Seismic Hazard Assessment for Canadian Urban Centres

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Canadian Seismic Research Network

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Overview

- Seismic hazard assessment approach for Canadian cities
- Input models for assessment of hazard in Canada
- New trends/data in ground-motion analysis
- Impact of new information on assessed hazard in Canadian cities
- Time histories for use in analysis of engineered structures

Seismic Hazard Analysis Methodology

1. Identify the potential sources of future earthquakes (seismic source zones)

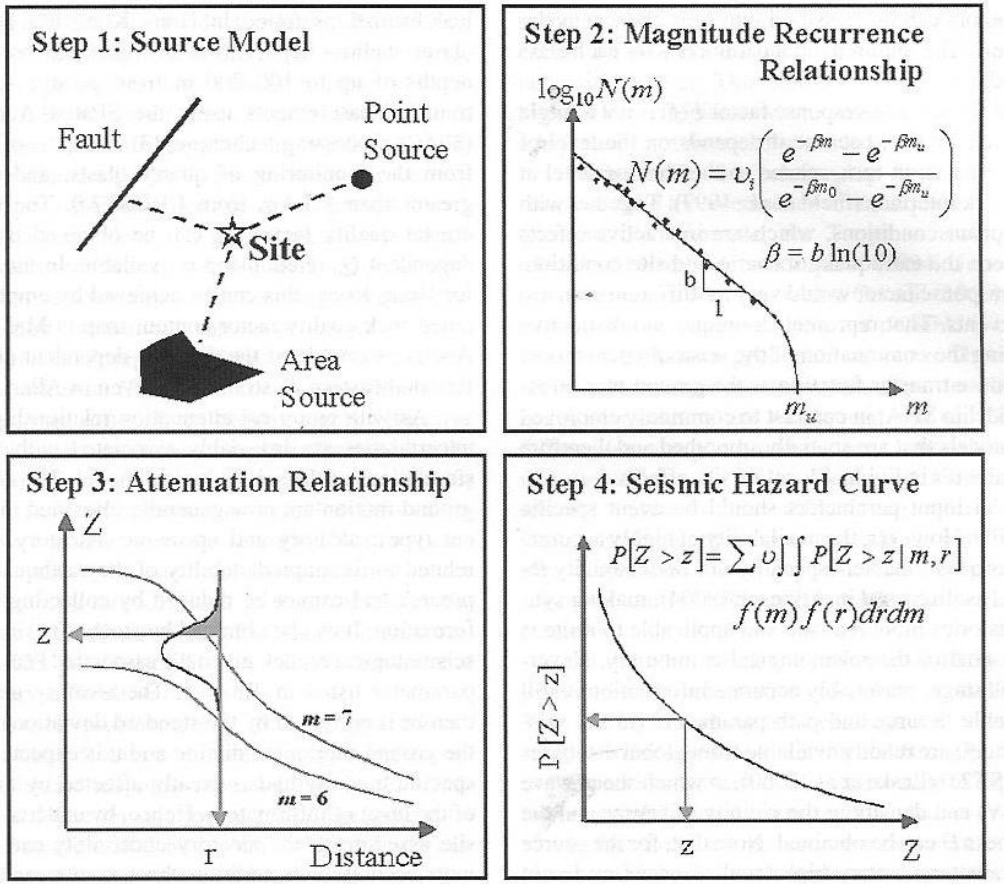


Figure 1. Steps involved in the conventional Cornell-McGuire probabilistic seismic hazard assessment (PSHA) (after Reiter, 1990).

2. Calculate the frequency of earthquakes of different magnitude occur within each source.

3. Define ground-motion prediction equations: amplitude as a function of magnitude, distance,…..

4. Calculate hazard by integration.

Note that for assessing hazards for particular cities,
we can focus on source zones/models of specific interest to city locations
(Site-specific rather than regional focus)

