Forecasting earthquake ground motions

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"Civilisation exists by geological consent, subject to change without prior notice."

William Durant, Historian

POLARIS

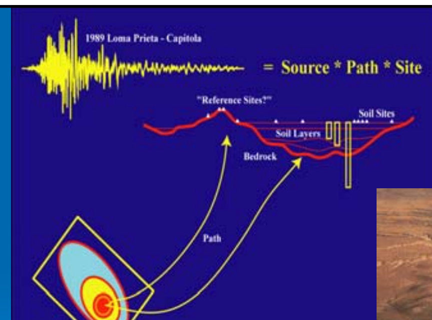
Outline

- What is "forecasting earthquake ground motions"?
- Why is it important?
- How are earthquake ground motion predictions used?
- Empirical ground-motion predictions
- Modeling of earthquake ground motions
- New synergy between data on ground motion amplitudes and engineering effects

What is "forecasting earthquake ground motions" ?

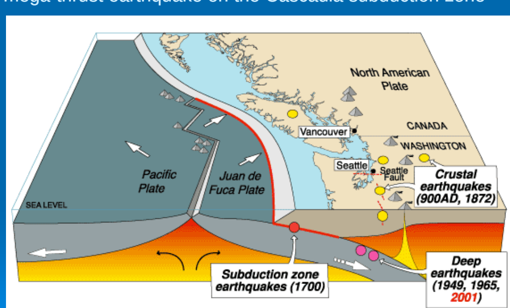
"Journalists and the general public rush to any suggestion of earthquake prediction like hogs toward a full trough"
(Charles F. Richter, 1977)

Our goal is to predict the ground motions that will occur at a site (eventually): there are generally two cases of interest…..



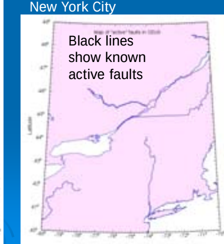
1. In some cases we want to predict the ground motions that will result at a site when a known fault ruptures (considering specific source, path, site effects)

Example: predict the ground motions in Vancouver for a M9 mega-thrust earthquake on the Cascadia subduction zone

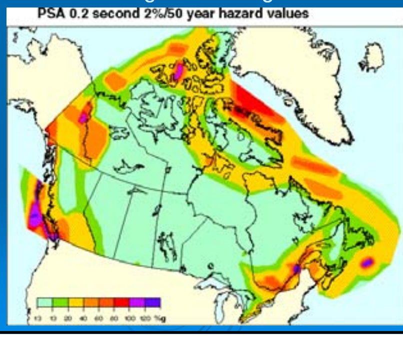


Case 2 - we want to predict the ground motions that are expected (at a specified probability level) due to earthquakes from all sources within the region…. considering all active fault sources

Example: Estimate ground motions for an engineered structure in New York City



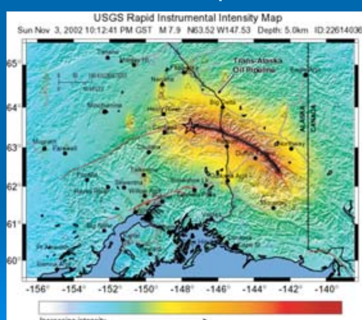
Example: National Building Code Seismic Parameter maps – used in the routine seismic design of buildings



Why is it important?

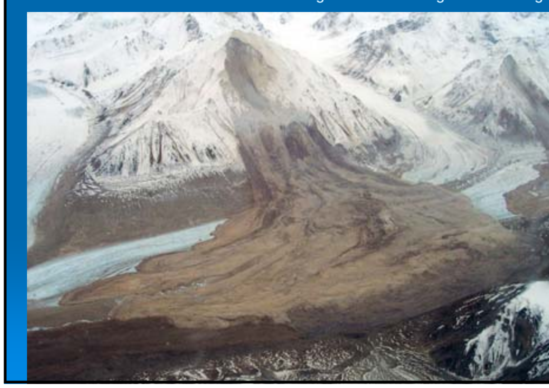
(to be able to forecast the ground motions)

Consider the M7.9 Denali, Alaska earthquake of 2002



Fault rupture>300km
Displacement>8 m

Denali event caused little structural damage due to remote location, but thousands of landslides attest to the strength and extent of ground shaking



