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Spatiotemporal modelling of induced seismicity with a stress-based statistical approach applied to different production sites

GEO:N project
SECURE

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Introduction

Motivation

Induced seismicity is caused by various man made activities (gas production, hydro-facturing, gas storage, geothermal sites). The settings and processes differ resulting in various models adapted to the different applications. In consequence each application has its own adapted model with several parameters and the results are not comparable to each other. In this part of the GEO:N project SECURE physical-based statistical seismicity models are investigated and applied to different types of production sites analyzing their perfomance to find a site independent model.

Aim

Creating one toolbox with programs modelling induced seismicity based on Coulomb Failure Stresses (CFS) describing the seismicity considering the influencing parameters and resulting uncertainies.

Toolbox

Seismicity Models

Poisson: $R = r$

background model; seismicity occurs arbitrary in space in time (m=1)

CM: $R = a \cdot \Delta CFS + r$

Coulomb Failure Model (CM): seismicity rate changes proportional to Coulomb failure stress changes on critically stressed faults (m=2)

$\text{CM}_{\text{subcrit}}$: $R = a \cdot \Delta CFS + r \;\; for\, S > S_0$

CM on subcritically stressed faults (m=3)

RS: $$R = \frac{r}{\dot{\tau}\,\gamma\,(t, x \mid \Delta CFS, A\sigma)}$$

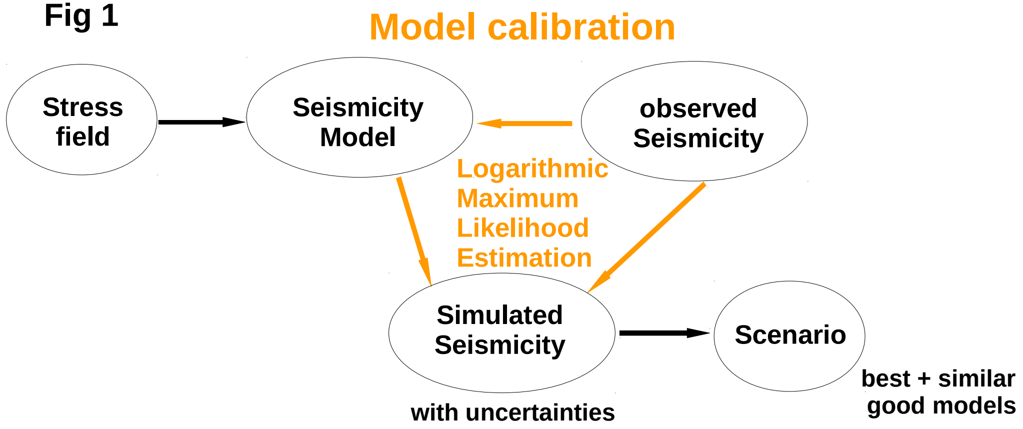
Coulomb Rate-and-State Model (RS): non-linear frictional behaviour; constant tectonic stressing rate causes a constant seismicity rate (Dieterich, 1994) (m=3)

Parameters

r	-	background rate
a	-	proportionality factor
A	-	friction parameter
$\dot{\tau}$	-	tectonic stressing rate
CFS	-	Coulomb failure stress
σ	-	effective normal stress

