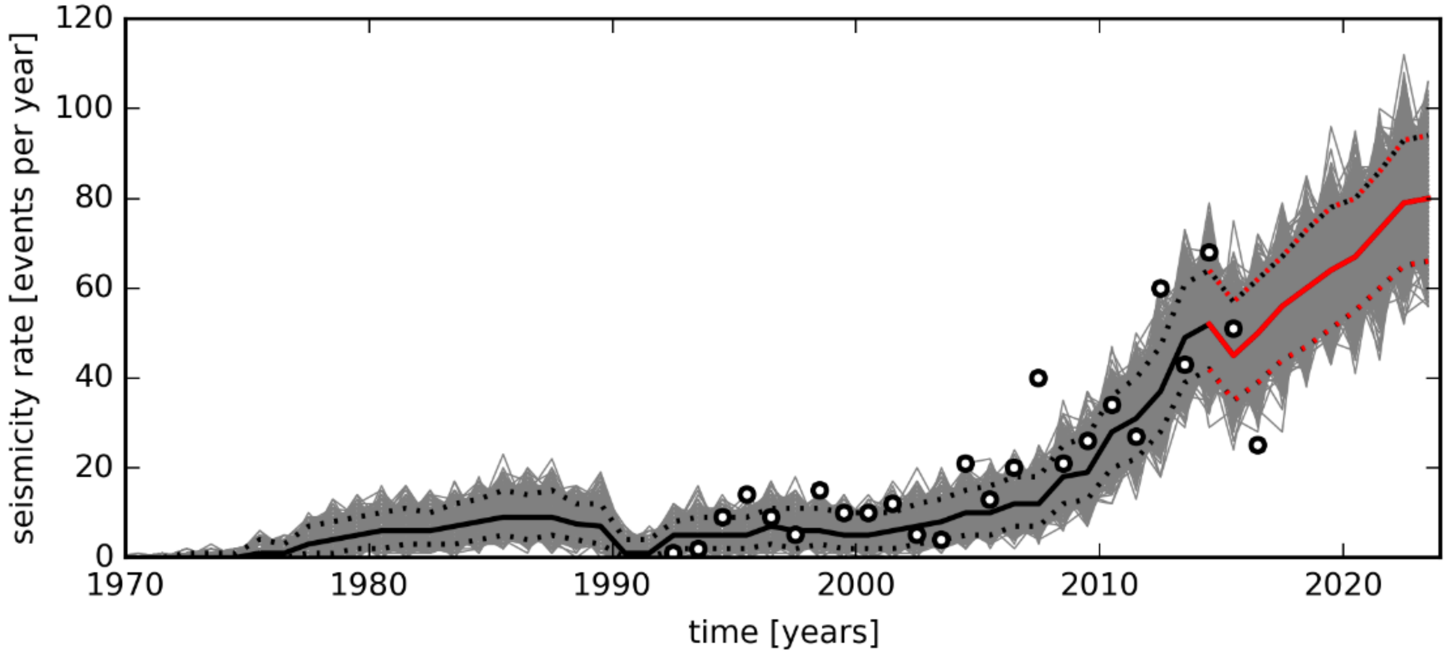
- Calibration occurs against the observed seismicity rate.



- 2000 realizations of the stochastic model are constructed (grey) with the mean value indicated by a solid line.
- Red profile indicates modeled seismicity in the prediction period.

Components:

1. Concepts
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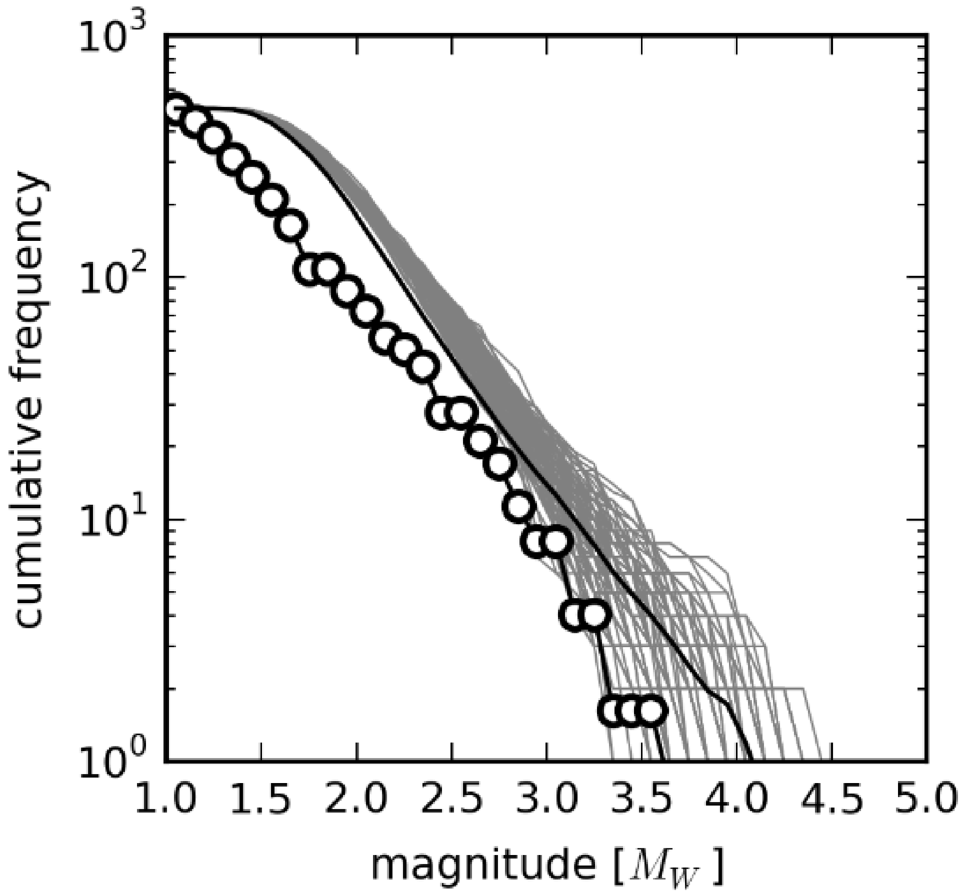
- Calibration also against the magnitude frequency distribution. We slightly overestimate magnitudes.



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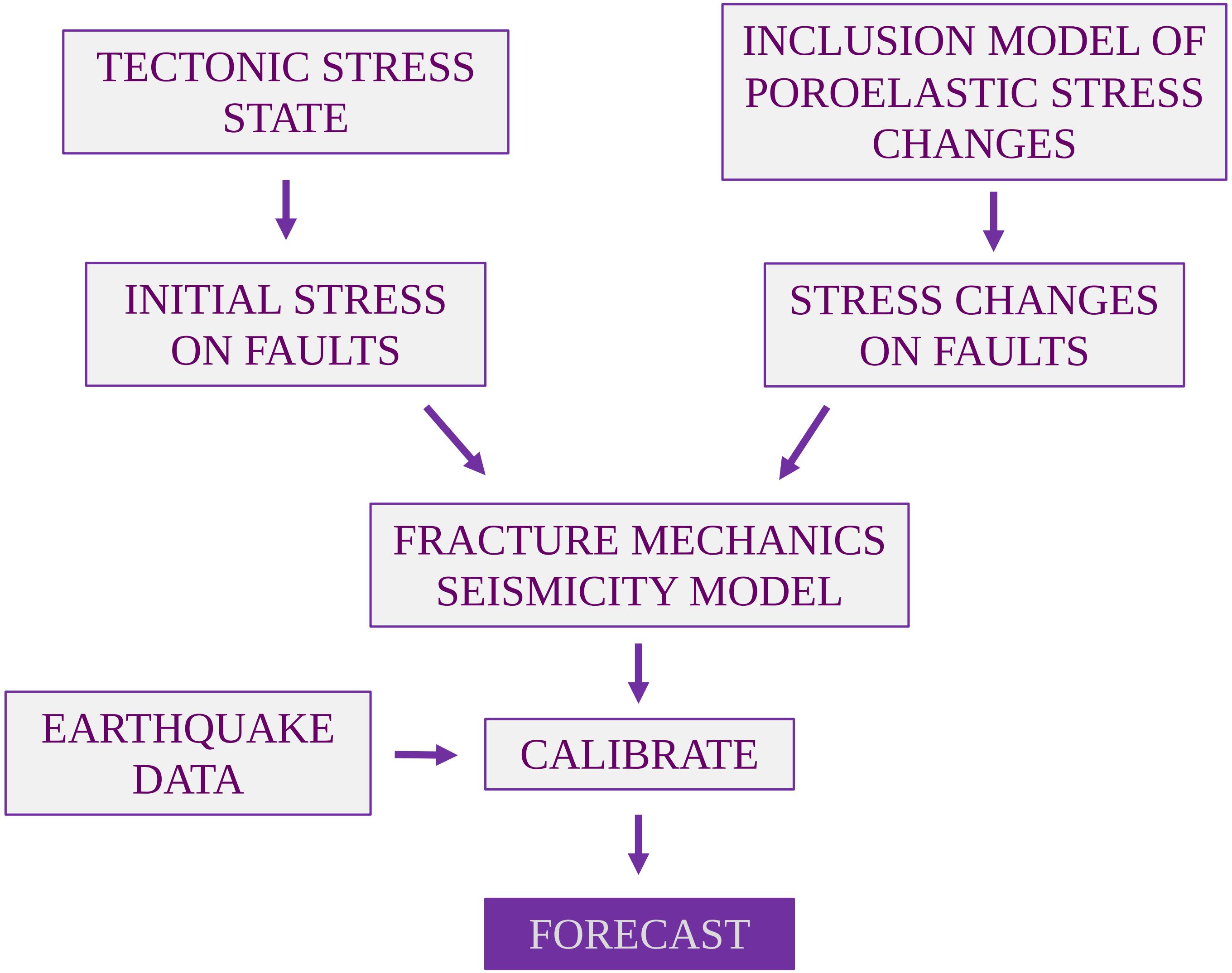

Components:

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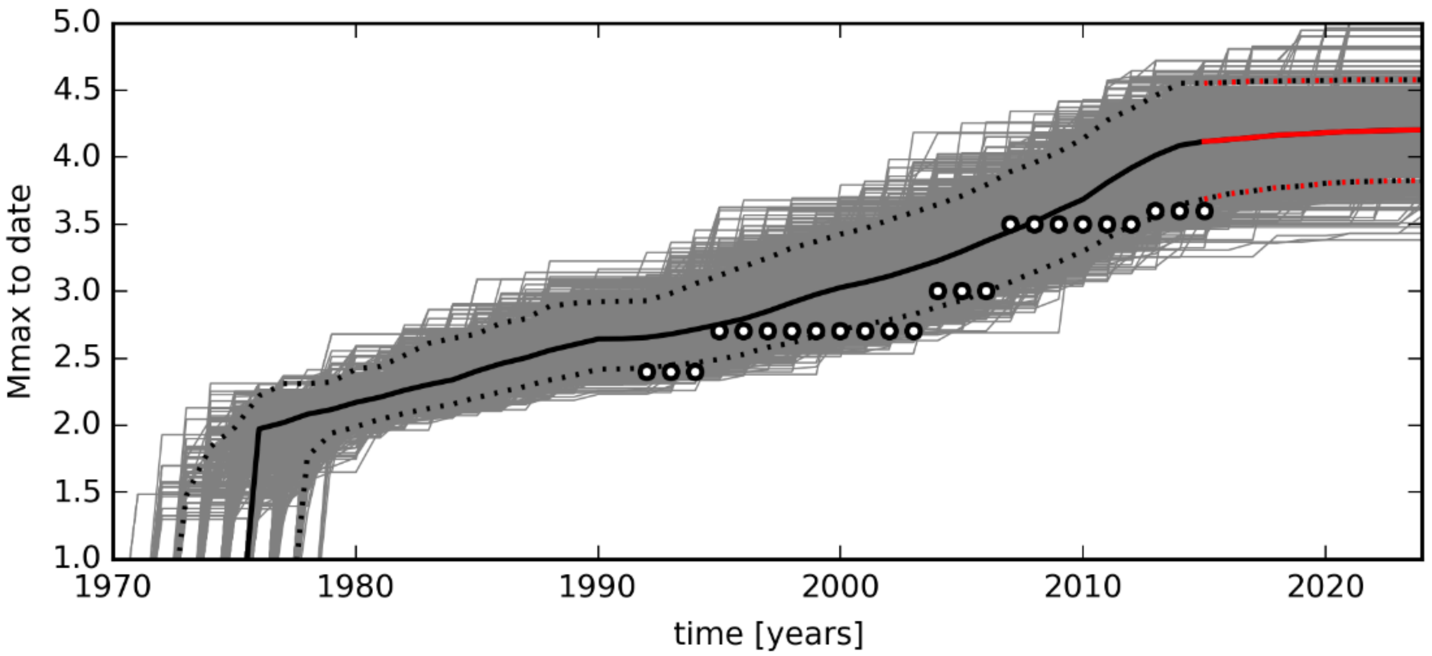
- Largest magnitude event to date, Mmax, increases over time. Model matches reasonably well, overestimates slightly.



- By the end of the prediction period (2024), median Mmax is 4.2 in 90% bounding interval [3.8, 4.6].

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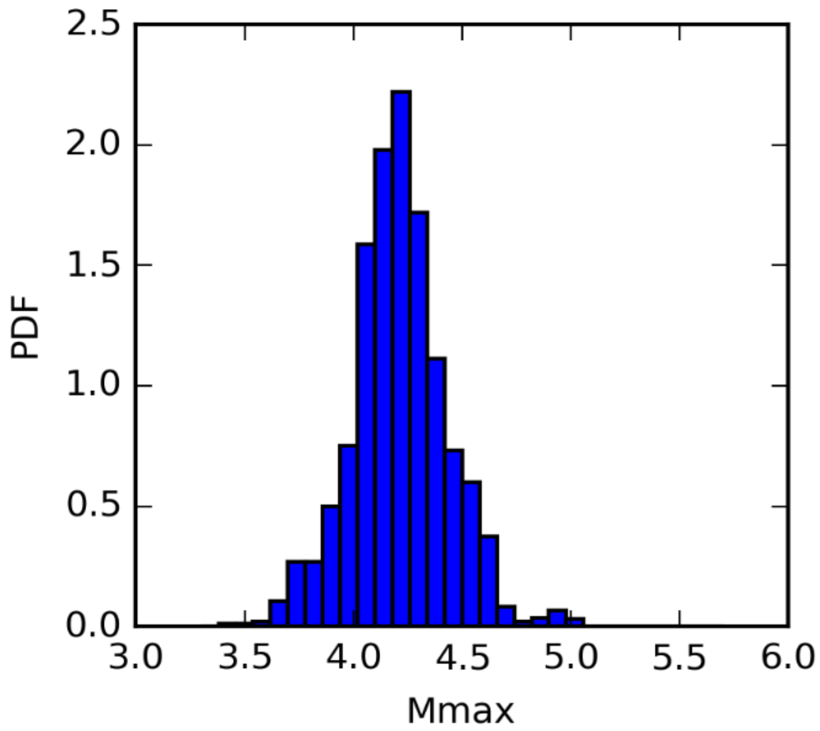

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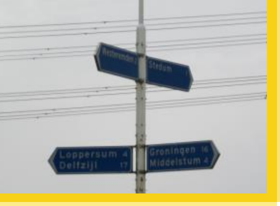
Final note:

The Eshelby inclusion model is too coarse to resolve differences between the three extraction scenarios.

Time evolution of the full stress tensor everywhere in the reservoir would be preferable as a loading condition for the induced seismicity model. This could be performed by a geomechanical simulator.

TNO and other M_{max} models for Groningen Induced Earthquakes

Steve Oates, Shell Rijswijk



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Overview

- Explanation – scope of presentation and disclaimer.
- Who are TNO?
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  - Early phase – M_{max} estimates based on fault dimensions and global moment budget
  - Later phase – spatially varying M_{max} estimates based on local moment budget
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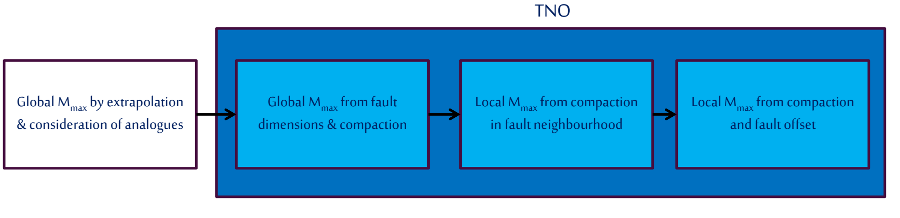

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Disclaimer/explainer

- TNO unable to present at M_{max} workshop themselves but were made aware that we would be presenting their views in this way.
- We present this as a necessary contribution to this workshop to ensure that a significant proponent view is given due consideration.
- This presentation is based on the content of the TNO documents available to me.
- The views presented are to the best of my ability a representation of the views expressed by TNO in those documents.
- Interpretation of the documents is based on my translations of the Dutch language originals and open to challenge.
- Final section on M_{max} distributions is provided courtesy of Dirk Kraaijpoel. This documents initial ideas rather than completed work and does not represent as yet accepted views of either KNMI or TNO.
- At the end I present some comments of my own but identify these clearly as being my own views rather than those of TNO.

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Who are TNO?

From Wikipedia:

- TNO = Nederlandse Organisatie voor Toegepast Natuurwetenschappelijk Onderzoek (Netherlands Organisation for Applied Scientific Research)
- Nonprofit company that focuses on applied science
- A knowledge organization for companies, government bodies and public organizations.
- Approximately 3,800 employees – largest research institute in the Netherlands.

See also: www.tno.nl

In the context of the Groningen project:

- TNO is a key advisor and consultant to the regulator, SodM
- TNO has been involved with issues around Groningen induced seismicity since at least 2012

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Raw material used for this presentation

- This presentation is based on the content of the following TNO documents

TNO 2013 R11953 | 30 April 2014 | TNO 2014 R11662

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Raw material used for this presentation ...

- The following TNO document was made available on 7th March 2016

TNO 2015 R11138

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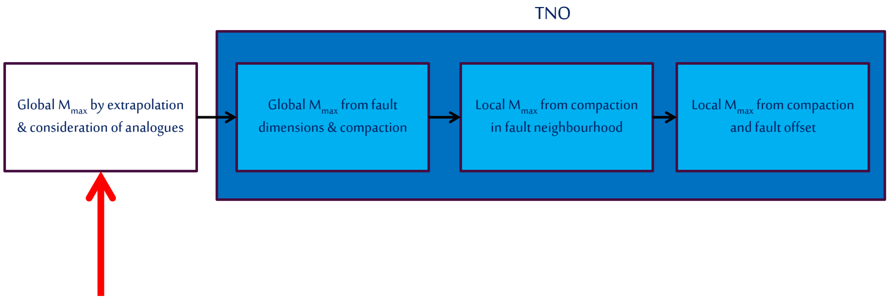

Mmax from global moment budget and fault dimensions

- KNMI's PSHA (as reported in 2013) used M_{max} = 5.0, derived from an analysis of other cases of induced seismicity world-wide.
- "M_{max} = 5.0 was a choice made by KNMI" – in the context of their PSHA calculations – but "this choice can not be supported".
- "A choice for M_{max} with a sound basis can be obtained from geomechanical considerations where compaction is viewed as the driving force behind the seismicity leading to an upper bound for the maximum seismic moment in the gas field."
- TNO proposed following this approach to obtain a better estimate for M_{max}.
- Proposed also a spatially varying derivation of the relationship between seismic moment release and reservoir compaction. Then also argued that M_{max} should therefore be spatially varying.
- Assume large earthquakes occur on existing faults but that microseismicity does not need to respect this limitation.

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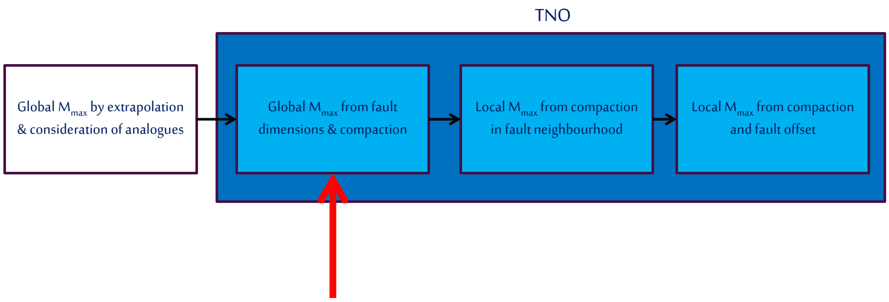
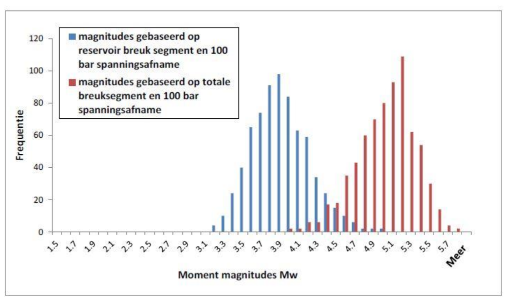


Bounds on magnitudes from interpreted fault areas

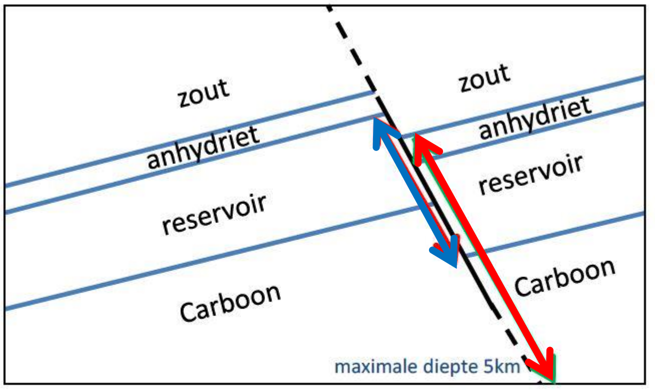
- Moment magnitude bounds calculated for interpreted faults using Brune model formulae & assumed parameter values
- Blue histogram: magnitudes based on fault area within reservoir: $M_{max} \approx 5.0$
- Red histogram: magnitudes based on fault area for an assumed continuation of faults into Carboniferous, to 5000m depth: $M_{max} \approx 5.8$
- Assumed stress drop of 10MPa

TNO-rapport | TNO 2013 R11953 | Eindrapport 111 / 211



Figuur 6.2 Moment magnitudes (M_w) berekend voor twee sets van breukoppervlaktes uit het 3D Petrel model: Magnitudes van set 1(blauw) zijn gebaseerd op het oppervlak van de breuken dat grenst aan reservoir gesteente; magnitudes van set 2 (rood) zijn gebaseerd op het totale oppervlakte van de breuken onder het Zechstein steenzout, onder aanname dat de breuken doorlopen tot een diepte van 5000 m beneden maaiveld. Magnitudes zijn berekend voor een spanningsafname van 100 bar (10 MPa) en een schuif modulus van 10GPa.

Explanation of fault area determinations



Figuur 6.1 Berekening van de parameter 'w' van de breuken in het Petrel breukmodel. Set 1 gaat uit van de breedte w van het breuksegment dat grenst aan het reservoirgesteente (rode pijlen). Set 2 gaat uit van de breedte w van het breuksegment, gemeten vanaf onderkant Zechstein zout tot een diepte van 5 km (groene pijlen).

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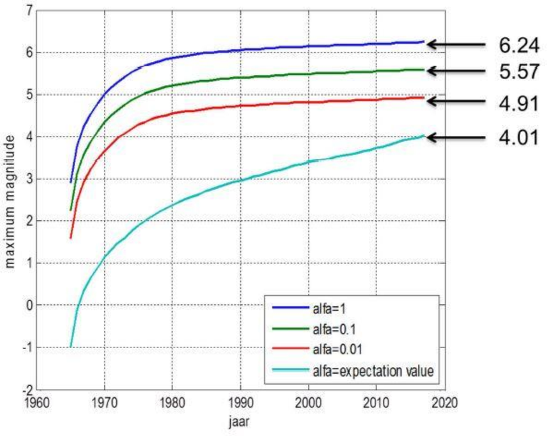
Bounds on M_{max} from global moment budget

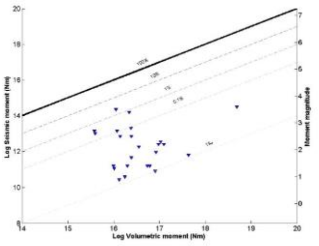
- A conservative upper bound is obtained by integrating the Kostrov-McGarr expression over the whole field. Using different partition coefficients and converting to M_{max} for a single event gives the following plot



Figuur 5.3. Maximum magnitude berekend op basis van het totaal reservoirmoment in het hele veld als functie van tijd voor vier partitiecoëfficiënten.

Assumptions regarding bounds on strain partitioning

- Observations so far over Groningen and other gas fields in the area show that partition coefficient is not greater than 0.01 (study by Buijze).



- A partition coefficient value of 1.0 gives M_{max} of around 6.0.
  - Such an event will have a negligible probability of occurrence;
  - Requires the release of whole moment budget in a single (composite?) event;
  - It is claimed that an important part of the total budget has already been released;
  - A part of the moment budget is released through (aseismic) subsidence;
  - It is claimed that a part of the moment budget is localised too far from large faults to be released by slip on faults.

Assumptions regarding bounds on strain partitioning

- TNO limit themselves to consideration of induced seismicity due to compaction.
- There is no contribution to the moment budget considered from tectonic strains.
- The moment budget is due to compaction only and this determines the maximum magnitude.
- TNO do acknowledge the possibility of release of shear stress on faults outside the reservoir but do not explicitly consider this in the induced seismicity moment budget. They claim that to understand this slip velocity dependent fault friction laws need to be incorporated in the geomechanical model.
- TNO comment that M_{max} of around 6.0 – 6.5 requires all compaction to be seismogenic and the entire global moment budget to be released by a single event and they consider both of these conditions to be very unlikely/unrealistic

Bounds on M_{max} from global moment budget

Tabel 7.1 Het totaal aan seismisch moment (Nm) wat kan vrijkomen in de periode 2013-2023 voor verschillende aannames van de relatie van de partitiecoëfficiënt met de compactie. Als dit seismisch moment in één keer zou vrijkomen zou dat leiden tot de maximale magnitude in kolom 3.

