Guidelines for Pumping Strategy during Geothermal-Well Stimulation

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Document Verification

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1. Executive Summary

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Executive Summary

- The seismicity induced by the stimulation of OTN-3 in June-July 2018 has been analysed, to establish the impact of the different injection parameters on the induced seismicity.

- Injection parameters examined were:
  - Injection pressure;
  - Injection rate; and
  - Injection pauses.

- Seismicity features examined were:
  - Seismicity rate;
  - Model for the magnitude-frequency distribution; and
  - Variation of the b-value throughout the stimulation

- Based on the results, a Python tool was developed for rapid quantitative assessment of expected seismicity during future geothermal stimulations.

Executive Summary

INJECTION PRESSURE

- Within the pressure range explored during the stimulation of OTN-3 (750 to 900 bar), injection pressure did not appear to have any impact on either:
  - The seismicity rate; or
  - The magnitude-frequency distribution of the seismicity.

- Varying the injection pressure does not appear like an effective seismic mitigation strategy during geothermal stimulation

Executive Summary

INJECTION RATE

- During the stimulation of OTN-3, the number of induced events appeared to be directly proportional to the volume injected.

$$\text{Number of events induced} \propto \text{Volume injected}$$

- This means that the seismicity rate is directly proportional to the injection rate.

$$\textbf{Seismicity Rate} \propto \textbf{Injection rate}$$

Executive Summary

INJECTION RATE

- The ratio between seismicity rate and injection rate is the earthquake productivity R_0.

$$\textbf{Seismicity Rate} \approx R_0 \times \textbf{Injection rate}^*$$

- R_0 is the number of events induced per 60 m^3 of water injected, i.e., the number of events per hour when injecting at a rate of 1 m^3/min.

- During the stimulation of OTN-3, R_0 appeared to be constant for one injection location. In fact R_0 was constant from phases 2 to 5, and was only different for the first phase.

* Seismicity rate in events/hour and injection rate in m^3/min

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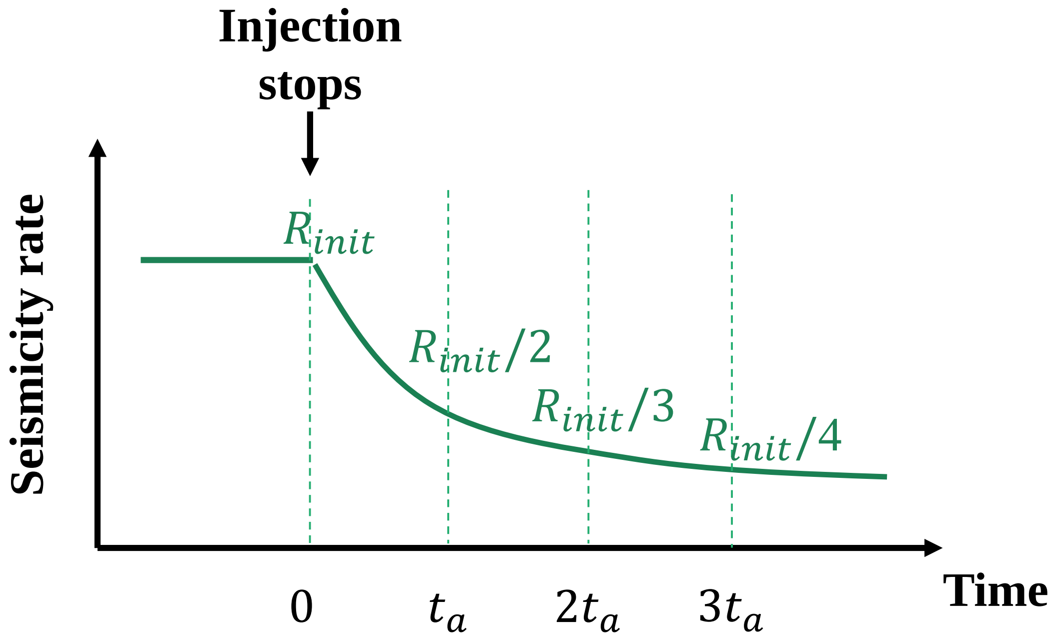
Executive Summary

INJECTION PAUSES

- When injection stops, the seismicity seems to decay following an Omori law.



- The characteristic time t_a is the time for the seismicity to initially decrease by half the pre-pause rate.

- t_a can be understood as the time taken by the seismicity to respond to changes in injection rate.

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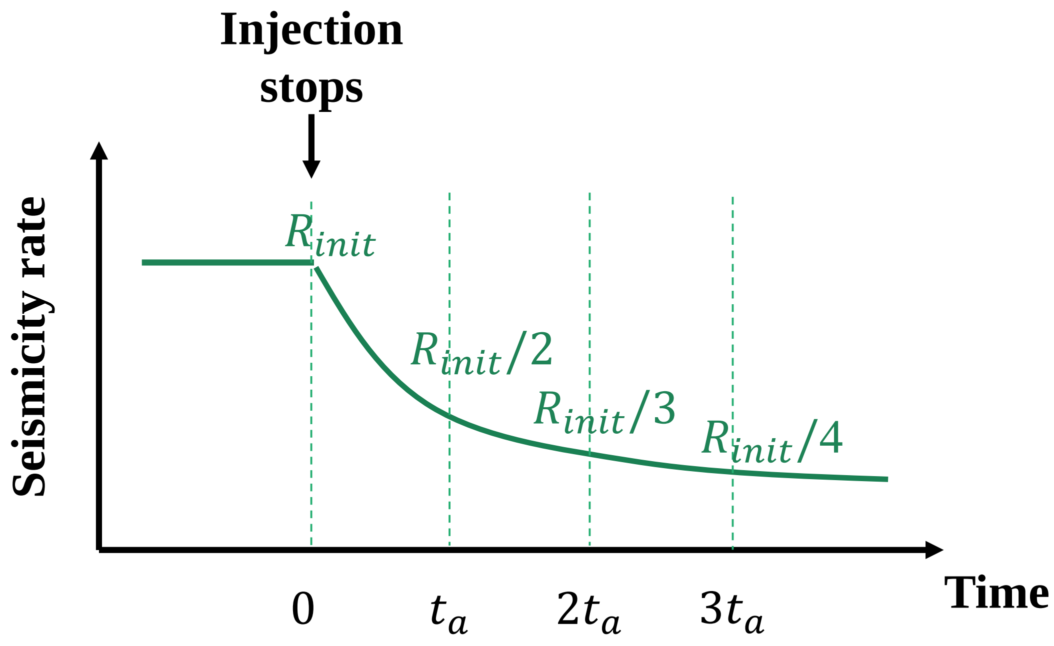
Executive Summary



INJECTION PAUSES

- The value of t_a increased during the stimulation of OTN-3 from about 1-5 hours during phase 1 to about 18h by the end of the stimulation.

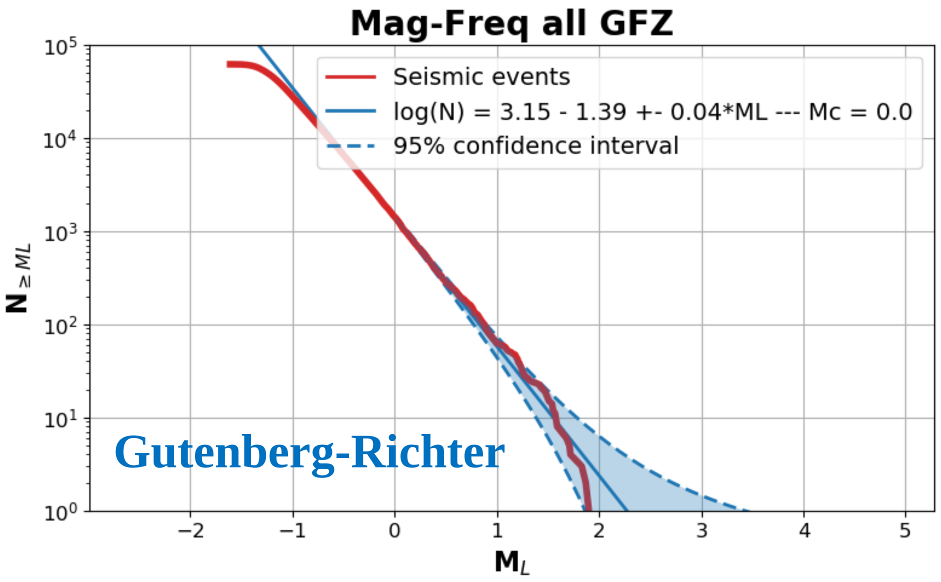
- **The pauses in injection did not appear to have any impact on the seismicity rate when injection resumed.**

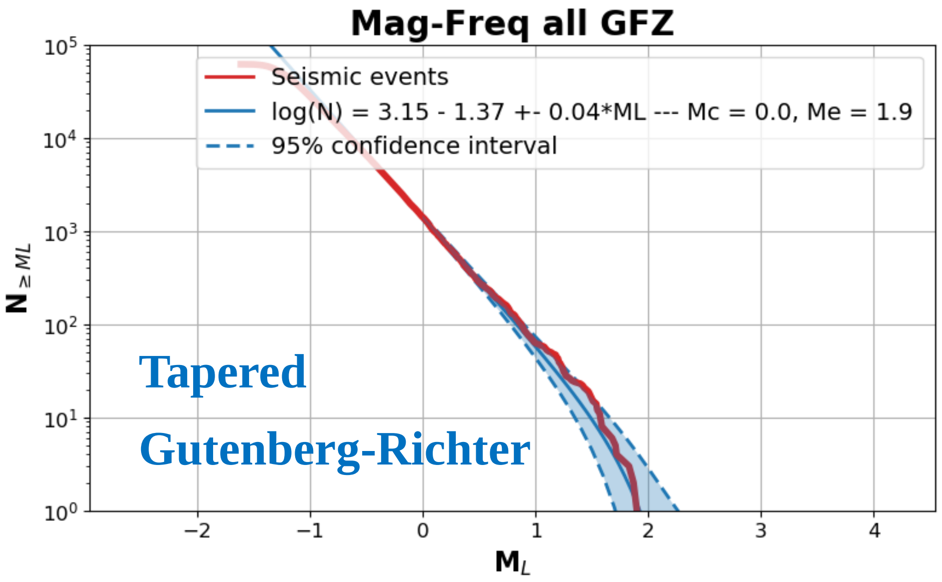
- As a result, the duration of the pauses did not seem to impact the seismicity rate when injection resumed.

Executive Summary

MAGNITUDE-FREQUENCY DISTRIBUTION

- The seismicity recorded during the stimulation of OTN-3 seems to follow a tapered Gutenberg-Richter distribution, characterised by a roll-off at larger magnitudes.





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Executive Summary

MAGNITUDE-FREQUENCY DISTRIBUTION

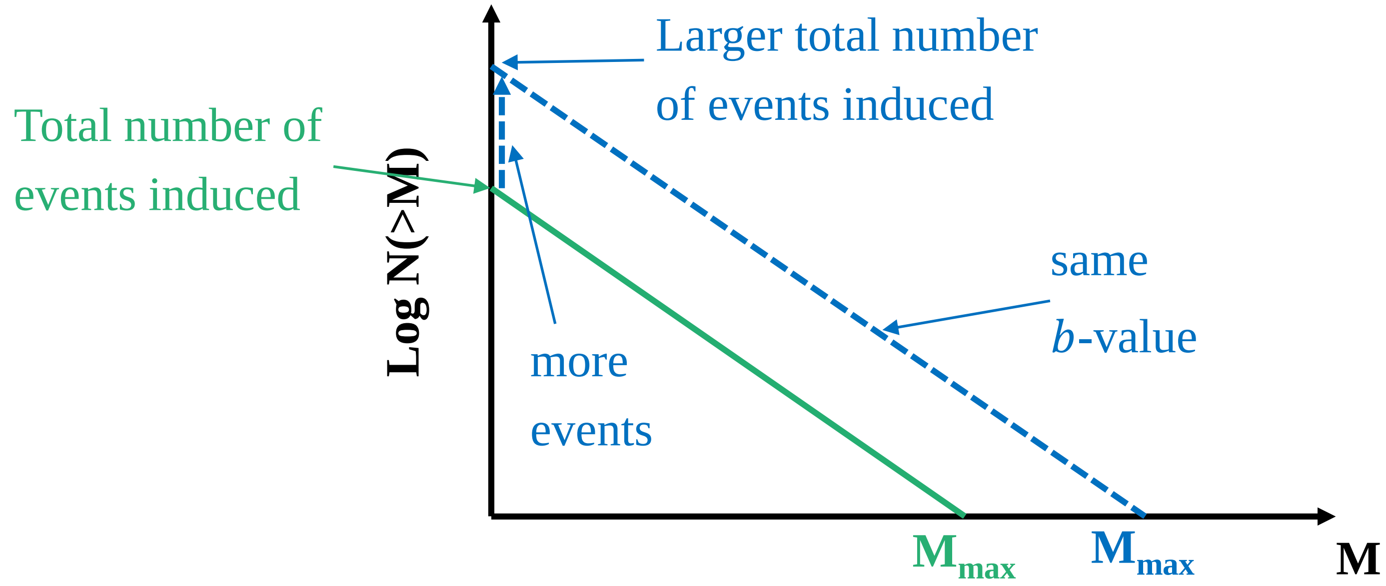
- The *b*-value of both the GR and TGR distribution, which characterises the ratio of larger to smaller events, did not appear to vary during the stimulation of OTN-3:
  - When injection pressure varied;
  - When injection rate varied;
  - When the injection stopped.