Free model parameters (m): $r, a, \dot{\tau}, A\sigma$

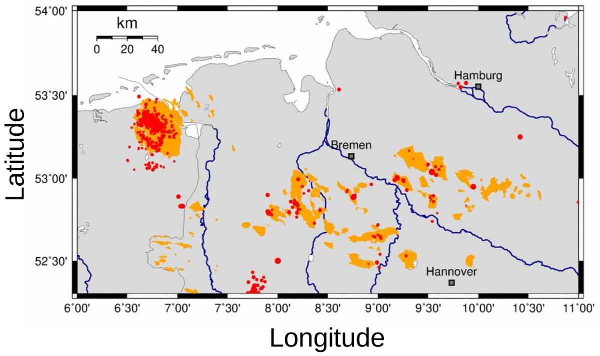
Fig 1



Applications

Gas fields

Fig 2

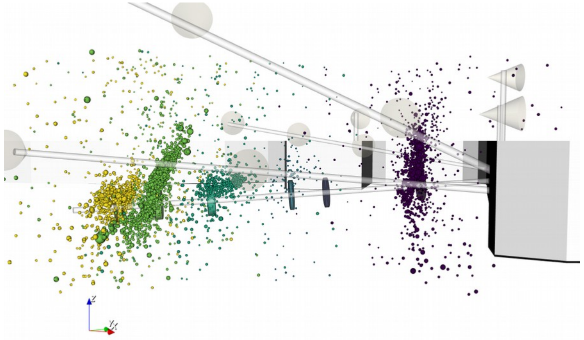


two gas fields in Rotliegend formation

field	**1**	**2**
size (km)	30 x 40	5 x 10
production start	1963	1995
first event	1991	2000
No. events	> 450	10

hydraulic fracturing mine experiment

Fig 3

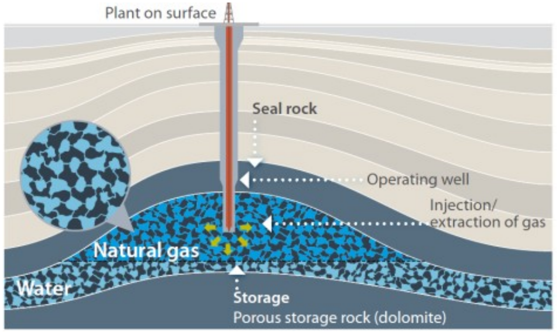


from Niemz et al., 2020

- hydraulic fracturing in granite
- 6 fracturing stimulations
- more than 2000 acoustic emissions (AE) of $M_{AEc} \geq 2.5$ with maximum distance of 14m from injection point

gas storage in an aquifer

Fig 4



Poster in this session: EGU2020-10311_Silverii et al, 2020

- carbon dioxid storage and production in an aquifer layer
- small seismic events redorded by local network at a close fault (natural or induced?)

Analysis

Gas fields

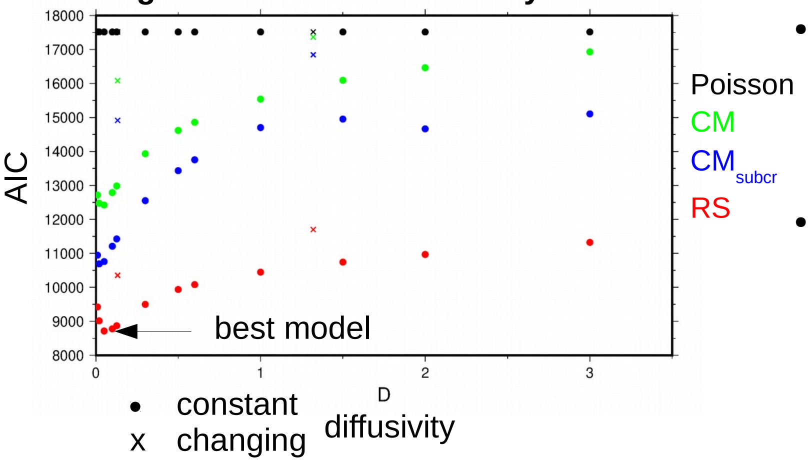
- ΔCFS based on pore pressure or compaction rate
- Influence of faults (density and orientation)
- Seismicity rates modelled on lateral grid and considering layer thickness and compared to observed seismicity
- Influence of fitting period on the results

- Evaluation of the models with the Akaike Information Criterion (see Fig 5):
  $AIC = 2 * (m – LL)$
  LL – log likelihood
  m – free model parameter

hydraulic fracturing mine experiment

- Injected fluid causes poroelastic pressure changes (Segal & Lu, 2015) in 2D (along fracture)
- Influence of diffusivity D
- Seismicity rates modelled on radial symmetric plane from injection point and compared to observed seismicity

Fig 5: Influence of diffusivity D



gas storage in an aquifer

- Pressure at wells as input for temporal fit to local seismicity
- Pressure changes modelled in a semi-analytic poroelastic layered model (see EGU2020-10311 for details) as input for modelling

First results:

- Background seismicity (M≥2.0; 1970-2012; 8 events) does not change significantly (> 2012; 2 events).
- RS model reproduces seismicity rate variatons between production and storage cycles based on a temporal fit.

