Foreshocks and Short-Term Earthquake Predictability on East Pacific Rise Transform Faults

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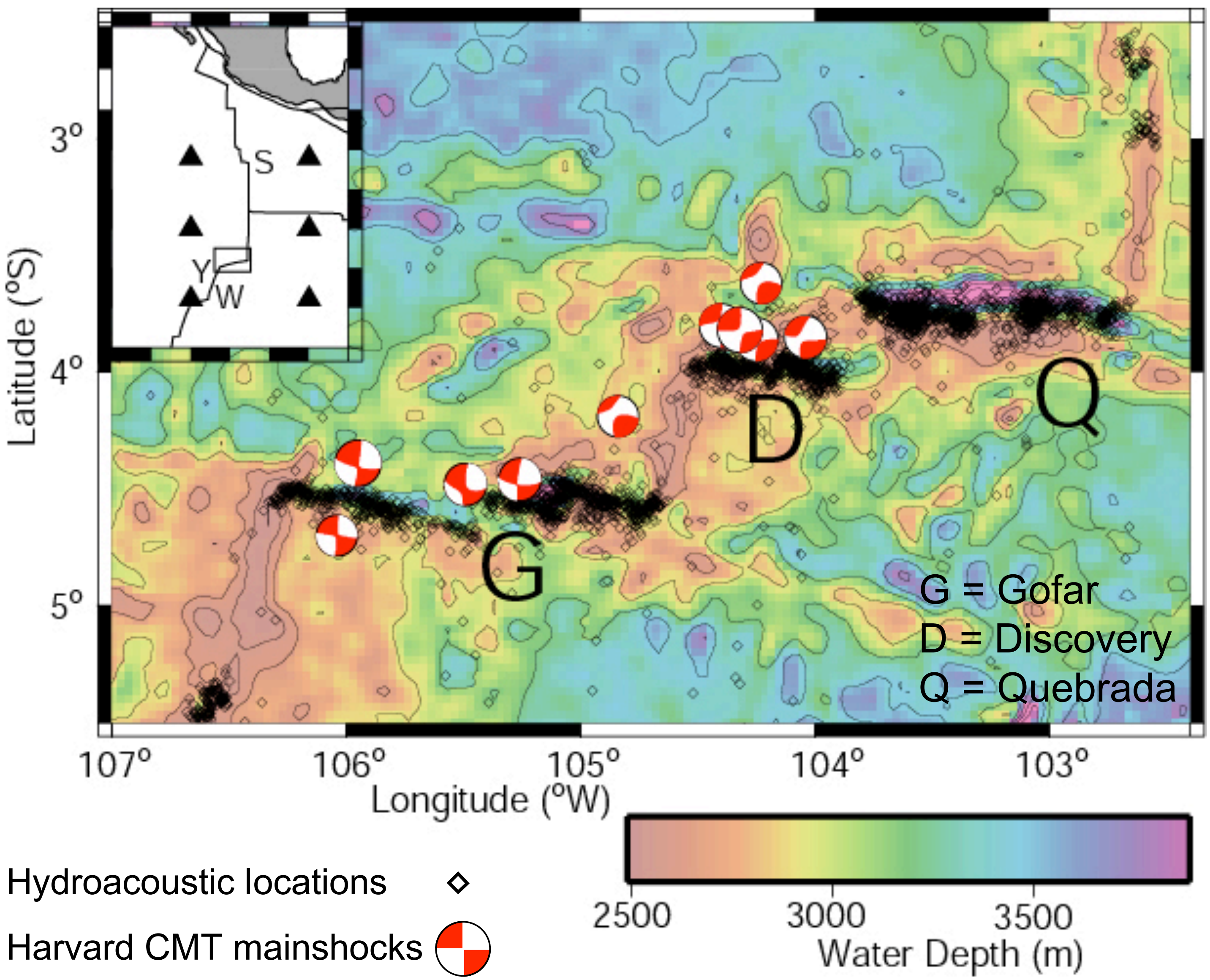
Summary

- Background
  - According to even the simplest models of earthquake triggering (e.g. ETAS), foreshocks should provide significant short-term predictability
  - In practice, however, prediction algorithms based on foreshocks in continental regions have delivered little probability gain
- Observation
  - On mid-ocean ridge transform faults (RTFs), foreshock occurrence rates from hydroacoustic data are anomalously high relative to ETAS

Summary

- Conclusions
  - From a retrospective analysis, we show that even naïve prediction algorithms based on RTF foreshocks can deliver high probability gain factors (100-1000) using small space-time windows (15 km x 1 hr)
  - The mechanism for this predictability appears to be slow transients on RTFs (“quiet” earthquakes) that trigger both foreshocks and mainshocks

GDQ Study Area

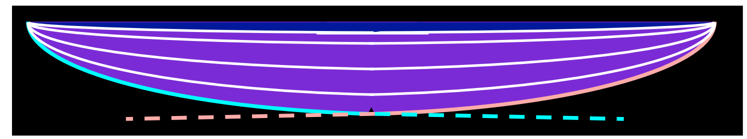


Properties of Mid-Ocean Ridge Transform Faults (RTFs)

- High seismic deficits
  - Brune (1968)
- Slow earthquakes
  - Kanamori & Stewart (1976), Okal & Stewart (1978)
- Compound earthquakes with slow precursors
  - Ihmlé & Jordan (1994), McGuire, Ihmlé & Jordan (1996),
- Multi-fault dynamics
  - Bonatti et al. (1996), McGuire & Jordan (2000)
- Simple (but surprising) scaling relations
  - Boettcher & Jordan (2004)
- Anomalous foreshock activity
  - McGuire, Boettcher & Jordan (2004)

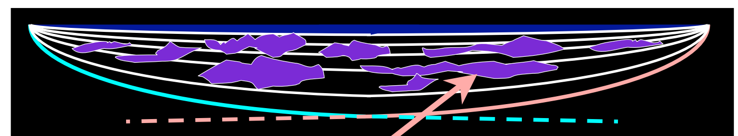
Three Types of RTF Area

Thermal area:



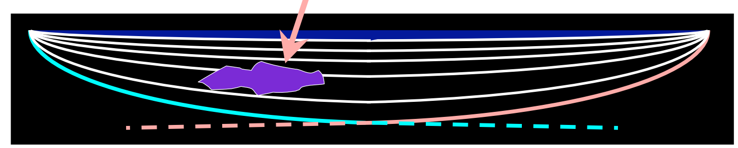
$$A_T \sim L^{3/2} V^{-1/2}$$

Effective area:



$$A_E = \frac{\Sigma M}{\mu V \Delta t}, \text{ where } \Delta t = \text{catalog length}$$

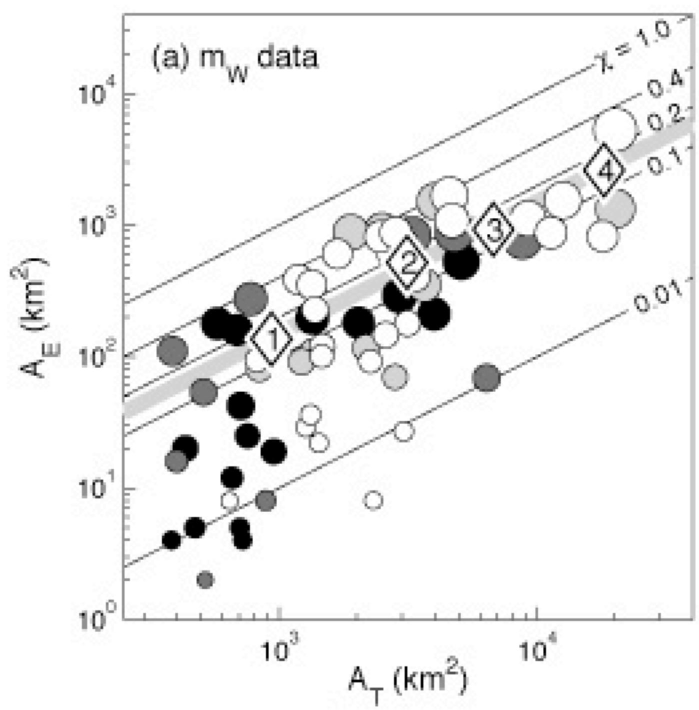
Upper-cutoff area:



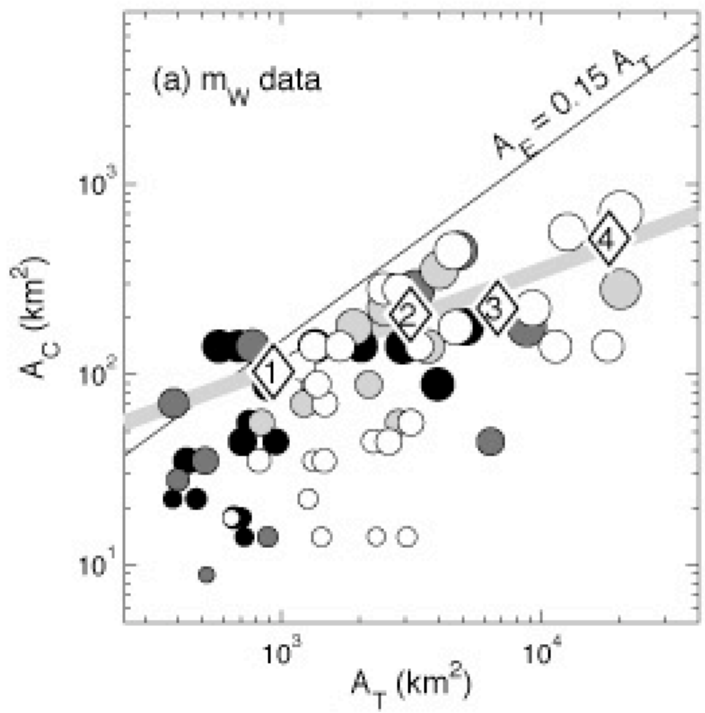
$$A_C = \frac{M_C}{\mu D_C}$$

Scaling Relationships

$A_E \sim A_T$

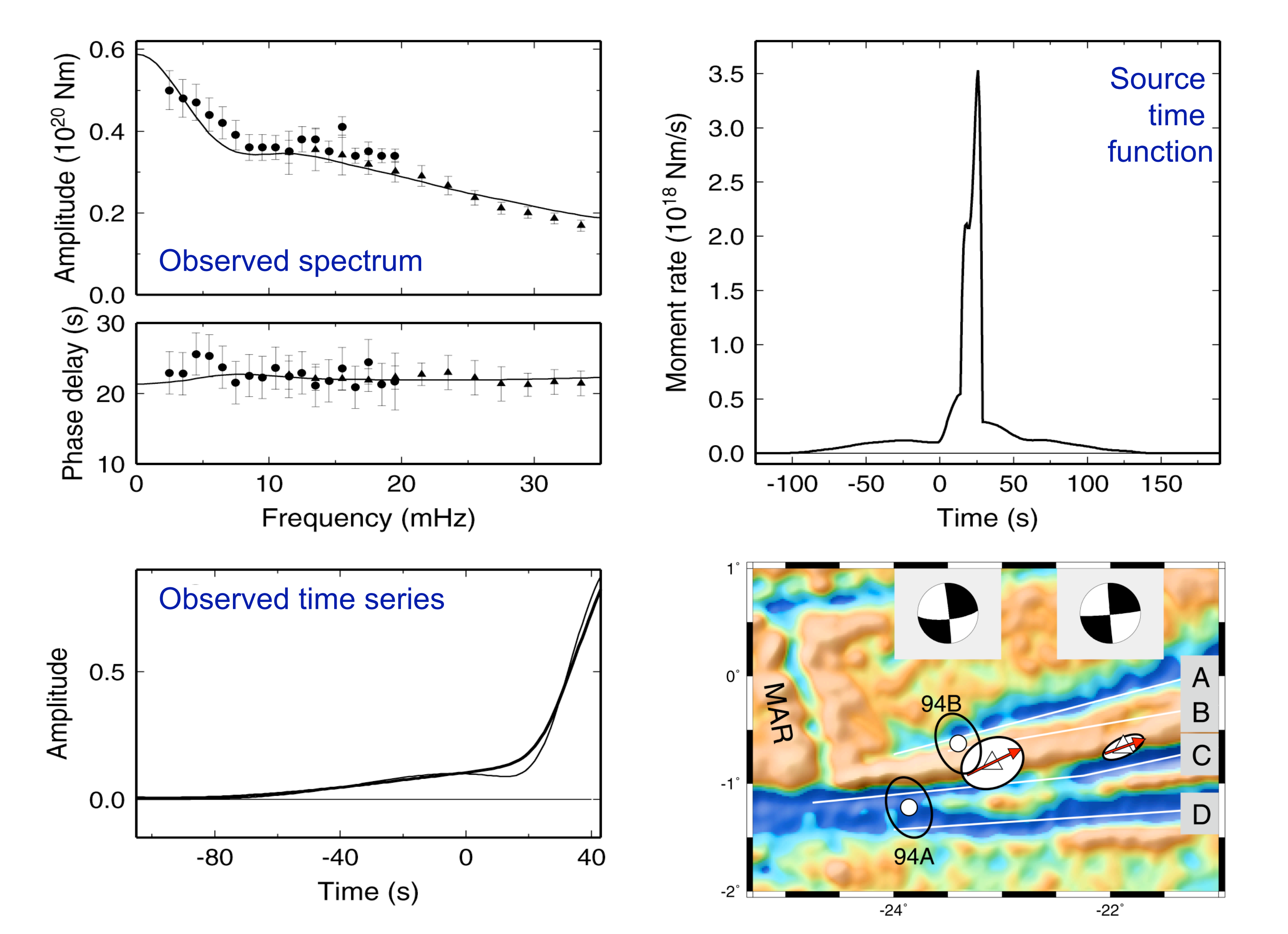


$A_C \sim A_T^{1/2}$



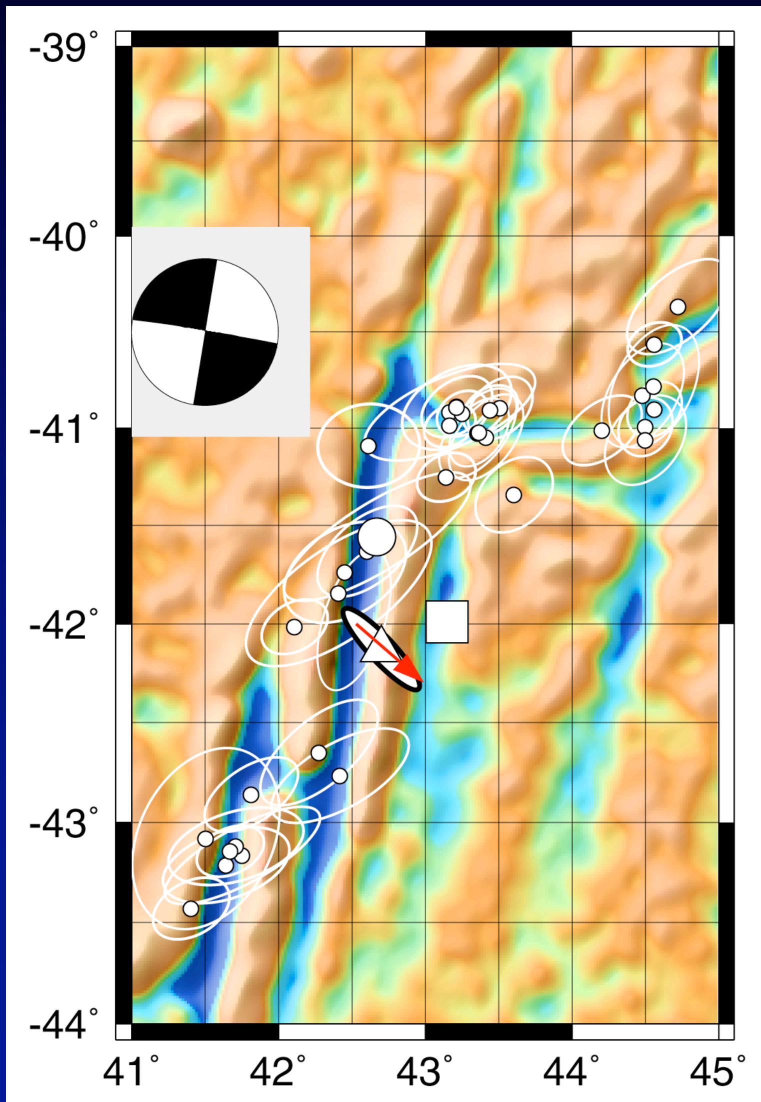
Boettcher & Jordan, *JGR*, in press.

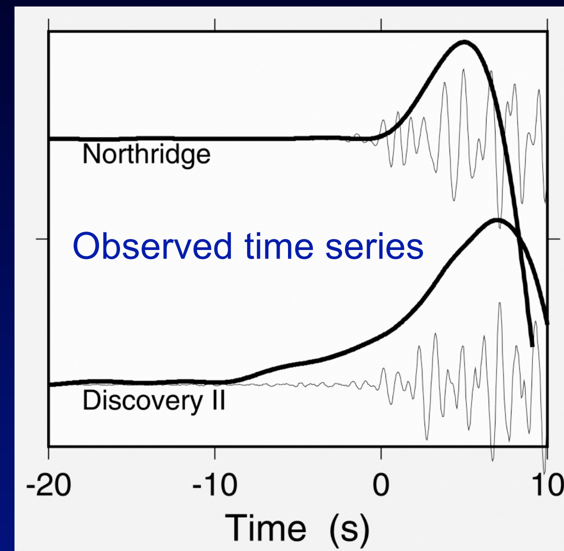
Slow Precursor to 1994 Romanche Earthquake