Partitiecoëfficiënt	Seismisch moment (Nm)	Maximale magnitude
Constant (10^{-3})	$1{,}1 \cdot 10^{15}$	4,0
Constant (1,0)	$1{,}1 \cdot 10^{18}$	6,0
Exponentieel	$7{,}6 \cdot 10^{15}$	4,5
+95% betrouwbaarheid	$4{,}4 \cdot 10^{16}$	5,0
+95% en bovengrens 1%	$1{,}1 \cdot 10^{16}$	4,6

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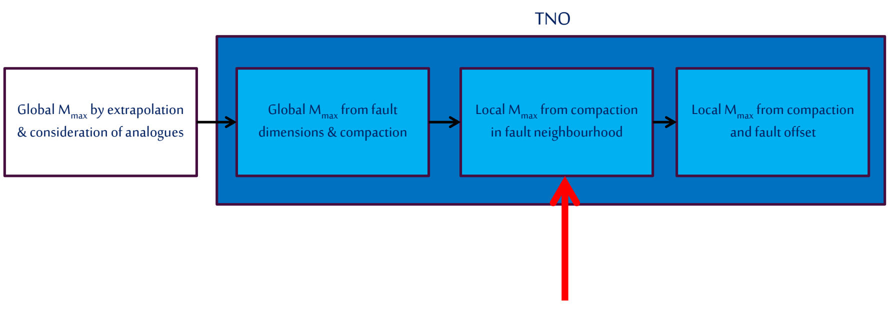


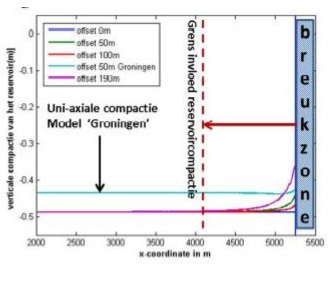
Local moment budgets and spatially-varying M_{max}

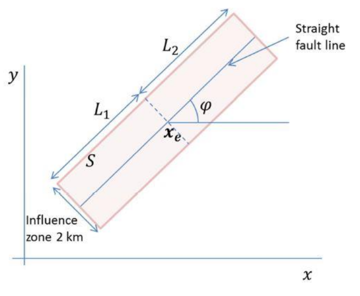
- Finite element simulations were run for a model of a compacting reservoir with a fault.
- Demonstrated the existence of a region of about 1km width from the fault over which the compaction transitioned between the simple uniaxial case and a configuration in which the fault offset and friction retards the compaction.
- Only the compaction difference relative to the far-field uniaxial value contributes to the moment budget available to the fault plane being considered.
- Kostrov-McGarr expression is integrated in the region around the fault where this compaction difference from the uniaxial background is non-zero to determine local moment budget for fault.
- Integration limited to 1km zone of influence around the fault, irrespective of fault dimensions.
- Several fixed partition coefficient values were used (ie. not a distribution).

Local moment budgets and spatially-varying M_{max}

- In Dec 2014 report (2014-R11662) applied earlier thinking (M_{max} estimates from global moment budget) to zone of influence around fault…
- Kostrov-McGarr expression taken from Bourne and Oates (2013) (up to a factor of 2) and used to determine local moment budget for fault – integration limited to 1km zone of influence around the fault:

$$M_r(t) = 2\mu \iint \Delta h(\mathbf{x},t)\alpha_f(\Delta h(\mathbf{x},t))dS$$





Figuur 5.2. Breuk en invloedszone voor het definiëren van het integratiegebied S gebruikt in de berekeningen.

Local moment budgets and spatially-varying M_{max}

- Maps of spatially varying local M_{max} generated as follows:
  - Faults of lengths 3km, 12km, 45km and field-spanning placed at each cell of simulation grid
  - Local moment budget calculated from Kostrov-McGarr integral, as explained above, for a range of fault orientations (1: all orientations 2: favoured orientations from fault map) and a range of partition coefficient values
  - Largest local M_{max} value obtained as a function of orientation taken as the local M_{max} for cell.
- See following panels of plots

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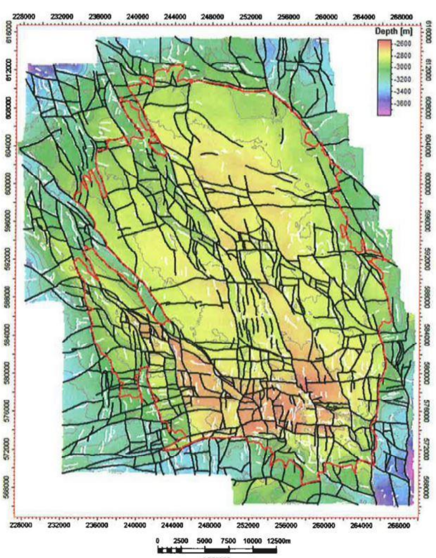
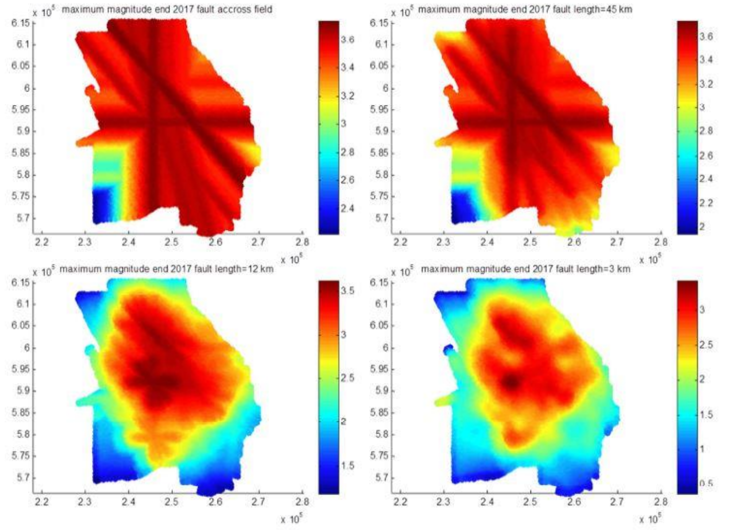
Top Rotliegend map with fault traces



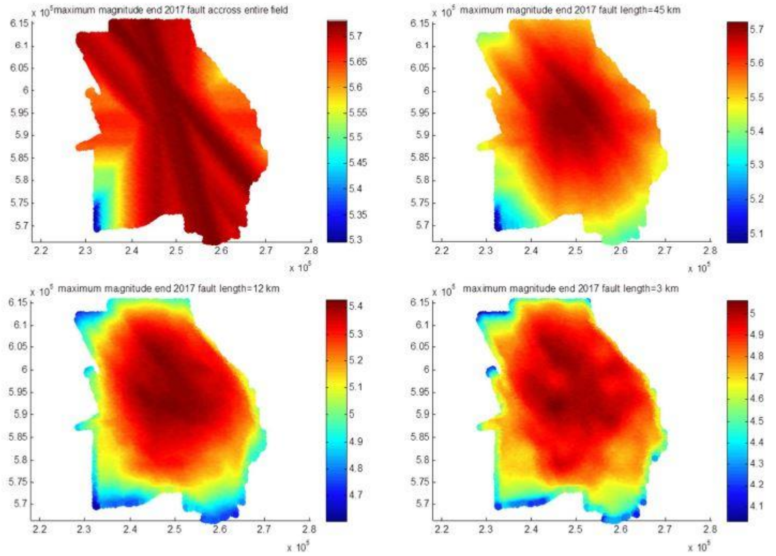
Figuur 5.11. Top Rotliegend dieptekaart met de gemodelleerde breuken (zwart) en de additionele breuken (wit).

Spatially-varying M_{max} for expectation value of α



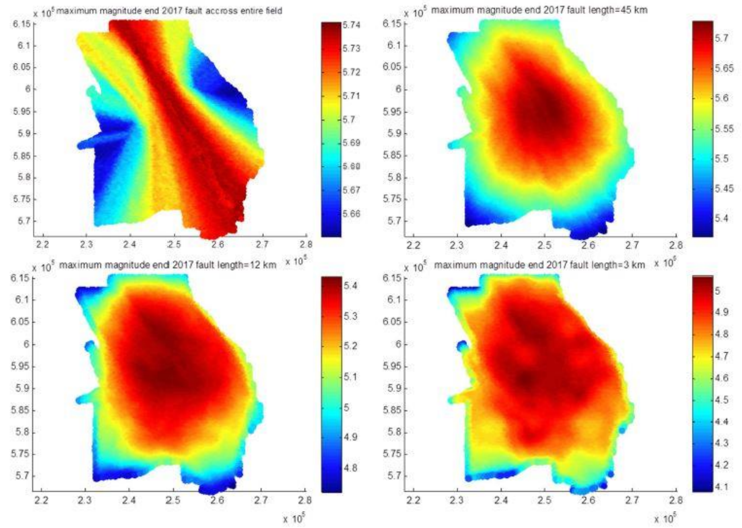
Figuur 5.12. Maximum magnitudes op basis van reservoirmoment berekend voor de verwachtingswaarde van de partitiecoëfficiënt voor breuken met oriëntaties voorkomend in het Groningen veld met lengtes 45, 12, 3 km en door het hele veld.

Spatially-varying M_{max} for α=1



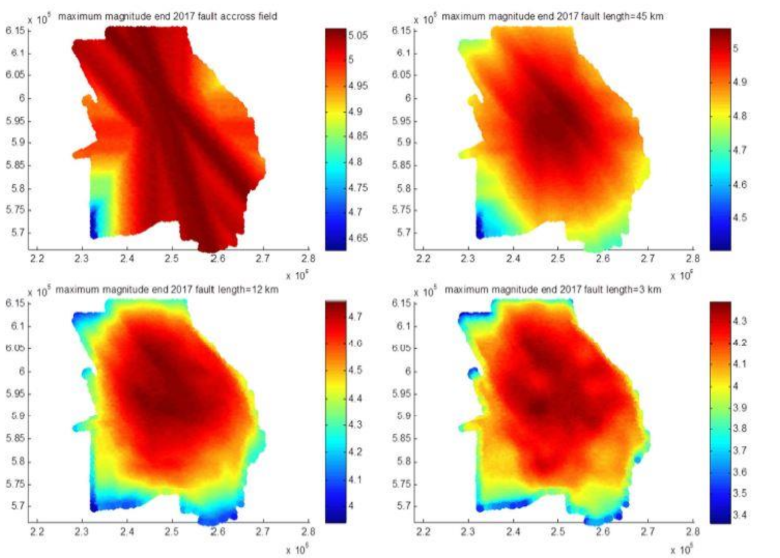
Figuur 5.13. Maximum magnitudes op basis van reservoirmoment berekend voor partitiecoëfficiënt 1 voor breuken met oriëntaties voorkomend in het Groningen veld met lengtes 45, 12, 3 km en door het hele veld.

Spatially-varying M_{max} for α=1, arbitrary fault orientations



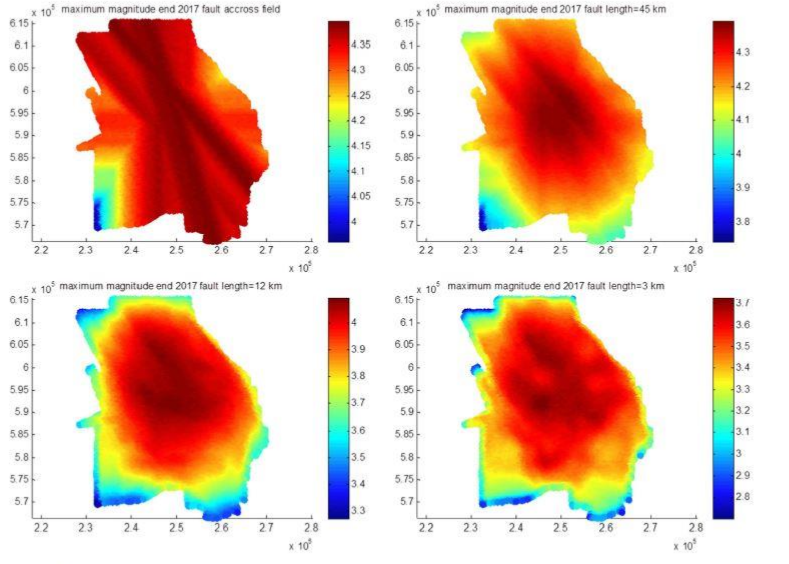
Figuur 5.6. Maximum magnitudes op basis van reservoirmoment berekend voor partitiescoëfficiënt 1 voor willekeurige georiënteerde breuken met lengtes 45, 12, 3 km en door het hele veld.

Spatially-varying M_{max} for α=0.1



Figuur 5.14. Maximum magnitudes op basis van reservoirmoment berekend voor partitiecoëfficiënt 0,1 voor breuken met oriëntaties voorkomend in het Groningen veld met lengtes 45, 12, 3 km en door het hele veld.

Spatially-varying M_{max} for α=0.01



Figuur 5.15. Maximum magnitudes op basis van reservoirmoment berekend voor partitiecoëfficiënt 0,01 voor breuken met oriëntaties voorkomend in het Groningen veld met lengtes 45, 12, 3 km en door het hele veld.

Summary & conclusions – 1

- Partition coefficient values of 0.01 or 0.1 considered conservative for short time periods
- Field spanning rupture considered unrealistic given the observed fault aspect ratios
- 12km fault length seen as a conservative maximum
- Above arguments lead to M_{max} in range 4.1 to 4.7 for the central field area. "M_{max} = 4.5 for central region in the short term is a possibility". On the flanks M_{max} is between 3.5 and 4.0
- "M_{max} = 5.0 looks too conservative for the short time periods being considered but may be reasonable for longer exposure periods – this needs to be further studied"

Tabel 7.1: Overzicht maximale magnitude

Partitiecoëfficiënt	Maximum magnitude bij breuk door hele veld	Maximum magnitude bij breuk door hele veld (Groningen oriëntatie)	Maximum magnitude bij 12 km breuk
0,01	4,4	4,4	4,1
0,1	5,0	5,0	4,7

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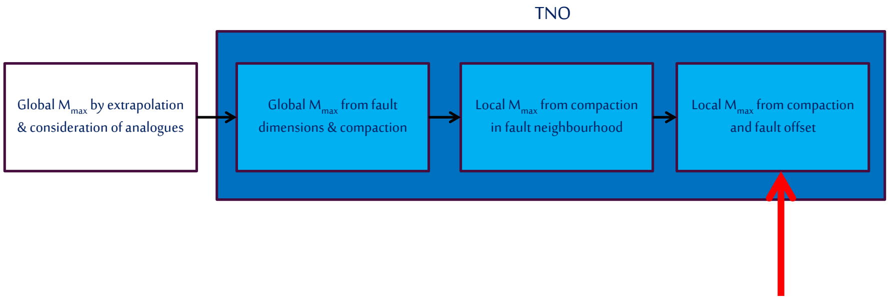

Spatially-varying M_{max} estimates using fault offsets

- The objective of the 2015 report was to inform the NPR 9998 committee in its choice for a hazard model for the next version of the NPR – this is part of the Netherlands' annex to Eurocode-8 and is used to determine which buildings need strengthening and to what degree.
- A fault based geomechanical approach is taken to determine the maximum earthquake magnitudes for the short term up to the end of 2017.
- The 2015 TNO approach makes use of the following expression from Bourne et al for the maximum seismic moment per unit area required to accommodate the deviatoric strains:

$$\frac{1}{A}\sum_{k=1}^{N(t)} M_o^k m_{ij}^k = \mu c(t)\left(\frac{1}{3}+\sqrt{1+|\nabla(z_o)|^2}\right)\begin{pmatrix}1&0&0\\0&\frac{\lambda_2'}{\lambda_1'}&0\\0&0&\frac{\lambda_3'}{\lambda_1'}\end{pmatrix}$$

- TNO analysis addr ult.

Spatially-varying M_{max} estimates using fault offsets

- Assumptions
  - there is no contribution from release of tectonic stresses;
  - fault slip is contained within the reservoir;
  - there is a zone of influence around a fault beyond which compaction is laterally homogeneous;
  - induced earthquakes occur on faults with interpretable offsets;
  - do not consider compound earthquakes (simultaneous failure of multiple fault segments).

Spatially-varying M_{max} estimates using fault offsets

- Finite element simulations of slip on a single fault in compacting reservoir.
- Initially, fault friction establishes shear stresses around fault
- Removal of fault friction allows slip on fault

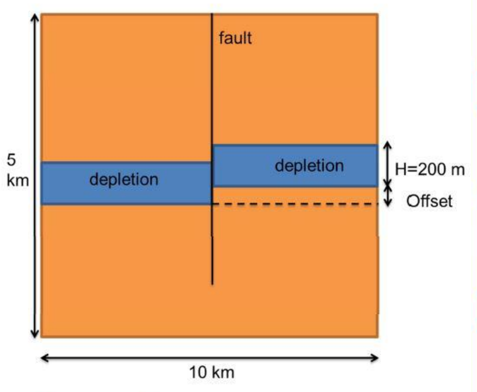

Figure 4.2 Setup of the finite element simulations.

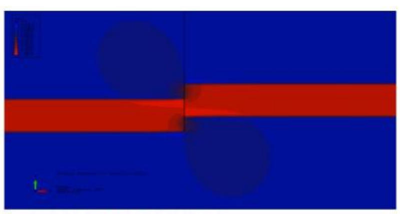

Figure 4.13 Vertical strain field when the fault is fully rough.

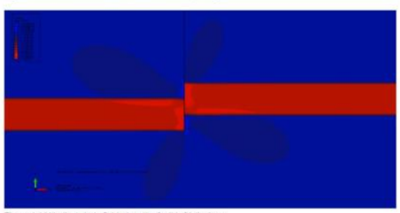

Figure 4.14 Vertical strain field when the fault is frictionless.

Spatially-varying M_{max} estimates using fault offsets

- Calculate seismic moment from simulations by integrating slip over fault surface
- Find a linear relationship between moment and fault offset, consistent with simple analytic model of Bourne et al 2015, up to a geometric factor (see McGarr 1976)

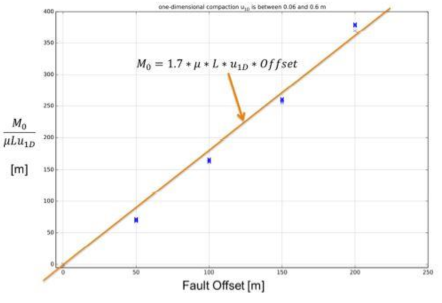

Figure 4.6 Seismic moment calculated from the simulation results versus fault offset. The seismic moment is scaled with the shear modulus and the one-dimensional compaction and is per meter fault length L.

The seismic moment is calculated by integrating the results of figure 4.5 over depth, using:

$$M_0 = \mu L \int u(z) dz$$

Spatially-varying M_{max} estimates using fault offsets

- At each grid point, calculate moment using above expression for moment release (and hence M_{max}) for a 12 km long fault with 200m offset, sampling all orientations. Take largest value as M_{max} at each location.

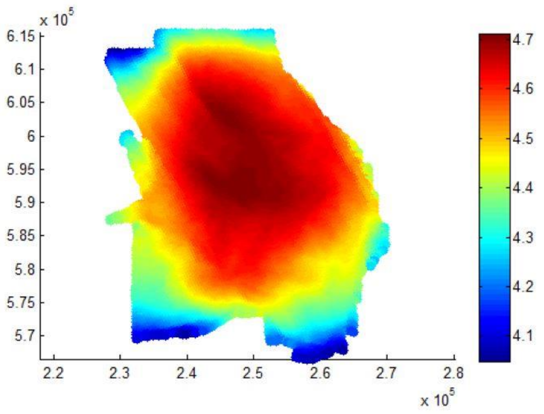

Figure 5.4 Earthquake magnitudes for a 12 km fault with offset 200 m.

Summary & conclusions – 2

- "For a 12 km long fault and a, rather large for the Groningen field, 200 m offset, the maximum earthquake magnitude at the end of 2017 is 4.7."
- "It is, however, not proven that these maximum magnitudes have a zero probability of exceedance for the Groningen field. It is therefore proposed to use a statistical distribution function for the maximum magnitude with a mean value."

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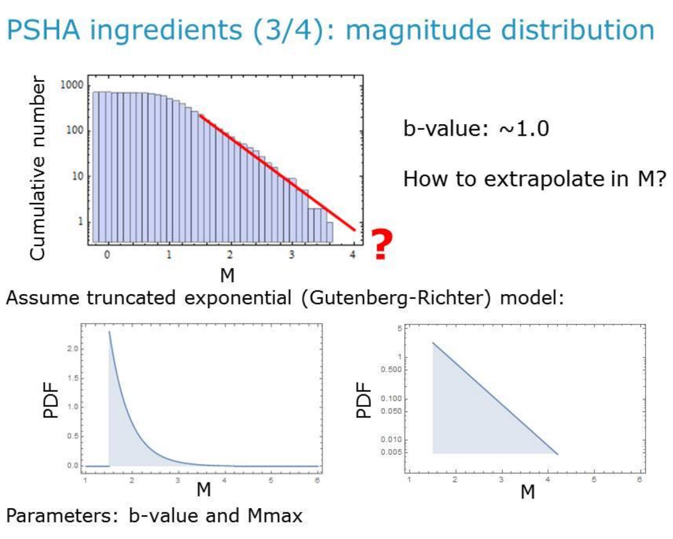
Proposals for M_{max} distributions



This slide, provided courtesy of Dirk Kraaijpoel (KNMI/TNO), summarises some of his initial ideas on possible M_{max} distributions and does not represent as-yet accepted views of either TNO or KNMI.

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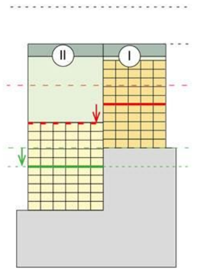
Proposals for M_{max} distributions

PSHA ingredients (3/4): magnitude distribution

How to constrain Mmax?
No evidence from statistics.



What can geomechanics do?

- Determine
  - Local medium properties (shear modulus)
  - Maximum fault area
  - Maximum slip

But:

- Larger faults: extend in depth, laterally or both?
- What stress drops can we expect?

Practical choices:
NPR: Mmax = 5 from literature study
Bourne et al.: Mmax = 6.5 from total compaction volume

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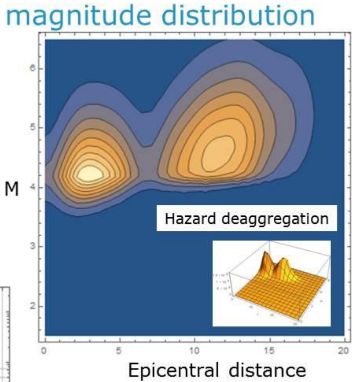
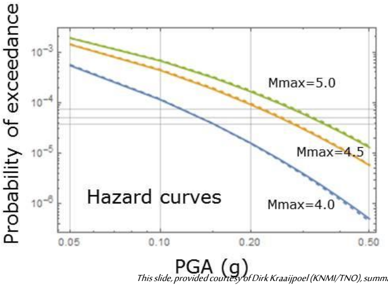
Proposals for M_{max} distributions

PSHA ingredients (3/4): magnitude distribution

Choice of Mmax can be critical.
Choosing high is conservative





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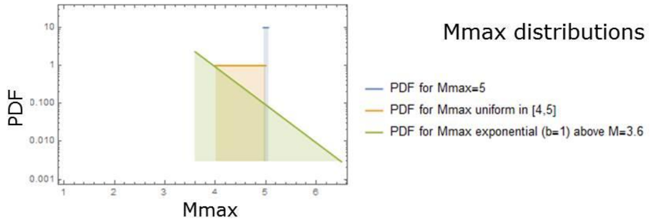
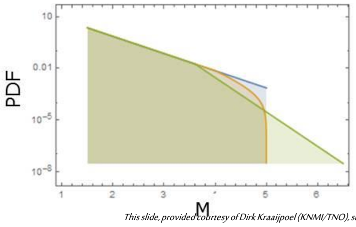
Proposals for M_{max} distributions

PSHA ingredients (3/4): magnitude distribution

Use distributions of Mmax:



effective
M distributions



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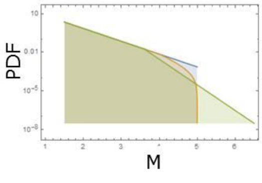
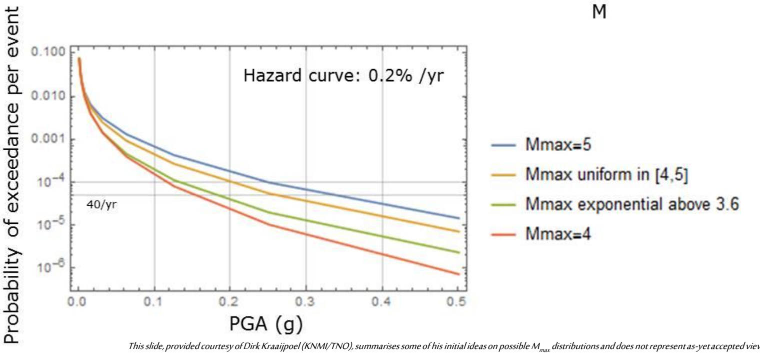
Proposals for M_{max} distributions

PSHA ingredients (3/4): magnitude distribution

Effect of using Mmax distributions





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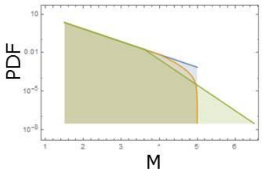
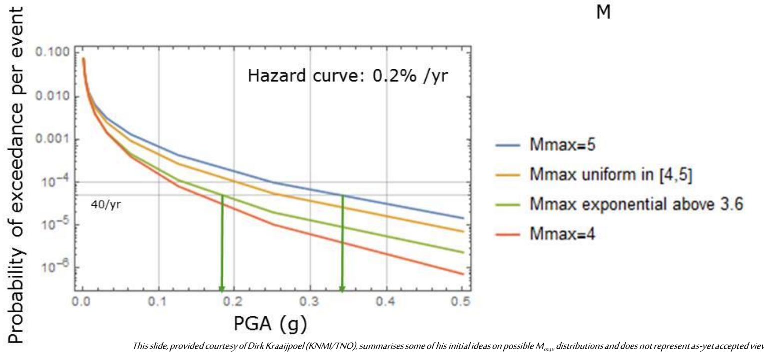
Proposals for M_{max} distributions

PSHA ingredients (3/4): magnitude distribution

Effect of using Mmax distributions





This slide, provided courtesy of Dirk Kraaijpoel (KNMI/TNO), summarises some of his initial ideas on possible M_{max} distributions and does not represent as-yet accepted views of either TNO or KNMI.

Confidential

Proposals for M_{max} distributions

PSHA ingredients (3/4): magnitude distribution

Motivation for exponential distribution:

- Based on scale-independence: seismogenic systems with larger Mmax are less likely than those with smaller Mmax (Bayesian prior)

Bayesian perspective:

- Posterior = Likelihood * Prior
- Non-informative prior / null information: exponential distribution over infinite range
- Likelihood:
  - Here: simplified as step function for Mmax > 3.6 (max observed)
  - Based on catalogue
  - Other (external) empirical evidence may be included

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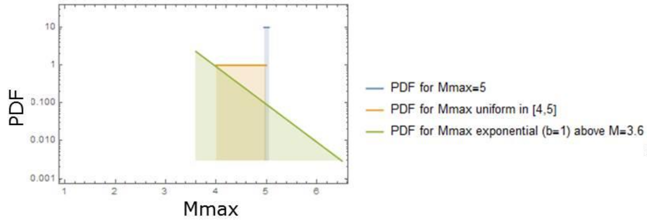
Confidential

Proposals for M_{max} distributions

PSHA ingredients (3/4): magnitude distribution



Bayesian perspective:

- Posterior = Likelihood * Prior
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- Likelihood:
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  - Based on catalogue
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Proposals for M_{max} distributions

PSHA ingredients (3/4): magnitude distribution

Advantages exponential prior

- Requires no (arbitrary / debatable) upper bound; lower bound from observations
- No magnitude is excluded

This slide, provided courtesy of Dirk Kraaijpoel (KNMI/TNO), summarises some of his initial ideas on possible M_{max} distributions and does not represent as-yet accepted views of either TNO or KNMI.

