New Opportunities to Study Tectonic Precursors

Synthesis, **Discussion** and Concluding Remarks

Roland Bürgmann

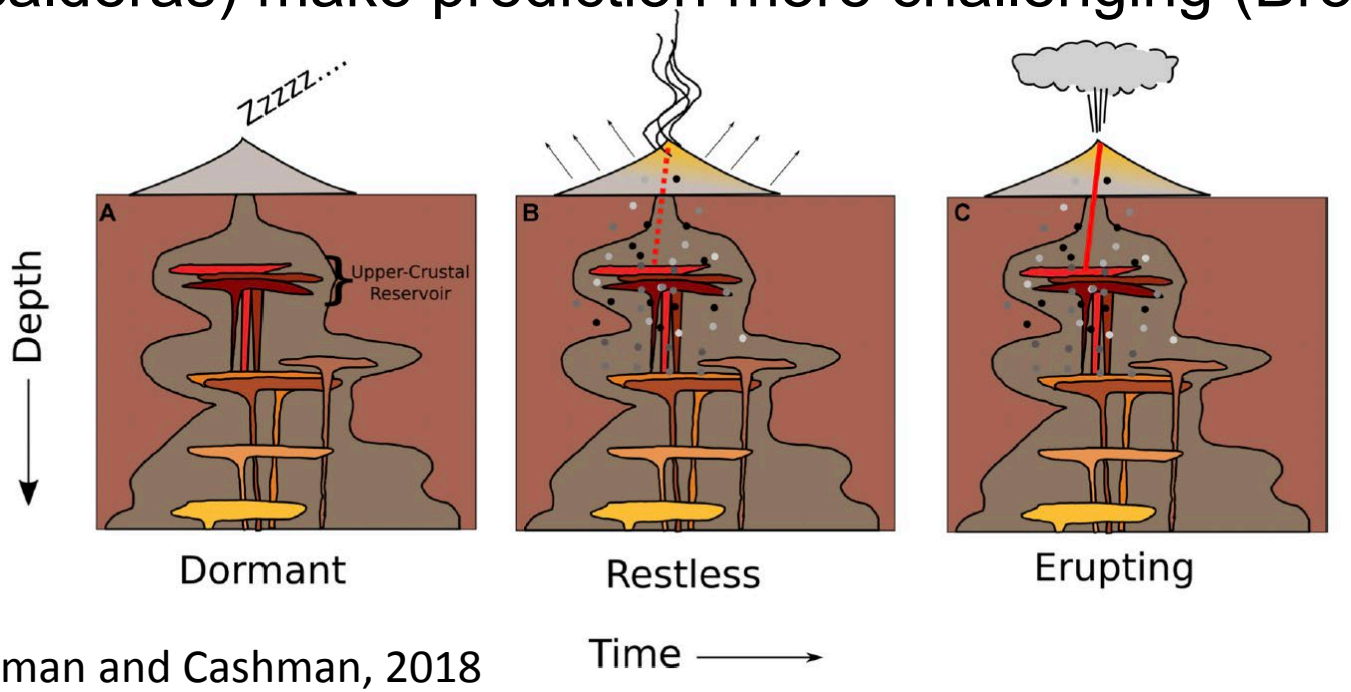
New Opportunities to Study Tectonic Precursors

- “The societal implications of understanding the range of precursory signals are large, but many questions remain.
- Are there certain characteristics of the precursor(s) that make them more or less likely to result in a large earthquake or eruption?”

