



# Operational Forecasting of Induced Seismicity (ORION) Toolkit



Background and Application to the Illinois Basin Decatur Project

Lead Developers: Kayla Kroll<sup>1</sup> and Christopher Sherman<sup>1</sup>  
Co-developers: Gina Geffers<sup>1</sup>, Chaoyi Wang<sup>1</sup>, Keurfon Luu<sup>2</sup>

<sup>1</sup>Lawrence Livermore National Laboratory

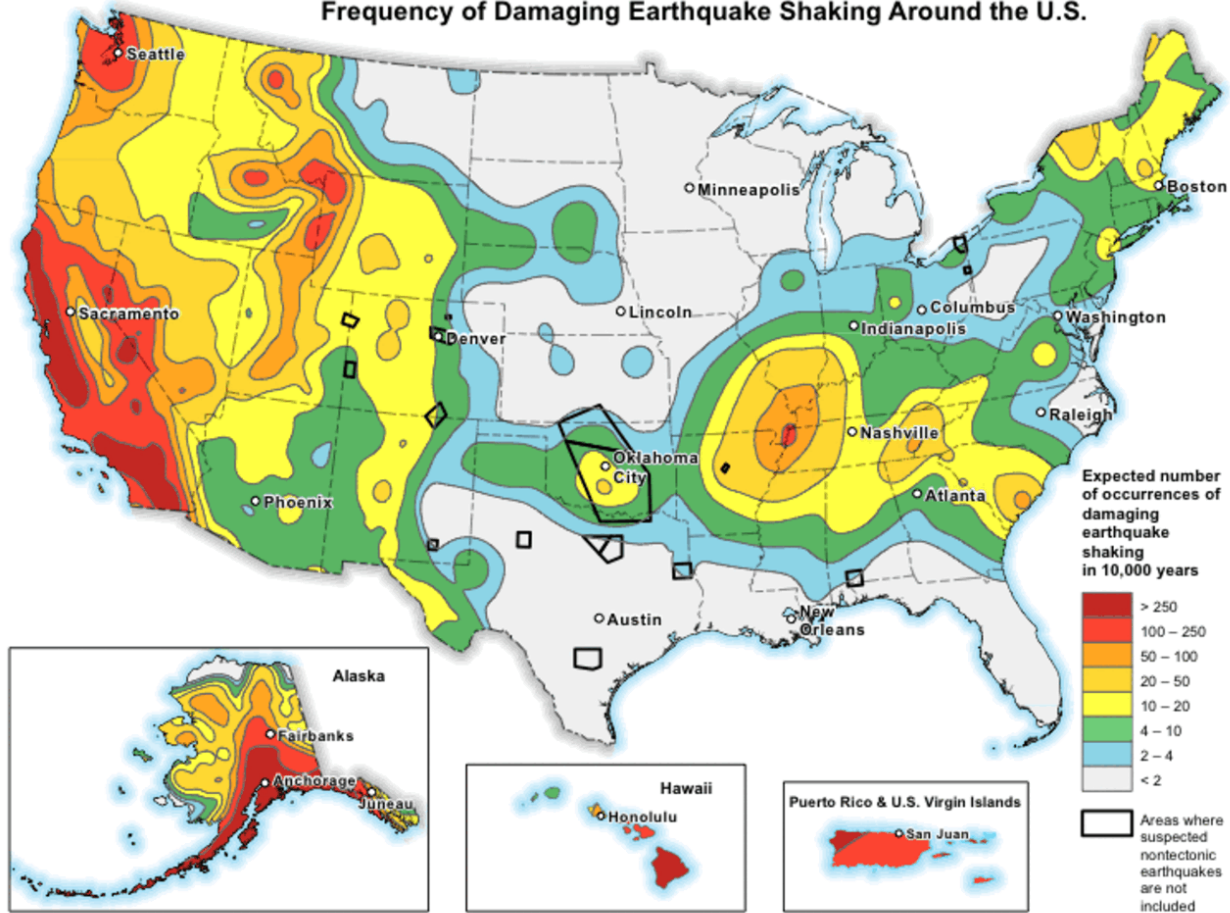
<sup>2</sup>Lawrence Berkeley National Laboratory



# Seismic Forecasting



Frequency of Damaging Earthquake Shaking Around the U.S.

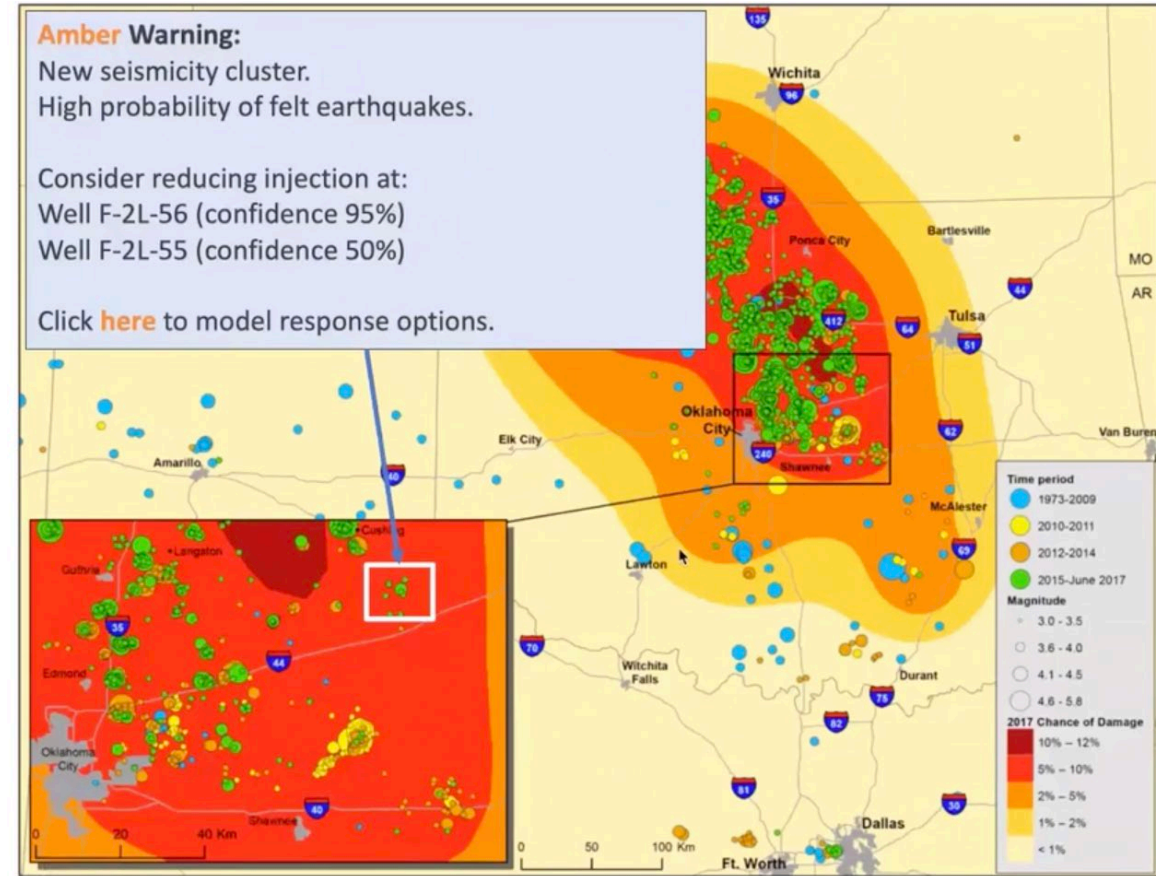


## Amber Warning:

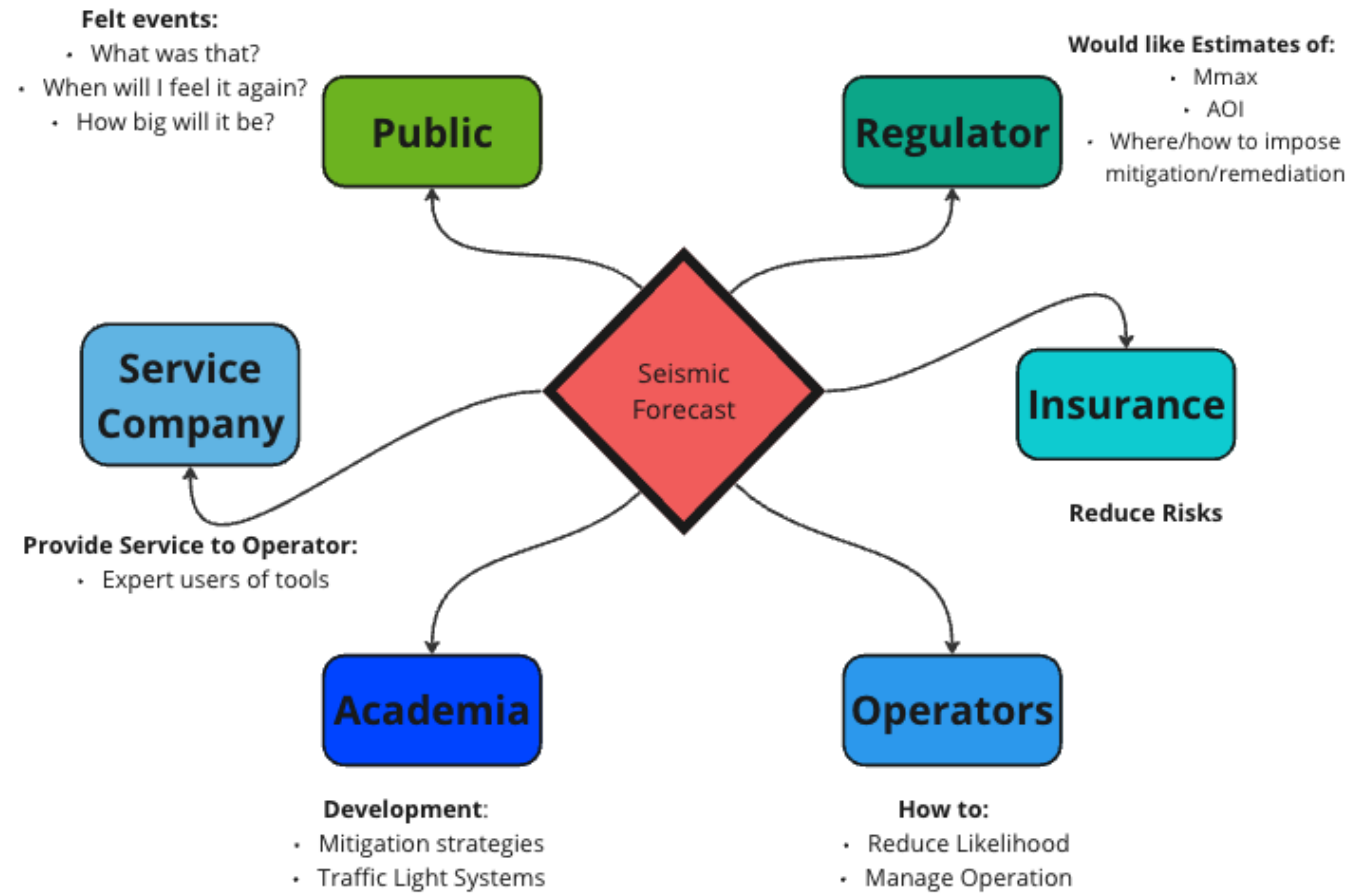
New seismicity cluster.  
High probability of felt earthquakes.