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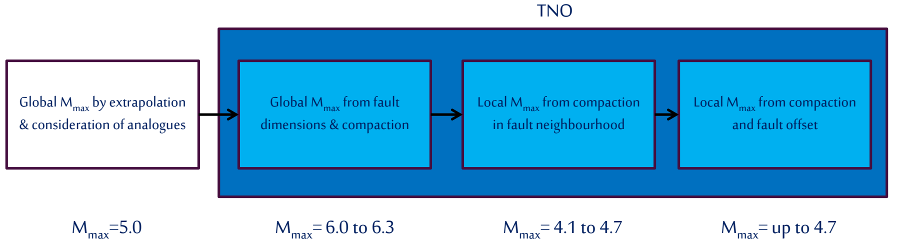
Summary & conclusions – 3

- Early global M_{max} estimates derived both from fault size and moment budget broadly agree with NAM (Bourne & Oates 2013) upper bounds.
- Calculations of local moment budgets around faults suggest reducing M_{max} values.
- Assumed bounds on strain partitioning and maximum length of rupture are needed to arrive at TNO's proposed M_{max} values in the range 4.1 to 4.7.
- Motivation for assumed bounds on strain partitioning comes from observations in other gas fields in the Netherlands.
- Exponential distribution for M_{max} proposed as a non-informative Bayesian prior



Presenter's own comments/criticisms of work presented

- TNO approach overlooks subseismic faulting – such faults can be big enough to host significant earthquakes – this somewhat undermines the argument behind local moment budgets.
- Local moment budget idea does not undermine the observed possibility of long range triggering
- Rejection of higher values of partition coefficient is partly a misunderstanding of what M_{max} should be – an upper bounding value – and also neglects the generic statistical models which do (all?) exhibit the escalating partitioning.
- In other words – can we know how far we are along the path to α=1?
- Region of influence around fault must surely be fault length dependent (Saint-Venant's principle?) or at least offset dependent?
- Local moment budget concept nevertheless deserves further consideration.
- Rejection of higher M_{max} values neglects possibility of large composite events where many fault segments fail simultaneously – can/should these be rejected as being to all intents impossible or must they be considered as upper bounds? Are there any examples of such events known?
- Uninformed Bayesian prior distribution for M_{max} – need to prove that this is indeed the appropriate objective prior distribution.
- Consult KNMI for more detail on their M_{max} estimates.

Spatially-varying M_{max} estimates from strain-thickness

- The 2015 TNO approach makes use of the following expression from Bourne et al. The maximum seismic moment per unit area required to accommodate the deviatoric strains:

$$\frac{1}{A}\sum_{k=1}^{N(t)} M_o^k m_{ij}^k = \mu c(t)\left(\frac{1}{3}+\sqrt{1+|\nabla(z_o)|^2}\right)\begin{pmatrix}1 & 0 & 0\\ 0 & \frac{\lambda_2'}{\lambda_1'} & 0\\ 0 & 0 & \frac{\lambda_3'}{\lambda_1'}\end{pmatrix}$$

- TNO analysis uses only the gradient term associated with displacement on a fault.
- Aside: the TNO 2015 report apparently overlooks the fact that the above expression is for the deviatoric part of the compaction strain, arguing instead that the non-gradient terms need to be subtracted for double-couple sources. Nevertheless, the TNO report is clear that they assume that the induced earthquakes will occur on pre-existing faults with offset in the reservoir – in other words, this minor criticism is not material to the work as reported.

Modelling of strong tremors in the Groningen field

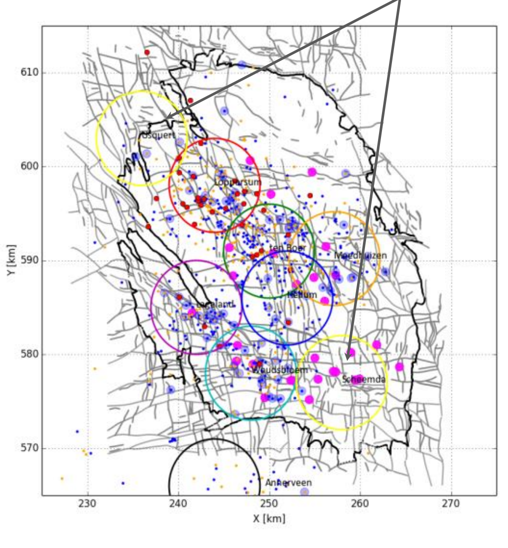
preliminary results

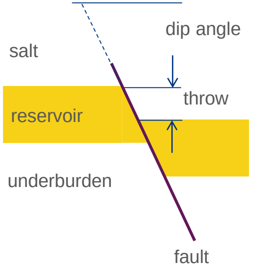
Presentation for the Groningen field Mmax workshop
march 2016

Rick Wentinck – SGS-I PTI/RC

Correlations between tremors and fault properties

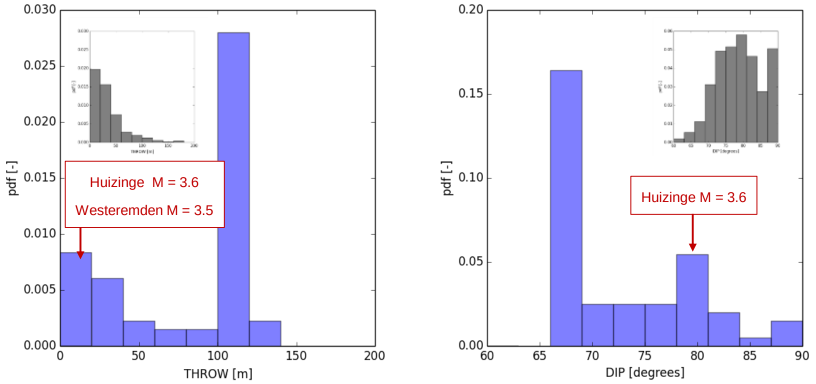
regions with hardly tremors





Correlations between tremors and fault properties

fault properties of about 60 tremors with M ≥ 2.5

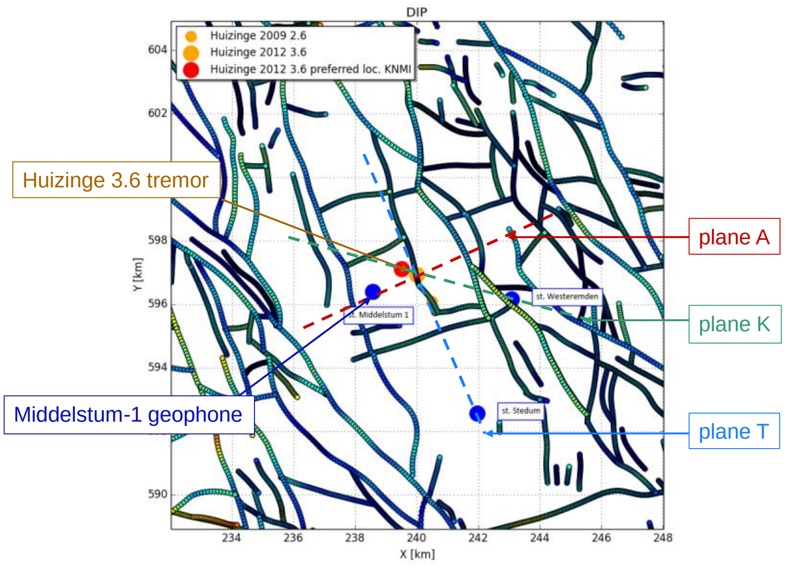


no other clear correlations observed so far between tremors and fault properties in the Groningen field

Question raised

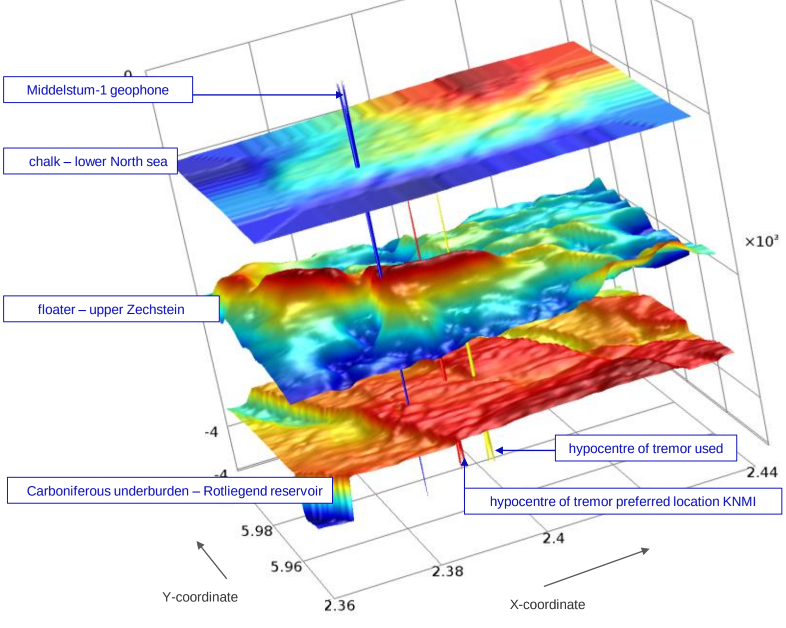
- Dynamic rupture modelling shows that ruptures in the reservoir may propagate into the Carboniferous underburden.
  Important parameters are:
  - dynamic or residual friction coefficient
  - fault dip, fault throw, horizontal/vertical field stress ratio
  - the amount of compaction (proportional to the pressure drop in the reservoir)
- If so, significant additional strain energy stored along the fault plane could be released making strong tremors possible.
- Is there evidence from the ground motions of strong tremors in the Groningen field that the rupture has propagated into the underburden?
- So far, the strongest tremors correlate with a certain fault dip and fault throw. But what about the Huizinge M = 3.6 and Westeremden M = 3.5 tremors?

Huizinge M = 3.6 tremor in 2012

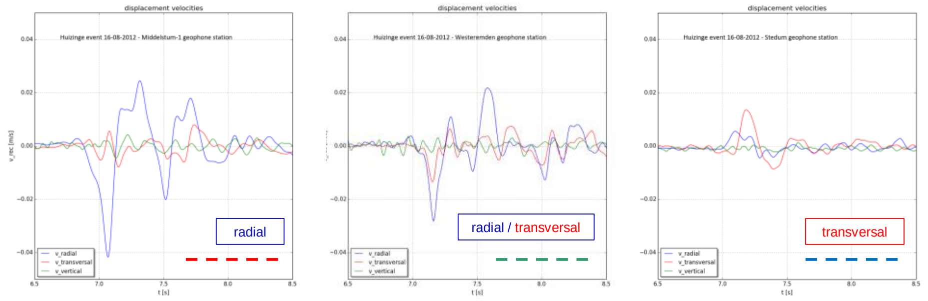


Shell Global Solutions

Subsurface horizons around Huizinge tremor



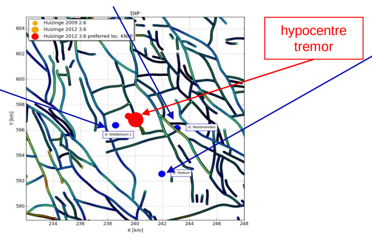
Huizinge tremor



Middelstum-1
distance 1.5 km

Westeremden
distance 3.2 km

Stedum
distance 4.8 km

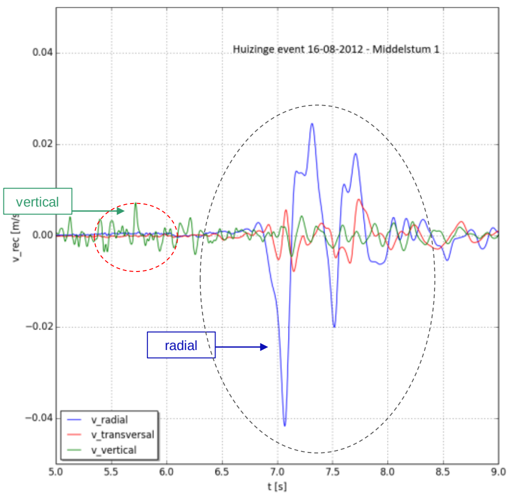


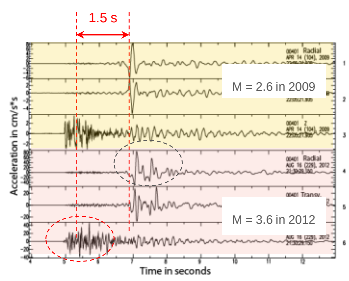
M ~ 3.6, f_c ~ 2 Hz, R_{slip} ~ 400 m
Dost and Kraaijpoel 2013

Huizinge tremor – Middelstum-1 geophone

Two clear large peaks in the radial velocity due to multiple reflections or multiple sources ?

Rupture plane equi-dimensional or in the form of a ribbon in the reservoir along fault strike?





Dost and Kraaijpoel 2013
M ~3.6, f_c ~ 2 Hz, R_{rup} ~ 400 m

Modelling

Focus on the low frequency part of wavelets generated by the tremor: f = 1 – 3 Hz

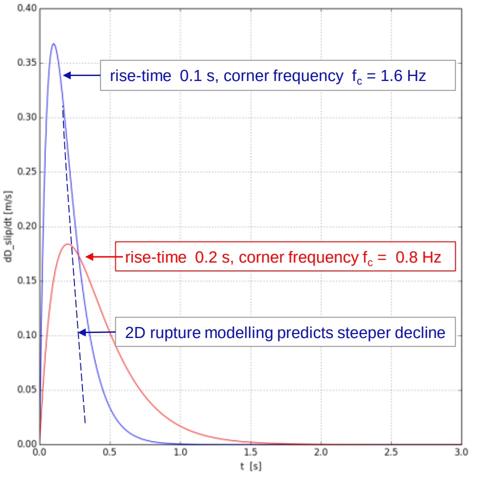
Mean velocities between reservoir and surface: V_p = 3200 m/s, V_s = 1500 m/s

Wavelength for f = 3 Hz and V = 1000 m/s: λ = V/f = 300 m

→

Anhydrite, floater or soil layers of 50 - 100 metres or variations in the depth and thickness of formations up to 200 metres distort only to “some extend” the low frequency part of the wavelets.

Source time function – modified Brune’s model



Brune’s model: rise time t_{rise} = 0.1 – 0.2 s, slip D_{slip} = 0.1 m

Source - receiver configurations

Geometrical configurations for extended sources of pure shear slip along fault dip

- Single equi-dimensional source

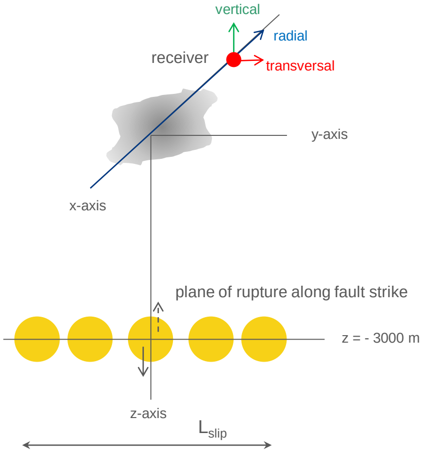
- Row of sources along fault strike
  - rupture velocity along fault strike v_{rup} = 2 km/s (sonic) and v_{rup} = 4 km/s (supersonic)
  - rupture proceeds in one direction
  - rupture proceeds in two directions starting in the hypocentre

- The receivers are located at the surface at 1 – 5 km distance from tremor hypocentre

Results from Green functions using Brune's STF

1 source or a row of 21 sources along fault strike over 1 km length fault, fault dip 80 degrees

Receivers at surface along x-axis



rock properties

E = 13.5 GPa, ν = 0.36, μ = 5 GPa, ρ = 2200 kg/m^3,
V_p = 3200 m/s, V_s = 1500 m/s

1 equi-dimensional source

W_{slip} = L_{slip} = 700 m, D_{slip} = 0.2 m,

M_0 ~ 400 TJ, M ~ 3.6.

21 sources in a row represent a rupture in the reservoir proceeding along fault strike

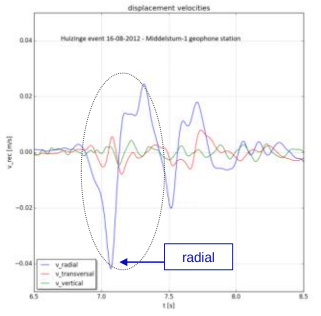
W_{slip} = 300 m, L_{slip} = 1000 m, D_{slip} = 0.2 m,

M_0 ~ 400 TJ, M ~ 3.6.

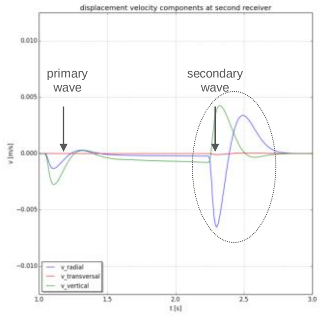
Results from Green functions

Single equi-dimensional source

Middelstum-1 geophone at 1.5 km distance west of tremor



observed



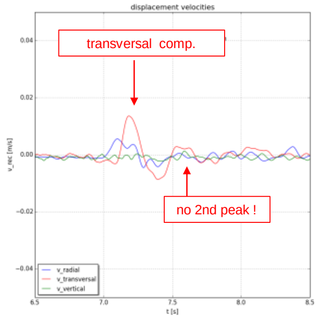
modified Brune's STF
t_{onset} = 0.05 s, t_{rise} = 0.2 s, n = 2

horizontal axis: total time 2 s
vertical axis - observed: displacement velocity -5, +5 cm/s,
vertical axis - model: displ. velocity -1.25, + 1.25 cm/s to account for factor 4 = 2 (free surface) x 2 (low velocity in soil)

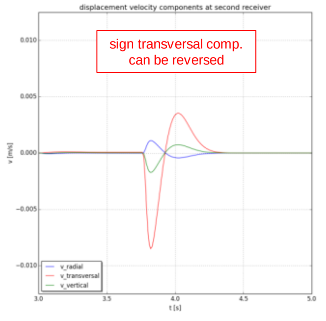
Results from Green functions

Single equi-dimensional source

Stedum geophone at 4.8 km distance south of tremor



observed



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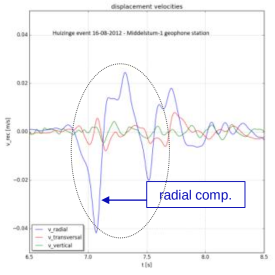
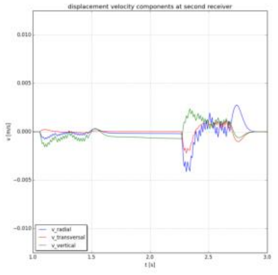
Results from Green functions

Rupture propagates in reservoir along fault strike in one direction from north to south

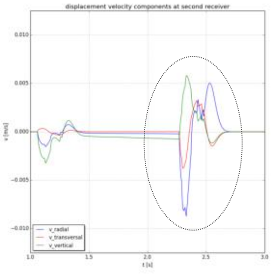
Middelstum-1 geophone at 1.5 km distance west of tremor



observed



mod. Brune's STF
t_{rise} = 0.08 s, n = 2
v_{rup} = 2 km/s



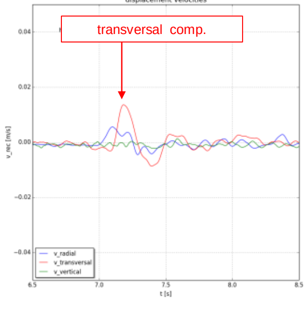
mod. Brune's STF
t_{rise} = 0.08 s, n = 2
v_{rup} = 4 km/s

horizontal axis: total time 2 s
vertical axis - observed: displacement velocity -5, +5 cm/s,
vertical axis - model: displ. velocity -1.25, + 1.25 cm/s to account for factor 4 = 2 (free surface) x 2 (low velocity in soil)

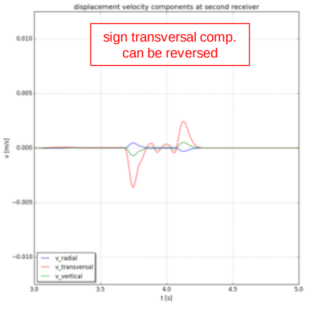
Results from Green functions

Rupture propagates in reservoir along fault strike in one direction from north to south

Stedum geophone at 4.8 km distance south of tremor



observed



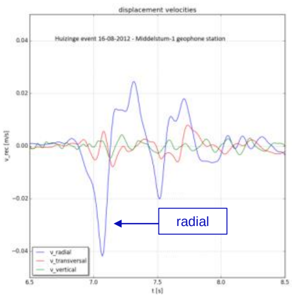
rupture along strike, v_{rup} = 4 km/s
modified Brune's STF
t_{rise} = 0.08 s, n = 2

horizontal axis: total time 2 s
vertical axis - observed: displacement velocity -5, +5 cm/s,
vertical axis - model: displ. velocity -1.25, + 1.25 cm/s to account for factor 4 = 2 (free surface) x 2 (low velocity in soil)

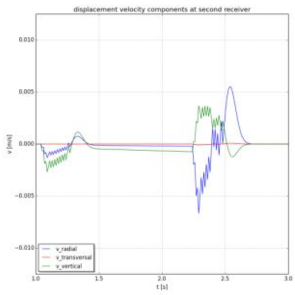
Results from Green functions

Rupture propagates in reservoir along fault strike in north and south directions starting in hypocentre

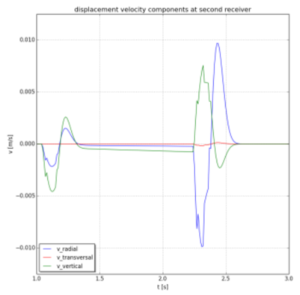
Middelstum-1 geophone at 1.5 km distance west of tremor



observed



mod. Brune's STF
t_{rise} = 0.08 s, n = 2
v_{rup} = 2 km/s



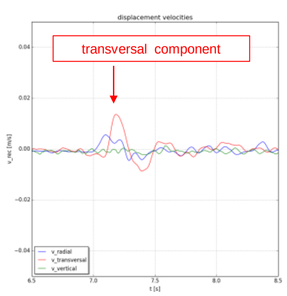
mod. Brune's STF
t_{rise} = 0.08 s, n = 2
v_{rup} = 4 km/s

horizontal axis: total time 2 s
vertical axis - observed: displacement velocity -5, +5 cm/s,
vertical axis - model: displ. velocity -1.25, + 1.25 cm/s to account for factor 4 = 2 (free surface) x 2 (low velocity in soil)

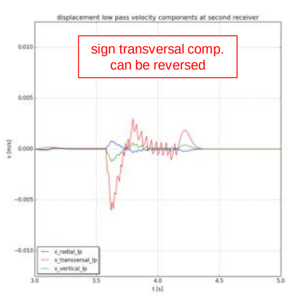
Results from Green functions

Rupture propagates in reservoir along fault strike in north and south directions starting in hypocentre

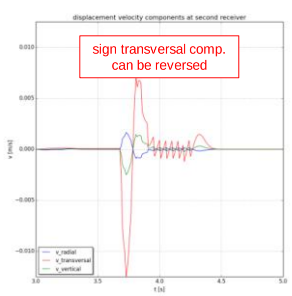
Stedum geophone at 4.8 km distance south of tremor



observed



mod. Brune's STF
t_{rise} = 0.08 s, n = 2
v_{rup} = 2 km/s



mod. Brune's STF
t_{rise} = 0.08 s, n = 2
v_{rup} = 4 km/s

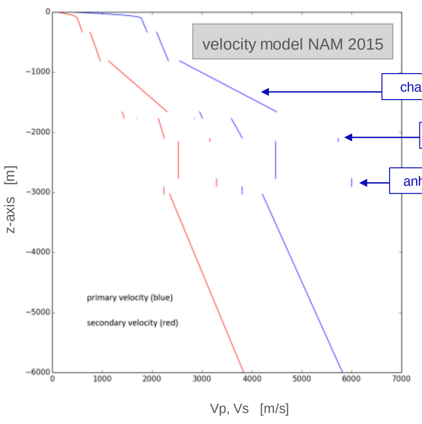
horizontal axis: total time 2 s
vertical axis - observed: displacement velocity -5, +5 cm/s,
vertical axis - model: displ. velocity -1.25, + 1.25 cm/s to account for factor 4 = 2 (free surface) x 2 (low velocity in soil)

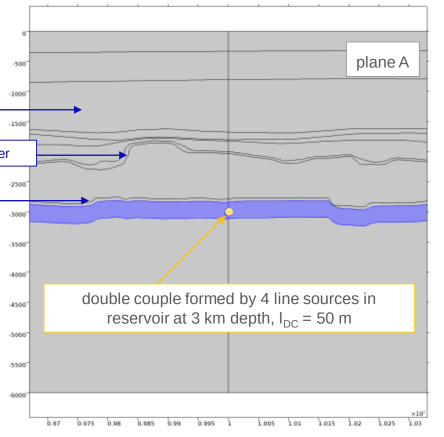
FEM for plane A – vel. model NAM 2015

2D - line source along fault strike with “infinite” rupture velocity along fault strike

Simulation includes low wave velocities and strong damping (low Q) at 0 – 100 m depth

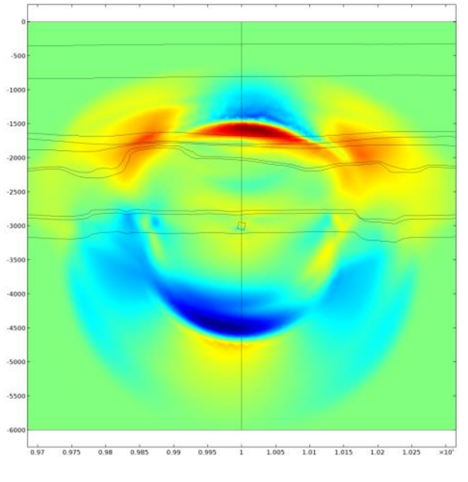
Double couple is rotated with 10 degrees according to fault dip of 80 degrees



