Earthquake early warning for information-based societies

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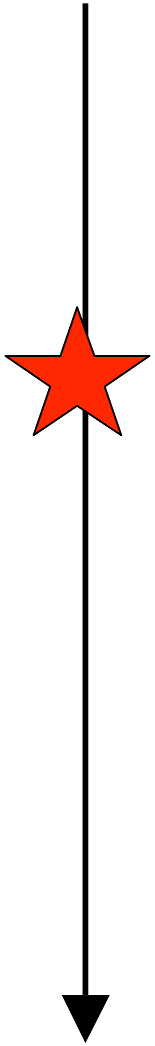
Outline

- What is early warning
- Chronology
- Different flavors of early warning
- Virtual Seismologist method
- Implementation efforts
- Conclusions

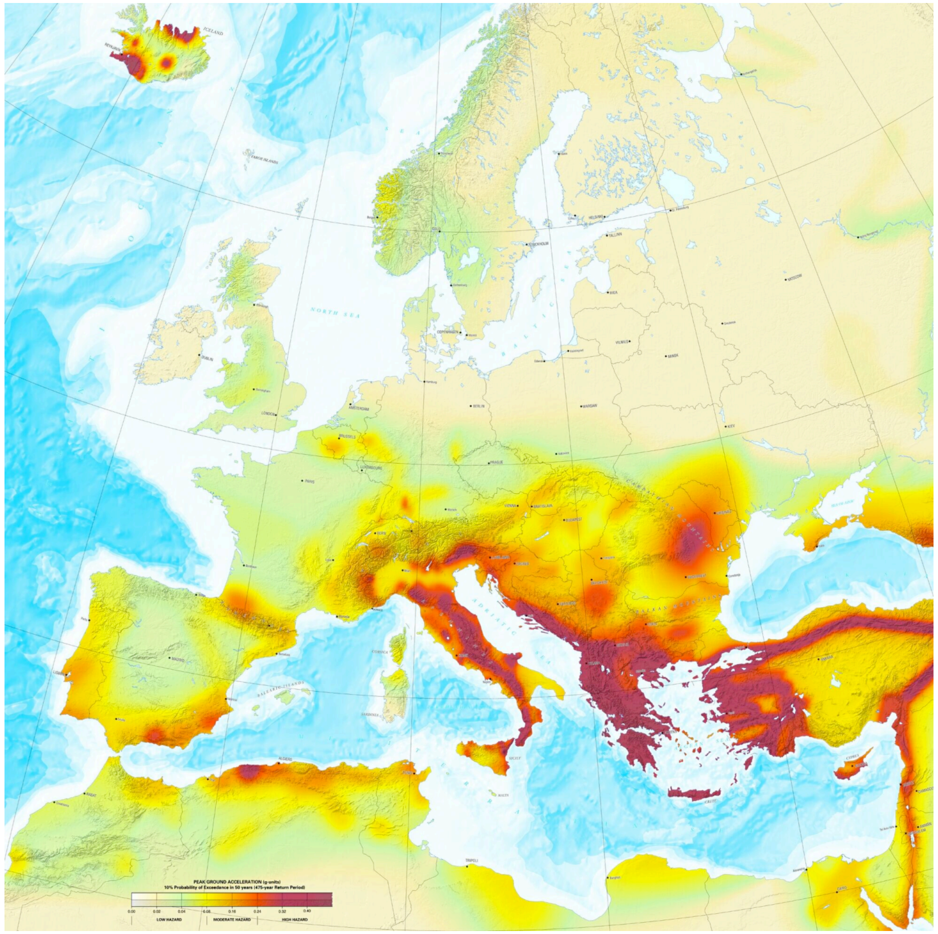
from http://www.jma.go.jp

Earthquake hazard information at different time scales

decades



Long term seismic hazard maps



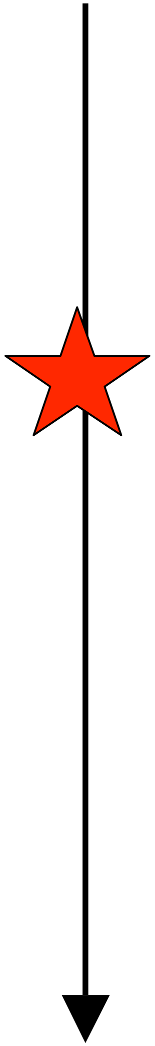
10% probability of being exceeded in 50 yrs

Euro-Med Seismic Hazard Map (Giardini et al, 2003)

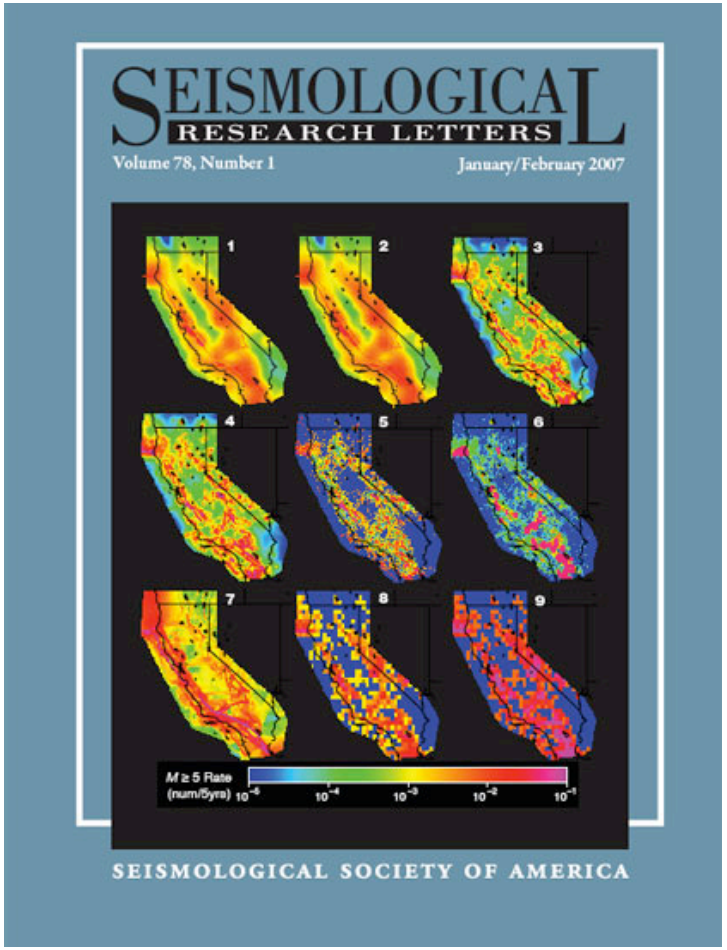
Earthquake hazard information at different time scales

decades

years



Intermediate-term forecasts

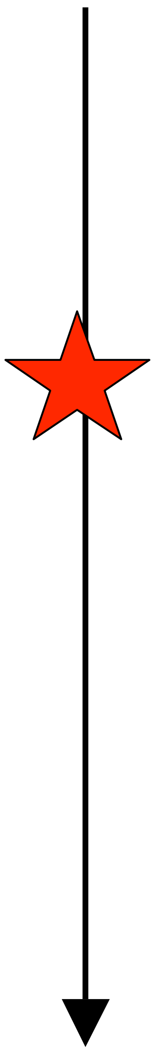


Earthquake hazard information at different time scales

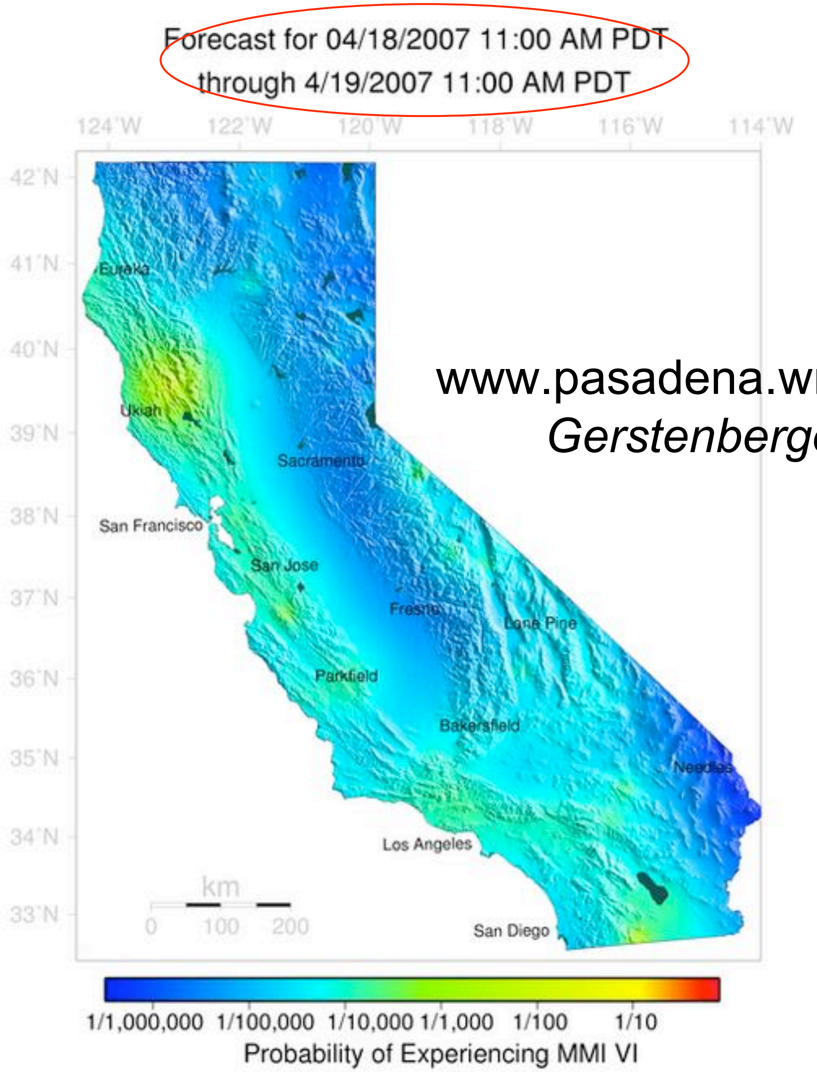
decades

years

hours



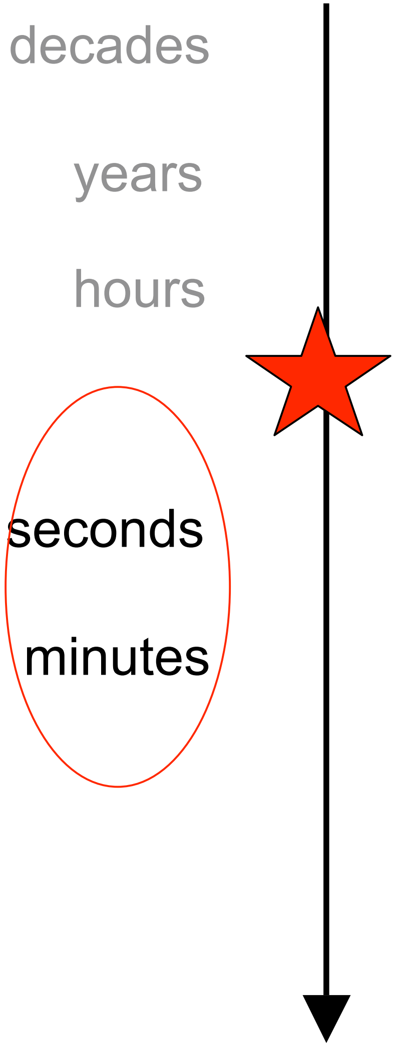
short-term forecasts



www.pasadena.wr.usgs.gov/step

Gerstenberger et al, 2003

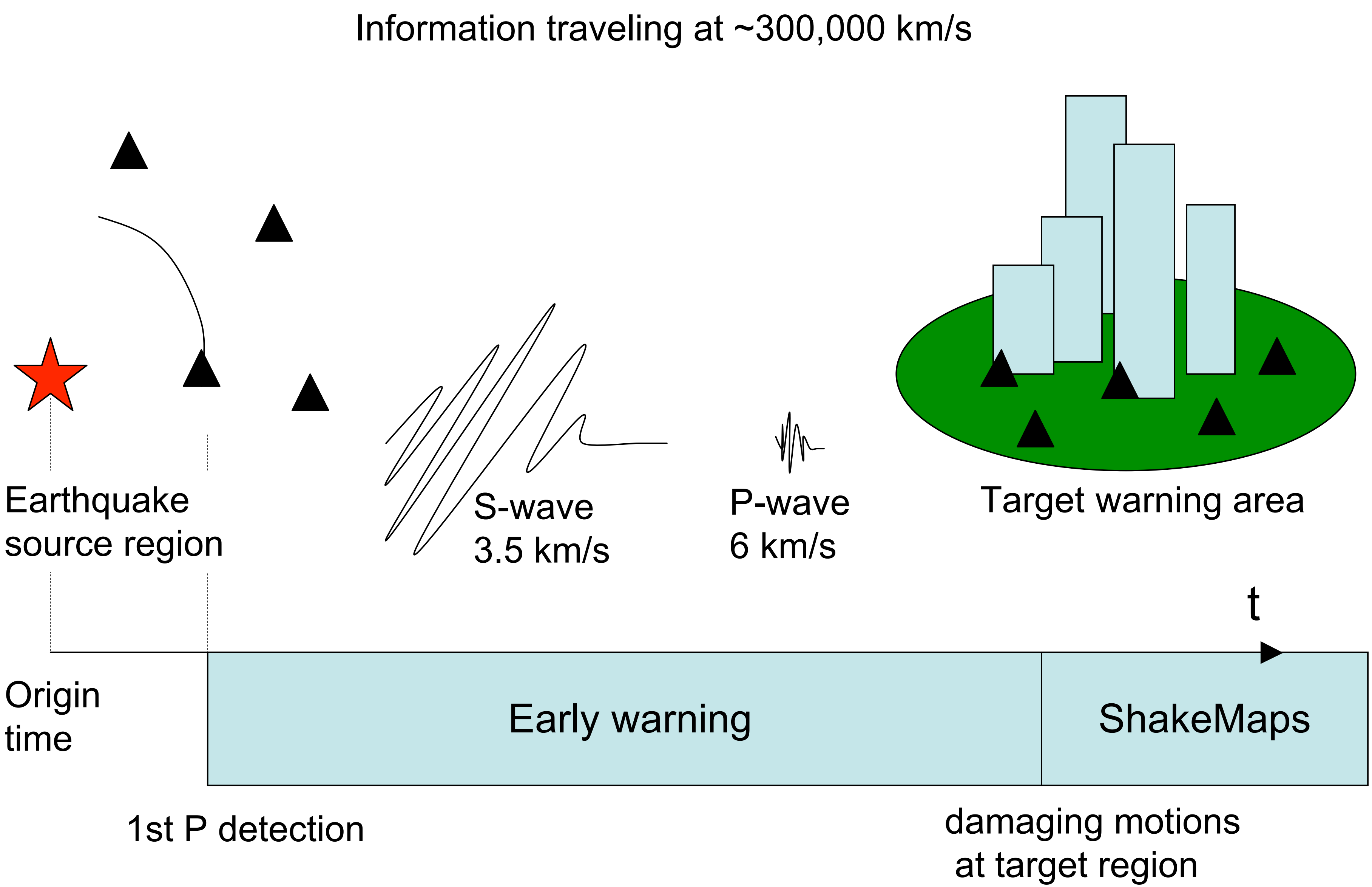
Earthquake hazard information at different time scales



Real-time seismology

- goal: provide timely information to assist in post-earthquake mitigation, response, recovery efforts

- early warning (earthquakes, tsunamis)
- rapid source characterization
- ShakeMaps
- human impact, casualty estimates (PAGER, QuakeLoss)
- economic loss estimates


Information traveling at ~300,000 km/s
Earthquake source region
S-wave 3.5 km/s
P-wave 6 km/s
Target warning area
t
Origin time
Early warning
ShakeMaps
1st P detection
damaging motions at target region