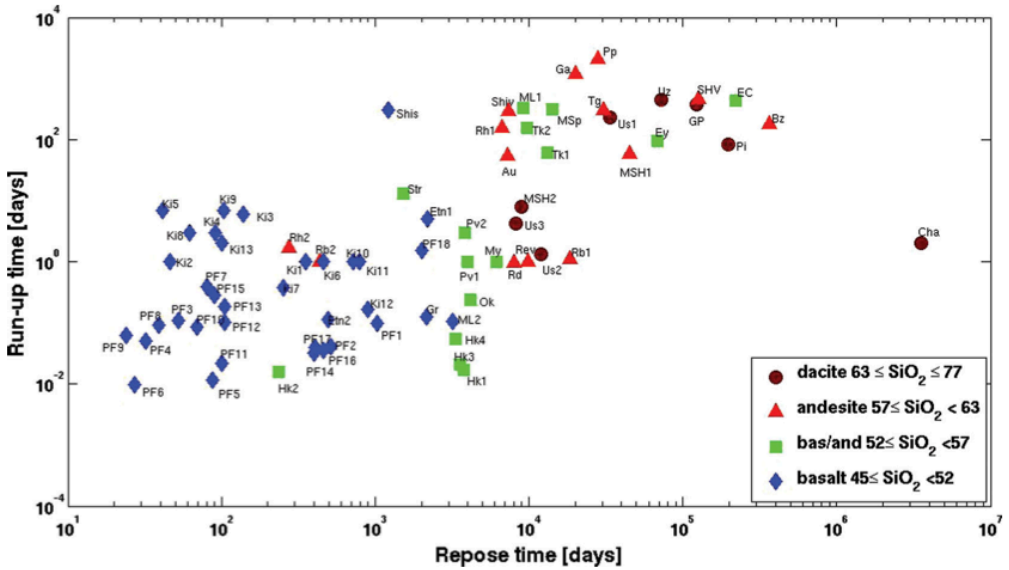
COSG meeting agenda

Eruption Precursors enable Prediction

- Magma transport, conduit formation and associated seismic unrest, gas emissions and strain precede most eruptions (e.g., Roman and Cashman, 2018; Dzurisin et al., 2018)
- Seismic unrest is the most commonly documented pre-eruptive unrest indicator
- Since 1973, all 21 confirmed volcanic eruptions in Iceland had a seismic precursor with duration from 15 min to 13 days. Warnings are issued (Einarsson, 2018).
- Some volcanic systems (e.g., open-conduit volcanoes, more silicic volcanoes, restless calderas) make prediction more challenging (Brodsky)



Roman and Cashman, 2018



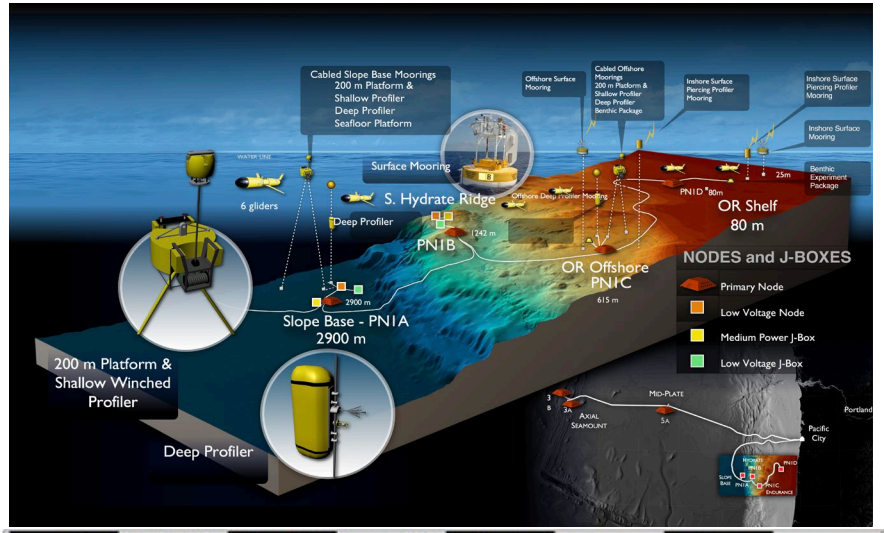
Passarelli and Brodsky, 2012

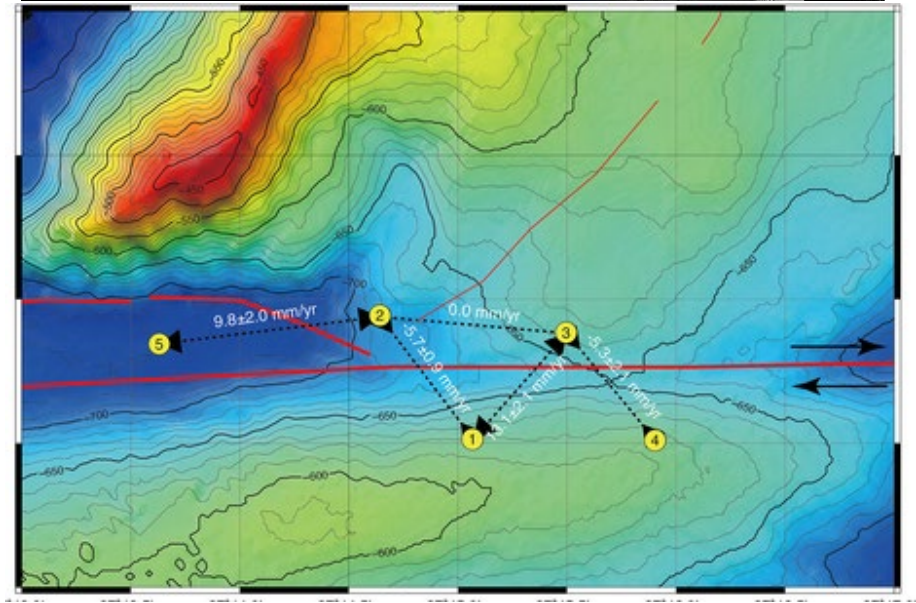
Status of **E**arthquake **P**recursors

- **P**recursor detection improved by powerful new observational tools
- **P**lenty of **p**recursors
- **P**lenty of physical **p**recursory **p**rocesses (with wide range of spatial and temporal scales)
- **P**recursors can be **p**reparation **p**rocess (but they can also be simple triggers)
- **P**lenty of **p**recursor-candidates fail to precede
- **P**rospects for **p**rediction are poor
- **P**recursor-candidates increase **p**robabilities
- **P**romise and incentives for more **p**recursor research using new tools and approaches