Consider reducing injection at:  
Well F-2L-56 (confidence 95%)  
Well F-2L-55 (confidence 50%)

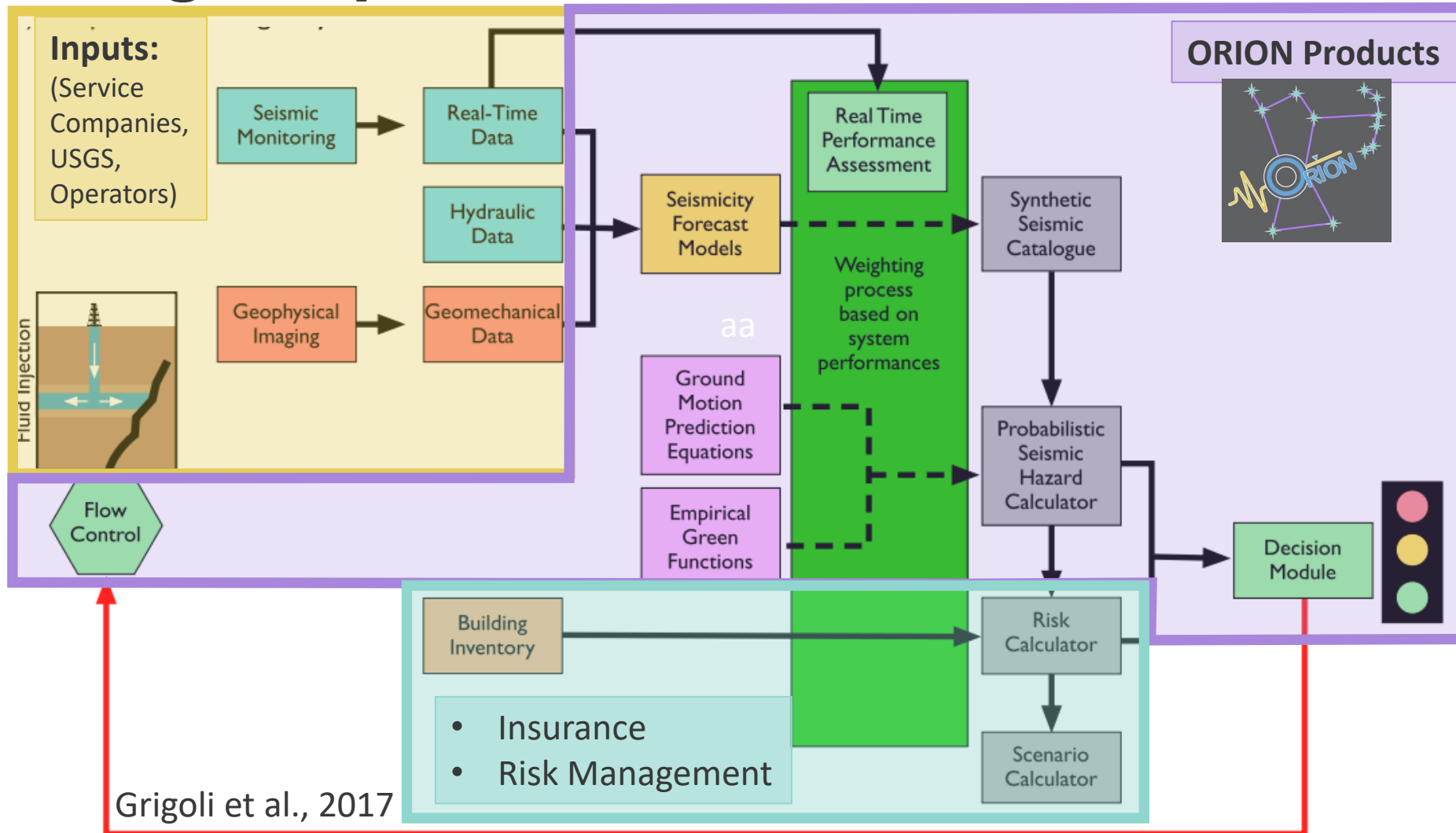
Click [here](#) to model response options.



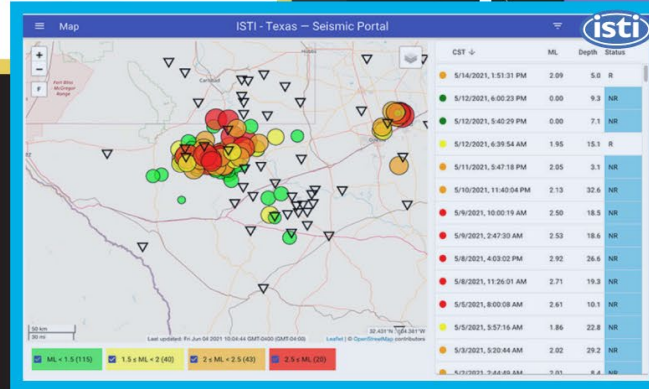
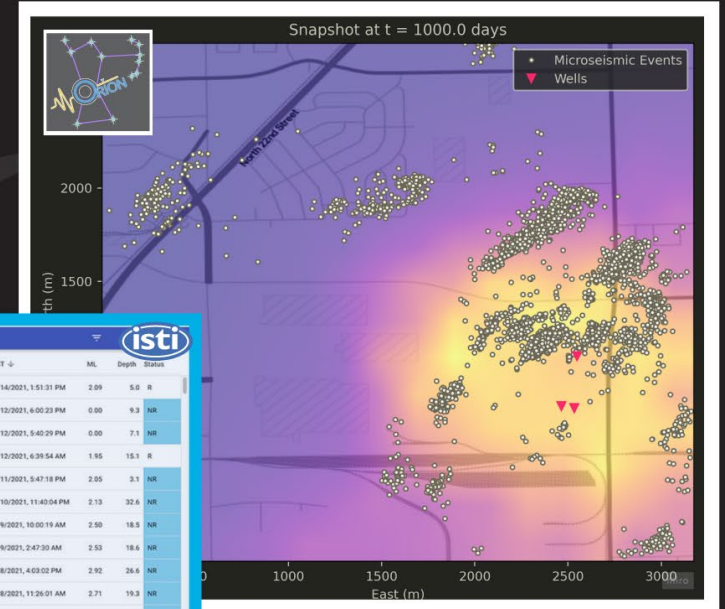
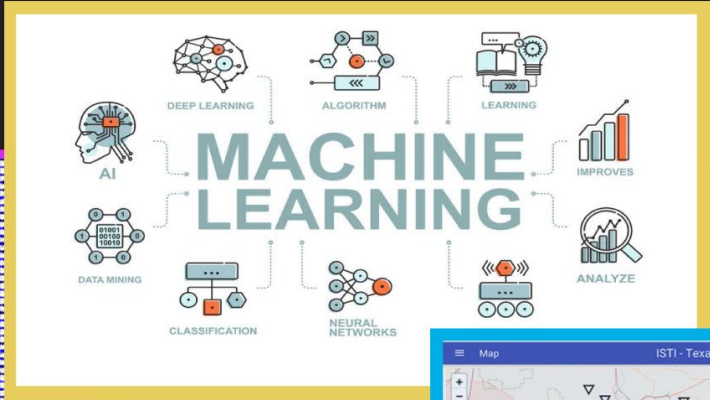
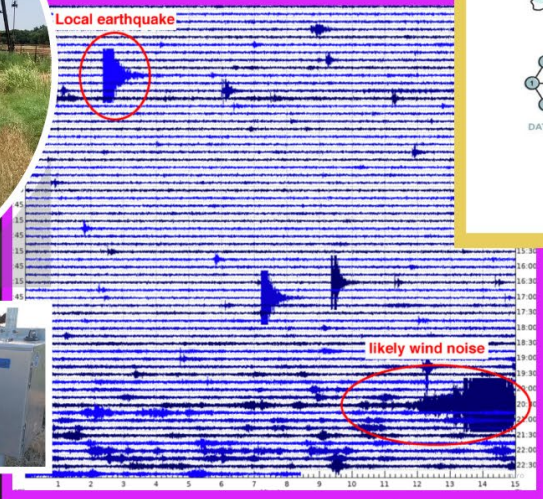
# Forecast Stakeholders



# Forecasting Requirements



# Required Input: Seismic Catalog



Passive seismic monitoring

Continuous seismic data

ML for event detection, location, and classification

Seismicity portal

Seismic forecasting

# Required Input: Pressure Model

- **Pre-calculated pressure table**

- ORION can support a variety of formats (using the USM as a converter), but prefers hdf5-format files

- **ML/ROM Pressure Model**

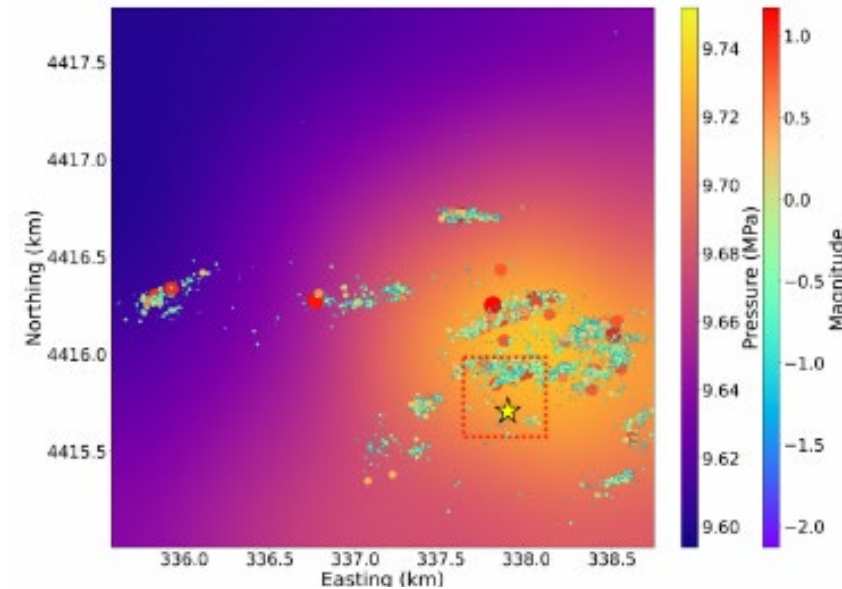
- Support through USM/other tools

- **Radial flow model (Theis)**

- Assumes an infinite homogeneous half-space
- Requires constant or time-varying flow rate data into wells