Updated Hazard Analysis Aspects-

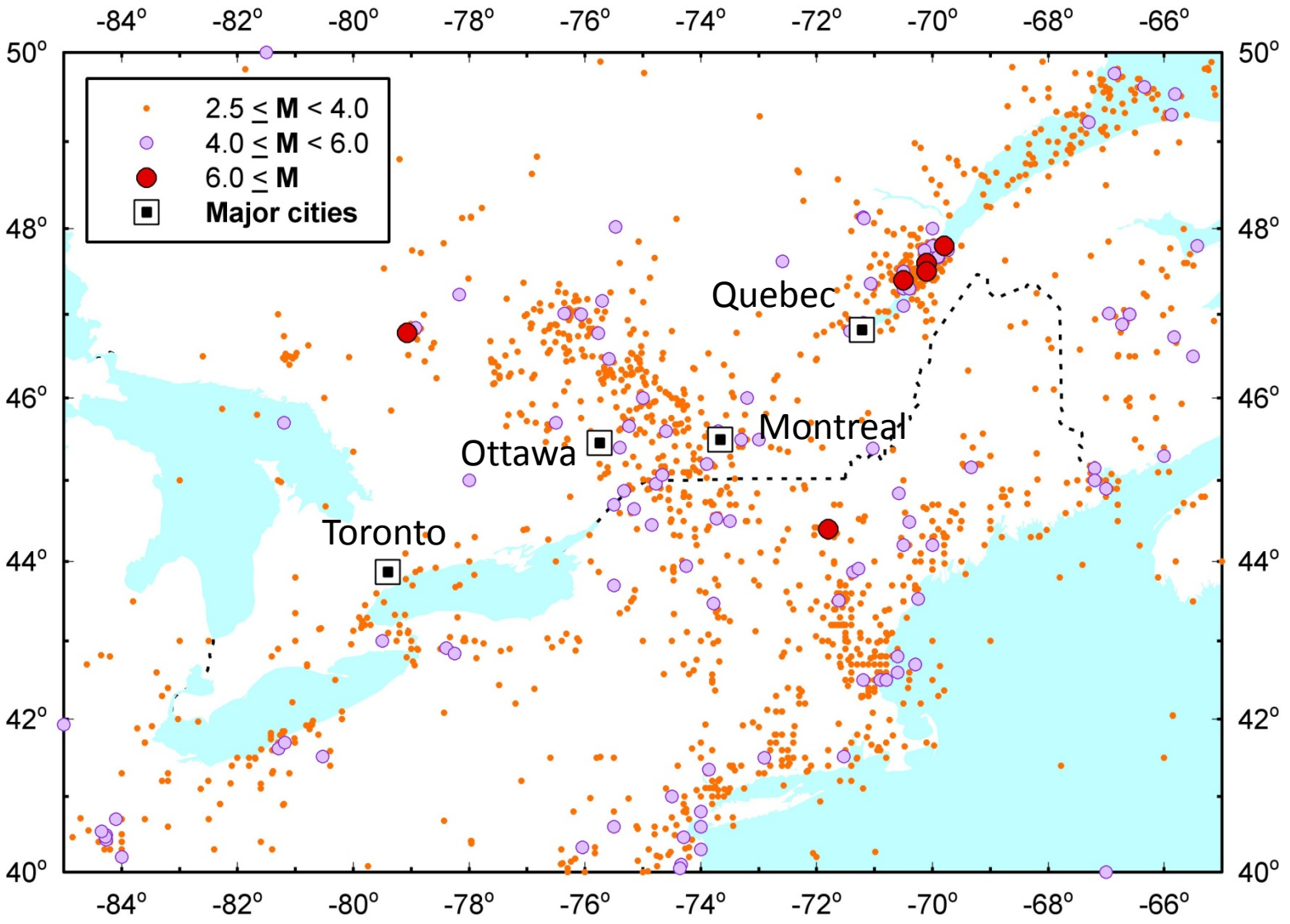
(what's new since 2005/2010 NBBC maps were developing in 1990s)

- **New seismicity catalogue (low impact)**
- **Proper conversion of magnitude statistics to moment M scale (moderate impact)**
- **New seismic source models (important only in east)**
- **New ground motion prediction equations (important all areas) – a suite of GMPEs from last decade are used**
- **Correct implementation of GMPEs (moderate importance)**
- **Probabilistic inclusion of Cascadia subduction events (important for long periods in the west)**