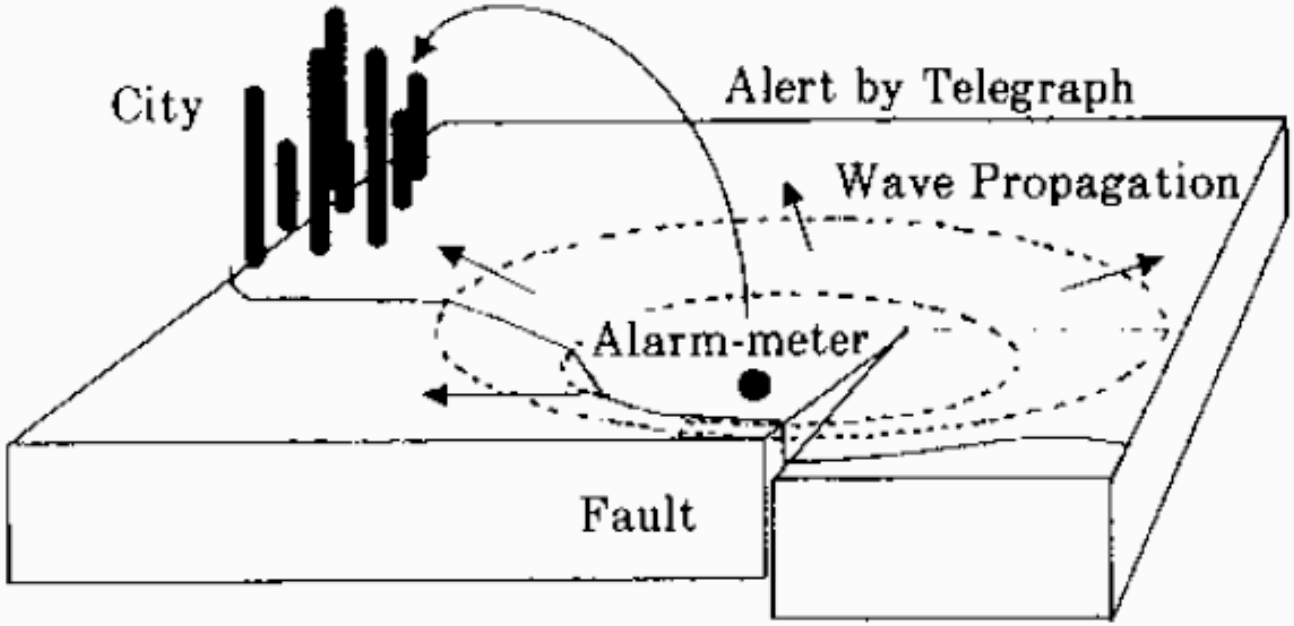


Fig. 1 Concept of the Front Alarm by Dr. J. D. Cooper.

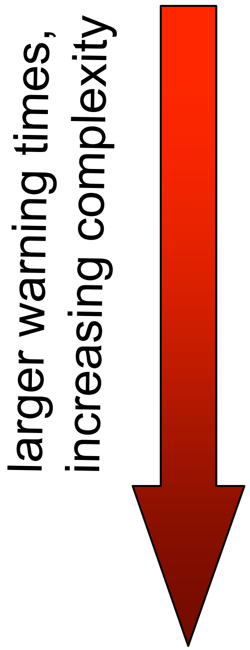
from J. D. Cooper, 1868
courtesy of H. Negishi, NIED

Chronology

- 1868: Cooper proposes setting up seismic detectors near Hayward fault, ring a bell in central San Francisco
- 1960s: Japan Railway starts developing early warning system to slow or stop high-speed trains (currently UrEDAS)
- 1989: Loma Prieta aftershock sequence - temporary seismic deployment provides constructions workers ~20 seconds of warning (Bakun, 1994)
- 1991: Mexico Seismic Alert System provides up to 70 seconds of warning to Mexico City from earthquakes nucleating in the Guerrero region, about 300 km away
- 1991: Taiwan Central Weather Bureau begins widespread deployment of strong motion instruments with goal of providing early warning
- 2006: Implementation of early warning systems are funded in EU and United States (in reaction to 2004 Sumatra earthquake and tsunami)
- 2007: Japanese Meteorological Agency (JMA) starts releasing early warning information in Japan via radio, television

Kanamori, 2005

In tens of seconds, you could (possibly)…



- duck and cover
- save data, stop elevators
- shut down gas valves, secure equipment, hazardous materials
- slow trains, abort airplane landings, direct traffic
- initiate shutdown procedures in manufacturing facilities
- protect emergency response facilities (hospitals, fire stations)
- in general, reduce injuries, prevent secondary hazards, increase effectiveness of emergency response; larger warning times better
- Structural control applications (Grasso, 2005)

- most of the time, “Light shaking in X seconds, just enjoy the ride” messages over mobile phones

JMA website, 2007
Goltz, 2002

P-wave frequency content

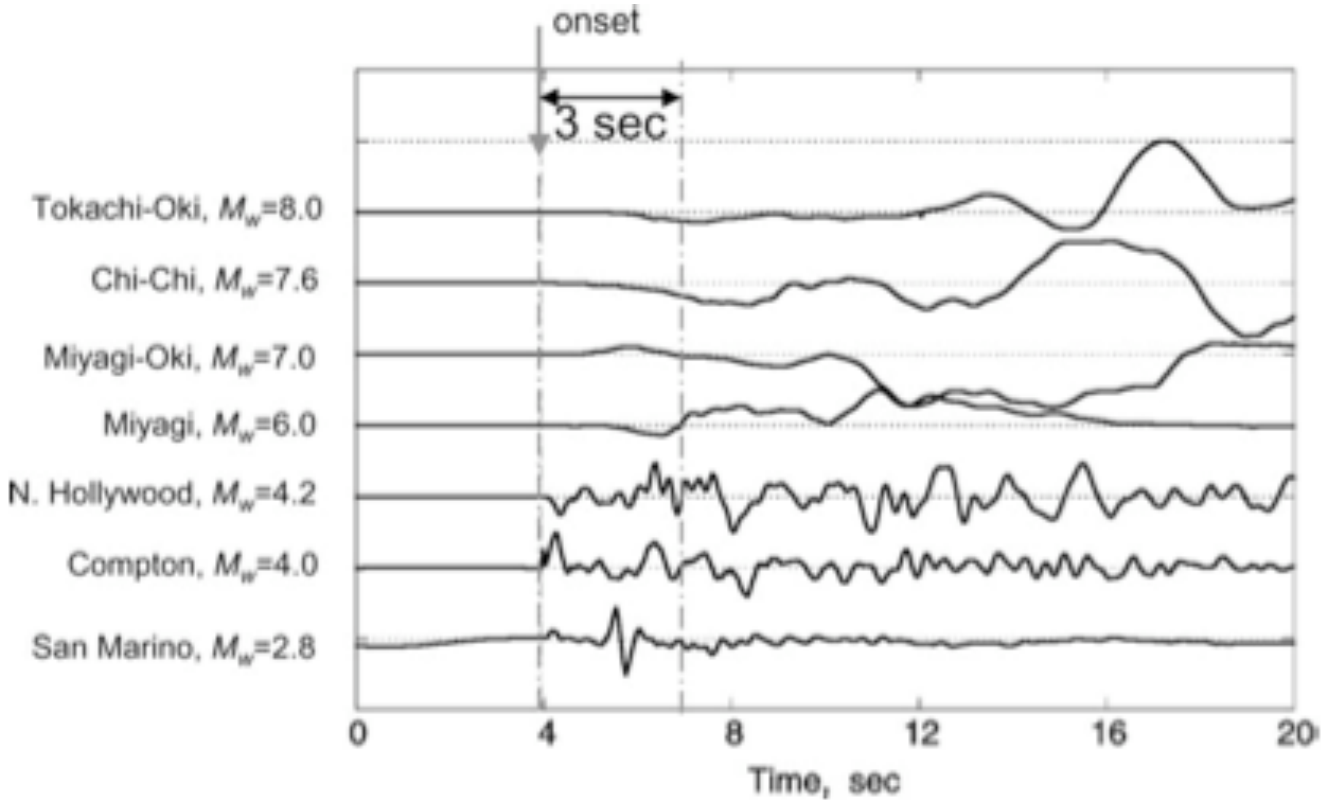
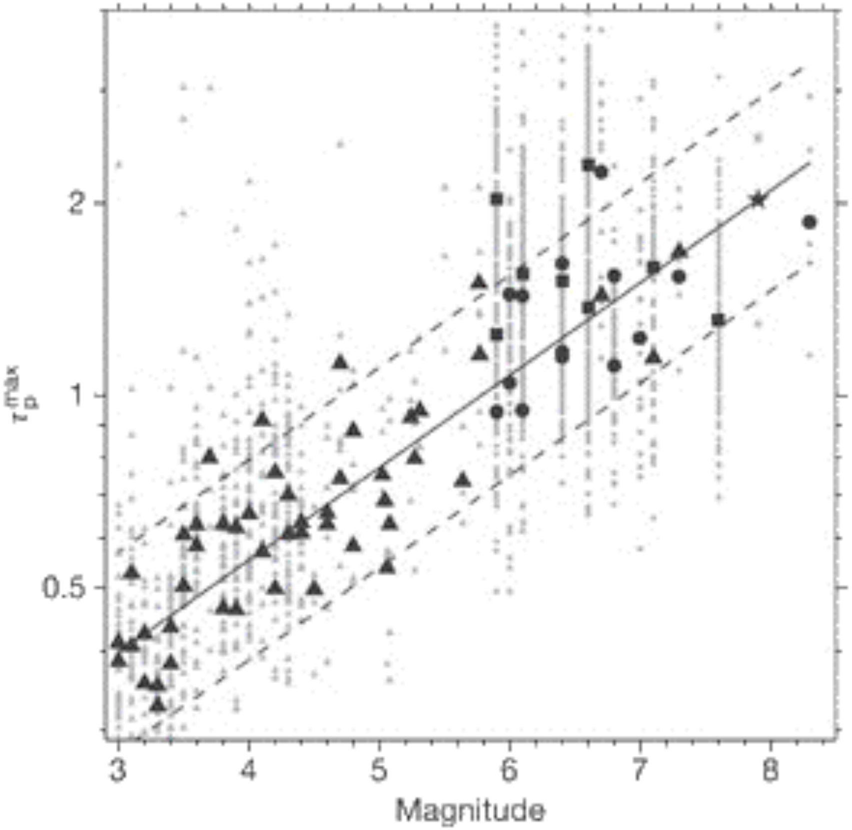


Figure 5 The wave forms of the beginning of close-in displacement records of earthquakes with magnitudes from 2.8 to 8. The amplitudes are in arbitrary scale. The first 3 s is indicated by two dash-dot lines.

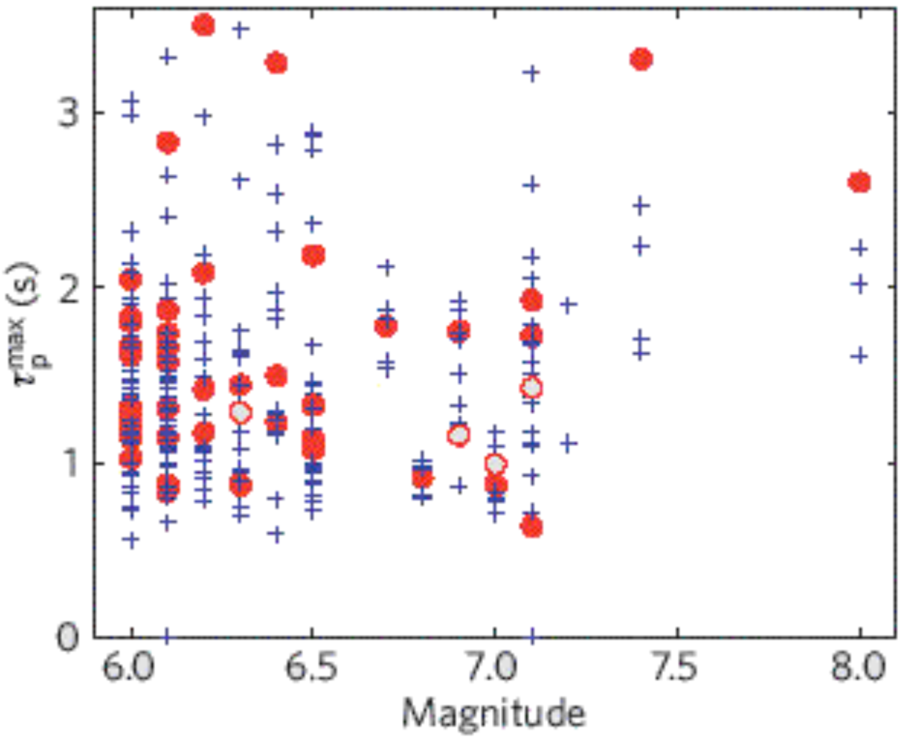
Kanamori, 2004

Are earthquakes deterministic or not?



(a)

Olsen and Allen, 2005



(b)

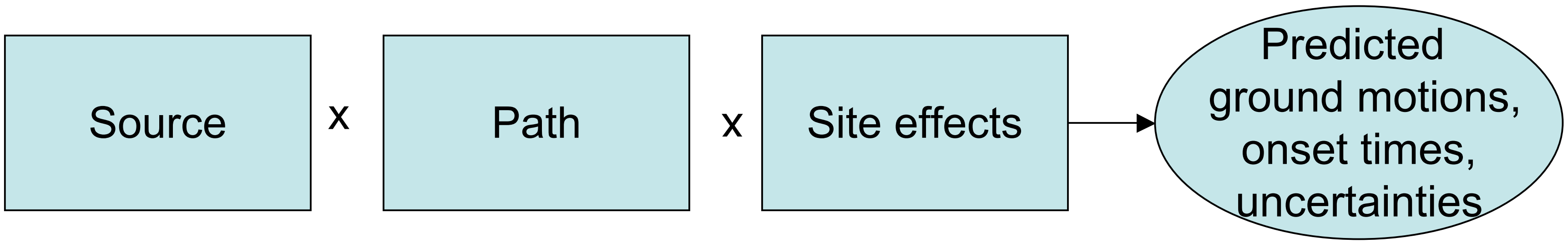
Rydelek and Horiuchi, 2006

Different flavors of early warning

- Single station approach
  - Tau-C approach (Wu and Kanamori, 2004)

- “Front detection”
  - known source region (eg. Mexico City, Bucharest)

- Network-based approach
  - Many possible source regions
  - Elarms (Allen and Kanamori, 2003), Virtual Seismologist (Cua and Heaton, 2006), Nowcast (Japan)
  - Same ingredients as non-real time seismic hazard analysis



Virtual Seismologist (VS) method for seismic early warning

- Bayesian approach to seismic early warning designed for regions with distributed seismic hazard/risk

- Modeled on “back of the envelope” methods of human seismologists for examining waveform data
  - Shape of envelopes, relative frequency content

- Capacity to assimilate different types of information
  - Previously observed seismicity
  - State of health of seismic network
  - Known fault locations
  - Gutenberg-Richter recurrence relationship

Bayes' Theorem: a review

Given available waveform observations Y_{obs}, what are the most probable estimates of magnitude and location, M, R?

