Regional Spectral Analysis of Moderate Earthquakes in Northeastern North America

John Boatwright, Linda Seekins, and Tim MacDonald (USGS)

1988 **M**5.8 Saguenay, Quebec
1997 **M**4.4 Cap-Rouge, Quebec
2000 **M**4.6 Kipawa, Quebec
2002 **M**5.0 Ausable Forks, New York
2005 **M**4.7 Rivière-du-Loup, Quebec
2010 **M**5.0 Val-des-Bois, Quebec
2011 **M**5.8 Mineral, Virginia
+ 11 earthquakes 3.0 < **M** < 4.0

NRC funded

$$|\dot{u}(r,f)| = \frac{\vec{F}F^S S(f)}{g(r,r_o)} \exp(-\pi f r/\beta Q) \frac{\dot{M}_o(f)}{4\pi\rho_o\beta_o^3}$$

FF^s - free surface amplification and average radiation pattern

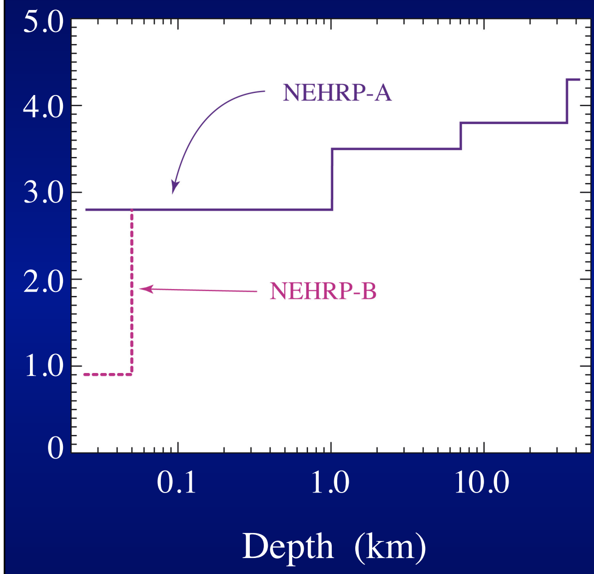
$S(f)$ - site amplification computed using average impedance from Boore and Joyner (1997)

$$g(r,r_o) = \begin{cases} r & r \le r_o \\ (r_o r)^{1/2} & r > r_o \end{cases}$$
- geometrical spreading from Street et al. (1975) with r_o = 50 km

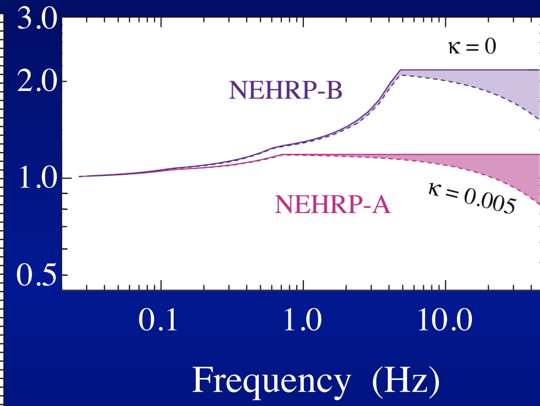
$Q = Q_o f^q$ - anelastic attenuation form of Aki and Chouet (1975)

$\rho_o\ \beta_o$ - density and S-wave velocity at the source depth

S-Wave Velocity (km/s)



Site Amplification $S_I(f)$



There are approximately twice as many NEHRP-A as B sites.

Using only NEHRP-A and B stations greatly reduces the site variability. NEHRP-B sites can exhibit resonances.

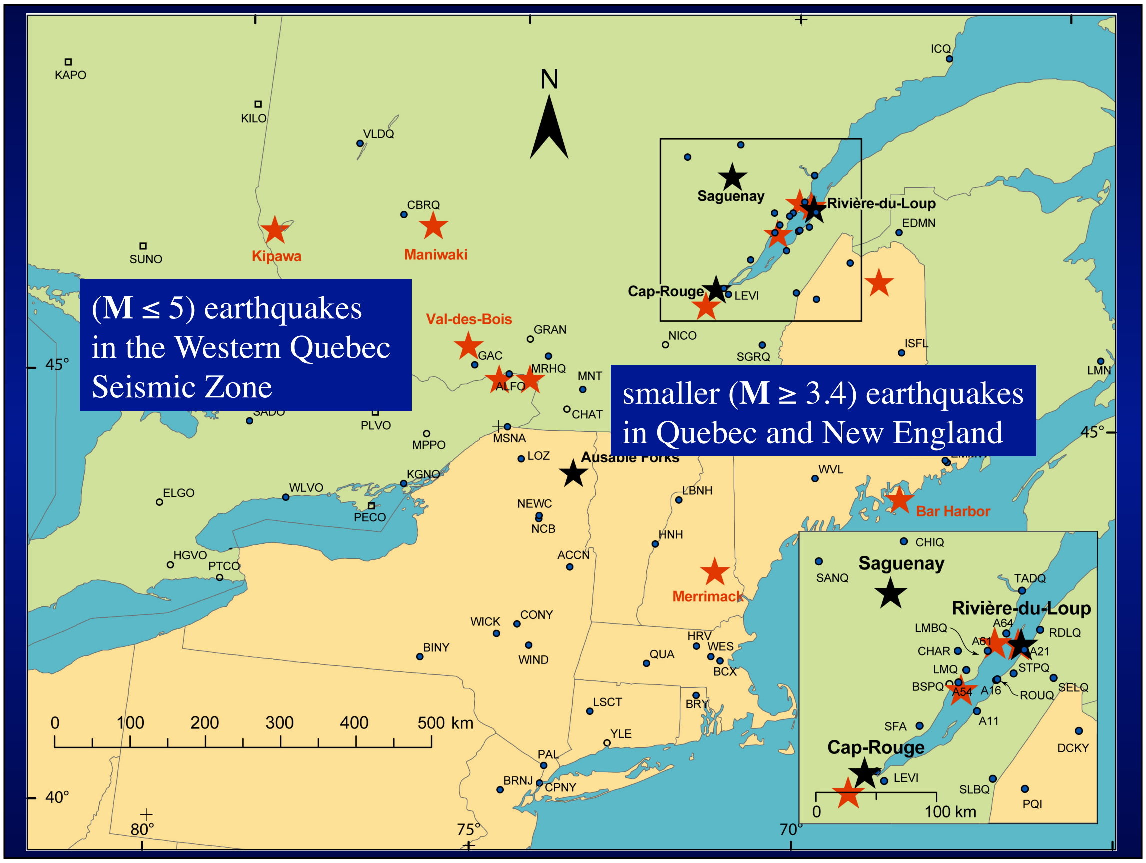
Why Use This Retro Analysis Technique?

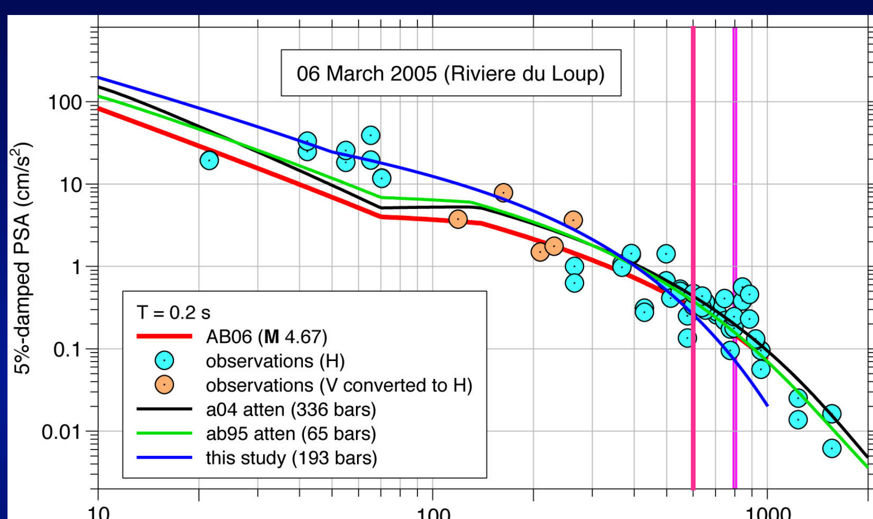
We assume $S_I(f)$, slightly revise $g(r, r_o)$, solve for $Q = Q_o f^q$, and then we directly correct the recorded ground motion to estimate source spectra.

Source-site decomposition (Andrews, 1986; Scherbaum, 1990; Boatwright *et al.*, 1992; Benz *et al.*, 1997; …) requires multiple recordings at each station and usually fits a source spectral shape. 44/61 of the stations only recorded one earthquake, so this decomposition only uses 27% of the available data.

EGF analysis (Hartzell, 1985; Shearer et al., 2006; Viegas *et al.*, 2010; …) requires recordings of aftershocks and fits the EGF spectral shape. NENA main shocks are poorly recorded within 150 km, and aftershock sequences are sparse. EGF analysis can introduce, rather than reduce, uncertainty.

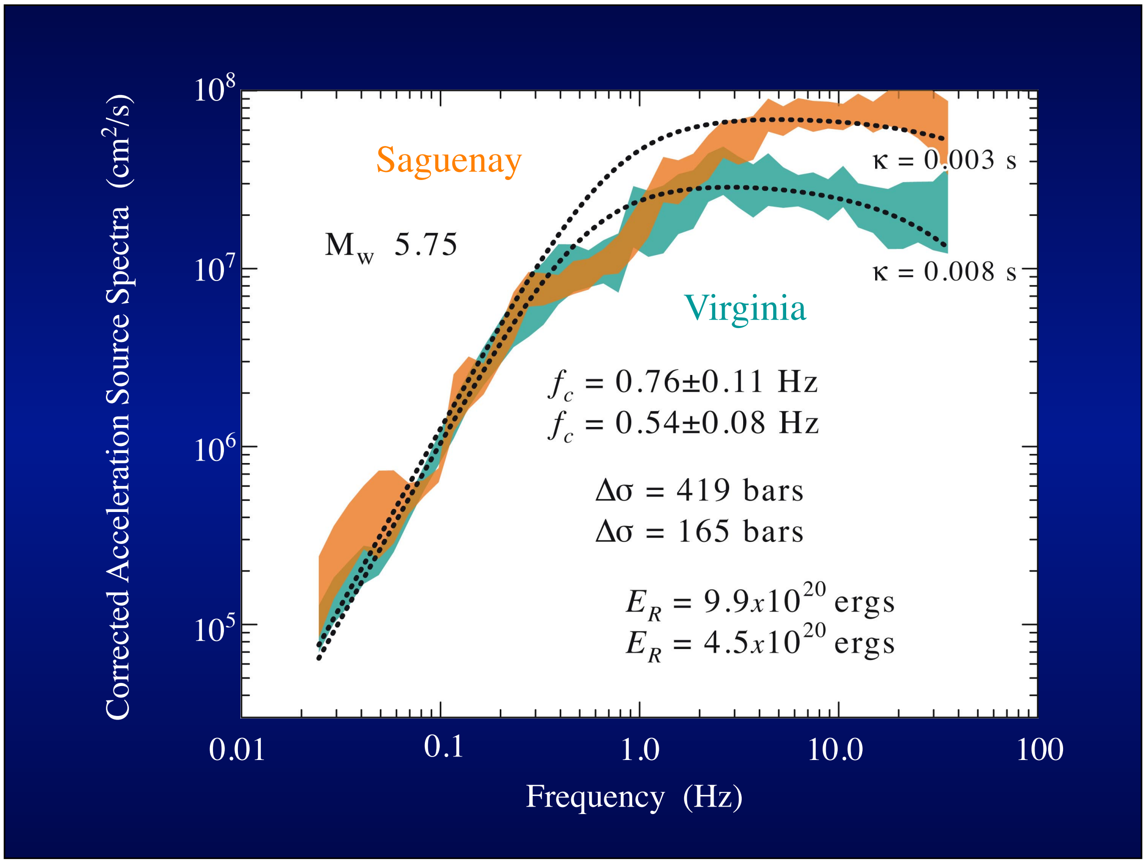
The upside of our choice is that most of the NENA broadband stations are sited on hard or soft rock. The downside is that the instrument corrections and site amplifications have to be checked closely.