M7.9 earthquake, 2002, Denali, Alaska

Strike-slip in M7.9 Denali, Alaska earthquake of 2002

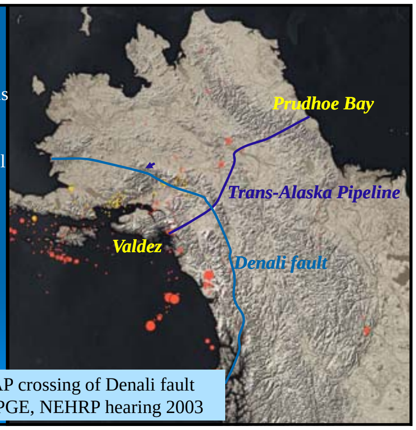
Trans-Alaska Pipeline

1 to 2 million barrels per day

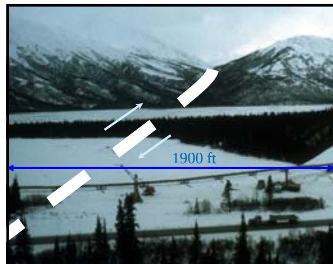
17% of US crude oil

80% of Alaska's revenue

1977 to 2003,
14 billion barrels



Note: Slides on TAP crossing of Denali fault from Lloyd Cluff, PGE, NEHRP hearing 2003



Construction at Denali fault crossing

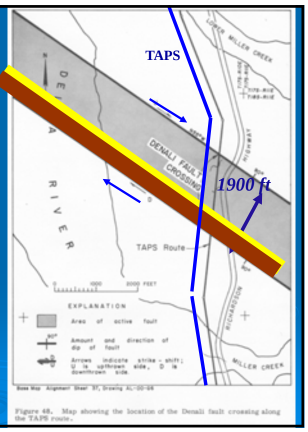
Denali fault-crossing design

- **Earthquake Magnitude 8.0**
- **Horizontal, 20 feet**
- **Vertical, 5 feet**
- **Minor compression**

November 3, 2002 rupture

- **Earthquake magnitude 7.9**
- **Horizontal Displ, 18 feet**
- **Vertical displ, 2.5 feet**
- **Minor compression**

Pipeline performed as designed, without spilling one drop of oil



Denali Fault Crossing (Before and After)

Before fault displacement **After 18 feet of fault displacement**

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When expected ground motions are correctly predicted, design to accommodate the motions and loads is possible. Therefore the challenge is to predict the ground motions.

This is the goal of engineering seismologists, and also defines the seismology-engineering interface.

Two typical types of earthquake ground motion forecasts

- Ground motion prediction equations to describe shaking in seismic hazard analysis (generic):

  Shaking=fn(M, Dist, freq)

- Simulations to predict motions at a site for a particular rupture scenario (specific)

Seismic hazard analysis to determine design ground motions

- Determine the level of ground shaking expected at a site - with an acceptable probability of being exceeded.
- If ground motions are specified, structures can be designed to withstand the earthquake-induced loads

Collapse of engineered buildings due to ground shaking is entirely preventable.

Seismic hazard analysis

- Used to produce seismic hazard zoning maps, as used in typical building codes
- Site-specific hazard analysis for critical structures such as dams, nuclear power plants, etc.
- Types differ in level of detail and reliability objectives

Typical probability levels for earthquake design ground motions

- 1/2500 per annum (= 2% in 50 years) for modern building codes
- 1/10,000 p.a. (=1% in 100 years) for dams and most other critical structures
- 1/100,000 to 1/1,000,000 p.a. for nuclear power plants/ nuclear waste

Seismic Hazard Methodology

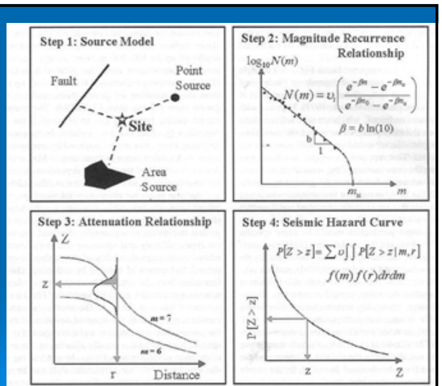
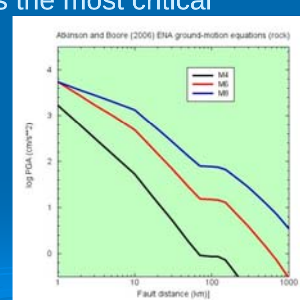


Figure 1. Steps involved in the conventional Cornell-McGuire probabilistic seismic hazard assessment (PSHA) (after Reiter, 1990).