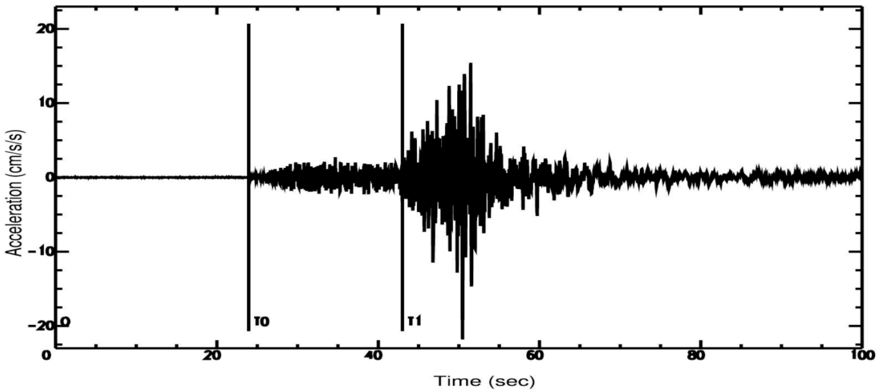
"posterior" "likelihood" "prior"

$$prob(M, R|Y_{obs}) \propto prob(Y_{obs}|M, R) \times prob(M, R)$$

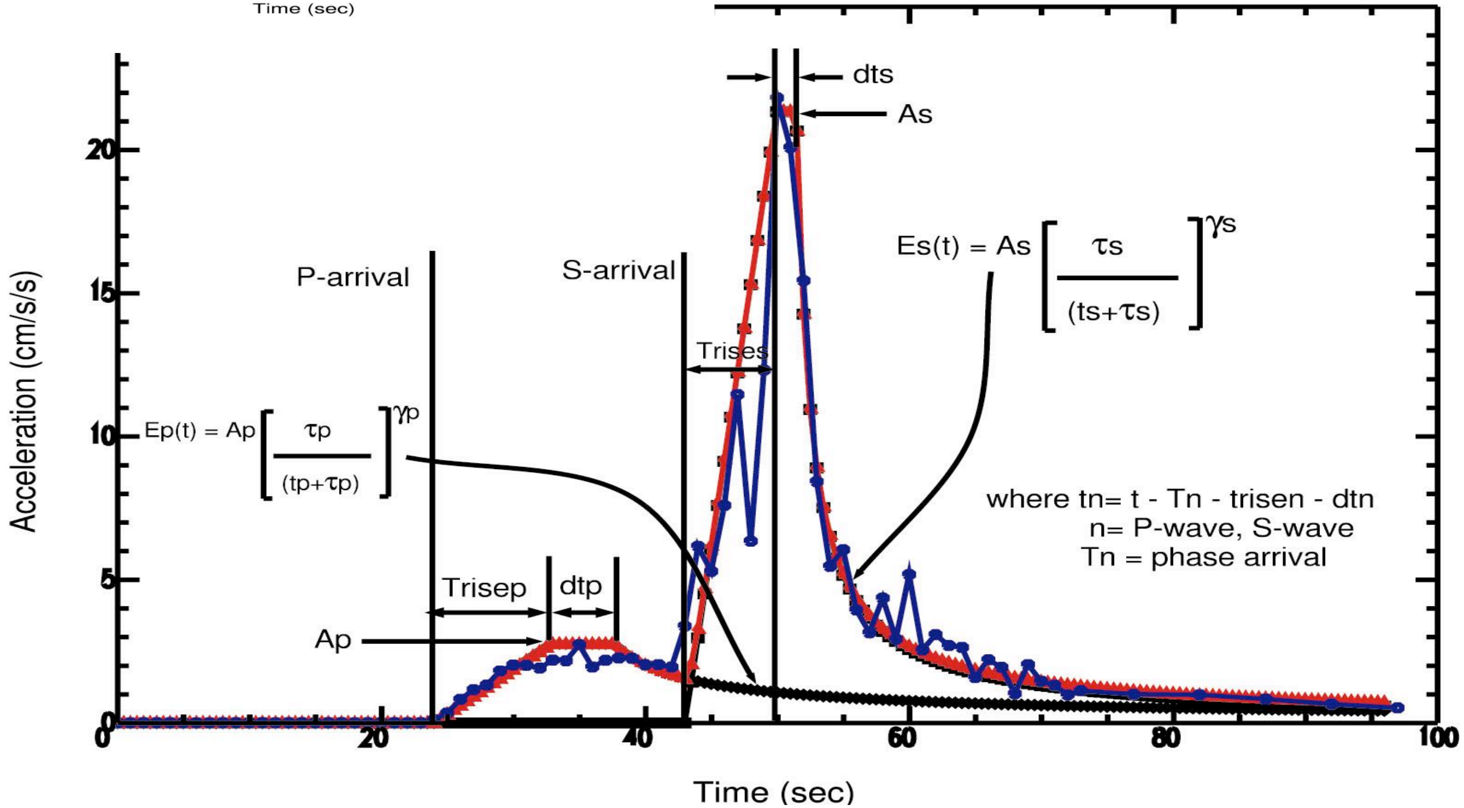
"the answer"

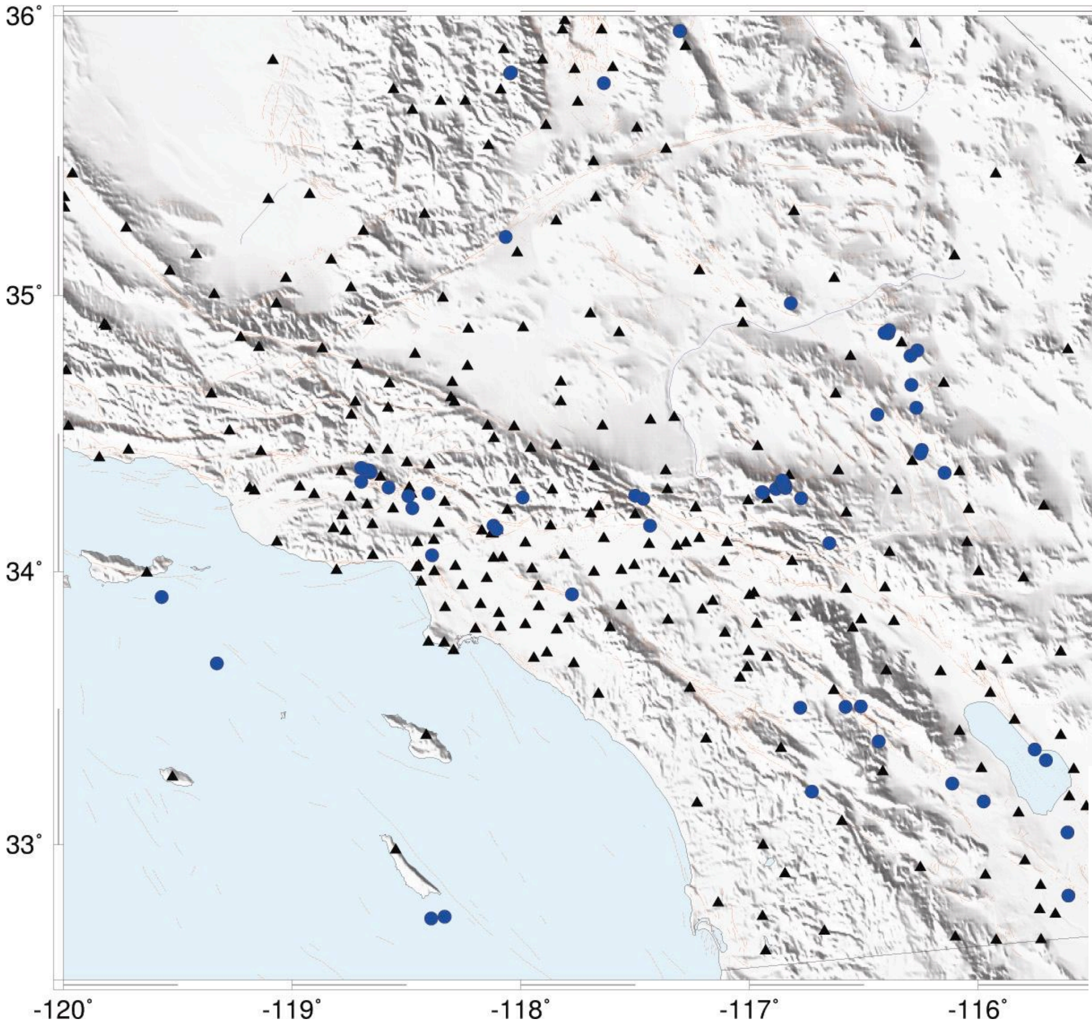
- Prior = beliefs regarding M, R before considering observations Y_{obs}
- Likelihood = how observations Y_{obs} modify beliefs about M, R
- Posterior = current state of belief, combination of prior and Y_{obs}
  - maxima of posterior = most probable estimates of M, R given Y_{obs}
  - spread of posterior = variances on estimates of M, R

$$prob(M, R|Y_{obs}) \propto prob(Y_{obs}|M, R) \times prob(M, R)$$



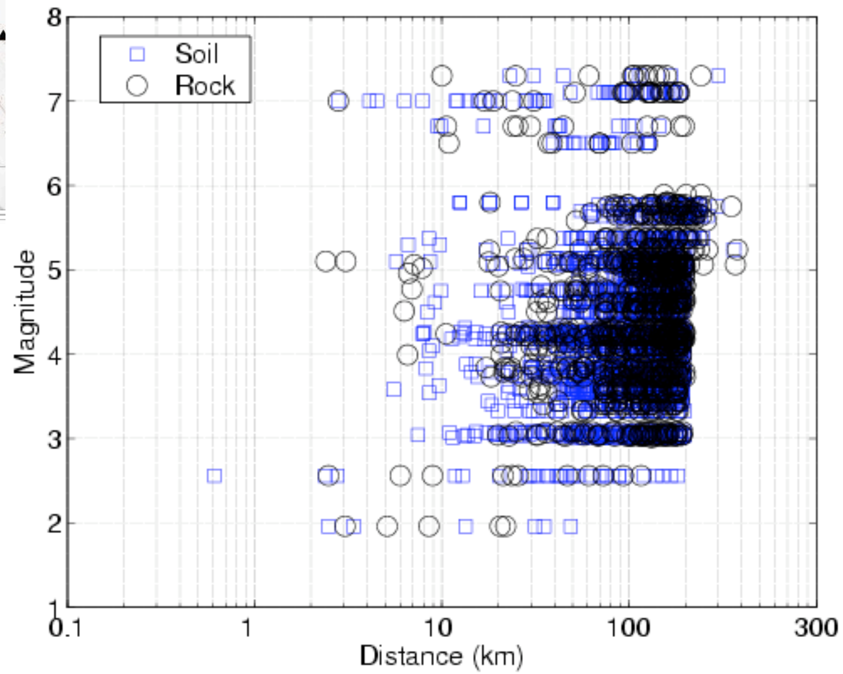
- 1-sec envelopes
- 9 channels (horizontal and vertical acceleration, velocity, and filtered displacement)
- 1 observed envelope => 11 envelope parameters





Data set for learning the envelope characteristics

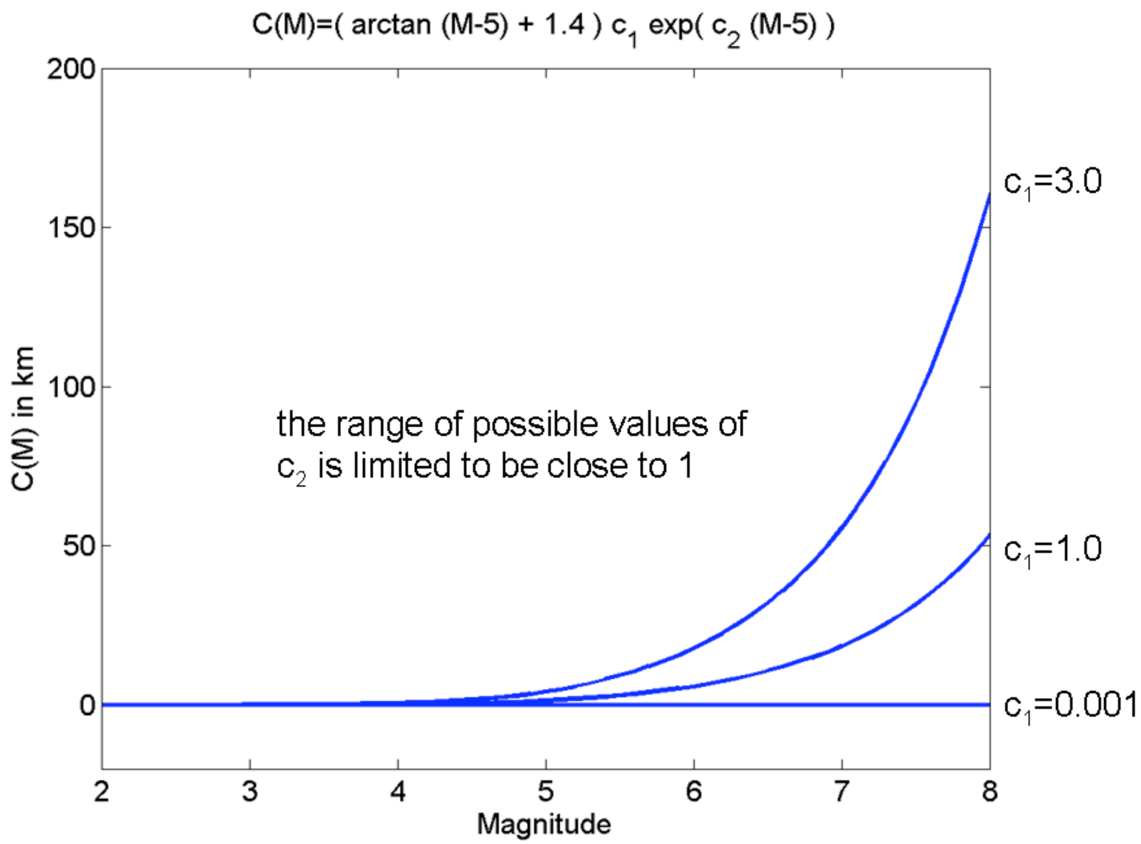
- 70 events, 2 < M < 7.3, R < 200 km
- Non-linear model estimation (inversion) to characterize waveform envelopes for these events
- ~30,000 time histories



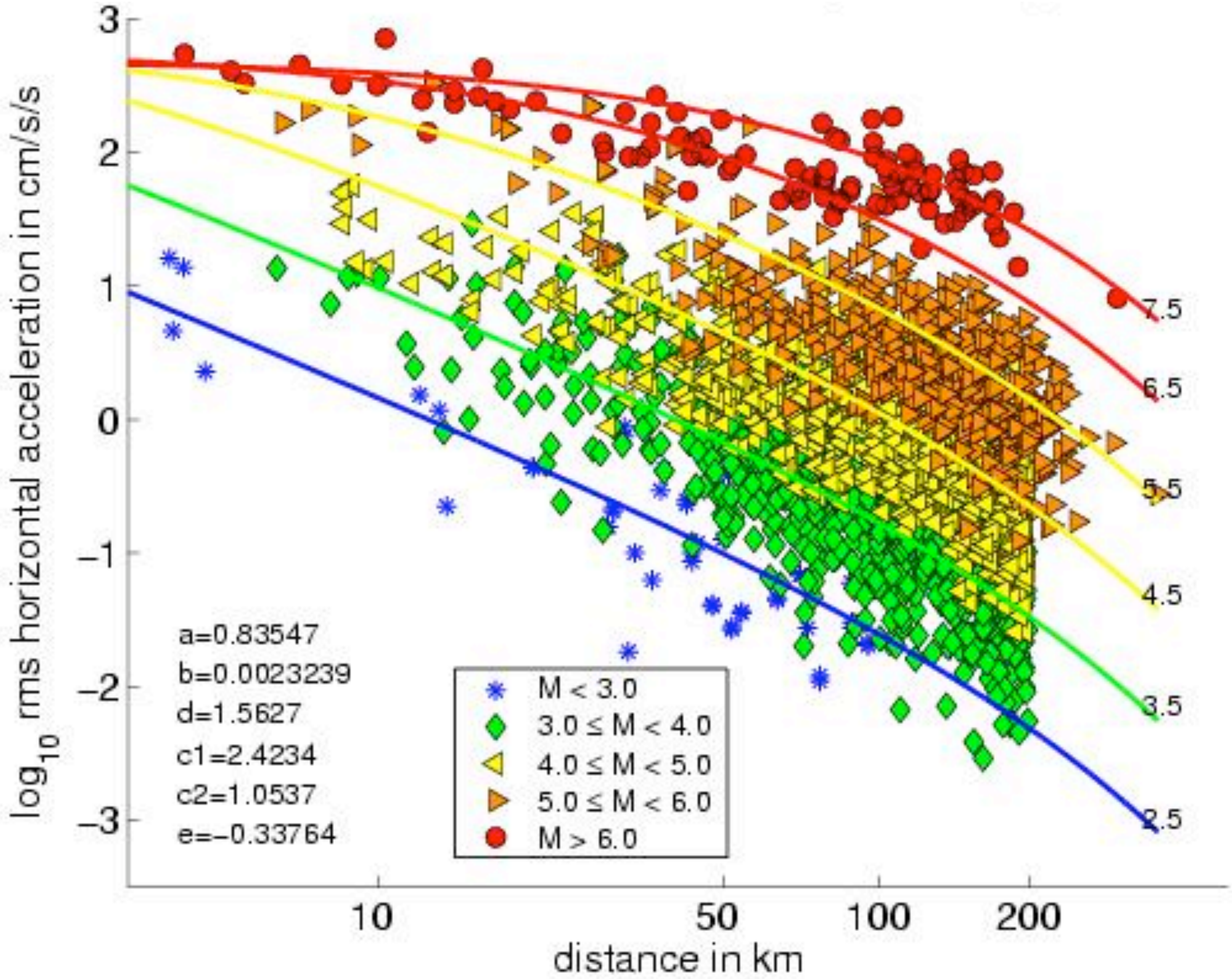
How do peak P- and S-wave amplitudes depend on magnitude, distance, frequency, site?