The fluid pressure,  $p$ , is given by the superposition of each well contribution:

$$p = \frac{\rho g}{4\pi T} \left( z + \sum_{i=1}^N q_i W(u_i) \right) \quad u_i = \frac{r_i^2 s}{4T(t - t_i)}$$



# Ensemble of Induced Seismicity Forecasting Models

## Physics-based Model

### Coupled Coulomb Rate-State Model (Dieterich, 1994; Kroll et al., 2017)

$$R = \exp\left(\frac{\Delta CFS}{a\sigma_{eff}}\right) \quad \text{Coseismic}$$

$$R(t) = \frac{1}{\frac{1}{\dot{S}f_r} + \left(\frac{1}{R_0} - \frac{1}{\dot{S}f_r}\right)\exp\left(\frac{-\dot{S}t}{a\sigma_{eff}}\right)}; \quad f_r = \frac{r}{\dot{S}}$$
 Interseismic

### Rate-State ODE

(Dieterich, 1994; Segall and Lu, 2015)

$$\frac{dR}{dt} = \frac{R}{t_a} \left( \frac{\dot{S}}{\dot{S}_0} - R \right) \quad \text{*Declustered}$$

## Statistical Models

### ETAS Models (Ogata, 1988; Bachmann et al., 2013)

$$\lambda_i(t) = \rho(M_i)\Phi(t - t_i)$$

Gutenberg-Richter Law:

$$\rho(M_i) = k10^{\alpha(M - M_0)}$$

$$\lambda_0(t) = \mu + c_f Q$$

Omori's Law:

$$\Phi(\Delta t) = \frac{k}{(t+c)^p}$$

$$\lambda(t) = \lambda'_0 + \sum_{\{i; t_i < t\}} \lambda_i(t)$$

### Seismogenic Index (Shapiro et al., 2010)

$$SI = \log_{10} N - \log_{10} \sum \dot{S} + bM$$

$$R = \dot{S}^2 10^{SI - bM}$$

# Ensemble of Induced Seismicity Forecasting Models

Physics-based Model  $\dot{S} = \dot{\tau} + \mu(\dot{\sigma} - \dot{p})$  Statistical Models

## Coupled Coulomb Rate-State Model (Dieterich, 1994; Kroll et al., 2017)

$$R = \exp\left(\frac{\Delta CFS}{a\sigma_{eff}}\right) \quad \text{Coseismic}$$

$$R(t) = \frac{1}{\dot{S}f_r + \left(\frac{1}{R_0} - \frac{1}{\dot{S}f_r}\right)\exp\left(\frac{-\dot{S}t}{a\sigma_{eff}}\right)}; \quad f_r = \frac{r}{\dot{S}_r} \quad \text{Interseismic}$$

## Rate-State ODE

(Dieterich, 1994; Segall and Lu, 2015)

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# Ensemble of Induced Seismicity Forecasting Models

## Physics-based Model

### Coupled Coulomb Rate-State Model (Dieterich, 1994; Kroll et al., 2017)

$$R = \exp\left(\frac{\Delta CFS}{a\sigma_{eff}}\right) \text{ Clustering (EQ interaction)}$$

$$R(t) = \frac{1}{\frac{1}{\dot{S}f_r} + \left(\frac{1}{R_0} - \frac{1}{\dot{S}f_r}\right)\exp\left(\frac{-\dot{S}t}{a\sigma_{eff}}\right)}; \quad f_r = \frac{r}{\dot{S}_r} \quad \text{Interseismic}$$

### Rate-State ODE

(Dieterich, 1994; Segall and Lu, 2015)

$$\frac{dR}{dt} = \frac{R}{t_a} \left( \frac{\dot{S}}{\dot{S}_0} - R \right)$$

\*Declustered

## Statistical Models

### ETAS Models (Ogata, 1988; Bachmann et al., 2013)

$$\lambda_i(t) = \rho(M_i)\Phi(t - t_i)$$

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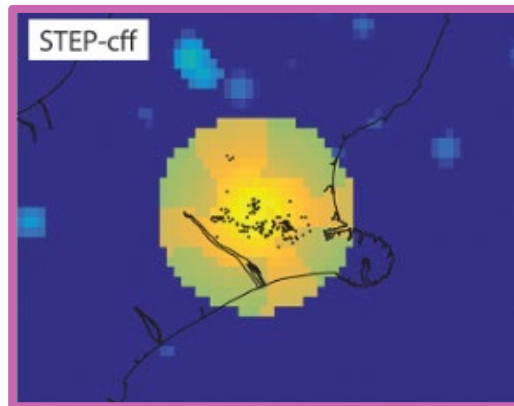
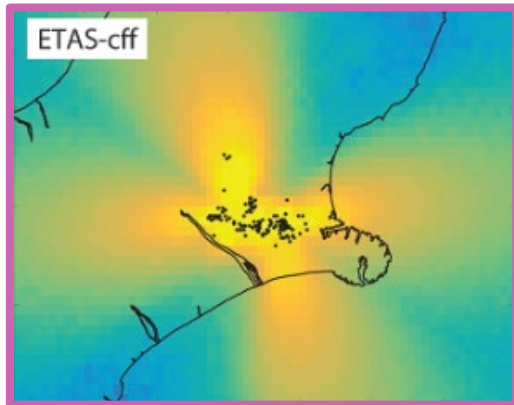
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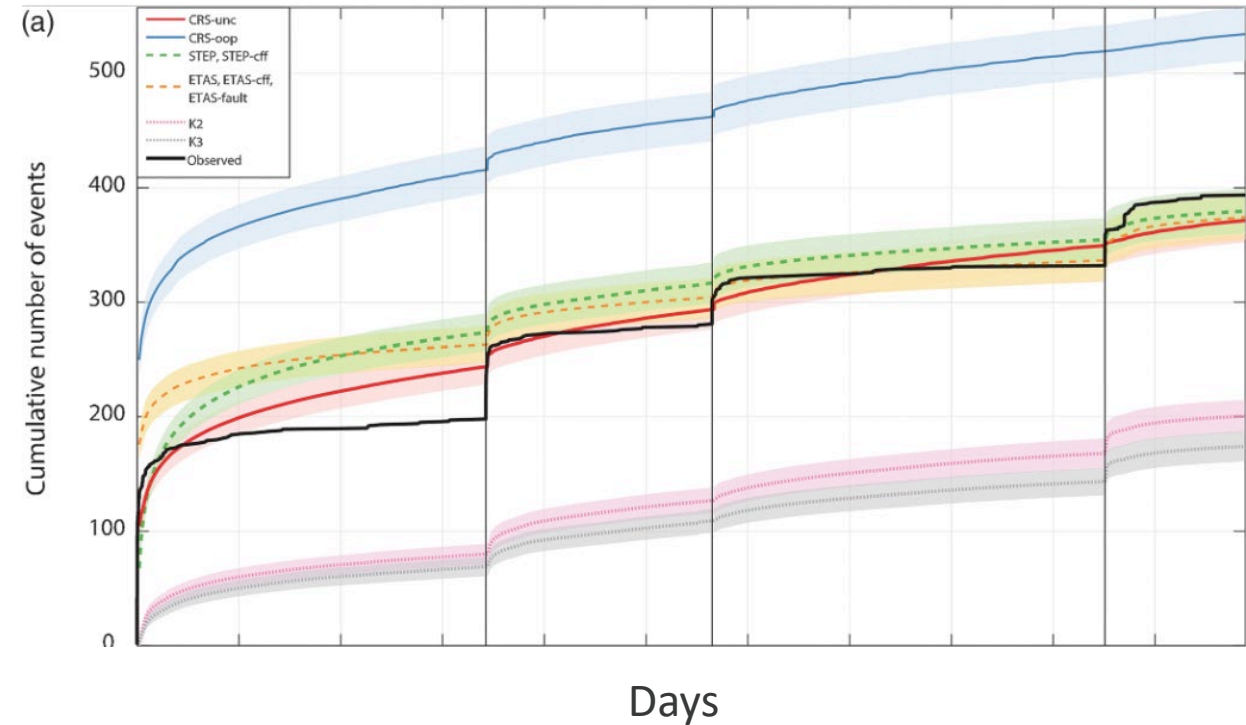
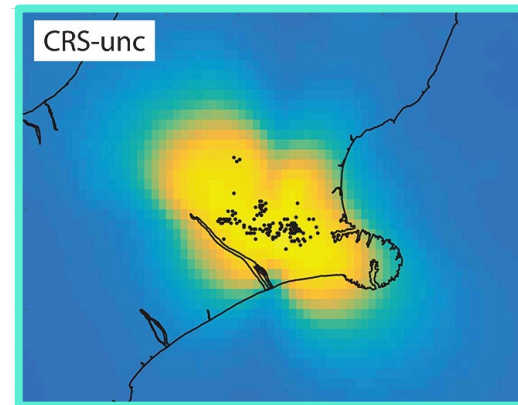
$$R = \dot{S}^2 10^{SI - bM}$$

