Real-Time GPS for Real-time Science

Rapid Magnitude Estimation from GPS Displacement

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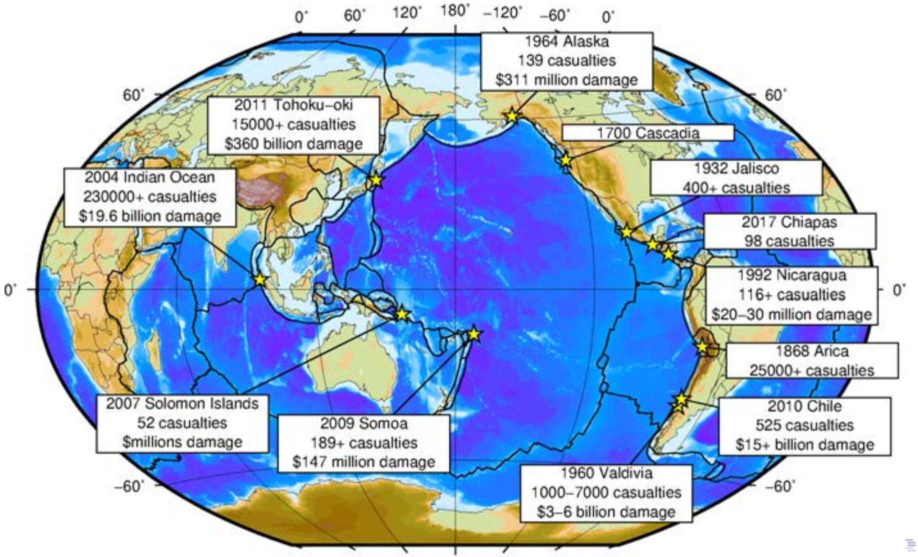
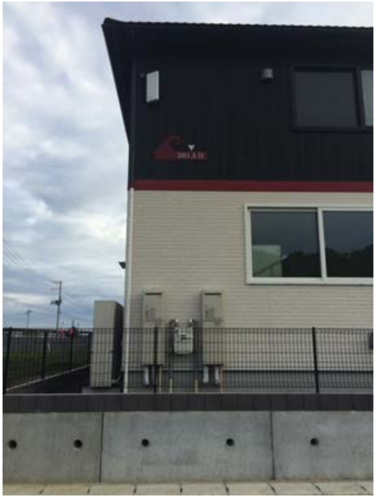
Motivation: Tsunami Warning



Goals of Local Tsunami Warning

- Locate
- Identify size
- Identify mechanism
- Initiate evacuation



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- Locate
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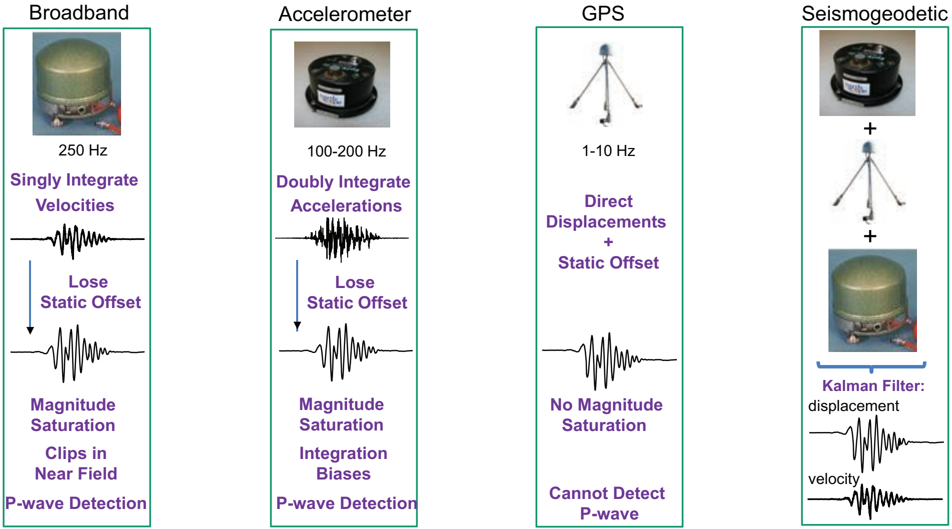
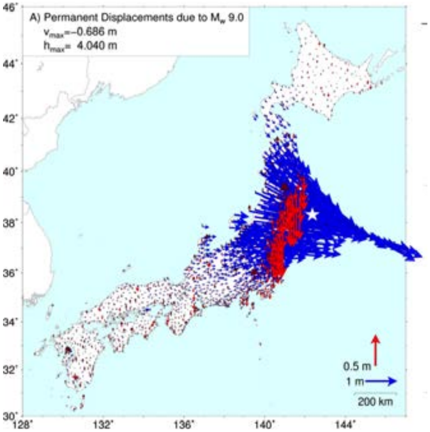
Why is constraining the magnitude so difficult in real-time?