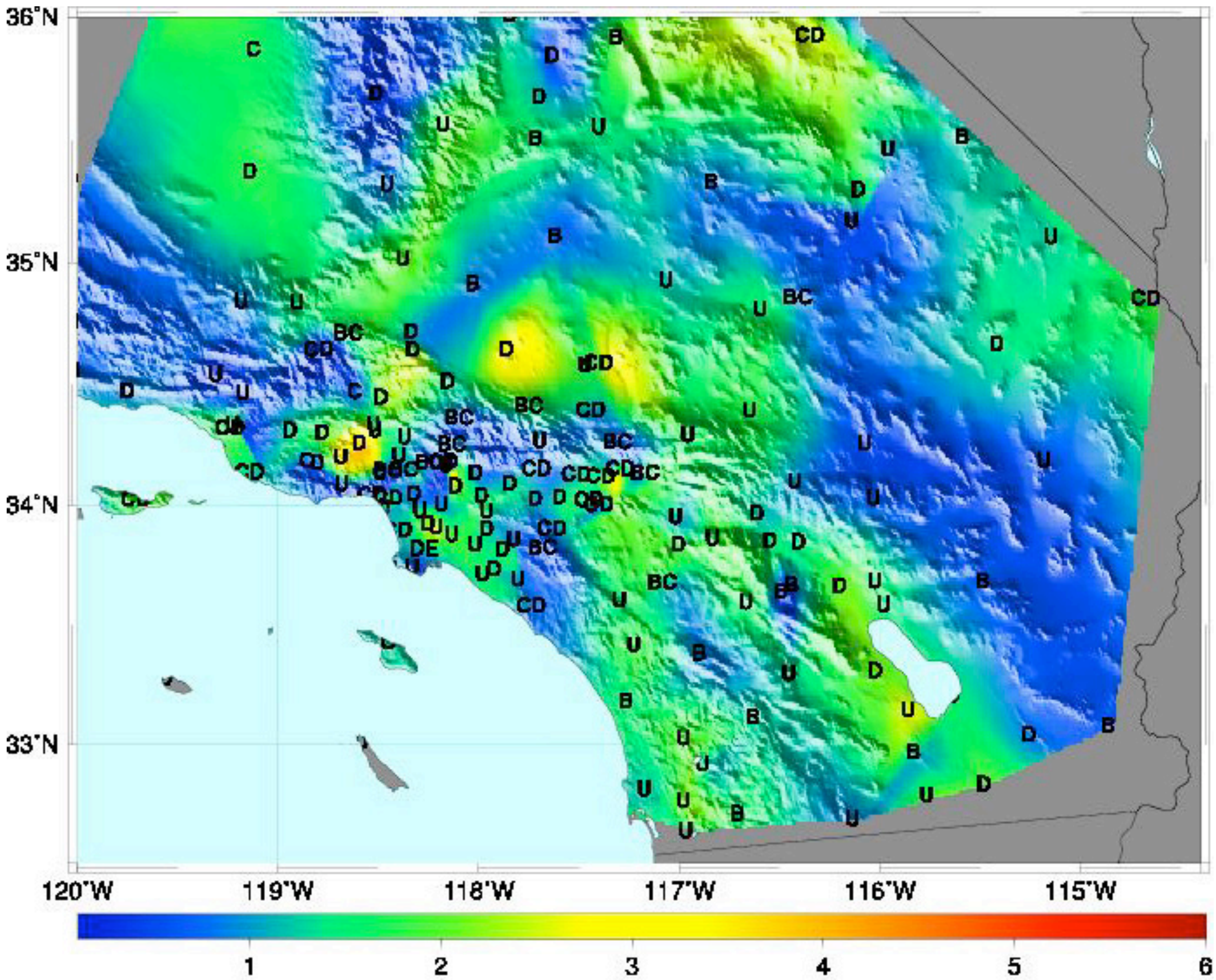
$$\log_{10} A = aM + b(R_1 + C(M)) + d\log_{10}(R_1 + C(M)) + e$$

$$R_1 = \sqrt{R + 9}$$



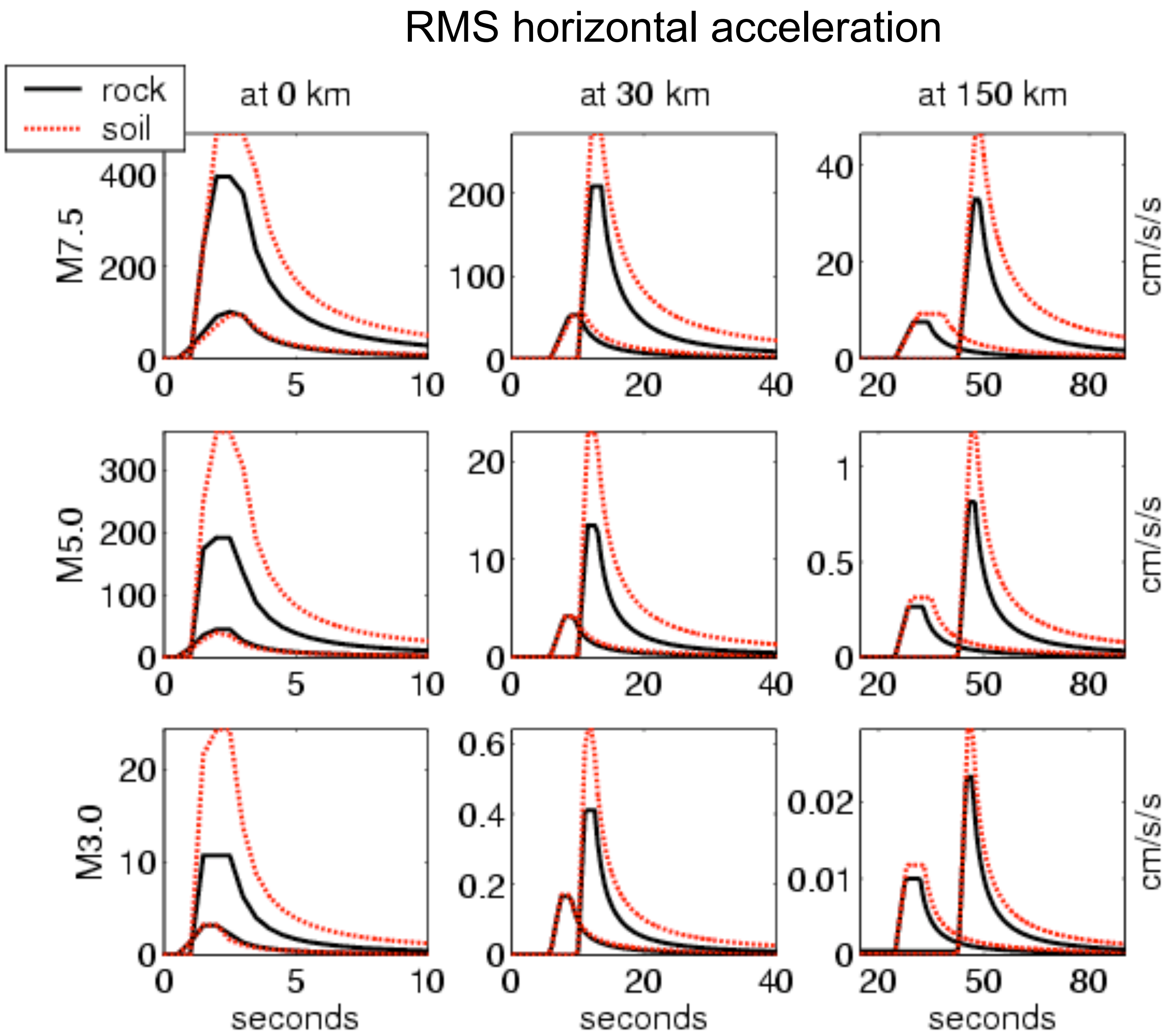
RMS S-wave horizontal acceleration (NEHRP sites C and below)



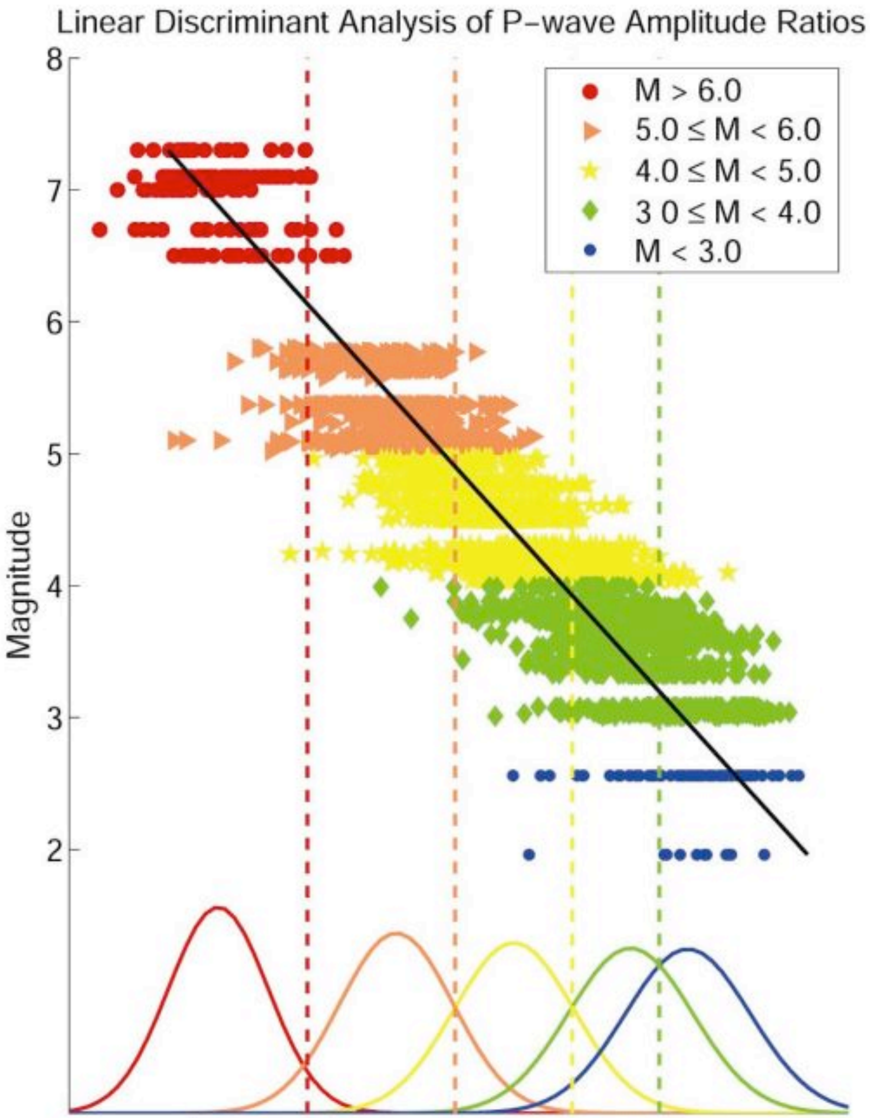


Acceleration amplification relative to average rock station

Average Rock and Soil envelopes as functions of M, R



Estimating M from ratios of ground motion



$$Z_{obs} = \log\left(\frac{PVA^{0.36}}{PVD^{0.93}}\right) = 0.36\log(PVA) - 0.93\log(PVD)$$

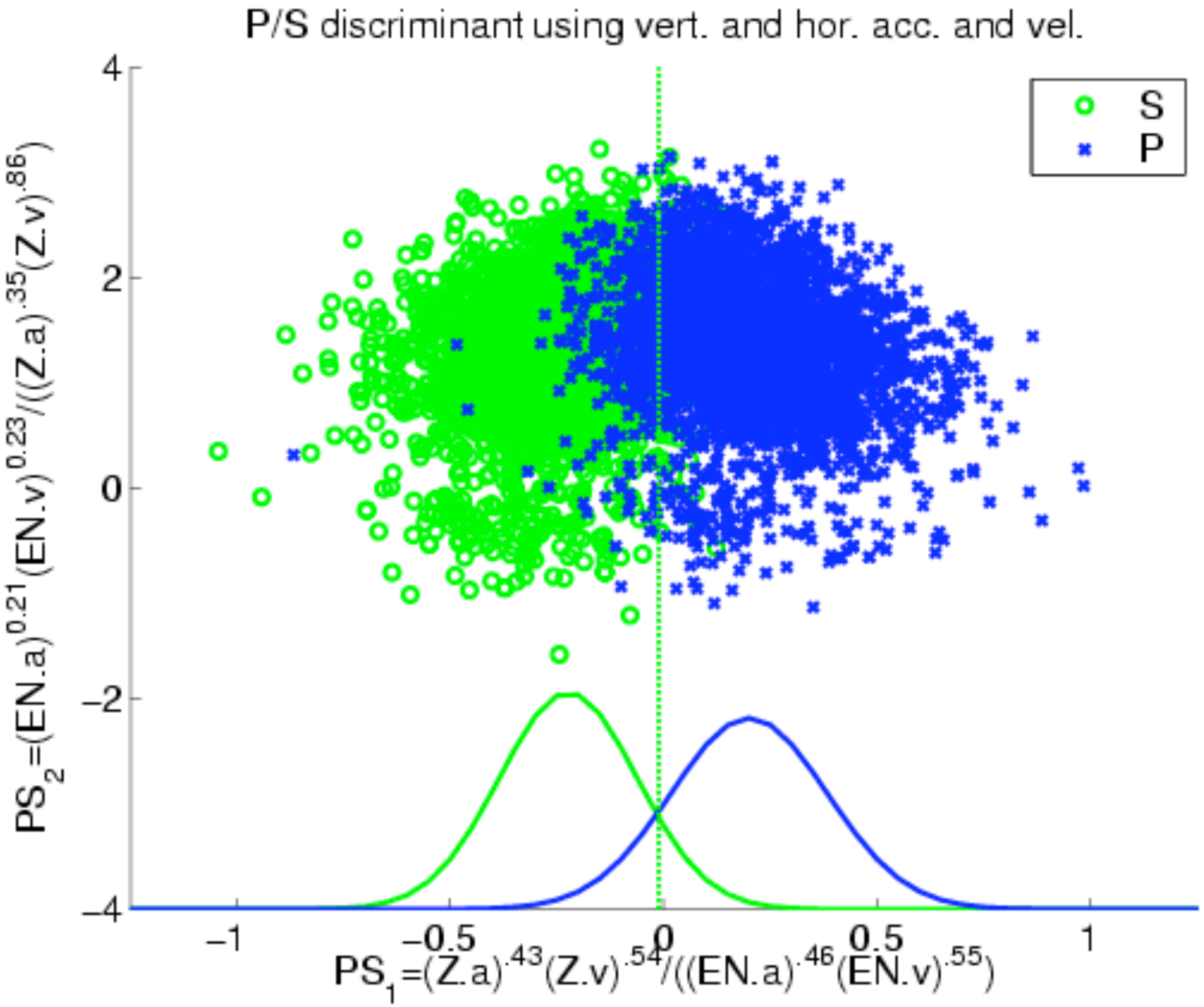
- P-wave frequency content scales with M (Allen and Kanamori, 2003, Nakamura, 1988)
- Find the linear combination of log(acc) and log(disp) that minimizes the variance within magnitude-based groups while maximizing separation between groups (eigenvalue problem)

$$Z_{ad} = 0.36\log(acc) - 0.93\log(disp) = \log\left(\frac{acc^{0.36}}{disp^{0.93}}\right)$$

- Estimating M from Z_{ad}

$$M_P = -1.627 Z_{ad} + 8.94, \sigma_{M_P} = 0.45$$
$$M_S = -1.459 Z_{ad} + 8.05, \sigma_{M_S} = 0.41$$

Distinguishing between P- and S-waves



$$PS = 0.43\log(Z.a) + 0.55\log(Z.v) - 0.46\log(EN.a) - 0.55\log(EN.v)$$

if $PS > 0$ P-wave; if $PS < 0$ S-wave

Bayes' Theorem (again)

$$prob(M, R|Y_{obs}) \propto prob(Y_{obs}|M, R) \times prob(M, R)$$

How are observed quantities (ground motion envelopes) related to magnitude and location?