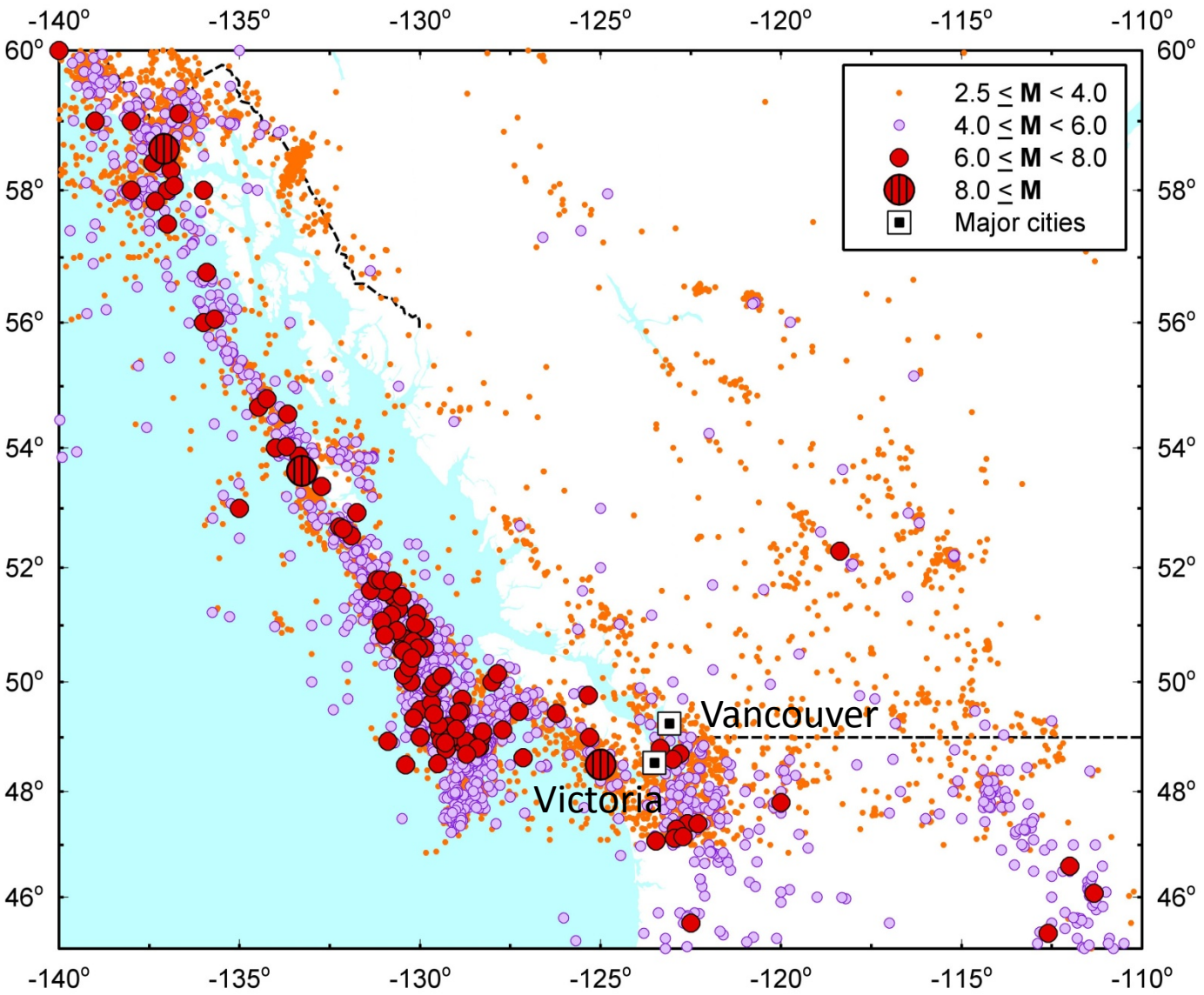
Updated hazard assessment: 1 – new seismicity catalogue