- The *b*-value therefore seems to be a property of the geothermal reservoir and is not sensitive to injection parameters.

Executive Summary

IMPACT FOR THE MAXIMUM MAGNITUDE AND PROBABILITIES OF EXCEEDANCE OF SPECIFIC MAGNITUDES

- Since the *b*-value does not change during stimulation, the maximum magnitude depends on the total number of events induced.



- The predicted maximum magnitude also depends on the model used: GR vs TGR.

As the total number of events increases, for a fixed b-value, M_{max} increases.

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Executive Summary

- Based on these observations, a Python tool has been developed to predict the seismicity for a given future injection scenario.

- This tool takes the recorded seismicity and the associated injection rate to derive seismic properties of the reservoir under stimulation.

- The tool then takes a future injection scenario (either a time series or a simple volume to be injected) and computes:
  - An estimate of the associated seismicity rate;
  - The maximum expected magnitude; and
  - The probability of exceedance of different magnitudes.

2. General Guidelines for Seismic Hazard Mitigation during Geothermal Stimulation

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Guidelines

- The following guidelines are based on the results of the analysis of the seismicity induced during the stimulation of OTN-3

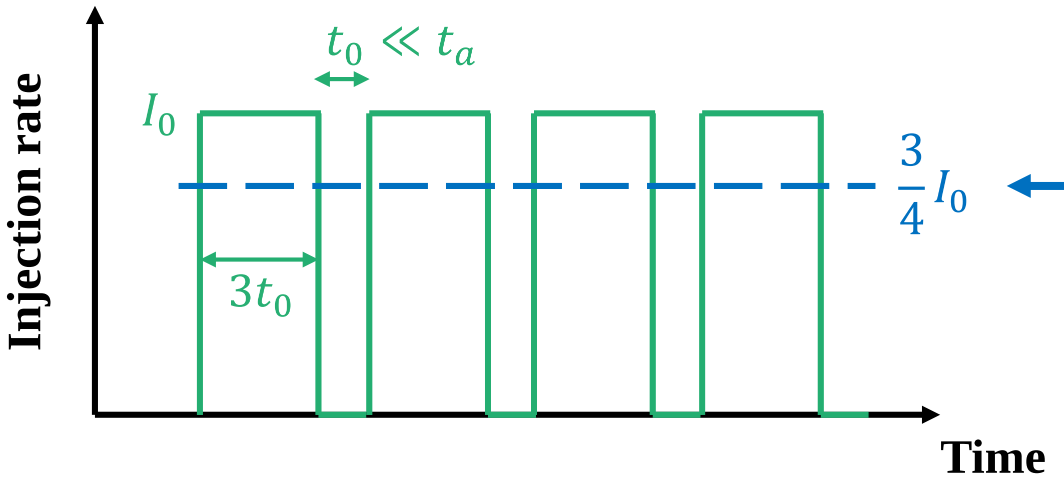
- They should be applicable in similar geological conditions as for OTN-3. A location where the geology is dominated by one or several large geologic faults might behave differently.

- They are intended to be a set of few simple and general rules for decision making during future geothermal well stimulations.

Guidelines

Frequent short pauses in injection can reduce the seismicity rate.

- Seismicity takes a time t_a to respond to the injection.
- For breaks in injection of duration much shorter than t_a, the seismicity "sees" a constant effective injection rate, which is the average of the injection rate.



Effective injection rate "seen" by the seismicity
When injecting ¾ of the time, the effective injection rate is simply ¾ of the injection rate.

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Guidelines

Modifying the injection pressure does not appear to be an effective seismic hazard mitigation strategy.

- Within the pressure range explored during the stimulation of OTN-3 (750 to 900 bar), injection pressure did not appear to have any impact on either:
  - The seismicity rate; or
  - The magnitude-frequency distribution of the seismicity.

Guidelines

Long pauses of injection do not seem to reduce the seismicity rate when injection resumes.

- The decay of seismicity is not exponential: stopping injection for a time t_a will reduce the seismicity by half. But waiting for another time t_a will not reduce the seismicity by half again, only to a third of the initial seismicity rate.
- When injection resumes, the seismicity rate quickly takes the same value as before the pause, regardless of the duration of the pause.
- **Pauses of injection do not need to be too long to mitigate seismicity** (duration t_a should be a good upper limit, as the decay after this is slow).

Guidelines

A rough estimate of the seismicity rate to be expected can be obtained by

$$\boldsymbol{R \approx R_0 \times u_{eff}}$$

- R is the expected seismicity rate.
- R_0 is the earthquake productivity: number of events per hour when injecting at 1 m^3/min, i.e., number of events induced when injecting 60 m^3 of water.
- u_{eff} is the effective injection rate, in m^3/min.

Guidelines

A rough estimate of the seismicity rate to be expected can be obtained by

$$\boldsymbol{R \approx R_0 \times u_{eff}}$$

- **Examples**:
  - If $R_0 = 90$ events/h*, and that the injection proceeds at 400 l/min (= 0.4 m^3/min), the expected seismicity rate is $90 \times 0.4 = 36$ events/h.
  - If $R_0 = 90$ events/h, and the injection proceeds at 400 l/min with pauses of 1h every 3 hour (so, injecting ¾ of the time), the expected seismicity rate is $90 \times 0.4 \times 3/4 = 27$ events/h.

- This rapid estimate can be used to **assess whether seismicity becomes abnormally high**.

* This was the productivity for events with $M \geq -1$ for phases 2 to 5 of the stimulation of OTN-3. The productivity for phase 1 was $R_0 = 60$ events/hour.

Guidelines

Use the tool to estimate future seismicity rates, maximum magnitudes and probability of exceedance of different magnitudes.

- The following two slides show the quantities estimated from the data provided to estimate the future seismicity:
  - Given a future injection rate time series; and
  - Given a maximum volume injected.

Tools to Predict Seismicity for a Given Future Injection Rate Time Series

- Computing **future seismicity rate** for a given future injection rate time series requires the estimation of the following seismic parameters:
  - R_0: earthquake productivity, i.e., hourly number of events above a given magnitude if injecting at 1 m^3/min
  - t_a: characteristic time of seismicity response

- Computing **future maximum magnitude** and **probability of exceedance** of given magnitudes for a given future injection rate time series:
  - R_0: earthquake productivity
  - b-value of the (tapered) Gutenberg-Richter distribution
  - M_e: corner magnitude for the MF distribution roll-off at larger magnitudes
  - (Note that, although not directly required, t_a is necessary to compute R_0)

Tools to Predict Seismicity for a Given Future Volume of Injection

- Without a time series for the injection rate, the **future seismicity rate** cannot be computed.

- However, knowing R_0 will give an indication of the number of events to expect for different injection rates: $R \approx u \times R_0$ events/hour, where u is an injection rate in m^3/min.

- Computing **future maximum magnitude** and **probability of exceedance** of given magnitudes for a given future injection volume requires the estimation of the following seismic parameters :
  - R_0: earthquake productivity
  - b-value of the (tapered) Gutenberg-Richter distribution
  - M_e: corner magnitude for the MF distribution roll-off at larger magnitudes
  - (Note that, although not directly required, t_a is necessary to compute R_0)

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3. Tool for Quick Analysis and Prediction of Seismicity

Python 3 script predict_seis.py

3.1 Inputs

3.2 Outputs

3.3 Performance on the Maximum Magnitude

Tool for Quick Analysis and Prediction of Seismicity

- A tool, implemented in Python 3, has been developed to quickly analyse the seismicity during a stimulation and predict the future seismicity.
- The script is called `predict_seis.py` and is described in details in this section.
- The script `predict_seis.py` calls a number of functions, all implemented in the python script `routines_seismo.py`.
- None of the functions implemented in `routines_seismo.py` need to be modified by the user.

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3.1 Inputs

3.1.1 Files

3.1.2 In-Code Options and Parameters

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3.1.1 File Inputs

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File Inputs

- Three files are required (times need to be in the same time zone):
  - Seismicity catalogue;
  - Pumping data; and
  - Possibly, bleed-offs (times and volumes)

- Formats (csv, xls) are the formats provided for OTN-3 stimulation.

File Inputs: Seismicity Catalogue

- Format: csv
- Columns required
- Reference file:
  - Cat_seis_OTN3.csv

Column name	Example	Comment
Year	2018	Year
Mo	6	Month
Da	4	Day
Hr	12	Hours
Mi	38	Minutes
Sec	34.774	Seconds
MHEL	-0.04	Magnitude

File Inputs: Pumping Data

- Format: xlsx
- Columns required:

Column name	Example	Comment
DATE_TIME_HEL	04/06/2018 09:27:20	Same time zone as seismic data
INJ_PRESSURE_bars	412.295	Injection pressure (bars)
INJ_RATE_m3/min	0.456056	Injection rate (m^3/min)
CUM_VOL_m3	2.944424	Cumulative injected volume from the start of the stimulation

- Reference file: st1_pump_data_final.xlsx

File Inputs: Bleed-offs

- Well bleed-offs were not included in the pumping data provided during stimulation. They are therefore provided in a separate file.

- Format: xlsx

- Columns required:

Column name	Example	Comment
VOL_BLEED_M3	13.8	Total volume extracted during bleed-off (m^3)
END_BLEED	04/06/2018 13:04:00	Time at which the bleed-off ended

- Reference file: Bleed_offs.xlsx

3.1.2 In-Code Options and Parameters

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In-code Options and Parameters

- Filenames with full path for inputs:
  - For the earthquake catalogue;
  - For the pumping data; and
  - For the bleed-offs.

- Folder for outputs

- Option whether or not to load the files, in case they have already been loaded and are still in memory.
  - Note that loading the earthquake catalogue will also plot the MF distribution with GR and TGR fit.

In-code Options and Parameters: Magnitudes

- **Mc** Magnitude of completeness of the catalogue:
  - Used to remove events with M < Mc from the catalogue and compute t_a
  - Can be estimated on the MF plot

- **Mmin** Magnitude above which the seismicity rate should be predicted

- **Mc_GR** Minimum magnitude used to compute the GR/TGR parameters
  - Given that the MF is slightly curved, rather than a perfect straight line, the *b*-value depends on the limit magnitude used.
  - Mc_GR should be selected so that it is close enough to the largest magnitudes, without being affected by the statistical effects at large magnitude.

In-code Options and Parameters: Magnitudes

- **Mc vs Mc_GR**

  - Mc is used to compute t_a, so as many events as possible are necessary.
  - Mc should be picked as the minimum value possible where **all** events are detected (no variations of number of events due to variation of detection threshold)

  - Mc_GR is used to compute the b-value and corner magnitude M_e for the GR/TGR distributions.
  - It is not necessary to have a lot of events of these, it is more important to select events that sample well the distribution of events around the larger magnitudes.