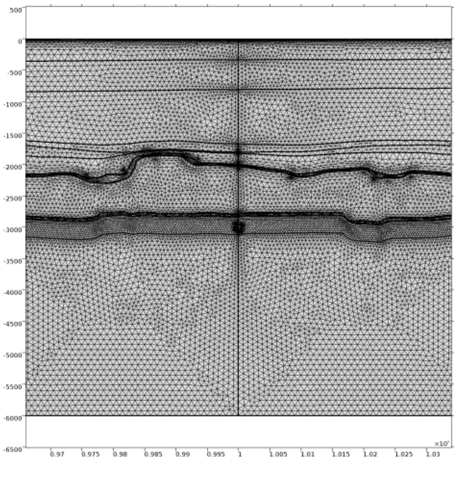


FEM results – velocity field and mesh

vertical velocity at 0.62 s

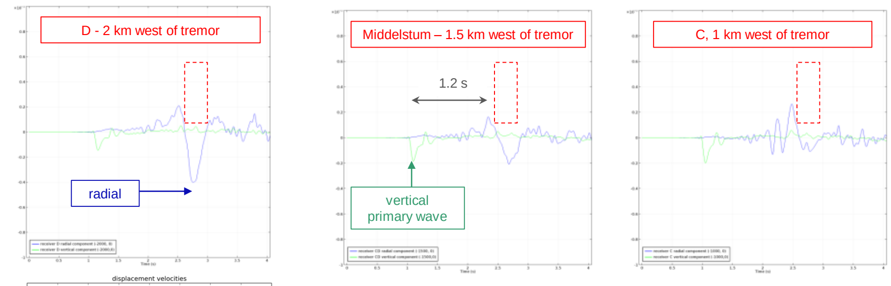


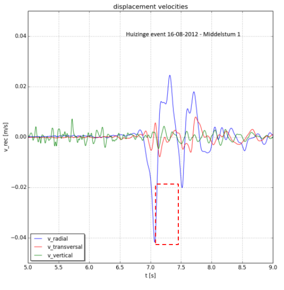
mesh



FEM results - ground motions

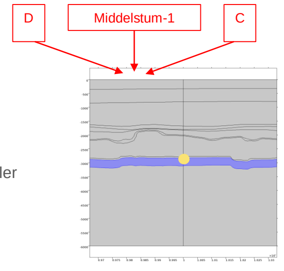
Brune's STF, t_{rise} = 0.1 s. Line source. Receivers C, D and Middelstum-1





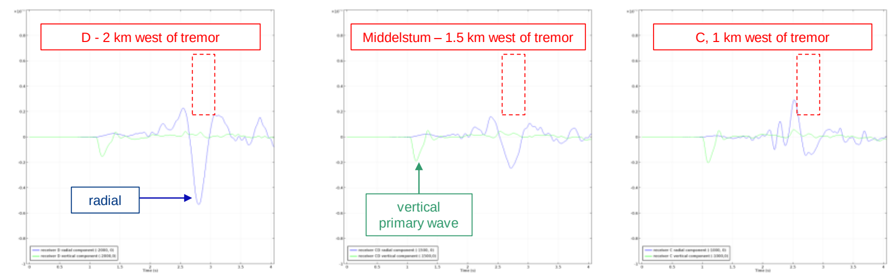
horizontal axis: total time 4 s

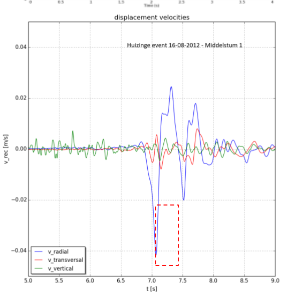
vertical displacement shear wave much smaller than from Green functions



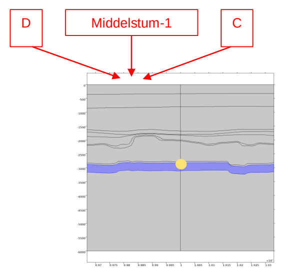
FEM results - ground motions

Modified Brune's STF, t_{onset} = 0.05 s, t_{rise} = 0.08 s, n = 2. Line source. Receivers C, D and Middelstum-1



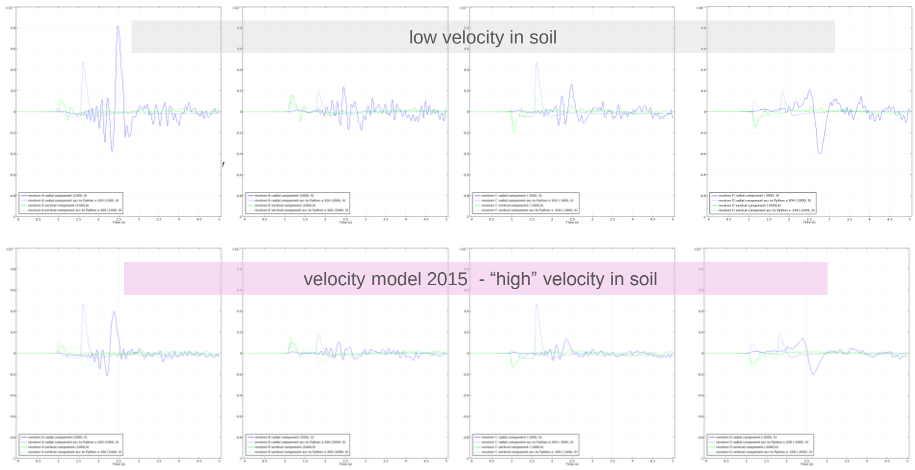


horizontal axis: total time 4 s



FEM- effect of low wave velocity in the soil

receiver A receiver B receiver C receiver D



Conclusions

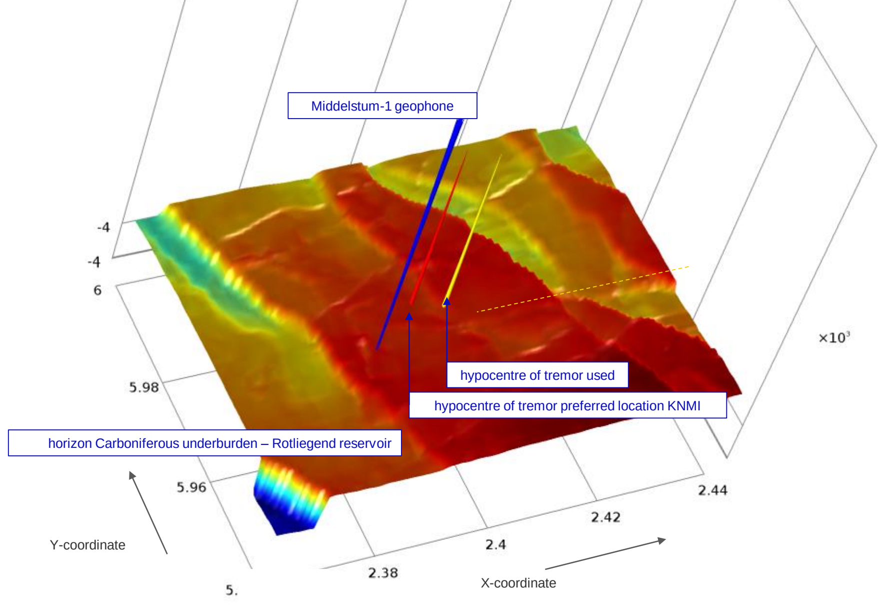
For the Huizinge M =3.6 tremor

- Comparing the observed motions at the Middelstum-1 and Stedum geophones with the present models, an equi-dimensional single rupture seems somewhat more likely than a rupture along fault strike contained in the reservoir.

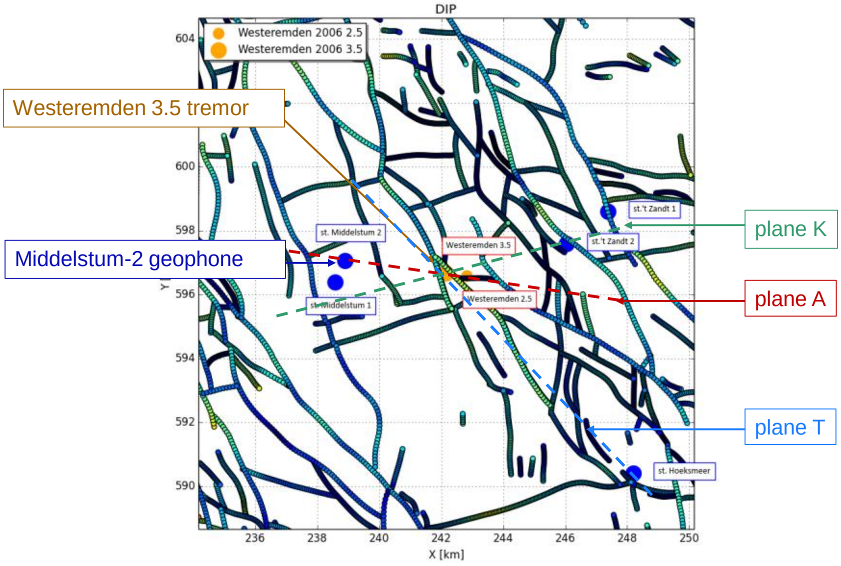
- The two dominant peaks in the radial velocity at the Middelstum-1 geophone do not follow from an equi-dimensional single rupture or a single rupture along fault strike. There is support from modelling that the two peaks follow from a major reflection of the tremor wavelet in the overburden.

Back-up slides

Carboniferous – Rotliegend horizon around Huizinge

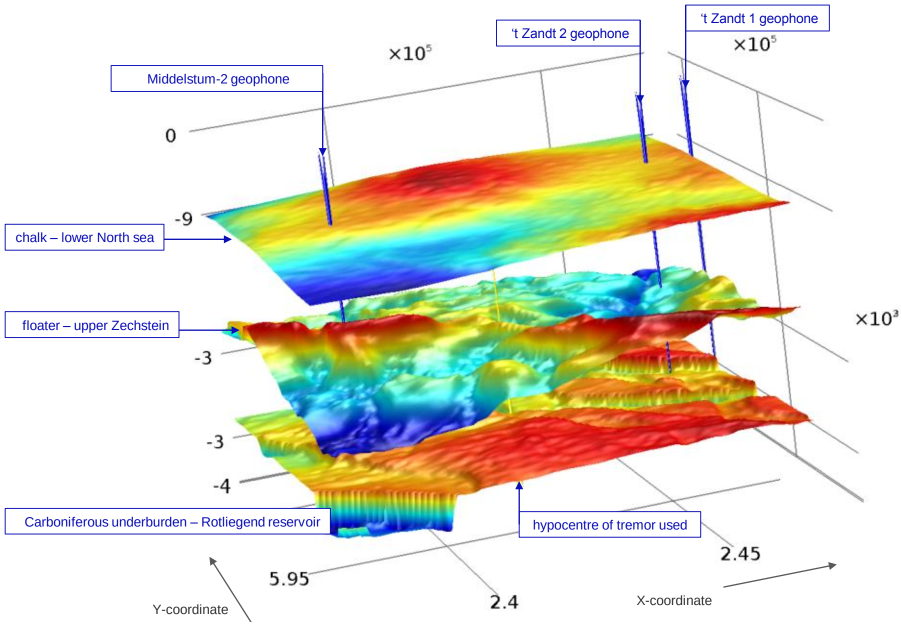


Westeremden M = 3.5 tremor in 2006

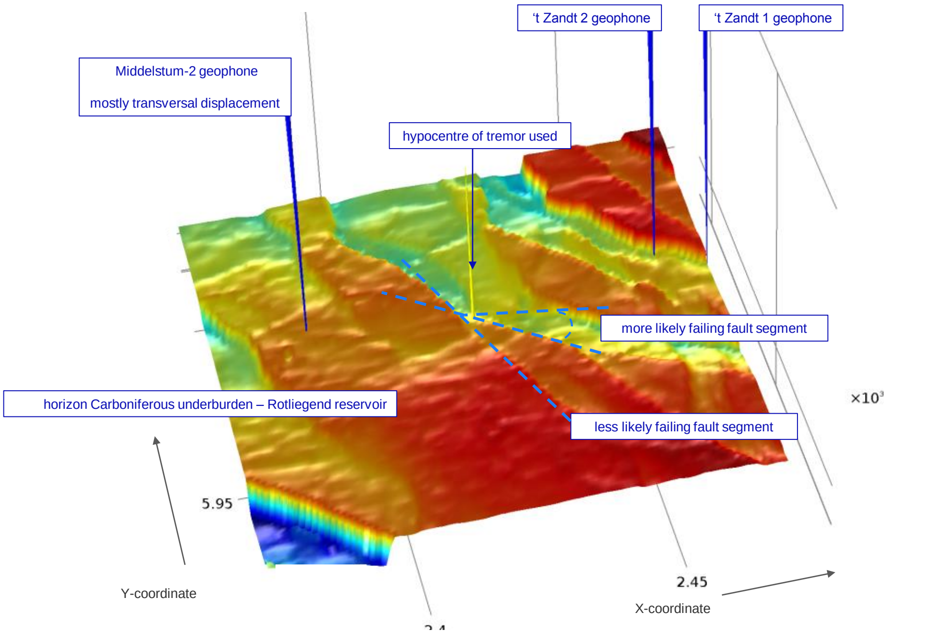


Shell Global Solutions

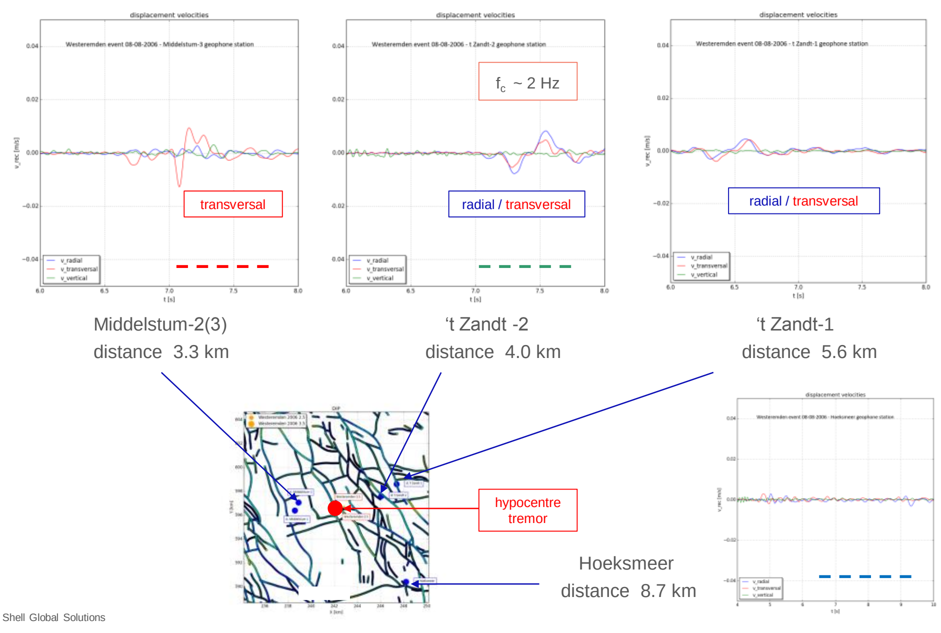
Subsurface horizons around Westeremden tremor



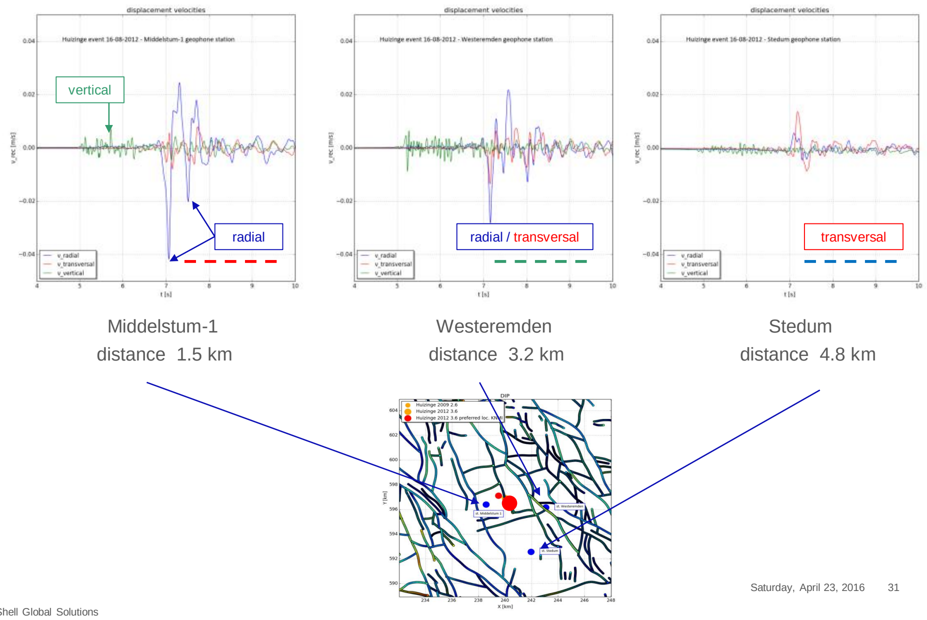
Carboniferous – Rotliegend horizon around Westeremden



Westeremden tremor



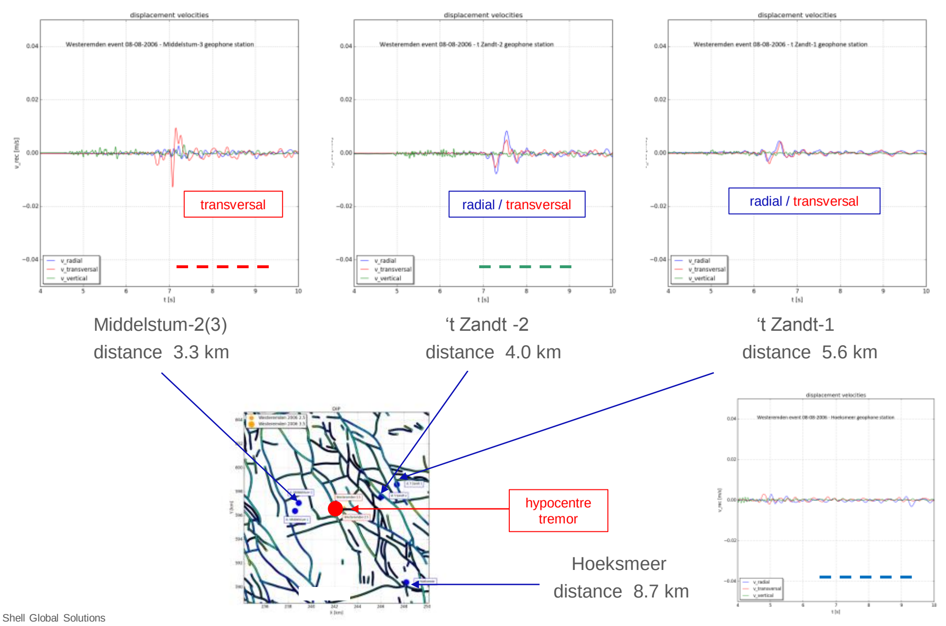
Huizinge tremor



Saturday, April 23, 2016 31

Shell Global Solutions

Westeremden tremor



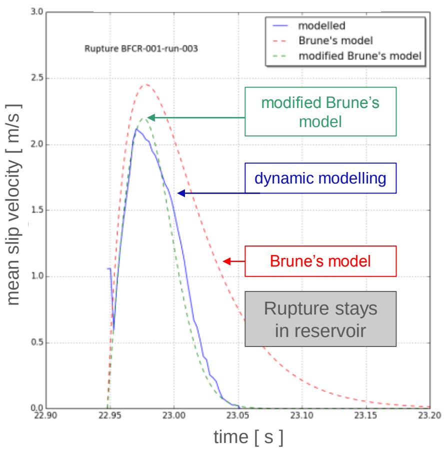
Shell Global Solutions

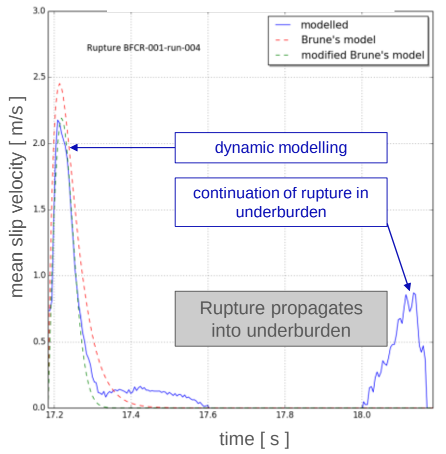
Source time function and 2D dynamic rupture modelling

Two examples of rupture over a length of 300 m in a 200 m thick reservoir with 100 m offset

rupture nucleation at two locations along dip, mean rupture velocity v_{rup} = 3 km/s / 2 = 1.5 km/s.

Modified Brune's model: rise time t_{rise} = 0.04 – 0.05 s, n = 2, mean slip D_{slip} = 0.1 – 0.2 m





Use of Green functions

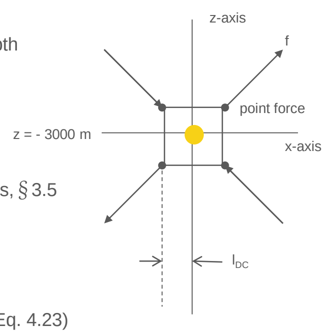
for homogeneous infinite linear elastic medium – rupture at 3000 m depth

Analytical expressions from

- Aki and Richards, Quantitative Seismology, 2nd ed., § 4.2
- Udias, Madariaga and Bufon, Source Mechanisms of Earthquakes, § 3.5

Ruptures are modelled from

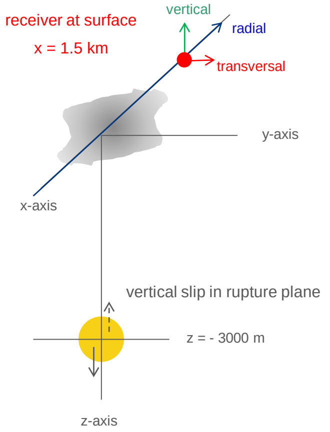
- 4 point forces forming a double couple around tremor centre (Aki, Eq. 4.23)
- moment tensor equivalent to this double couple (Aki, Eq. 4.29)



$M_0 = 2.f.l_{DC}$

QC - Green functions and Brune's STF

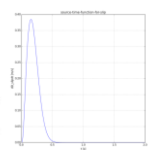
Receiver at surface in xz-plane at a distance from the hypocentre of 1.5 km

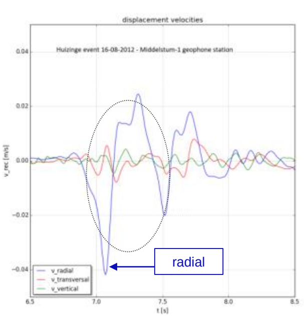


Results from Green functions

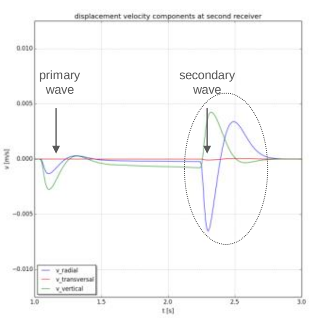
Single equi-dimensional source

Middelstum-1 geophone at 1.5 km distance west of tremor





observed



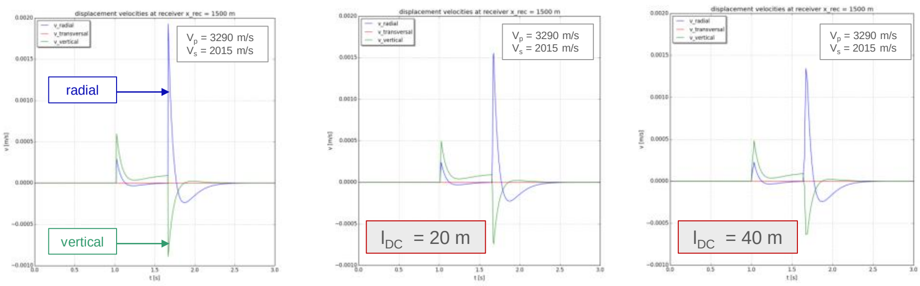
modified Brune's STF
t_{onset} = 0.05 s, t_{rise} = 0.2 s, n = 2

horizontal axis: total time 2 s
vertical axis - observed: displacement velocity -5, +5 cm/s,
vertical axis - model: displ. velocity -1.25, + 1.25 cm/s to account for factor 4 = 2 (free surface) x 2 (low velocity in soil)

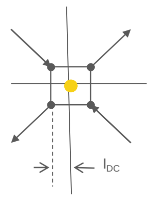
QC - Green functions and Brune's STF

Receiver at surface in xz-plane at a distance of 1.5 km from hypocentre

t_{rise} = 0.1 s, D_{slip} = 0.1 m, R_{circ} = 100 m, M_0 ~ 20 TJ, M ~ 2.8



moment tensor

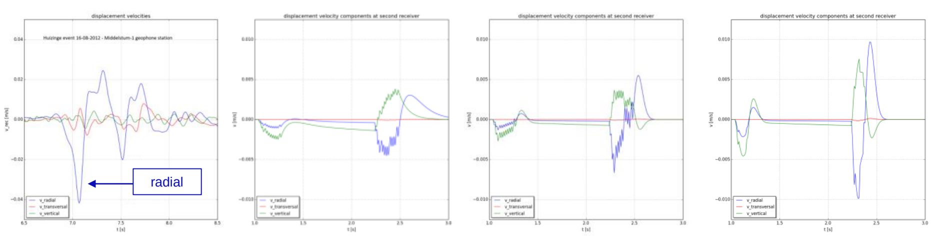


double couple point forces

Results from Green functions

Rupture propagates in reservoir along fault strike in north and south directions starting in hypocentre

Middelstum-1 geophone at 1.5 km distance west of tremor



observed	Brune's STF	mod. Brune's STF	mod. Brune's STF
	t_{rise} = 0.1 s v_{rup} = 2 km/s	t_{rise} = 0.08 s, n = 2 v_{rup} = 2 km/s	t_{rise} = 0.08 s, n = 2 v_{rup} = 4 km/s

horizontal axis: total time 2 s
vertical axis - observed: displacement velocity -5, +5 cm/s,
vertical axis - model: displ. velocity -1.25, + 1.25 cm/s to account for factor 4 = 2 (free surface) x 2 (low velocity in soil)

Results from Green functions

Rupture propagates in reservoir along fault strike in north and south directions starting in hypocentre

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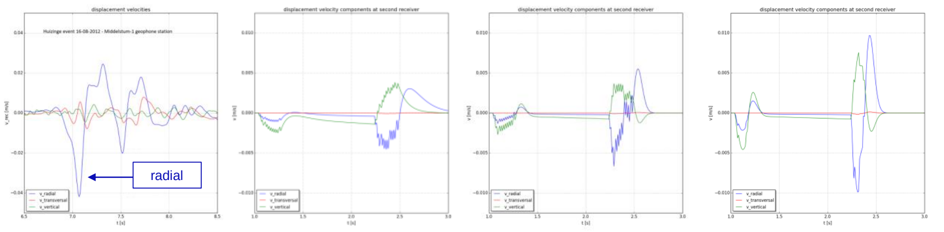


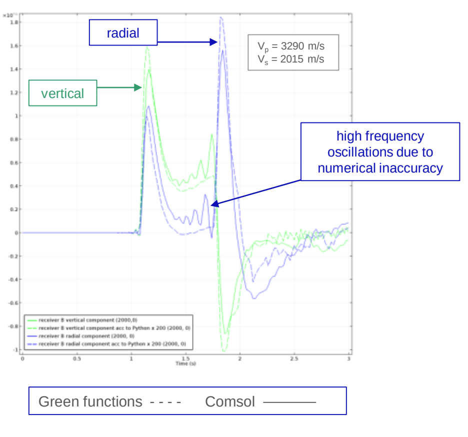
observed	Brune's STF	mod. Brune's STF	mod. Brune's STF
	t_{rise} = 0.1 s v_{rup} = 2 km/s	t_{rise} = 0.08 s, n = 2 v_{rup} = 2 km/s	t_{rise} = 0.08 s, n = 2 v_{rup} = 4 km/s