- Updated composite seismicity catalogue (Canadian Composite Seismicity Catalogue, CCSC)
- CCSC compiles all events in Canadian and U.S. catalogues to 2011, retaining all magnitude measures, and converting preferred measure (where required) to moment magnitude
- Published by Fereidoni et al., Seism.Res.L., 2011
- Available at www.seismotoolbox.ca
- (similar to new GSC catalogue being compiled for 2015 seismic hazard mapping update)

Earthquake catalogue for eastern Canada: www.seismotoolbox.ca

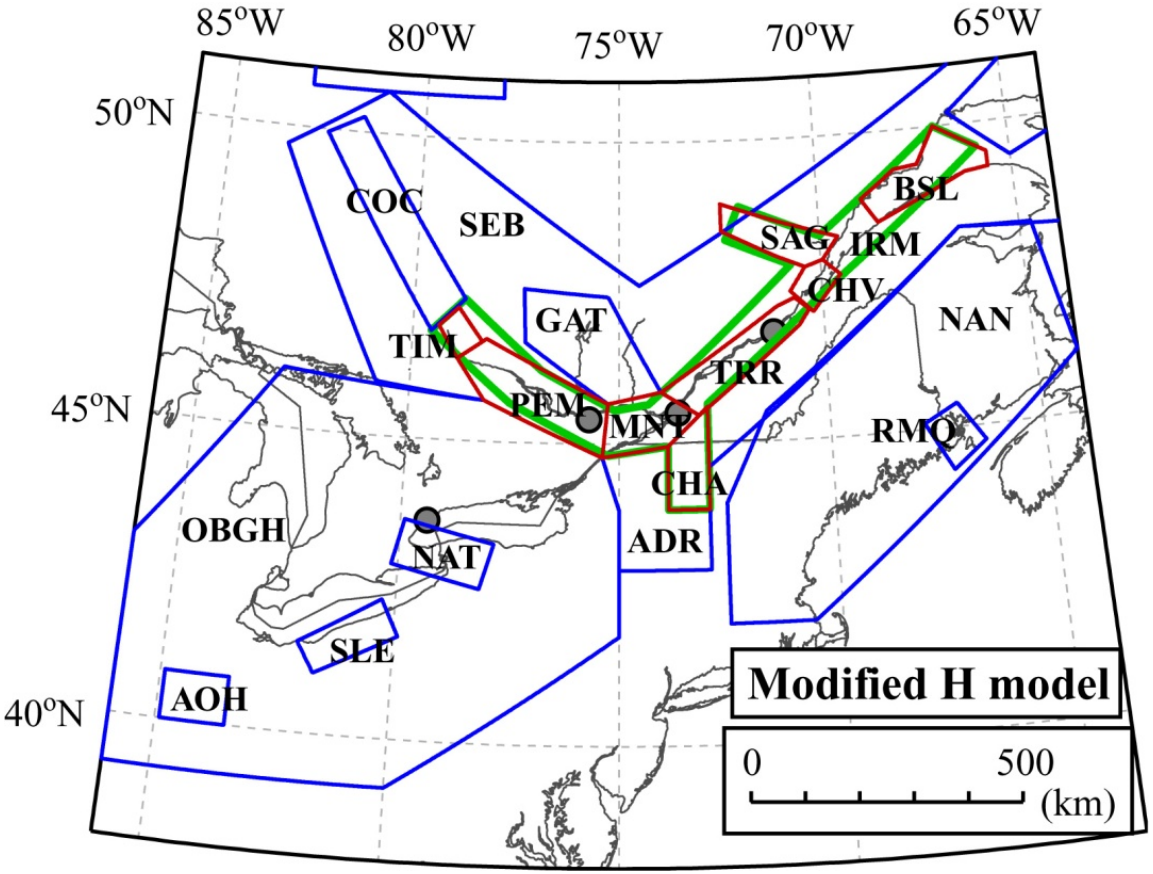


Earthquake catalogue for western Canada
www.seismotoolbox.ca



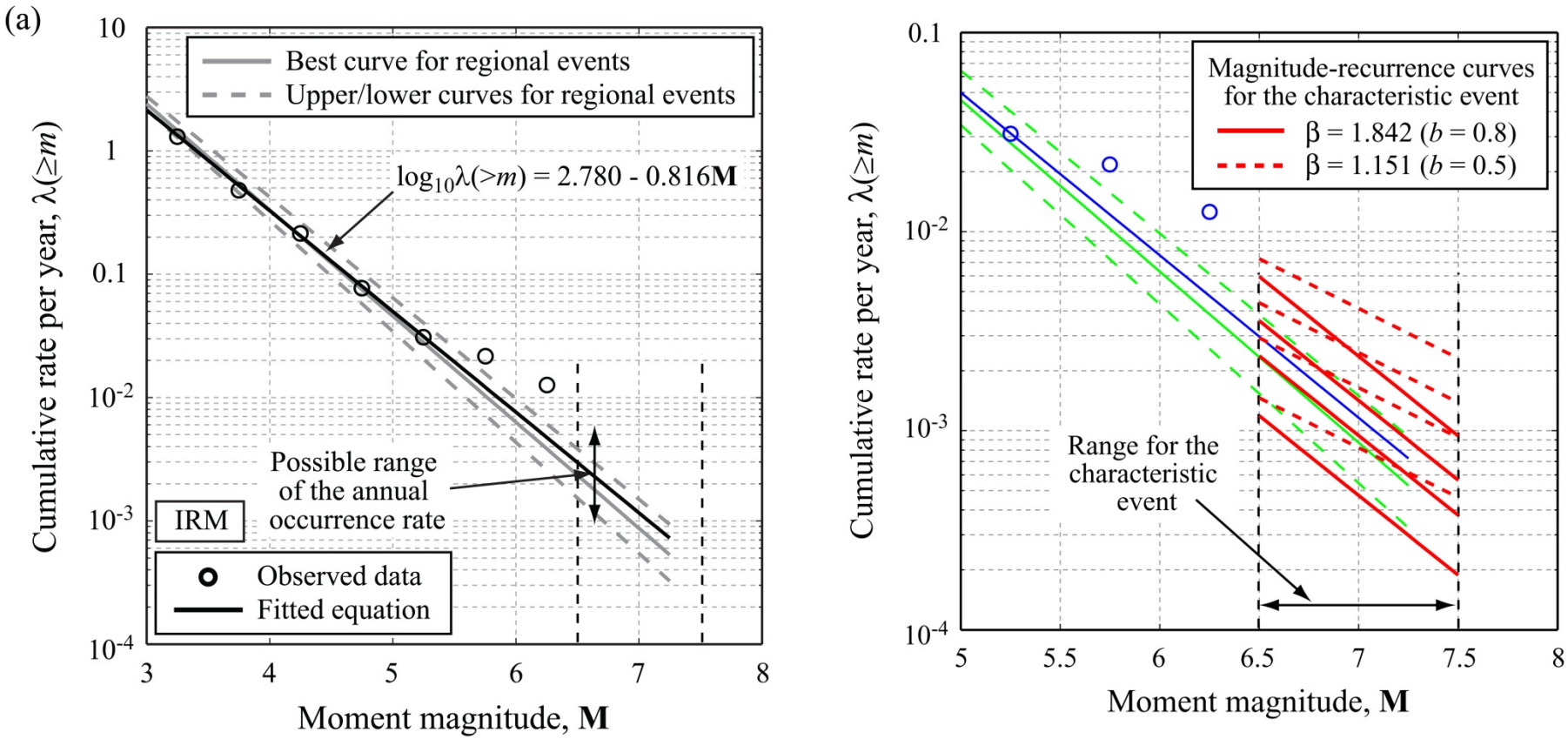
Updated Seismic Hazard Model – changes in seismic source zone characterization in East (Atkinson and Goda, 2011, BSSA)
Consider events in historically-active cluster (to M6.5), plus "characteristic" or wandering large events along the rift model

Modified seismic source zones



- Seismic rates are reevaluated using a longer and homogeneous *CCSC09* earthquake catalog compiled by Fereidoni et al.
- For the **St. Lawrence rift region** (IRM, **green color**), small-to-moderate events are characterized by several GR relations for smaller zones, whereas large events are characterized by a semi-characteristic model. (similar to model being developed by GSC)