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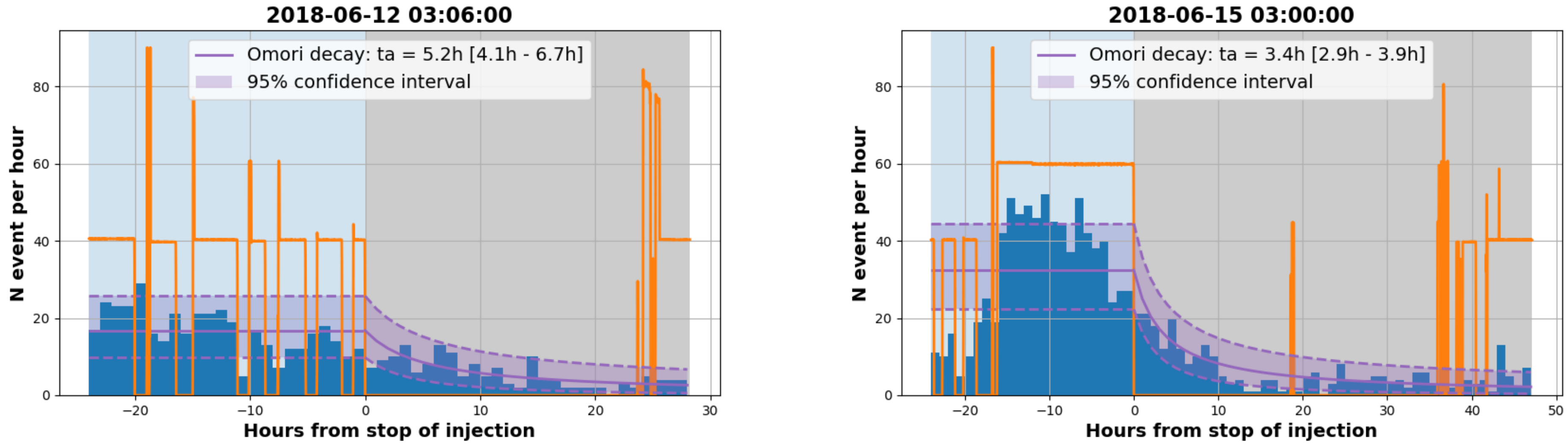
In-code Options and Parameters: Magnitudes

- **Mc vs Mc_GR**



Mc used to compute t_a (here taken as Mc = -1). If Mc is too large, the decay might not be obvious enough in the data to compute t_a. If Mc is too small, artificial daily variations of seismicity rate will pollute the data, due to the daily variations of detection limit.

For the stimulation of OTN-3, Mc = -1 was taken as the appropriate value.

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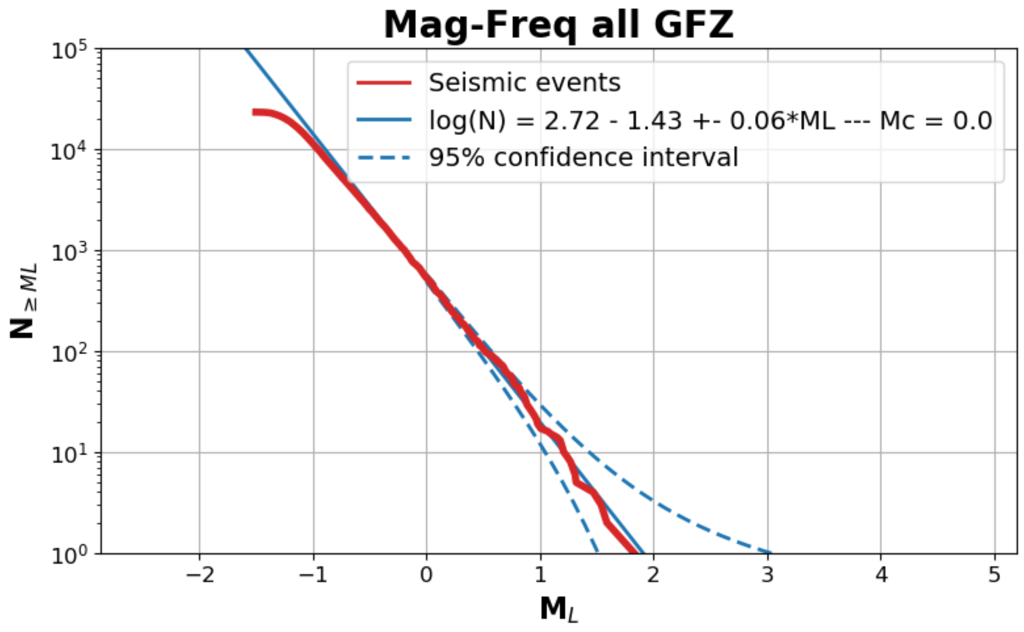
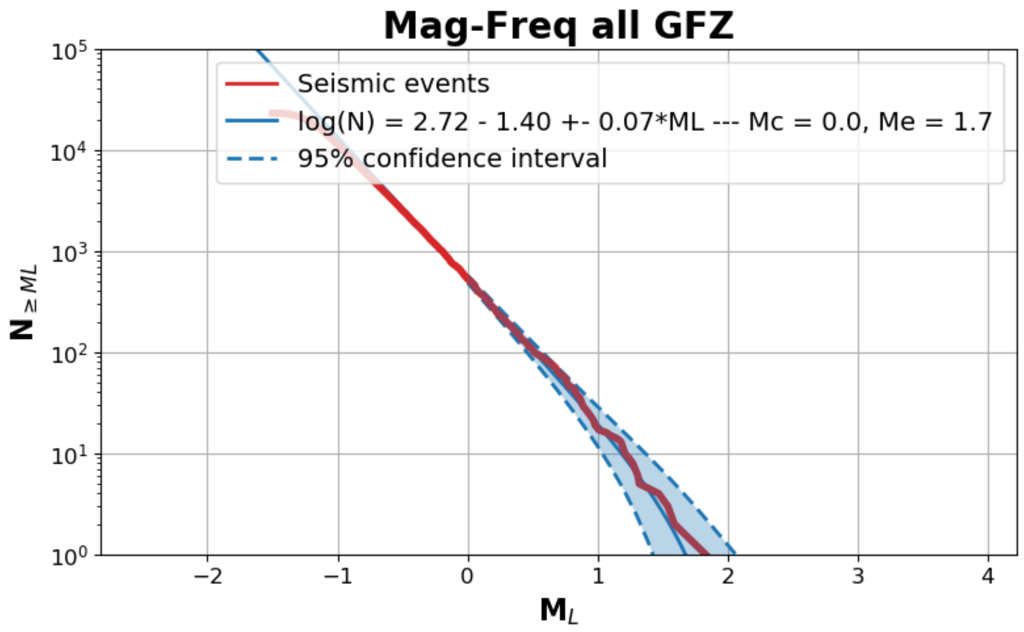
In-code Options and Parameters: Magnitudes

- **Mc vs Mc_GR**

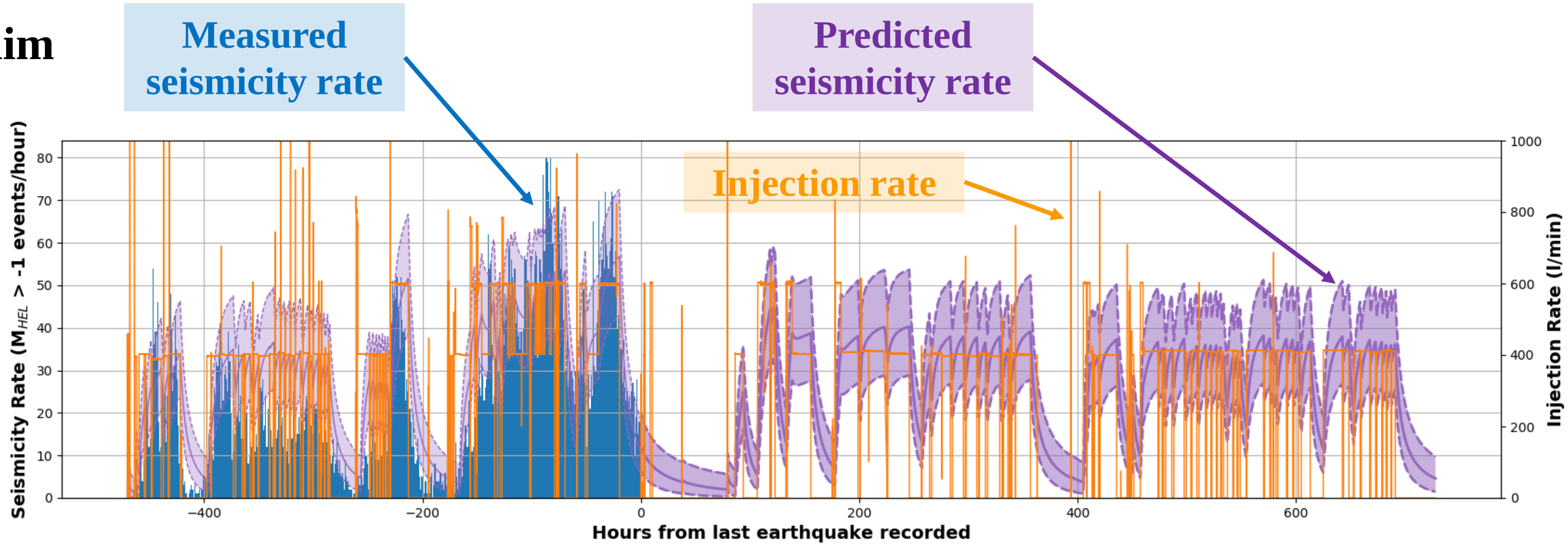




Mc_GR used to compute the GR and TGR parameters. In this case (seismicity during the stimulation of OTN-3), a value of Mc_GR = 0 was deemed appropriate.

In-code Options and Parameters: Magnitudes

- **Mlim**



Mlim is used to compute the predicted seismicity rate. Similarly to Mc for the computation of t_a, Mlim should be low enough so that the number of events per hour is large enough.

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In-code Options and Parameters

- **M_spec_arr**
  - Array of specific magnitudes for which a probability of exceedance will be computed as a function of time (following future injection history) and injected volume (for a total volume injected).
- **Vmax**
  - Maximum volume to be injected, for the computation of the maximum magnitude and probability of exceedance of the different specified magnitudes.