Instrumentation



The Utility of GPS for Magnitude Estimation

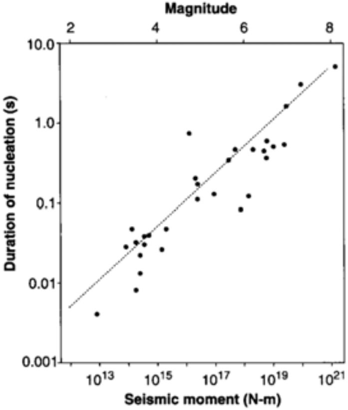
- Direct measurement of displacement
- Static offset scales with magnitude
- Peak displacement scales with magnitude
- Results in a few minutes
- Not fully utilized for early warning



Grapenthin and Freymueller, 2011

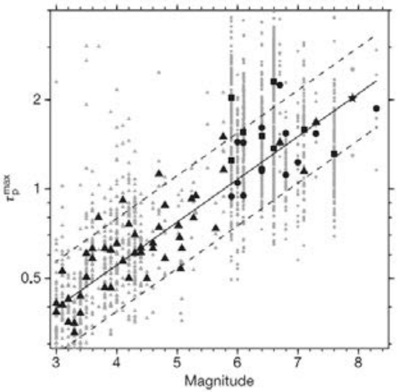
How Early Can we Estimate Magnitude?

Nucleation Duration:



Ellsworth and Beroza, 1995

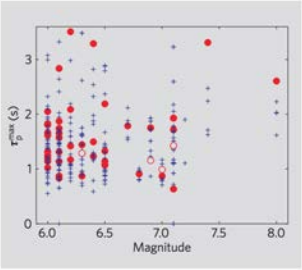
Maximum P-wave Period:



Olsen and Allen, 2005

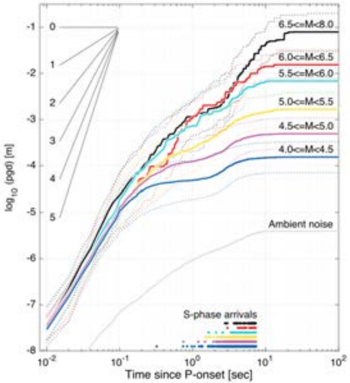
How Early Can we Estimate Magnitude?

Maximum P-wave Period:



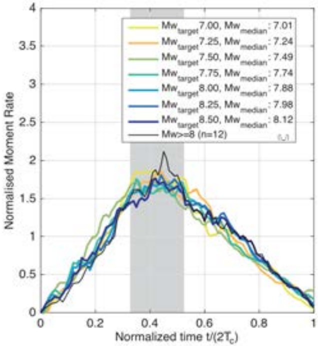
Rydelek and Horiuchi, 2006

Maximum Displacement:



Meier et al., 2016

Moment Rate Function:



Meier et al., 2017

How Early Can we Estimate Magnitude?

Instrumentation

Need broadband instrumentation capable of identifying first seismic wave arrivals and accurately measuring displacements.

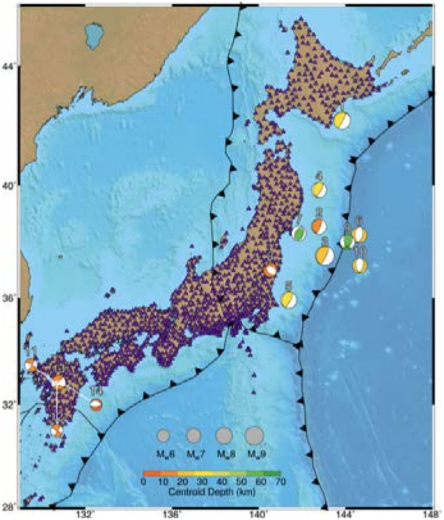
Magnitude Estimation

Identify earliest reliable metric for magnitude scaling.

Rupture Evolution

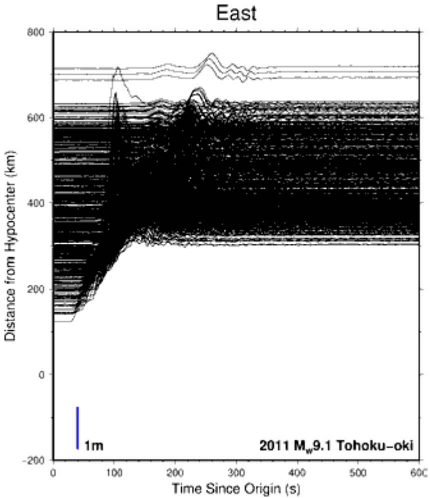
If earliest metric is available prior to rupture completion (deterministic), what is the physical basis?