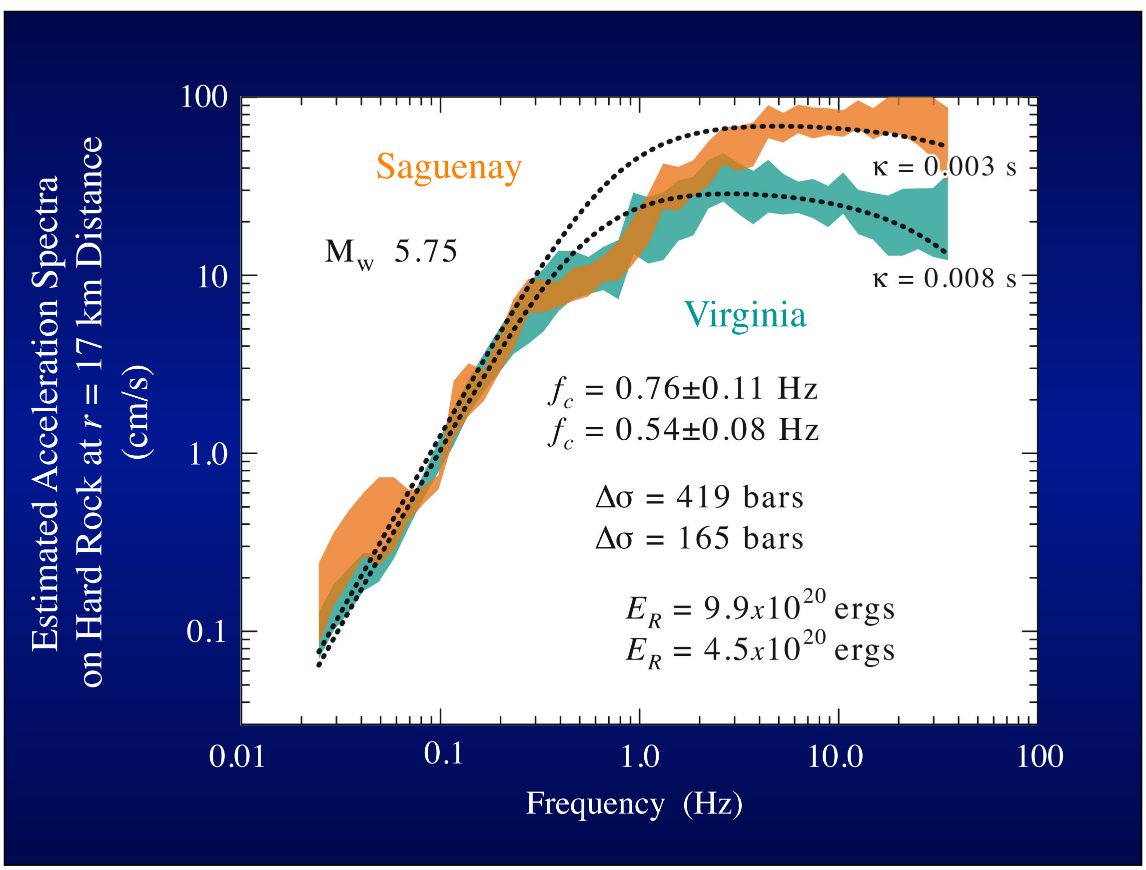


Boore et al. (2010) re-evaluated stress parameters for AB95 and AB06

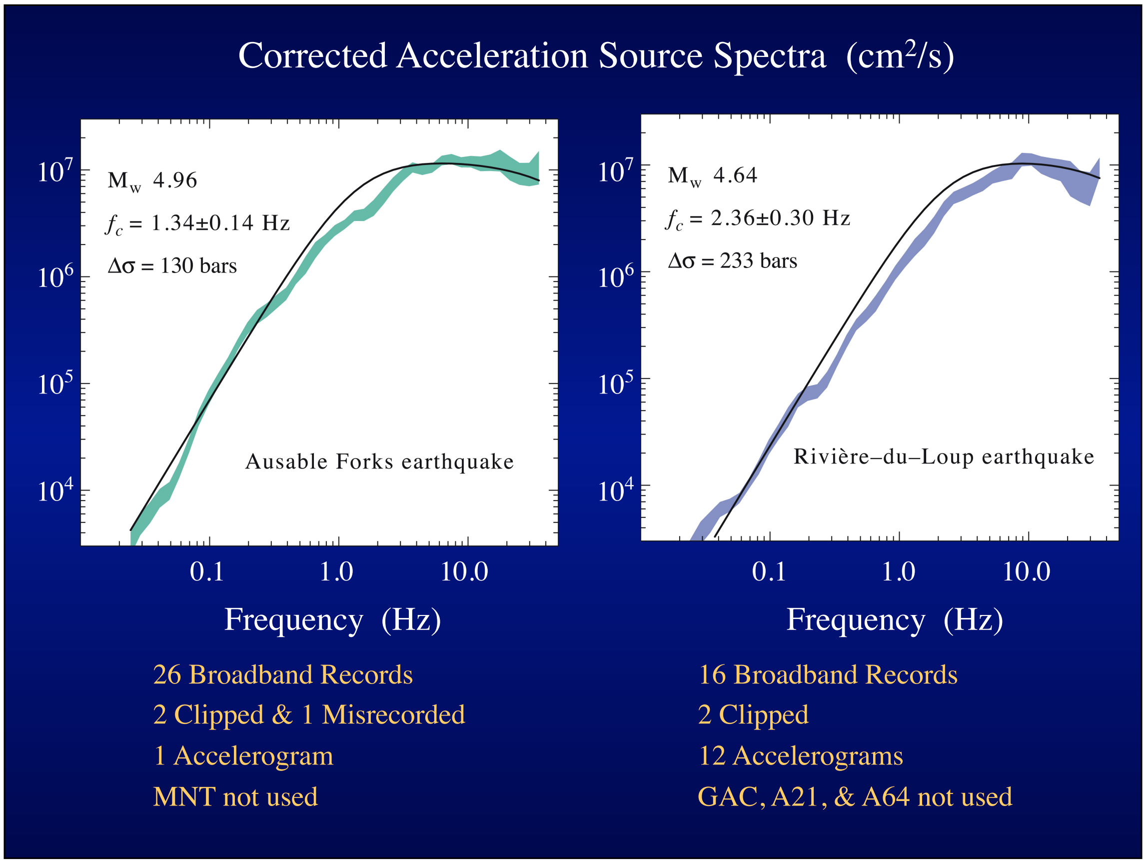
Stronger attenuation produces better fits from 30 to 200 km but cannot be extended past 600 km

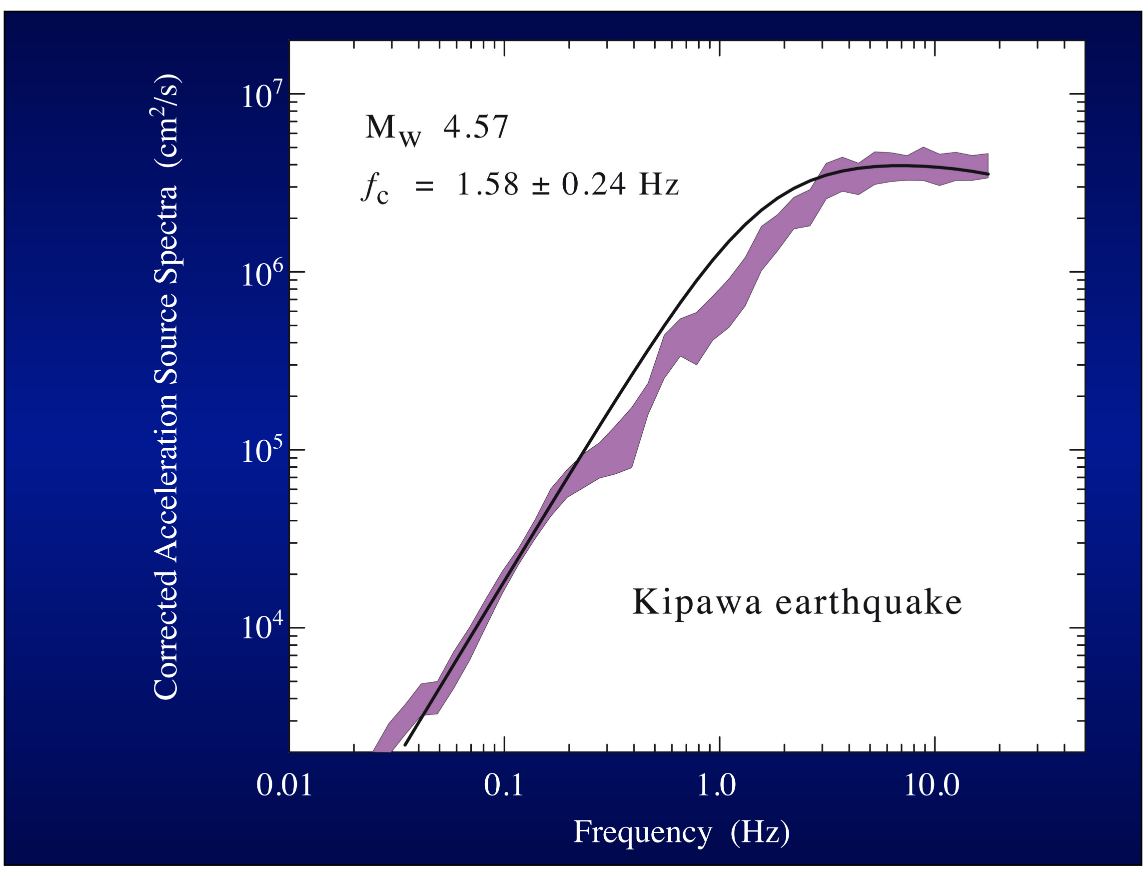


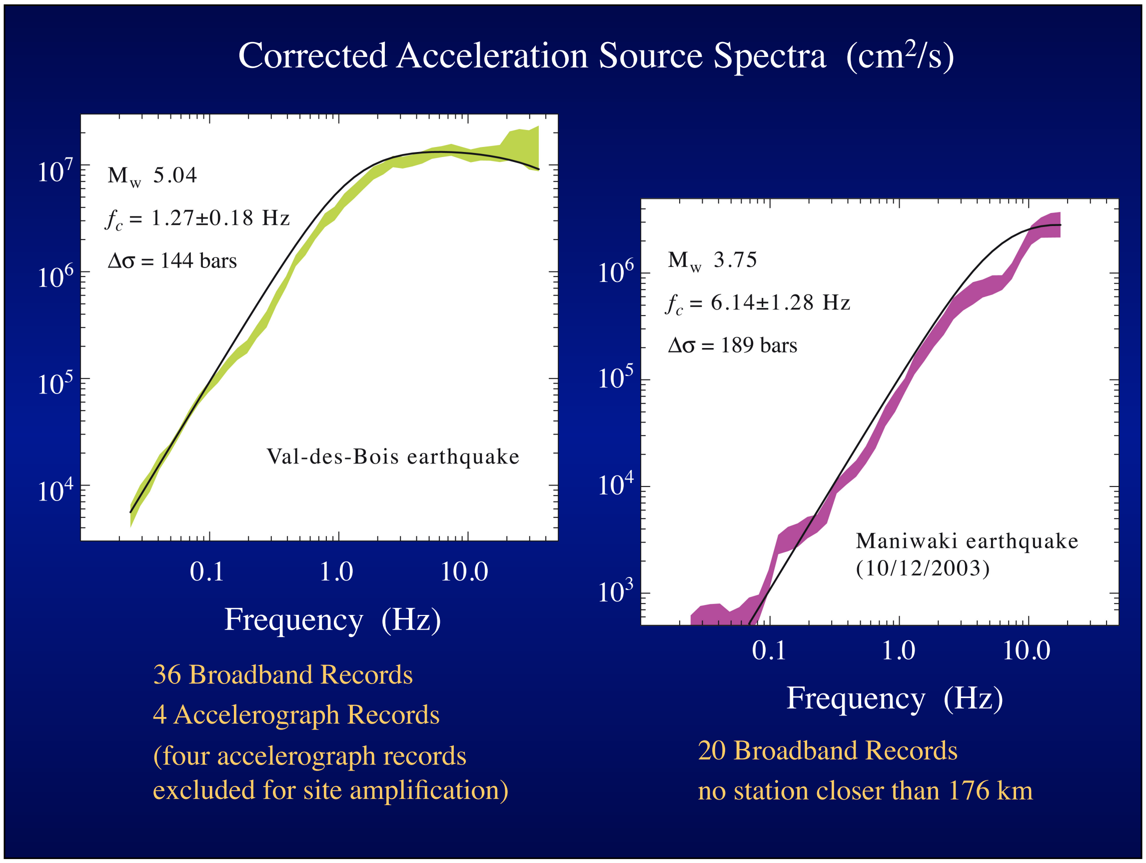
Corrected Acceleration Source Spectra (cm²/s)
10⁸
10⁷
10⁶
10⁵
0.01
0.1
1.0
10.0
100
Frequency (Hz)
Saguenay
Virginia
Mw 5.75
κ = 0.003 s
κ = 0.008 s
fc = 0.76±0.11 Hz
fc = 0.54±0.08 Hz
Δσ = 419 bars
Δσ = 165 bars
ER = 9.9x10²⁰ ergs
ER = 4.5x10²⁰ ergs