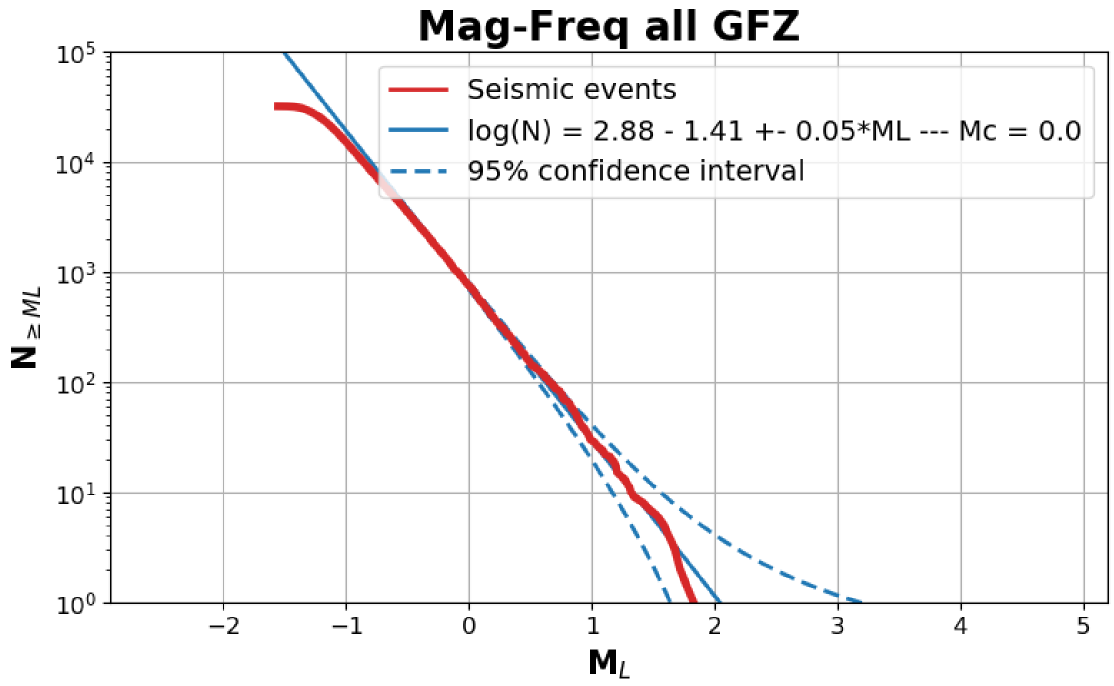
In-code Options and Parameters

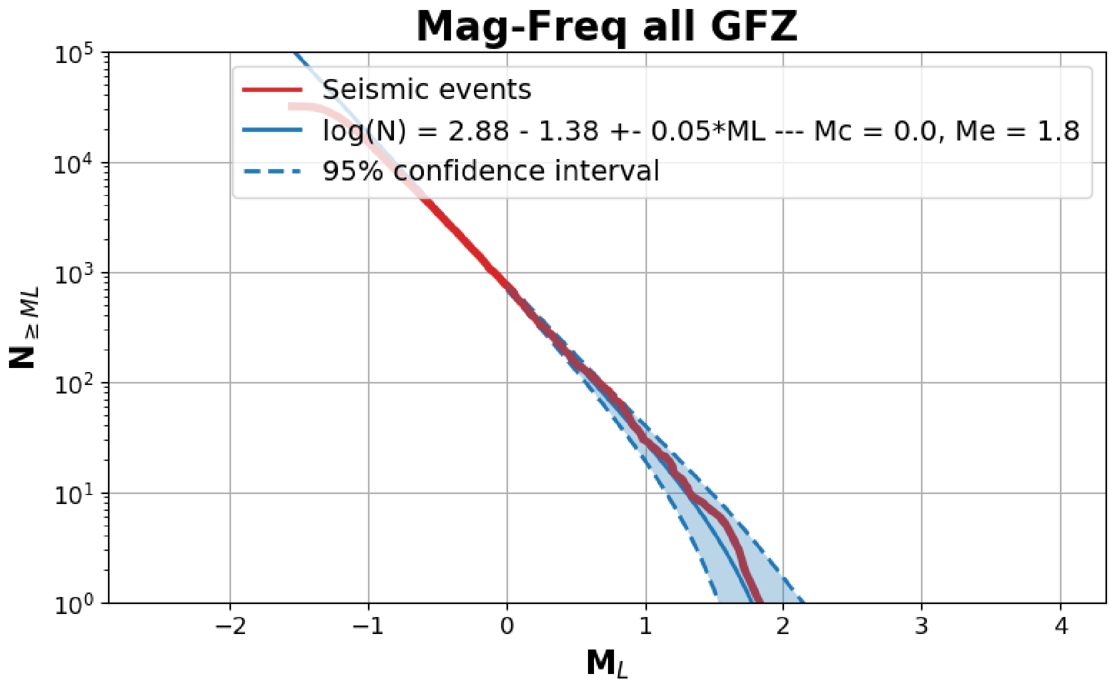
- Options to compute t_a and display, plot and save the pauses in injection to compute t_a :
  - Min_pause_dur_ta: minimum pause duration to compute t_a;
  - ta_plot: plot the fit to the decaying seismicity rate during injection pauses to compute t_a;
  - ta_verbose: display text information about t_a (pause duration, pause end time, value of t_a with 95% confidence intervals).

- Option to use manually input values for the different parameters:
  - List of two values:
    - First value True/False to specify whether or not to use the default value; and
    - Second value is the value to use.
  - The values computed for the stimulation of OTN-3 are input as default values in `predict_seis.py`.

3.2 Outputs

Magnitude-Frequency Plots of the Input Seismicity Catalogue





The two features represented on this plot are:

- **Seismicity recorded** up to now; and
- Gutenberg-Richter and Tapered GR **fit** to the recorded seismicity up to now.

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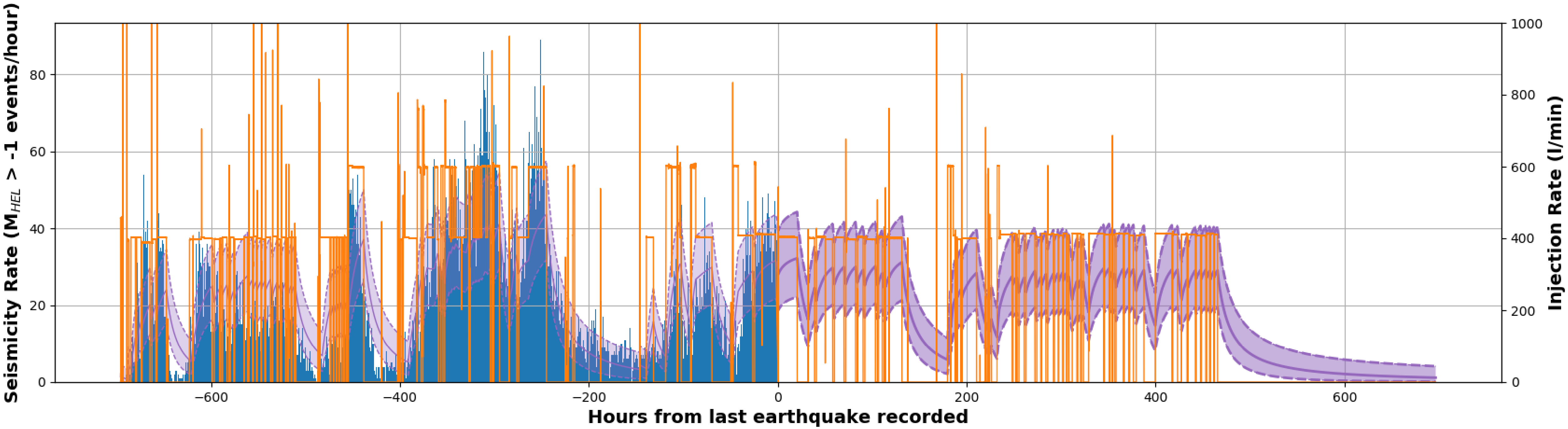
Predicted Seismicity Rate (for $M \geq M_{lim}$)

- Bar plot of the **recorded seismicity rate**
- Plot of the past and future **injection rate**
- **Predicted seismicity rate** with 95% confidence intervals



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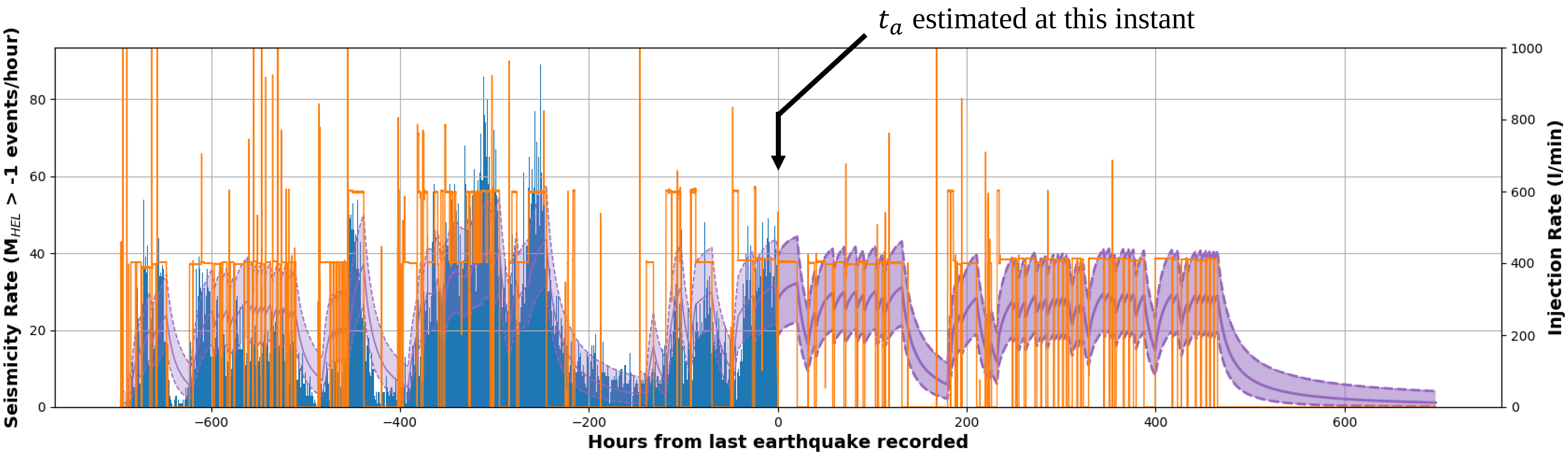
Predicted Seismicity Rate (for $M \geq M_{lim}$)

- Note that t_a is taken at the time of last recorded event (time 0 on the plot below).
- It is therefore normal that it does not fit very well the decay of seismicity during the first injection pauses of the stimulation.



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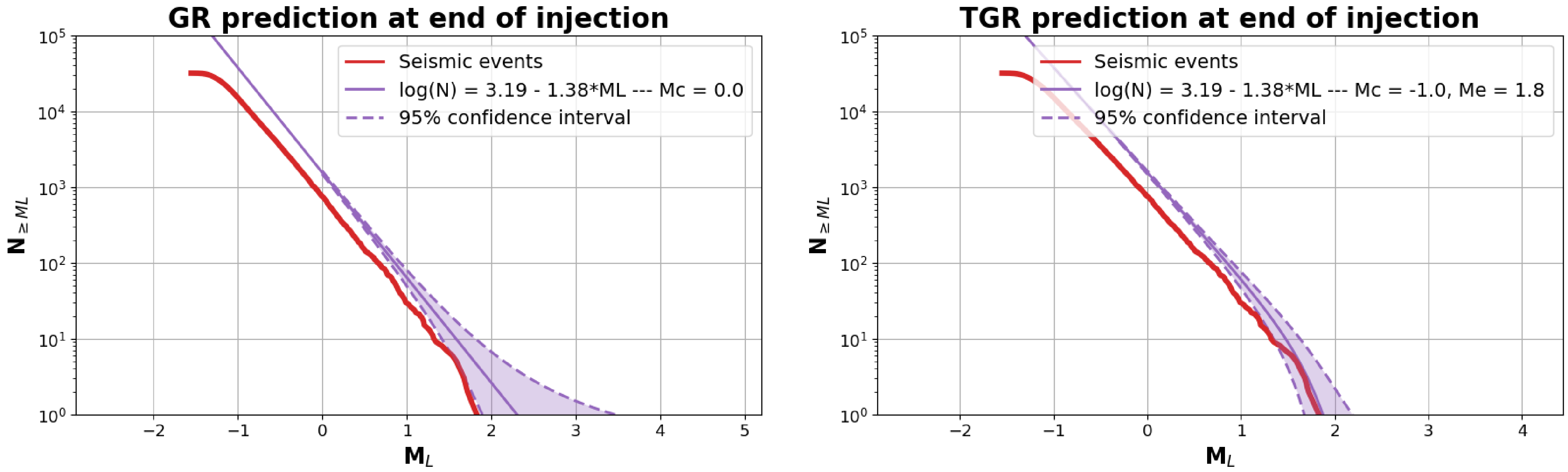
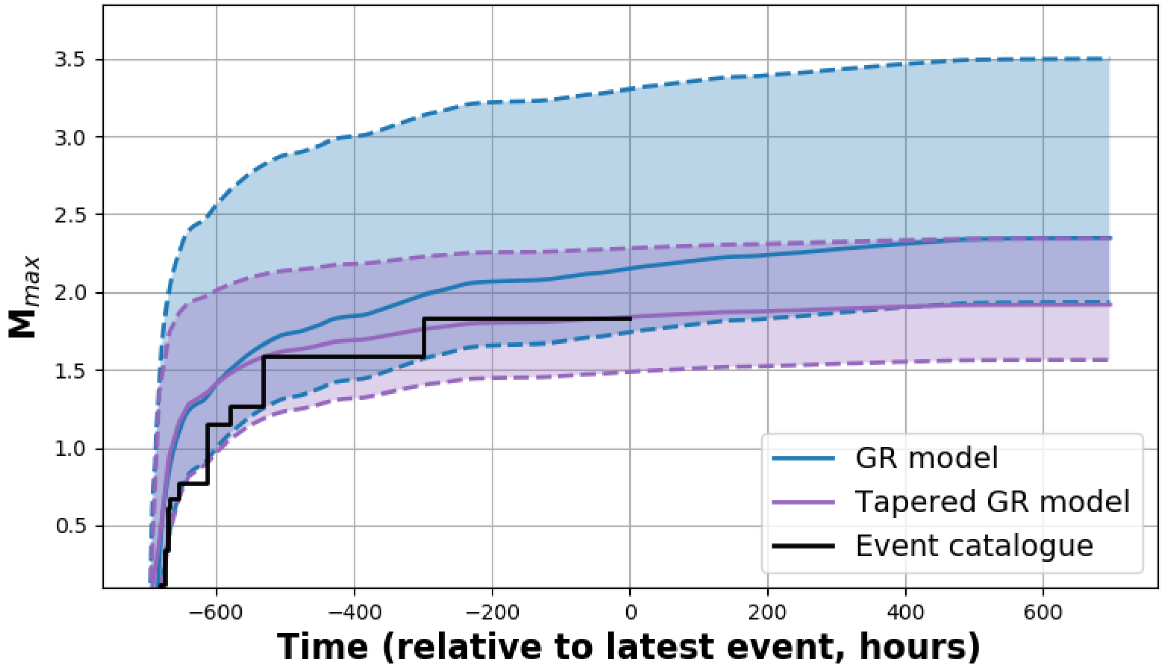
Predicted Magnitude-Frequency Plots at the End of Input Injection