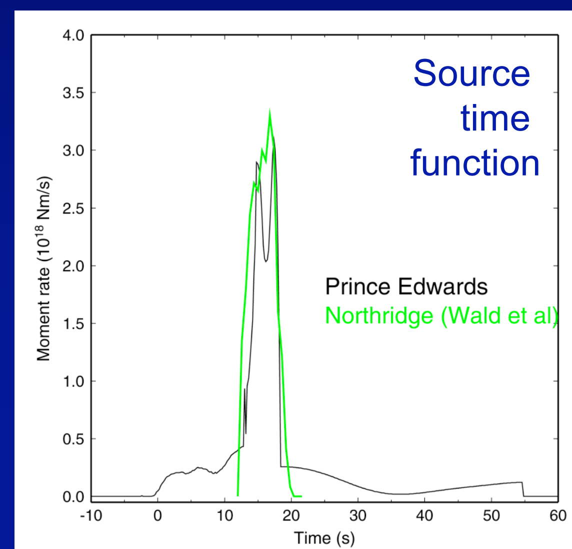


J. J. McGuire, P. F. Ihmlé, and T. H. Jordan, *Science*, **274**, 82-85, 1996.

Slow Precursor to 1997 Prince Edward Is. Earthquake



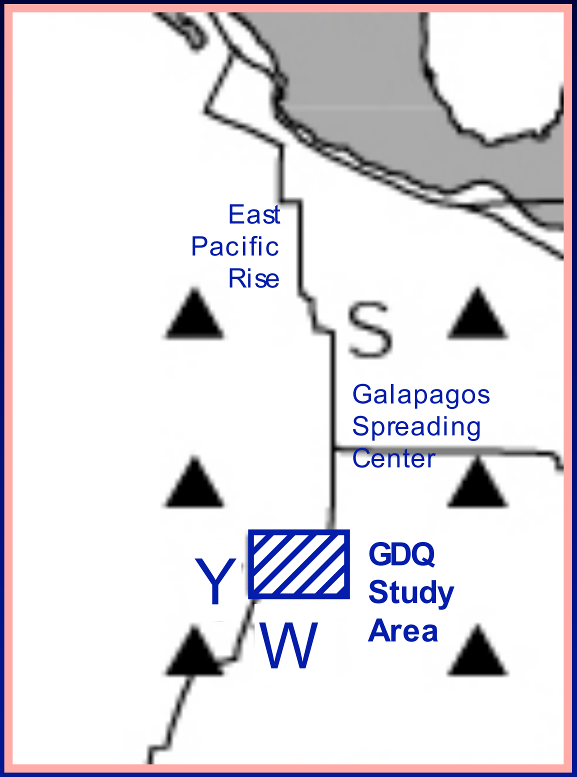




J. J. McGuire & T. H. Jordan, *J. Geophys. Res.*, **105**, 7819-7827, 2000.

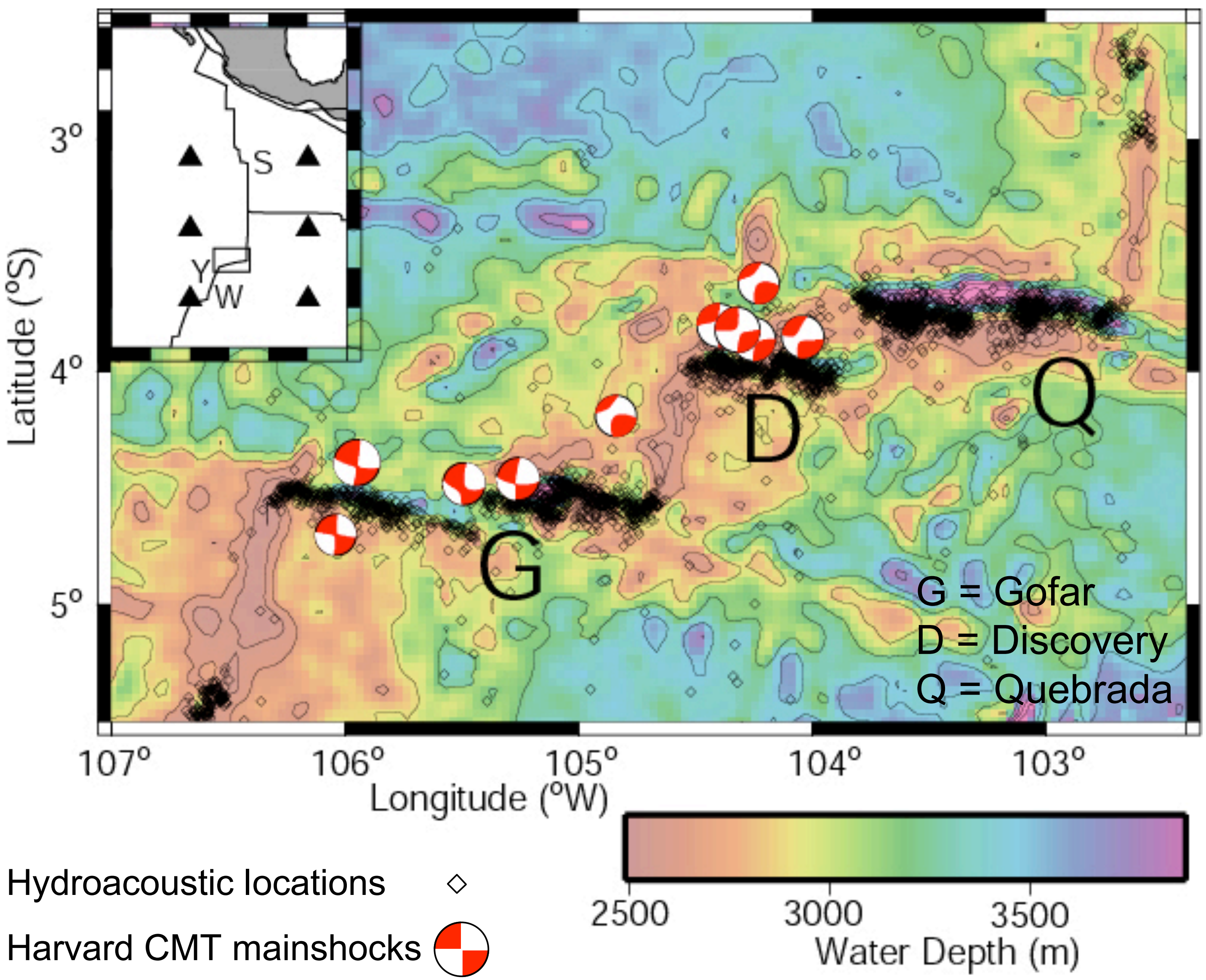
NOAA-PMEL Hydroacoustic Array

- 6-station array deployed by National Oceans and Atmosphere Administration's Pacific Marine Environmental Laboratory (NOAA-PMEL) in 1996