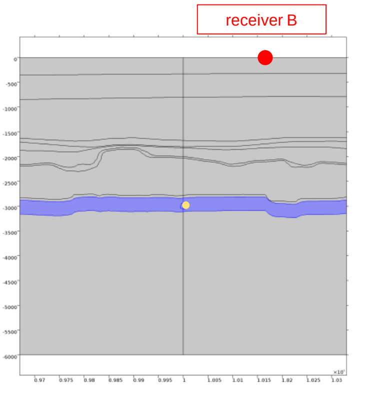
horizontal axis: total time 2 s
vertical axis - observed: displacement velocity -5, +5 cm/s,
vertical axis - model: displ. velocity -1.25, + 1.25 cm/s to account for factor 4 = 2 (free surface) x 2 (low velocity in soil)

QC - Green functions/2D-Comsol sim. using Brune's STF

Receiver B at surface in xz-plane at a distance of 2 km from hypocentre

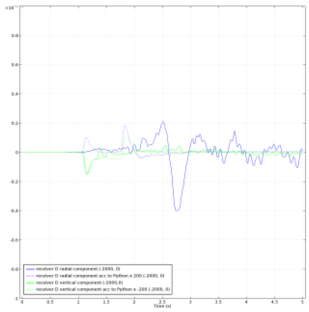
Green function solution by 101 double couples over 10 km length along fault strike, infinite v_{rup}



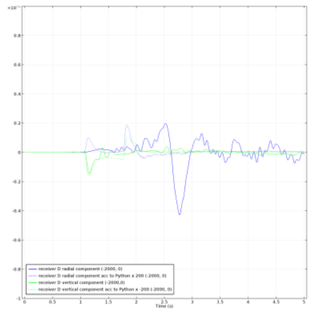


FEM simulations - NAM 2015 velocity model

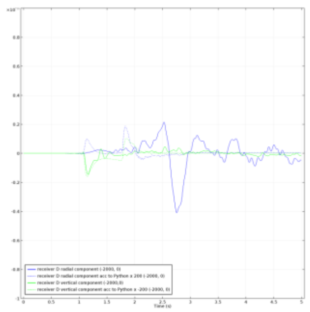
Effect of domain size and mesh in boundary layer at surface, small changes at receiver D



domain 8 km



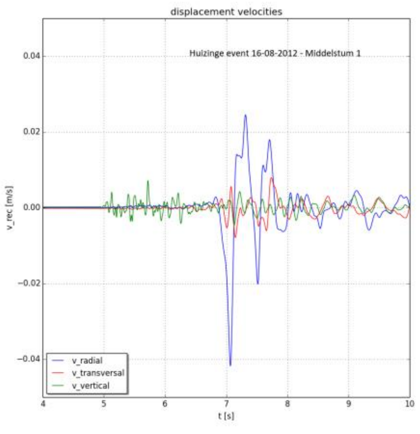
domain 12 km

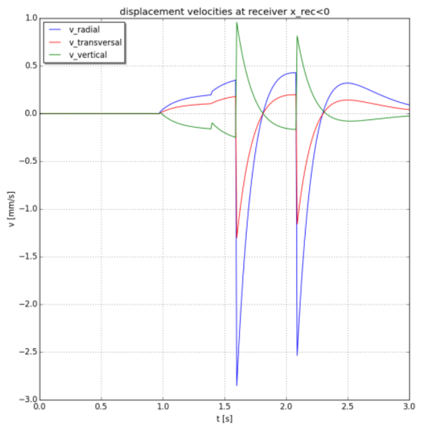


fine boundary layer

Multiple sources - Green functions and Brune's STF

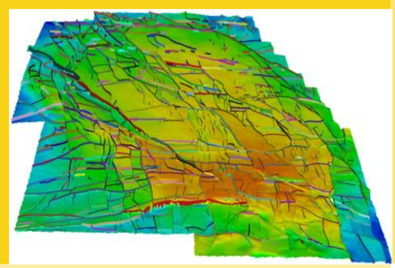
Example: 2 sources along fault dip





ESTIMATING MOMENT MAGNITUDE

from 2D dynamic rupture simulations



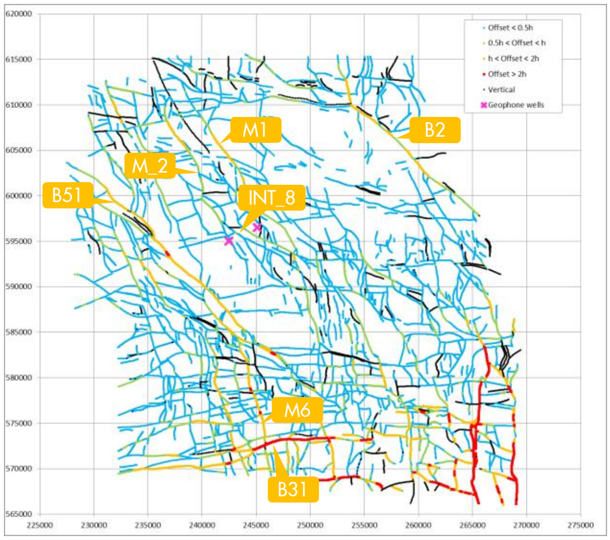
Peter van den Bogert, Alexander Droujinine, Steve Oates

10 March 2016

MAIN MESSAGES

- Dynamic rupture simulations can be used for comparing with seismic event data (wave form)
  - preliminary results are promising; more work required
- Seismic potential is dependent on fault properties and varies over the Groningen field. Larger magnitudes are possible in case of
  - faults with a small or very larger reservoir offset (<0,5 or > 2 reservoir thickness)
  - Larger stress drops (smaller residual friction coefficient)
- Within the assumptions made (a.o. rupture confined within reservoir bounds) and sensitivities considered :
  - Largest seismic Magnitude is about ~ 4 for small offsets
  - Seismic Magnitude may be up to 4.7 at an offset twice

GRONINGEN FAULT MAP WITH OFFSET



DIP ANGLE AND NORMALISED OFFSET FREQUENCY

Fault dip angle [deg]

Normalised reservoir offset [-]

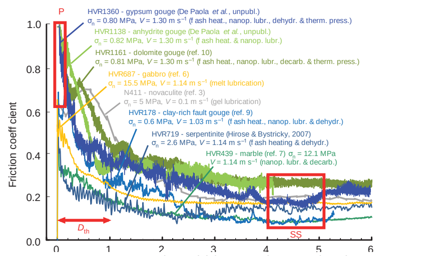
Count of Fault-ID Column Labels

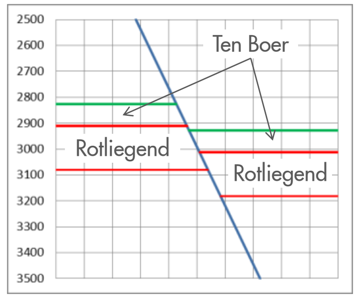
Row Labels	0	0.05	0.1	0.15	0.2	0.25	0.3	0.35	0.4	0.45	0.5	0.55	0.6	0.65	0.7	0.75	0.8	0.85	0.9
50	2																		
53	17	8																	
54	5	1																	
55		4	1						1										
56		3	1	2	2			2		1			1			1	2	6	
57	3		2	1	2			3		1		2	2	1			1		
58	2	1	5	2	2	4	2	1	1	2						2			1
59	3	5	6	3	1	5	1	2			2			1	2	1			
60	2	3	18	2	4	2	1								2	2			
61	10	8	9	7	2	1	3	2				1	3		1	1			
62	31	9	6	11	6	4	3	2			1	1	1		1		1		
63	8	20	12	9	12	4	4	1	1		3	1	2	2	1	1	4	2	
64	24	15	15	18	18	12	21	7	4	2	1	1	1			3	1	3	3
65	43	21	15	24	31	22	15	9	5	8	3	3	1	5		2	5		
66	33	34	37	30	24	26	9	17	14	13	9	7	5	6	4	3	6	3	1
67	33	39	43	31	22	27	16	13	21	11	4	6	2	6	3	3	3	1	
68	62	64	50	50	25	30	27	19	22	8	9	1	1	6	4	1	4	3	5
69	78	91	63	78	64	35	46	28	25	17	6	10	8	12	6	6	5	7	4
70	108	80	108	93	65	44	43	30	34	35	18	20	23	10	16	7	7	8	3
71	95	117	103	103	89	60	47	44	33	28	32	15	23	17	24	13	8	14	4
72	129	156	120	114	90	70	62	36	45	24	19	20	18	26	13	10	7	7	6
73	134	153	141	123	124	107	66	41	36	33	36	30	35	33	21	13	15	8	10
74	179	191	151	140	113	87	82	82	59	46	42	49	32	26	23	25	12	11	13
75	201	177	182	164	150	139	110	75	82	47	44	42	32	35	38	30	16	25	19
76	213	215	194	175	178	135	100	91	71	78	56	51	34	29	28	31	30	17	12
77	210	193	171	197	181	138	101	73	86	60	45	56	28	18	22	14	28	26	24
78	211	231	231	238	194	159	114	102	71	55	57	54	51	30	21	13	24	23	29
79	245	235	250	247	184	156	138	98	83	82	101	65	47	26	24	15	24	21	17
80	225	286	265	228	218	152	131	97	89	67	64	46	38	39	21	35	14	19	20
81	240	250	182	179	170	142	110	107	63	55	48	30	31	44	22	25	20	23	11
82	242	208	181	181	129	101	86	90	79	48	33	20	22	22	16	11	9	11	16
83	197	227	185	155	142	100	90	69	63	48	33	21	12	16	21	8	7	5	9
84	178	158	207	137	92	97	69	63	43	36	33	27	17	15	11	14	17	11	8
85	166	146	168	121	79	65	70	61	47	37	23	18	14	12	13	9	9	5	6
86	146	167	150	92	53	59	60	50	35	24	19	11	18	9	4	7	6	4	3
87	126	128	122	109	65	46	28	18	19	19	18	8	10	8	11	6	3		5
88	109	117	111	84	45	37	34	15	14	13	8	10	6	4	7	5	3	2	6
89	112	113	80	66	56	34	36	21	19	17	19	2	4	3	6	4	4	3	
90	816	632	581	510	408	320	244	175	154	94	95	100	90	47	30	28	27	8	5
Grand Total	4638	4506	4166	3724	3040	2420	1969	1544	1319	1009	881	728	612	508	416	349	322	276	240

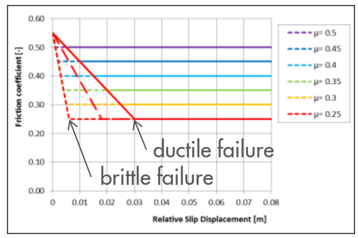
Row Labels	0.95	1	1.05	1.1	1.15	1.2	1.25	1.3	1.35	1.4	1.45	1.5	1.55	1.6	1.65	1.7	1.75	1.8	1.85	1.9	Grand Total
50																					2
53																					25
54																					6
55																					6
56																					21
57																					18
58																					25
59					1																33
60																				6	42
61								1							1					6	56
62	1	1		3		1			2						1				1	4	91
63	3	1		2	1		1	1	1	1		1		1				1		7	108
64	1		2		2		2				1						1			9	167
65		1			1				1		1				1				1	10	228
66		1		1		6	1					1	1		1	3	2			25	323
67	4	1	2	2	1	2	2	5	3	2	1	2	1					1	1	22	336
68	5			1		1	2	1		1	1		2		2					15	422
69		7	1	7	1	6	2	1				1	1	1	4				1	14	636
70	7	5	3	9	8	2	4	2	2	2		1	2	5	2	2	2		2	29	841
71	7	11	4		4	2	5	1	4	3	1		4	1	2		3	2	1	22	946
72	8	10	4	3	6	5	3	2	2	1	4	2	3	1	1	2	2		2	33	1066
73	9	12	8	4	4	7	3	4	7	2	1	5	2		1	2	4		1	36	1271
74	4	10	12	12	10	7	4	5	5	5	3	6	5	15	1	3	5	2	2	48	1527
75	13	24	11	9	8	7	9	13	3	5	11	6	7	9	2	3	4	2	3	60	1817
76	12	12	16	11	7	14	9	11	15	8	6	5	5	8	9	2	5	5	6	64	1968
77	14	22	21	14	13	14	13	5	6	4	4	6	2	8	4	2	4			53	1880
78	16	22	16	14	14	9	9	13	8	5	3	3	5	4	3	3	3	2		42	2102
79	13	16	18	9	8	6	10	5	6	4	5	5	1	2	3	5	2	1		25	2202
80	12	16	16	10	10	9	7	6	1	2	2		1	2	4	3	1	2	2	13	2173
81	11	16	9	7	9	5	6	1	4	4	11	1	6	5	5	2	1	3	2	18	1878
82	16	9	4	3	4	2	6	3	3		3	6	7	3	2	1	4	1		21	1603
83	7	9	1	5	3	3	1	7	8	4	1	1	2		1					27	1488
84	2	5	5	5	12	1	3	4	3	1		1	1	2	2	2	2	3	2	14	1303
85	3	3	1	5	5	1	2	3	2	1	3	1			1		1			10	1111
86	2	4	4	1	1	1		1		1			2	1	2	1				17	955
87	3	9	3	4	2	3				1		2			1		1			11	789
88	4	6	2		1	1									1				1	5	651
89	2	1	2	1	3	3	1								1					2	615
90	9	9	11	6		3	1	3	3	3	3	3	3	2	3	3	2		2	61	4494
Grand Total	188	243	176	148	139	121	106	98	89	60	65	59	63	70	61	39	47	27	30	729	35225

CASE DESCRIPTION (FAULT INT_8)

- Fault dip 66°
- Rotliegend reservoir
  - Thickness 200 m
  - Offset **0 – 400 m**
- Slip-weakening cohesion-less fault
  - Initial friction 0.55
  - Residual friction **0.50 – 0.25**



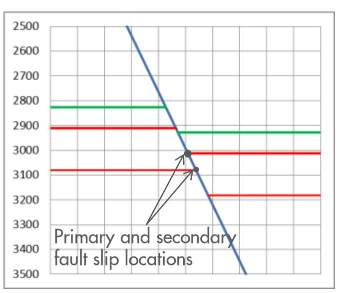


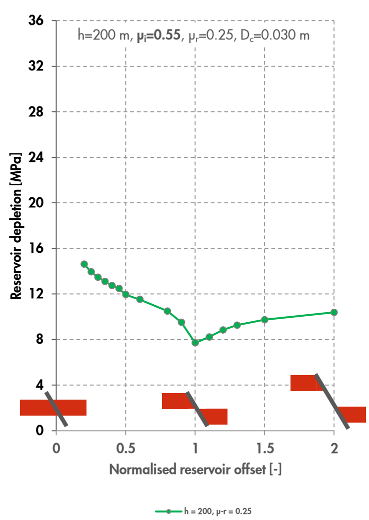


Source: G. Di Toro et. Al. "Fault lubrication during earthquakes", Nature, 2011

ONSET OF FAULT SLIP

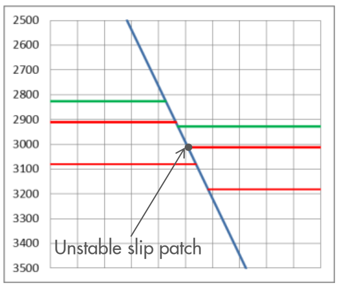
- Onset of (a-seismic) fault slip
  - influenced by initial friction coefficient μ_i

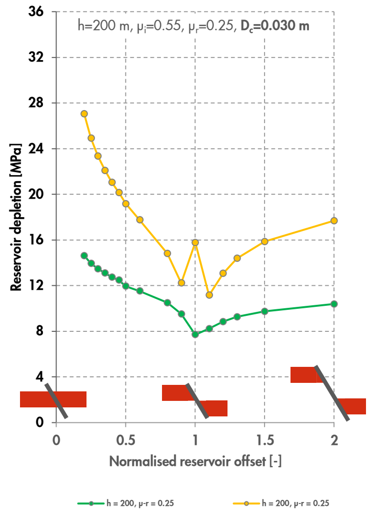




NUCLEATION OF SEISMIC SLIP

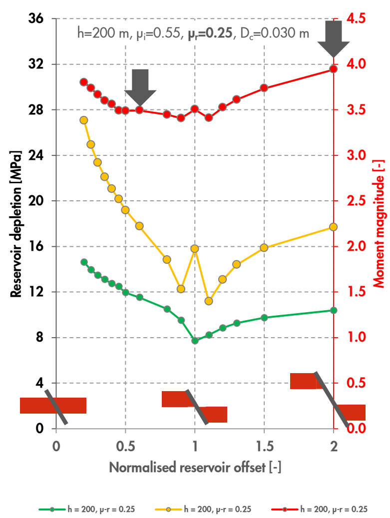
- Nucleation of dynamic rupture
  - Dependent on the slope of the slip-weakening diagram
  - No dynamic rupture below 30 MPa depletion for normalised offset < 0.2 and μ_i =0.55





MOMENT MAGNITUDE (M_r=0.25)

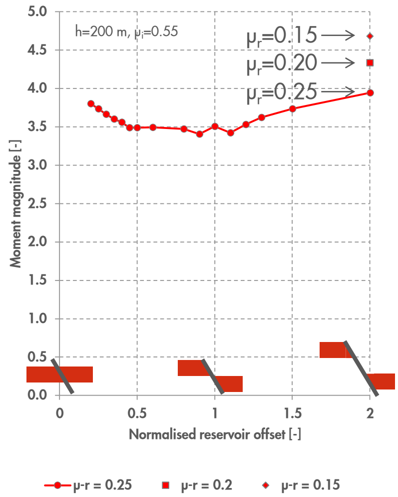
- Seismic moment
  - assuming rupture width equal to rupture height
  - smallest at an offset about equal to reservoir thickness



INFLUENCE OF RESIDUAL FRICTION COEFFICIENT

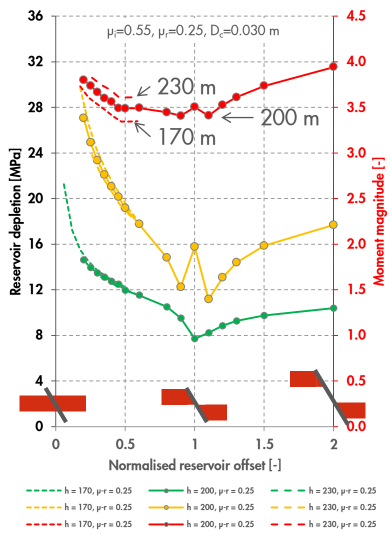
Can get things worse?

- Magnitude > 4 calculated for
  - residual friction coefficient < 0.25
  - large reservoir offset
  - slip patch penetrating into carboniferous



INFLUENCE OF RESERVOIR THICKNESS

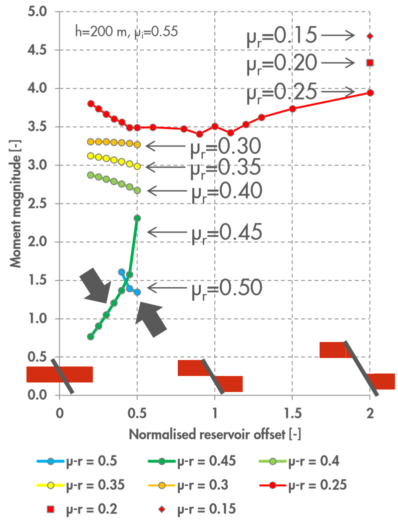
- Onset of (a-seismic) fault slip
  - dependent on **normalised** offset
- Nucleation of dynamic rupture
  - dependent on **normalised** offset
- Seismic moment larger for
  - larger depletion level at nucleation
  - larger reservoir thickness



INFLUENCE OF RESIDUAL FRICTION COEFFICIENT

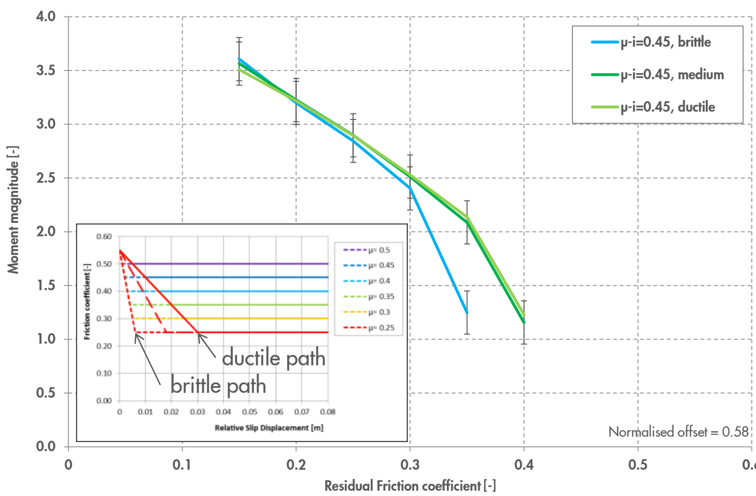
Can get things worse?

- Magnitude > 4 calculated for
  - residual friction coefficient < 0.25
  - large reservoir offset
  - slip patch penetrating into carboniferous
- Magnitudes < 2 calculated for
  - residual friction coefficient > 0.45
  - Offset < 0.5 x reservoir thickness



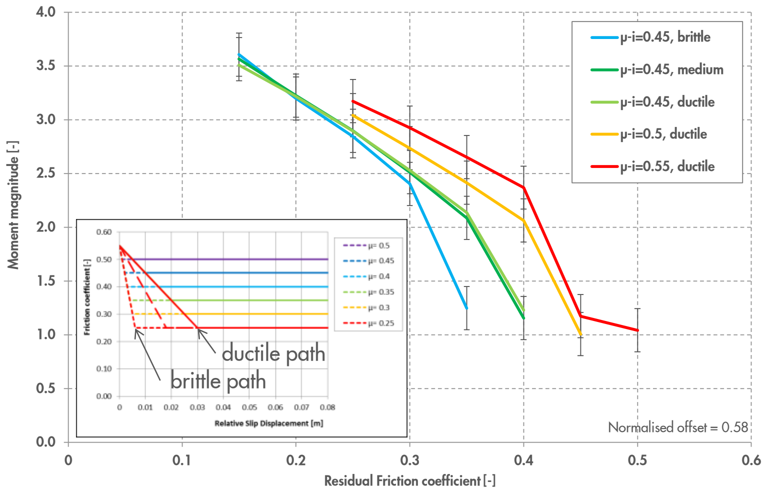
INFLUENCE OF SLIP-WEAKENING BEHAVIOUR

- Brittle slip-weakening behaviour yields somewhat lower magnitude, because nucleation of seismic slip occurs at lower depletion level



INFLUENCE OF INITIAL FRICTION COEFFICIENT

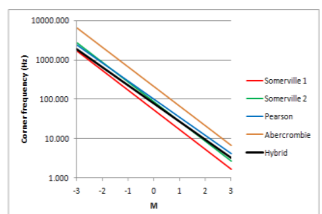
- Lower initial friction coefficient yields lower magnitude, because nucleation of seismic slip occurs at lower depletion level

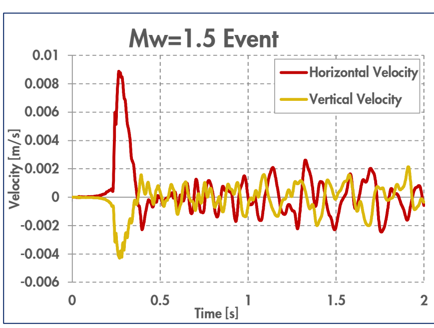


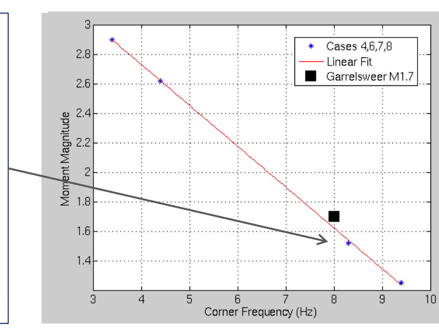
MEASURED & SIMULATED EVENT DATA

Preliminary findings

- Simulated corner frequency close to actual event interpretation
  - Suggest rupture width to height ratio 1 is realistic
  - events with more complex wave forms to be evaluated



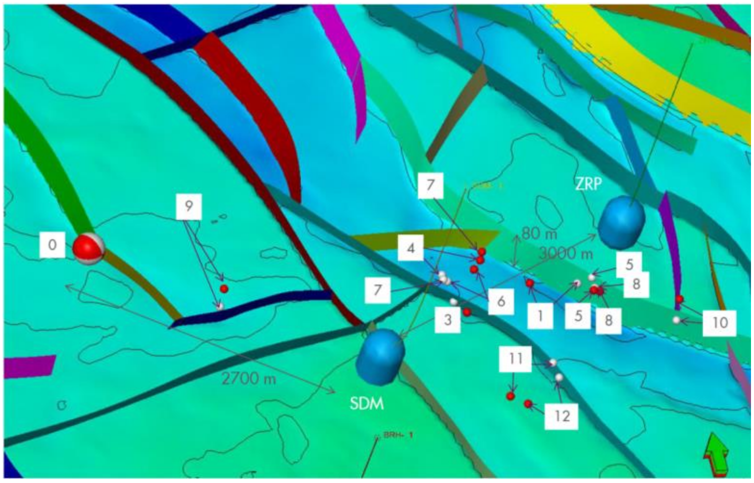




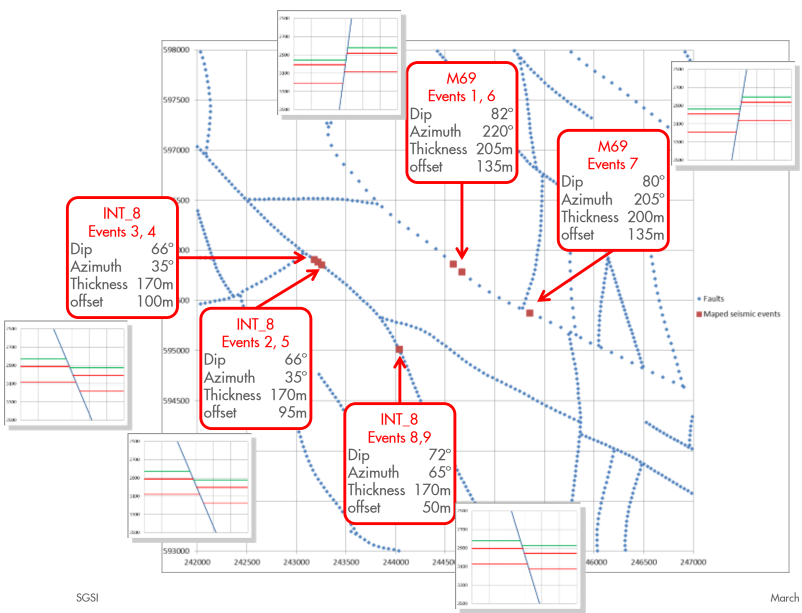
CONCLUSIONS

- Dynamic rupture simulations can be used for comparing with seismic event data (wave form)
  - preliminary results are promising; more work required
- Seismic potential is dependent on fault properties and varies over the Groningen field. Larger magnitudes are possible in case of
  - faults with a small or very larger reservoir offset (<0,5 or > 2 reservoir thickness)
  - Larger stress drops (smaller residual friction coefficient)
- Within the assumptions made (a.o. rupture confined within reservoir bounds) and sensitivities considered :
  - Largest seismic Magnitude is about ~ 4 for small offsets
  - Seismic Magnitude may be up to 4.7 at an offset twice
- Other measures than magnitude may be more appropriate as input to risk assessment