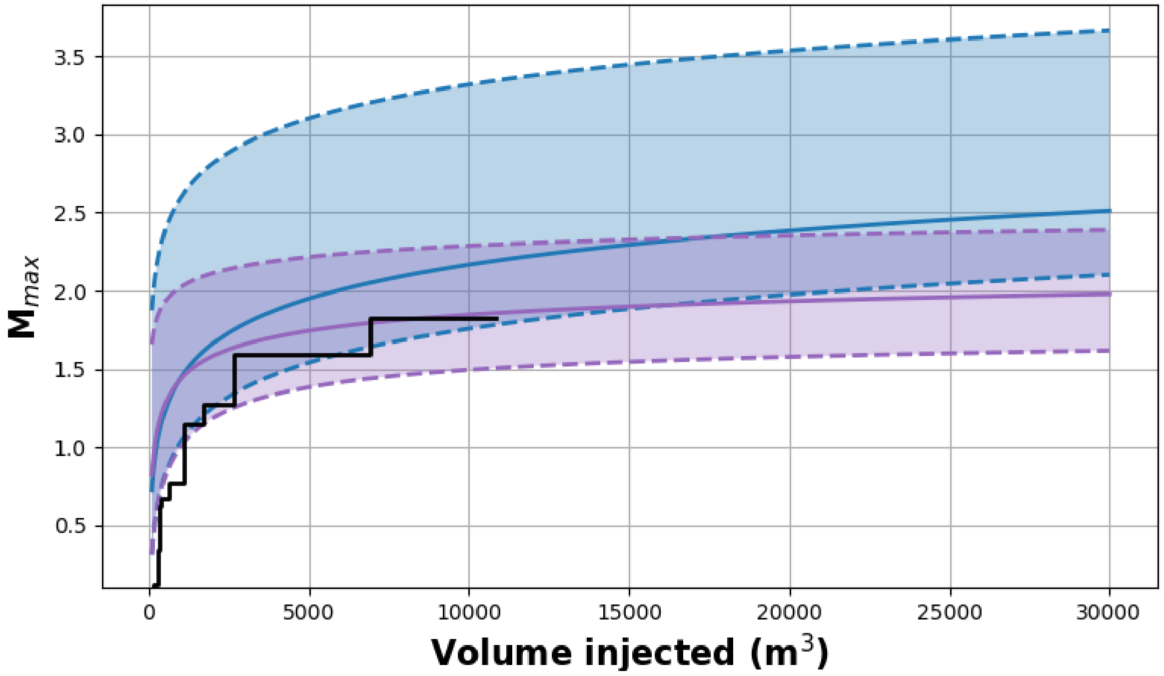


The two features represented on this plot are:

- **Seismicity recorded** up to now; and
- Gutenberg-Richter and Tapered GR **prediction** by the end of the stimulation.

Evolution of the Maximum Magnitude with Time and Injected Volume





- Predictions are made with the **GR model** and the **TGR model**.
- The 95% confidence intervals are plotted for each model.

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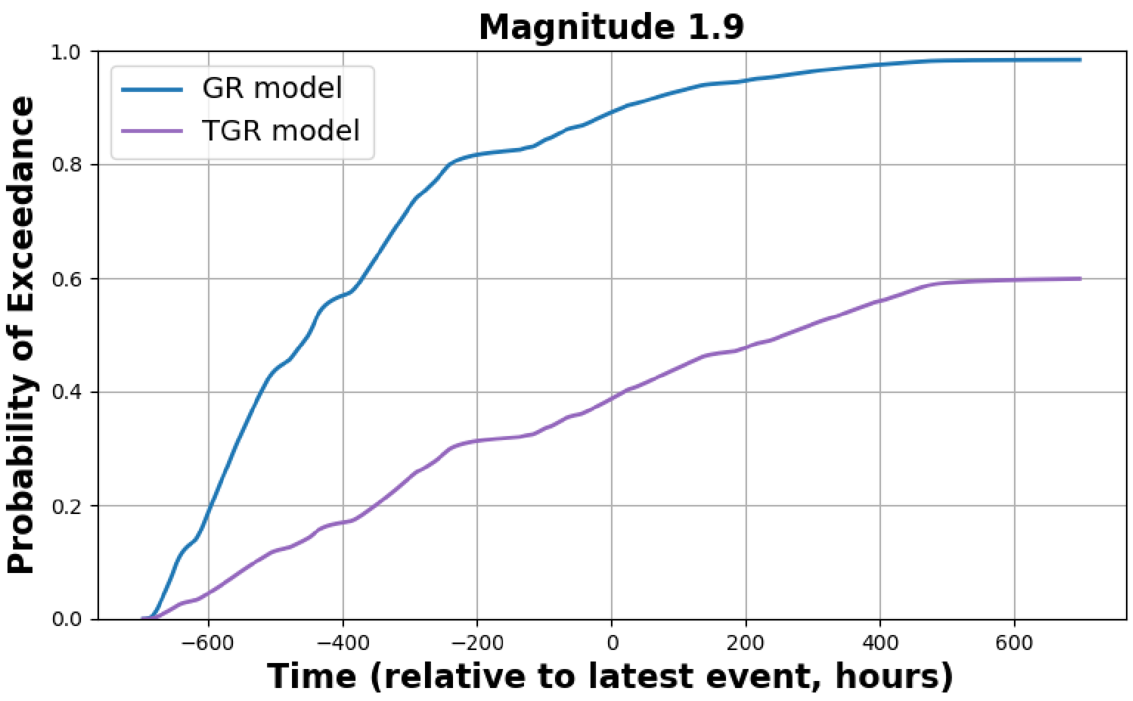
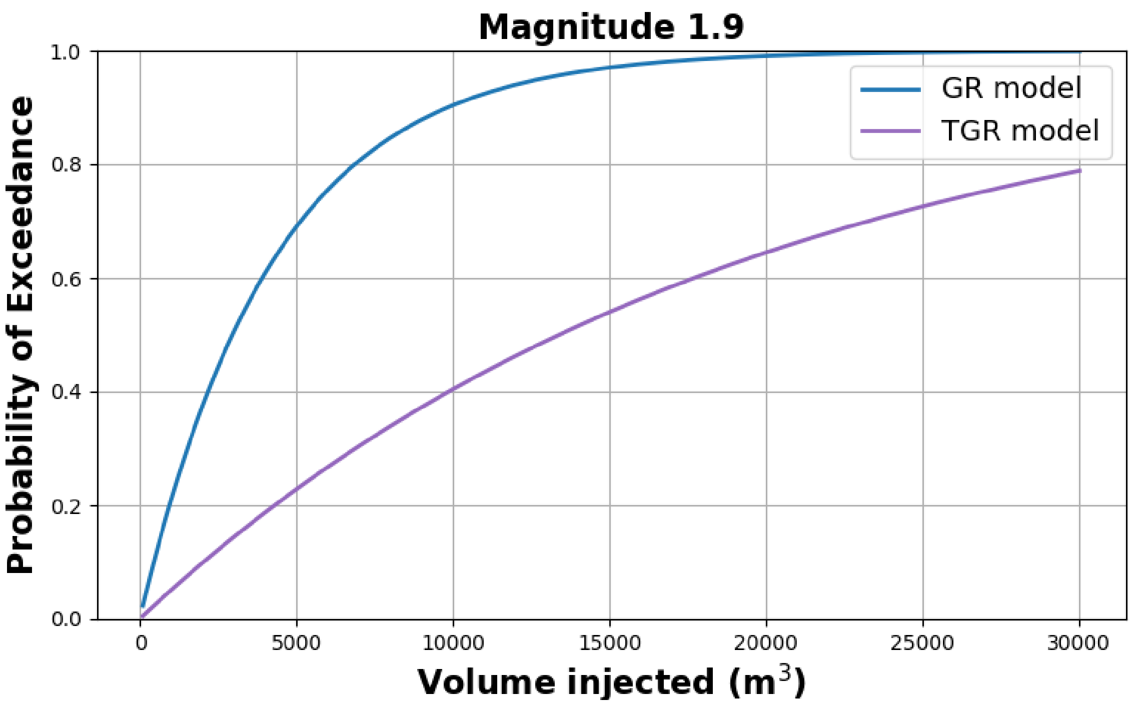
Probability of Exceedance of Specified Magnitudes with Time and Injected Volume





- Predictions are made with the **GR model** and the **TGR model**.
- Predictions are made with respect to time (left) and volume (right).

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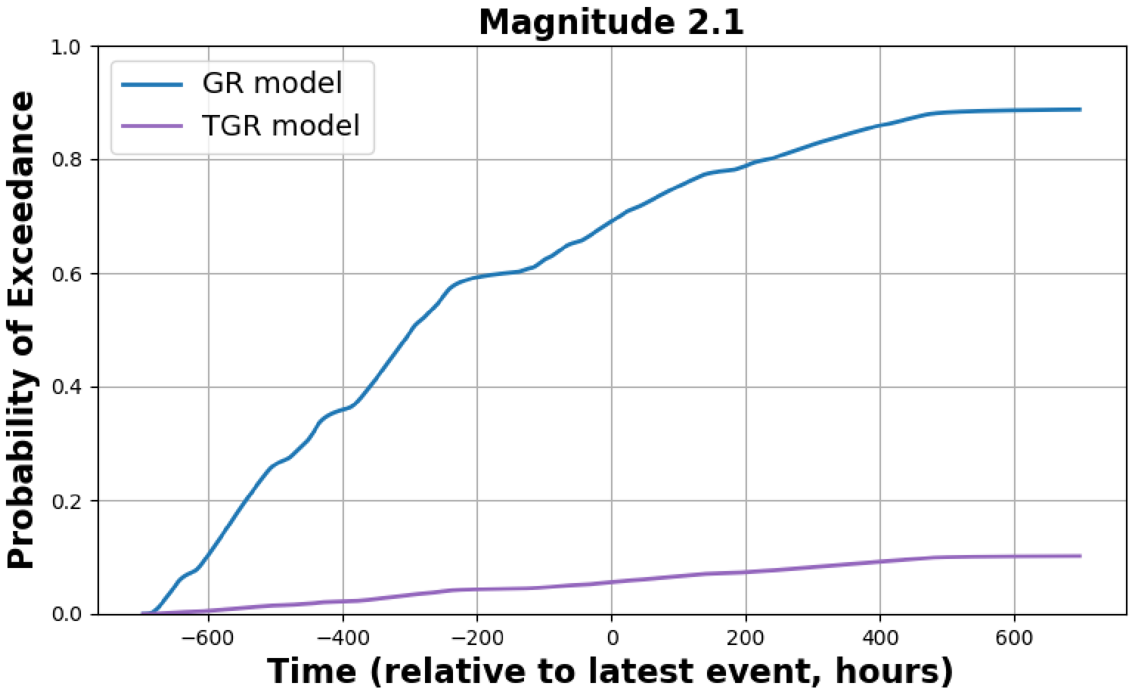
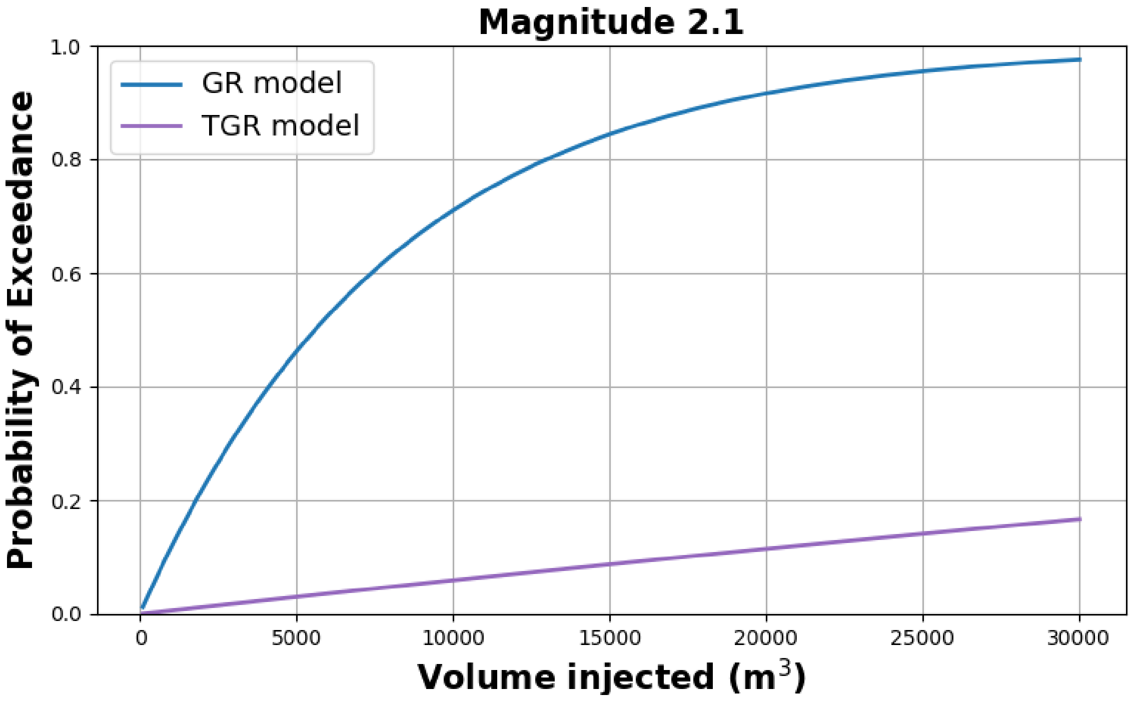
Probability of Exceedance of Specified Magnitudes with Time and Injected Volume





- Predictions are made with the **GR model** and the **TGR model**.
- Predictions are made with respect to time (left) and volume (right).