- Data recovered and processed on annual basis
- Event catalog available for 5/96 - 12/01
- Magnitude threshold M_{ASL} > 2.5
  - ASL = acoustic source level (dB)
  - M_{ASL} = 0.107 ASL – 19.6 (ISC m_b calibration)
- Location uncertainties:
  - Orgin time ± 10 s
  - Epicenter ± 2 km



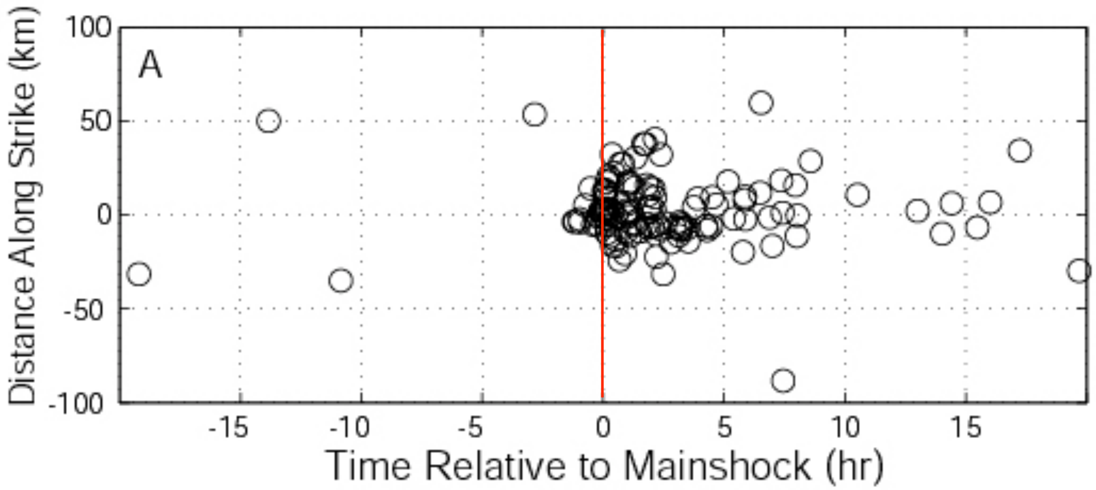
NOAA-PMEL Array on East Pacific Rise

GDQ Study Area

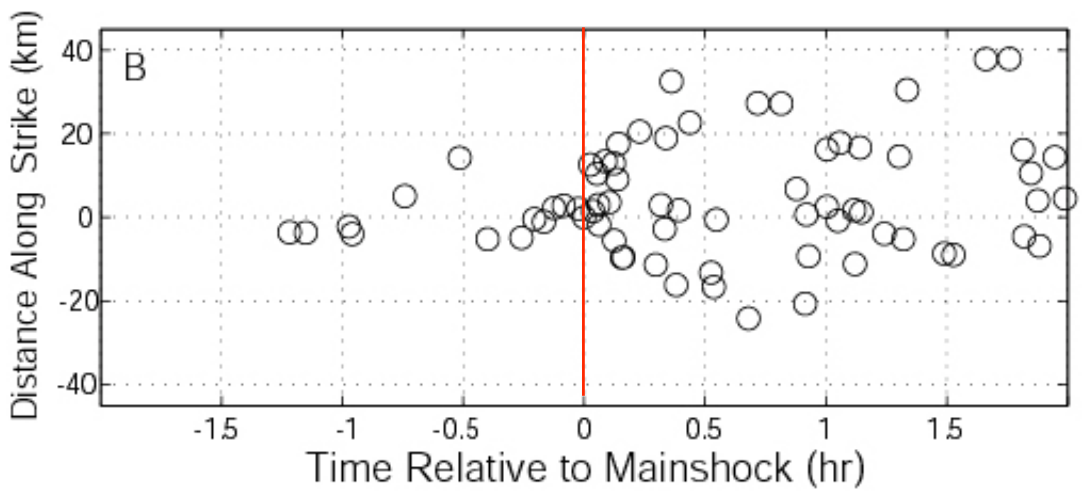


GDQ Seismicity Stacked on Mainshock Origin Times

(9 mainshocks, Mar 1996 - Nov 2001)