# Various Induced Seismicity Forecasting Models

## Statistical Models

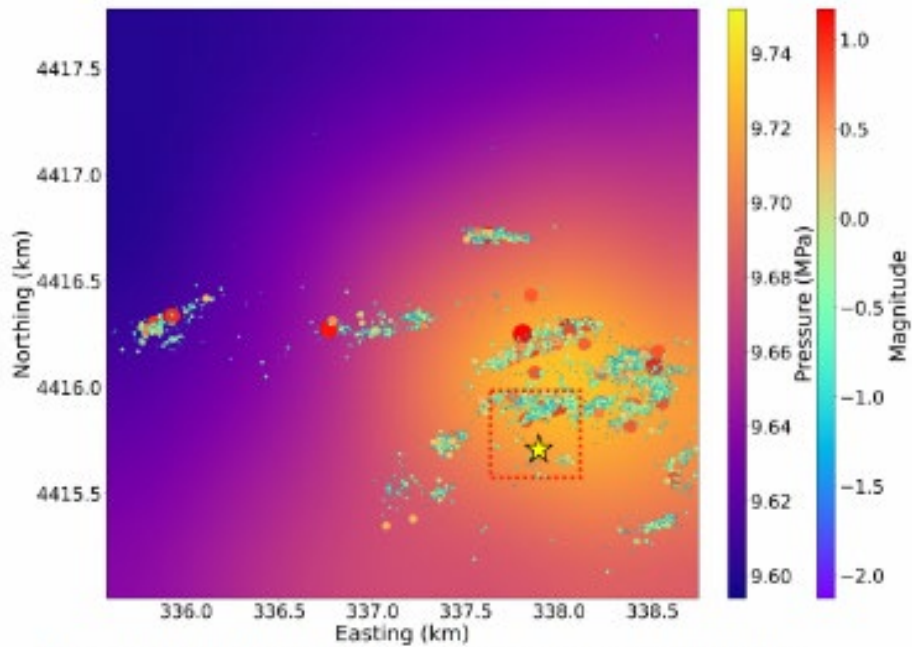


## Physics-based Model

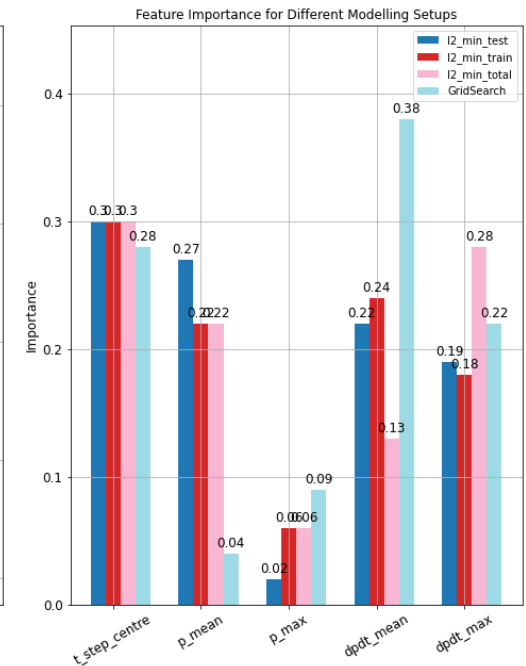
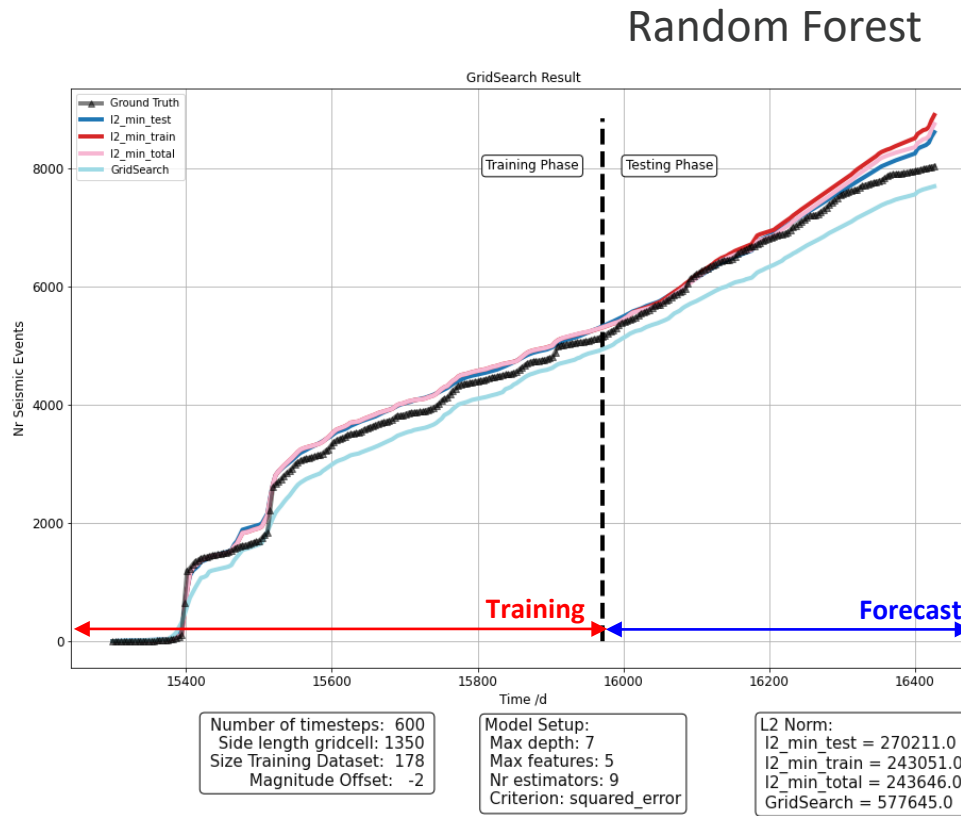
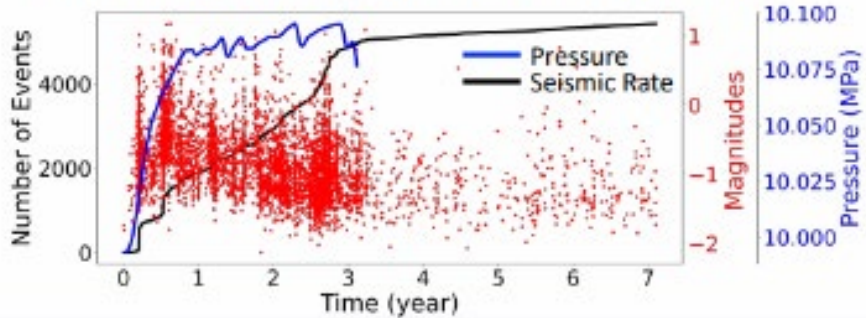


Cattania et al., 2018

# ML-based Forecasts

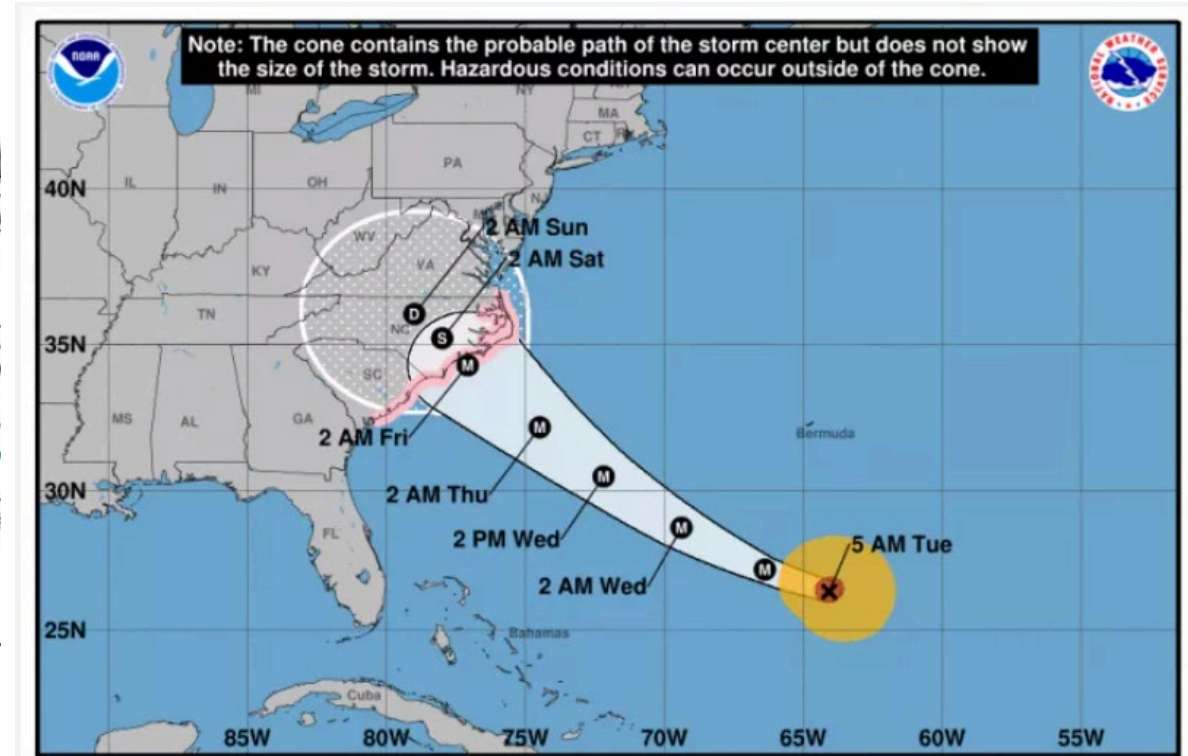
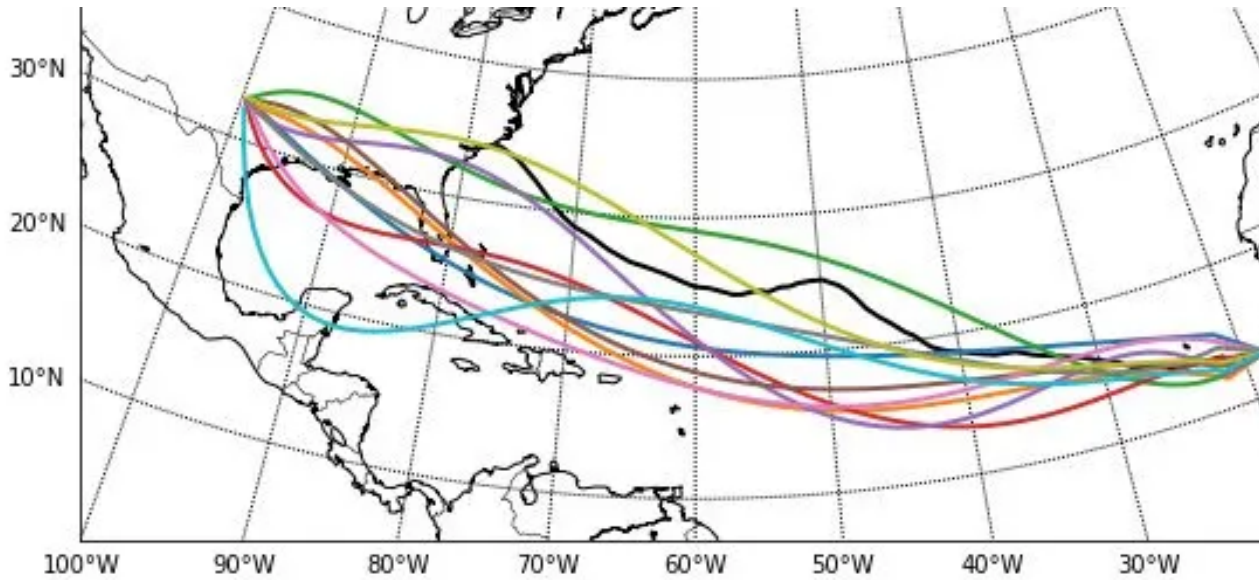