The 3rd piece of seismic hazard analysis (a generic ground-motion forecast) is the most critical

- define ground shaking amplitude as a function of magnitude and distance
- Need relationships for ground-motion parameters=fn(M,D)



Measures of ground-motion intensity for engineering purposes

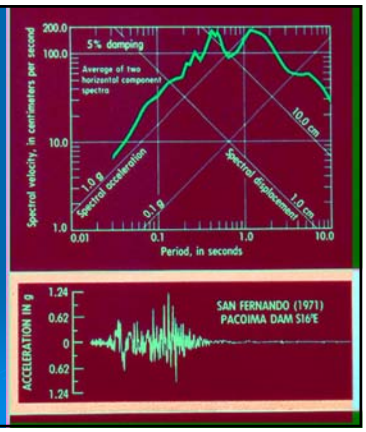
- PGA, PGV
- Response spectra (elastic, inelastic)
- Others (avg. spectra over freq., power spectra, Fourier amplitude spectra)
- Time series

Response spectrum: Describes ground motion in terms of building response

Photo: Jeffrey S. Barker, Department of Geological Sciences, Binghamton University

- Tall buildings respond to low frequency shaking (10 story building has natural frequency of 1 Hz)
- Small buildings respond to high frequency shaking (2 story building has natural frequency of 5 Hz)
- Acceleration that building will "feel" depends on its natural frequency

Response spectrum plots the maximum displacement (or velocity or acceleration) of a damped SDOF oscillator in response to an input ground motion



Earthquake ground motion characteristics

- Large earthquakes are rich in energy at low frequencies (to which long-period structures like bridges and high rises are sensitive)
- Small earthquakes nearby are rich in high-frequency energy (to which low-rise buildings respond)
- Larger magnitudes and larger distances result in longer duration, which is important if structure is sustaining damage (nonlinear)

How to describe ground-motion characteristics?

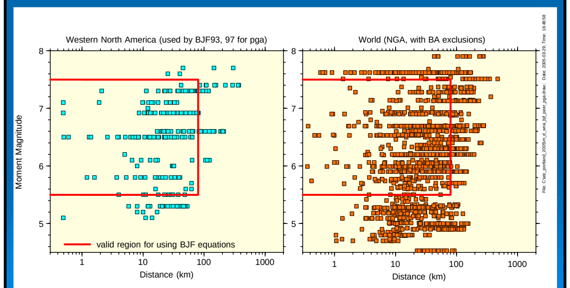
Response spectra are the most useful input to many engineering analysis of earthquake response.

So we need ground-motion prediction equations for response spectra (=fn(M,dist)) at each vibration period for use in seismic hazard analysis.

Empirical ground-motion prediction equations

The "Brute Force" approach to ground-motion forecasting: use database of ground motions and regress against predictive variables such as magnitude, distance and site condition

WNA strong motion data: 1995 vs. 2005 (data for crustal events in active tectonic regions)



Empirical regression: typical form

log y = c1 + c2(M-6) +c3(M-6)**2 – b log R – g R + S

Common 2 step regression approach as follows

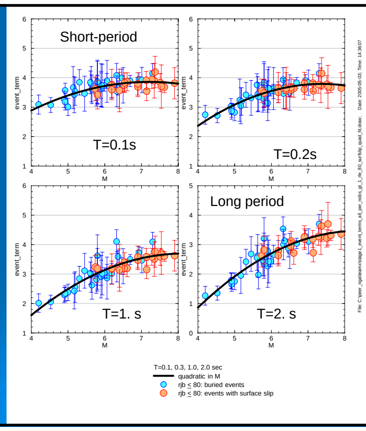
Step 1: Given Yij, Rij
Find Ei(i=1,n), Sj(j=1,m), b, g
Fit Yij values to:
Log Yij= Ei + Sj – b log Rij – g Rij

- Yij = amplitude from earthquake i at stn j
- Rij = distance from i to j
- Ei = source ampl.(R=1) for quake j
- Sj = site response at j
- b = geometric spreading coefficient
- g = anelastic attenuation coefficient

Step 2: Given Ei, M
Find c1, c2, c3
Fit source terms to:
E = c1 + c2(M-6)
+ c3(M-6)**2

- c1, c2, c3 are the coefficients

Some interesting recent empirical results:
Observed M-scaling for earthquakes from active tectonic regions (Boore and Atkinson, 2006)
Note magnitude saturation!