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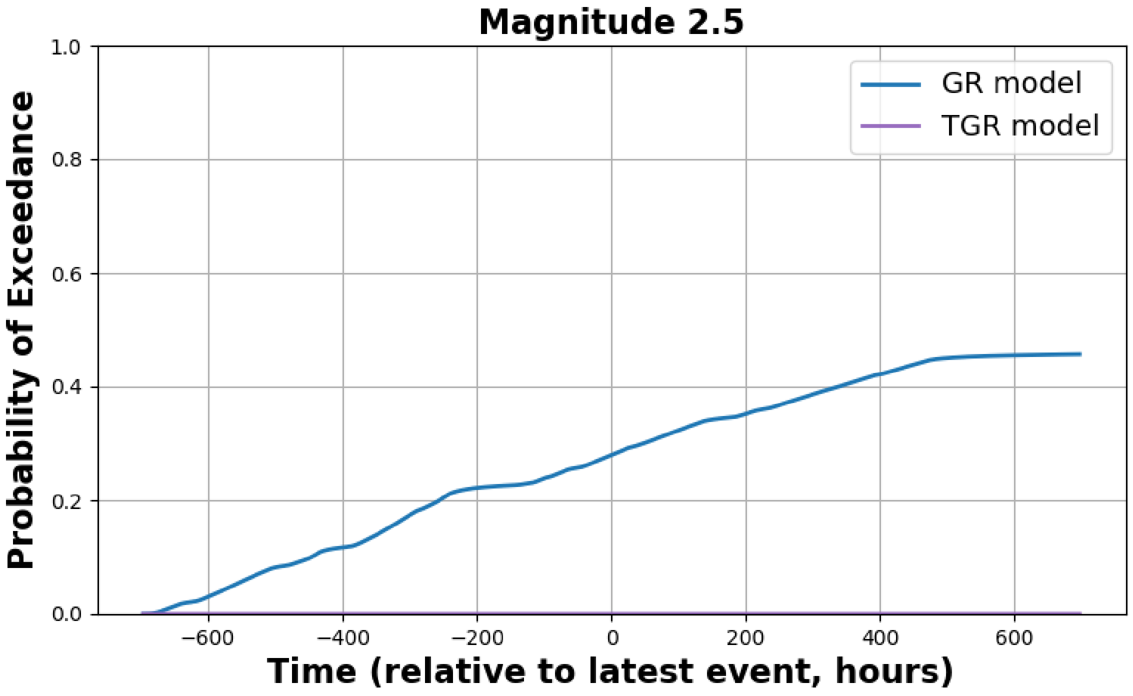
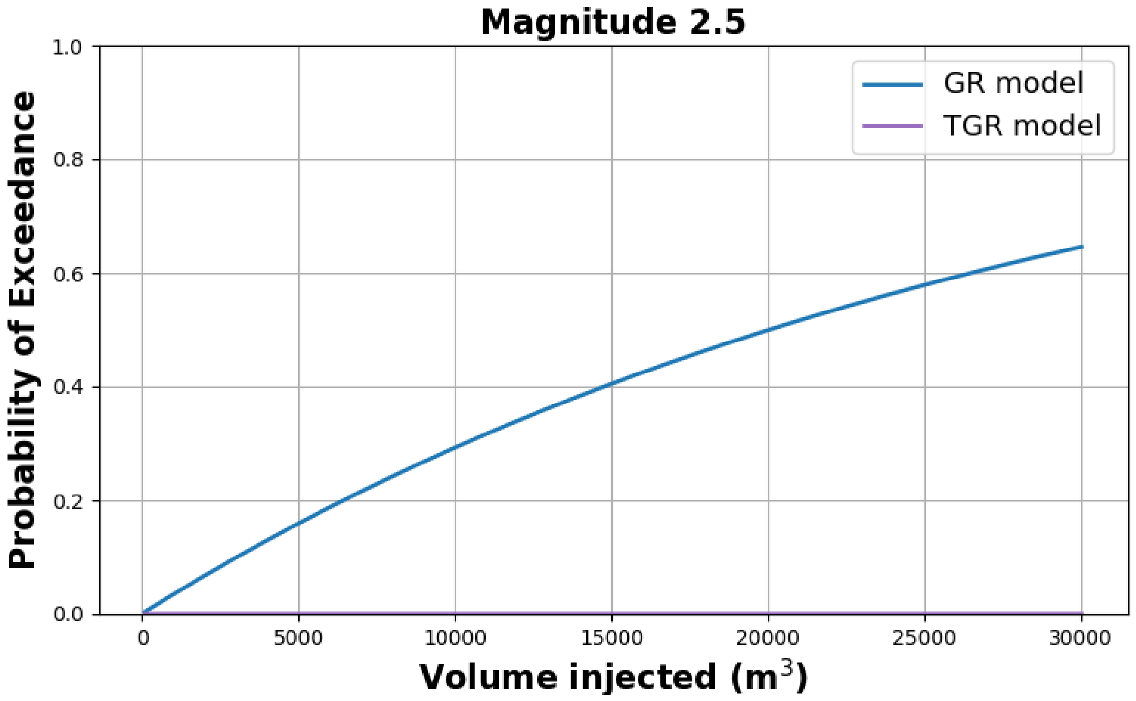
Probability of Exceedance of Specified Magnitudes with Time and Injected Volume





- Predictions are made with the **GR model** and the **TGR model**.
- Predictions are made with respect to time (left) and volume (right).

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3.3 Performance on the Maximum Magnitude

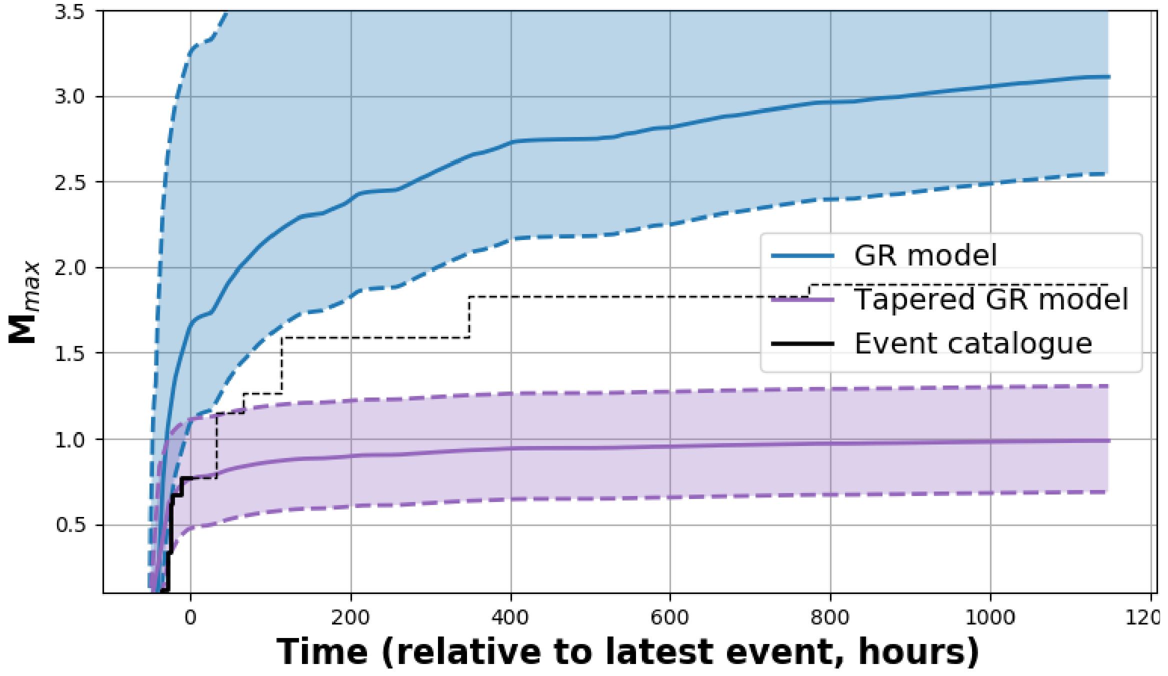
Performance on the Maximum Magnitude

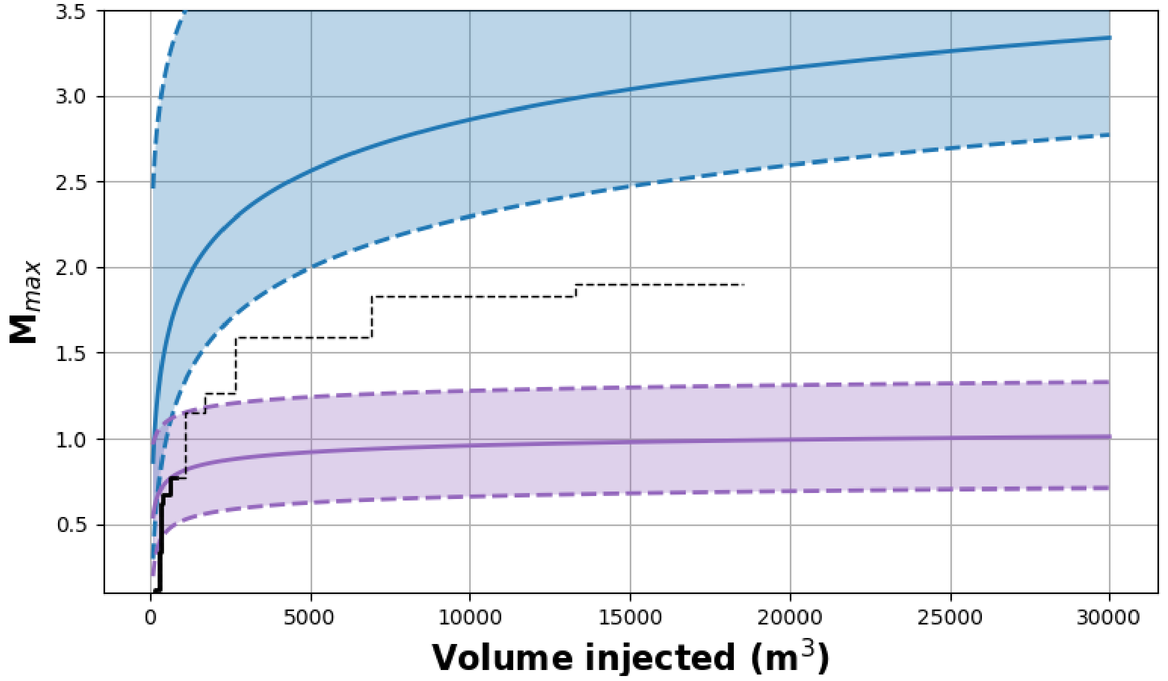
- As shown in the following slides, the forecast of maximum magnitude needs to be updated during the stimulation.

- A few days of stimulation (3 at the very least) are necessary to have an initial reasonable estimate, within 95% confidence intervals, of the maximum magnitude to expect by the end of the stimulation.

- During the stimulation of OTN-3, the different earthquake productivity during phase 1 meant that the seismicity recorded during phase 2 was necessary to have a good estimate of the maximum magnitude by the end of the stimulation.

M_{max} Predicted as of 06 June 12:00 (36 hours of stimulation, no pauses)





- After 36 hours of stimulation, the recorded seismicity was low and not representative of the global seismicity. The **GR prediction** was widely above what would turn out to happen, which the **TGR model** was much below.

