Is the Ongoing Earthquake Scaling Controversy Simply a Matter of Different Modelling Approaches and Underestimated Uncertainties?

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Compare EGF Coda & Direct for Wells and Northridge earthquake sequences Mayeda, Malagnini & others use Coda waves – find a breakdown

Malagnini et al., JGR 2010

Apply coda spectral ratio method and find breakdown in selfsimilarity

Coda? Always large in ratio is larger stress drop?



Baltay *et al.*, JGR 2010: Variation on coda spectral ratio method No breakdown in self-similarity

Similar examples could be found for Direct waves. Suggests analysis methods are contributing to uncertainty...

So .. apply multiple methods to the same earthquakes. Try and improve uncertainty measurements



A Note on Energy: Either "independent" measure  $\sim \Sigma v^2$ OR from  $f_c$ , proportional to  $f_c^3$  and Stress drop

# Extracting Source from Seismograms

Use Empirical Green's Function to Correct for Path and Site effects

Needs: Same location, depth, focal mechanism,  $\Delta M>1$  How similar is good enough?



time

# Wells, Nevada, 21 February 2008 M5.9





Within USArray TA Stress drops from coda waves for mainshock and 6 large (M>4) aftershocks Mayeda & Malagnini (2009)



Frequency (Hz)

# Mayeda & Malagnini Wells earthquake Sequence

coda spectral ratio method and find breakdown in self-

frequency

# Wells Aftershocks – Source parameters

#### Mayeda & Malagnini approach:

- 1. Coda Wave ratios: Mainshock / large aftershocks
- 2. Constrain M<sub>0</sub> ratio
- 3. Invert for 1 mainshock corner frequency
- 4. Invert for scaling relation between all events

#### What did I do?

- 1. Refit SAME coda ratios using methods I use for Direct:
  - 1. individual, no M<sub>0</sub> constraint
  - 2. individual, M<sub>0</sub> constrained as Mayeda & Malagnini
- 2. Direct: small EGF (M~3) for each large Ashock
  - 1. Fit individual ratios
  - 2. Select good ratios: Correlation Coefficient, STF, fit quality
- 3. Direct: Mainshock / large aftershocks
  - 1. Select and fit as for other ratios
  - 2. Are EGFs good enough?





## Wells: Direct Wave large / small EGF



## Wells Direct waves

#### Source Time Functions

#### **Spectral Ratios**



### Wells Direct: Main/large Ashock v. large Ashock/M~3 EGF M~4/M~3

#### M5.9/M~4





10

10

10

10

10<sup>-1</sup>



Coda

10<sup>0</sup>

Fit





10<sup>0</sup>

10<sup>1</sup>

10<sup>1</sup>

## Wells: Source Parameter Results

ALL Stress drops recalculated from fc following Madariaga 1976

frequency

division



Not so much Coda v. Direct, but it matters whether the earthquake is on top or bottom of ratio (frequency range of EGF assumptions)



# Mori, Abercrombie & Kanamori 2003: EGF Study of M>4 aftershocks of the 1994 Northridge earthquake

Source Time Functions from (*P wave*); small EGFs for 47 large **aftershocks** 

Measure pulse half-width (T/2) Boatwright 1980 → radius Energy: Kanamori *et al.* 1993, time domain



# **Direct wave Spectral Method: Fitting**



Grid search, and Quality Criteria to fits as for Wells.

# Northridge Coda Analysis M6.7 / Large aftershocks: Fitting

Walter and Gök fit approach



Malaghini and Mayeda fit approach



"Direct Wave" Individual fit approach



Boatwright,

Brune, Mo ratio free



# Northridge: Source Parameter Results



#### Older data – less good resolution

# Northridge: Comparison of Methods



Some correlation, but a LOT of variability



# Conclusions

- 1. A lot of uncertainty! Systematic and random errors can be larger than published
- 2. Different results if earthquake is on top or bottom of spectral ratio
- 3. Need to improve quantification of uncertainties, accept limitations, and understand method differences to solve controversy..

See Poster for more including: Investigation using repeating Parkfield SAFOD clusters, and multiple EGFs



# Map of Parkfield (CA) Area



# Poster



Christchurch, New Zealand Sequence 2010-?

# eted by rkfield,



Canterybury Aftershock Sequence: M7 1 M6-6.9 3 M5-5.9 54



Map showing the Darfield mainshock, the February M6.3 (Christchurch), the June M6.3 and the December M6.0 earthquakes, together with aftershocks above magnitude 3 and fault ruptures in Canterbury.



Earthquake mechanisms for the larger aftershocks since the start of the December 23 sequence.

Focal mechanisms for the M6.3 quake (red) and the larger aftershocks (blue) after the first 10 days of the sequence; yellow dots are locations of the other aftershocks. Note that focal mechanisms are offset from the true location for better visibility.













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Source Time Functions from Mori *et al.* 2003 (*P wave*)

Measure pulse half-width (T/2) Boatwright 1980 → radius Energy: Kanamori *et al.* 1993, time domain

#### Repeat 1: Direct Wave Spectral Methods Frequency domain division of P & S wave seismograms (multi-taper - Prieto)



# **Compare Regions**

Brazil RIS has high stress drop

Do all induced earthquakes have high stress drop?