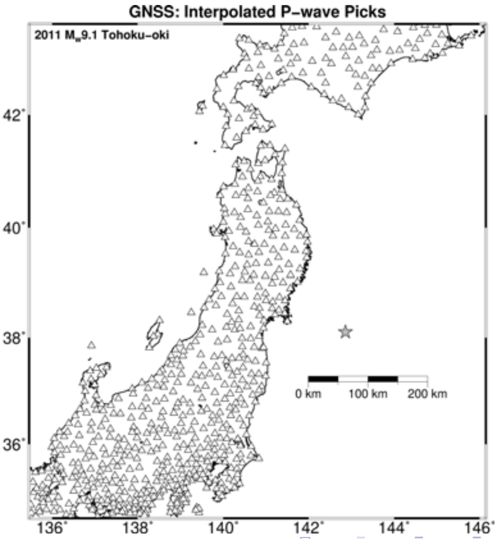
Dataset



- 14 earthquakes
- $5.7 \leq M_w \leq 9.1$
- 1200+ GNSS Stations (GEONET)
- 1700+ Strong-Motion Sites (KiK-net/ K-NET)
- Triggered strong-motion stations, occasionally late
- Too few collocated sites to complete study with true seismogeodesy

Dataset: Simulating Seismogeodesy





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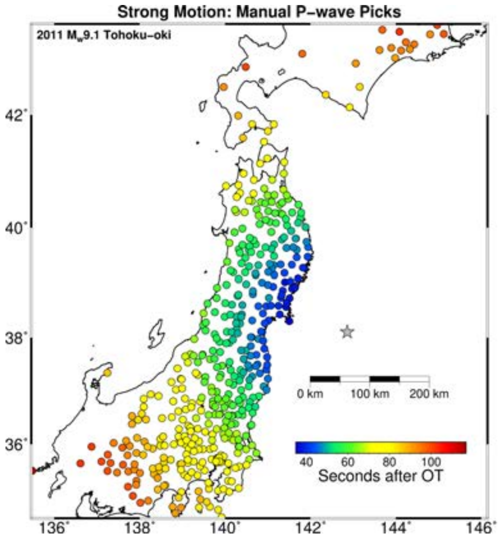

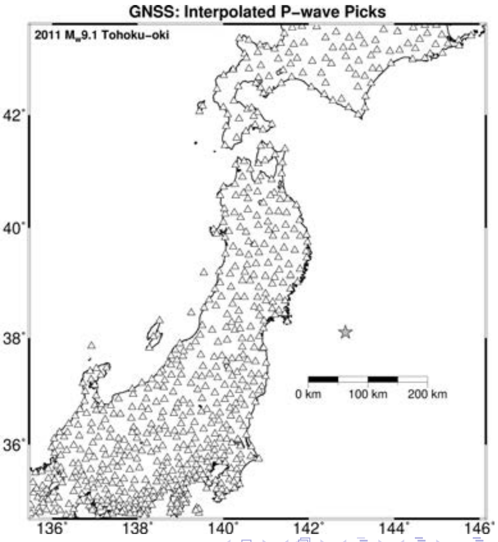

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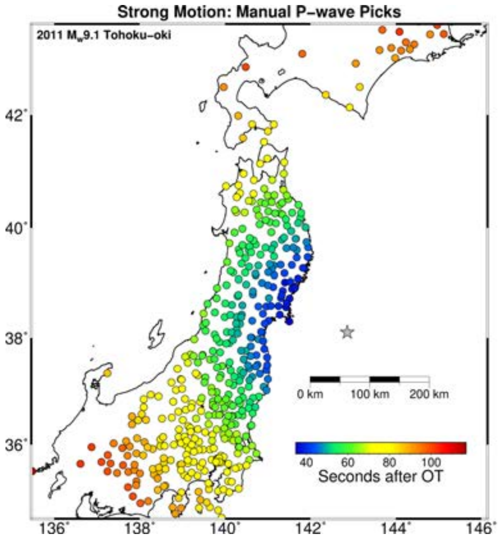