Intriguing questions in empirical ground-motion forecasting

- Do ground motions really saturate (or over-saturate) at short-periods? What are the hazard implications?
- Scatter (aleatory variability) in ground-motion prediction equations is large – and very important for low probability applications. Can it be reduced?

" Uncertainty is no stranger to assessments in the Earth Sciences, but it has rarely been a welcome guest at such functions."

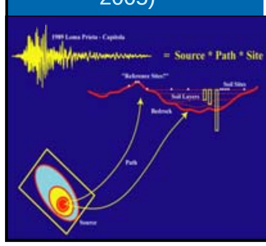
Working Group on California Earthquake Probabilities, 2002-2031.

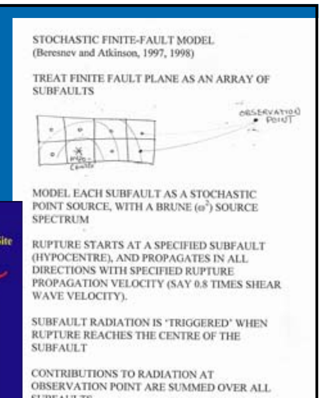
Modeling of earthquake ground motions

Simulating ground motions to:

- understand source/attenuation properties of earthquakes;
- supplement a sparse database in the development of regional ground-motion relations
- Predict ground motions at a site for a particular rupture scenario

Stochastic finite-fault simulation model (Beresnev and Atkinson, 1997; Motazedian and Atkinson, 2005)




STOCHASTIC FINITE-FAULT MODEL
(Beresnev and Atkinson, 1997, 1998)

TREAT FINITE FAULT PLANE AS AN ARRAY OF SUBFAULTS

MODEL EACH SUBFAULT AS A STOCHASTIC POINT SOURCE, WITH A BRUNE (ω^2) SOURCE SPECTRUM

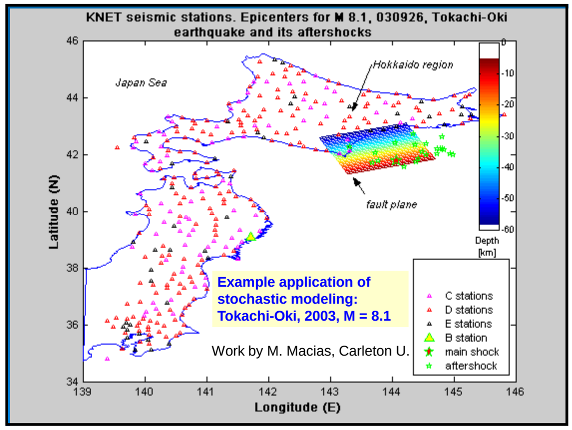
RUPTURE STARTS AT A SPECIFIED SUBFAULT (HYPOCENTRE), AND PROPAGATES IN ALL DIRECTIONS WITH SPECIFIED RUPTURE PROPAGATION VELOCITY (SAY 0.8 TIMES SHEAR WAVE VELOCITY).

SUBFAULT RADIATION IS 'TRIGGERED' WHEN RUPTURE REACHES THE CENTRE OF THE SUBFAULT

CONTRIBUTIONS TO RADIATION AT OBSERVATION POINT ARE SUMMED OVER ALL SUBFAULTS.

Parameters needed to apply stochastic finite-fault model

- Stress drop for earthquake subfaults
- Geometry of fault
- Description of ground-motion attenuation with distance
- Model of duration with distance
- Optional:
  - Direction of rupture propagation (can assume random or bilateral)
  - Slip distribution on fault (can assume random)



Model ground motions using stochastic finite fault model – work by Macias with EXSIM program of Motazedian and Atkinson (2005 BSSA)

Attenuation model:

- geometric attenuation with slope b=-1
- (note no data at R<40 km)
- anelastic attenuation: $Q = Q_0\ f^{\,eta}$

  $Q_0 = 175$, $eta = 0.76$
- Duration model for increasing duration with distance (about 0.09R)

EXSIM model parameters (cont.)