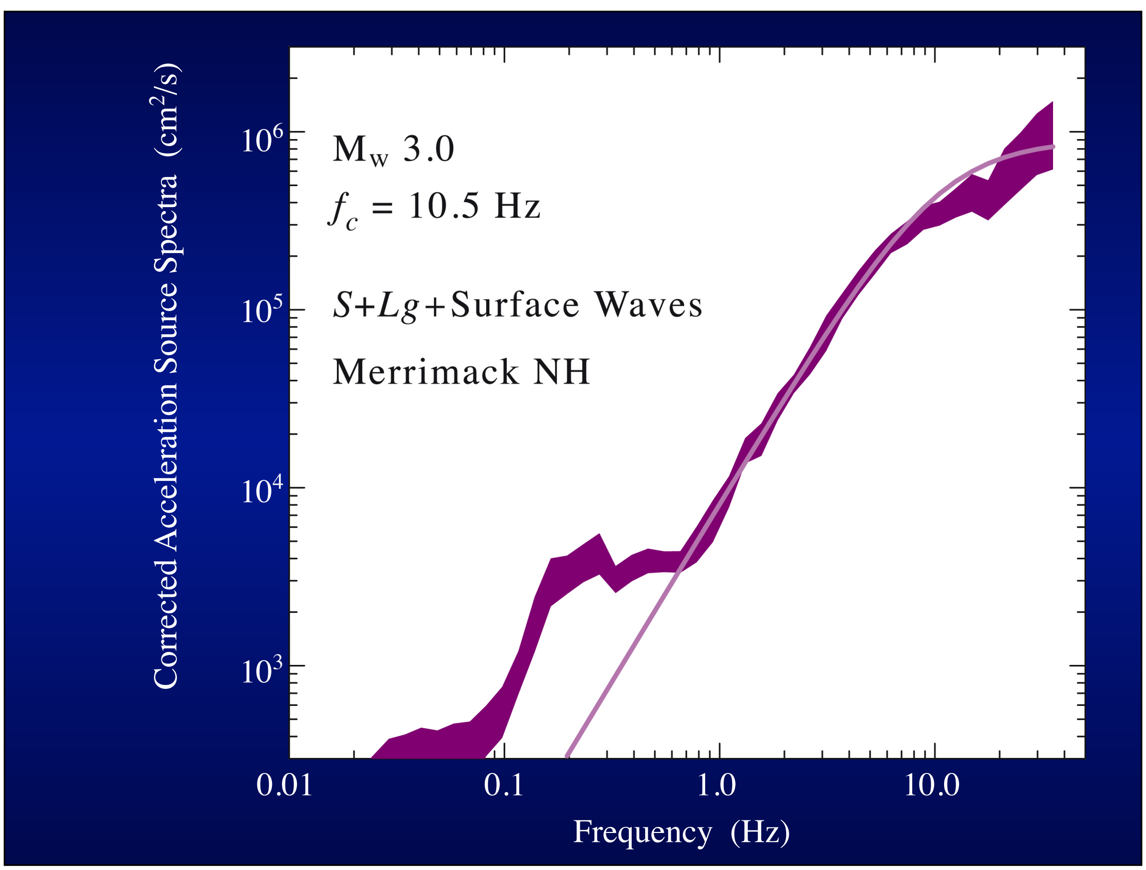


Estimated Acceleration Spectra
on Hard Rock at r = 17 km Distance
(cm/s)
100
10
1.0
0.1
0.01
0.1
1.0
10.0
100
Frequency (Hz)
Saguenay
Virginia
Mw 5.75
κ = 0.003 s
κ = 0.008 s
fc = 0.76±0.11 Hz
fc = 0.54±0.08 Hz
Δσ = 419 bars
Δσ = 165 bars
ER = 9.9x10²⁰ ergs
ER = 4.5x10²⁰ ergs


Corrected Acceleration Source Spectra (cm²/s)
M_w 4.96
f_c = 1.34±0.14 Hz
Δσ = 130 bars
Ausable Forks earthquake
M_w 4.64
f_c = 2.36±0.30 Hz
Δσ = 233 bars
Rivière–du–Loup earthquake
Frequency (Hz)
Frequency (Hz)
26 Broadband Records
2 Clipped & 1 Misrecorded
1 Accelerogram
MNT not used
16 Broadband Records
2 Clipped
12 Accelerograms
GAC, A21, & A64 not used


Corrected Acceleration Source Spectra (cm²/s)
M_W 4.57
f_c = 1.58 ± 0.24 Hz
Kipawa earthquake
Frequency (Hz)


Corrected Acceleration Source Spectra (cm²/s)
M_w 5.04
f_c = 1.27±0.18 Hz
Δσ = 144 bars
Val-des-Bois earthquake
10^7
10^6
10^5
10^4
0.1
1.0
10.0
Frequency (Hz)
36 Broadband Records
4 Accelerograph Records
(four accelerograph records
excluded for site amplification)
M_w 3.75
f_c = 6.14±1.28 Hz
Δσ = 189 bars
Maniwaki earthquake
(10/12/2003)
10^6
10^5
10^4
10^3
0.1
1.0
10.0
Frequency (Hz)
20 Broadband Records
no station closer than 176 km


Corrected Acceleration Source Spectra (cm²/s)
M_W 3.0
f_c = 10.5 Hz
S+Lg+Surface Waves
Merrimack NH
10^6
10^5
10^4
10^3
0.01
0.1
1.0
10.0
Frequency (Hz)

Do NENA earthquakes have a consistent non-Brune spectral shape?

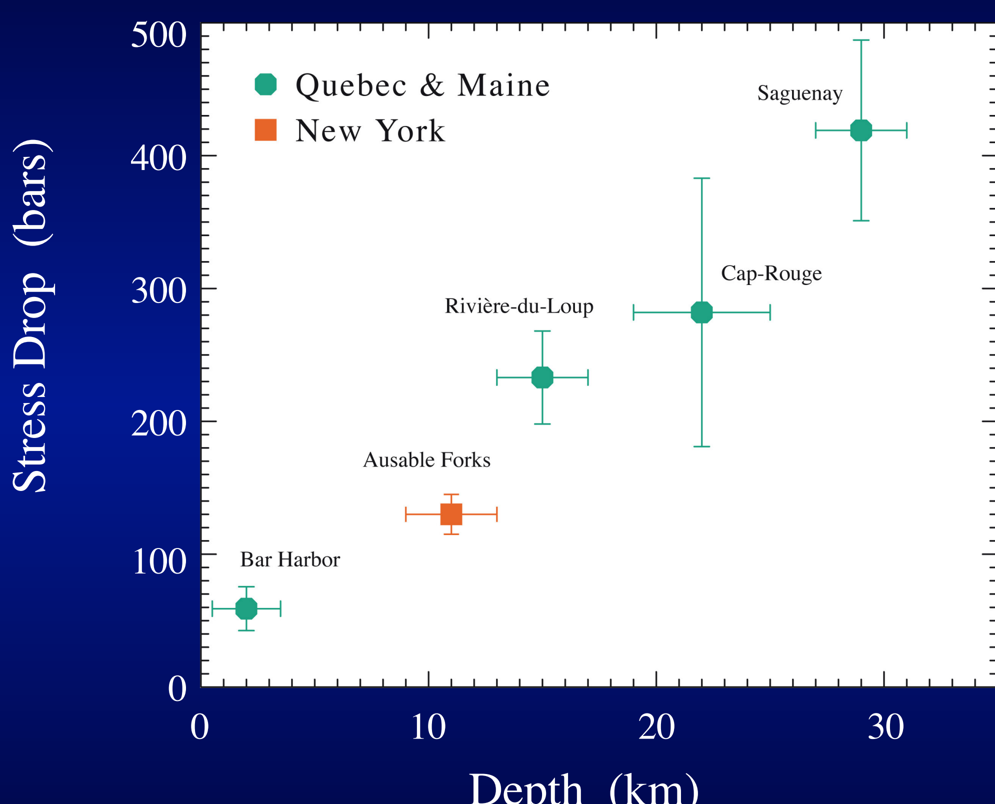
M5.8 Saguenay spectrum “sags” the most among the earthquakes I have analyzed, but it is also the deepest and has the highest stress drop

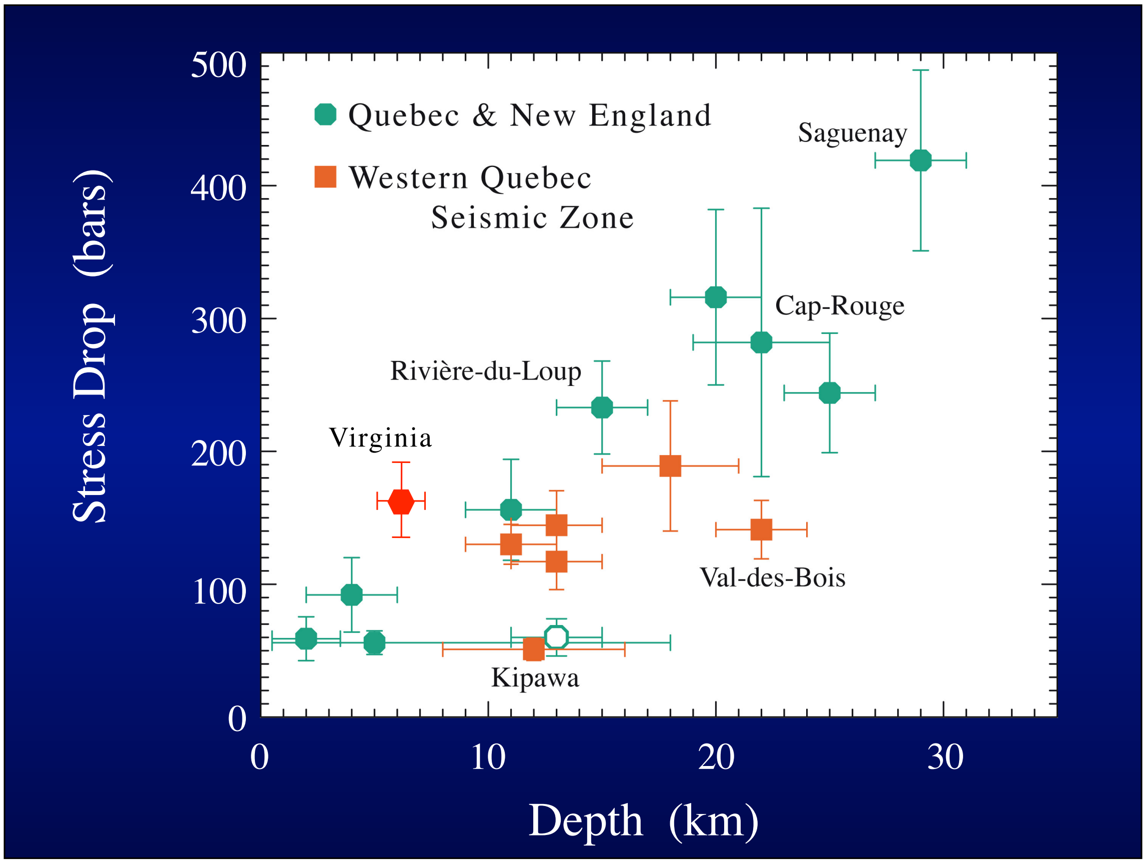
M5.8 Virginia and M5.0 Ausable Forks spectra exhibit slight sags, and both of these events are relatively shallow with smaller stress drops