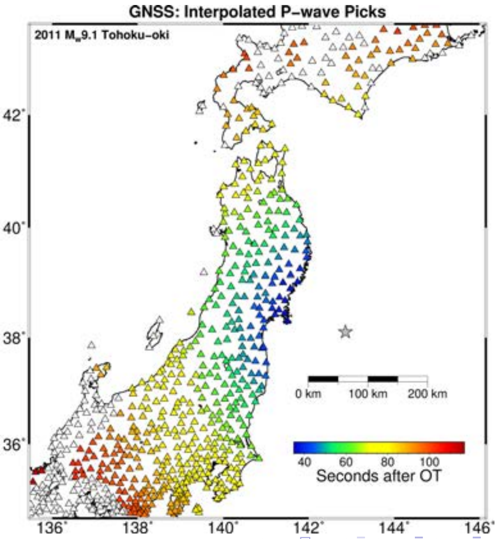

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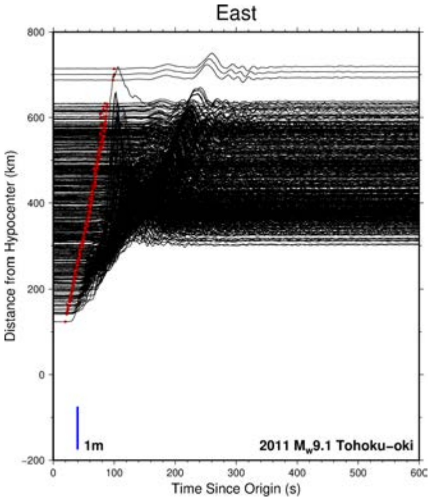
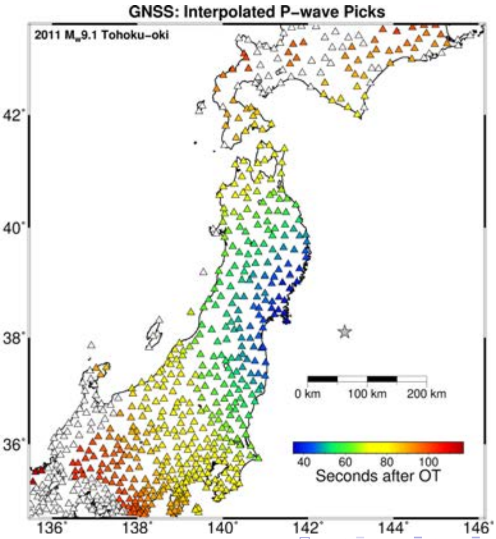
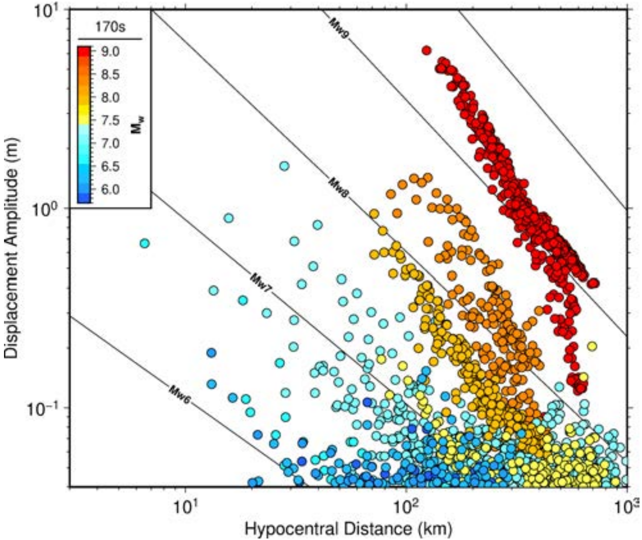




Evolution of Displacement



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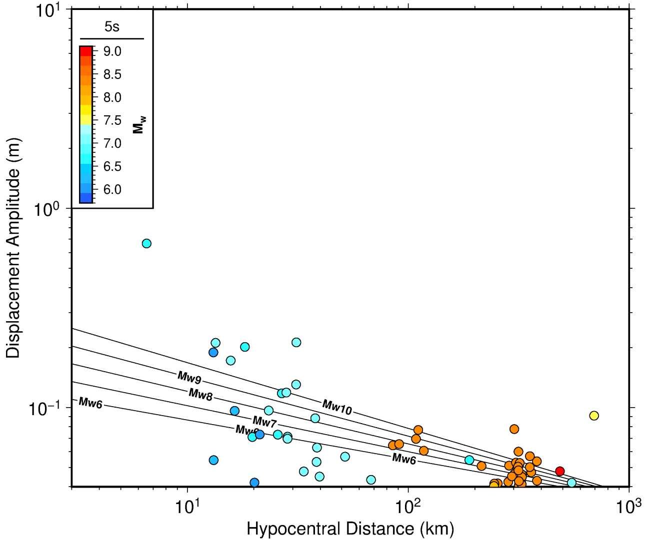