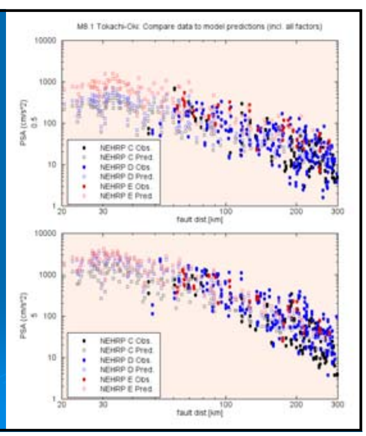
Source: 120 bar stress parameter (M8.1)
50% pulsing area
prescribed slip distribution (Yagi, 2004)

Site: Generic amplification function for C, D, E sites, by adjusting standard models (quarter-wavelength estimates for typical profiles) to minimize residuals by site class (nonlinearity considered)

Other: Geologic variables for fore-arc, back-arc, Basin or non-basin, Cenozoic or Pre-Cenozoic are all significant modifiers to the site class functions

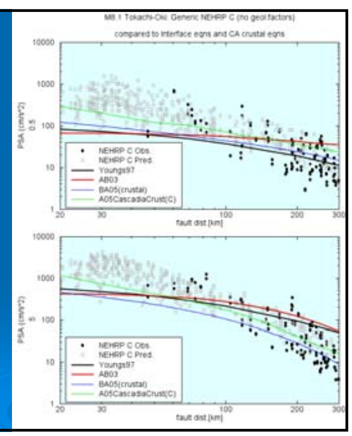
Note: this stress drop is higher than values for large global crustal events like 1999 M7.6 Chi Chi (40 bars using similar model)

Comparing data to model predictions (for observed site conditions): PSA at 0.5 and 5 Hz



Comparing model predictions (generic Class C) to various equations

(Note the equations were derived empirically, based on global databases – pre-2000 – for subduction events)



Implications

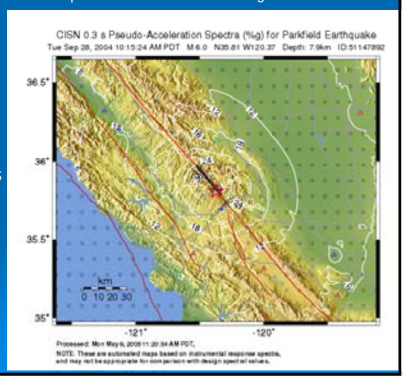
- Global empirical models may not do a satisfactory job of predicting future ground motions in a specific region
- Revision of models used in building code maps for great mega-thrust event are warranted

New synergy between data on ground motion amplitudes and engineering effects (MMI)

ShakeMap and Did You Feel It?

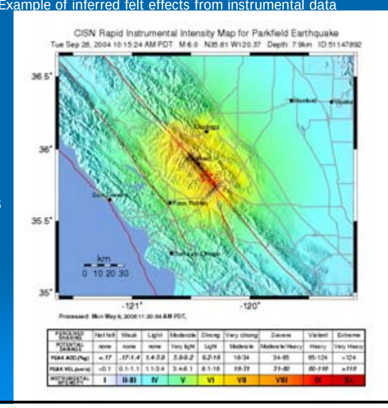
Example of measured instrumental ground-motions

ShakeMap: a powerful tool for describing instrumental ground-motion recordings and their implications for felt effects in near-real time
eg. PSA3Hz M6 2004 Parkfield CA



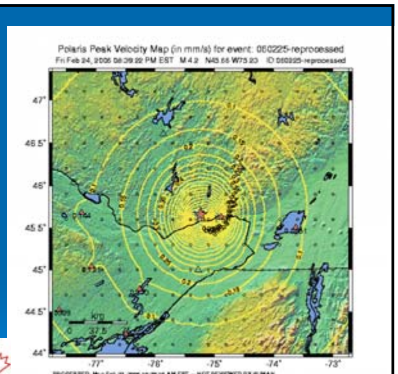
Example of inferred felt effects from instrumental data

ShakeMap: a powerful tool for describing instrumental ground-motion recordings and their implications for felt effects in near-real time
eg. M6 2004 Parkfield CA



ShakeMap has been implemented in Ontario, thanks to POLARIS www.shakemap.carleton.ca