Temporal evolution of pressure and microseismicity

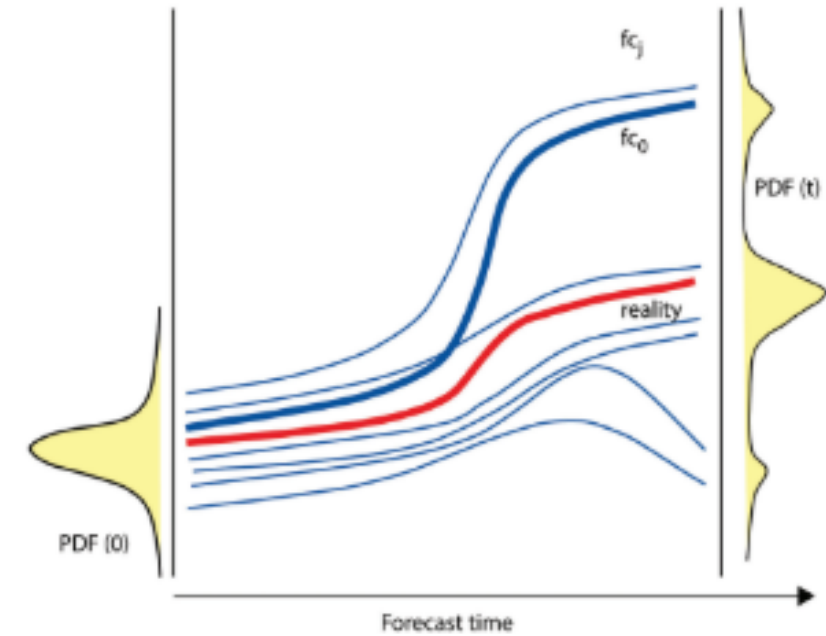
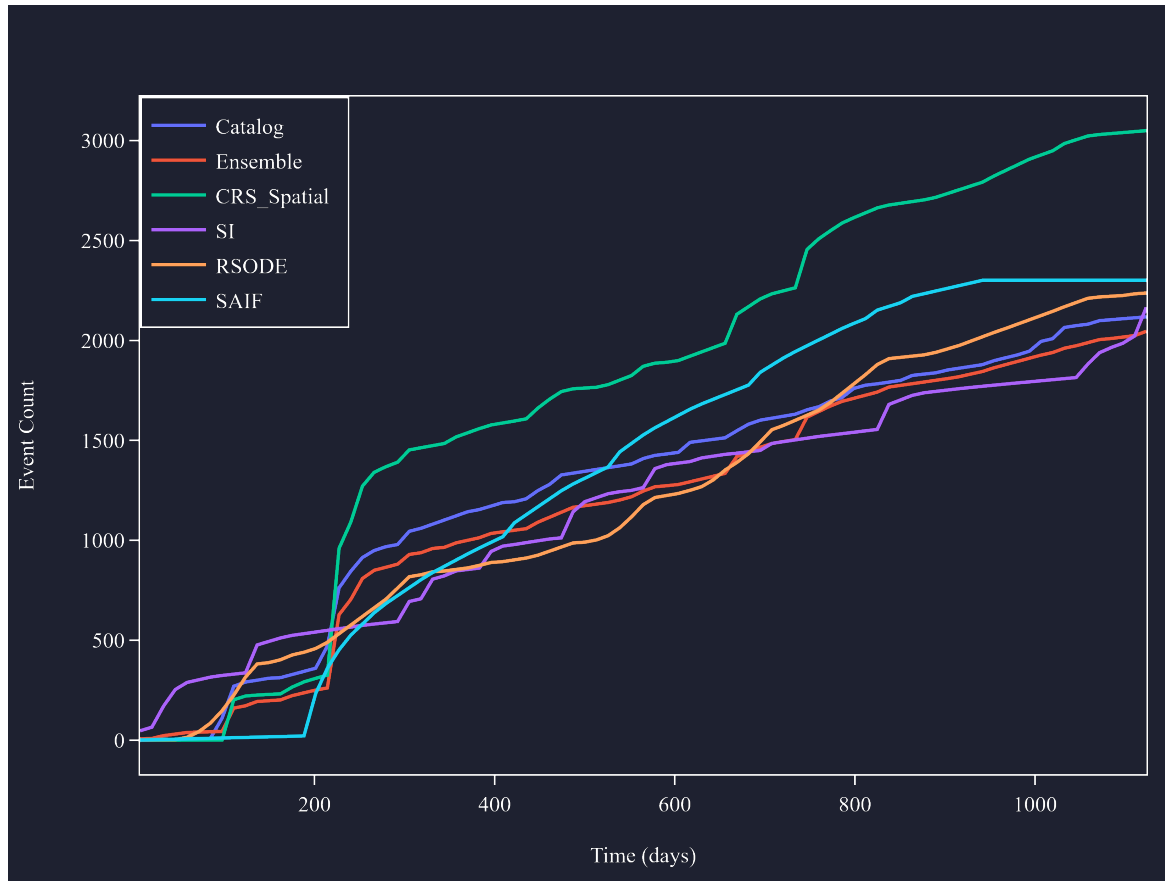


