Whose Fault Is it Anyway?

A Spatially-Varying Parameters Point Process Model of Earthquake Occurrence in the Pacific Northwest

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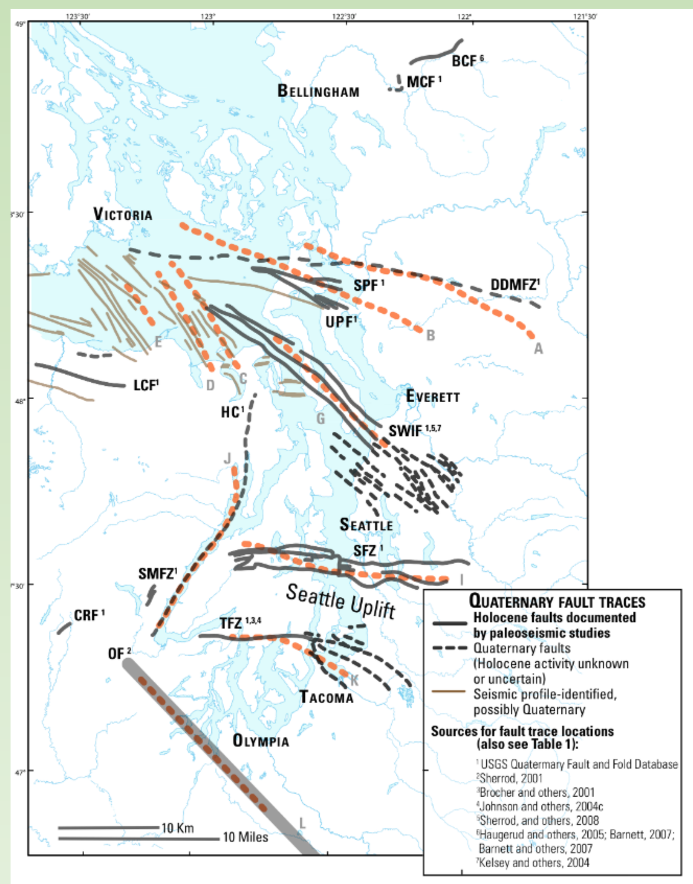
Fig. 1: Faults of the Puget Sound region (Fig. 5 from Barnett et al, 2010)



Introduction

The crustal faults under urban areas in the Pacific Northwest (PNW) generate damaging earthquakes. Accurate modeling of their occurrence distribution is necessary to reduce regional earthquake risk. Such risk reduction forms the mission of the M9 project at the University of Washington, where our work is situated. We build novel space-time point process models for crustal earthquakes using the Epidemic-Type Aftershock Sequence (ETAS) method. A new dataset for the PNW containing measurement errors is used. ETAS is governed by several parameters which model well the spatiotemporal clustering of earthquakes and are directly relevant to earthquake risk reduction. As the PNW has tectonically distinct regions, we build an extension with spatially-varying parameters (the Hierarchical Space-Time ETAS (HIST-ETAS)) to study their effect on forecast performance. Such a model will uncover spatiotemporal dynamics in PNW seismicity and can serve as an input to, e.g., ground motion models and corresponding emergency preparedness plans. It can also provide a spatially-explicit short-term earthquake forecast, a key goal of the United States Geological Survey (Gomberg and Ludwig, 2017). The uncertainty of both the data and model will be quantified and visualized, tailored to the needs of dissimilar audiences.

Research Objectives

This project aims to meet three objectives:

1. Build and compare HIST-ETAS models with both spatially-varying and -invariant parameters.
2. Estimate uncertainty of model results which incorporate both the known data errors and model uncertainties.
3. Improve visualization of the different uncertainties to embetter their communication to policy-makers and scientists who use such model results as inputs for their work.