POLARIS



ShakeMap for moderate M4.2 earthquake in SE Canada

Felt effects of Feb. 24, 2006 M4.2 event www.shakemap.carleton.ca

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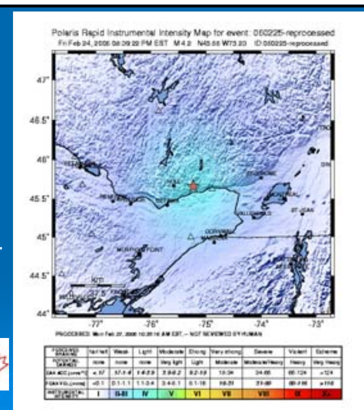
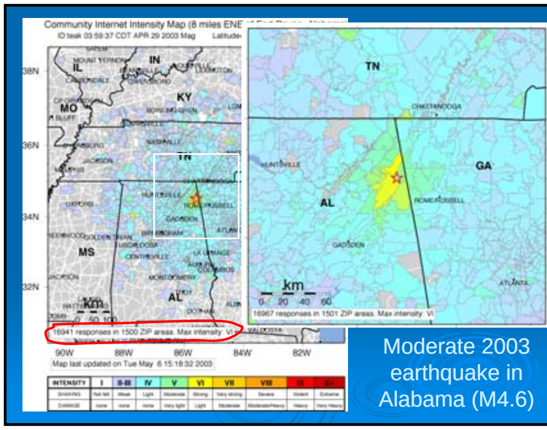
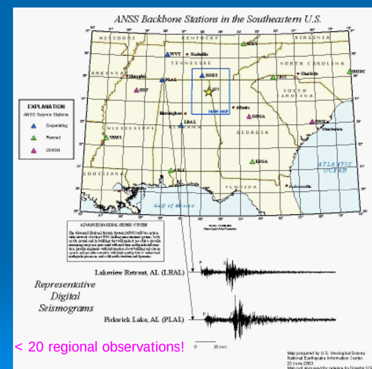




Moderate 2003 earthquake in Alabama (M4.6)

Instrumental data for Fort Payne, Alabama earthquake (2003)

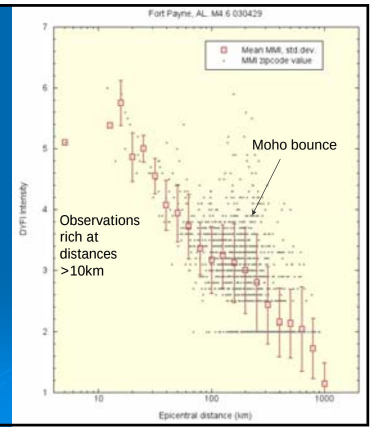


7 years of USGS "Did You Feel It?" data:
Over 3/4 Million Individual Responses Nationally

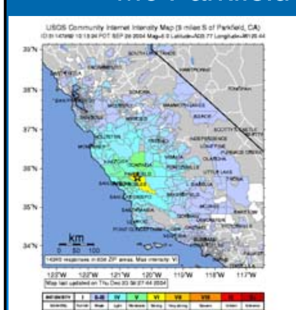
INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+
SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy

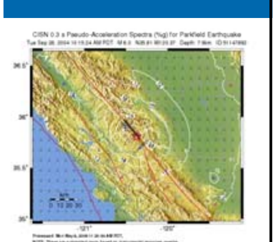
Decay of DYFI intensity with distance for an M4.6 Fort Payne, Alabama event:

Note stable behavior of mean intensity when binned in distance



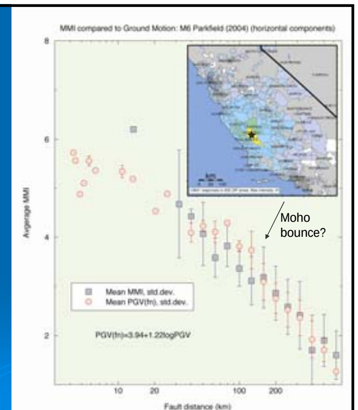
DYFI and ShakeMap data for 2004 M6 Parkfield earthquake





Note close correlation of instrumental (PGV) and MMI data (both binned by distance from fault): 2004 M6 Parkfield earthquake

People are good seismometers!



Implications

Combination of ShakeMap instrumental data and DYFI intensity data present new opportunities for understanding:

- Regional differences in source and attenuation characteristics of ground motions
- Ground motions experienced during large historical earthquakes

Conclusions

- Forecasting earthquake ground motions enables the cost-effective seismic design of engineered structures
- Ground-motion forecasting requires analysis/interpretation of earthquake source, path and site processes
  - Empirical regression analysis
  - Model-based interpretation
- A wealth of new data present unprecedented opportunities for furthering our understanding of earthquake processes

Thank-you