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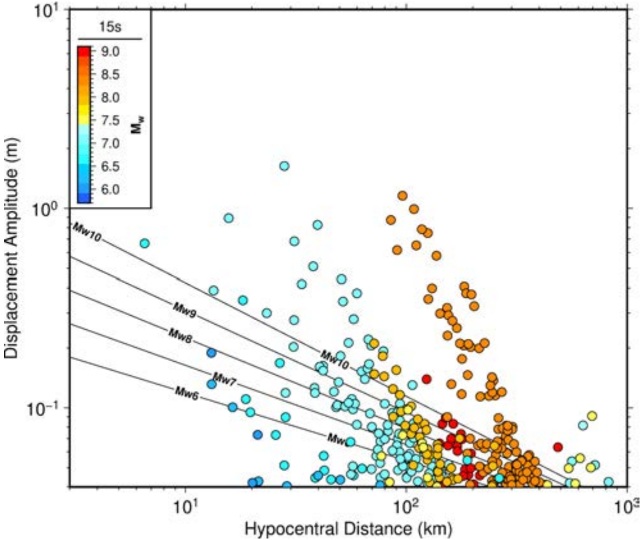
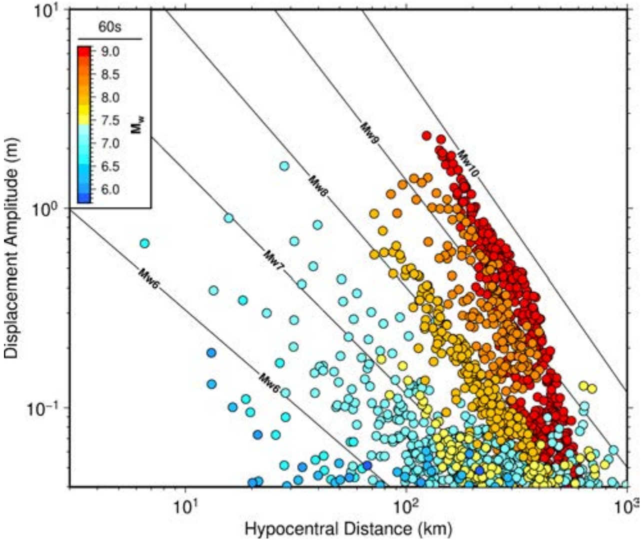


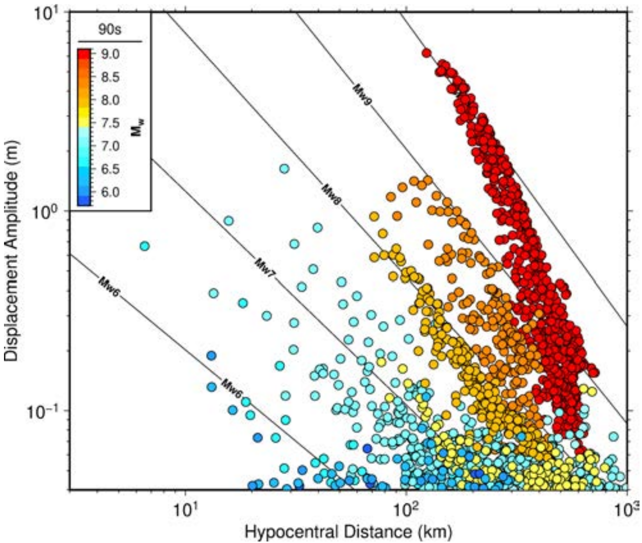
- No clear scaling from early observations

Evolution of Displacement



- No clear scaling from early observations
- Separation between events of different magnitude occurs first at close stations, then at farther stations

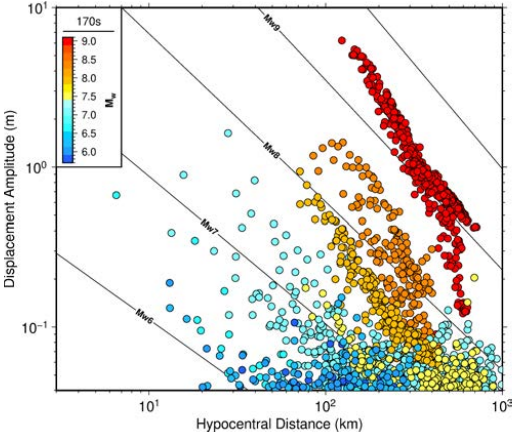
Evolution of Displacement

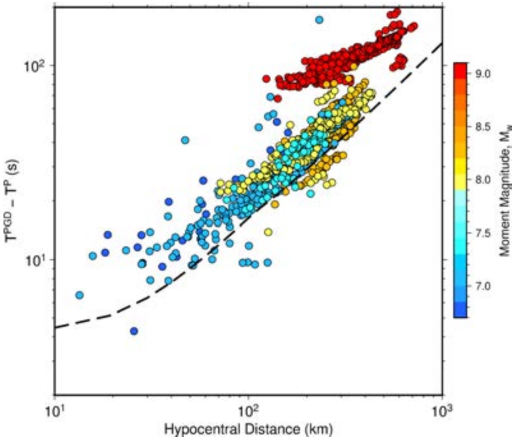


- No clear scaling from early observations
- Separation between events of different magnitude occurs first at close stations, then at farther stations
- Observations from larger earthquakes exceed those from smaller earthquakes only when the smaller earthquake reaches **peak ground displacement**

When can we expect to observe PGD?