Walter et al., 2023

# Ensemble Forecasting Approach

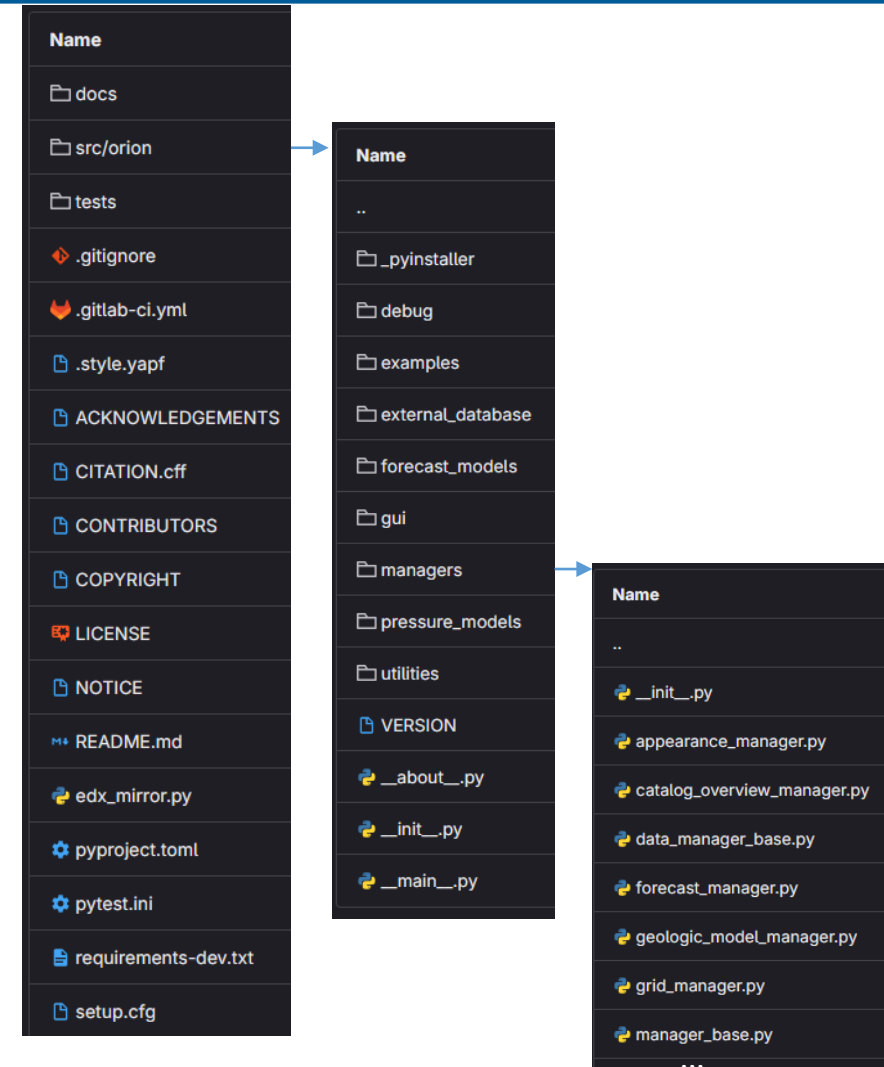


# Ensemble Forecasting Approach



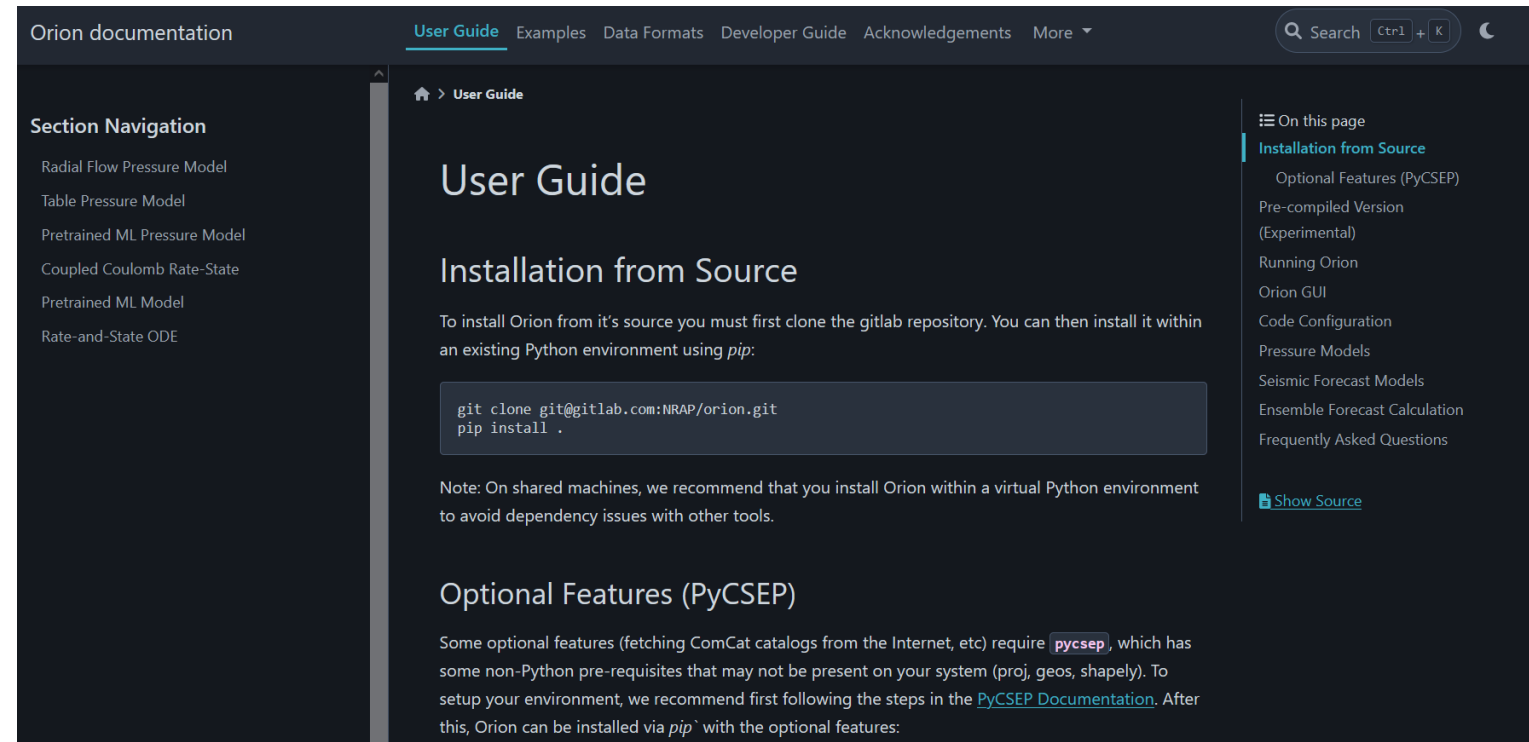
# ORION Code Structure

- ORION is organized as a pure-python, pip-installable package
- Hosted on Gitlab:
  - <https://gitlab.com/NRAP/orion>
- Submodules contain tools for managing data, forecasting, visualization, etc.
- Code formatting/Structure guidelines:
  - PEP8 standards, enforced using the YAPF tool
  - Developers are expected to use human-readable variables, modern object-oriented coding practices
  - Classes, functions, methods, etc. include google format docstrings



# ORION Documentation

- **Documentation is written in .rst format, and built using Sphinx**
  - The build/hosting process is managed automatically by the Gitlab CI
  - [https://nrp.gitlab.io/orion/user\\_guide.html](https://nrp.gitlab.io/orion/user_guide.html)
- **Components:**
  - User guide
  - Examples
  - Description of data formats
  - Developer guide
  - ORION API



The screenshot displays the Orion documentation website. The main content area is titled "User Guide" and features a section for "Installation from Source". This section includes a code block with the following commands:

```
git clone git@gitlab.com:NRAP/orion.git
pip install .
```

Below the code block, a note states: "Note: On shared machines, we recommend that you install Orion within a virtual Python environment to avoid dependency issues with other tools." The page also includes a sidebar with "Section Navigation" (listing models like Radial Flow Pressure Model, Table Pressure Model, etc.) and a right-hand sidebar with "On this page" (listing links like Installation from Source, Pre-compiled Version, etc.).

# Version Control and Testing Pipeline

- Developers commit/push local code changes using git
- Merge Requests are used for code review, testing, record keeping, etc.
- The CI pipeline runs a variety of tests to ensure the quality of the code

```
14 from orion.managers import manager_base
15 from orion.utilities import plot_tools
16 from orion.utilities.plot_config import gui_colors
17 from orion import _frontend
18 import numpy as np
19
20
21 class SpatialForecastManager(manager_base.ManagerBase):
22     """
23     Spatial Forecast Plot Manager
24     """
25
26     def set_class_options(self, **kwargs):
27         """
28         Spatial Forecast initialization
29
30         Args:
31             config_fname (str): An optional json config file name
32
33         """
34
35         # Set the shorthand name
36         self.short_name = 'Spatial Forecast'
37
38     def set_user_options(self, **kwargs):
39         self.catch_pressure_errors = 1
40         self.spatial_slice_depth = 1.0
41         self.spatial_slice_time = 1.0
```

Local code modification

The screenshot shows a GitLab Merge Request interface. At the top, the title is "Allow Multiple Pressure Models" and it indicates that Christopher Sherman requested to merge the feature branch into develop. Below the title, there are statistics for Overview (0), Commits (9), Pipelines (6), and Changes (11). A prominent green checkmark indicates that the "Merge request pipeline #1126213618 passed". The pipeline details show a test coverage of 38.00% (0.00%) from 1 job. On the right side, the Assignee is Christopher Sherman and the Reviewer is Kayla Kroll. There are labels for "priority: high" and "type: feature". At the bottom, there are checkboxes for "Delete source branch", "Squash commits", and "Edit commit message", and a "Merge" button.

Gitlab Merge Request

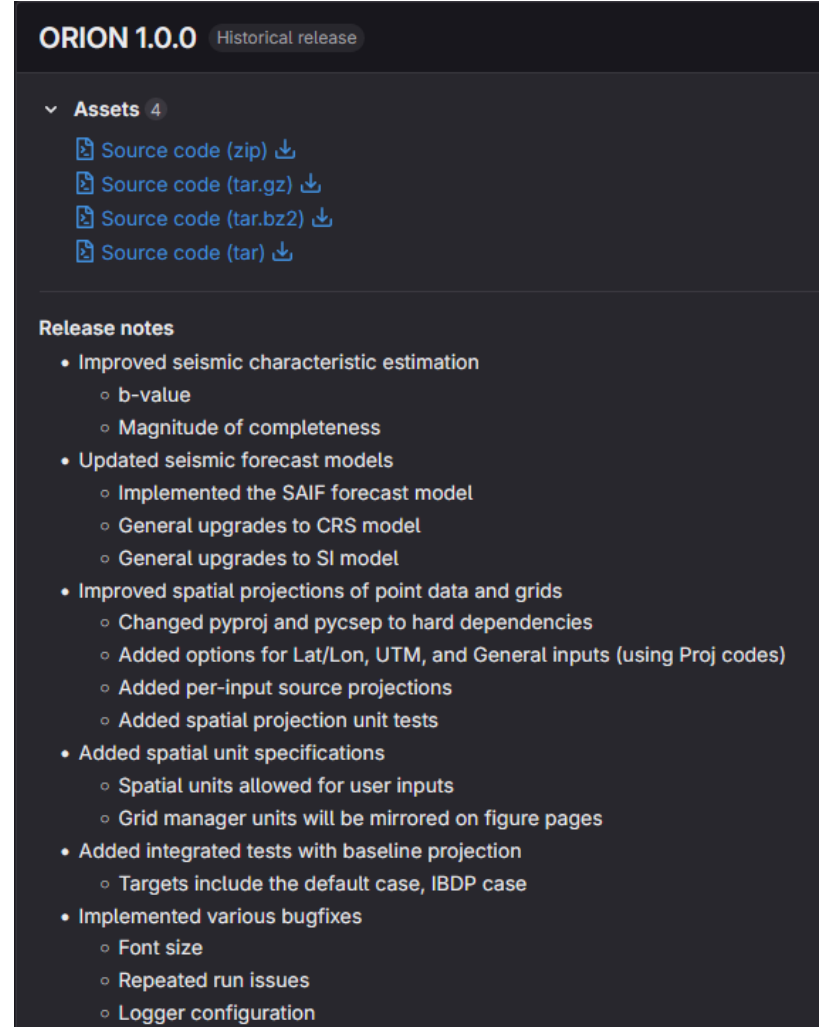
The screenshot shows a vertical list of test results under the heading "test". Each item has a green checkmark and a refresh icon to its right. The items are: docs, install, integrated, style, and unit.

CI Pipeline



# ORION Distribution

- Depending on a user's skill level / interest, they can work with ORION in a few different ways
- From easiest to hardest:
  - Pre-compiled executable (built using pyinstaller, includes all of the necessary pre-requisites to run the code)
  - Install the package from a package manager (e.g. pypi)
  - Install the package from source (git)
- Work in progress:
  - For STRIVE-enabled ORION, users should simply need to visit a website



**ORION 1.0.0** Historical release

Assets 4

- Source code (zip) ↓
- Source code (tar.gz) ↓
- Source code (tar.bz2) ↓
- Source code (tar) ↓

Release notes

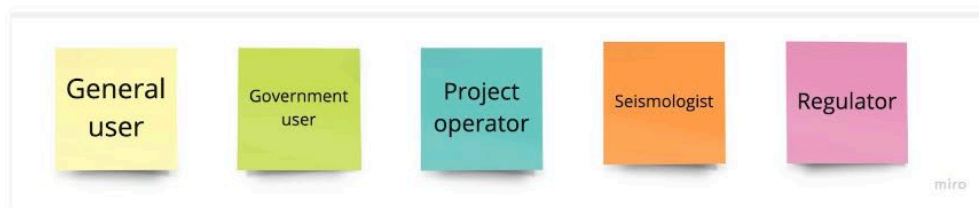
- Improved seismic characteristic estimation
  - b-value
  - Magnitude of completeness
- Updated seismic forecast models
  - Implemented the SAIF forecast model
  - General upgrades to CRS model
  - General upgrades to SI model
- Improved spatial projections of point data and grids
  - Changed pyproj and pycsep to hard dependencies
  - Added options for Lat/Lon, UTM, and General inputs (using Proj codes)
  - Added per-input source projections
  - Added spatial projection unit tests
- Added spatial unit specifications
  - Spatial units allowed for user inputs
  - Grid manager units will be mirrored on figure pages
- Added integrated tests with baseline projection
  - Targets include the default case, IBDP case
- Implemented various bugfixes
  - Font size
  - Repeated run issues
  - Logger configuration