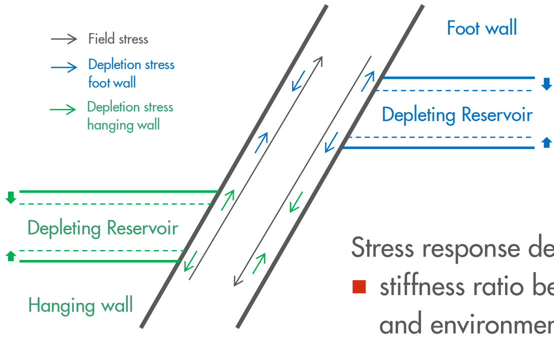
EVENTS IN THE LOPPERSUM AREA



EVENTS' NEAREST FAULT LOCATIONS



ONSET OF FAULT SLIP

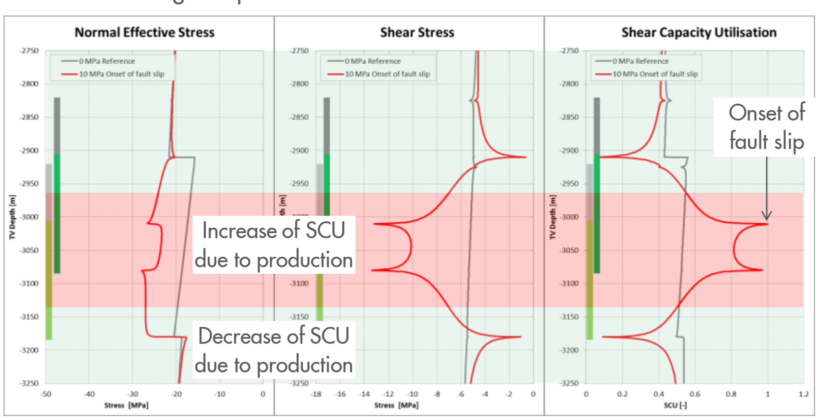


Stress response dependent on:

- stiffness ratio between reservoir and environment <u>across</u> the fault

ONSET OF FAULT SLIP AT 10 MPA DEPLETION

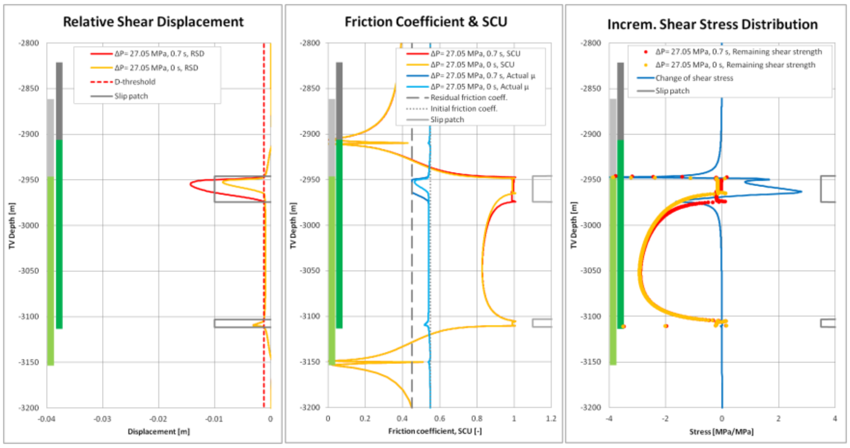
- Fault interval with depletion on both sides:
  - Reduced normal stress and high shear stress
  - Peak loading at top and bottom of interval



ONSET OF FAULT RUPTURE CASE MU55-142 (M_R = 0.45)

40 m reservoir formation offset

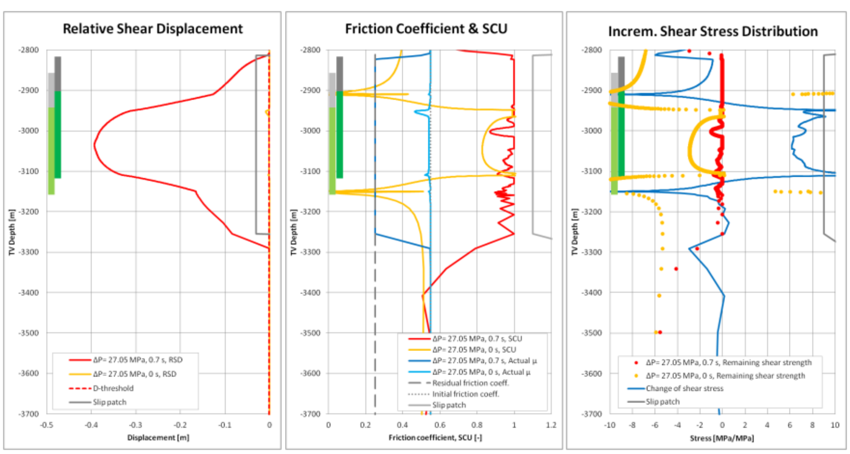
Residual friction coefficient is NOT reached at onset of fault rupture



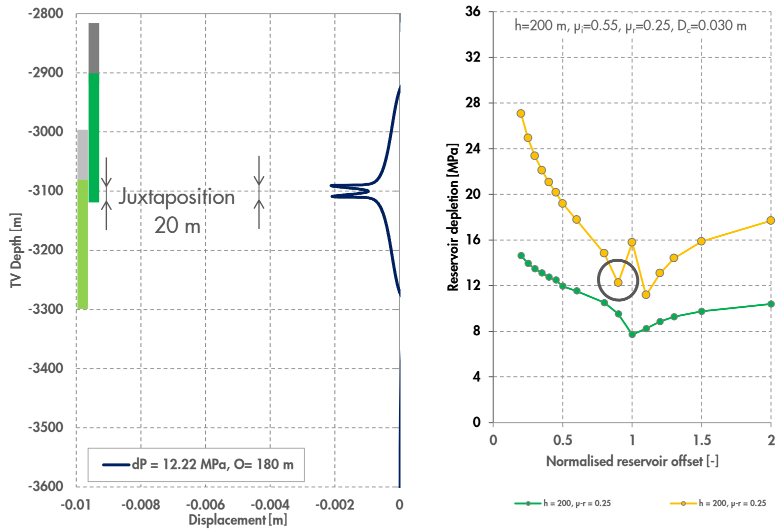
ONSET OF FAULT RUPTURE CASE MU55-146 (M_R = 0.25)

40 m reservoir formation offset

Residual friction coefficient is NOT reached at onset of fault rupture



NUCLEATION OF SEISMIC SLIP
OFFSET 180 M, RESERVOIR THICKNESS 200 M



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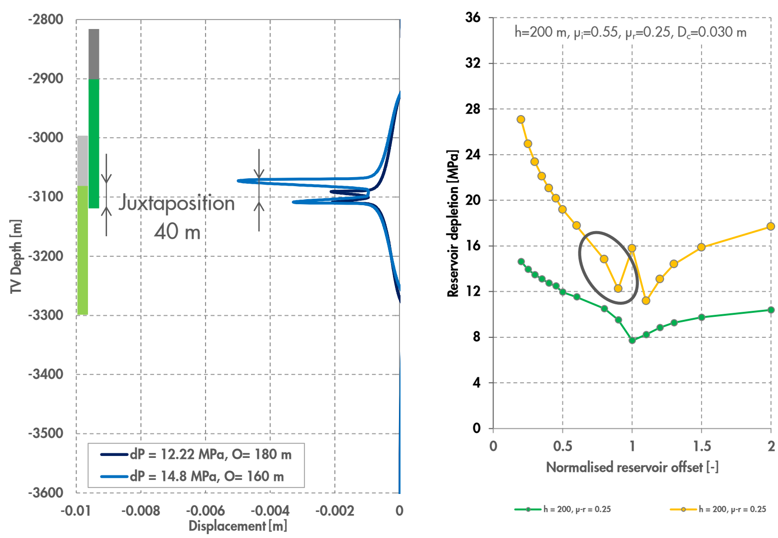
NUCLEATION OF SEISMIC SLIP
OFFSET 160 M, RESERVOIR THICKNESS 200 M



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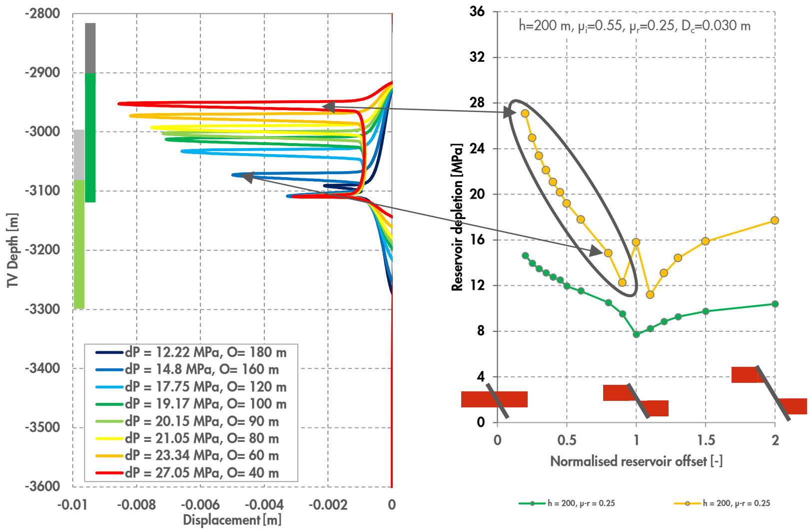
NUCLEATION OF SEISMIC SLIP (2)



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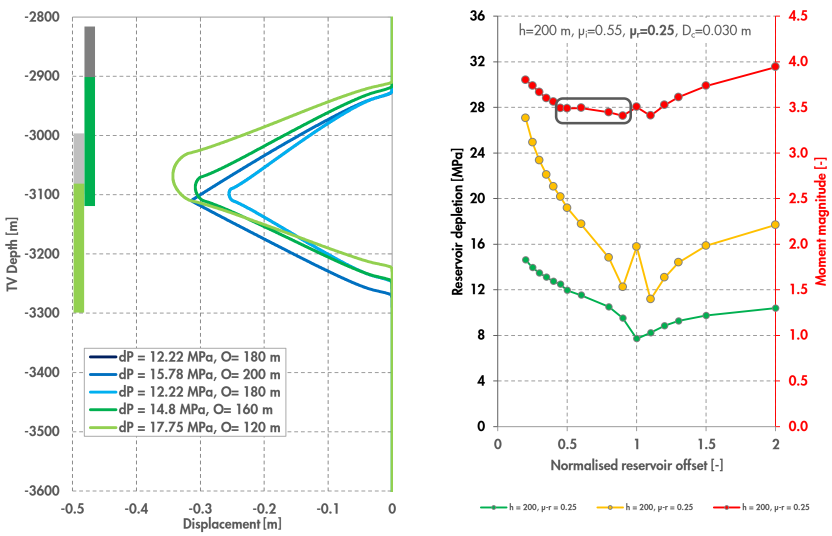
MAGNITUDE – NORMALISED OFFSET BETWEEN ½ AND 1

- M_w ~ 3.5 earthquake contained to reservoir interval for offset between ½ and 1 reservoir thickness



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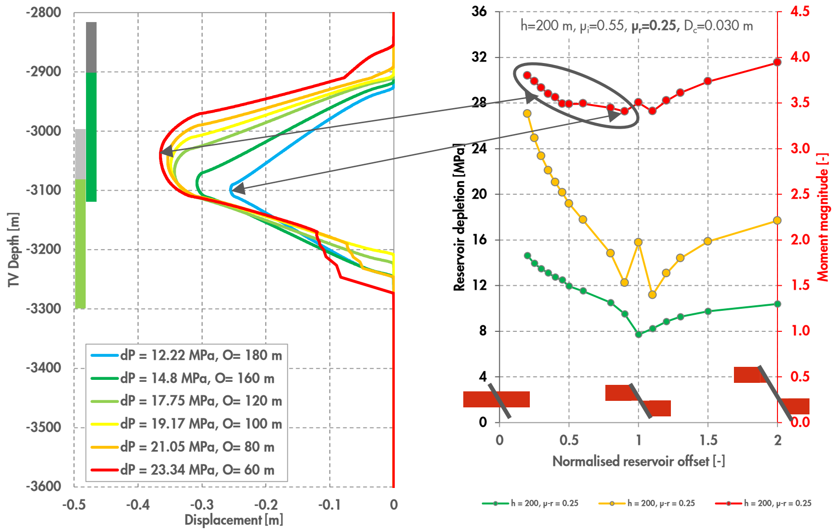
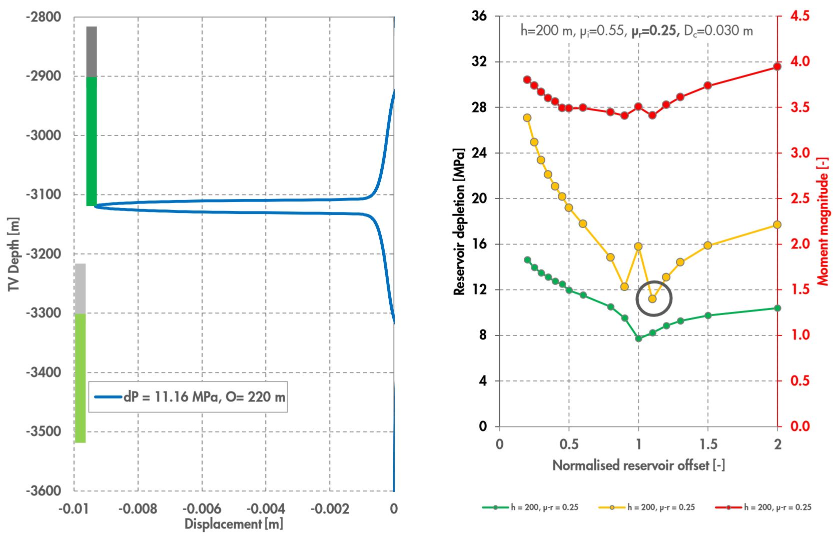
MAGNITUDE – NORMALISED OFFSET BETWEEN 0 AND 1

- M_w between 3.5 and 4.0 with seismic slip patch propagating outside reservoir interval for offset smaller than ½ reservoir thickness



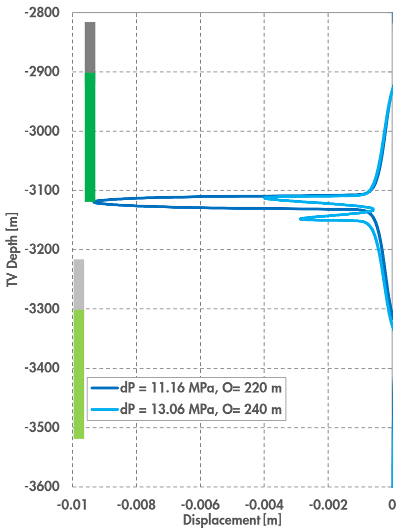
MAGNITUDE – NORMALISED OFFSET LARGER THAN 1

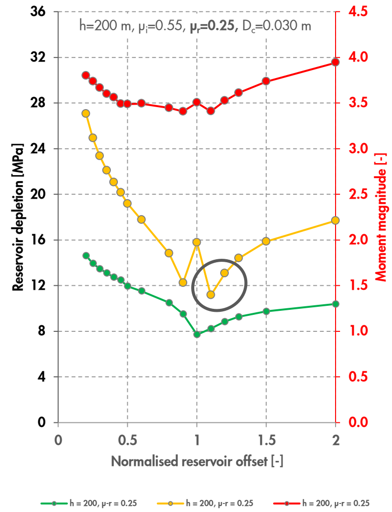
- Larger depletion required to merge slip patches at larger offset, leading to M_w ~ 4.0 at normalised offset of 2.



MAGNITUDE – NORMALISED OFFSET LARGER THAN 1

- Larger depletion required to merge slip patches at larger offset, leading to M_w ~ 4.0 at normalised offset of 2.





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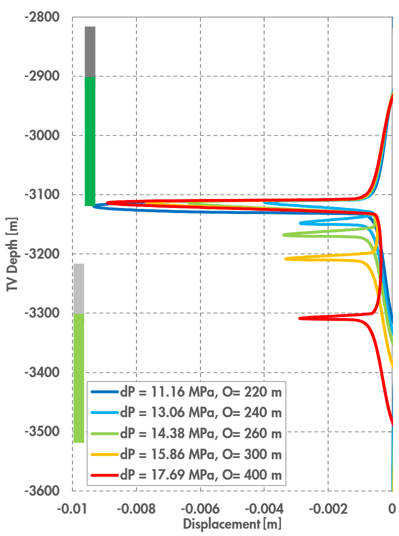
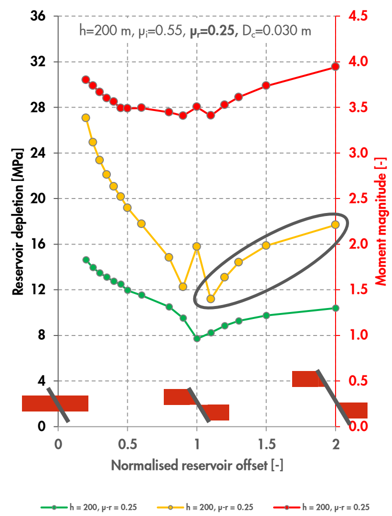
MAGNITUDE – NORMALISED OFFSET LARGER THAN 1

- Larger depletion required to merge slip patches at larger offset, leading to M_w ~ 4.0 at normalised offset of 2.





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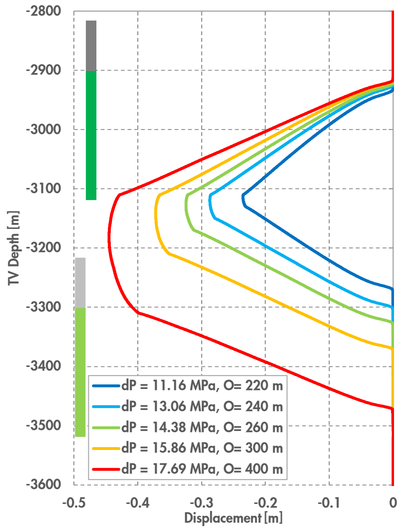
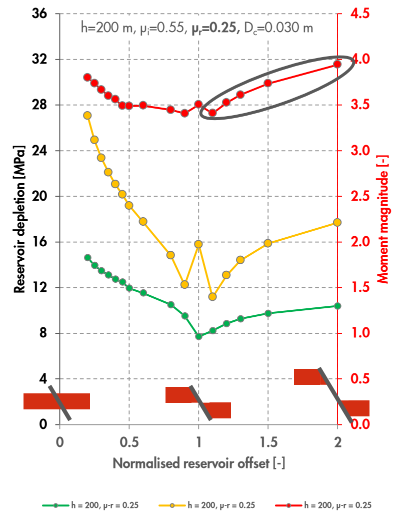
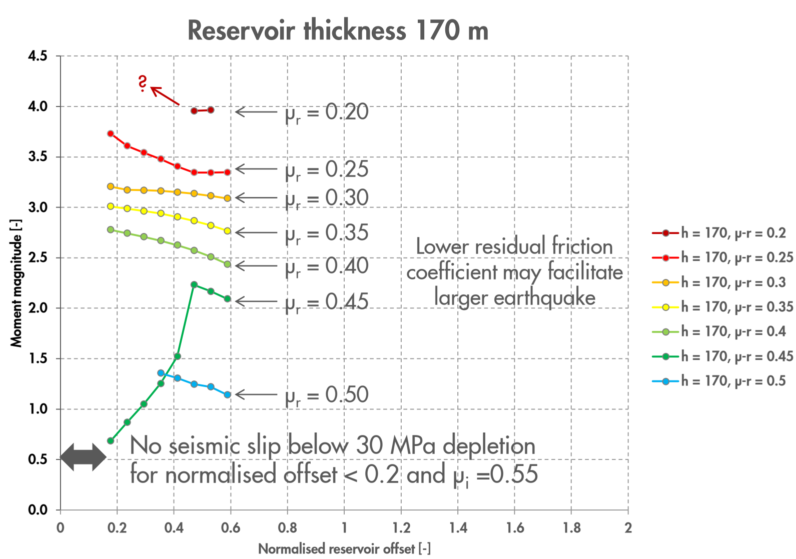
MAGNITUDE – NORMALISED OFFSET LARGER THAN 1

- Larger depletion required to merge slip patches at larger offset, leading to M_w ~ 4.0 at normalised offset of 2.





INFLUENCE OF RESIDUAL FRICTION COEFFICIENT



Seismic lines for shallow faulting

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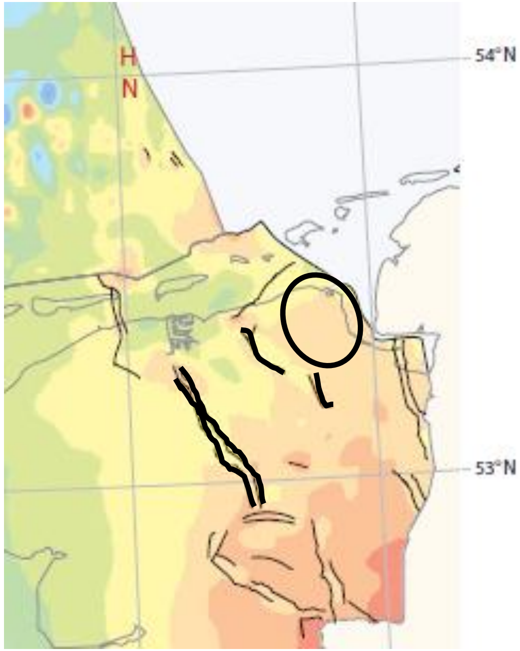
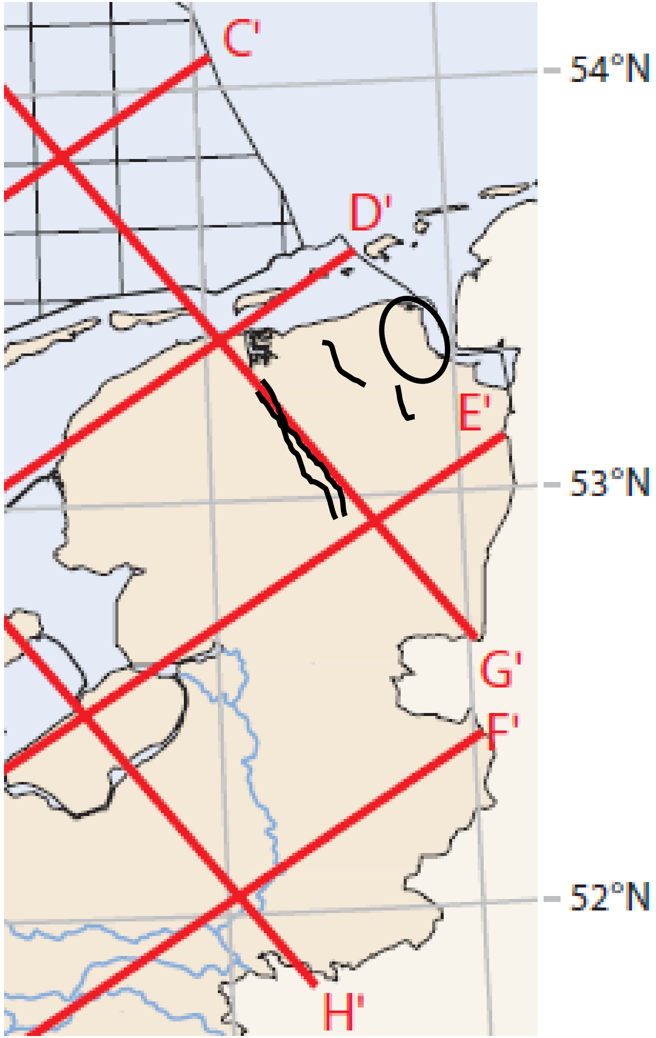
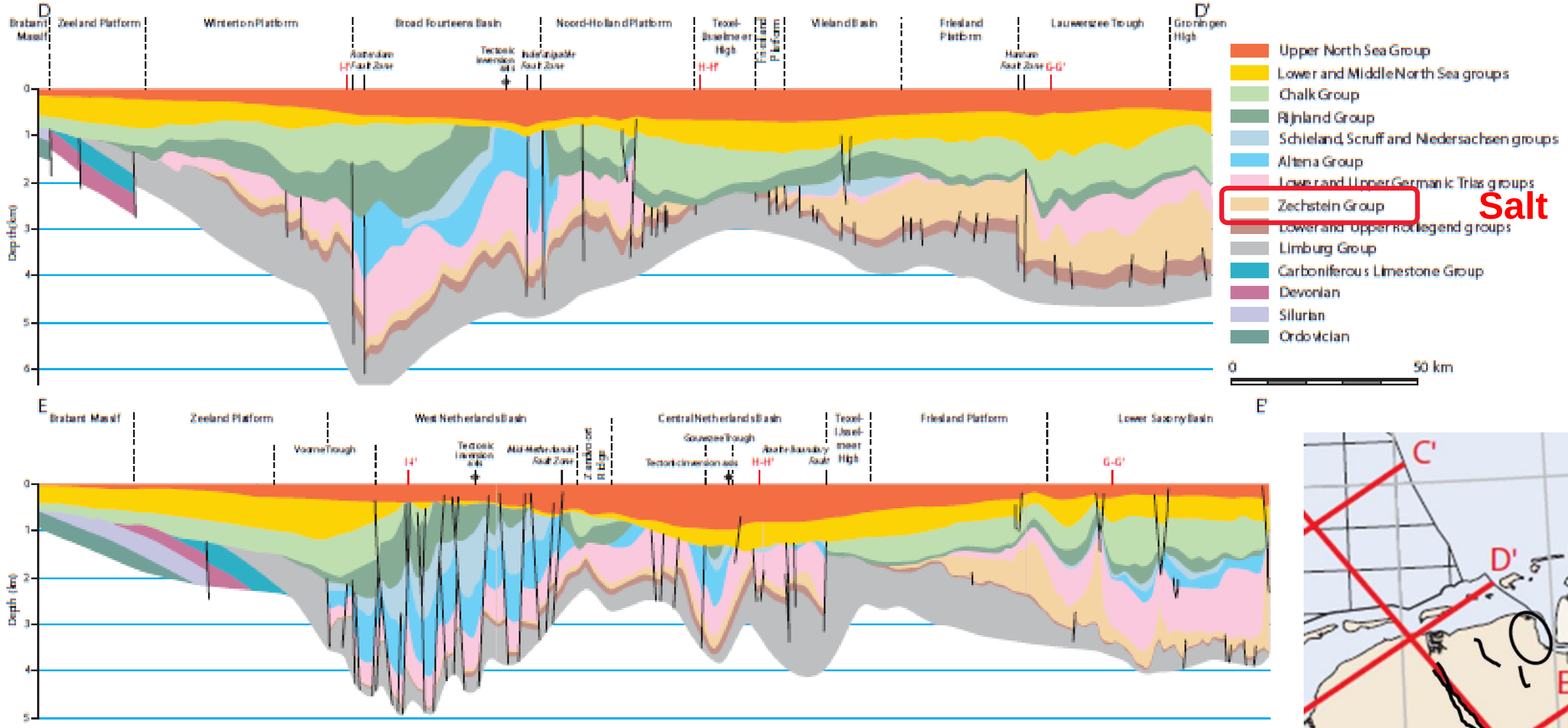
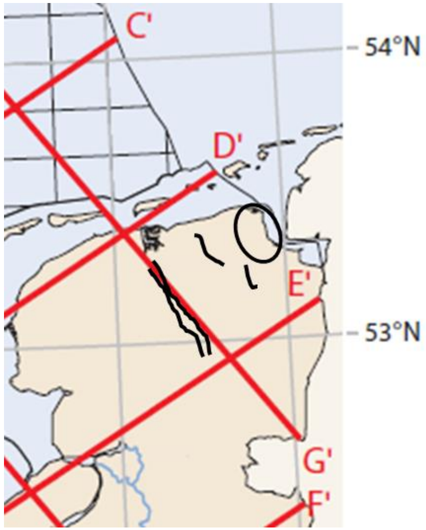
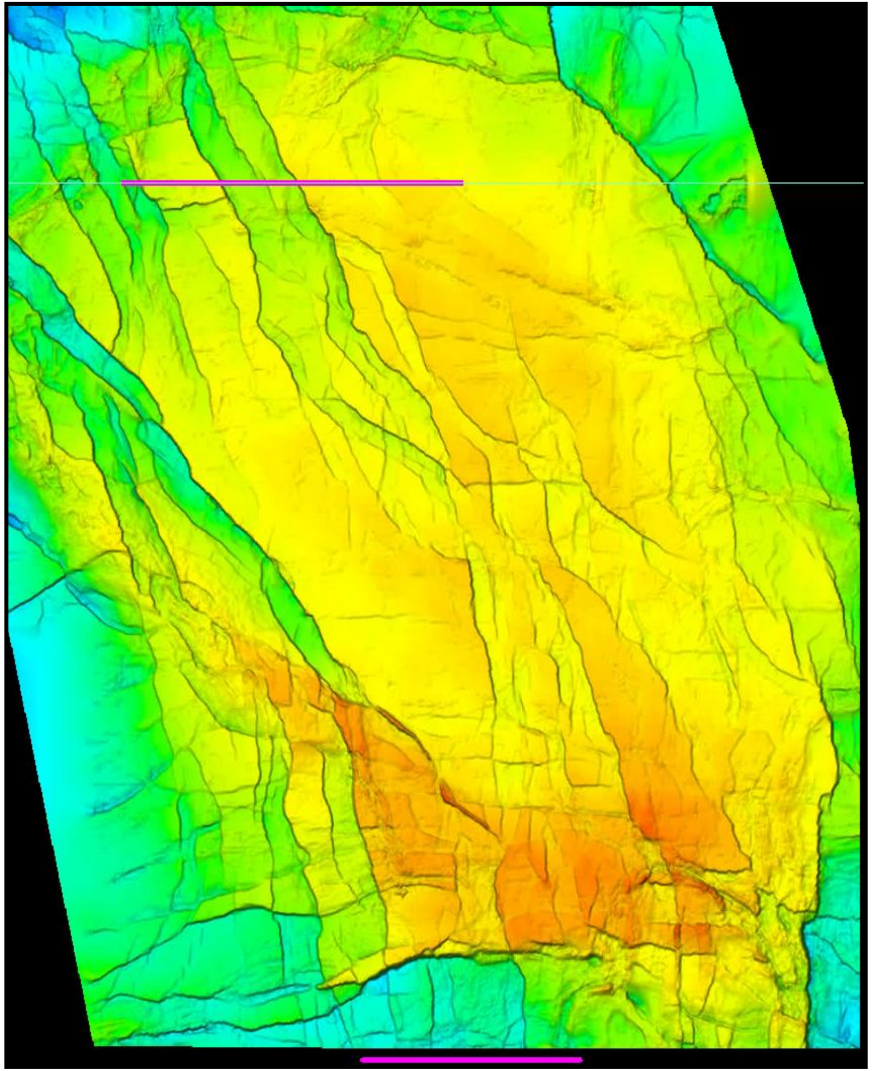
Confidential for Groningen Tremors Study