– – – – S - P

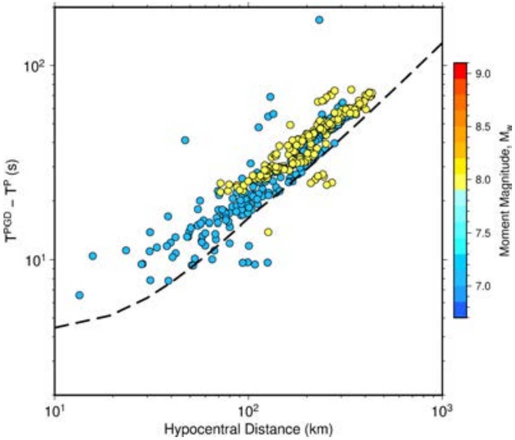




When can we expect to observe PGD?

- Magnitude 9 event takes much longer to reach PGD
- Most events asymptote the expected S-P line
- At close distances, T^{PGD}-T^{P} exceeds S-P line
- The distance at which T^{PGD}-T^{P} meets S-P appears to increase with increasing magnitude

– – – – S - P



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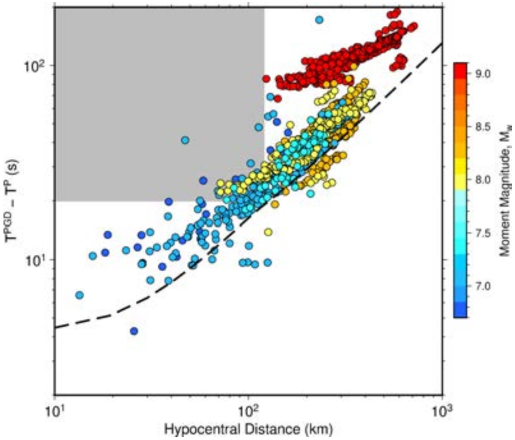
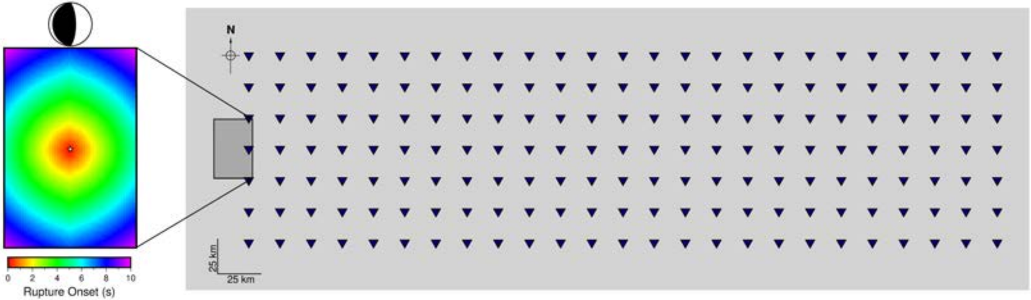
- Most events asymptote the expected S-P line
- At close distances, T^{PGD}-T^{P} exceeds S-P line
- The distance at which T^{PGD}-T^{P} meets S-P appears to increase with increasing magnitude
- What would we see if we had instrumentation at closer distances?

– – – – S - P



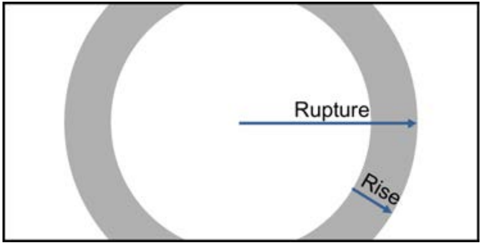
Model Configuration



How Does Slip Manifest?