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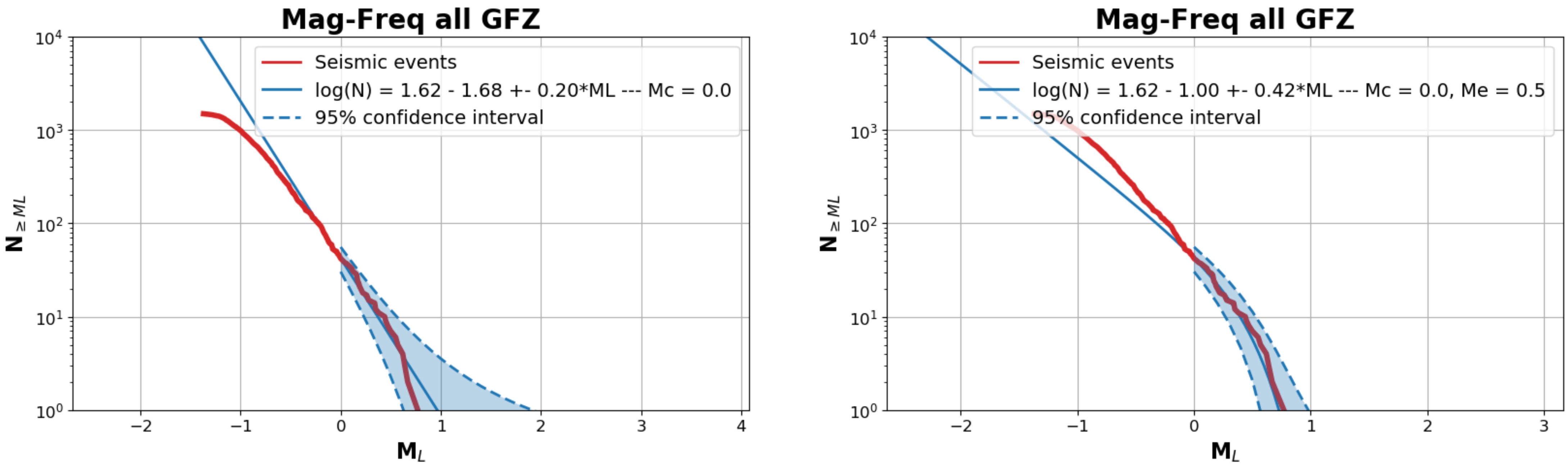
M_{max} Predicted as of 06 June 12:00 (36 hours of stimulation, no pauses)



FIT OF GR AND TGR MODELS TO RECORDED SEISMCITY

- At this stage, magnitudes are too low to estimate the roll-off magnitude Me.
- The estimates of the TGR will therefore underestimate M_{max}.

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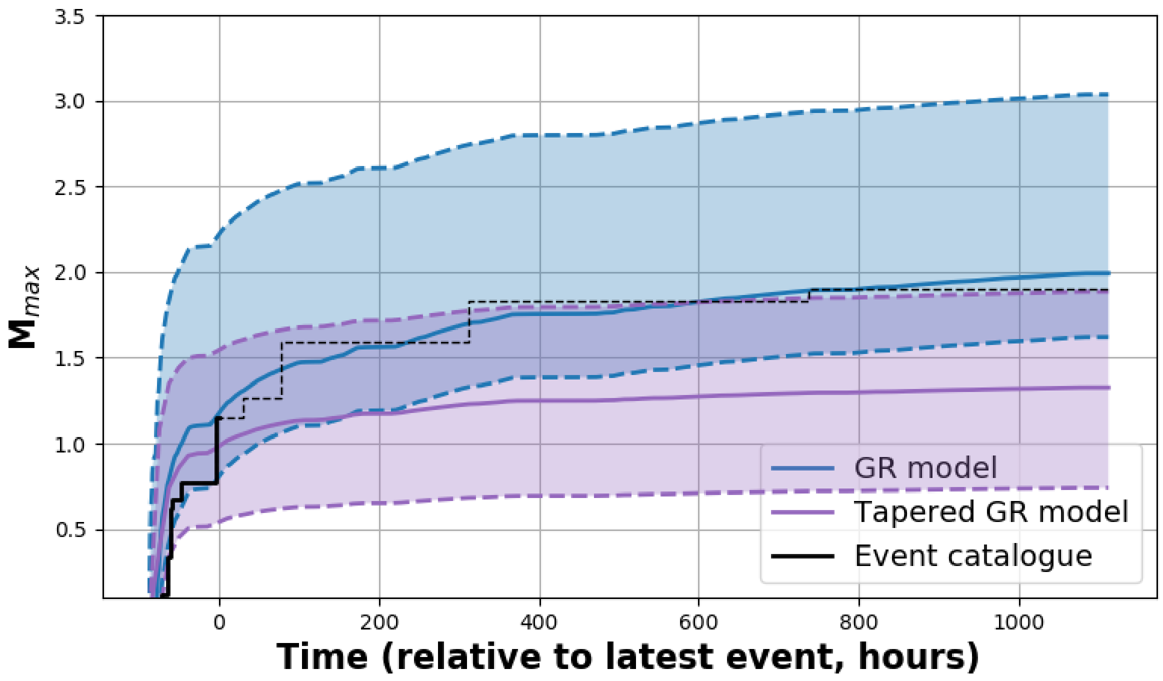
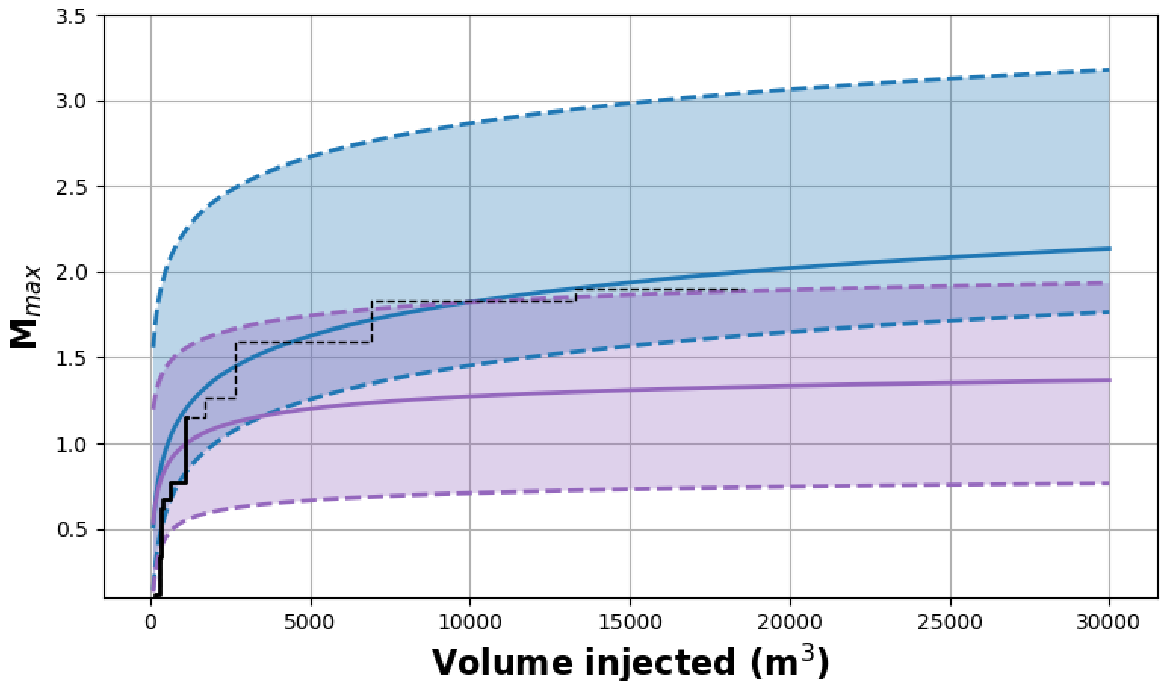
M_{max} Predicted as of 08 June (3 days of stimulation, 1 pause of 26h)

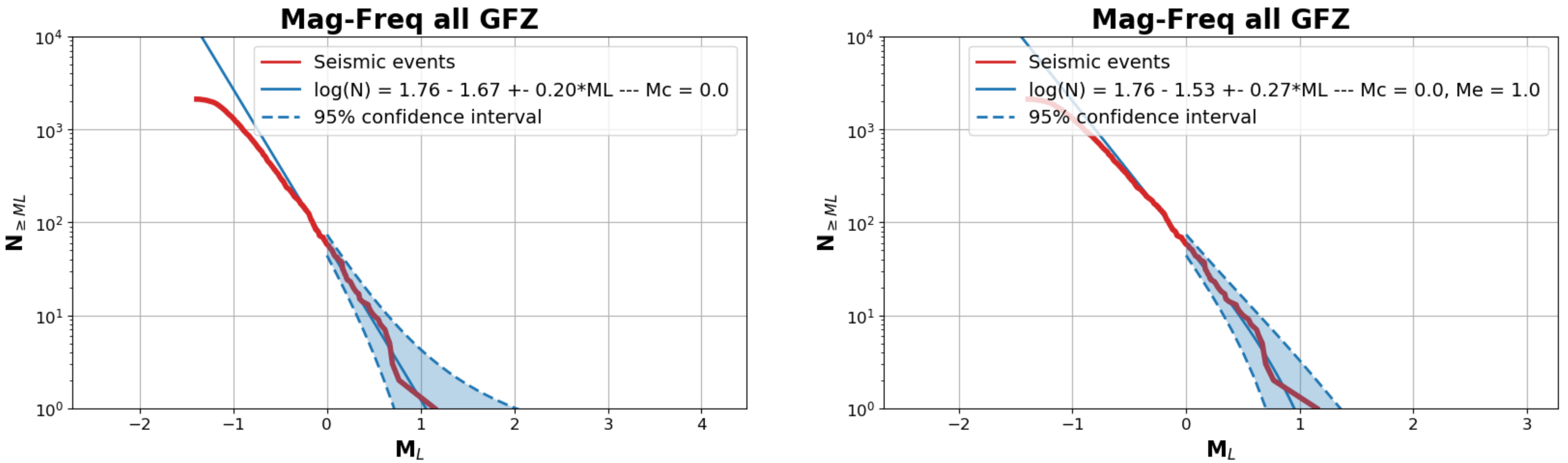




- After 6 days of stimulation, both the **GR** and the **TGR** model were able to predict the maximum magnitude within their 95% confidence intervals.

ARUP

M_{max} Predicted as of 08 June (3 days of stimulation, 1 pause of 26h)

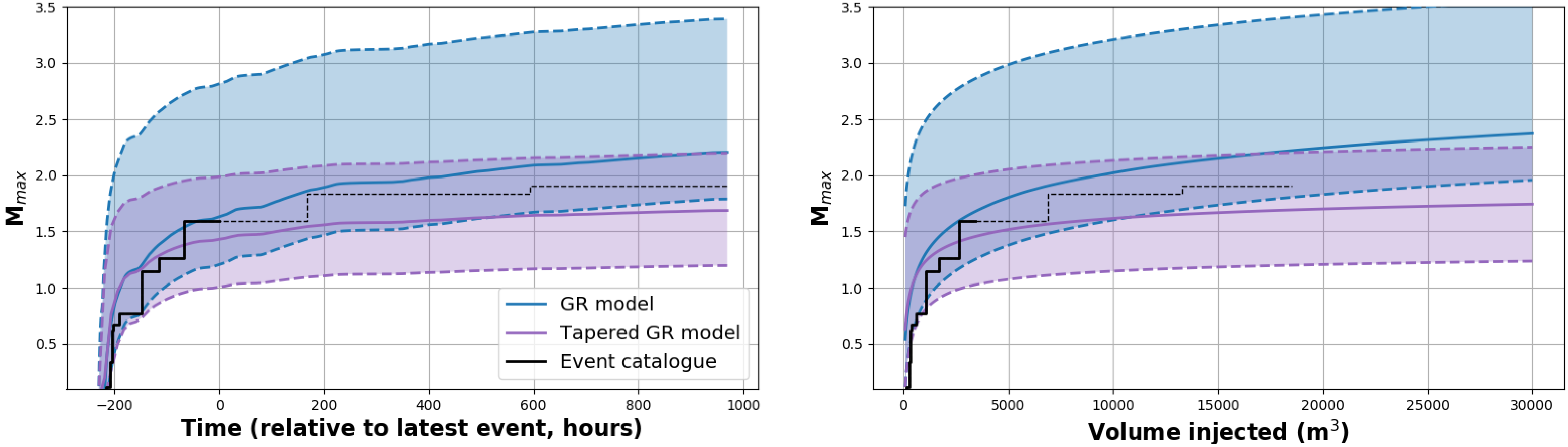


FIT OF GR AND TGR MODELS TO RECORDED SEISMCITY

- Magnitudes seem still too low to properly estimate the roll-off magnitude Me.
- The estimates of the TGR will therefore underestimate M_{max}.