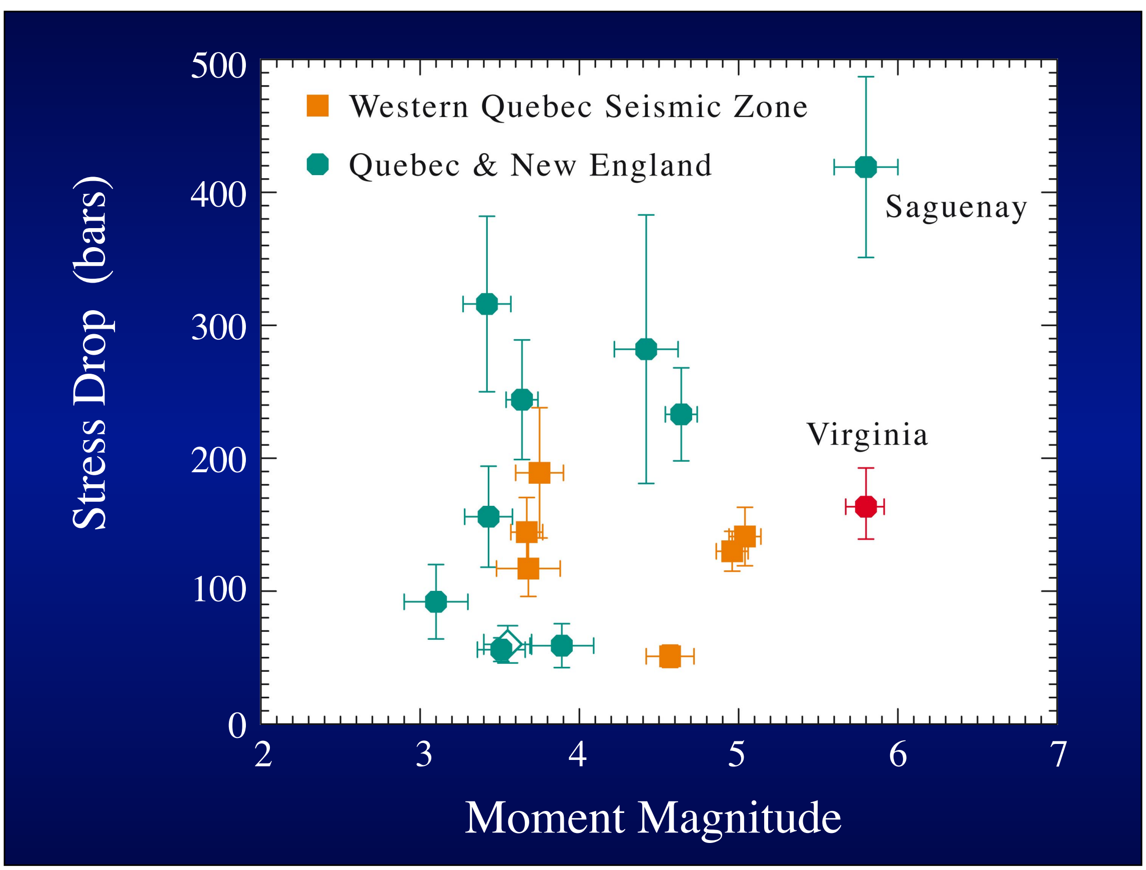
Two smaller earthquakes, M3.7 Maniwaki and M3.6 L’Ile-aux-Coudres exhibit sags, and these events are deeper, *h* ~ 18 and 25 km, and have somewhat higher stress drops, 192 and 241 bars

The rest of the 17 earthquakes, including M4.6 Kipawa, M5.0 Val-des-Bois, and M4.0 Bar Harbor, exhibit Brune-like spectra

It is important to use a consistent analysis technique!




500
400
300
200
100
0
0
10
20
30
Stress Drop (bars)
Depth (km)
Quebec & New England
Western Quebec
Seismic Zone
Saguenay
Cap-Rouge
Rivière-du-Loup
Virginia
Val-des-Bois
Kipawa


500
400
300
200
100
0
2
3
4
5
6
7
Stress Drop (bars)
Moment Magnitude
Western Quebec Seismic Zone
Quebec & New England
Saguenay
Virginia

Does Stress Drop Depend on Source Depth?

If stress drop depends on source depth, it should have critical implications for estimating probabilistic seismic hazard in northeastern North America

The stress drop of 1988 Saguenay earthquake (419 bars) determines the crustal maximum rather than the crustal mean stress drop. To estimate the probabilistic seismic hazard requires a distribution function for rupture area as a function of depth, $\Sigma(z)$. Then we can evaluate the probabilistic ground motion through the probable source model.

The probabilistic ground motions would also be decreased by the source-distance effect. The sources with the strongest stress drop are the deepest, so that the ground motions from these sources are decreased by the greater distance from the source to the ground surface.

Conclusions

- The crustal waveguide in northeastern North America can be modeled very simply by revising r_o = 50 km and using $Q = 410\,f^{\,0.5}$ for the Appalachian and southeastern Grenville Provinces and $Q = 532\,f^{\,0.5}$ for western Ontario
- We can analyze broadband records from $\mathbf{M} \geq 3.4$ earthquakes for Brune stress drop and spectral shape
- Recent $3.4 \leq \mathbf{M} \leq 5.8$ earthquakes in the Charlevoix region exhibit stress drops that increase with source depth – the Saguenay earthquake having the largest
- If stress drop increases with source depth instead of source size, probabilistic estimates of ground motion for large NENA earthquakes become far more tractable

How Noise Affects Attenuation Estimates

If we revise the usual decomposition to include noise

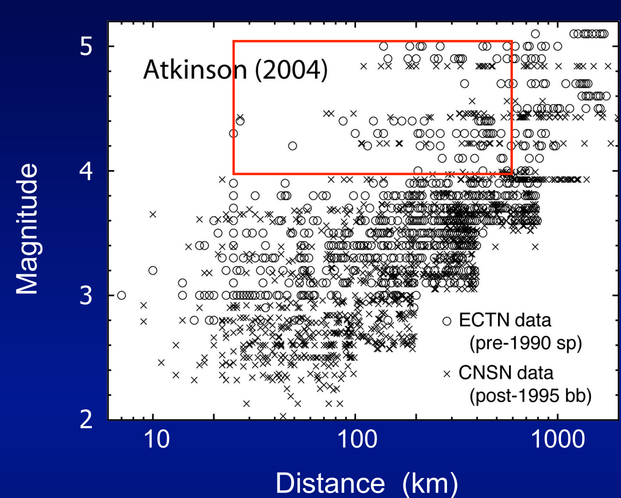
$$\ln|v(r, f)+n_I(f)| = \ln\Omega(f) + \ln S_I(f) - \ln g(r, r_o) - \pi f r/\beta Q$$

where $|v(r, f)|$ are the instrument-corrected spectra, $n_I(f)$ is the noise spectrum at the site, $\Omega(f)$ is the source term, $S_I(f)$ are the site terms, $g(r, r_o)$ is the geometrical spreading, and $\pi f r/\beta Q$ is the anelastic attenuation

Noise is always additive in the power spectrum $\ln|v(r, f)+n_I(f)|$ and affects recordings of smaller earthquakes and more distant stations more strongly

When $n_I(f)/v(r, f)$ increases, $\pi f r/\beta Q$ decreases and Q increases.

Worse, the more distant stations strongly control the attenuation estimates, because of the large r in the linear term $\pi f r/\beta Q$, so researchers need to be careful when they add distant stations

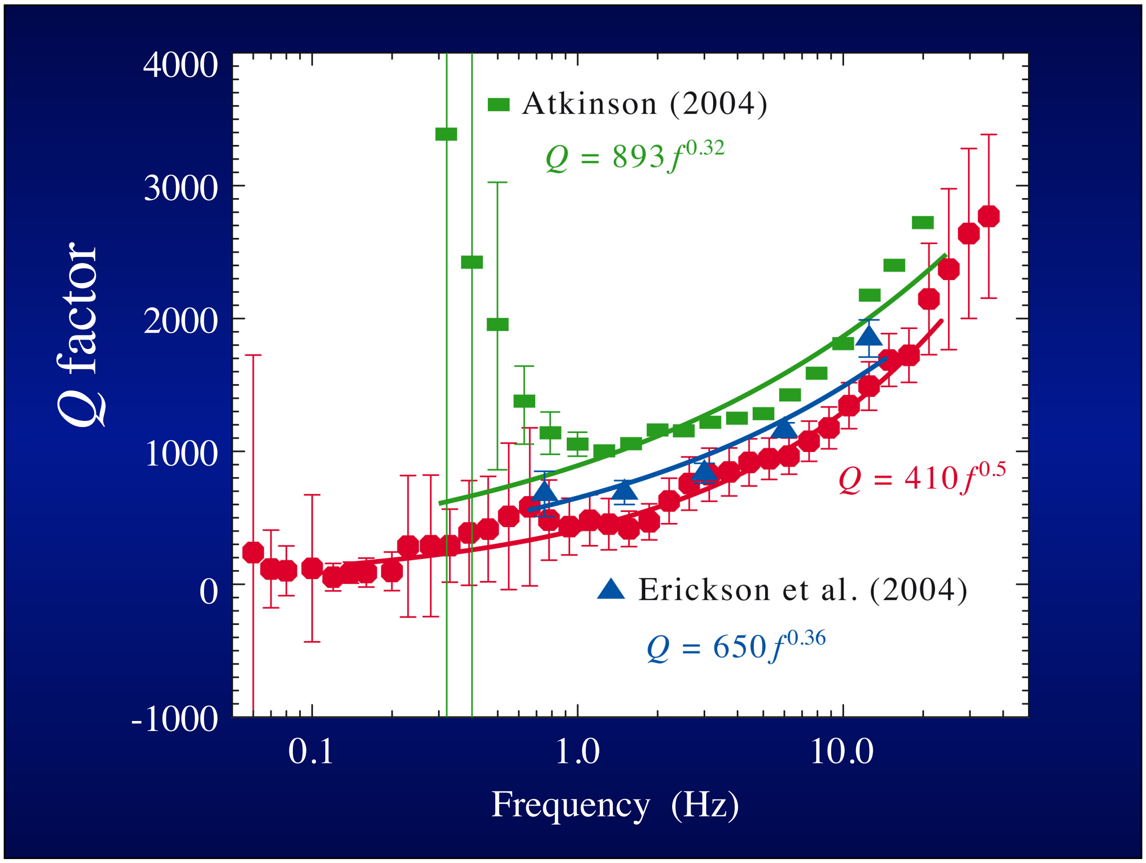


There are few recordings of large earthquakes in NENA

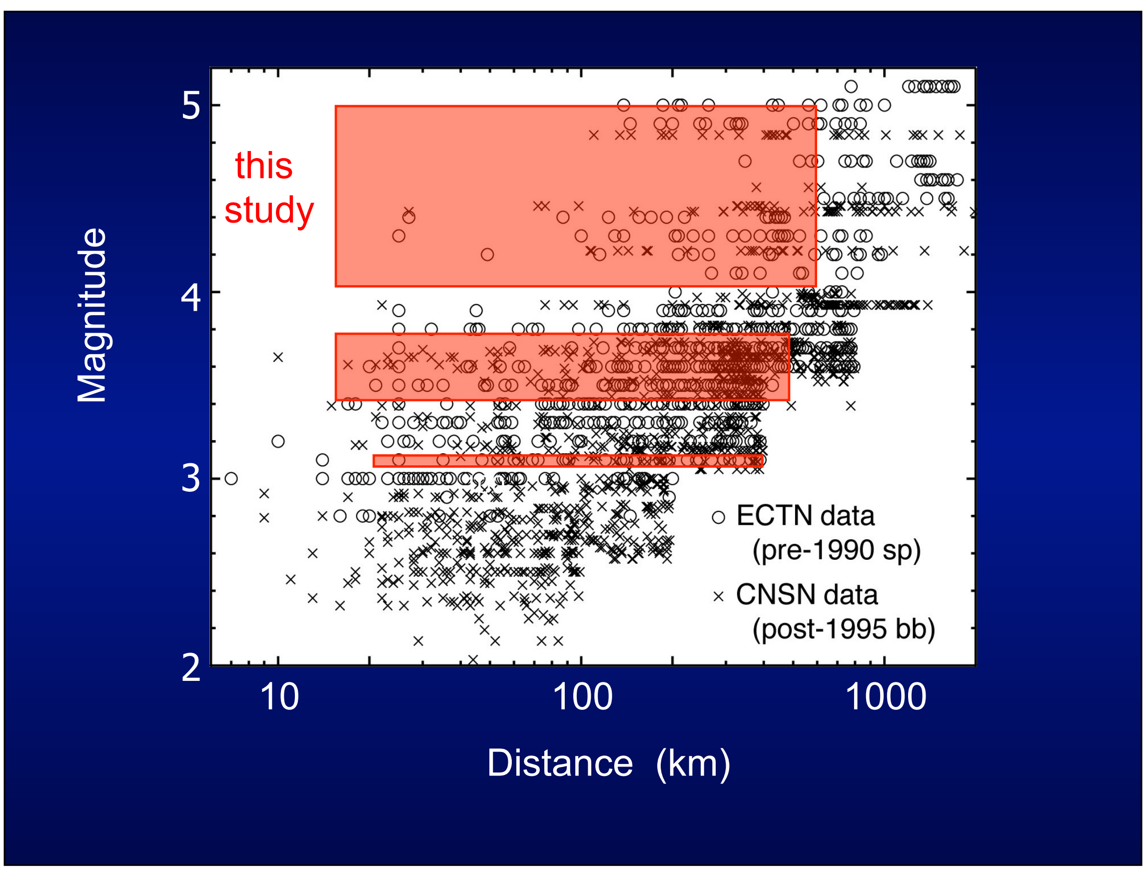
- Use small & moderate earthquakes to determine ground motion attenuation
- Estimate suitable $\Delta\sigma$ from largest earthquakes

Atkinson (2004) analyzed vertical and horizontal CNSN recordings down to **M** > 2 and out to $r < 2000$ km