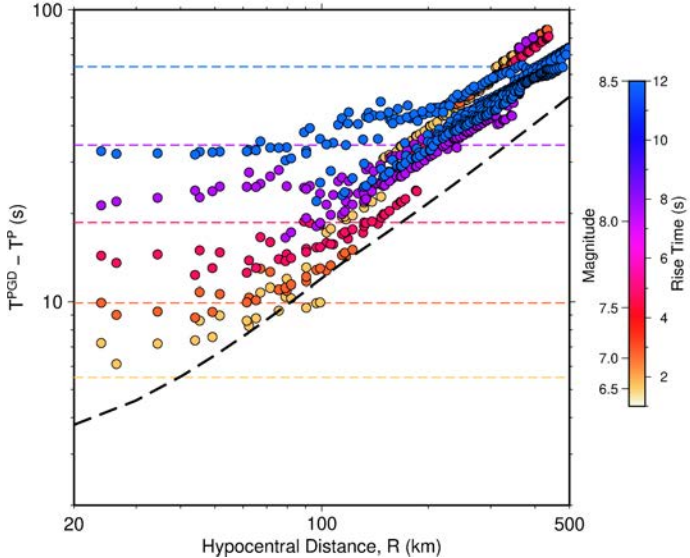
- Assume pulse-like slip
- Magnitude-dependent pulse width (rise time)
- Magnitude-dependent fault dimensions
- Fill in what happens at close distances
- Do results look like the observations?

Pulse-like Slip

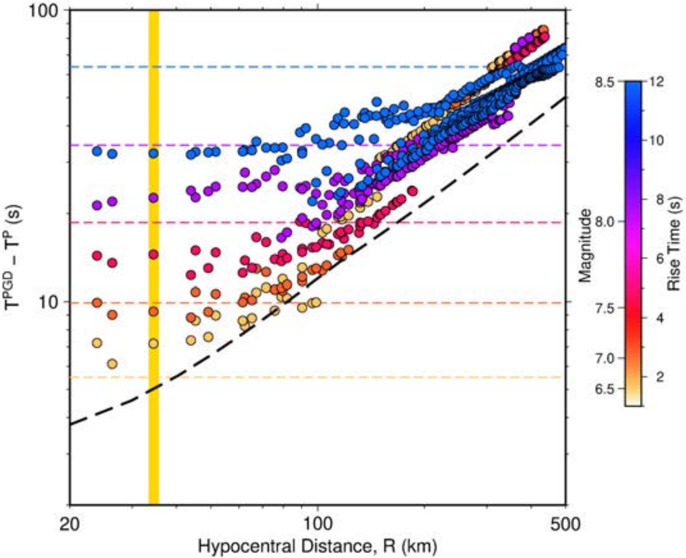


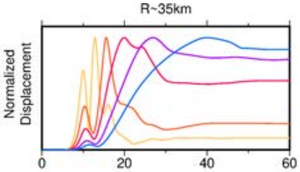
Rise time: local duration of slip
Pulse width is magnitude-dependent

Results

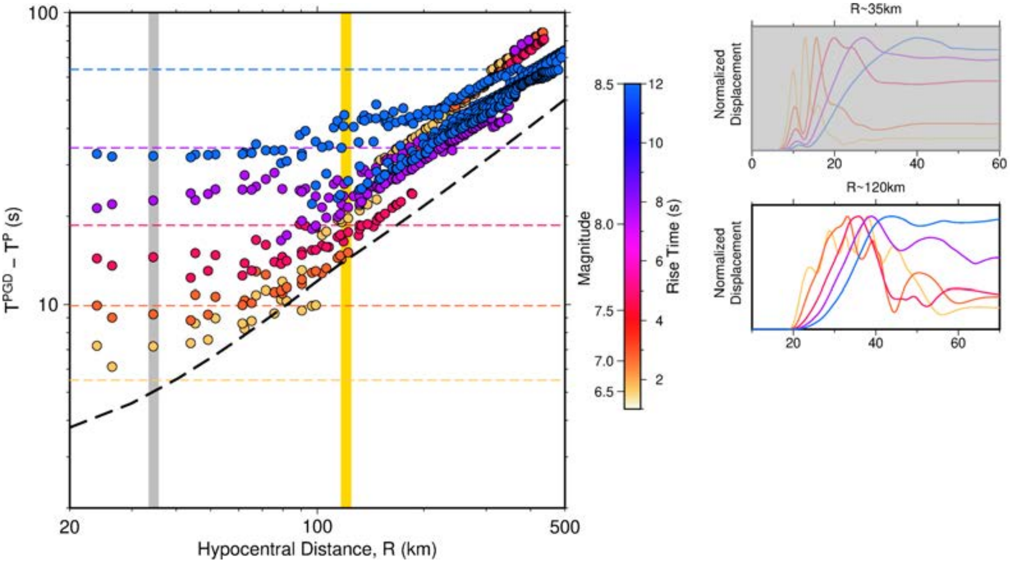

100
10
$T^{PGD} - T^{P}$ (s)
20
100
500
Hypocentral Distance, R (km)
Magnitude
8.5
8.0
7.5
7.0
6.5
Rise Time (s)
12
10
8
6
4
2

Results


100
10
$T^{PGD} - T^{P}$ (s)
20
100
500
Hypocentral Distance, R (km)
8.5
8.0
7.5
7.0
6.5
Magnitude
12
10
8
6
4
2
Rise Time (s)