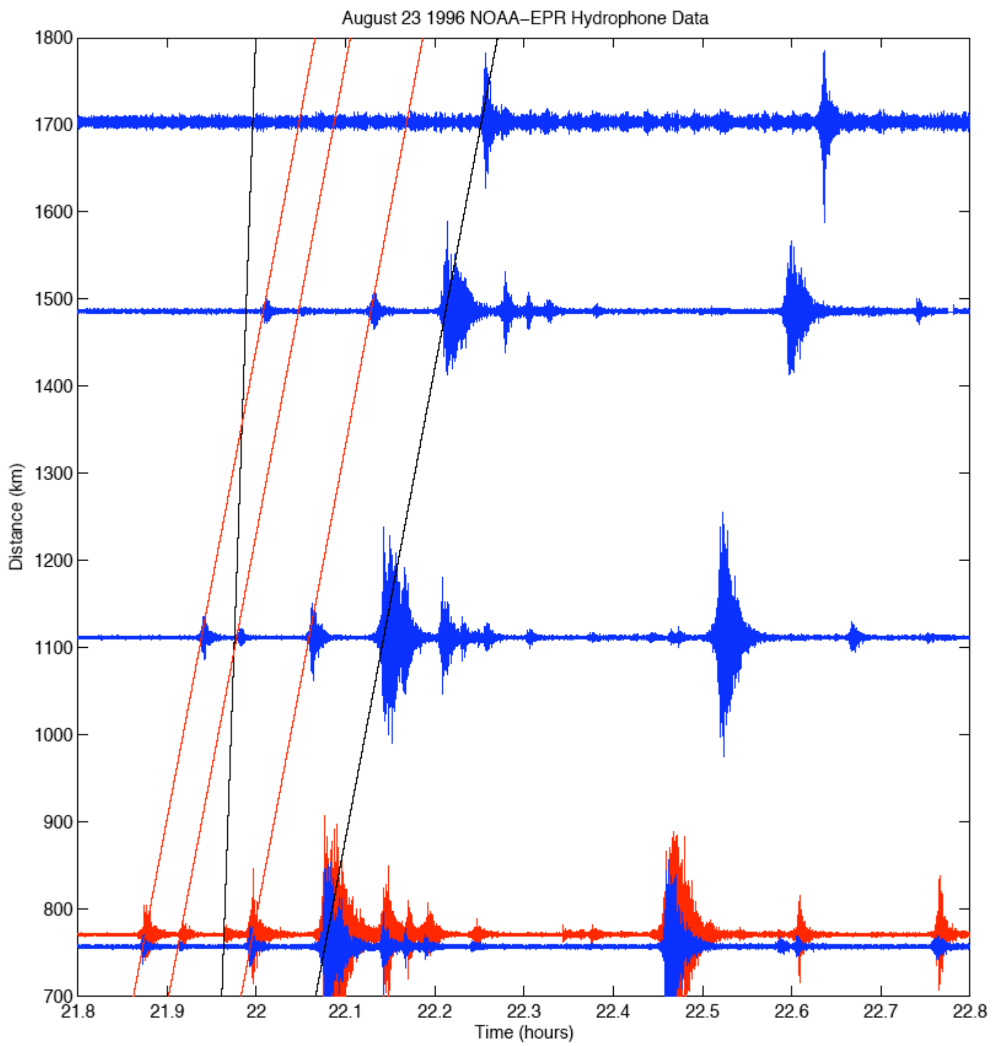


± 20 hr



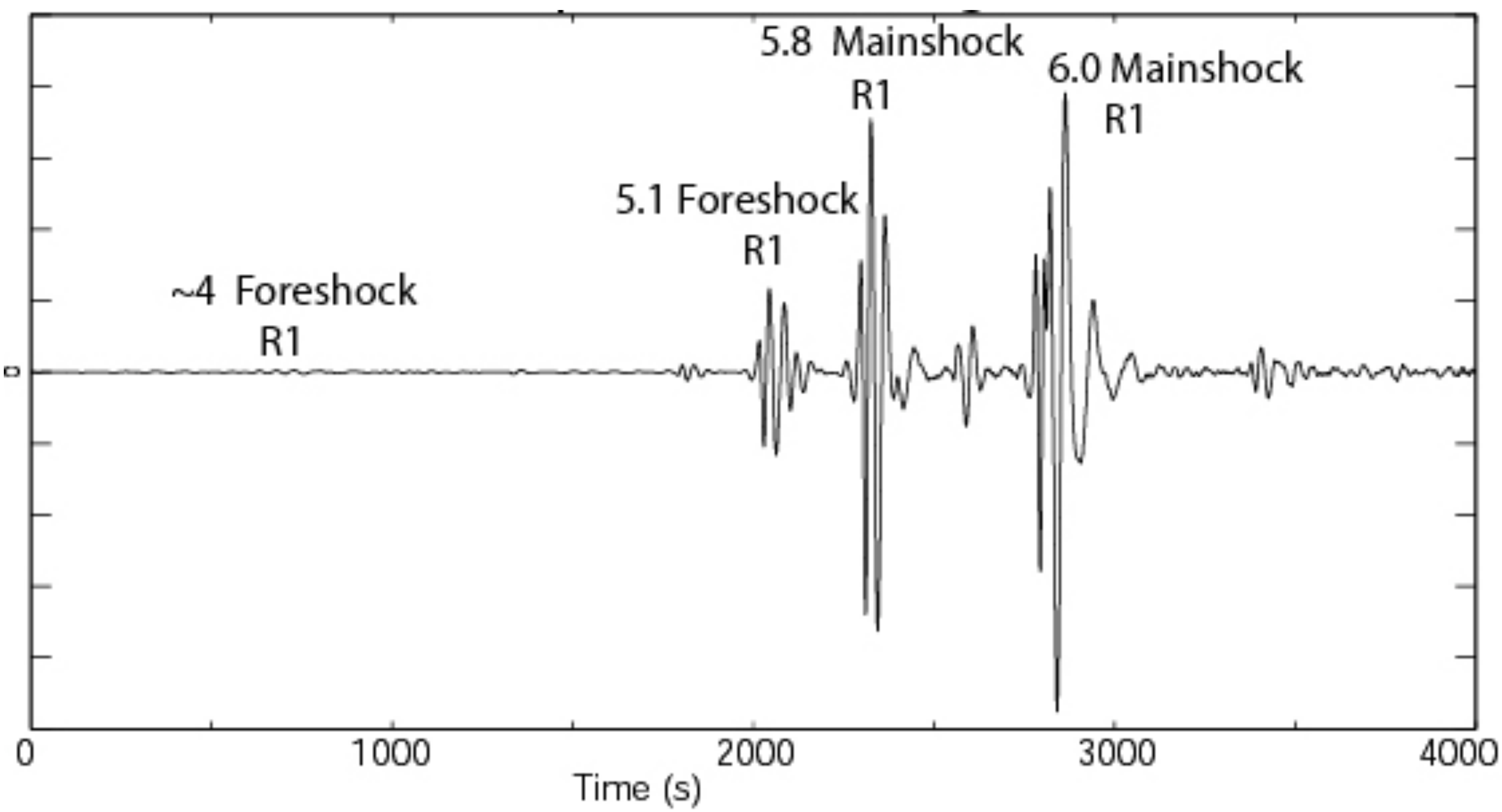
± 2 hr

Earthquake Clustering on EPR Faults



NOAA-PMEL Array, Aug 23, 1996

Earthquake Clustering on EPR Faults



PAGY-Z Seismogram, 17 June 2002

Null Hypothesis

Epidemic Type Aftershock Sequence (ETAS) model:

Clustering of foreshocks, mainshocks, and aftershocks on RTFs can be described by the same seismic triggering mechanism

- Y. Ogata, *J. Am. Stat. Assoc.* **83**, 9 (1988)
- Helmstetter, D. Sornette, *J. Geophys. Res.* **107**, 10.1029/2001JB001580 (2002)
- K. Felzer, R. E. Abercrombie, G. Ekstrom, *Bull. Seism. Soc. Am.* **94** (2004)