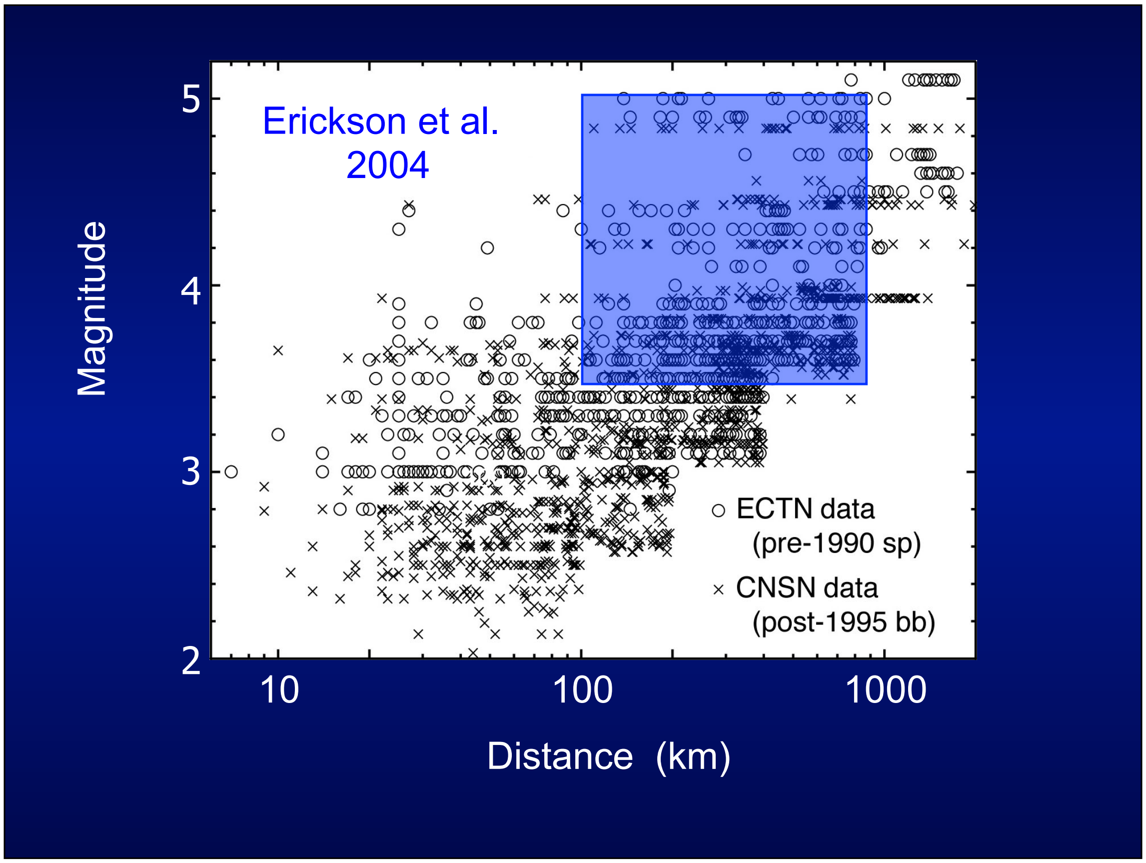
We analyzed the four best recorded moderate ($4 \le$ **M** ≤ 5) earthquakes using stations out to $r < 600$ km

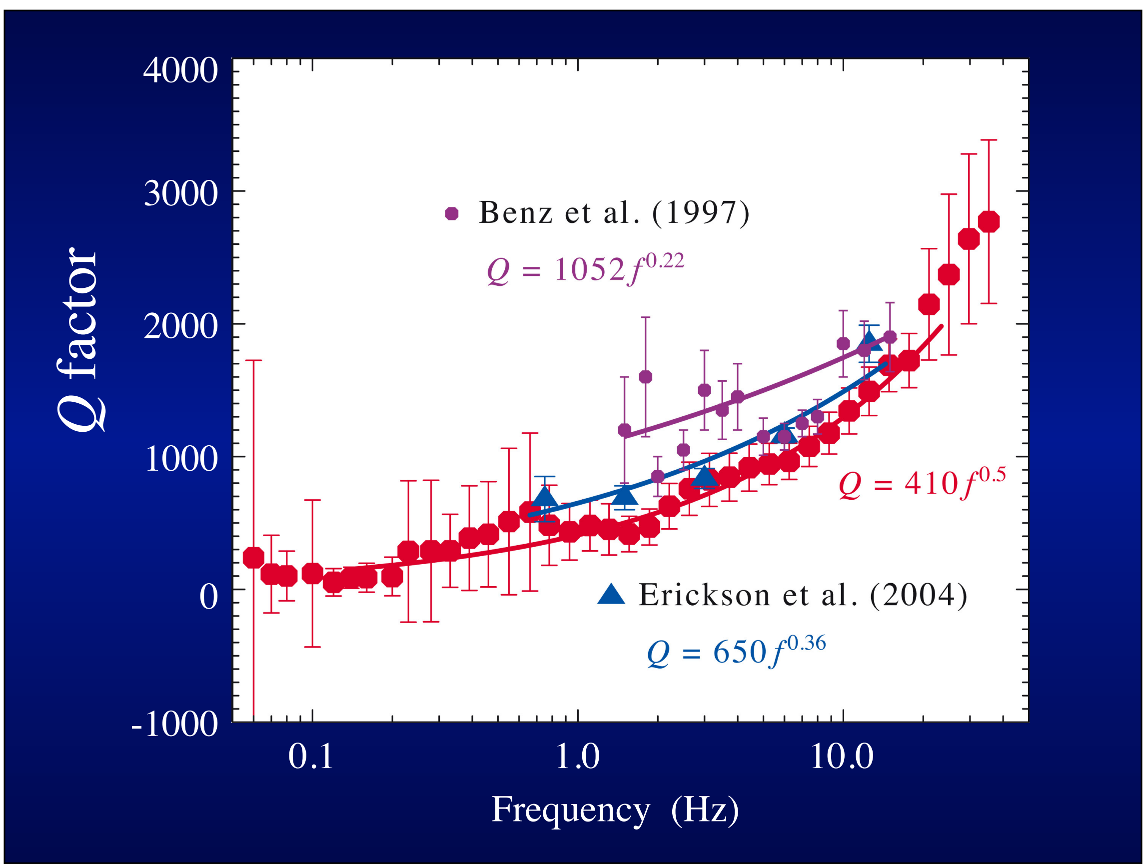


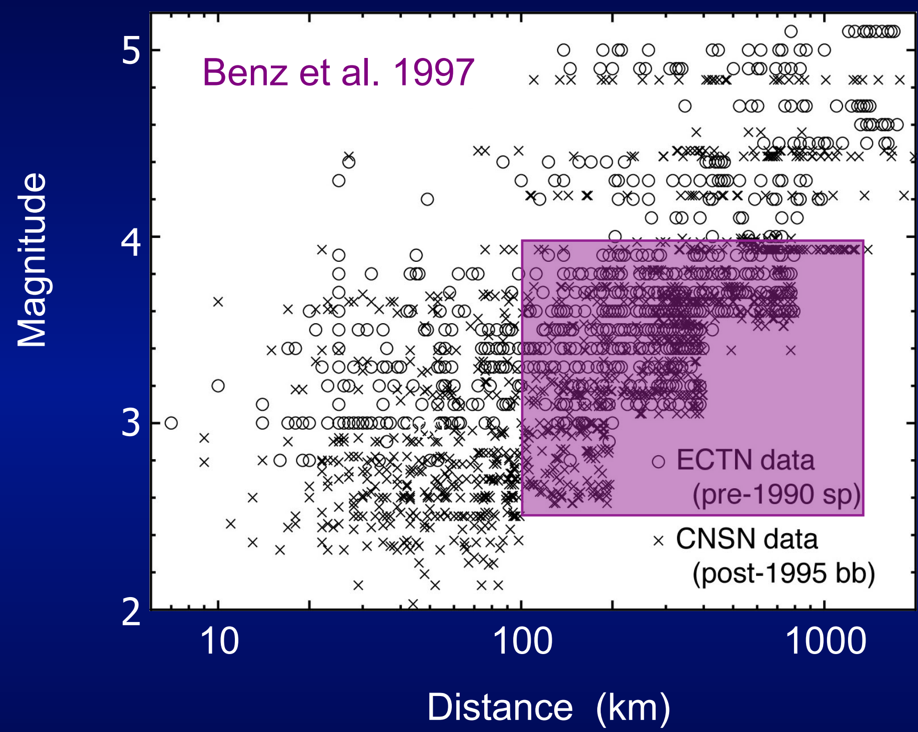
Atkinson (2004)
Q = 893 f^0.32
Q = 410 f^0.5
Erickson et al. (2004)
Q = 650 f^0.36
Q factor
Frequency (Hz)
4000
3000
2000
1000
0
-1000
0.1
1.0
10.0



this study
ECTN data
(pre-1990 sp)
CNSN data
(post-1995 bb)
Magnitude
Distance (km)
5
4
3
2
10
100
1000


Erickson et al.
2004
Magnitude
Distance (km)
ECTN data
(pre-1990 sp)
CNSN data
(post-1995 bb)
5
4
3
2
10
100
1000


Benz et al. (1997)
Q = 1052 f^0.22
Q = 410 f^0.5
Erickson et al. (2004)
Q = 650 f^0.36
Q factor
Frequency (Hz)
4000
3000
2000
1000
0
-1000
0.1
1.0
10.0



Final Speculation about Attenuation

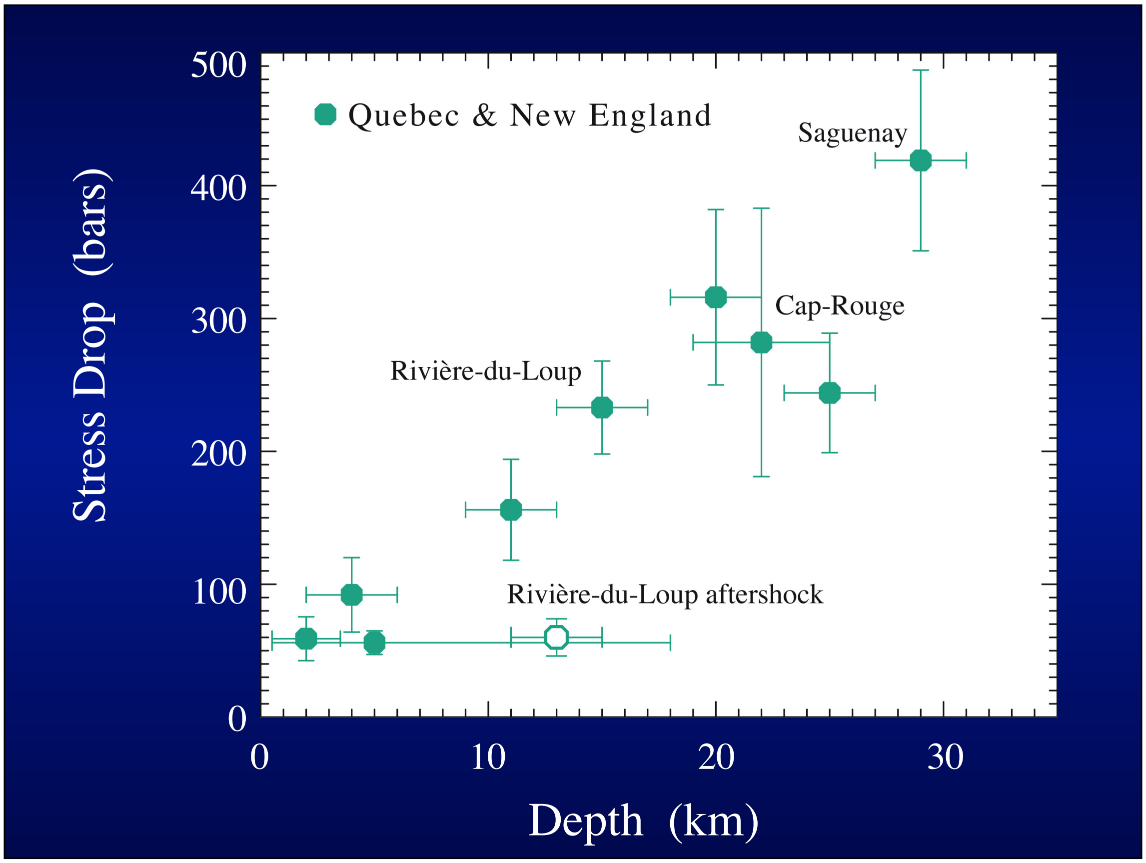
Two characteristics argue that the attenuation