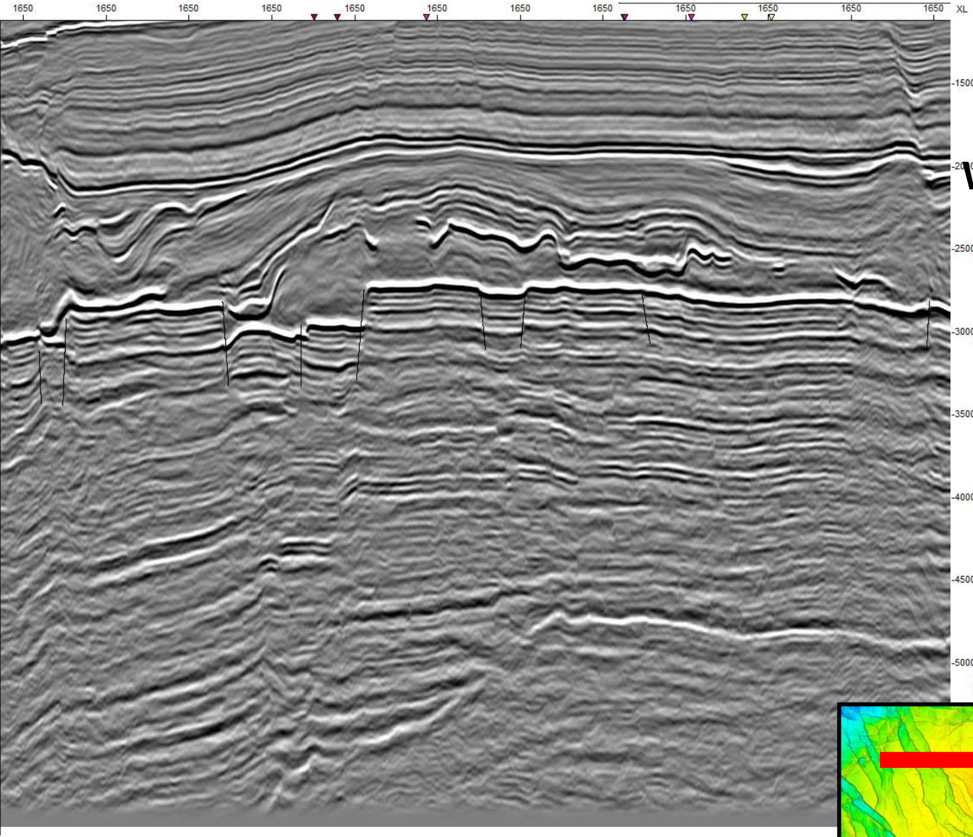

H
N
54°N
53°N

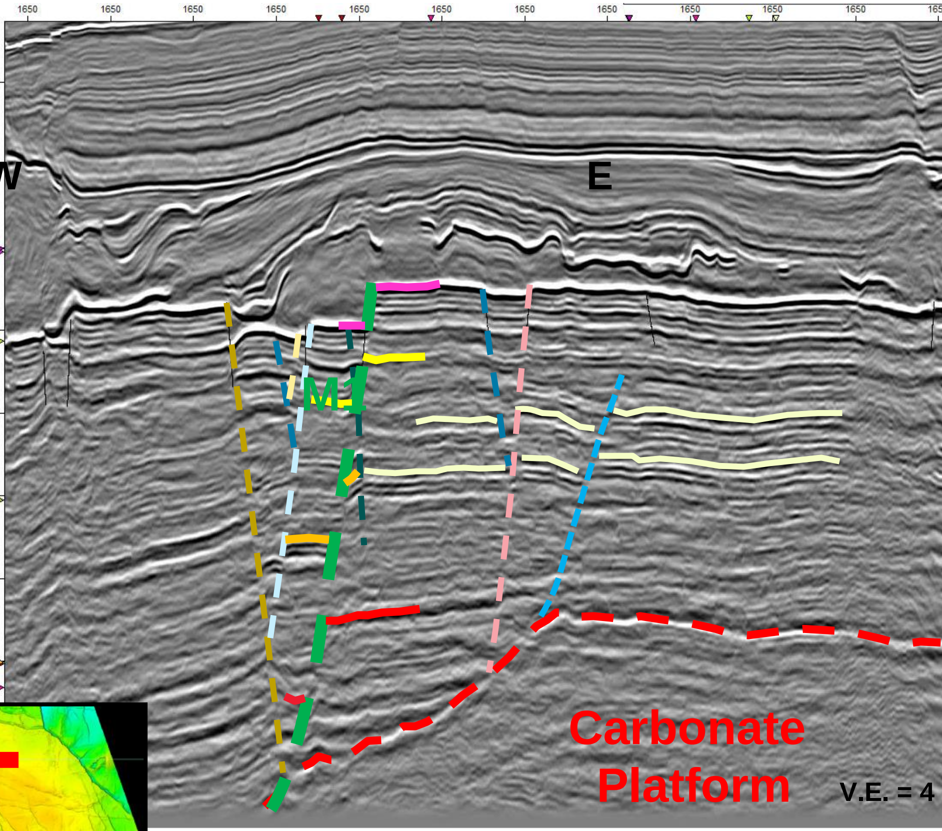

C'
D'
E'
G'
F'
H'
54°N
53°N
52°N

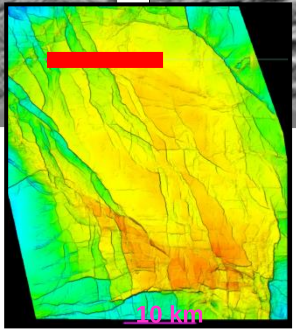

D
D'
Brabant Massif
Zeeland Platform
Winterton Platform
Broad Fourteens Basin
Noord-Holland Platform
Vlieland Basin
Friesland Platform
Lauwerszee Trough
Groningen High
Depth (km)
Upper North Sea Group
Lower and Middle North Sea groups
Chalk Group
Rijnland Group
Schieland, Scruff and Niedersachsen groups
Altena Group
Lower and Upper Germanic Trias groups
Zechstein Group
Salt
Lower and Upper Rotliegend groups
Limburg Group
Carboniferous Limestone Group
Devonian
Silurian
Ordovician
0
50 km
E
E'
Brabant Massif
Zeeland Platform
West Netherlands Basin
Central Netherlands Basin
Friesland Platform
Lower Saxony Basin
Depth (km)