Mining events – some do, some don't

Au Sable and Wells are high. some of Northridge are also fairly high



After Abercrombie and Leary (1993)

### Repeating Parkfield Sequence: FRO Target 1





8 earthquakes from 1986-2006, M~2



Excellent opportunity to compare event and EGF relative variation

### **Repeating Parkfield Sequence Target 1**



#### Variability by EGF & Station: Can we distinguish main events?



Colour by Main (Mean EGF), Black by EGF (Mean Mains), Colour by Main (Mean BStationys), Colour by Stn (Mean EGFs)



# Dreger *et al.*, 2007: Finite fault Models of SAFOD Repeaters



Calculate Source time functions using 1 EGF Model inter-station variability Uncertainties?



# Earthquakes in stable continental interiors are more widely felt



Lower seismic attenuation (Measured) and Earthquake source effect?

Large Intraplate earthquakes: infrequent, poorly recorded, BUT have the potential of being more damaging

M<sub>w</sub>7.3: Landers and New Madrid earthquakes *Important for:* <u>Earthquake physics</u> Seismic hazard

Nuclear monitoring

#### M5 2002 Au Sable Forks, NY, earthquake

Largest earthquake since the M6 1988 Saguenay earthquake

# Regional seismicity 0.1% of California





earniquaxe rocations by the carnon cooperative sensingraphic reteinion, os deological survey and the deological survey of carnoa. September 2006, Won-Young Kim, Lamont-Doherty Earth Observatory of Columbia University, <www.ldeo.columbia.edu/LCSN: M<sub>w</sub>5 Thrust earthquake Depth 11 km Damaged roads, bridges, chimneys and water lines *Best recorded sequence!* 





Viegas et al., JGR, submitted 2009

# Calculate and fit spectral ratios



EGF Analysis – relies on "perfect" EGF

How to choose pairs? High cross correlation Large  $\Delta M$ A source pulse?

What are the uncertainties on fit? Same answer top and bottom?

 $Good - both f_c$  are clear

# Stress Drop in NE USA: Previous studies



Shi et al. (1998),various ENA Xie *et al.* (1991),Goodnow, NY Li et al. (1995),Charlevoix, Quebec.

Previous studies suggested breakdown of self-similarity below ~M3. An artefact of limited frequency bandwidth. All Studies consistent at larger magnitudes

# What about Induced Earthquakes? Açu, Brazil



Aderson do Nascimento et al., 2004

- Events from cluster a
- Events from cluster b
- Events from cluster C
- Non clustered events

NE-SW structures, and anisotropy Crystalline basement rock



**NE Brazil** 

Açu - Maranhão, Brazil

## Açu earthquake source parameters



Tomic et al., Geophys. J. Int., 2009

# Açu, M2.1 earthquake

# Source time functions from EGF







Vary with azimuth – can estimate rupture velocity...

# Rupture velocity: Directivity



Shape of pulse radiated from earthquake depends on **direction** and **velocity** of rupture



Fig. 1. TERRAscope stations, the mainshock of the 1992 Landers earthquake, and the aftershocks of  $M \ge 3.0$  from 28 June to 30 September 1992.



Fig. 5. Moment rate functions determined from the records of GSC, PAS and PFO. Kanamori *et al.*, 1992

## **Observations: Static Parameters**



To first order: Constant  $\Delta \sigma$ Variability, but similar over wide M range **Uncertainties:**  $L > M_{o}$ Is scatter real? Depends on tectonic setting? Do induced earthquakes have low  $\Delta\sigma$ 

#### Higher stress drop implies higher seismic hazard

2 earthquakes with same  $M_0$  and different  $\Delta\sigma$ 



Stress drop,  $\Delta\sigma$ Static stress released by the rupture

 $\Delta \sigma \sim slip/length$ 

higher ∆σ ⇒ higher slip, smaller length, shorter duration

# EGF Assumptions and Frequency of Seismic Waves





Large/Small: EGF: Colocated Over what frequency range?



*Earthshaking Science, Sue Hough, 2002* 

# Earthquake Source Scaling



Stress Drop ~ Strain ~ s/L ~ constant

### Extracting Source from Seismograms

Seismogram (X):

X(t) = S(t) \* G(t) \* I(t)

Calculate Frequency spectra of Direct waves OR Coda waves

 $X(f) = S(f) \times G(f) \times I(f)$ 

Correct for Instrument (I) known (we hope!)





#### Correct for Path and Site effects (G)

1. Individual Model – assumptions about source and path effects

Eg. Brune (1970) model "Omega-square"

$$M_0(f) = \frac{Ce^{-\pi ft/Q}}{1 + \left(\frac{f}{f_c}\right)^2}$$



### Wells: Direct Wave large / small EGF



### Wells Direct Mainshock/Large Ashock





Regional Stations

Calculate cod envelopes

Obtain ratios at multiple frequency ranges



# Energy and Moment – No consensus on scaling

Individual studies use different methods, combine different sets.

Which observations do you prefer?

Better data?

All data



*After Ide and Beroza, 2001* 