- shape of envelopes as functions of M, R
- estimating M from ground motion ratio
- distinguishing between P- and S-wave
- station corrections

$$L(M,lat,lon) = \sum_{i=1}^{stations} \sum_{j=1}^{P,S} L(M,lat,lon)_{ij}$$

$$L(M,lat,lon)_{ij} = \frac{(ZAD_{ij} - \bar{Z}_j(M))^2}{2\sigma_{ZAD_j}^2} + \sum_{k=1}^{4} \frac{Y_{obs,ijk} - \bar{Y}_{ijk}(M,lat,lon)}{2\sigma_{ijk}^2}$$

Bayes' Theorem (again)

$$prob(M, R|Y_{obs}) \propto prob(Y_{obs}|M, R) \times prob(M, R)$$

What else do we know about earthquakes?
About the network monitoring the region?

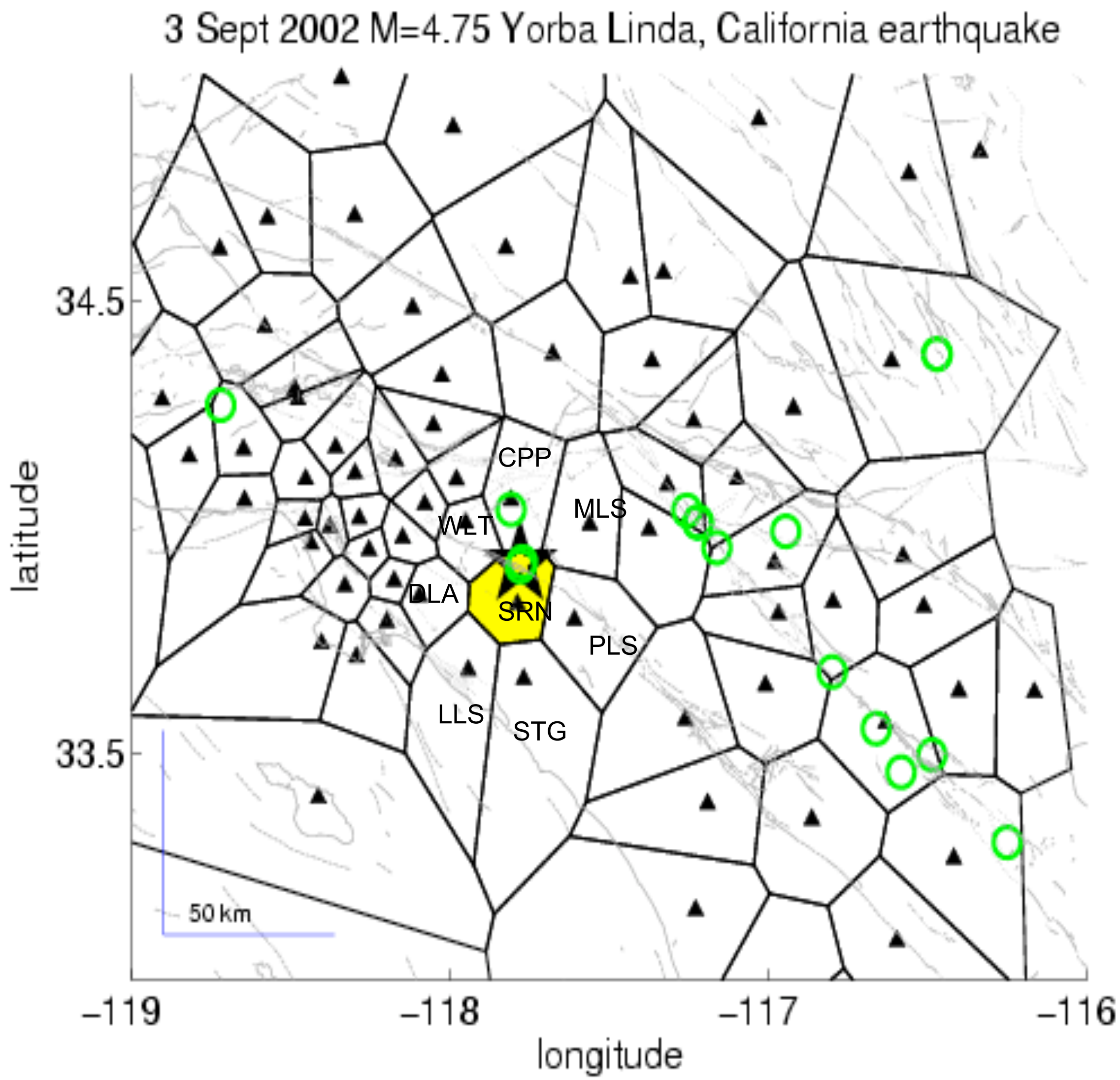
- fault locations
- Gutenberg-Richter relationship

$$\log N(M) = a - bM$$

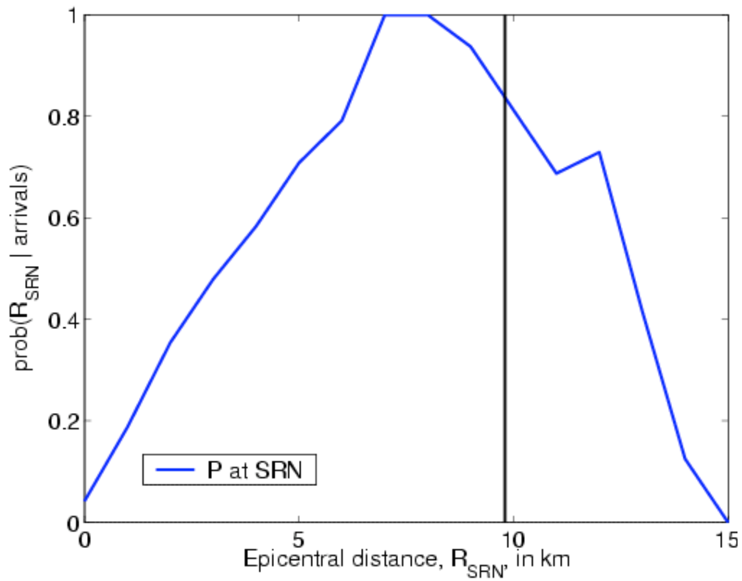
- previously observed seismicity

- station locations
  - not yet arrived data (Horiuchi, 2003, Rydelek and Pujol, 2003))

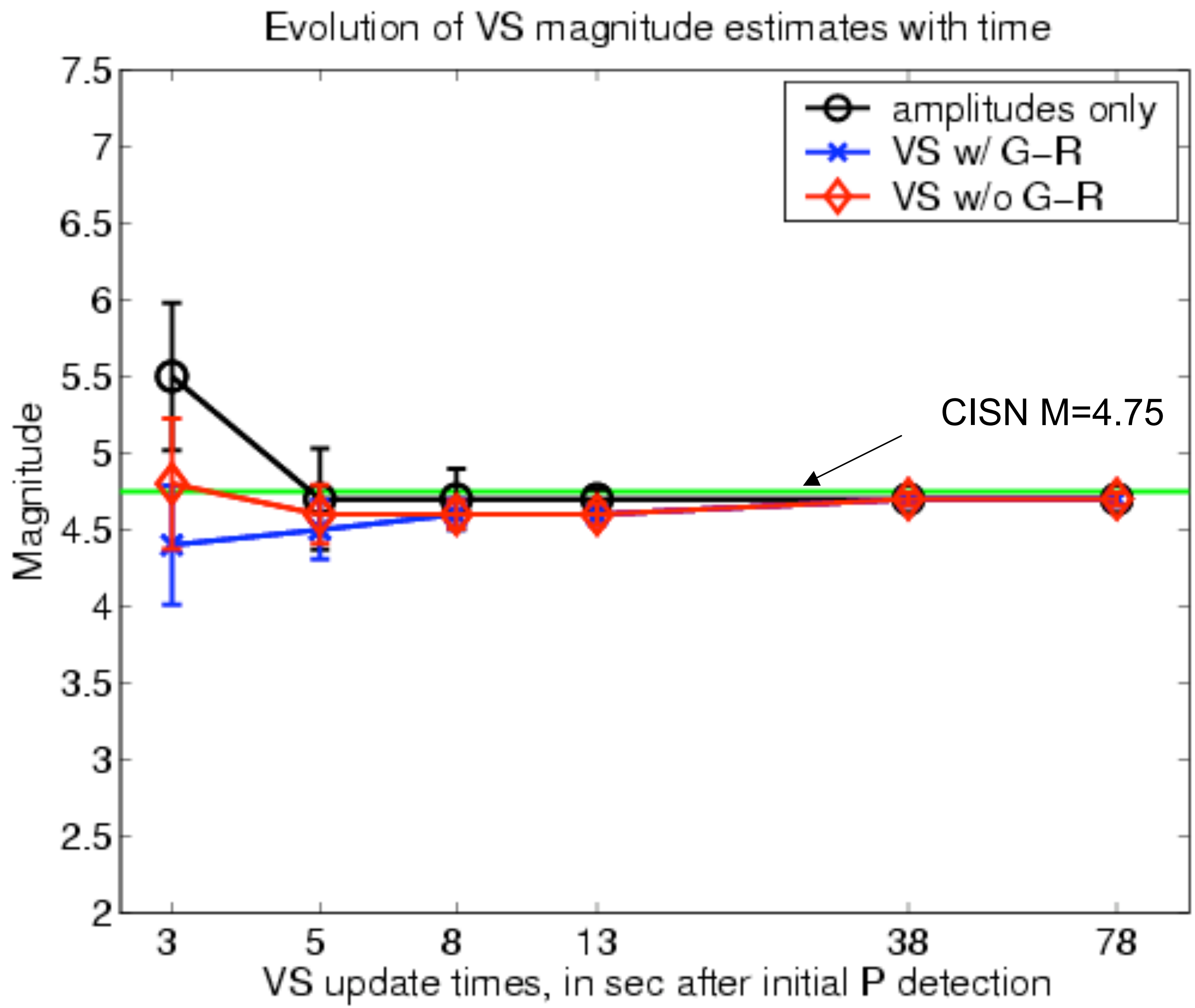
High station density



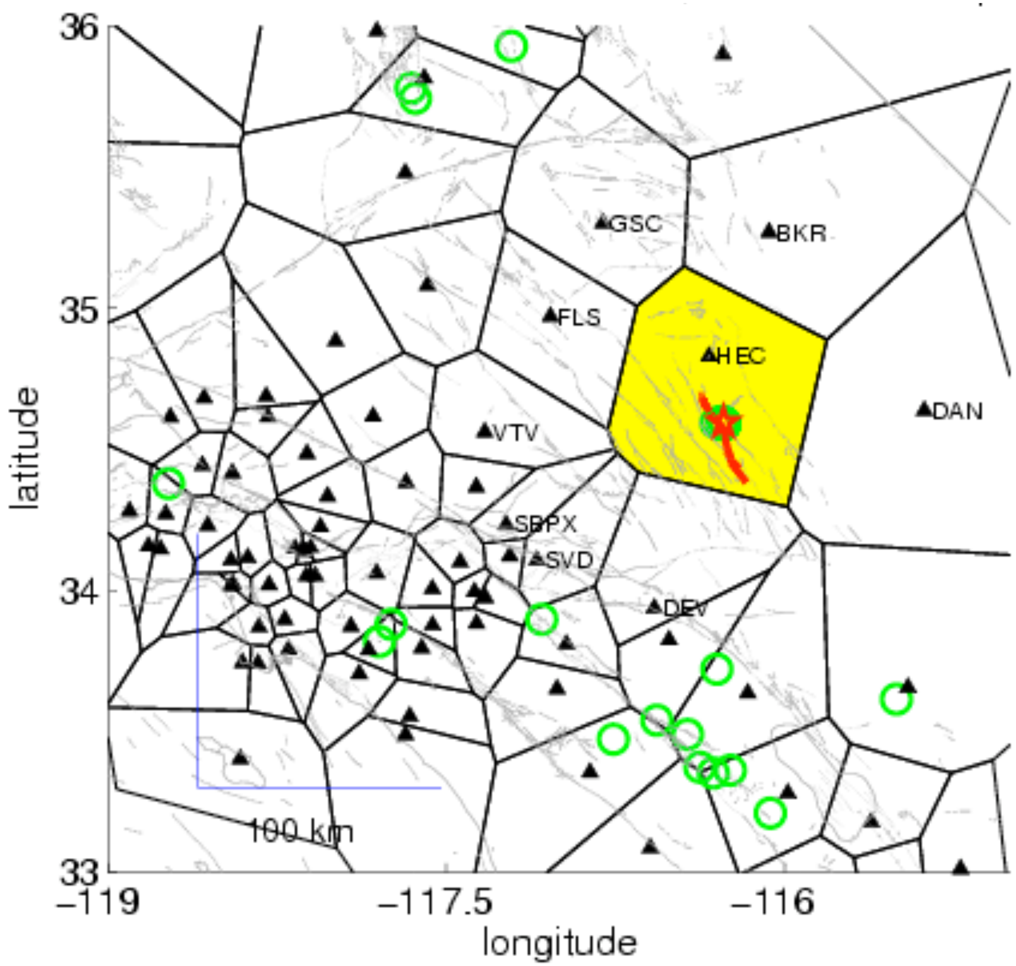
Station	Voronoi Area (km^2)
SRN	436
CPP	556
WLT	269
PLS	710
MLS	612
STG	1591
LLS	1027



- Polygons are voronoi cells (nearest neighbor regions)
- 1st arrival at SRN implies EQ location within SRN voronoi cell
- Green circles seismicity in preceding 24 hrs


Evolution of VS magnitude estimates with time
7.5
7
6.5
6
5.5
5
4.5
4
3.5
3
2.5
2
Magnitude
amplitudes only
VS w/ G–R
VS w/o G–R
CISN M=4.75
3
5
8
13
38
78
VS update times, in sec after initial P detection