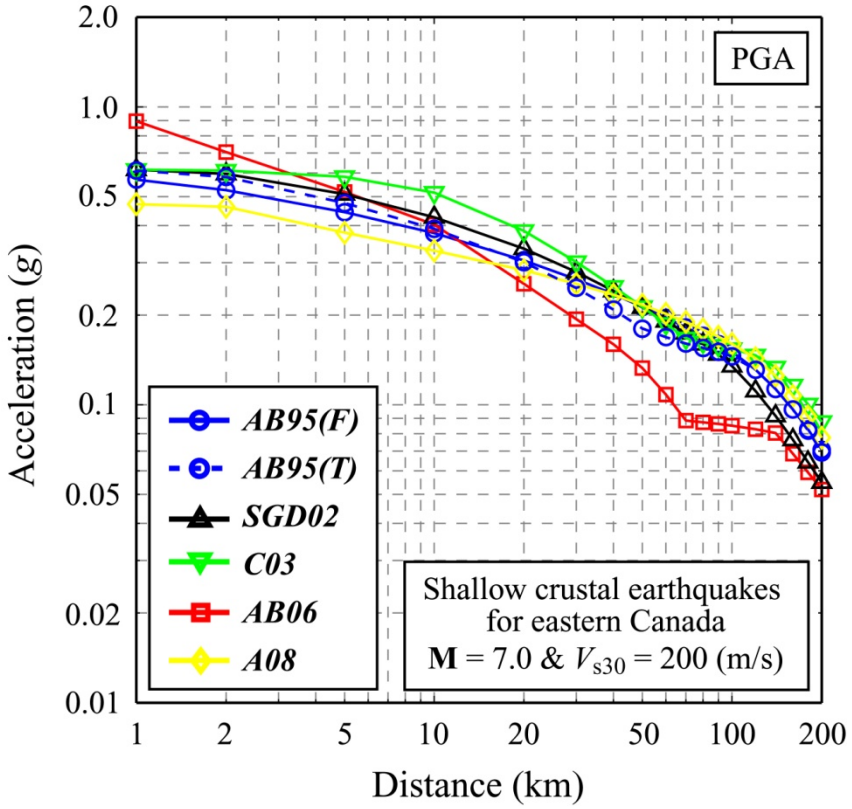
Characteristic model magnitude recurrence
St. Lawrence Rift zone



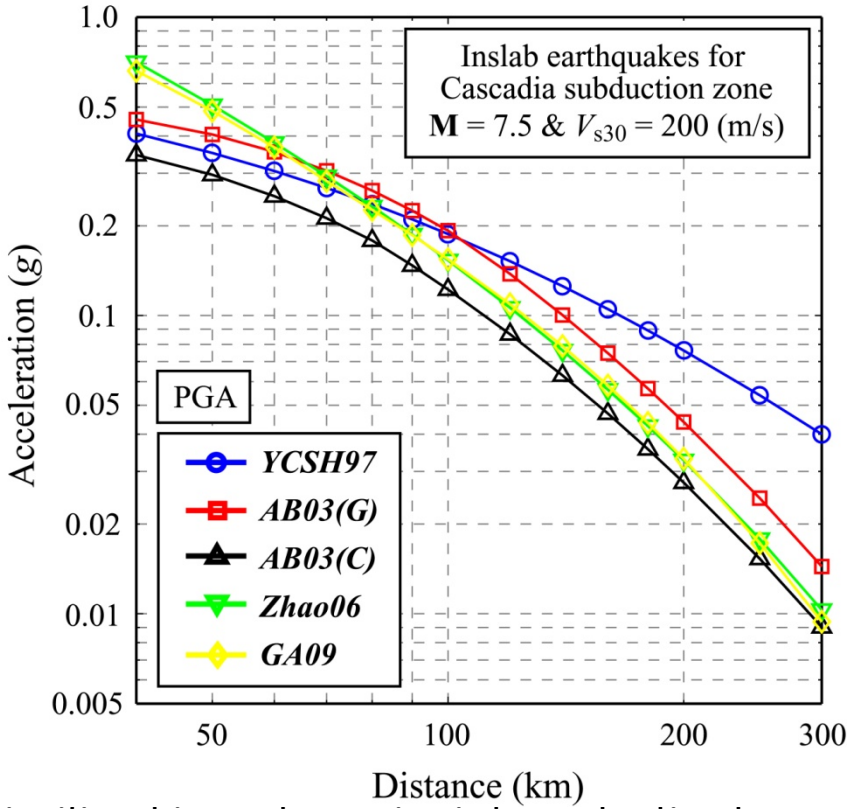
GR relation for IRM Model, compared to adopted characteristic model for large events along the zone (M6.5 – 7.5)