Precursor detection improved by Powerful new observational tools

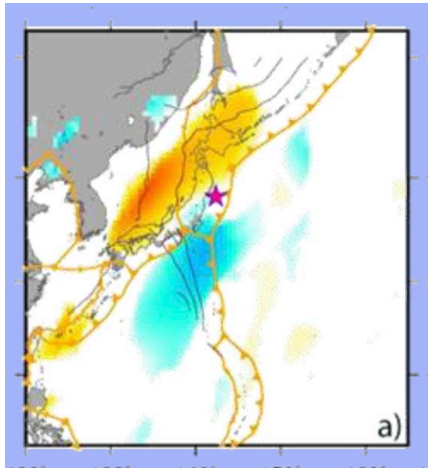
- Geodesy, including satellite remote sensing of deformation and gravity (e.g., Panet, Segall, Wallace)
- Advanced seismological technologies and methods (Brodsky, Lindsey, Segall, Wallace)
  - Fiber-optic DAS, borehole sensors, nodal arrays, ...
  - Study of tremors and low-frequency earthquakes, repeating earthquakes, swarms, use of template matching techniques, spectral analysis, ambient noise tomography, machine learning etc.
- Seafloor geodesy and seismology, including use of pressure sensors, GPS/A, GPS buoys, wavegliders, cabled observatories, acoustic ranging, borehole tilt. "No sensor is adequate for all signals!" *Webb* (e.g., Haines, McGuire, Minson, Wallace, Webb, Wilcock)



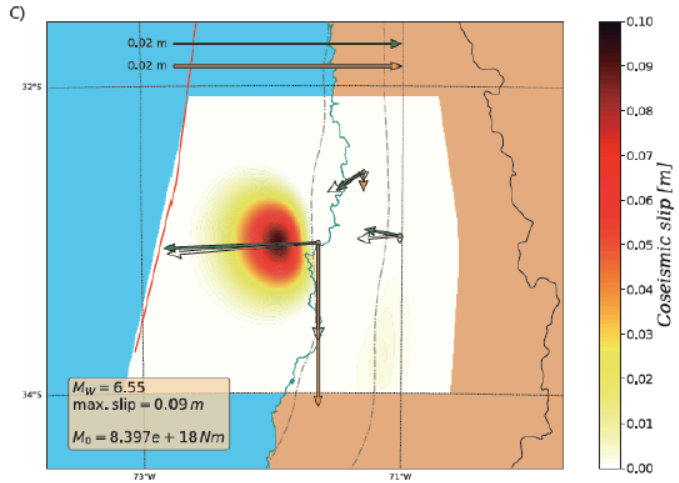


Plenty of Precursors

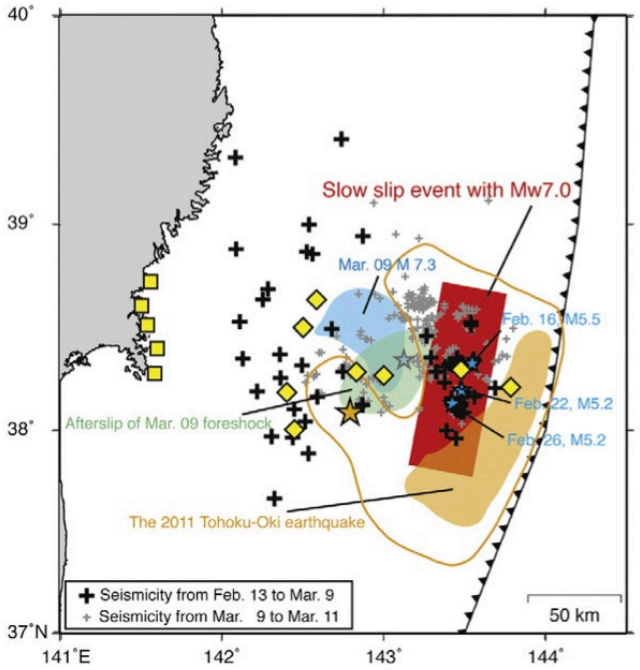
- **P**recursors are common (Brodsky, Page, Panet, Ruiz, Segall)
  - 20-50 % of earthquakes have foreshocks (maybe 75 % in CA, Trugman, Ross et al., unpublished 2019)
  - Increasing number of detections of slow slip precursors (from repeaters, swarms, deformation measurements pre Tohoku, Iquique, Valparaiso etc.)
- **P**lenty of **P**hysical **P**recursory **P**rocesses (with wide range of spatial and temporal scales)
  - Foreshocks, slow slip, fluid flow …
  - Seconds to decades
  - Meters to thousands of kilometers