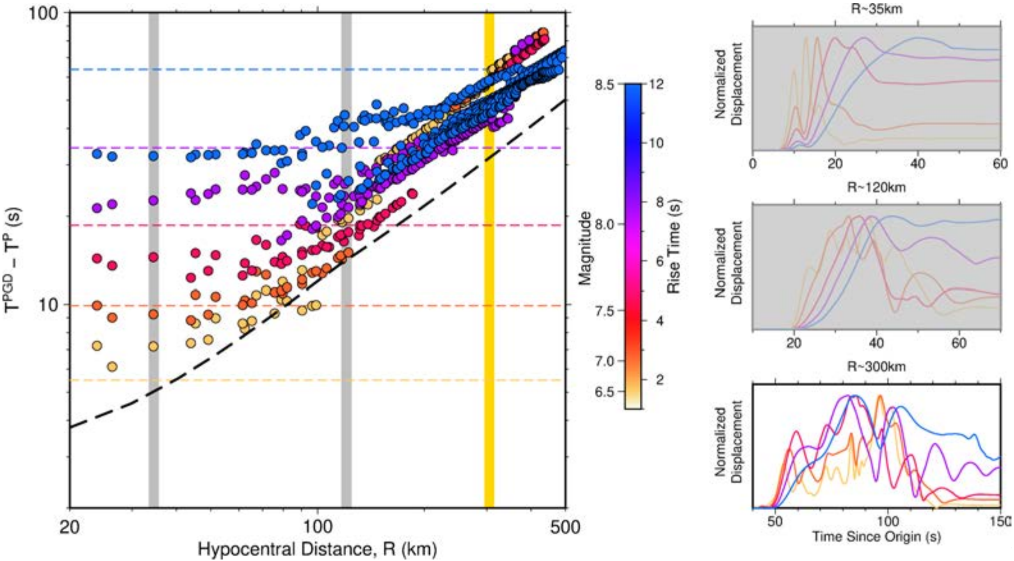

R~35km
Normalized Displacement
0
20
40
60

Results

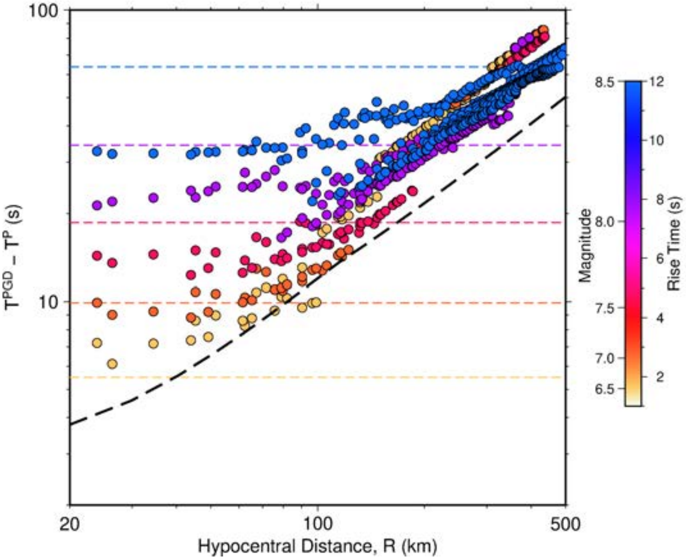


100
10
20
100
500
$T^{PGD} - T^{P}$ (s)
Hypocentral Distance, R (km)
Magnitude
8.5
8.0
7.5
7.0
6.5
Rise Time (s)
12
10
8
6
4
2
R~35km
Normalized Displacement
0
20
40
60
R~120km
Normalized Displacement
20
40
60

Results


100
10
20
100
500
$T^{PGD} - T^{P}$ (s)
Hypocentral Distance, R (km)
Magnitude
Rise Time (s)
8.5
8.0
7.5
7.0
6.5
12
10
8
6
4
2
R~35km
R~120km
R~300km
Normalized Displacement
Time Since Origin (s)

Results



- Near-fault observations are sensitive to the rise time
- Near-fault observations are impacted by nearby fault patches and the pattern of slip
- Receivers at distance observe the integrated fault signal
- Stations <90km observe PGD with ∼35s of observation, up to a M_w8.5, despite a rupture duration of ∼65s.

Implications for Early Warning with GNSS

- Earthquake magnitude can be reliably estimated once PGD has been observed.
- At close distances, PGD is delayed by increasing fault dimension and rise time.
- If observed at close enough distances, PGD can be observed *prior* to rupture completion, implying a weak determinism.
- PGD estimates will be available faster with direct displacement measurements from **GNSS**.
- Collocated seismogeodetic instrumentation will allow proper earthquake detection **and** magnitude scaling improving real-time local tsunami warning.