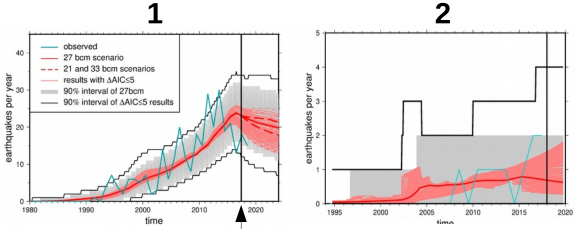
Results

hydraulic fracturing mine experiment

Gas fields

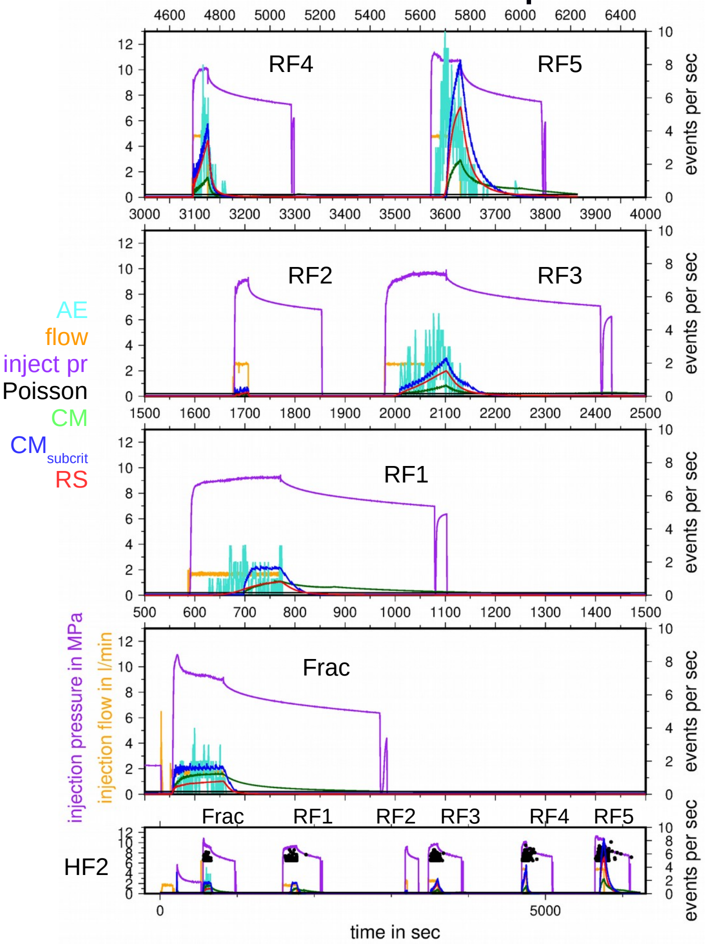
- Knowledge of faults is a key parameter to impove the model
- Larger model uncertainties for smaller data sets (little seismicity/shorter fitting period)
- Spatial and temporal patterns can be modelled (Richter et al, 2020)

Fig 6: Seismicity forecast



observed seismicity
modeled seismicity for all scenarios
models with ΔAIC≤5 + uncertainties