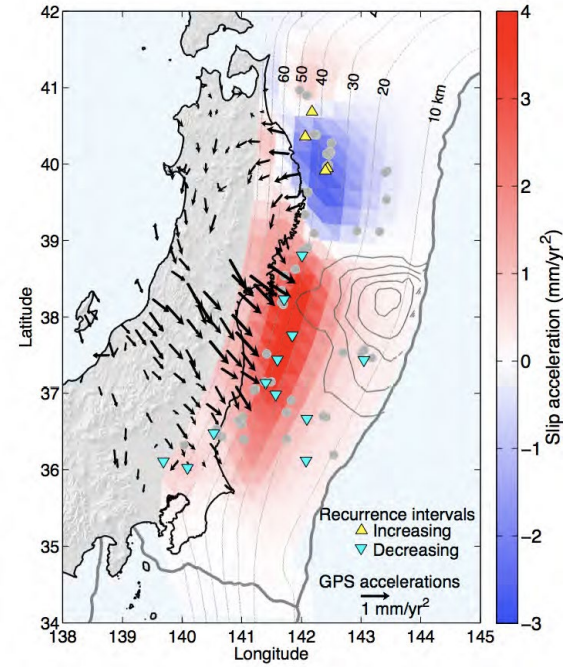
Panet et al., 2018



Ruiz et al., 2017



Ito et al., 2013

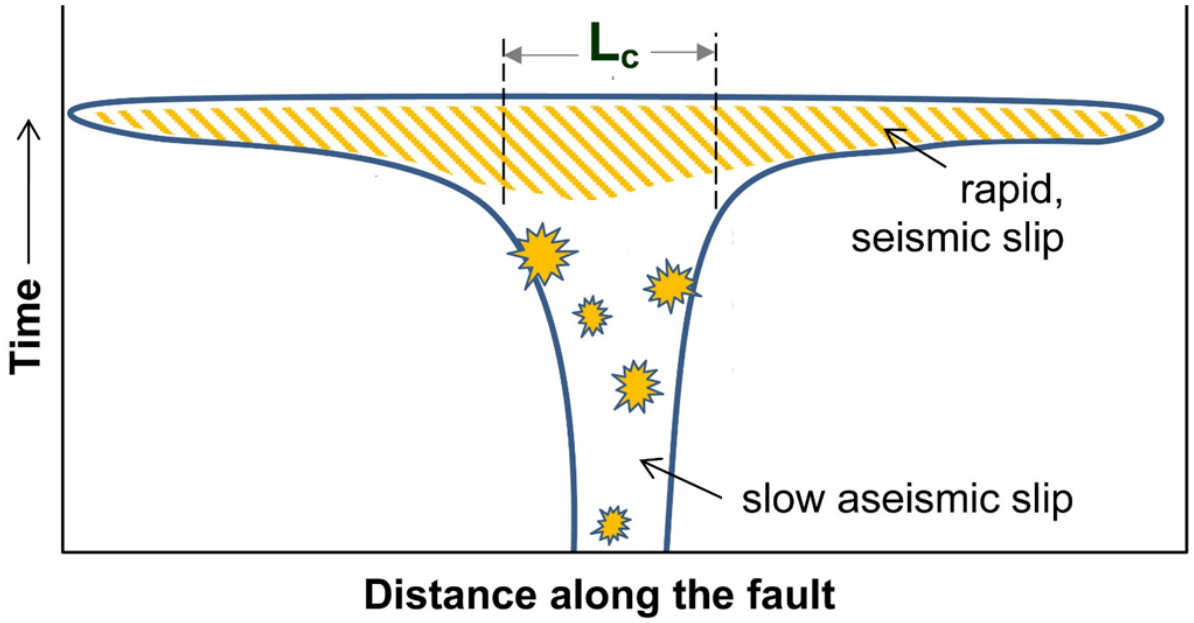


Mavrommatis et al., 2016

Precursors can be Preparation Process, - but can also be simple triggers

"Preslip" model

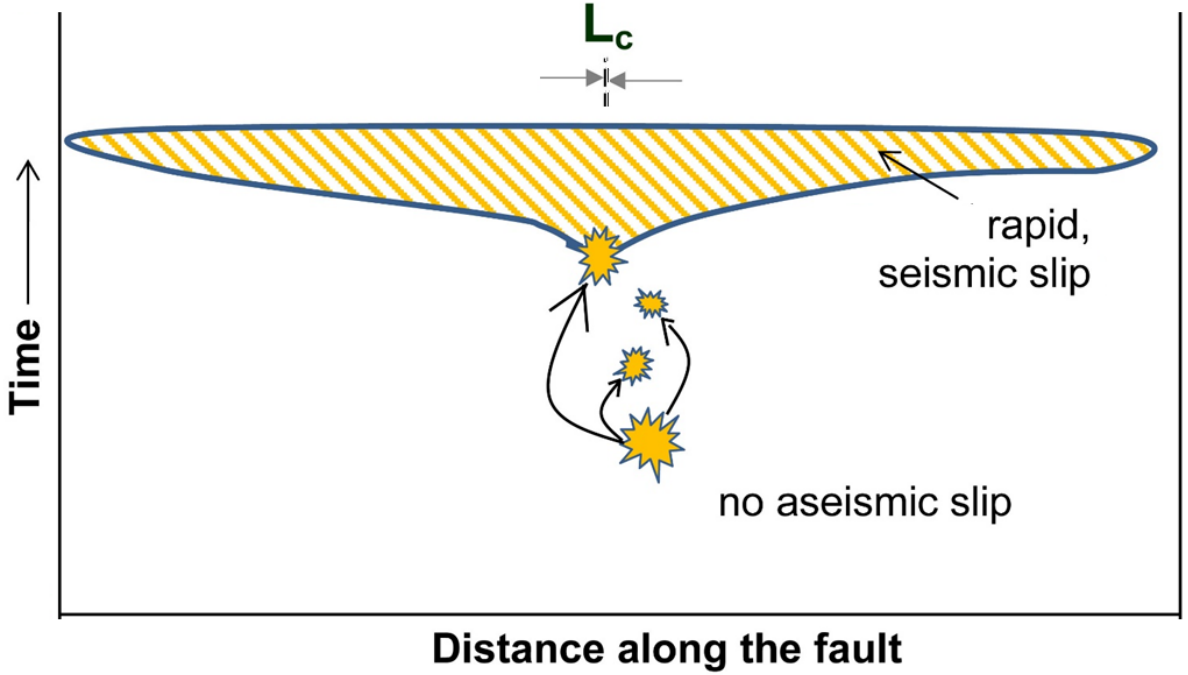
Foreshocks are a **byproduct of a larger nucleation process**