Updated Seismic Hazard Model – changes in GMPEs

Eastern Canada

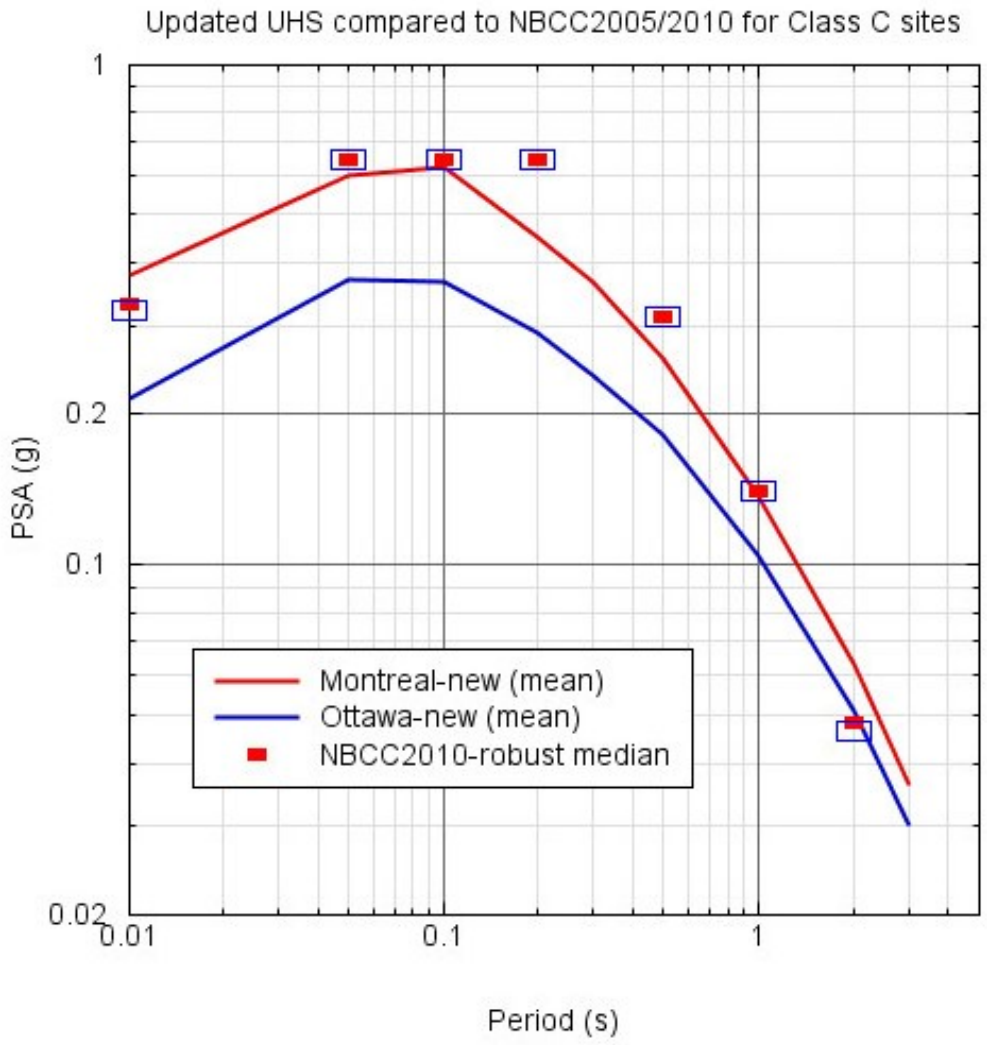


Western Canada (inslab events)