16 October 1999 M=7.1 Hector Mine, Califoria, Earthquake



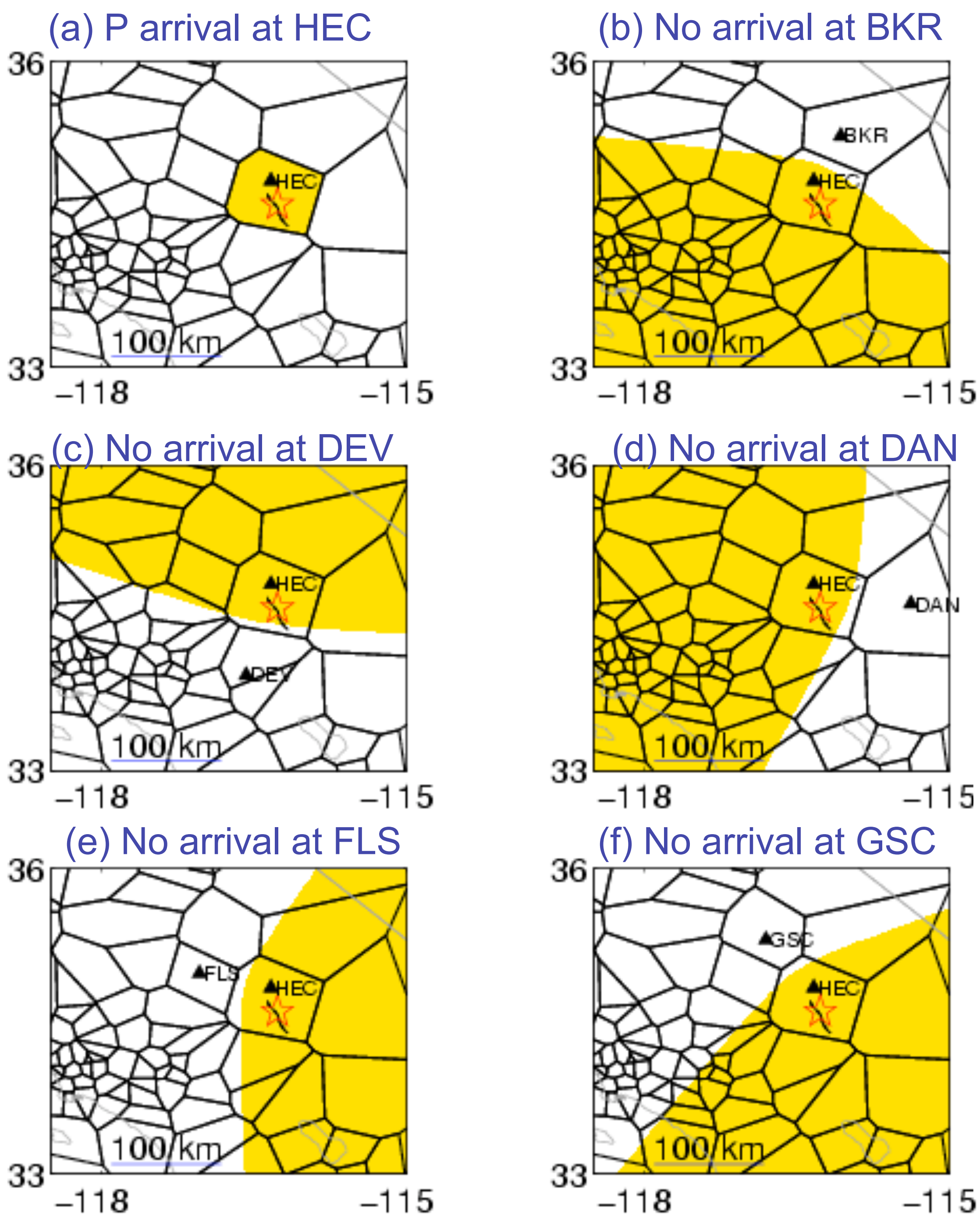
Voronoi cells from Hector

Station	Voronoi Area (km^2)	Epi. dist (km)	Fault dist. (km)	P arrival (sec)
HEC	5804	26.7	10.7	6
BKR	8021	77.1	68.6	13.7
DEV	3322	78.8	62	13.9
DAN	9299	81.8	77.6	14.5
FLS	2933	81.8	67.9	14.5
GSC	4523	92.5	77.6	16.2
SVD	1513	93.4	88.2	16.3
VTV	2198	97.2	89.2	16.9

Voronoi cells from Yorba Linda

Station	Voronoi Area (km^2)	Epi. Dist (km)	P arrival (sec)
SRN	436	9.9	2.2
CPP	556	17.1	3.1
WLT	269	19.1	3.65
PLS	710	20.5	3.95
MLS	612	22.1	4.05
STG	1591	28.1	4.9
LLS	1027	30.1	5.9

- Previously observed seismicity within HEC's voronoi cell are related to mainshock

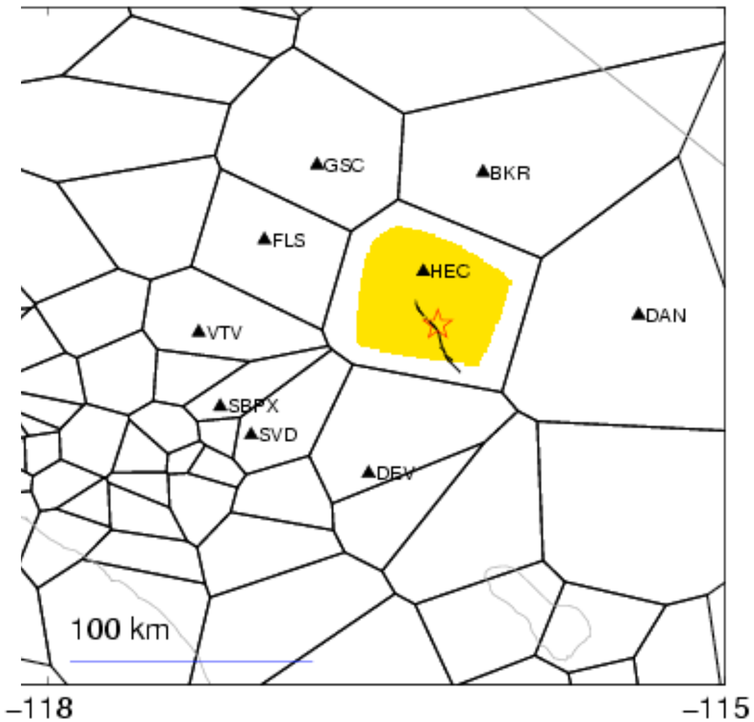


Constraints on location from arrivals and non-arrivals 3 sec after initial P detection at HEC

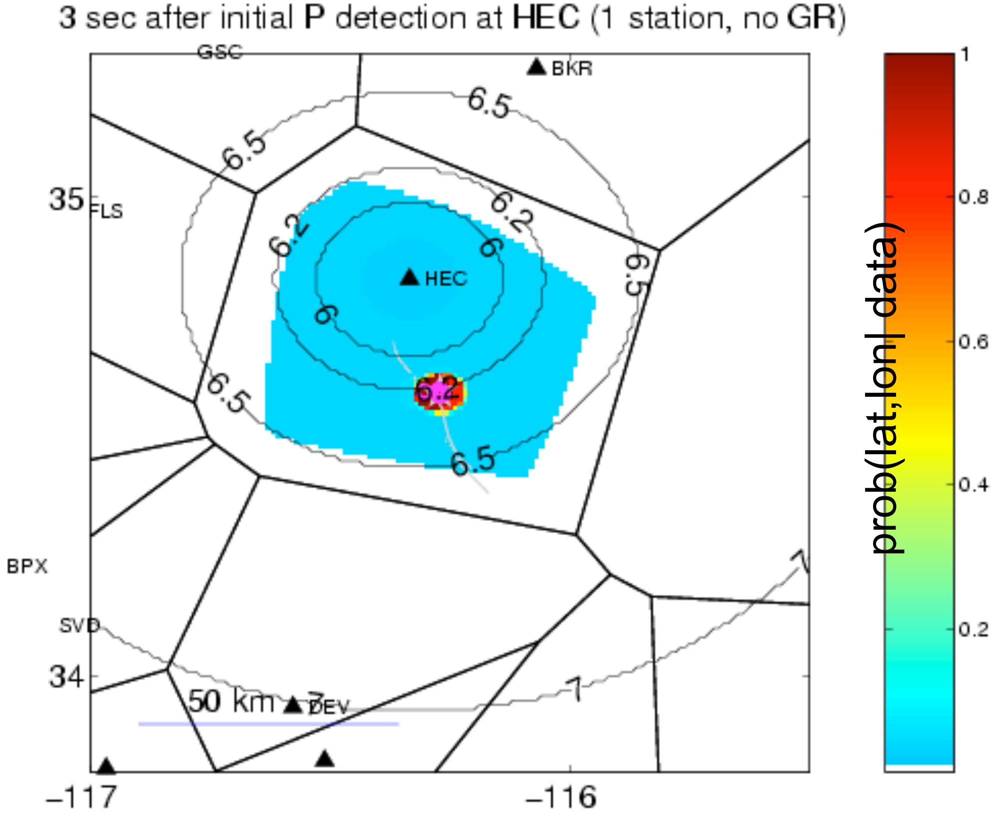
$$R_i - R_1 \geq \Delta T \times \alpha$$

$$\Delta T = 3 \ \mathrm{sec}$$

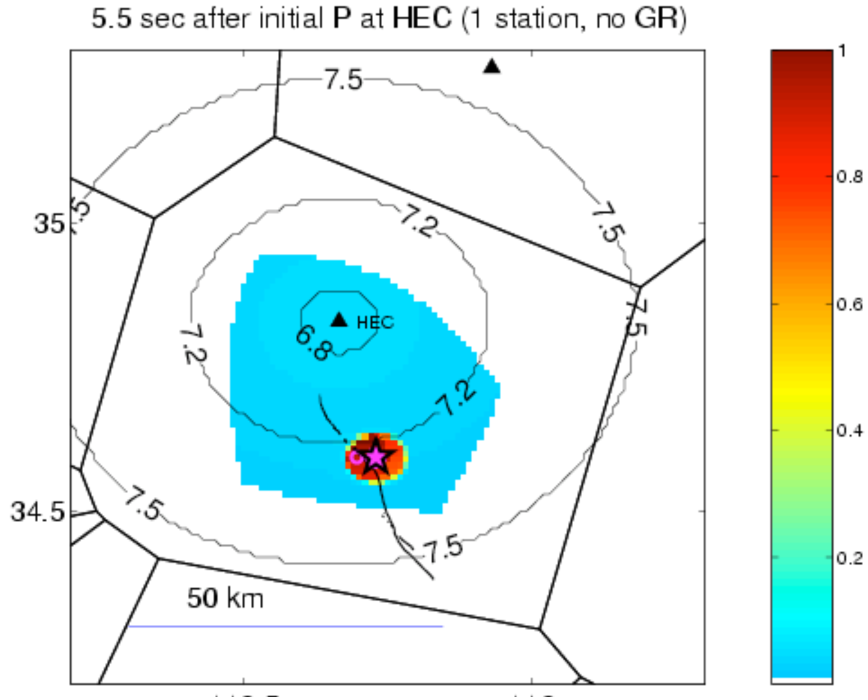
$$\alpha \approx 6 \ km/s$$

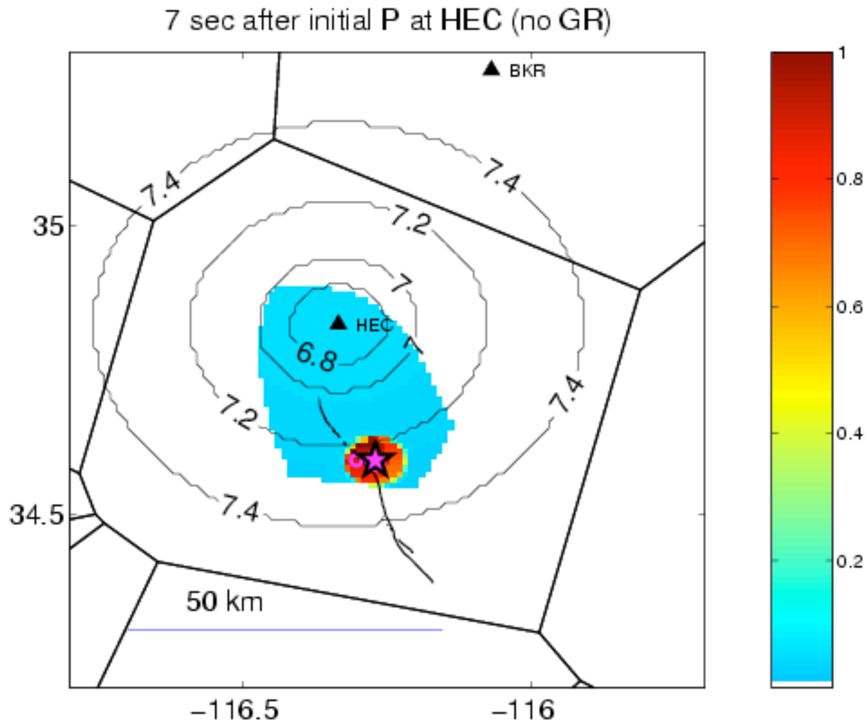


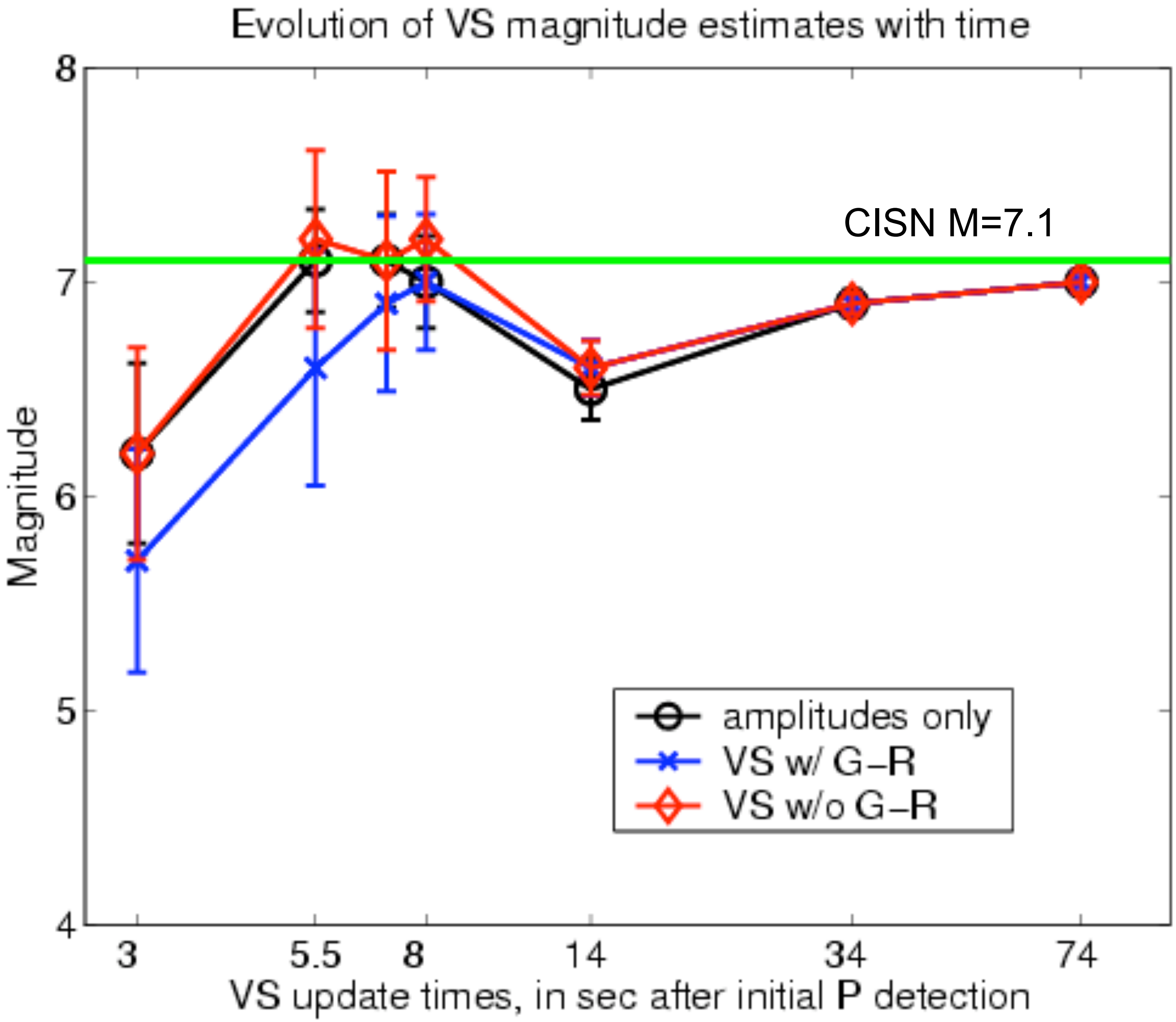
Evolution of single station (HEC) estimates