$$Q = 410\, f^{0.5} \text{ for } 0.2 \leq f \leq 20 \text{ Hz}$$

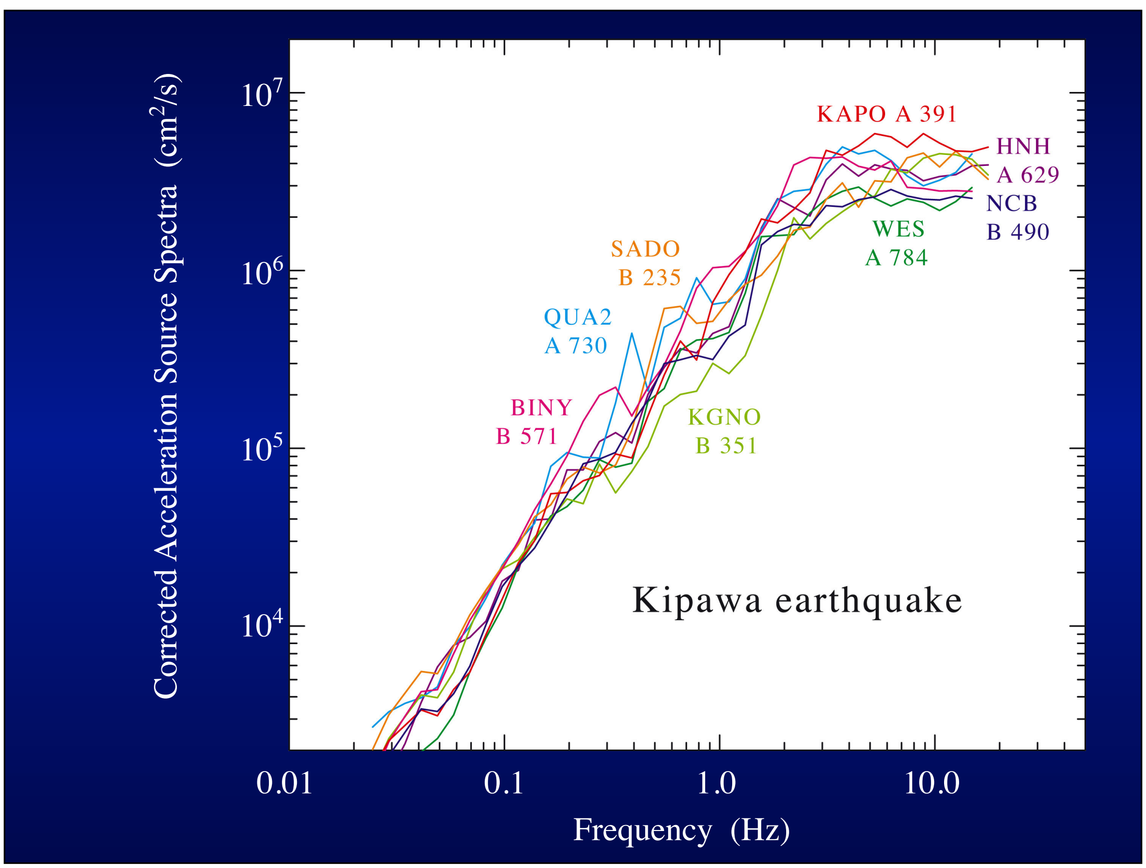
we have obtained for the Appalachian and southeastern Grenville Provinces is reasonable.

• We have restricted the recordings analyzed to the largest earthquakes at smaller distances ($r < 600$ km). This strategy optimizes the signal to noise in the data and may enable us to resolve the stronger attenuation. This strategy also serves to limit the area that the raypaths sample.

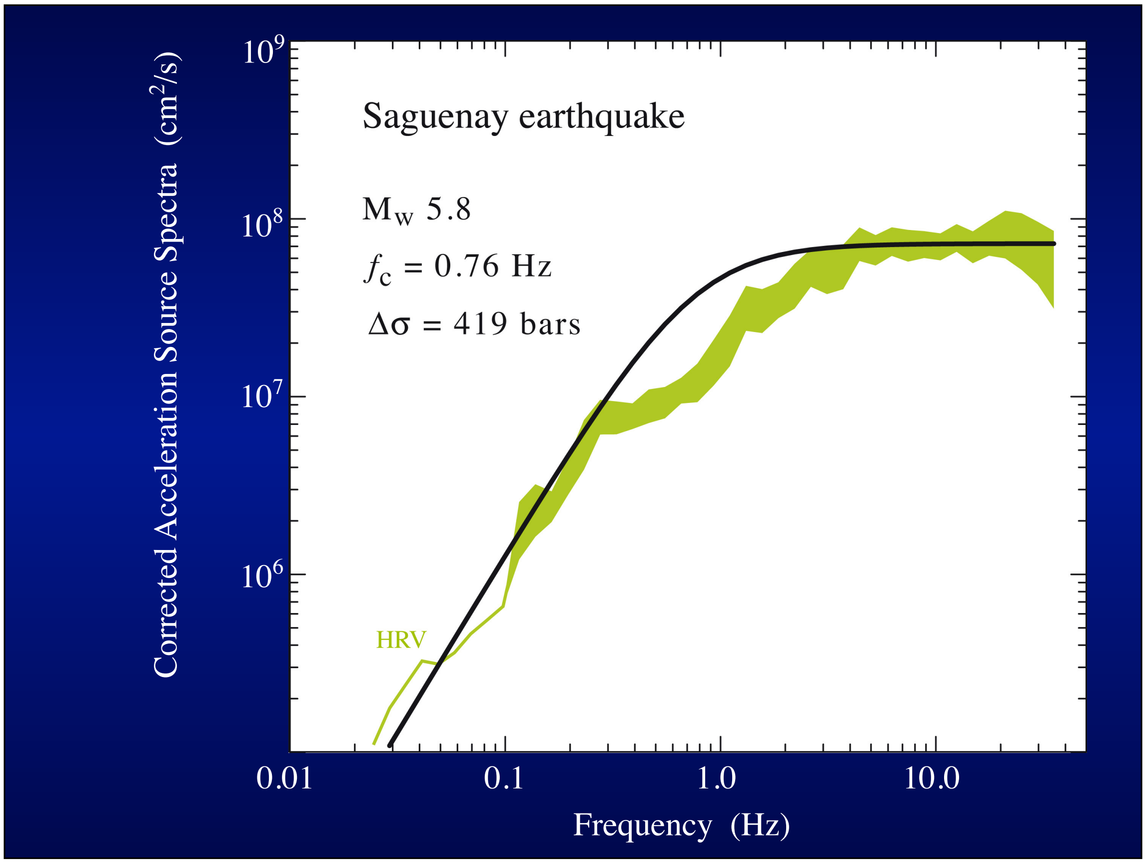
• The estimates of $Q(f)$ are remarkably well fit by the Aki and Chouet (1975) function $Q_o f^q$ on a broad frequency band

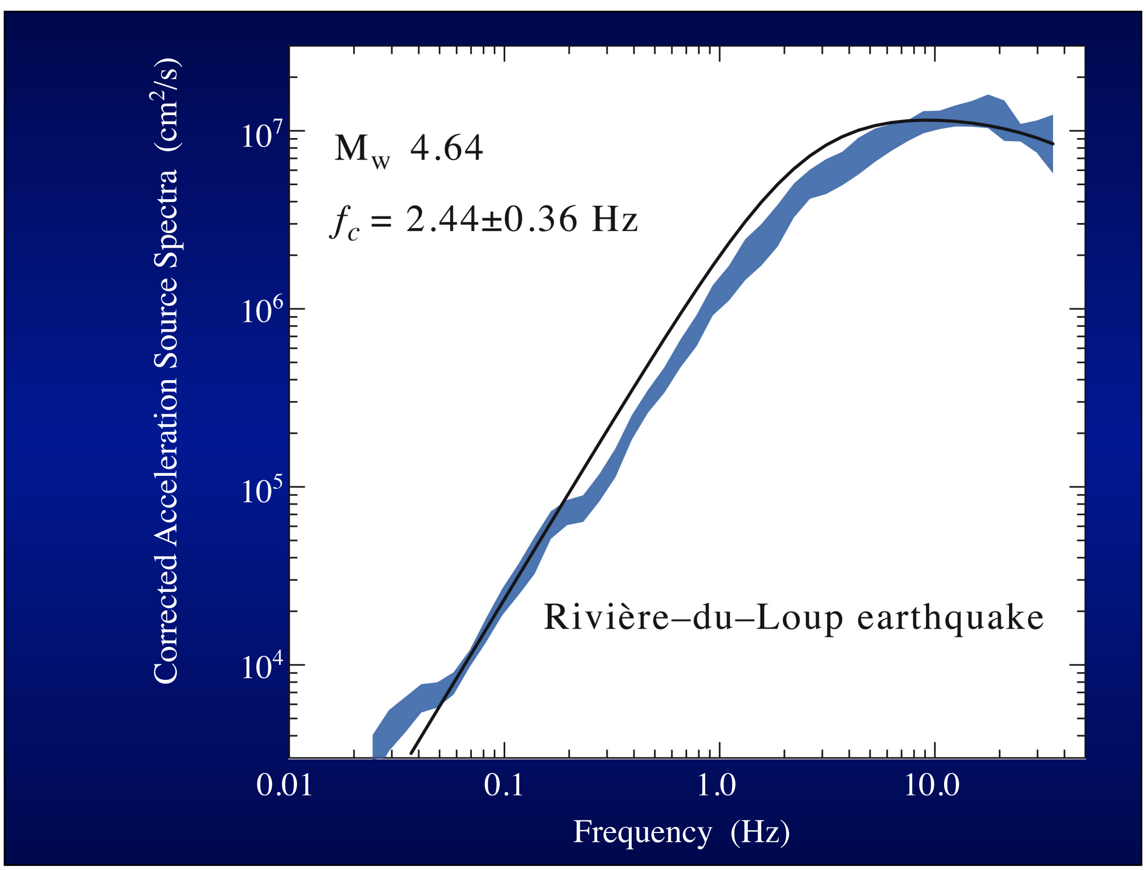


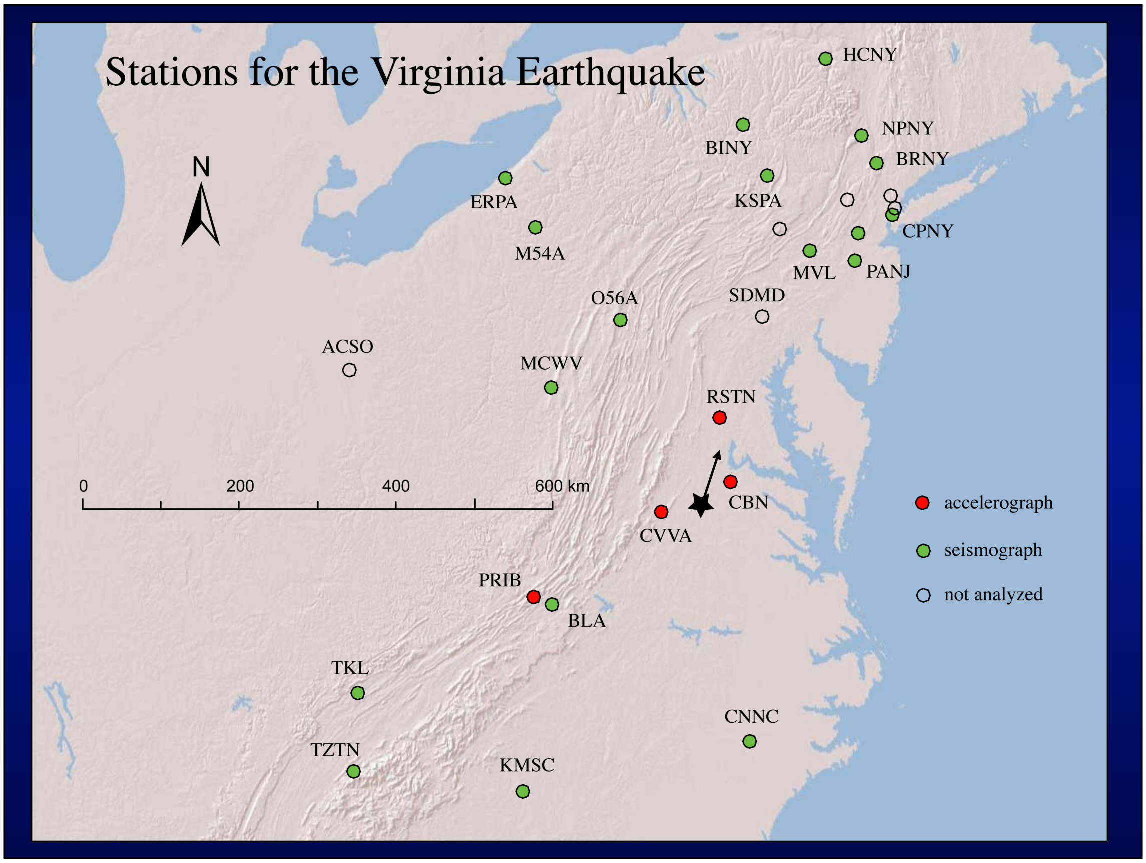
Quebec & New England
Saguenay
Cap-Rouge
Rivière-du-Loup
Rivière-du-Loup aftershock
Stress Drop (bars)
Depth (km)
0
100
200
300
400
500
0
10
20
30