Tohoku 2011, Iquique 2014, Valparaiso 2017, etc.?

"Cascade" model

Foreshocks are regular earthquakes **that happen to trigger a larger event**



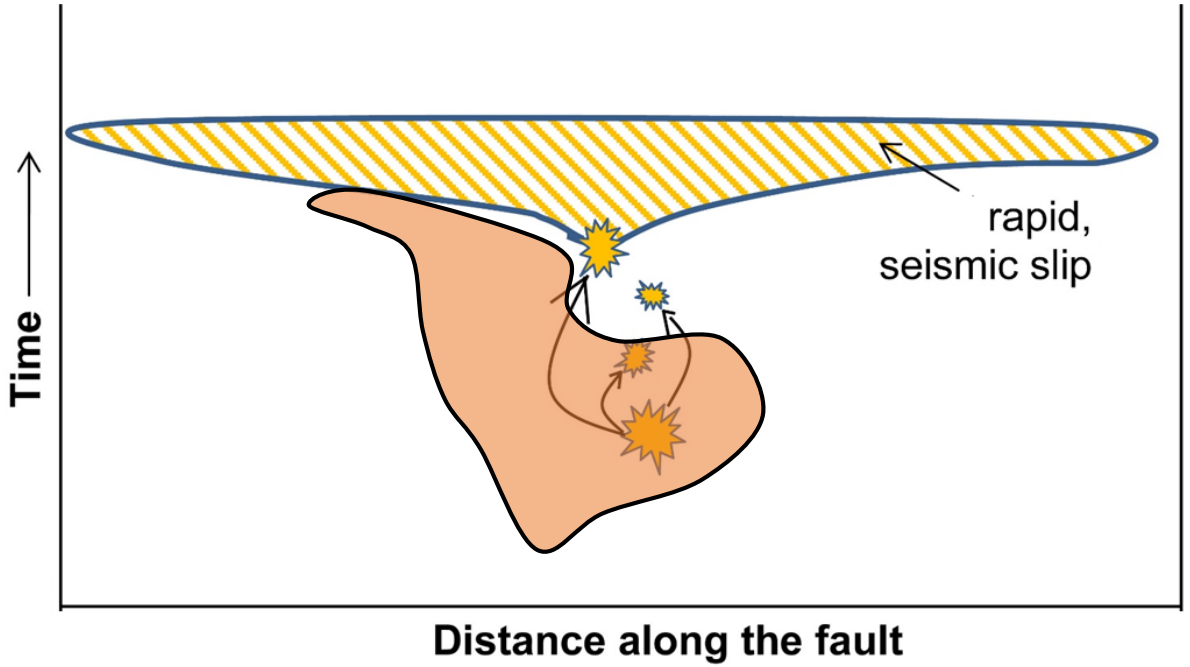
Landers 1992, Hector Mine 1999, EMC 2010, Kumamoto 2016 etc.?

Slide modified from McLaskey, 2019 SSA

Precursors can be **P**reparation **P**rocess, - but can also be simple triggers

"Trigger" model

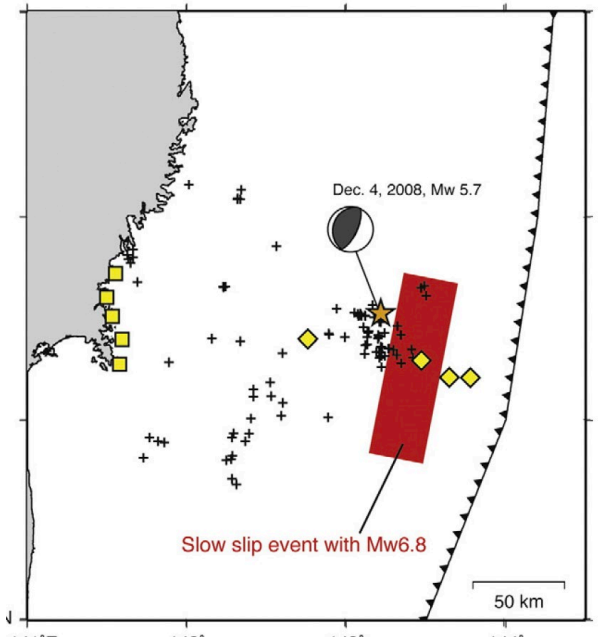
Small and large seismic and aseismic slip episodes can simply **trigger** a larger event