Est. time	M (no GR)	M (GR)
3	6.2 (0.5)	5.7 (0.52)
5.5	7.2 (0.42)	6.6 (0.55)
7	7.1 (0.33)	6.9 (0.41)

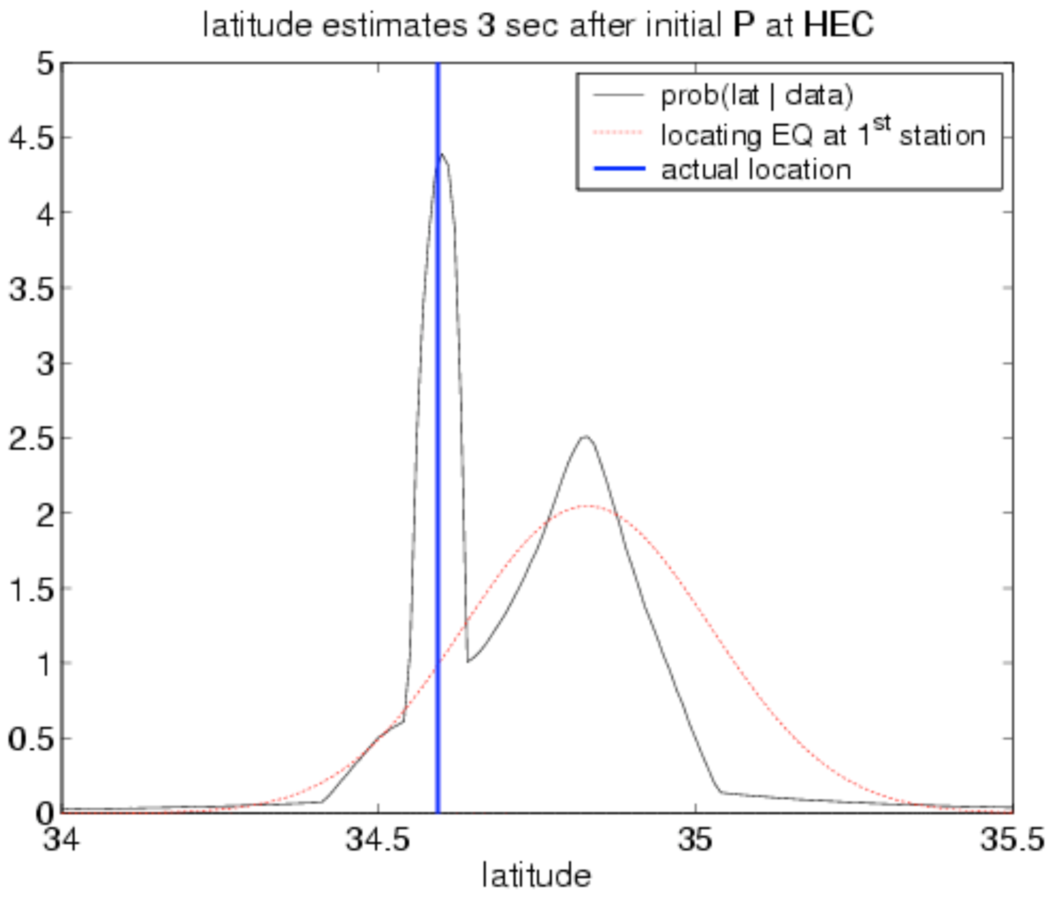


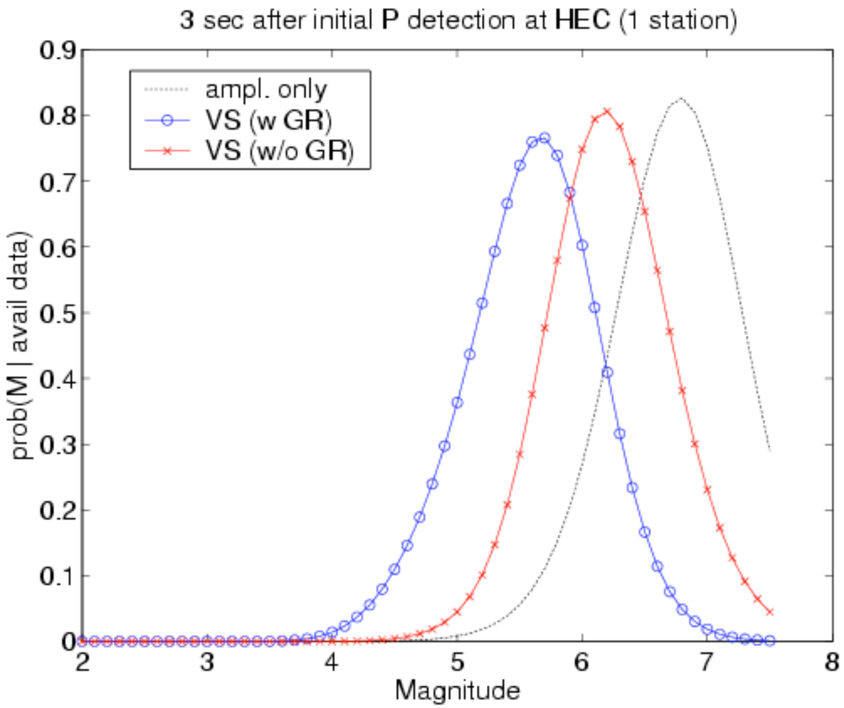




Evolution of VS magnitude estimates with time
CISN M=7.1
Magnitude
8
7
6
5
4
3
5.5
8
14
34
74
VS update times, in sec after initial P detection
amplitudes only
VS w/ G−R
VS w/o G−R

Marginal pdfs for Hector Mine, 3 sec after initial P detection





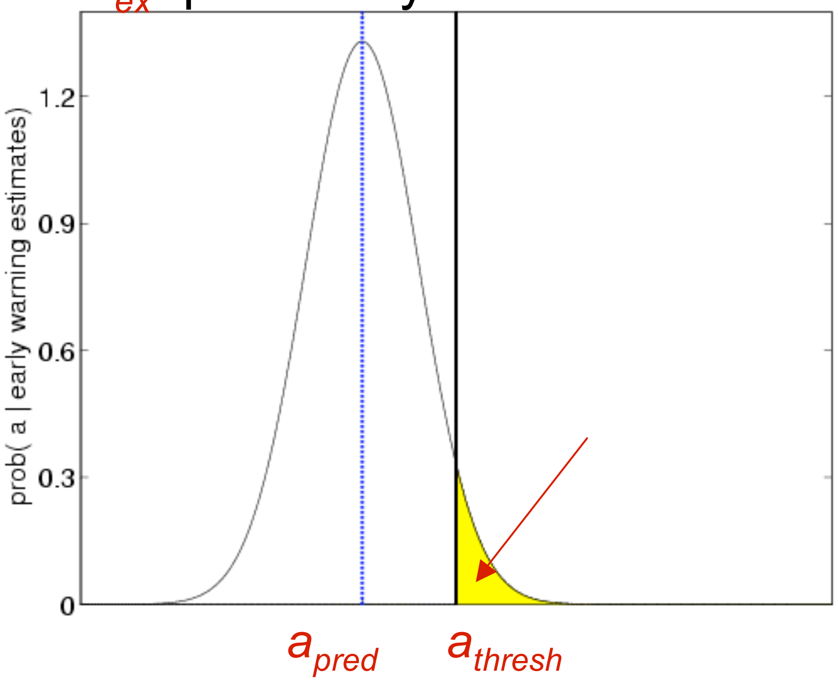
- Prior information is important for regions with relatively low station density
- Magnitude estimate can be described by by Gaussian pdfs; location estimates cannot
- Possibly large errors (~60 km) in assuming the epicenter is at the 1st triggered station

Cost-benefit analysis for early warning users

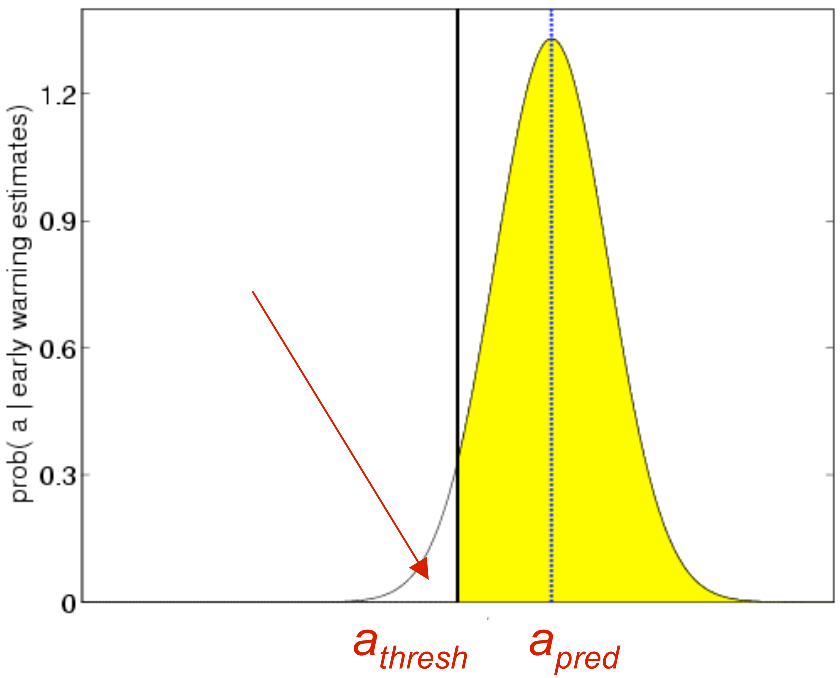
a = actual peak ground motion level at user site (we don't know this)
a_{thresh} = ground motion level above which damage occurs
a_{pred} = predicted ground motion level from EWS
σ_{pred} = uncertainty on predicted ground motion level

Assume for now that user initiates actions when $a_{pred} > a_{thresh}$

when $a_{pred} < a_{thresh}$
P_{ex}=probability of missed alarm



when $a_{pred} > a_{thresh}$
$1\text{-}P_{ex}$=probability of false alarm



$\$C_{damage}$ = cost of damage if no action was taken and $a > a_{thresh}$

$\$C_{act}$ = cost of initiating action; also the cost of false alarm

$\$C_{ratio} = \$C_{damage} / \$C_{act}$

state of nature	prob. of state of nature given a_{pred}	cost of "Do nothing"	cost of "Act"
$a > a_{thresh}$	P_{ex}	$\$C_{damage}$	$\$C_{act}$
$a < a_{thresh}$	$1-P_{ex}$	free!	$\$C_{act}$

It is cost-effective to act when $P_{ex}=P_{crit}=1/C_{ratio}=C_{act}/C_{damage}$

user threshold

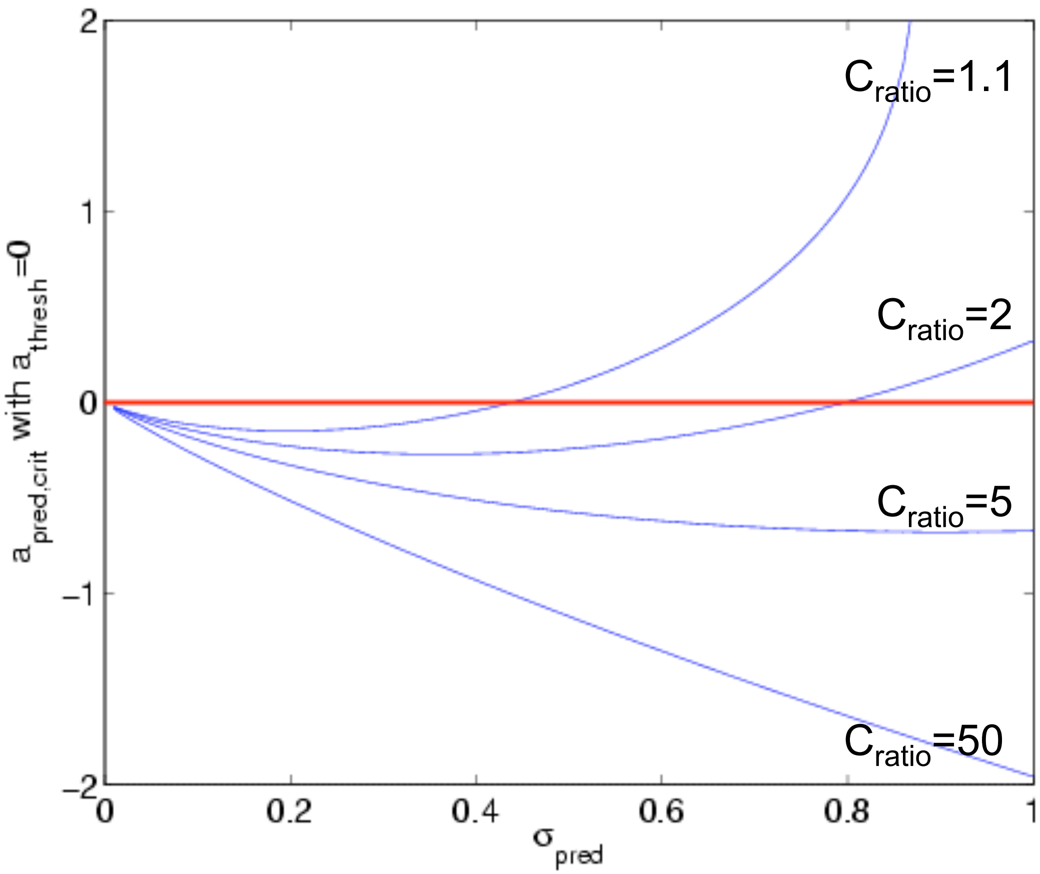
$$a_{pred,crit} = a_{thresh} - \sigma_{pred}\sqrt{2}\left[erf^{-1}\left(1 - \frac{\sqrt{2\pi}\,\sigma_{pred}}{C_{ratio}}\right)\right]$$

predicted ground motion level at which user should act

uncertainty on predicted ground motion

error function

$$a_{pred,crit} = a_{thresh} - \sigma_{pred}\sqrt{2}\left[erf^{-1}\left(1 - \frac{\sqrt{2\pi}\sigma_{pred}}{C_{ratio}}\right)\right]$$