# Basin Scale Spatio-temporal Forecasts

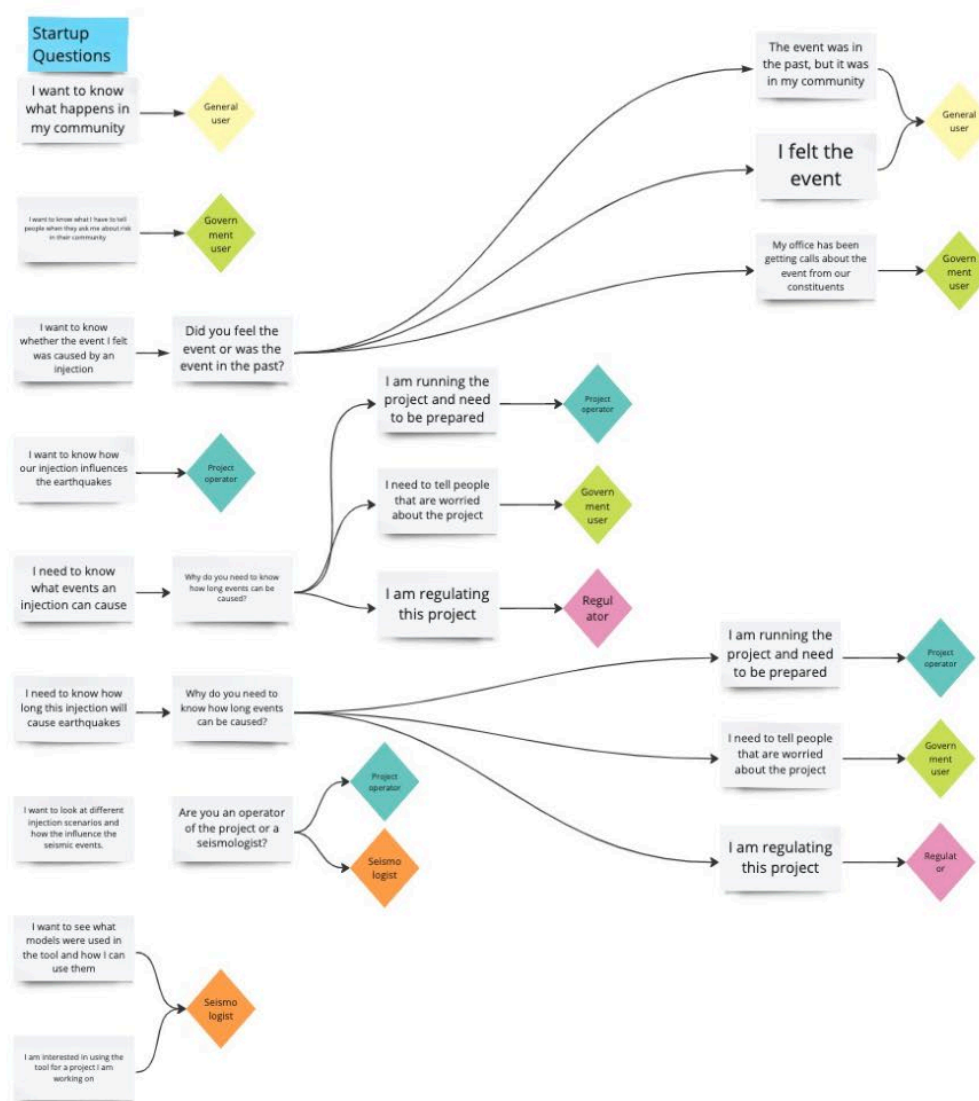
- Tailoring forecasting capabilities to various end-users:



## Start up questionnaire



- Define user groups / stakeholders
  - Define access each group will have
  - Define use cases for each group
- Start with set of simple questions
  - Answer lead to different groups
    - Refine questions to get more specific / distinguish different groups
- Do not overcomplicate it
  - Max three to four layers

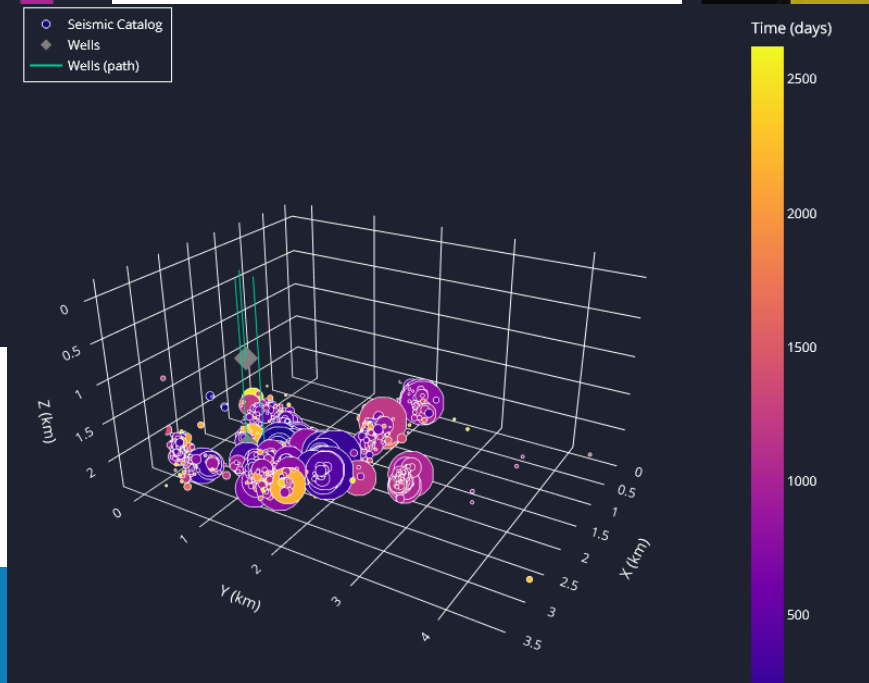
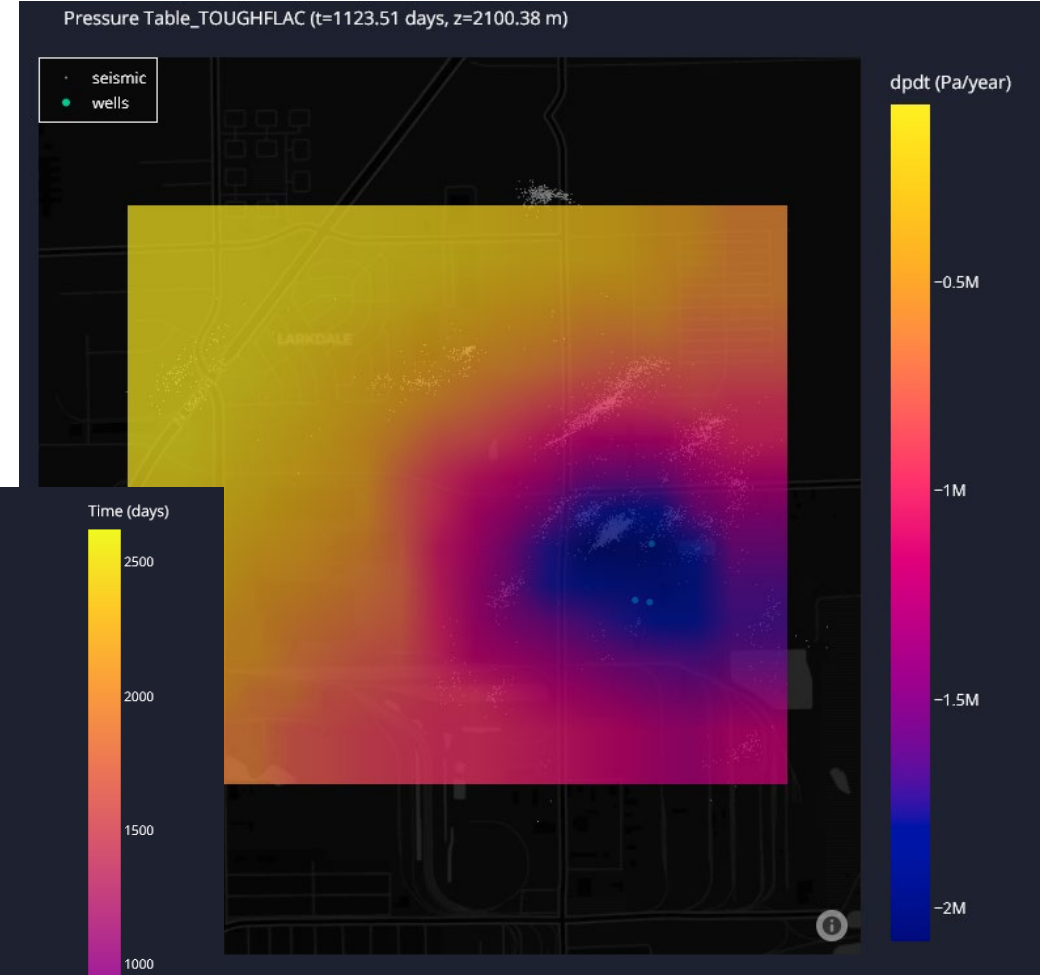
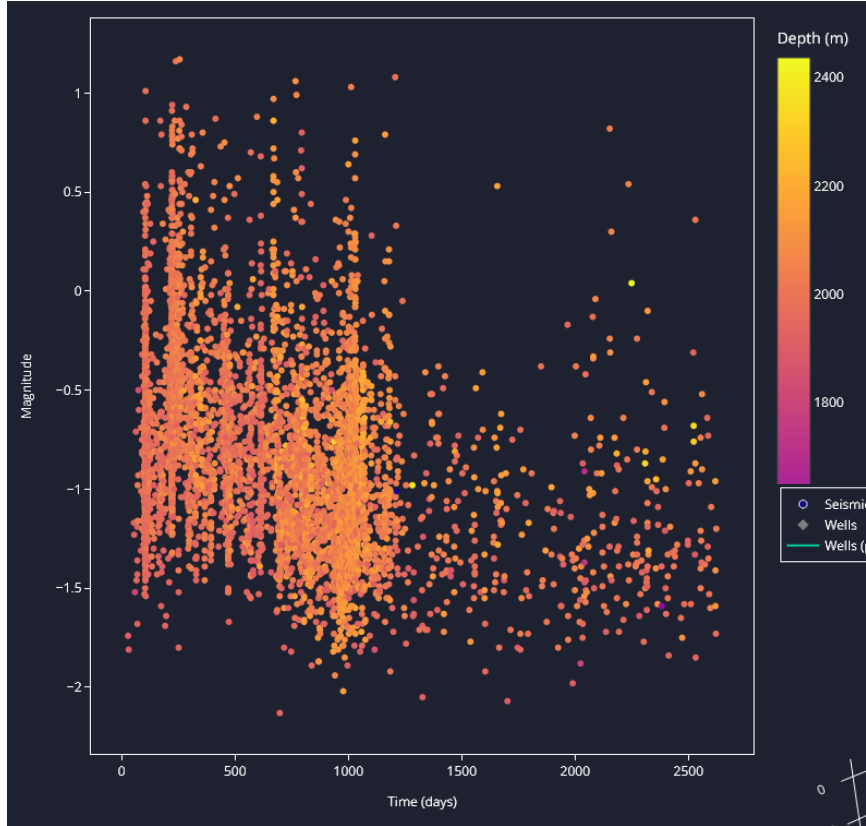