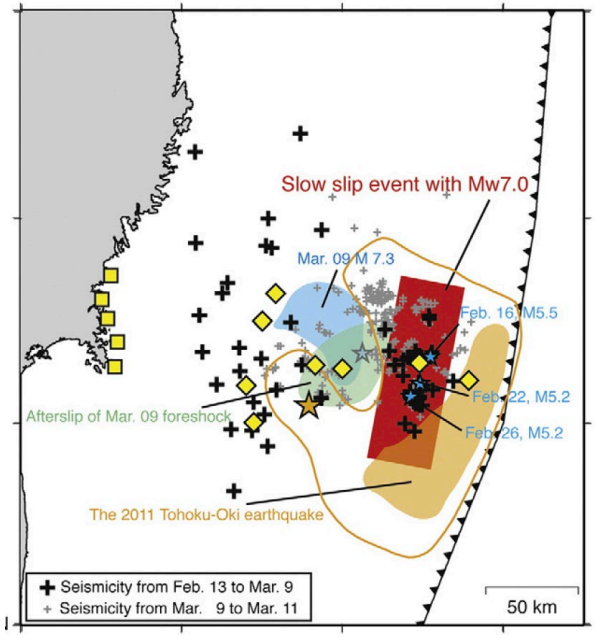


Plenty of Precursor-candidates fail to Precede

- **P**recursor candidates are even more common
- Most slow slip events, earthquake clusters and other deformation transients do not precede mainshocks