Fig 7: HF2; constant D=0.1265; rates summed over modelled plane



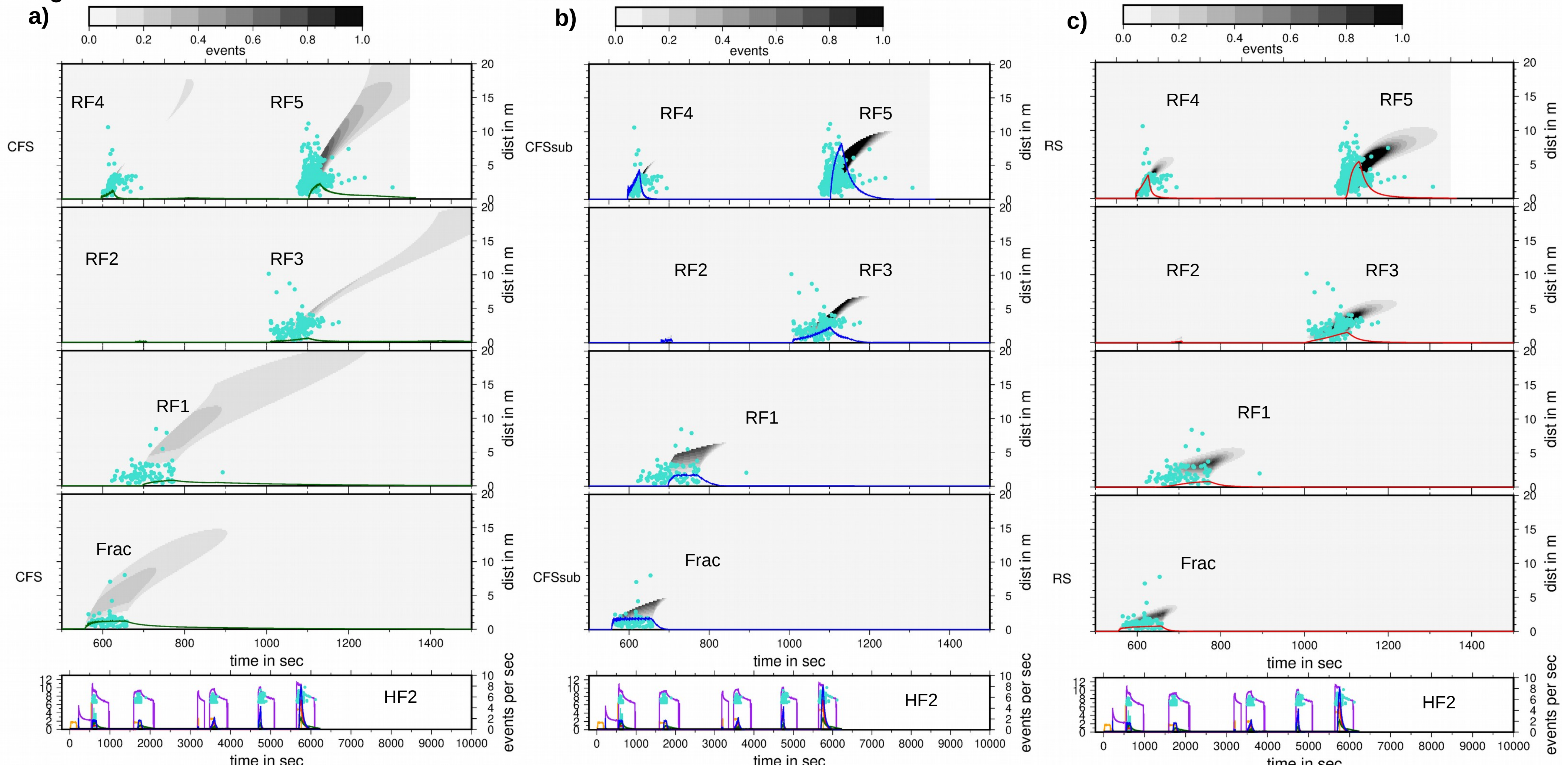
- Temporal seismicity pattern change for the ReFracs (RF1-5). These changes can be modelled and display the Kaiser-Effect.
- The models $CM_{subcrit}$ and RS predict the seismicity closer to the injection point than the CM (see Fig 8). This fits to the observed seismicity.
- For smaller diffusivities the spatial fit improves a lot (see Fig 5: ΔAIC>1000). Changing diffusivities from one RF to the next according to measured permeabilities can not improve the fit.

Results

hydraulic fracturing experiment spatial model comparison

HF2; constant D=0.1265

Fig 8



Conclusions

- The program toolbox for modelling the induced seismicity has been applied to three different production sites with
  a) different background seismicity
  b) different dimensions (m ➡ 10 km)
  c) different processes (extraction, injection, cyclic changes)
  d) different material/depth (sediments, hard rock)
  The seismicity was sucessfully modelled in space and time capturing the most conspicuous features of the induced seismicity.

- From all models tested the Rate-and-State model shows the best fitting results.

- The influence of parameters like faults or diffusivity were quantified and shown by the change in induced seismicity.

- Uncertainties of the modelled seismicity rates can be gained by taking similarly good models into account.

References:

EGU2020-10311: Silverii, F., Al-Halbouni, D., Stefanova Vassileva, M., Richter, G., Wang, R., Gonzalez Cansado, B., Hainzl, S., Dahm, T., Maccaferri, F., Underground seasonal storage of gas: testing numerical modelling tools with application to i) a deep aquifer-layer, and ii) salt caverns.

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