Epidemic Type Aftershock Sequence (ETAS) Model

1. All earthquake magnitudes above a lower cutoff m_0 are independent samples of the Gutenberg-Richter probability distribution,

$$P(m) = 10^{-b(m-m_0)}$$

2. All earthquakes give birth to daughter events at an average rate

$$\phi(m,t) = \rho(m)\ \psi(t)$$

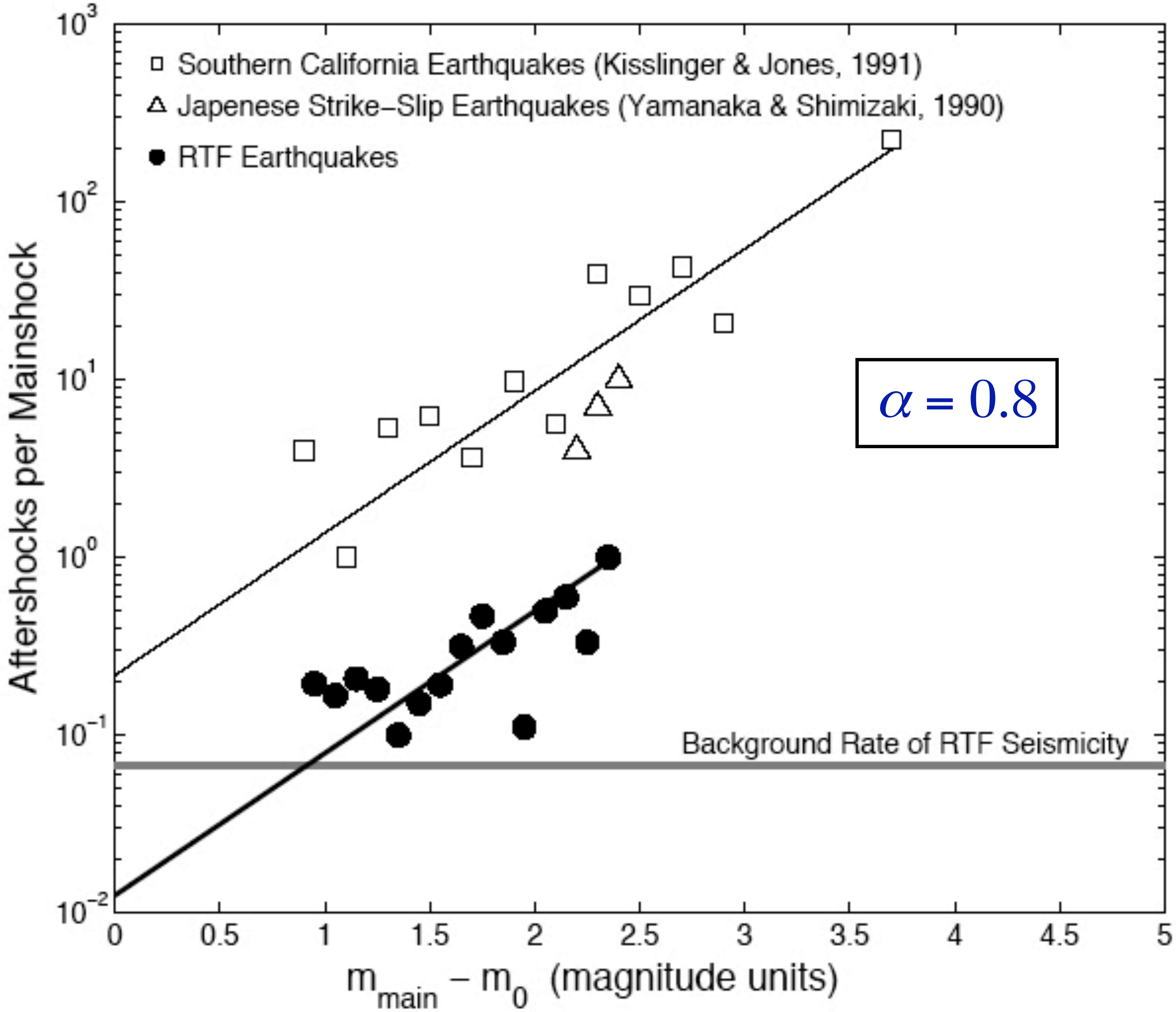
3. This triggering rate is assumed to increase exponentially with magnitude,

$$\rho(m) = k\ 10^{\alpha(m-m_0)}$$

4. and to decay with time after a mother event according to the modified Omori law,

$$\psi(t) = \theta\, c^{\theta} / (c+t)^{1+\theta}$$

Aftershock Statistics



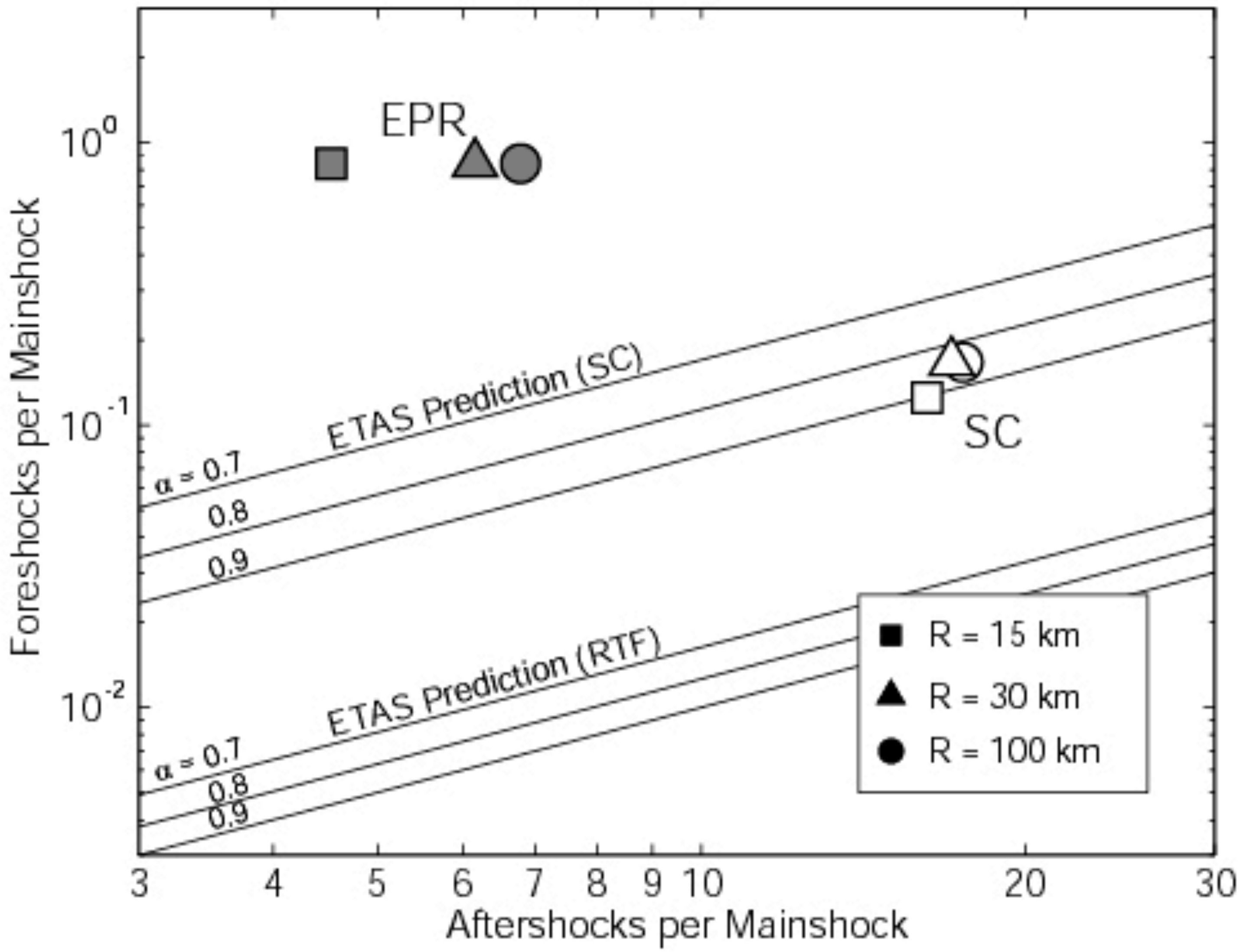
Epidemic Type Aftershock Sequence (ETAS) Model

An appropriate analysis of the ETAS model yields the foreshock/aftershock ratio,

$$\frac{N_{\mathrm{f}}}{N_{\mathrm{a}}} \approx n\left(\frac{b}{b-\alpha}\right)\left[\frac{10^{(b-\alpha)\Delta m_{\mathrm{f}}}-1}{10^{b\Delta m_{\mathrm{a}}}-1}\right]$$

where we count events in the magnitude range $(m_{\mathrm{main}}, m_{\mathrm{main}} - \Delta m_{\mathrm{a,f}})$.