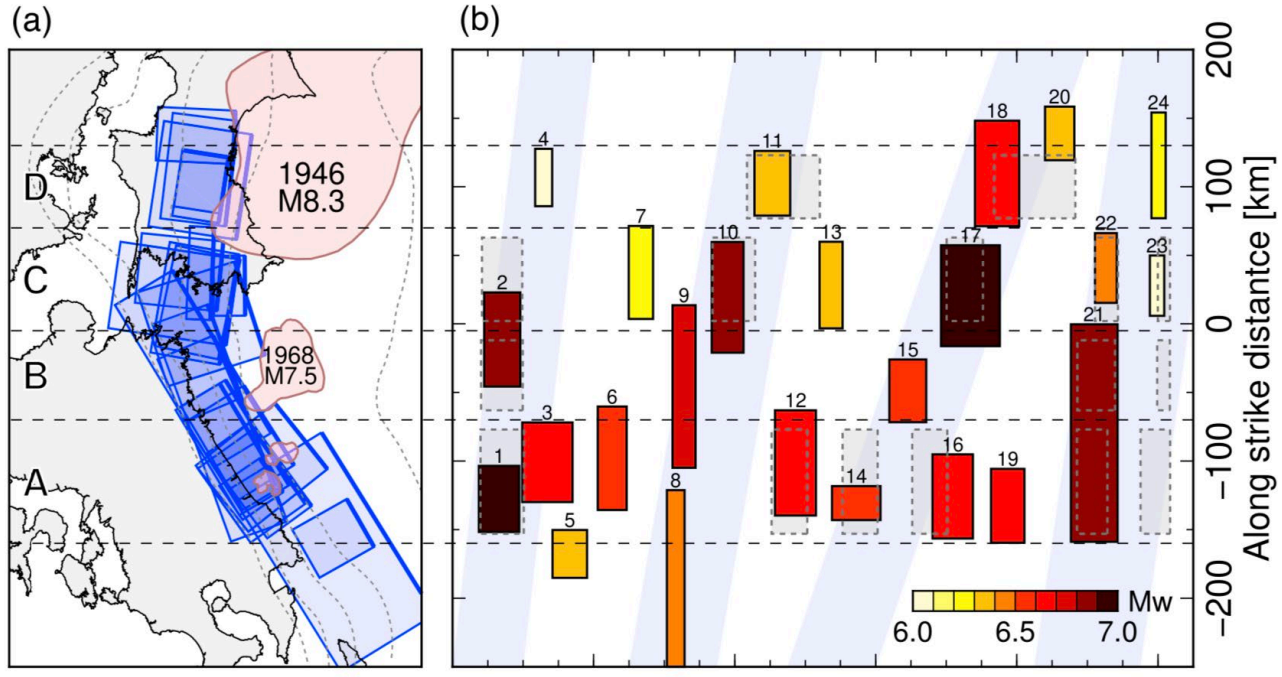
Tohoku-oki





Ito et al., 2013

Western Nankai subduction zone long-term SSEs

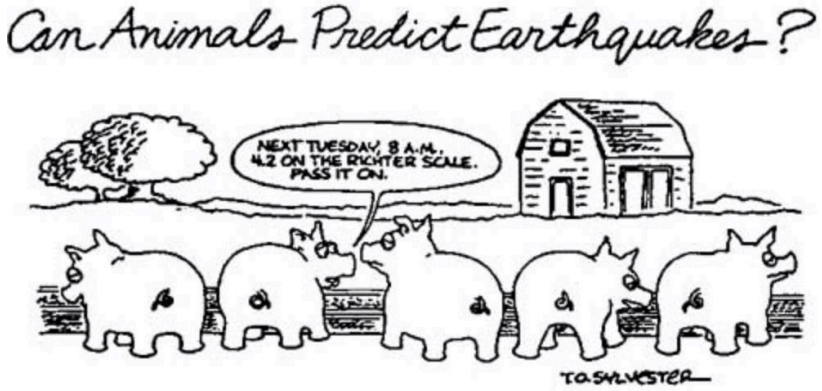


Takagi et al., 2019

Prospects for Prediction are Poor

- "An **earthquake prediction** is a statement that one or more earthquakes of a clearly stated magnitude range will occur within a clearly specified time interval and a clearly specified geographic region." *NEPEC 2016*

- The diversity of processes and scales of known precursors and their non-unique association with mainshock characteristics do not support prediction



Precursor candidates increase Probabilities

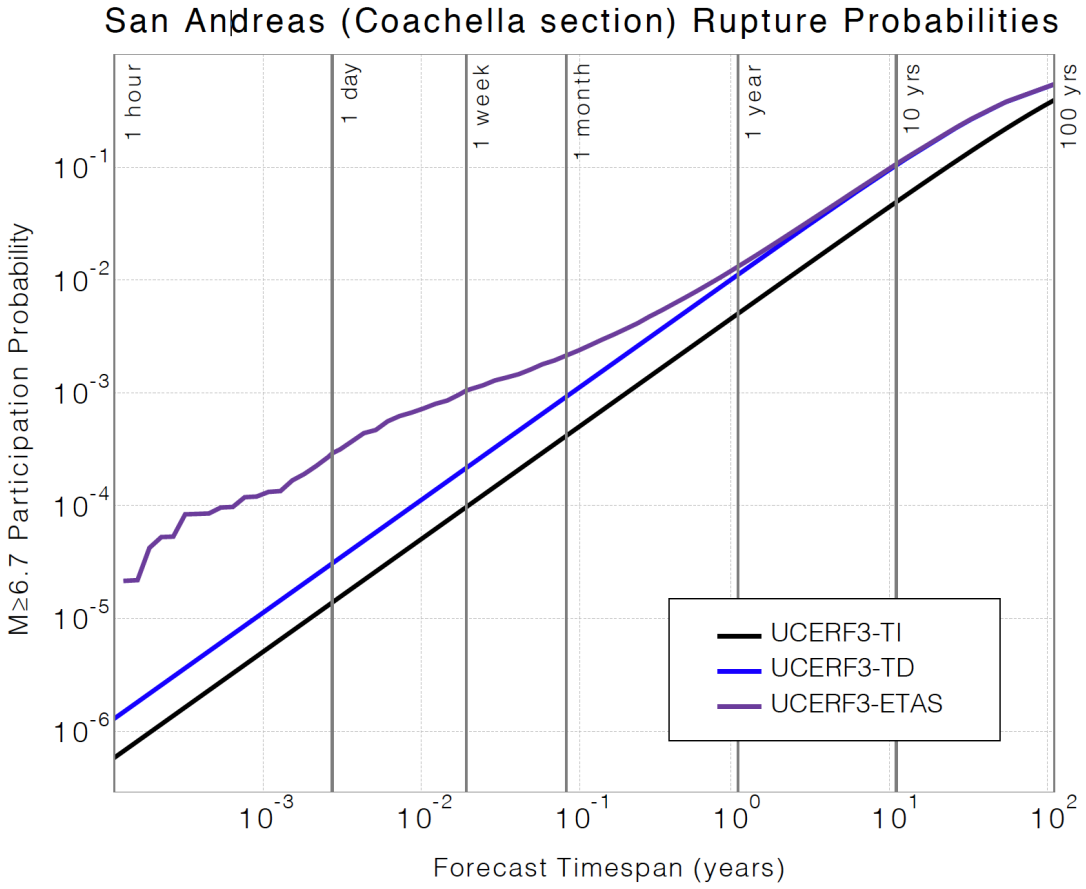
- "An **earthquake forecast is a statement of probabilities** that one or more earthquakes of a clearly specified magnitude range may occur within a clearly specified time interval and a clearly specified geographic region."
  NEPEC 2016

- Earthquakes, slow slip events and other precursor candidates increase earthquake probabilities from "peace-time probabilities" (Page, Wallace)

- Forecast models can incorporate aseismic precursor candidates (Wallace)

- Operational Earthquake Forecasting (OEF) "is an automated process through which earthquake probabilities are being continuously updated and disseminated" *NEPEC 2017*

UCERF3 Forecast following Bombay Swarm



"Changes in seismicity have predictive information about earthquake rate and provide predictive power about the chance of a large earthquake; however, foreshocks are not predictive of earthquake size." Morgan Page