# ORION Application Example: IBDP



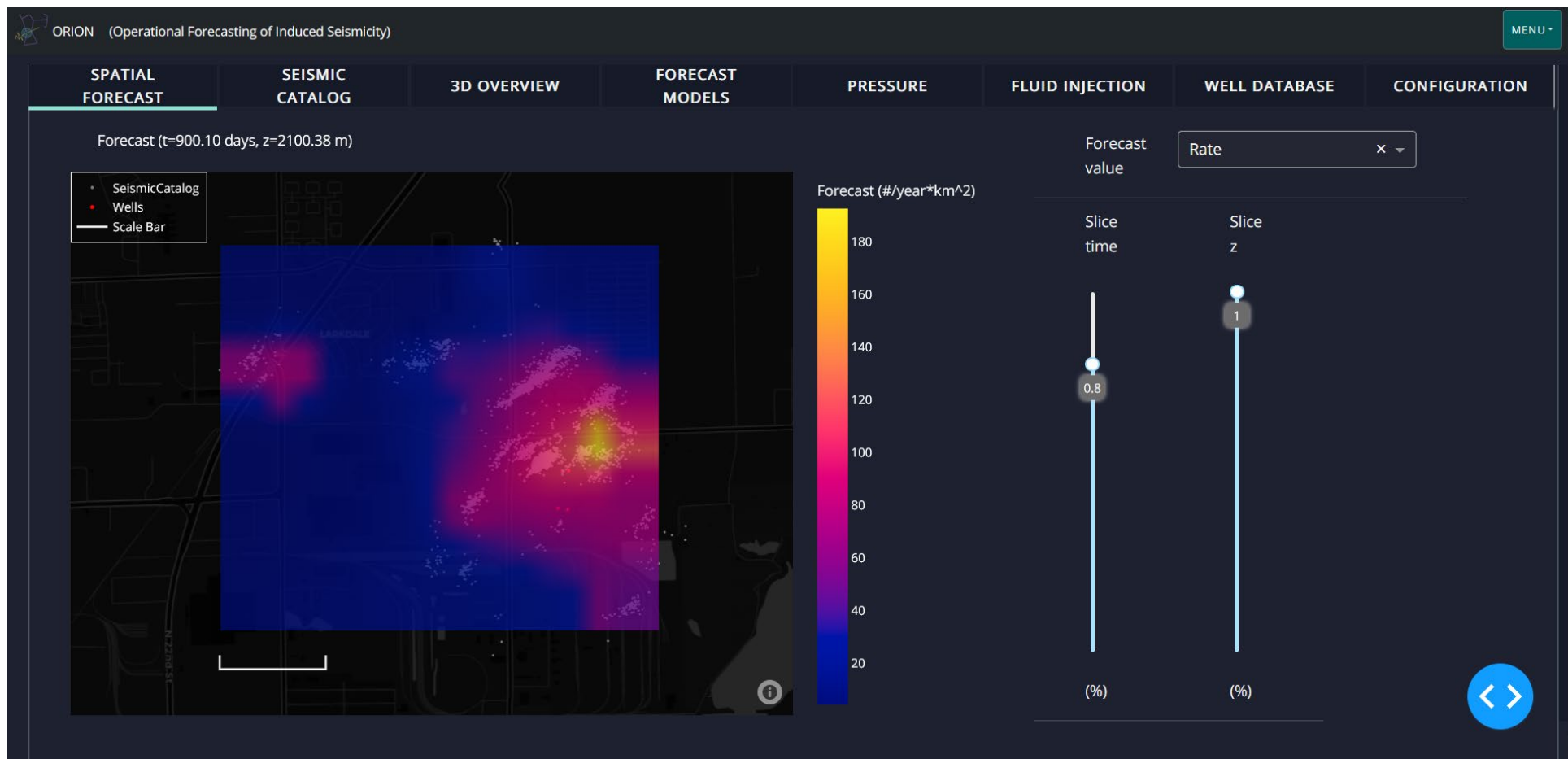
Local seismic catalog, well information

Pressure model (source: TOUGH+FLAC)





# ORION Application Example: IBDP





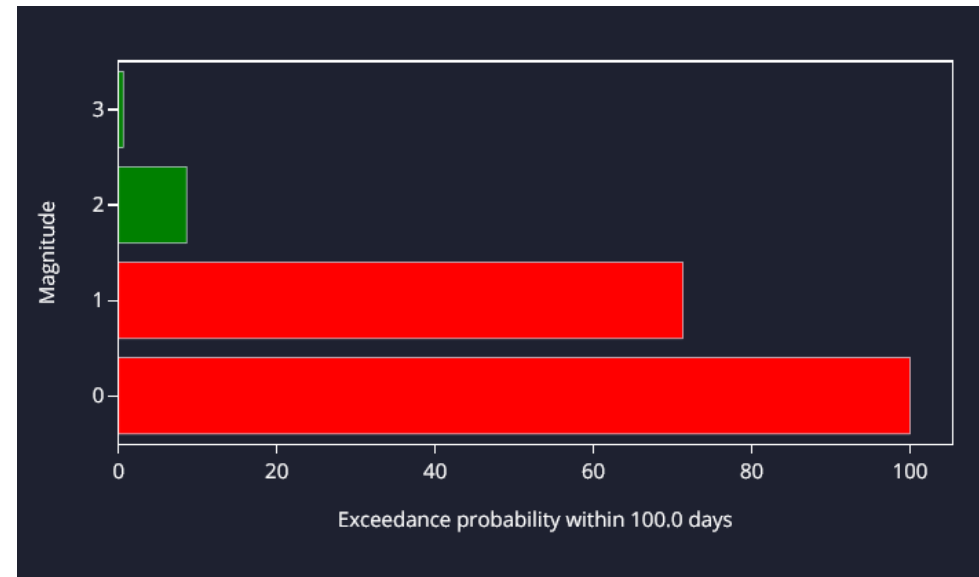
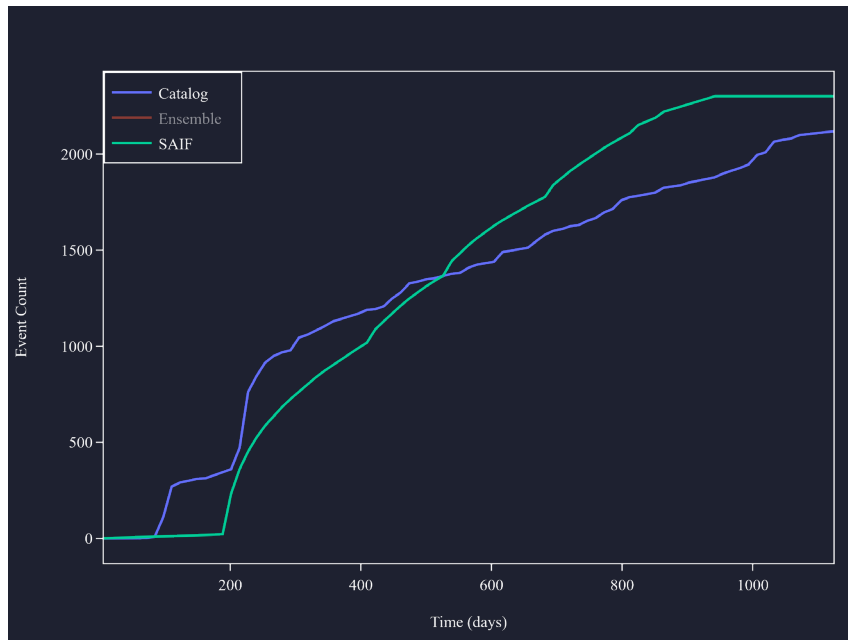
# ORION Application Example: IBDP



# ORION+SAIF

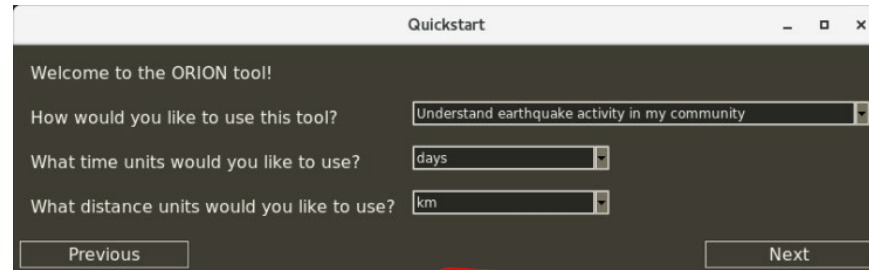


- Direct re-implementation of physics-based forecast model in pyTorch
- Extremely fast run time
- Enables automatic optimization of forecast parameters



# ORION Startup Wizard

This window opens on a first-time run, or via user request:



Quickstart

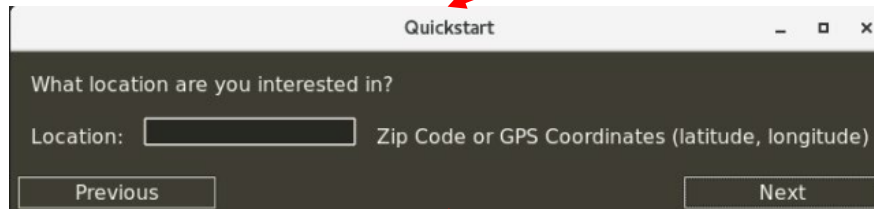
Welcome to the ORION tool!

How would you like to use this tool?

What time units would you like to use?

What distance units would you like to use?

(Other options)



Quickstart

What location are you interested in?

Location:  Zip Code or GPS Coordinates (latitude, longitude)



Quickstart

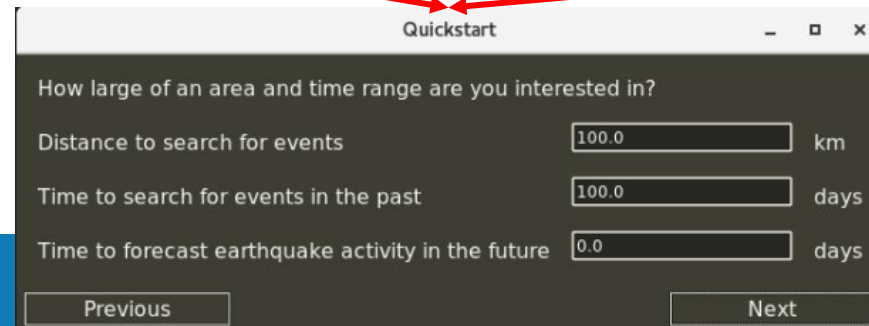
Tell us more when and where you felt the earthquake:

I felt it within the last  days

Where did you feel it?  Zip Code or GPS Coordinates (latitude, longitude)

or

Provide the USGS URL or ID



Quickstart

How large of an area and time range are you interested in?

Distance to search for events  km

Time to search for events in the past  days

Time to forecast earthquake activity in the future  days