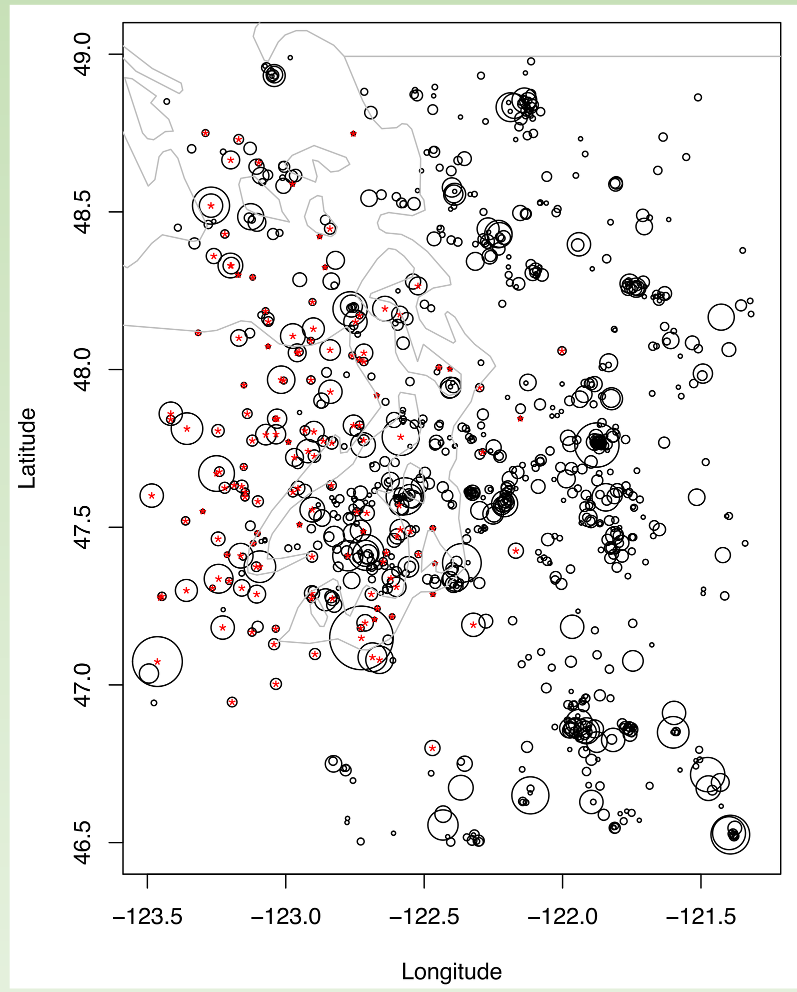
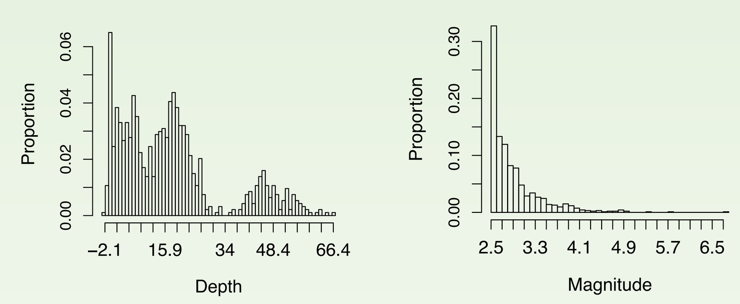


Fig. 2: (Top) Earthquakes in catalog (radius of circle ~ magnitude, red stars are depth > 35 km. (Bottom) Depth and magnitude distributions of catalog



Earthquake Catalog

Three datasets were used to construct a comprehensive catalog for the PNW:

Dataset	Variables
PNSN	(US) PNW earthquake data (estimated locations, times, magnitudes, depths), measured by modern instruments on a growing network of seismic stations, since 1970 (incomplete data since 1929)
NRCAN	Canadian earthquake data, since 1985
ComCat	US earthquake data and uncertainty measurements: measured errors for estimated location, magnitude and depth; number of stations reporting, nearest station reporting, among others

The datasets were cleaned and merged into an initial catalog with these parameters for model-building:

Variable	Values	Rationale
Latitude Longitude	46.5º – 49º -121.3º – -123.5º	Puget Sound region has good station density, high earthquake risk
Magnitude	M2.5 –	M2.5 is the magnitude of completeness for full PNW
Time	1970-01-01 – 2011-01-01	The period of 1970-2011 has consistent data processing for earthquake measurements

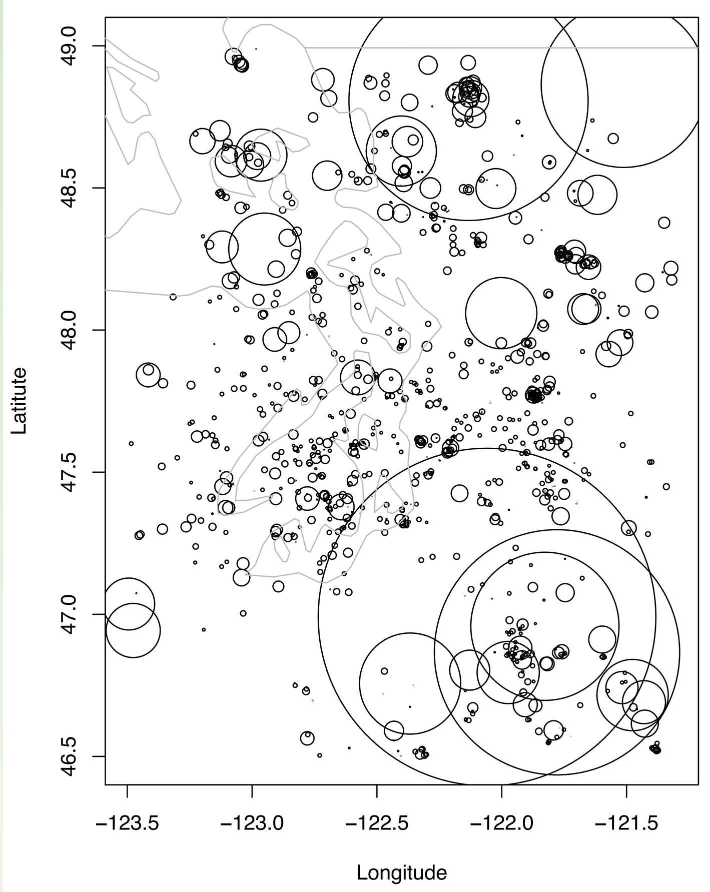


Fig. 3: Location errors for earthquakes in catalog

Additional data processing and cleaning was required for the following problems:

- Duplicate earthquakes and data mismatches between datasets were removed, taking PNSN values as authoritative
- (Aseismic) earthquake swarms were identified through an algorithm that compared co-located earthquake sequences with their magnitude-time distribution
    - Swarms were removed from the catalog as their originating source and behavior are distinct from seismic activity
- PNSN re-analyzed magnitude values but updated them in ComCat inconsistently, leading to mismatches when merging datasets

HIST-ETAS Models

ETAS is a Hawkes-type self-exciting point process model, based on the idea that earthquakes trigger aftershocks, which themselves can trigger aftershocks (Ogata 1988).

Intensity at a space-time point, conditional on past points — Background seismicity rate — Rate of earthquakes triggered by another earthquake, over time, location, magnitude

$$\lambda(t,x,y|\mathcal{H}_t) = \mu + \int_0^t \int\int_A \int_{M_0}^\infty h(t-p, x-\xi, y-\eta; M)N(dp, d\xi, d\eta, dM)$$

With earthquake activity assumed stationary, we can factorize h into temporal, spatial, and number aftershock distributions:

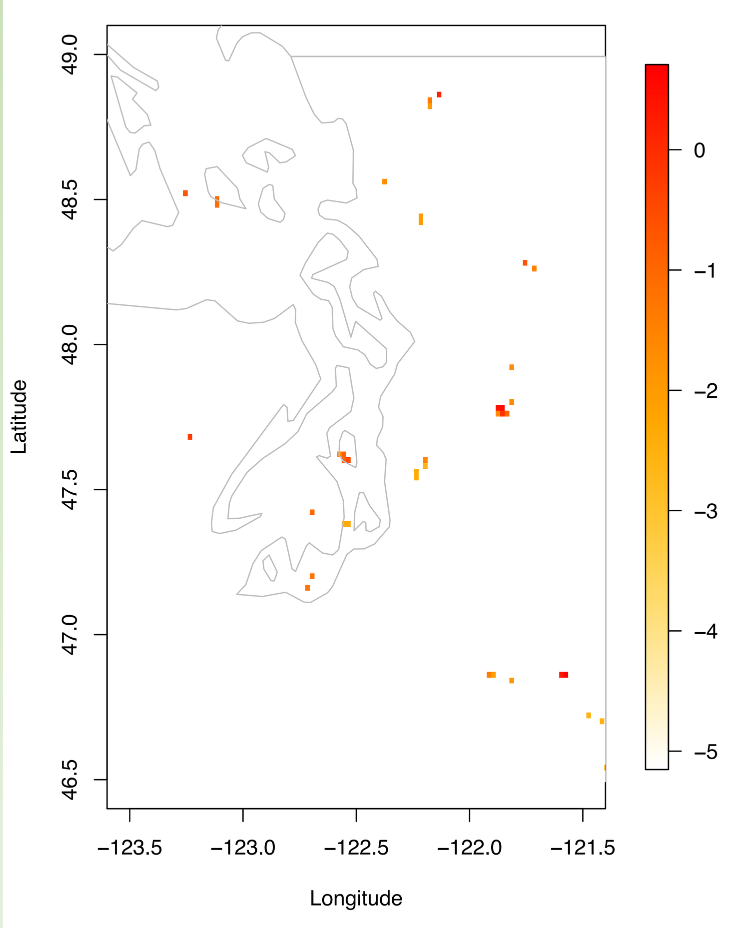
Strength of aftershock activity, as a function of mainshock magnitude — Covariance matrix of anisotropic spatial clusters — Relation between magnitude-frequency distribution and area of aftershocks

$$h(t-s, x-\xi, y-\eta; M) = \frac{K(M)}{(t-s+c)^p}\left(\frac{(x-\xi, y-\eta)S(x-\xi, y-\eta)'}{e^{aM}} + d\right)^{-q}$$

Scaling parameter — Aftershock decay rate — Magnitude efficiency of a mainshock in generating aftershock activity — Scaling parameter

The HIST-ETAS model allows the ETAS parameters *(μ, K, p, a, q)* to vary over space and thus better represent tectonically diverse regions (Ogata 2011). Parameters are estimated on a Delaunay triangulation over the region using an iterative joint likelihood procedure. Initial values are taken as the spatially-invariant maximum penalized likelihood estimates. This represents the spatially-constant model, which has biased estimates for μ (background seismicity depends on location). The spatially-invariant MLEs are taken as initial values and a Linear Search is performed to find the steepest direction of the gradient of the joint penalized likelihood function. We repeat this iteratively until the likelihood reaches its maximum, yielding optimal spatially-varying estimates for *(μ, K, p, a, q)* over the Delaunay triangulation.

Fig. 4: Logged conditional intensity of spatially-constant ETAS model



Preliminary Results and Next Steps

A spatially-invariant model was first built, using the HIST-PPM software package. The ETAS conditional intensity function was fit to a regular rectangular spatial grid using the resulting MLEs for the ETAS parameters. There is a need for a spatially-varying estimate of μ.

Future Work

- Construct spatially-varying HIST-ETAS model using standard approach
- Implement both model types with Bayesian approach, informing priors on ETAS parameters with measurement errors and PNW seismological features
- Characterize and visualize uncertainty of model results for modeller and policy-maker audiences

References and Acknowledgements

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