Precursor candidates increase Probabilities

- "An **earthquake forecast is a statement of probabilities** that one or more earthquakes of a clearly specified magnitude range may occur within a clearly specified time interval and a clearly specified geographic region."
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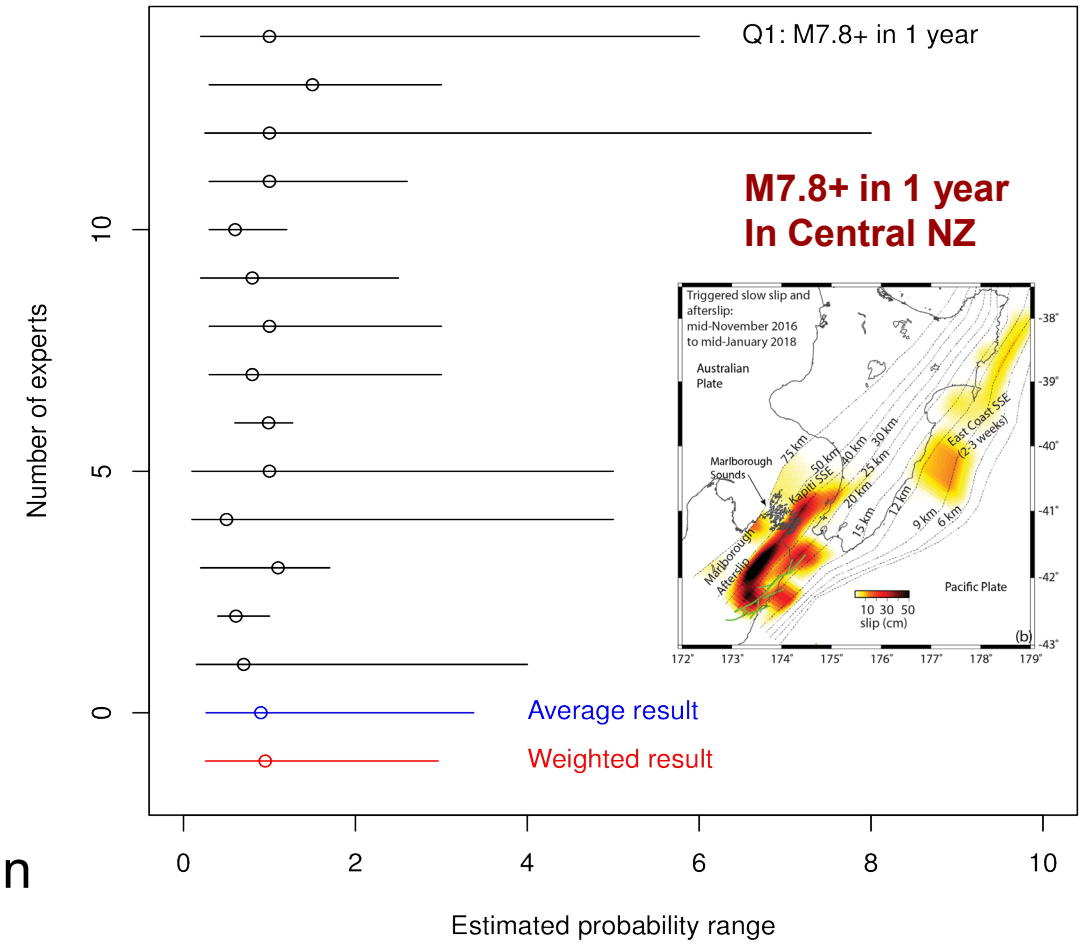
- Earthquakes, slow slip events and other precursor candidates increase earthquake probabilities from "Peace-time Probabilities" (Page, Wallace)

- OEF models can incorporate precursor candidates (Wallace)

- Operational Earthquake Forecasting (OEF) "is an automated process through which earthquake probabilities are being continuously updated and disseminated" *NEPEC 2017*

Enhanced probability considering mainshock AND triggered SSE



"We need to develop OEF models that incorporate transient slip events, and not just make ad hoc decisions" Laura Wallace

NEPEC

The National Earthquake Prediction Evaluation Council (NEPEC) was created in 1980 by legislation reauthorizing the National Earthquake Hazards Reduction Program (NEHRP). The Council provides advice and recommendations to the Director of the U.S. Geological Survey on earthquake predictions and related scientific research. https://earthquake.usgs.gov/aboutus/nepec/

(Jonathan Godt (ex officio), Mike Blanpied (Designated Federal Official), Roland Bürgmann (chair), Gail Atkinson, Cliff Frohlich, Sue Hough, Andy Michael, Kate Scharer, Peter Shearer, John Vidale)

Areas of discussion and reports have included:

- operational earthquake forecasting (OAF & OEF) and communication of forecast information in Cascadia
- proper procedures for posing earthquake predictions and testing earthquake prediction methods
- New Madrid Seismic Zone Earthquake Hazards
- Collaboratory for Study of Earthquake Predictability (CSEP), its relevance for USGS, and potential avenues of future development

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