Foreshock/Aftershock Statistics



Conclusions

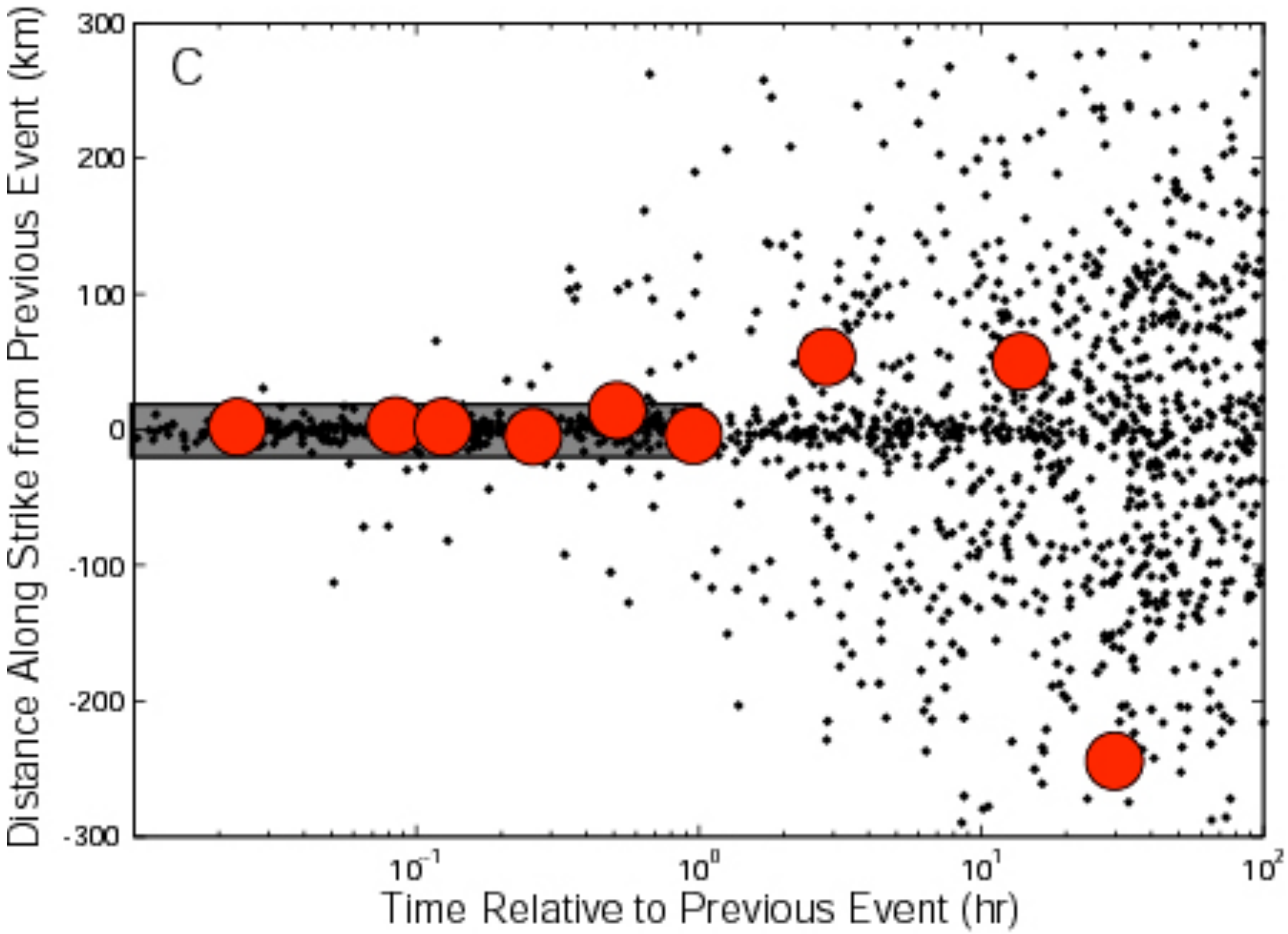
- Foreshock rates from the NOAA-PMEL catalogs are more than two orders of magnitude greater than the ETAS predictions
  - Results are robust with respect to the choice of windows and declustering procedures.
- ETAS hypothesis can be rejected
  - Clustering of foreshocks, mainshocks, and aftershocks on RTFs cannot be described by the same seismic triggering mechanism
- Alternate hypothesis: large earthquakes on EPR faults are preceded by an extended preparation process driven by subseismic transients (silent and quiet earthquakes) that can often be observed through foreshocks
  - Consistent with the localized distribution of the foreshocks about the mainshock in both space and time, which does not conform to the inverse-diffusive behavior expected from the ETAS model

Naïve Prediction Algorithm for Ridge Transform Faults

- The high rate of proximate foreshocks suggests a naïve scheme for short-term earthquake prediction:
  - We simply assume *every* event is a foreshock of an impending large earthquake.
- Formalization into a 4-parameter prediction algorithm:
  - For every RTF event with $m \geq m_0$, we issue an alert that an earthquake $m \geq m_P$ will occur sometime during time window of length t_P immediately following the event and somewhere in a spatial window of radius r_P about the event's epicenter.