C'
D'
E'
G'
F'
54°N
53°N

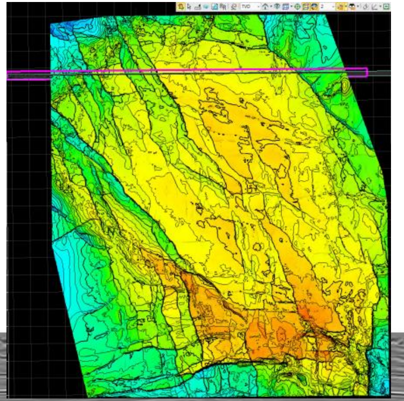
Top Rotliegend

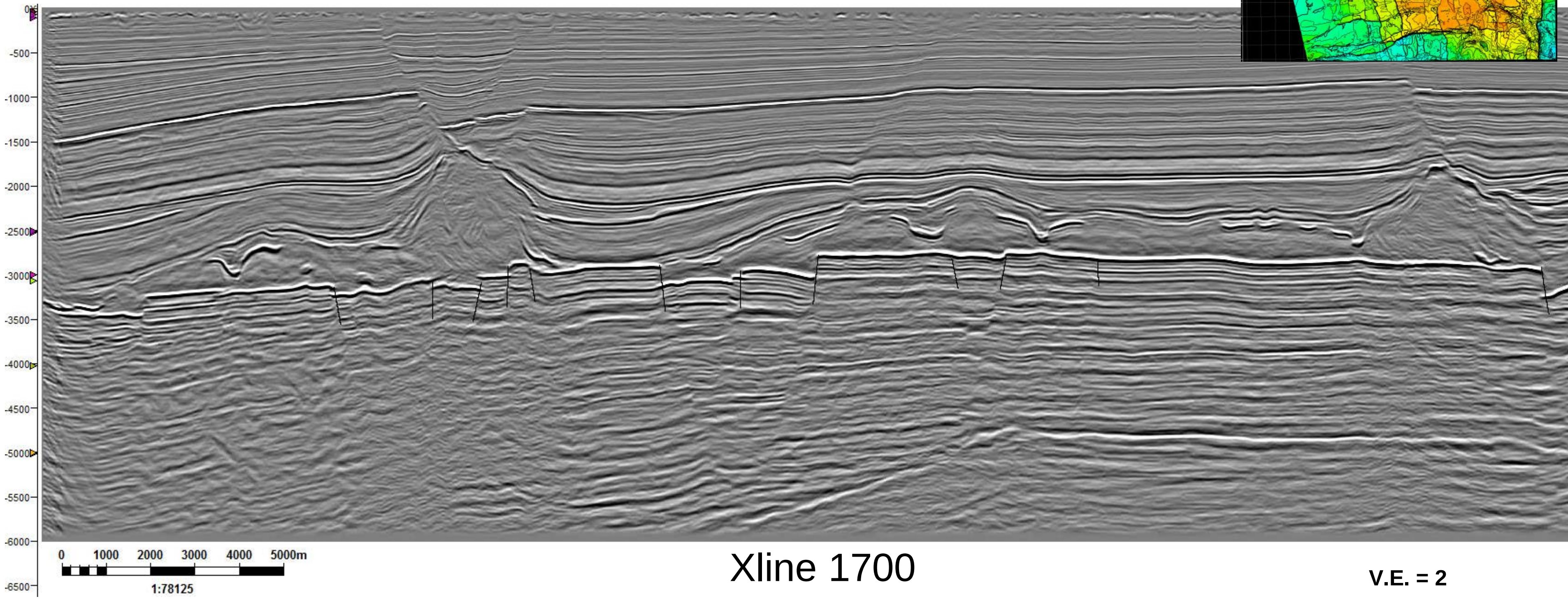



1650
XL
-1500
-2500
-3000
-3500
-4000
-4500
-5000


1650
W
E
M1
Carbonate
Platform
V.E. = 4


10 km

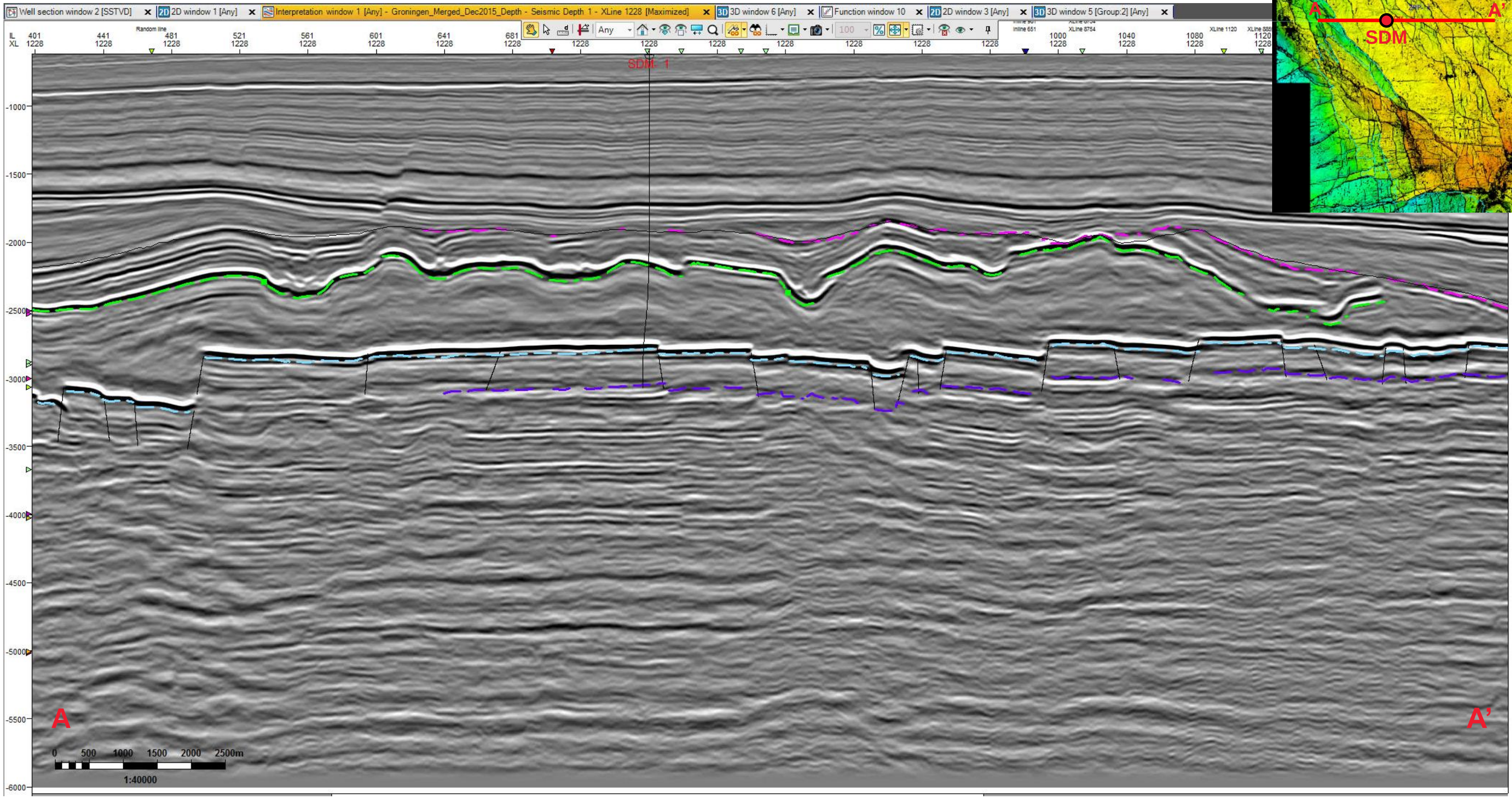


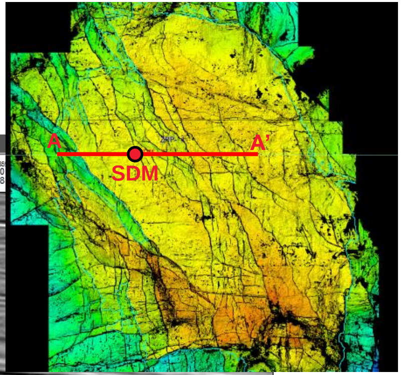


Xline 1700

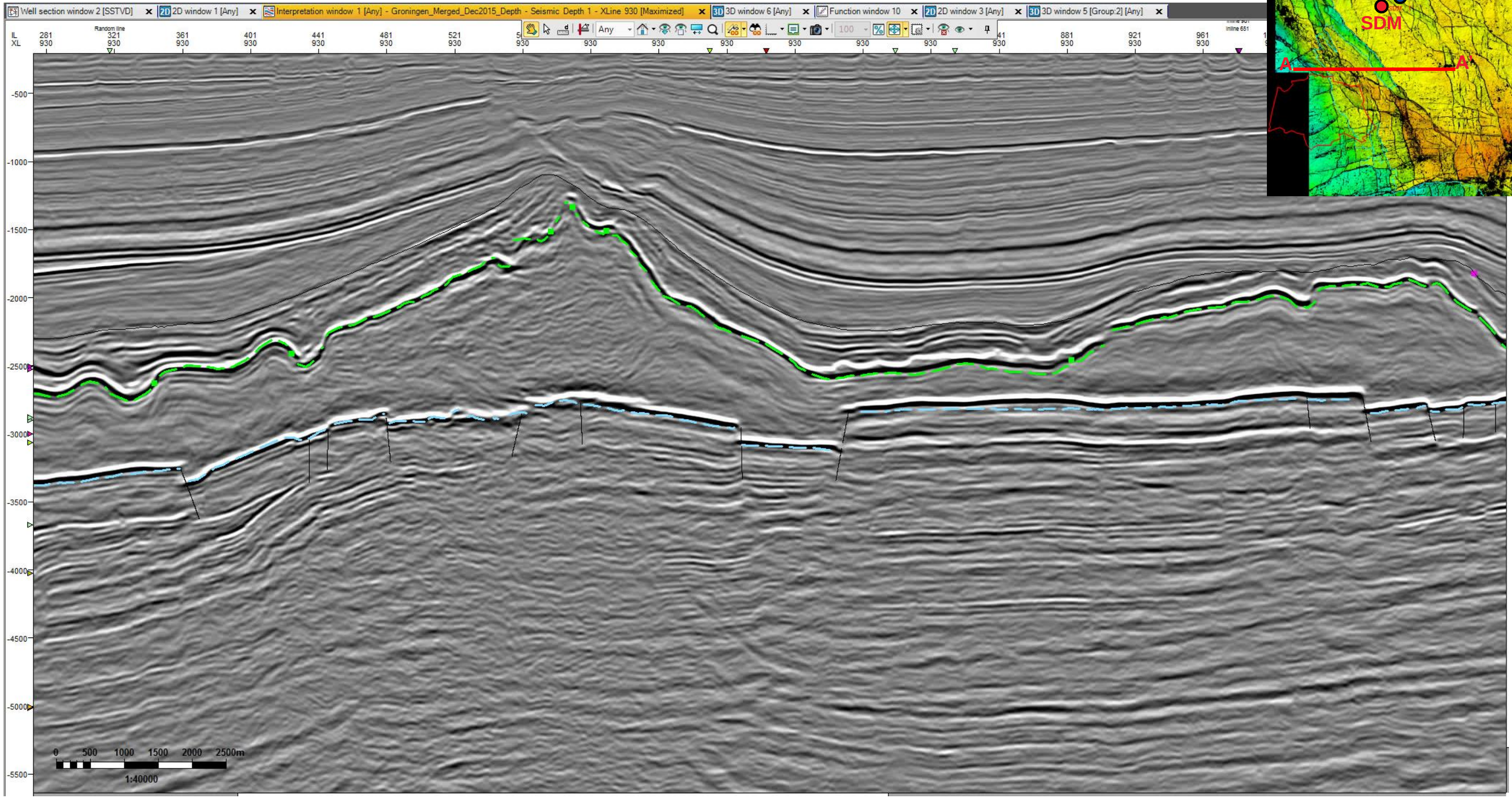
V.E. = 2

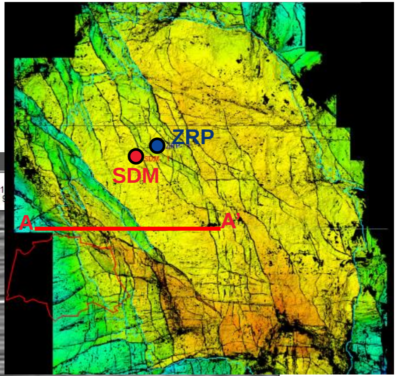
New Seismic – Old Interpretation



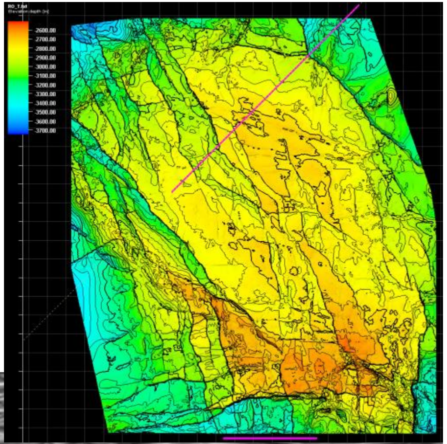


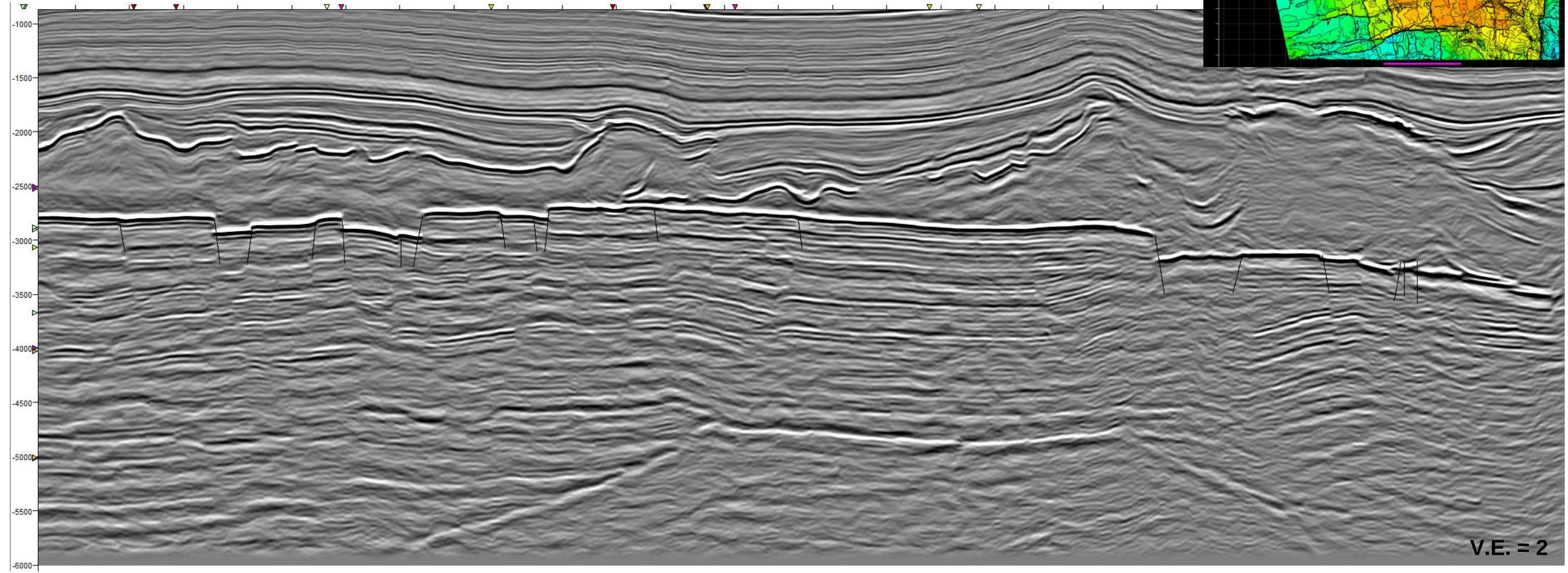
New Seismic – Old Interpretation



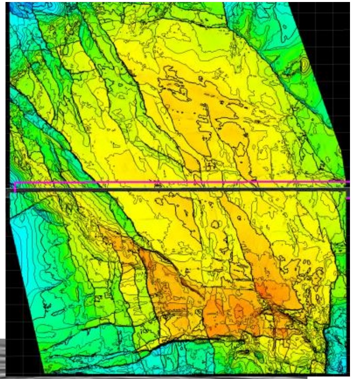


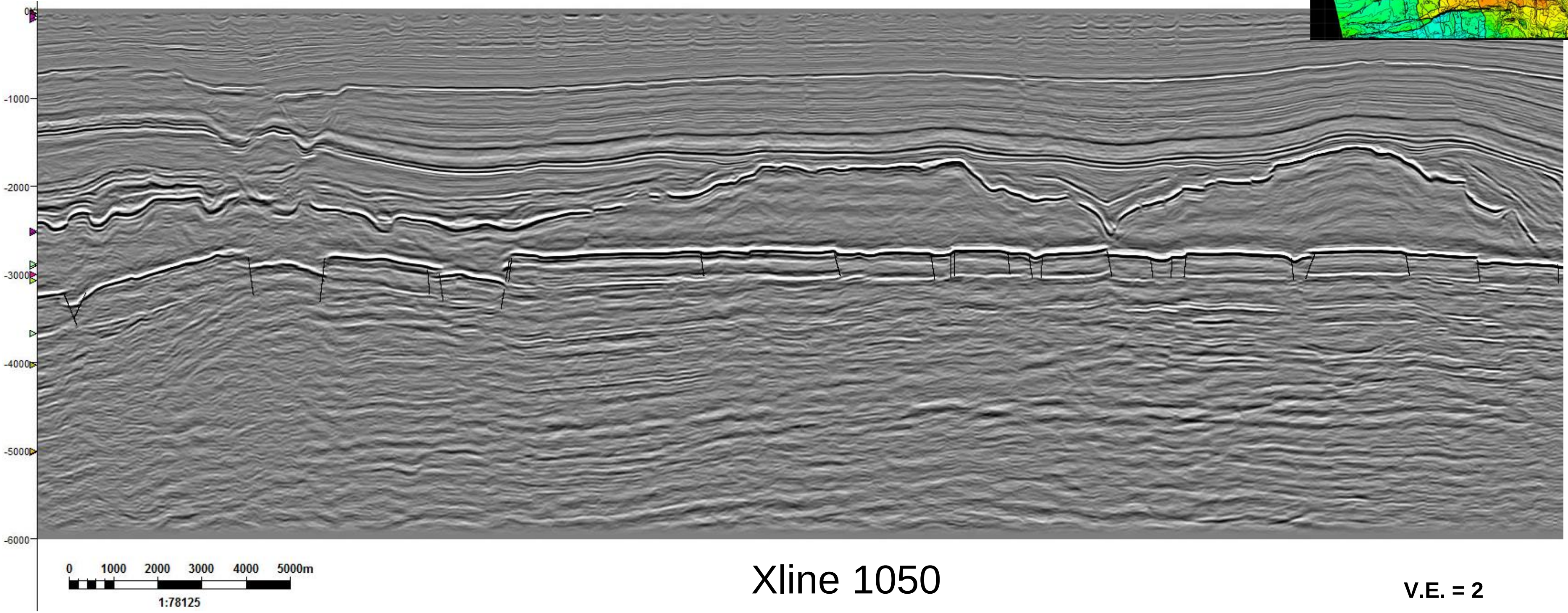
Random Line





B51 Fault





Xline 1050

V.E. = 2

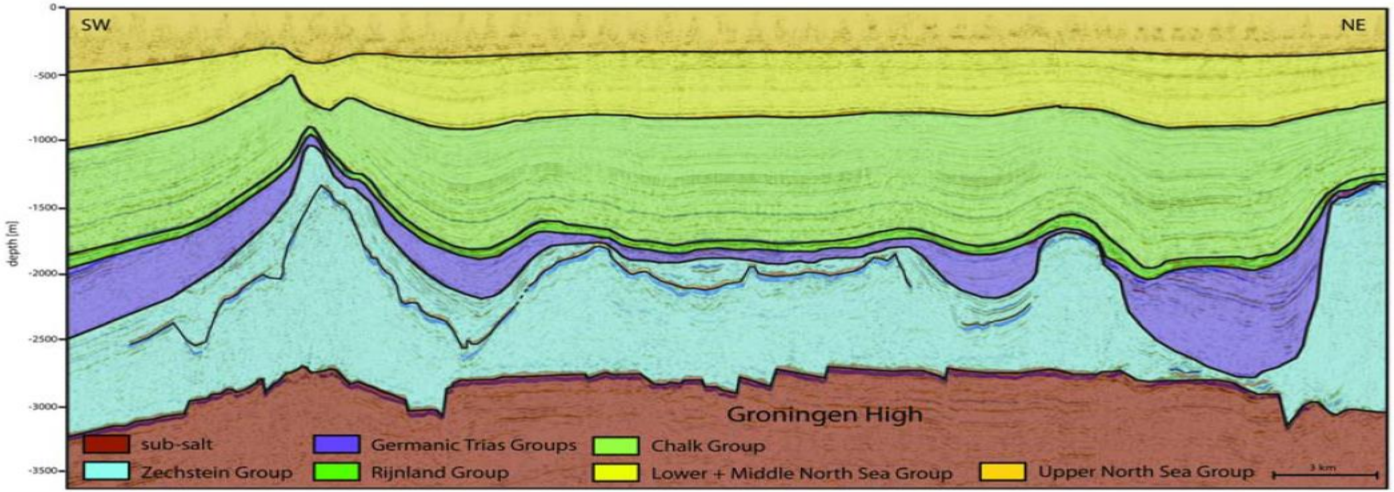


Fig. 6. Seismic line on the Groningen High, SW-NE orientated, indicating the interpreted sequences.

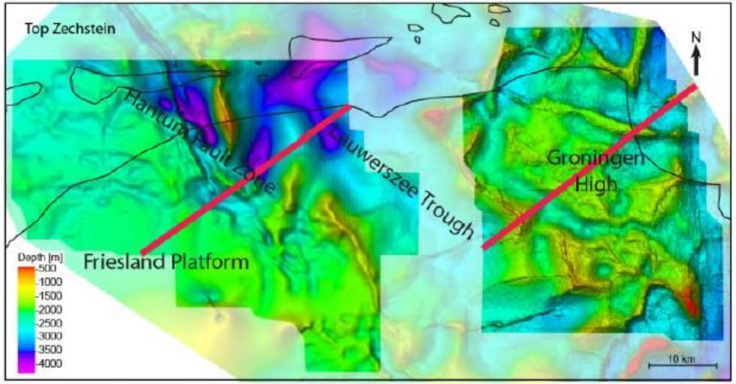
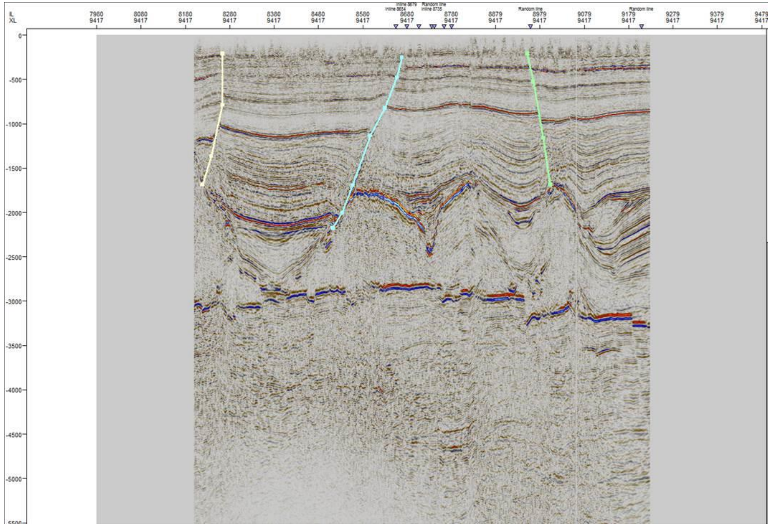


Fig. 3 Depth map of the Top Zechstein. Red lines represent the 2D profiles (Fig. 4 + 5) used for kinematic restoration.



W-E line on the northern edge of the Groningen field showing overburden faults "dying out" to the surface. Please note also that this seismic has been processed especially to bring out deeper features.

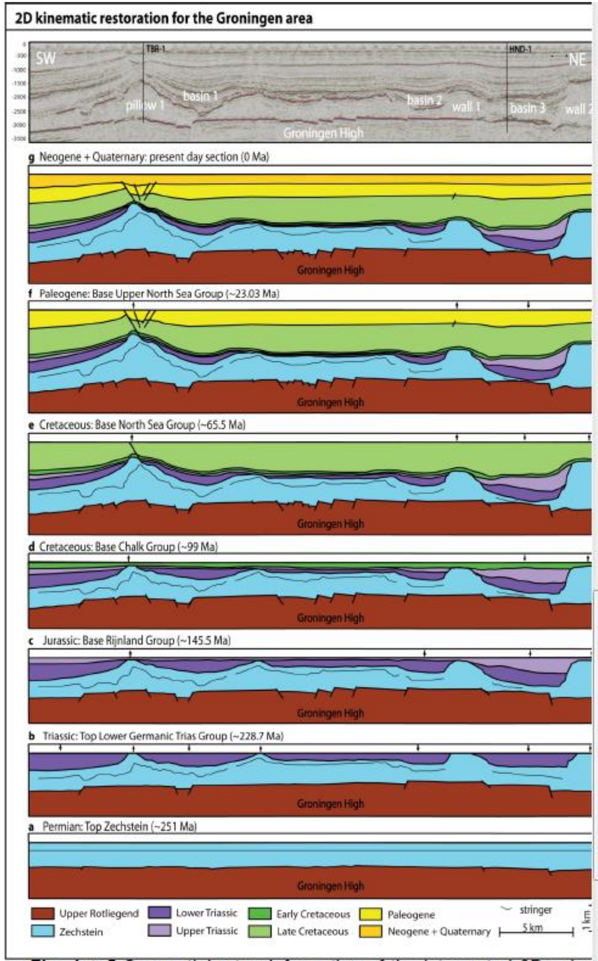


Fig. 4 + 5 Sequential retro-deformation of the interpreted 2D seism lines, from the Top Zechstein (Permian) to present day. The Z3 string is only an assumed sketch, it is not actively retro-deformed.

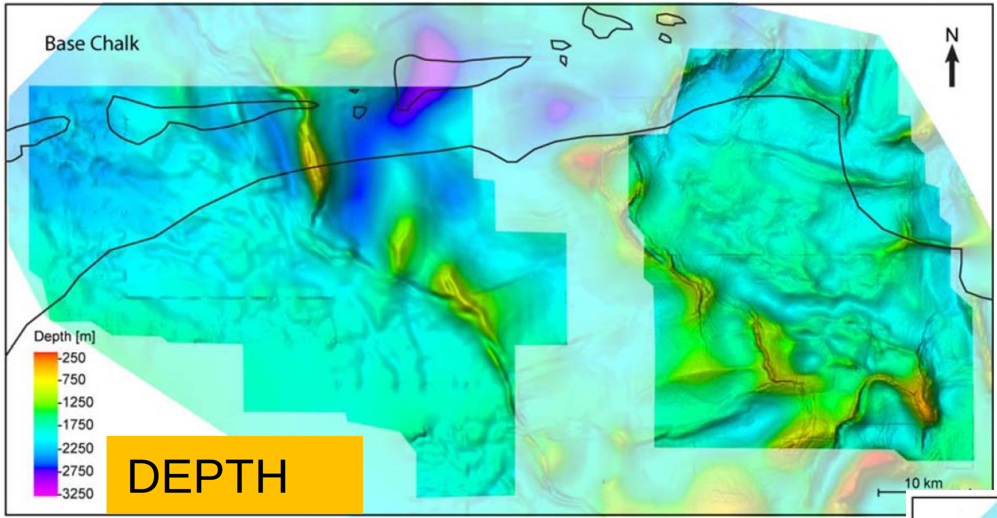


Fig. 11. The depth map illustrates the Base Chalk surface in the northern Netherlands

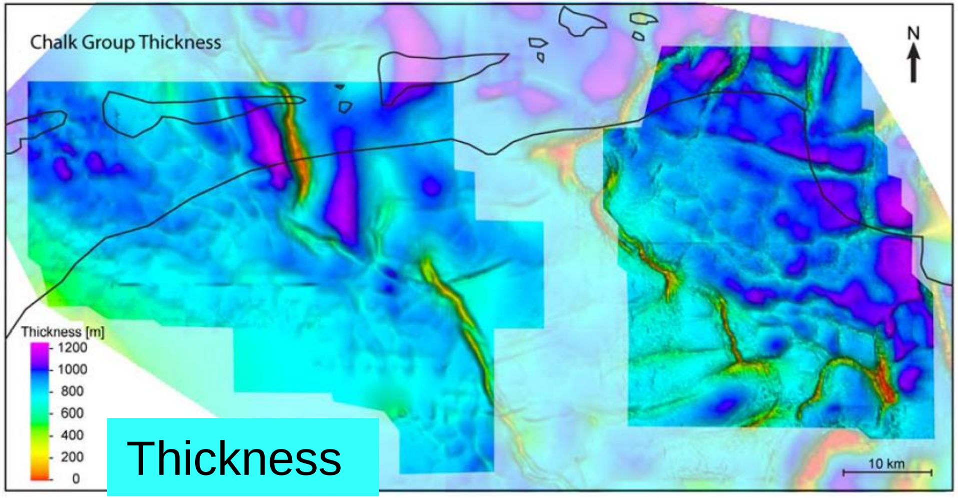


Fig. 19. The isopach map illustrates the Chalk Group thickness between Base Chalk and Base North Sea.

Thesis Eva Krejci, 2011

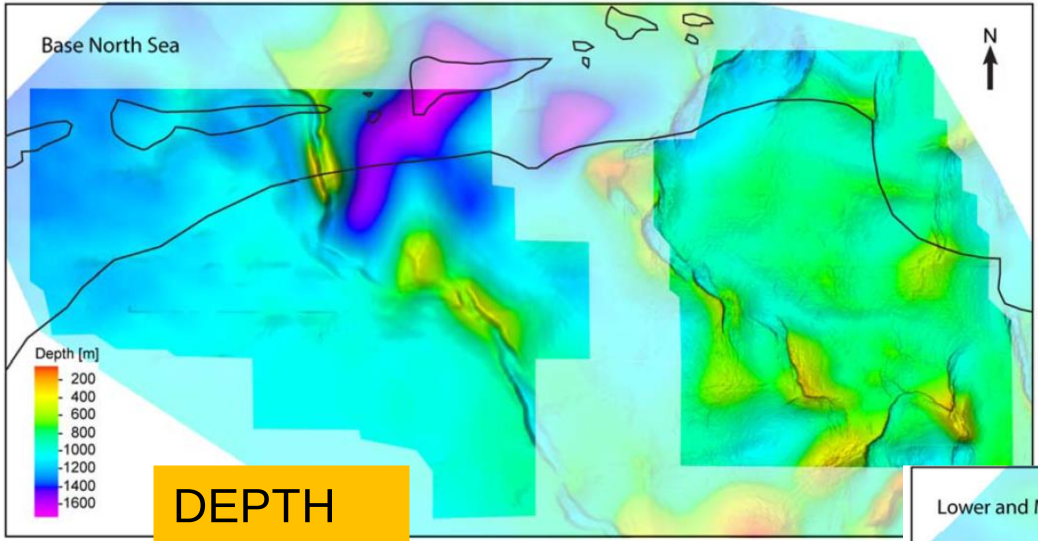


Fig. 12. The depth map illustrates the Base North Sea surface in the northern Nether

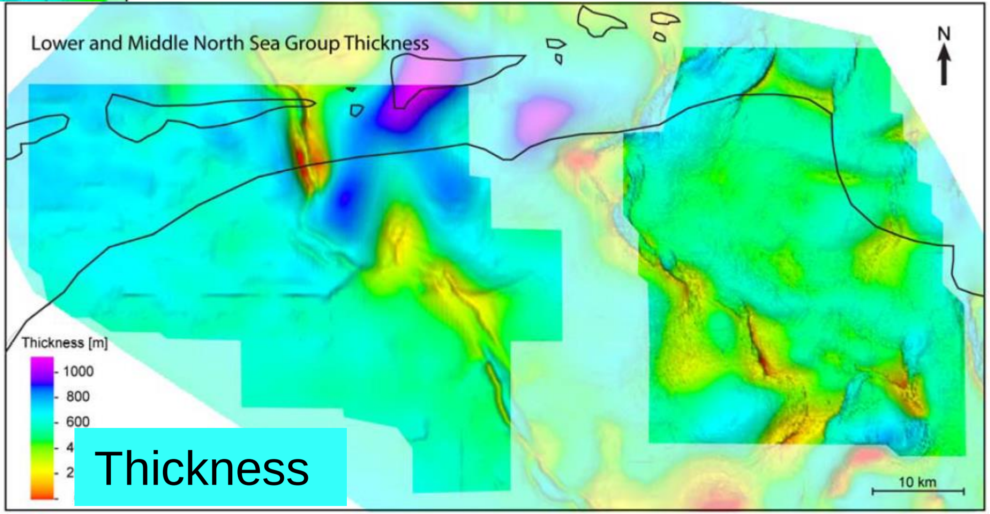


Fig. 20. The isopach map illustrates the Lower and Middle North Sea Group thickness between Base North Sea and Base Upper North Sea.

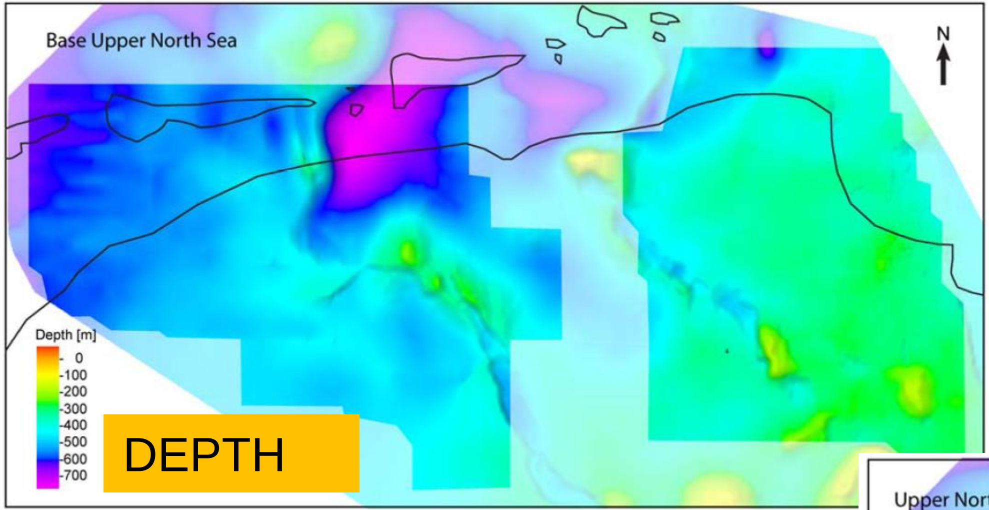


Fig. 13. The depth map illustrates the Base Upper North Sea surface in the northern Neth

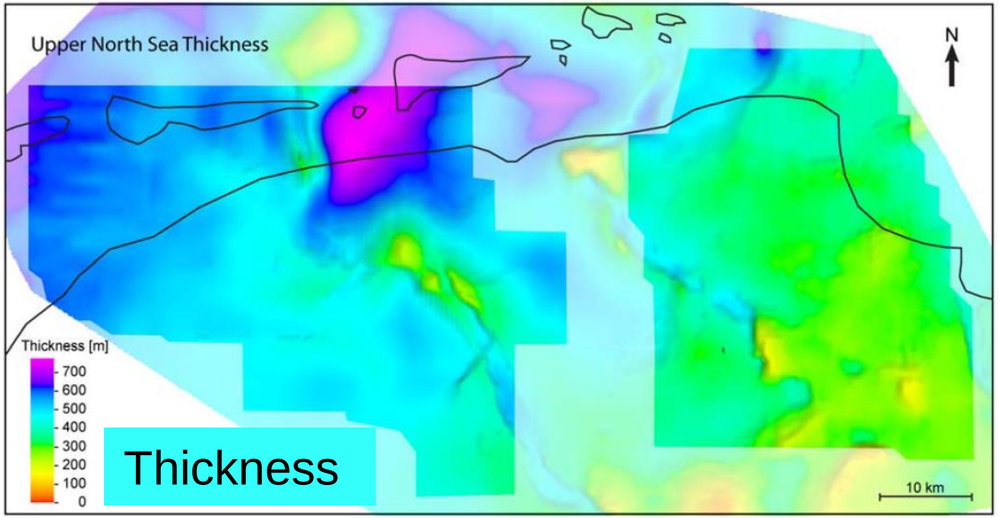
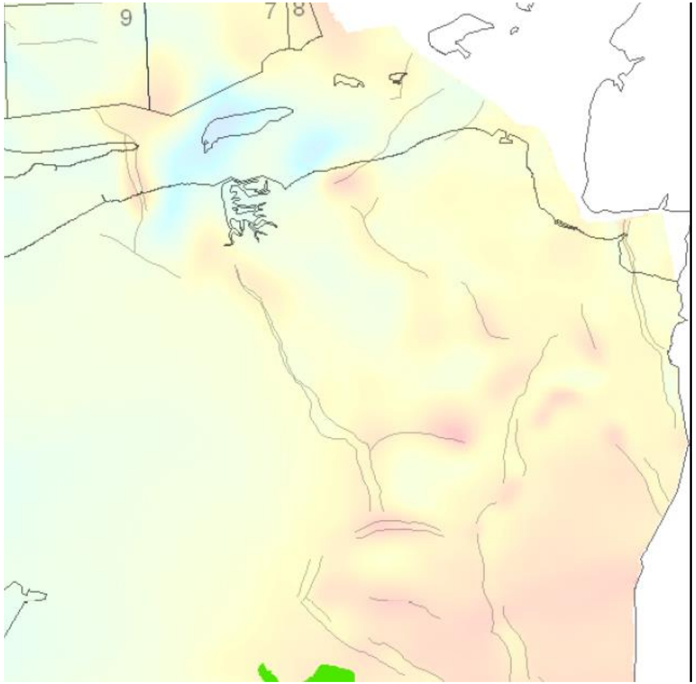
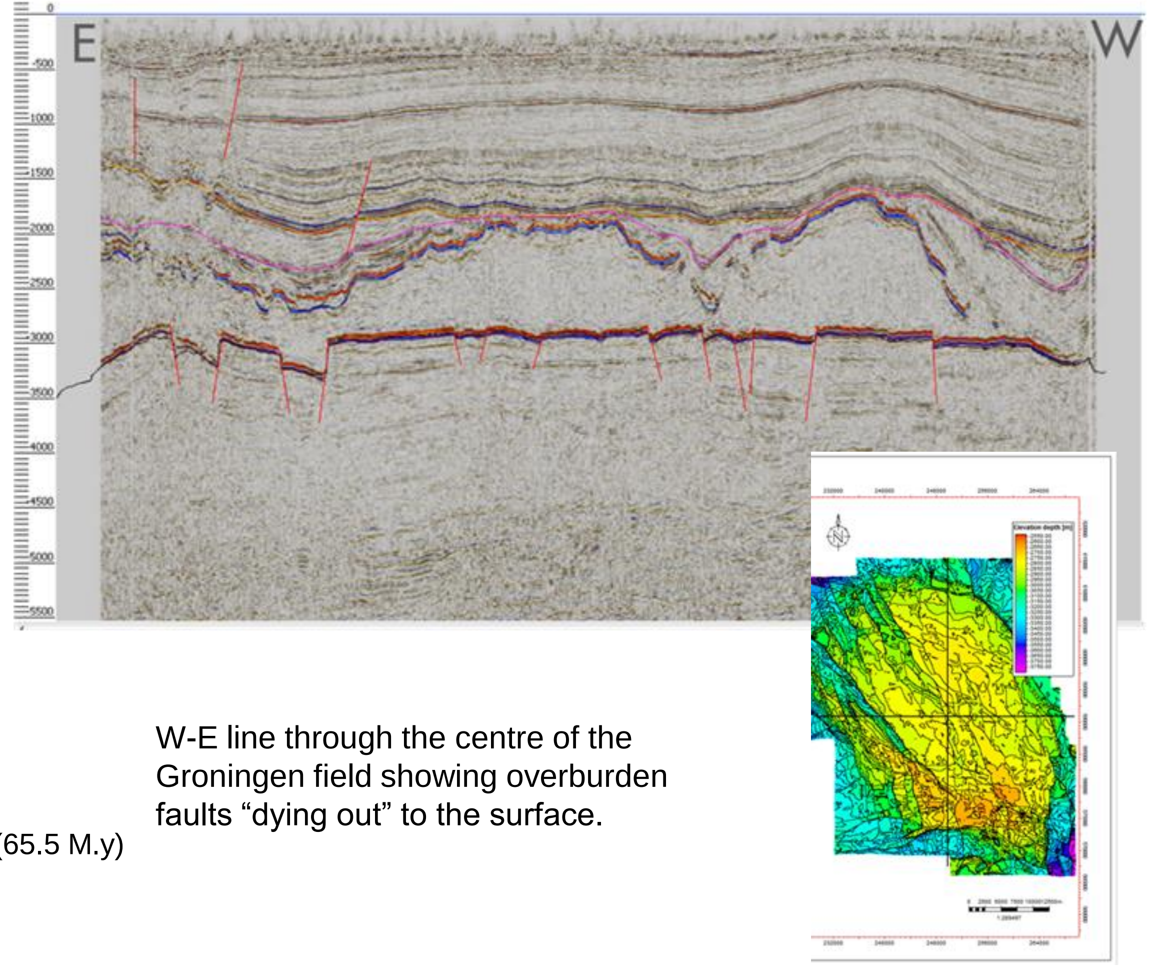


Fig. 21. The isopach map illustrates the Upper North Sea Group thickness between Base Upper North Sea and Earth (Sea) Surface.



TNO depth and fault map Over NEN area for Top Chalk (65.5 M.y)



W-E line through the centre of the Groningen field showing overburden faults “dying out” to the surface.

Conclusion: Faults in the Tertiary sequence above and around Groningen.

Faults are present, mostly above the salt ridges.

While still visible at Base Paleogene (23 M.y), the faults become largely "smothered" by sedimentation in the Neogene and Quarternary such that there are **no or only very limited and small** faults (low offset / low fault length) discernible* in sediments deposited over Groningen in the last 20 Million years.

* Minimum trow visible at the depth concerned ~ 10- 20m (to be confirmed for this particualr depth range for the seismic available).

We have also used edge detection filters on autotracked horizons in seismic in the Tertiary overburden. The results confirm the conclusion given above.

Signed: Dr. Ide van der Molen, Senior Structural Geologist, NAM
Date: 3/10/2016