ARUP

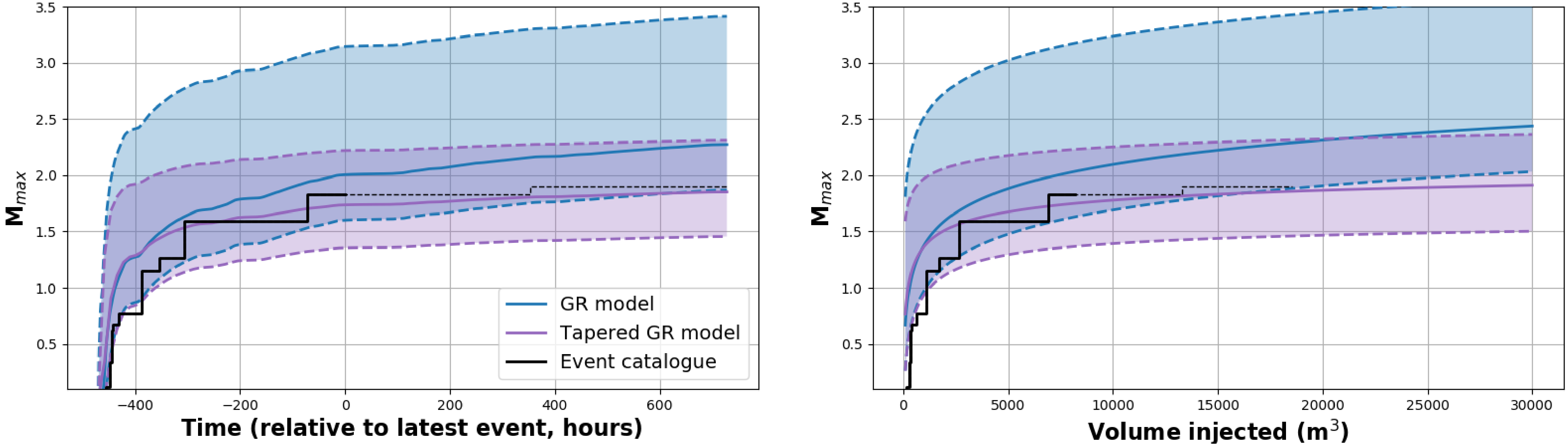
M_{max} Predicted as of 14 June (9 days of stimulation, 2 pause of more than 24h)



- Predictions of GR and TGR with 95% confidence intervals

ARUP

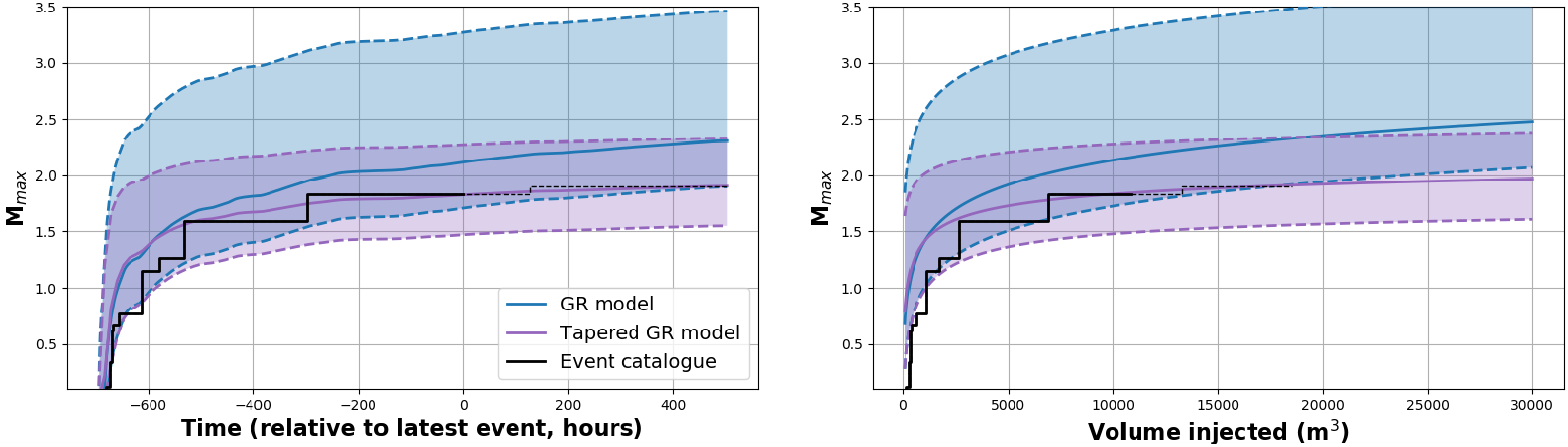
M_{max} Predicted as of 24 June (19 days of stimulation)



- Predictions of GR and TGR with 95% confidence intervals

ARUP

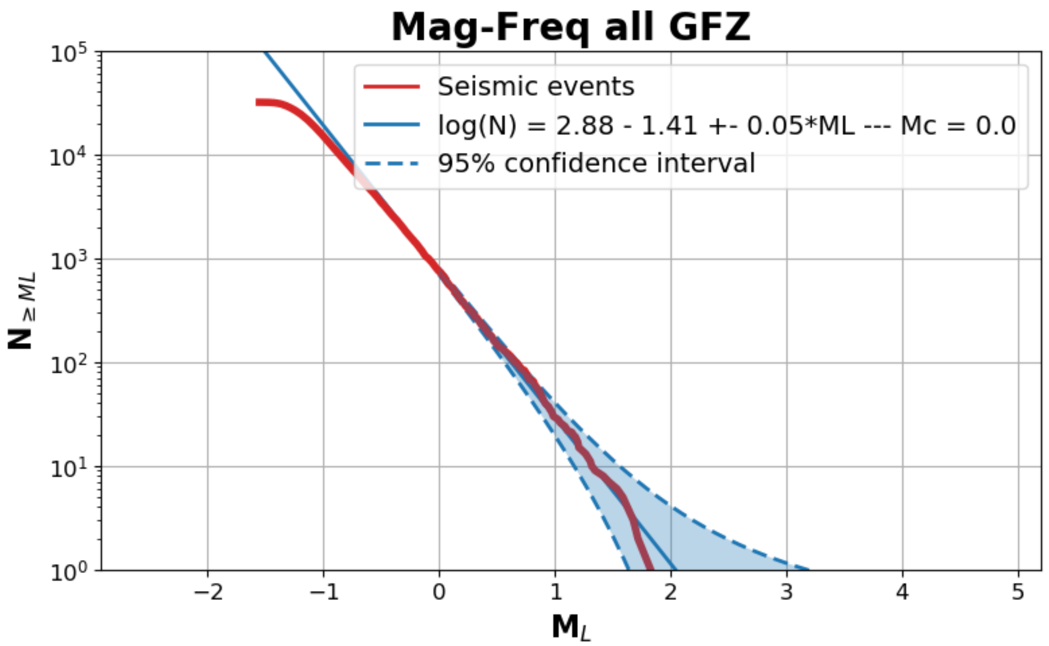
M_{max} Predicted as of 03 July (28 days of stimulation)

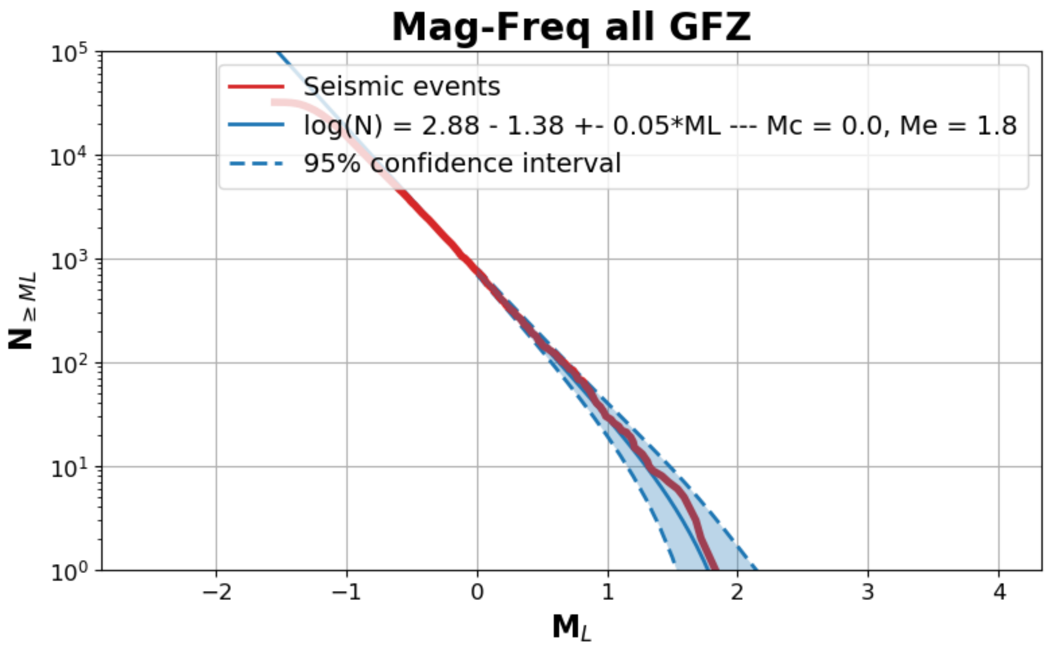


- Predictions of GR and TGR with 95% confidence intervals

ARUP

M_{max} Predicted as of 03 July (28 days of stimulation)

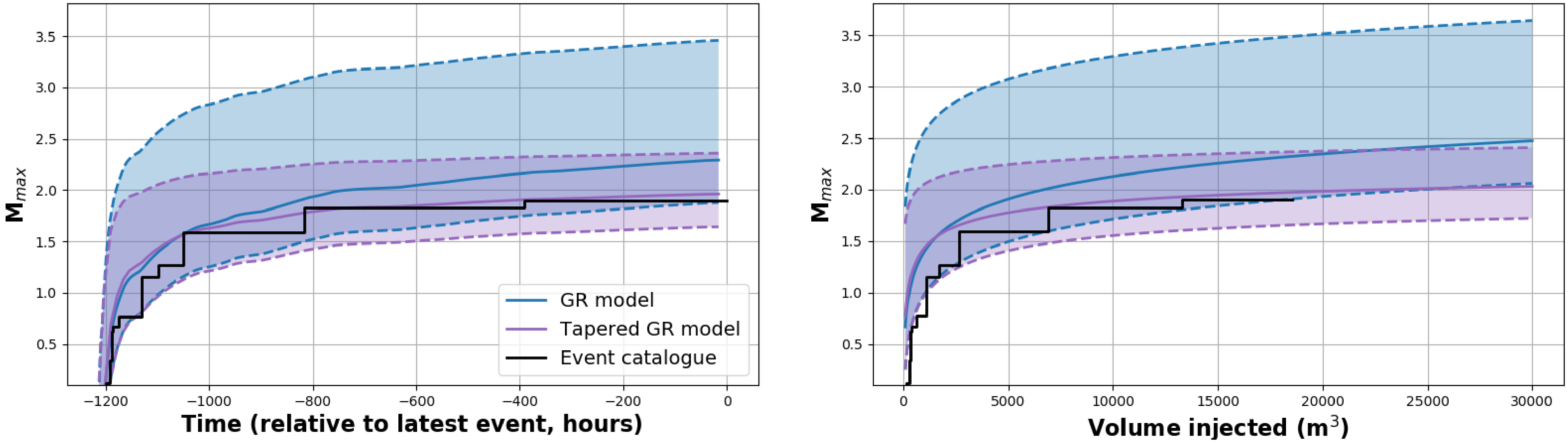




FIT OF GR AND TGR MODELS TO RECORDED SEISMCITY

- Magnitudes are getting high enough to see the roll-off occur and estimate magnitude Me.
- The estimates of the TGR will therefore provide a reliable estimate of M_{max}.

M_{max} Predicted as of End of Stimulation



- Predictions of GR and TGR with 95% confidence intervals

ARUP

Performance on M_{max}

- The TGR model tends to under-estimate M_{max} at the start of the stimulation, while the estimates are good later on.

- This is due to the fact that, at the beginning of the stimulation, magnitudes are too low to estimate the roll-off magnitude.

- Whether to rather follow the prediction of the GR or of the TGR model will depend on how well each model seem to fit the MF distribution of the recorded seismicity. Looking at the MF distribution of the seismicity will tell if the roll-off is appearing or not.