Results for GDQ Transform Faults

m_0 = 2.5 (M_{ASL}), m_P = 5.4 (M_W), t_P = 1 hr, r_P = 15 km

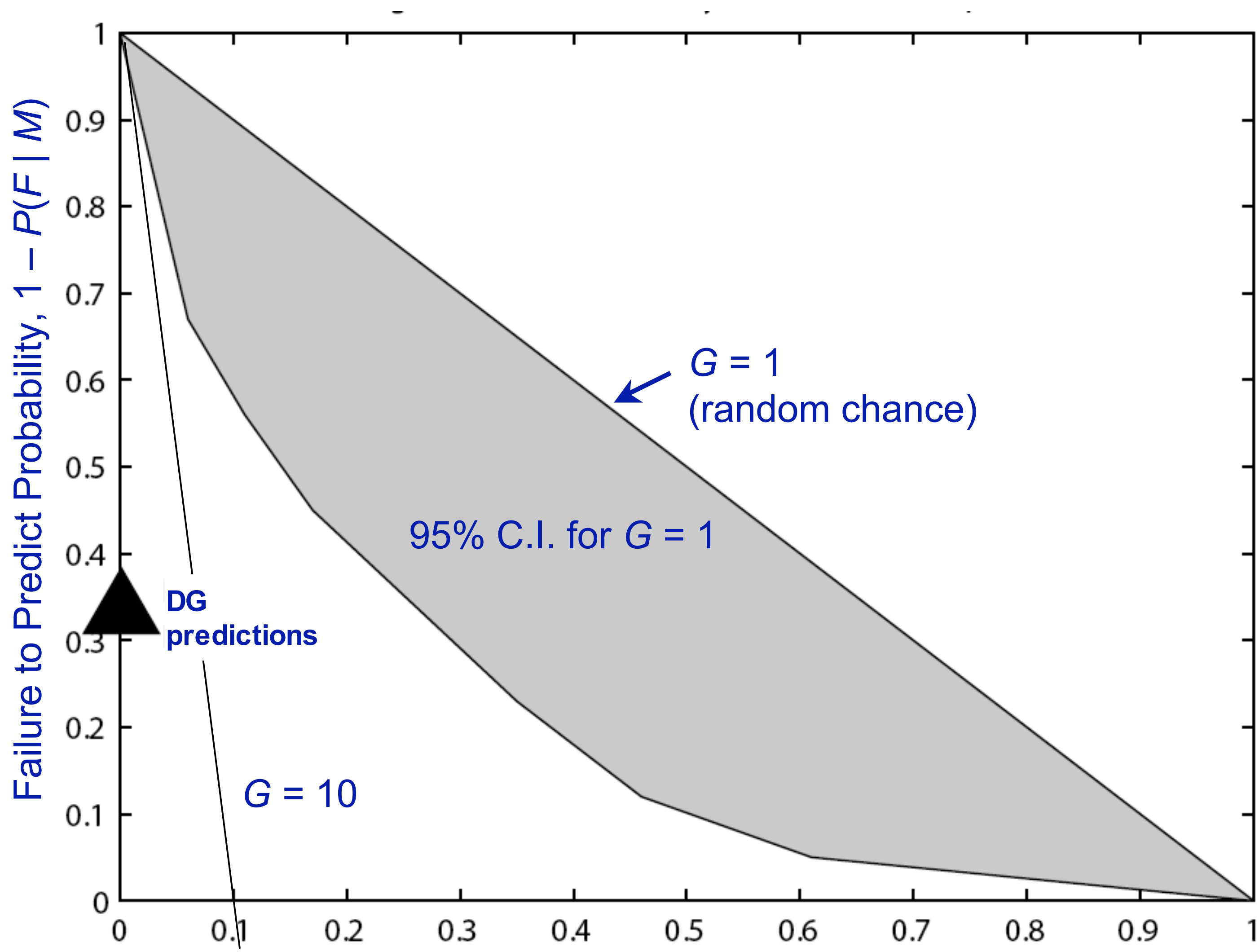


Retrospective Performance of the Naïve Prediction Algorithm

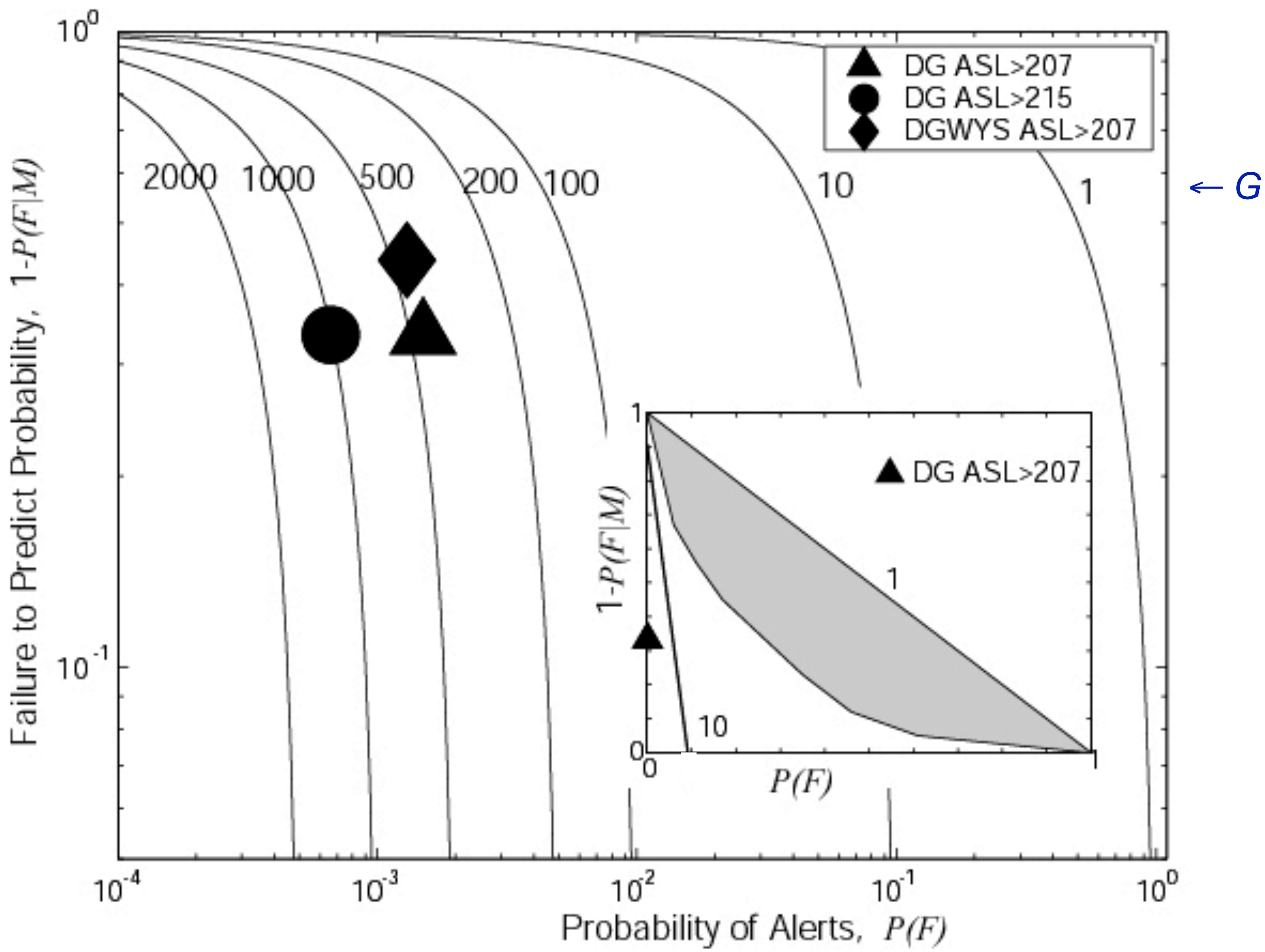
- Algorithm: m_0 = 2.5 (M_{ASL}), m_P = 5.4 (M_W), t_P = 1 hr, r_P = 15 km
- For the GD catalog (5/96-11/01, 9 mainshocks):
  - 6 successful predictions (66%)
  - 3 failures-to-predict (33%)
  - ~1400 false alarms
  - Alarms occupy 0.15% of space-time volume
  - g = 450
- Increasing m_0 to 3.4 (M_{ASL}) improves performance:
  - ~400 false alarms
  - Alarms occupy 0.04% of space-time volume
  - g = 1500
- Further optimization is clearly possible!

Molchan's Error Diagram

$P(M \mid F) = G\,P(M)$, where $G = P(F \mid M) / P(F)$ is the probability gain



Molchan's Error Diagram



Conclusions

- Mid-ocean ridge transform faults have many properties that are distinct from continental transform faults: most plate motion is accommodated aseismically, many large earthquakes are slow events enriched in low-frequency radiation, and the seismicity shows depleted aftershock sequences and high foreshock activity.
- Because of the high ratio of foreshocks to aftershocks, RTF earthquakes cannot be explained by standard point-process models of seismic triggering, in which there is no fundamental distinction between foreshocks, mainshocks, and aftershocks.
- A retrospective analysis of the post-1996 NOAA-PMEL hydroacoustic seismicity catalogs demonstrates that foreshock sequences on East Pacific Rise transform faults can be used to achieve statistically significant short-term prediction of large earthquakes (magnitude ≥ 5.4) with good spatial (15-km) and temporal (1-hr) resolution.
- The predictability of EPR transform earthquakes is consistent with a model in which slow slip transients trigger earthquakes, enrich their low-frequency radiation, and accommodate some of the subseismic plate motion.

End