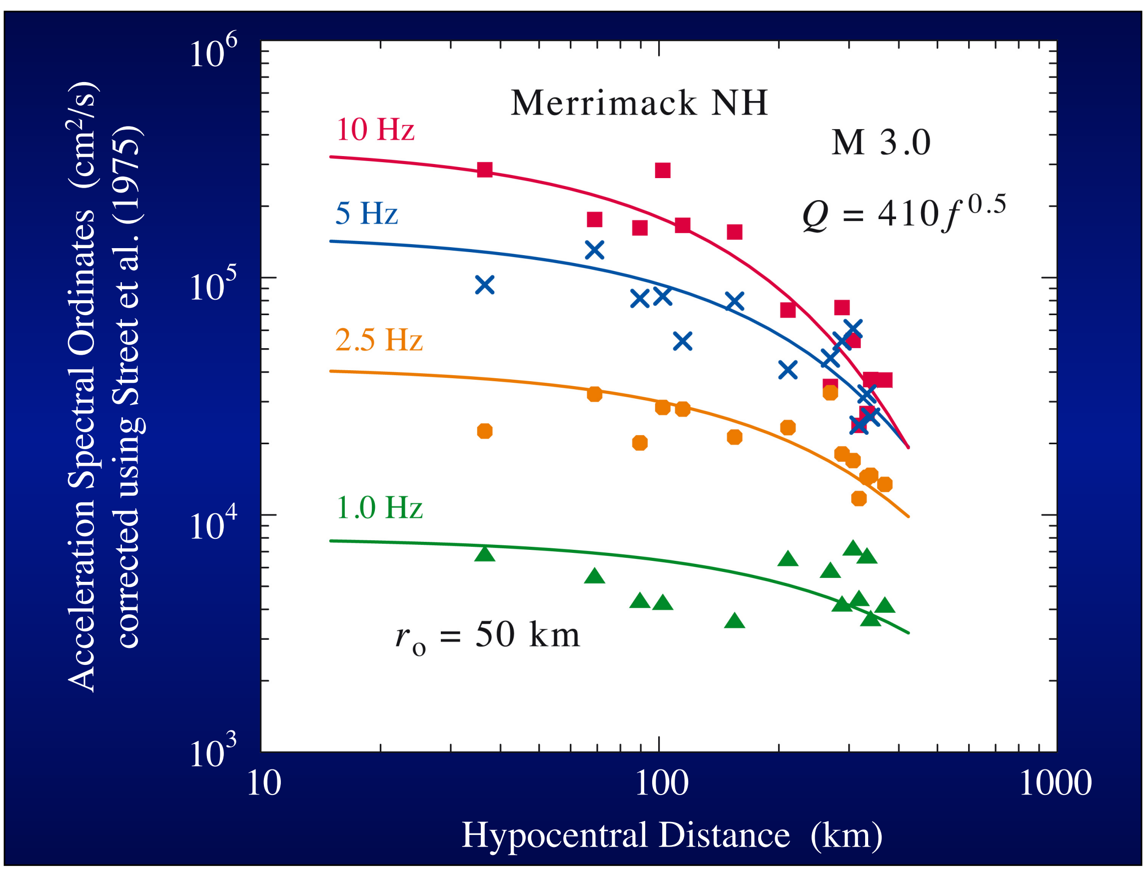


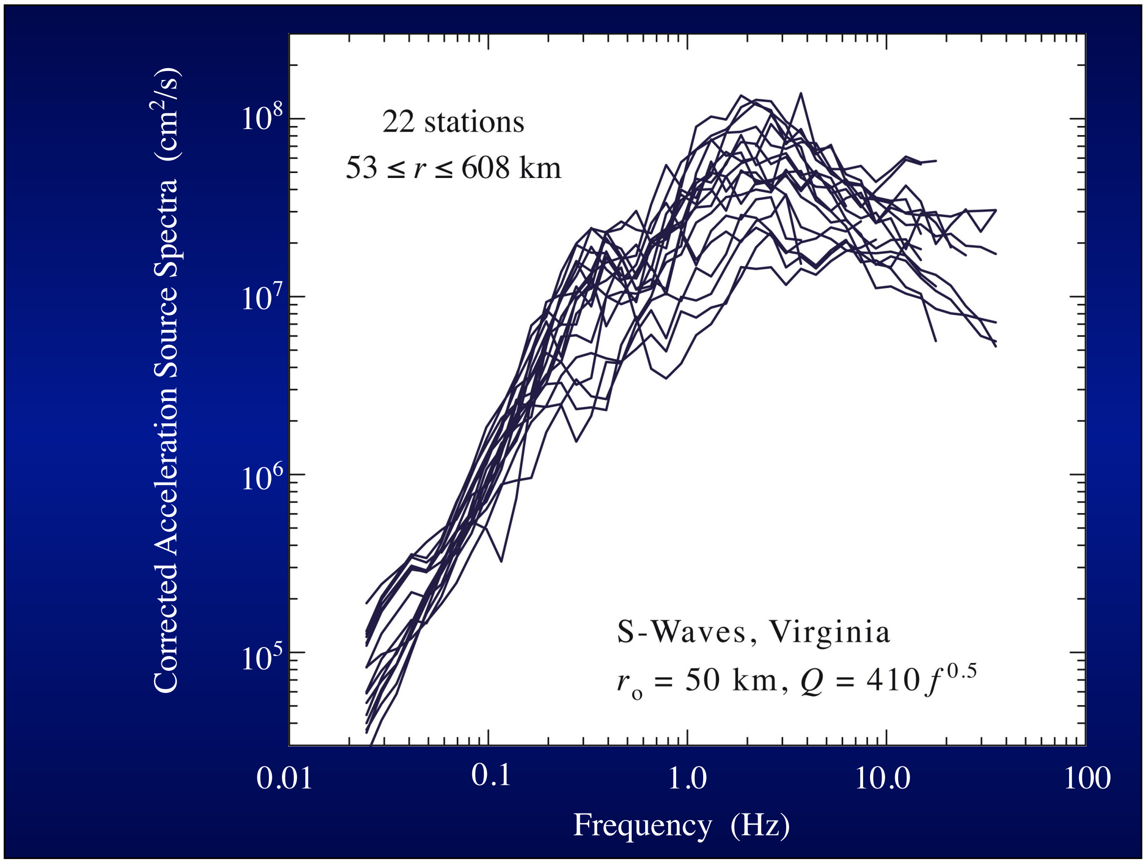
KAPO A 391
HNH
A 629
NCB
B 490
WES
A 784
SADO
B 235
QUA2
A 730
BINY
B 571
KGNO
B 351
Kipawa earthquake
Corrected Acceleration Source Spectra (cm²/s)
Frequency (Hz)
0.01
0.1
1.0
10.0
10⁷
10⁶
10⁵
10⁴


Saguenay earthquake
Mw 5.8
fc = 0.76 Hz
Δσ = 419 bars
HRV
Corrected Acceleration Source Spectra (cm2/s)
Frequency (Hz)
10^9
10^8
10^7
10^6
0.01
0.1
1.0
10.0

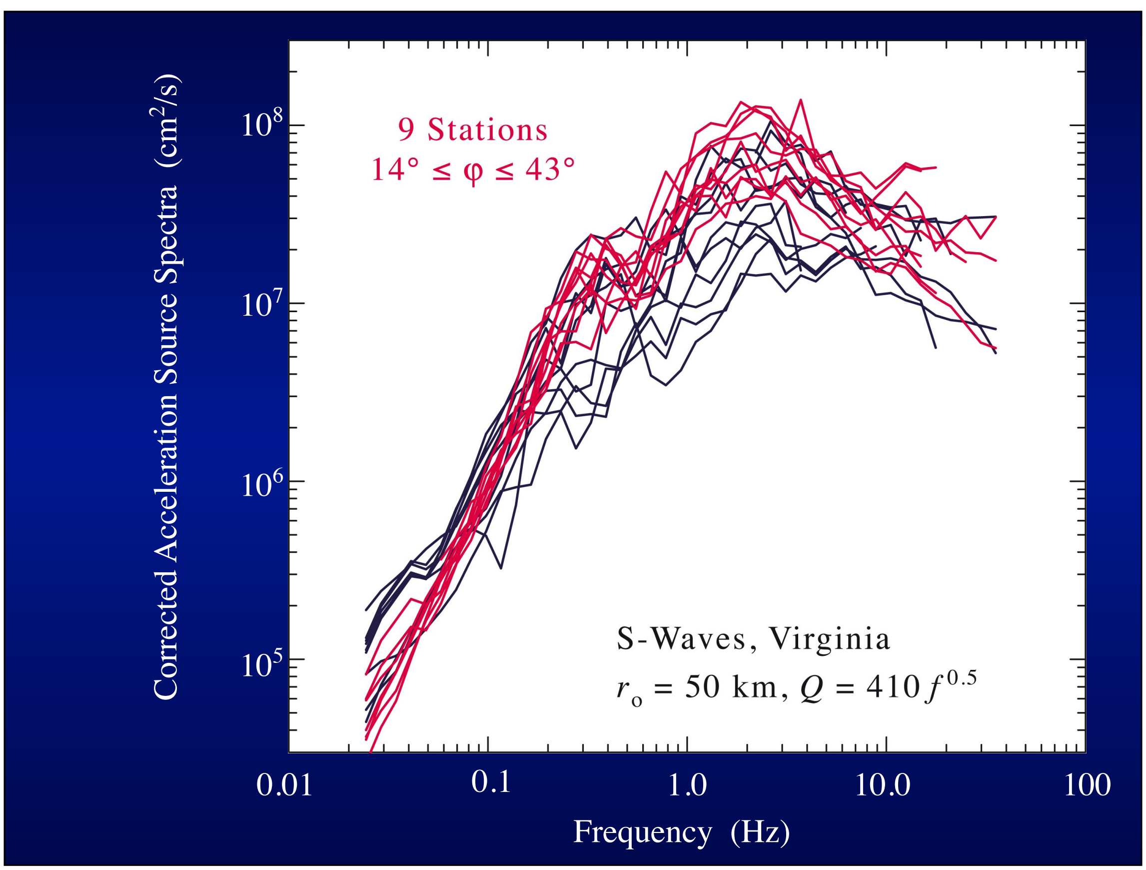

Mw 4.64
fc = 2.44±0.36 Hz
Rivière–du–Loup earthquake
Corrected Acceleration Source Spectra (cm2/s)
Frequency (Hz)
10^7
10^6
10^5
10^4
0.01
0.1
1.0
10.0


Stations for the Virginia Earthquake
N
HCNY
BINY
NPNY
BRNY
ERPA
KSPA
CPNY
M54A
MVL
PANJ
O56A
SDMD
ACSO
MCWV
RSTN
0
200
400
600 km
CBN
CVVA
accelerograph
seismograph
not analyzed
PRIB
BLA
TKL
CNNC
TZTN
KMSC


Merrimack NH
M 3.0
$Q = 410 f^{0.5}$
10 Hz
5 Hz
2.5 Hz
1.0 Hz
$r_o = 50$ km
10^6
10^5
10^4
10^3
10
100
1000
Acceleration Spectral Ordinates (cm^2/s) corrected using Street et al. (1975)
Hypocentral Distance (km)



Corrected Acceleration Source Spectra (cm²/s)
10⁸
10⁷
10⁶
10⁵
22 stations
53 ≤ r ≤ 608 km
S-Waves, Virginia
r_o = 50 km, Q = 410 f^0.5
0.01
0.1
1.0
10.0
100
Frequency (Hz)



Corrected Acceleration Source Spectra (cm²/s)
10⁸
10⁷
10⁶
10⁵
9 Stations
14° ≤ φ ≤ 43°
S-Waves, Virginia
r_o = 50 km, Q = 410 f^0.5
0.01
0.1
1.0
10.0
100
Frequency (Hz)

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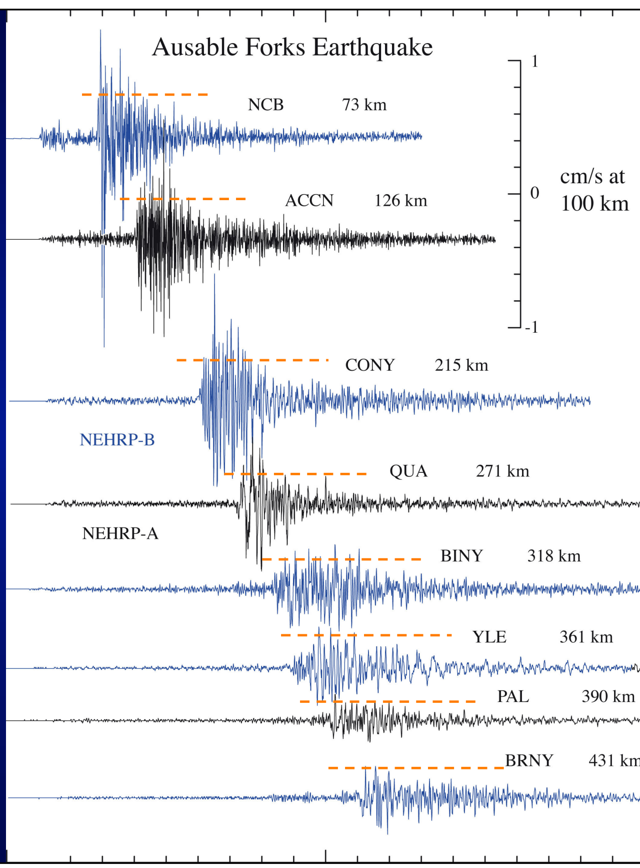
John Boatwright and Tim MacDonald

2000 **M**4.6 Kipawa, Quebec
2003 M3.7 Maniwaki, Quebec
2003 M3.5 Cap-Saint-Fidele, QC
2006 M3.7 Thurso, Ontario
2006 M3.5 L'Ile-aux-Coudres, QC
2006 M3.4 Eagle Lake, Maine
2006 M4.0 Bar Harbor, Maine
2008 M3.5 Rivière-du-Loup, QC
2010 M5.0 Val-des-Bois, Quebec
2010 M3.4 Donnacona, Quebec
2010 M3.1 Merrimack, NH
2011 M3.7 Hawkesbury, Ontario

Why analyze more earthquakes?