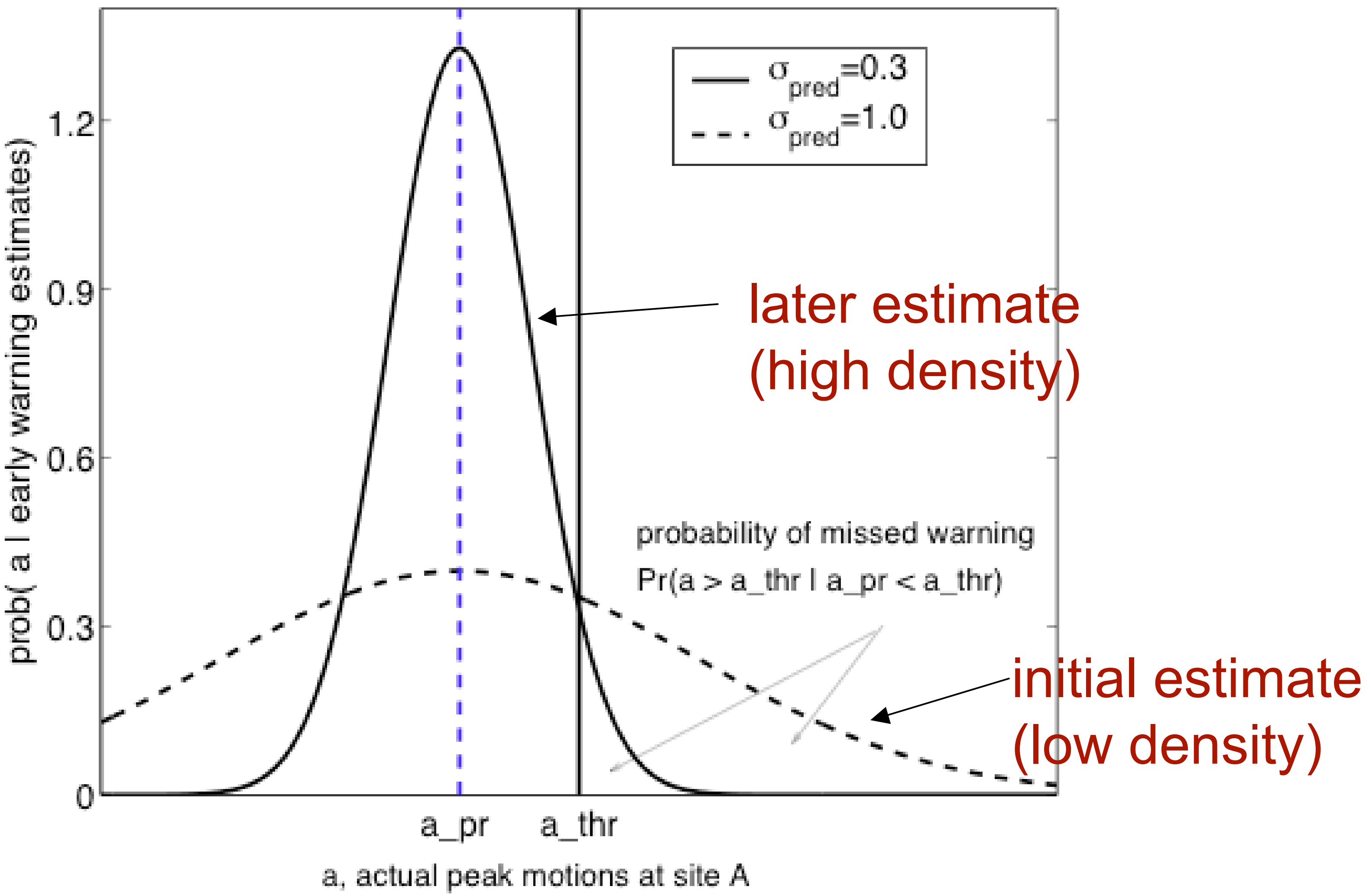


$$C_{ratio} = C_{damage} / C_{act}$$

- Applications with *C_{ratio} < 1* should not use early warning information
- *C_{ratio} ~ 1* means false alarms relatively expensive
- *C_{ratio} >> 1* means missed warnings are relatively expensive; initiate actions even when *a_{pred}<a_{thresh}*, *need to accept false alarms*

- Simple applications with *C_{ratio} >> 1* stopping elevators at closest floor, ensuring fire station doors open, saving data

From the user's perspective, it is optimal to wait whenever possible (the real reason we procrastinate)

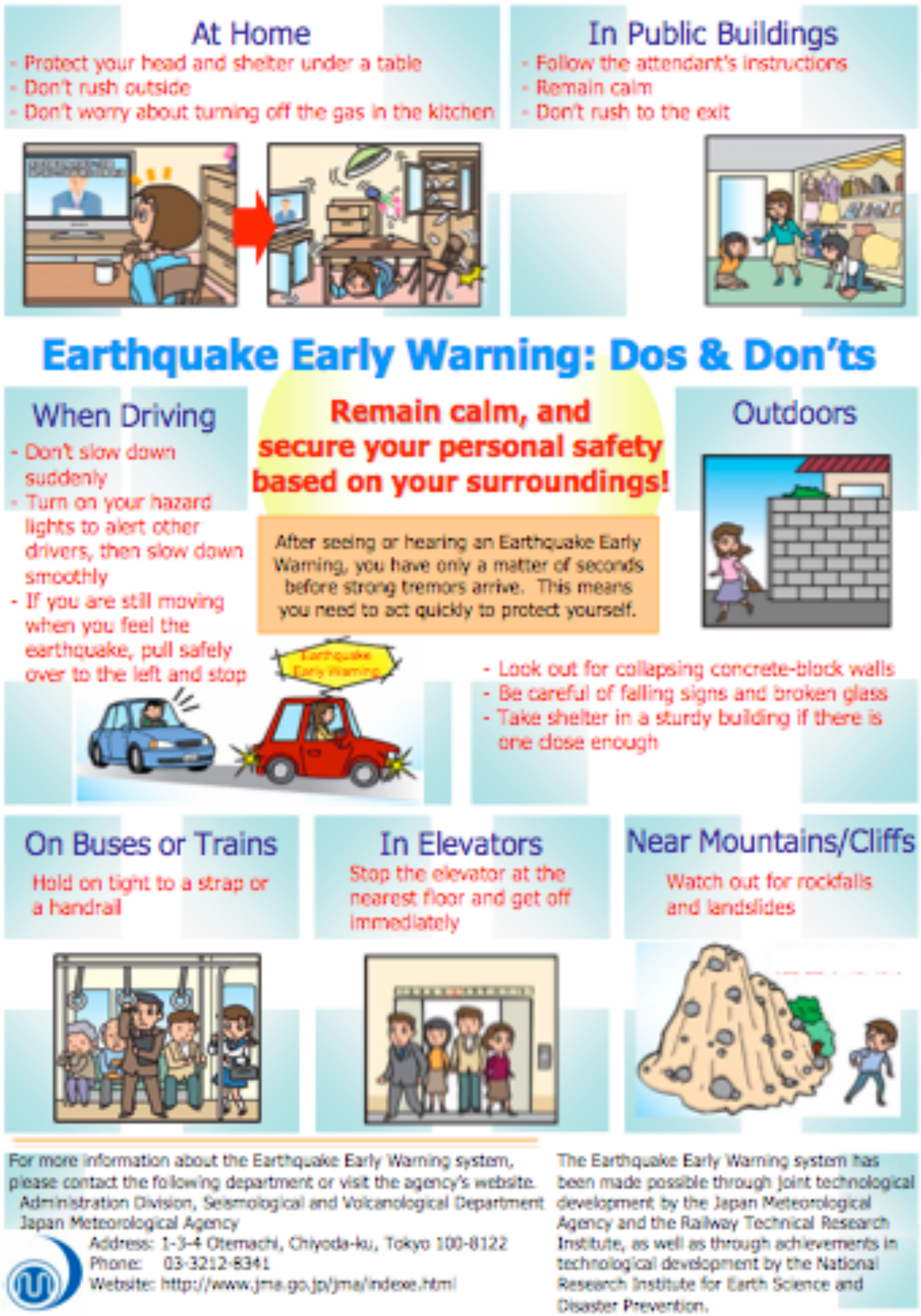


JMA Implementation

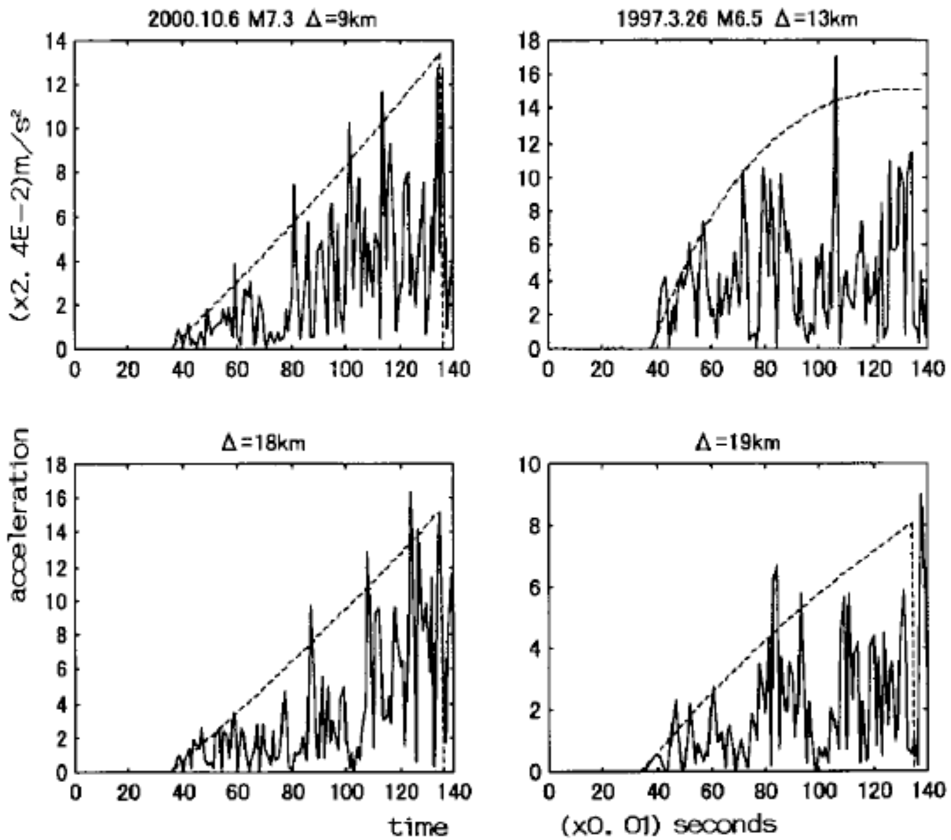
- JMA releasing warning information via TV, radio as of Oct 2007
- Criteria for releasing warning:

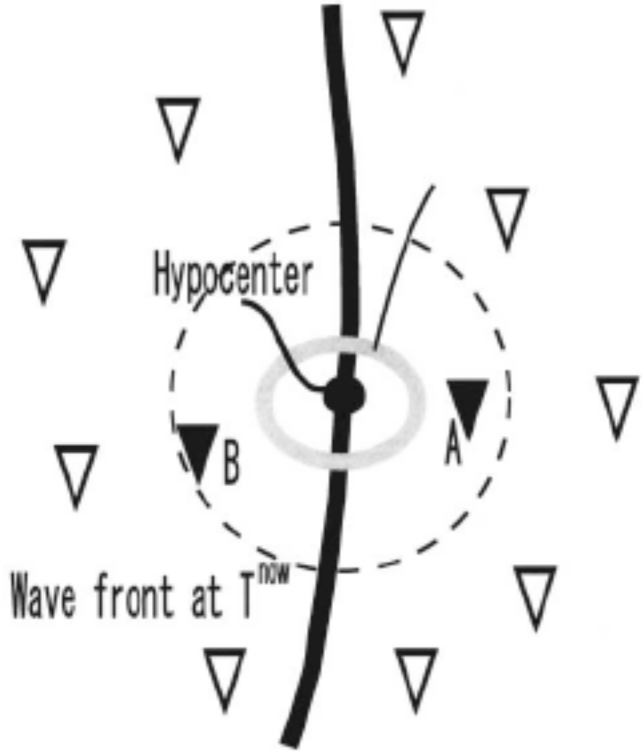
  more than 2 stations recording event, and predicted JMA intensity > 5
- Type of information: regions to experience JMA intensity 5 or greater, epicenter location
- Method: Odaka 2003, Horiuchi 2005
- http://www.eqh.dpri.kyoto-u.ac.jp/~masumi/eq/ews.htm

  (Masumi Yamada website)
- http://www.jma.go.jp



JMA methodology



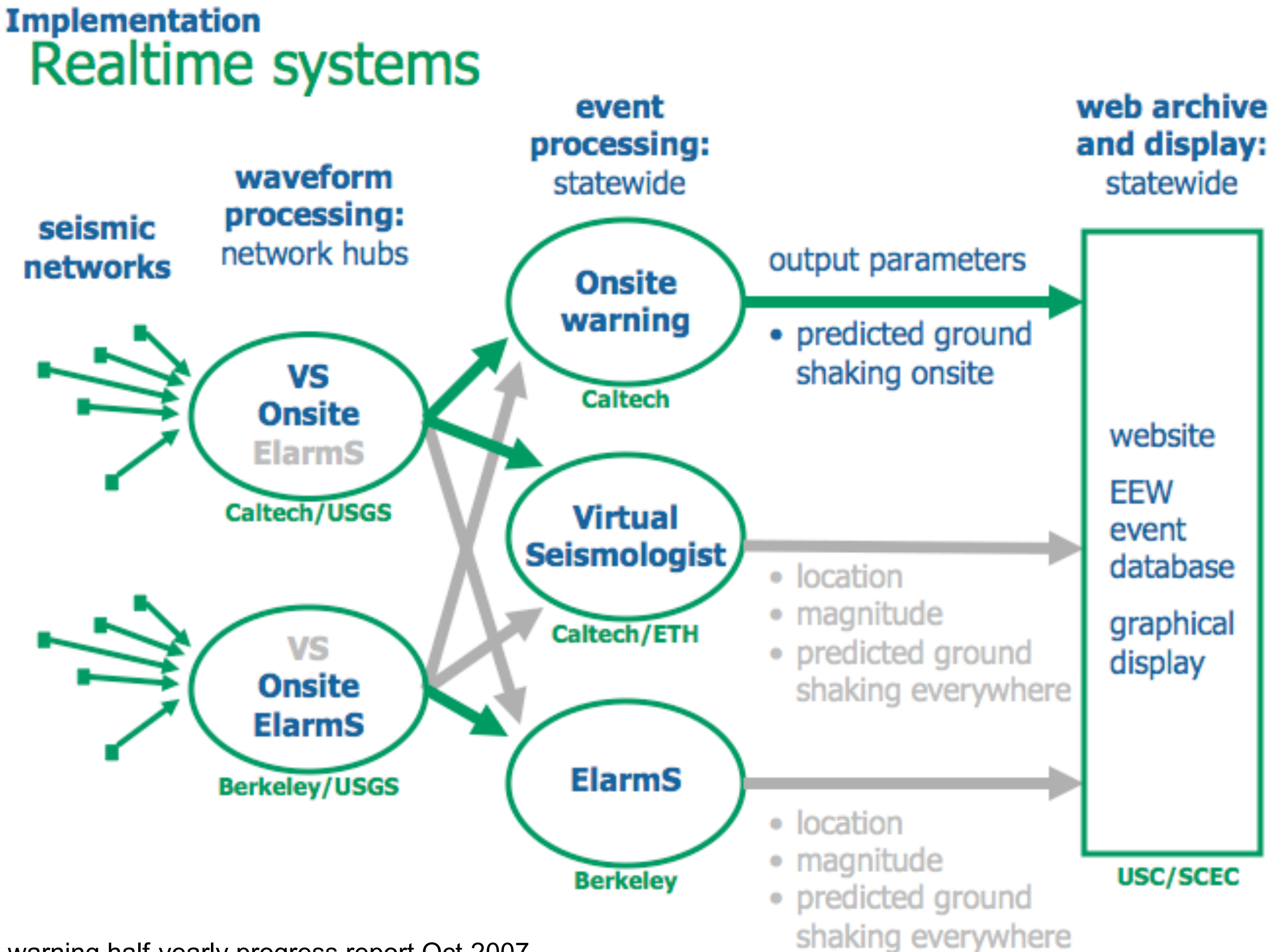


Horiuchi, 2005

$$Bt\exp(-At)$$

Odaka, 2003

CISN early warning implementation



European implementation

- SAFER (Seismic Early wArning for Europe)
- Elarms in INGV Rome
- Virtual Seismologist in Switzerland
- RT-mag, RT-loc in Naples
- All focused on off-line implementation

Conclusions

- Bayesian framework allows integration of many types of information to produce most probable solution and uncertainty estimates
- Robustness of source estimates is proportional to station density. Prior information is useful in regions with low station density, but increases complexity of information
- Need to carry out Bayesian approach from source estimation through user response. Gutenberg-Richter relationship can reduce false alarms at cost of increasing vulnerability to missed alarms
- Need dialogue between seismologists developing warning systems, and potential user community
- Certain level of false alarms must be tolerated if user wants to ensure proper actions are taken during the infrequent, damaging event

Thank you