To test and refine the attenuation model which is significantly different from Atkinson (2004), Erickson et al. (2004), Shi et al. (1996), …

To determine whether the stress drop varies with depth or magnitude

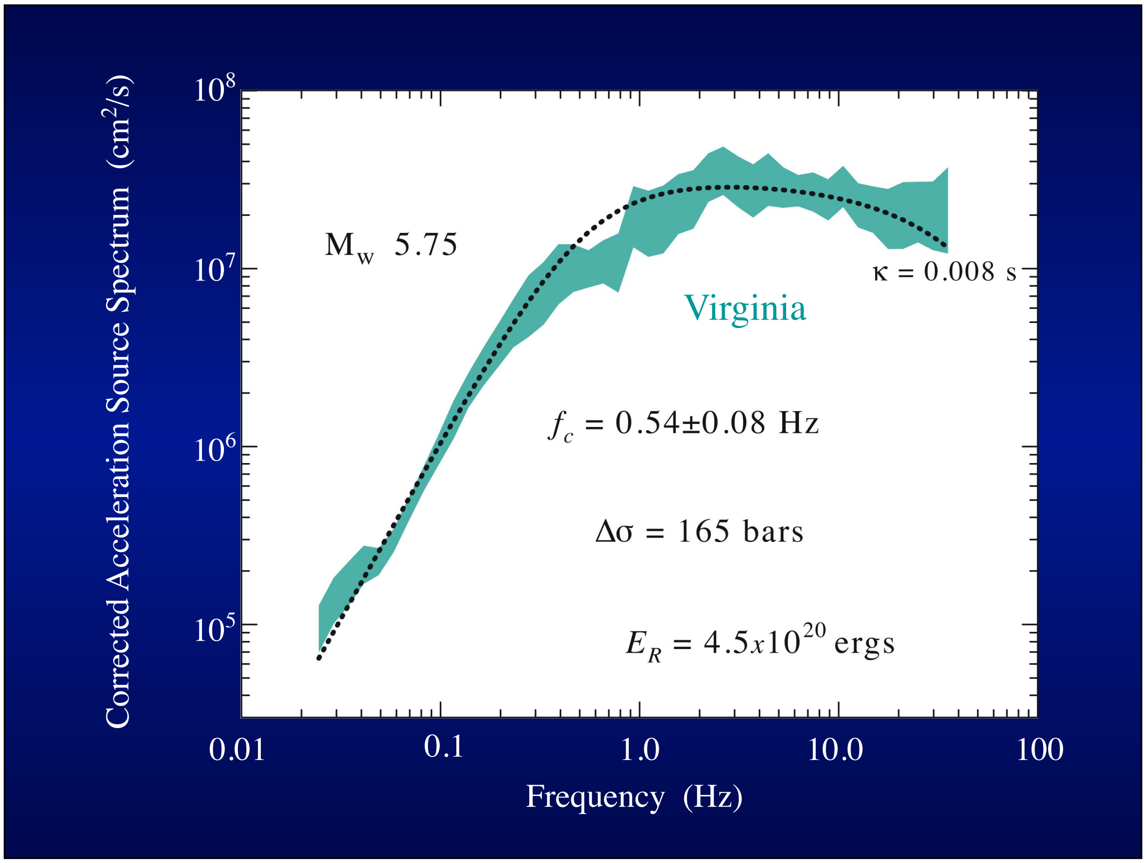


"Record Section" EW-Component Seismograms

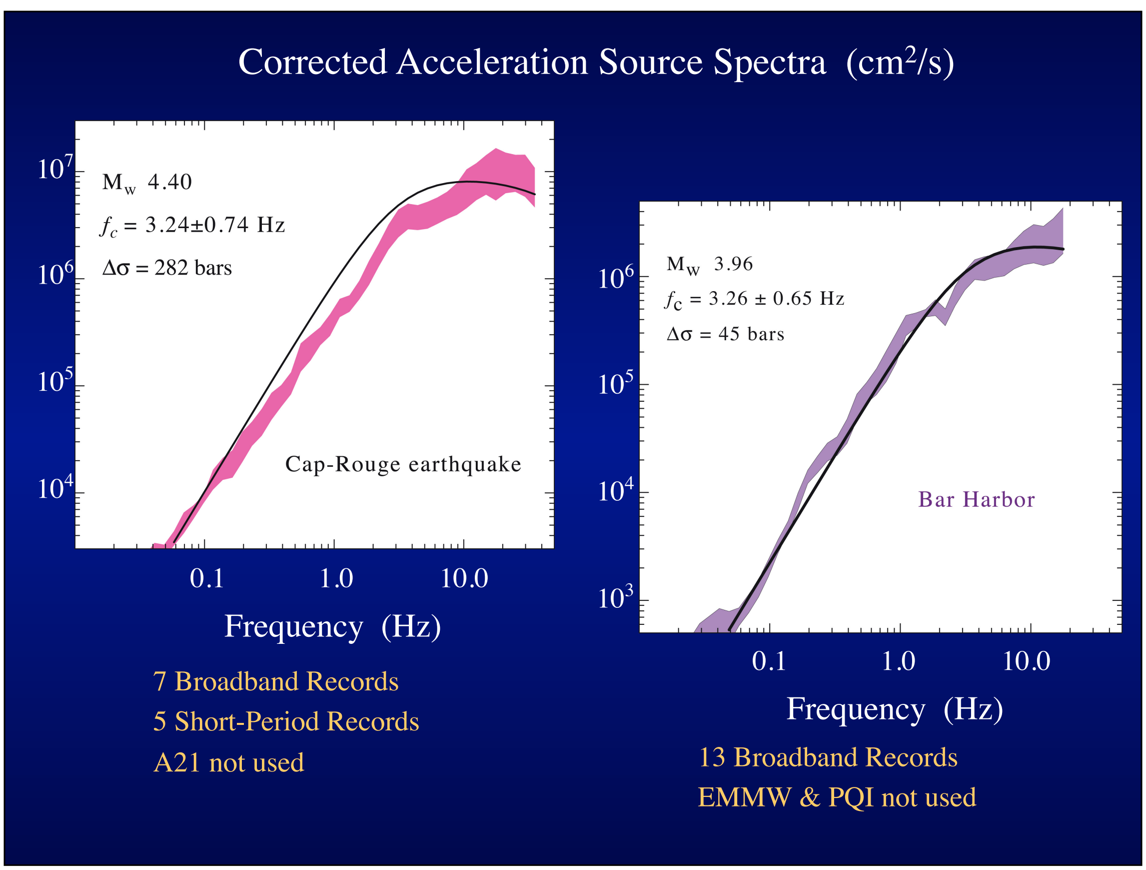
Amplitudes Normalized for Distance as $r^{1/2}$

Hard Rock (NEHRP-A) & Soft Rock (NEHRP-B)

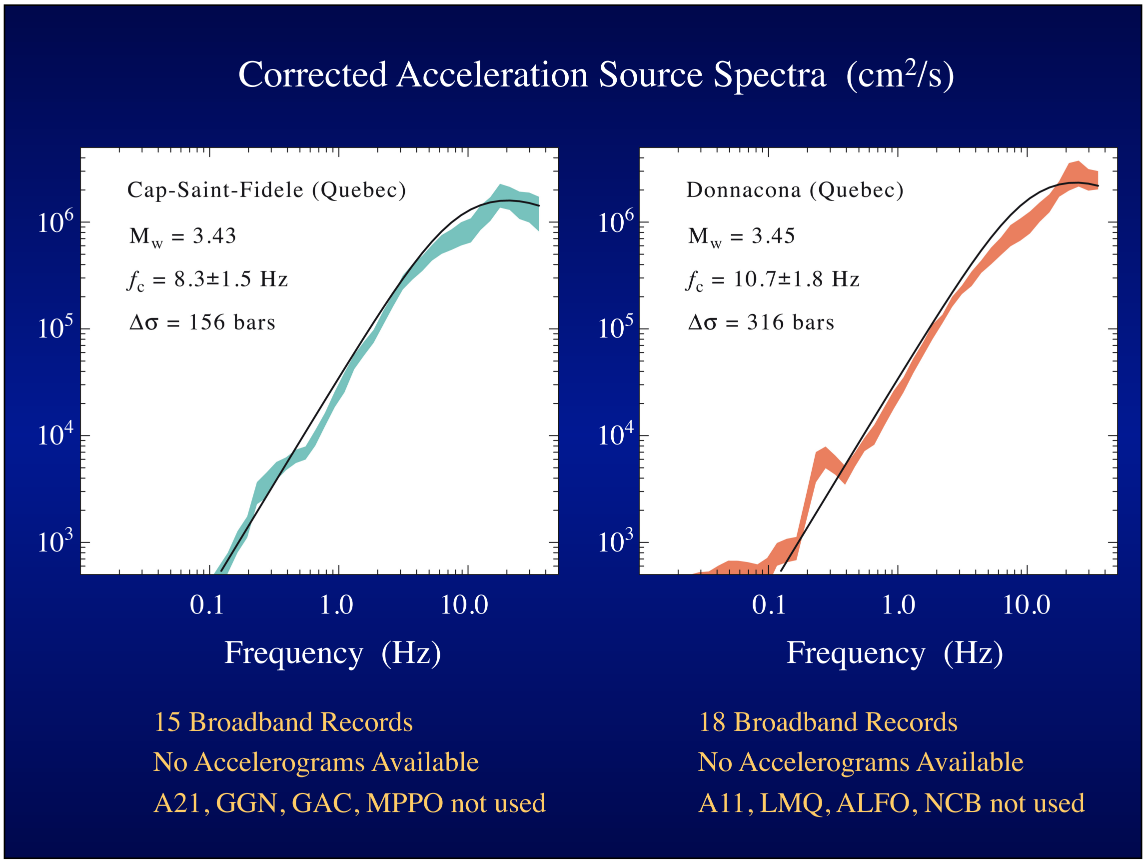
Avoid resonant sites (sediment on rock)



Corrected Acceleration Source Spectrum (cm²/s)
Mw 5.75
Virginia
κ = 0.008 s
fc = 0.54±0.08 Hz
Δσ = 165 bars
ER = 4.5x10^20 ergs
Frequency (Hz)



Corrected Acceleration Source Spectra (cm²/s)
Mw 4.40
fc = 3.24±0.74 Hz
Δσ = 282 bars
Cap-Rouge earthquake
Frequency (Hz)
7 Broadband Records
5 Short-Period Records
A21 not used
Mw 3.96
fc = 3.26 ± 0.65 Hz
Δσ = 45 bars
Bar Harbor
Frequency (Hz)
13 Broadband Records
EMMW & PQI not used



Corrected Acceleration Source Spectra (cm2/s)
Cap-Saint-Fidele (Quebec)
Mw = 3.43
fc = 8.3±1.5 Hz
Δσ = 156 bars
Donnacona (Quebec)
Mw = 3.45
fc = 10.7±1.8 Hz
Δσ = 316 bars
10^6
10^5
10^4
10^3
0.1
1.0
10.0
Frequency (Hz)
15 Broadband Records
No Accelerograms Available
A21, GGN, GAC, MPPO not used
18 Broadband Records
No Accelerograms Available
A11, LMQ, ALFO, NCB not used