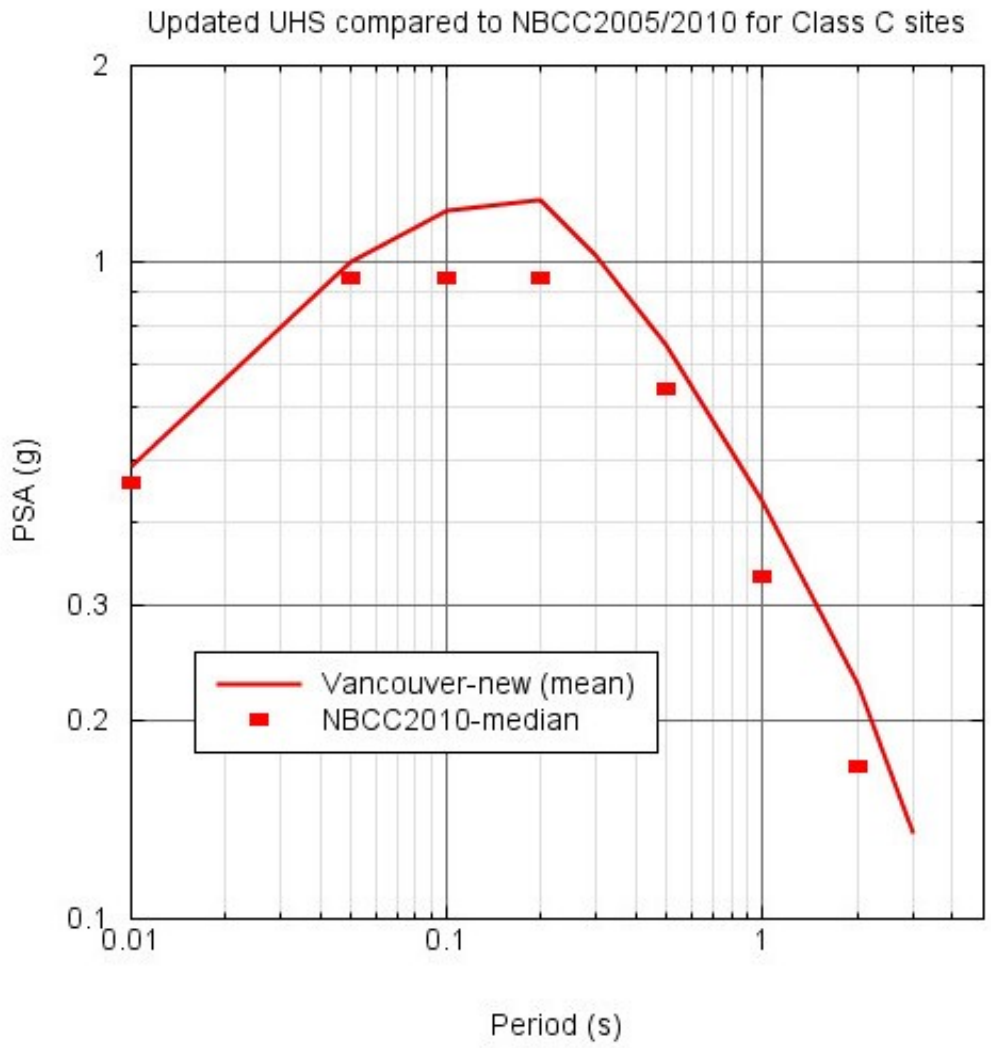
- Ground motion prediction equations have most significant impact on seismic hazard estimates.
- We consider multiple recent ground motion prediction equations to account for epistemic uncertainty regarding their selection.
- In NBCC2005/2010, AB95 was used in the east. YCSH97 in west (blue curves);
- we consider newer GMPEs as shown by alternative curves above

Updated Seismic Hazard Assessment – Montreal and Ottawa (Atkinson and Goda, 2011)



- Updated seismic hazard estimates (mean UHS) for Montreal are lower than robust median as given in 2005/2010 NBCC at short periods, slightly larger at long periods
- Updated mean-hazard UHS for Ottawa significantly lower than 2005/2010 NBCC robust median at most periods
- Note that median-hazard UHS would be even lower

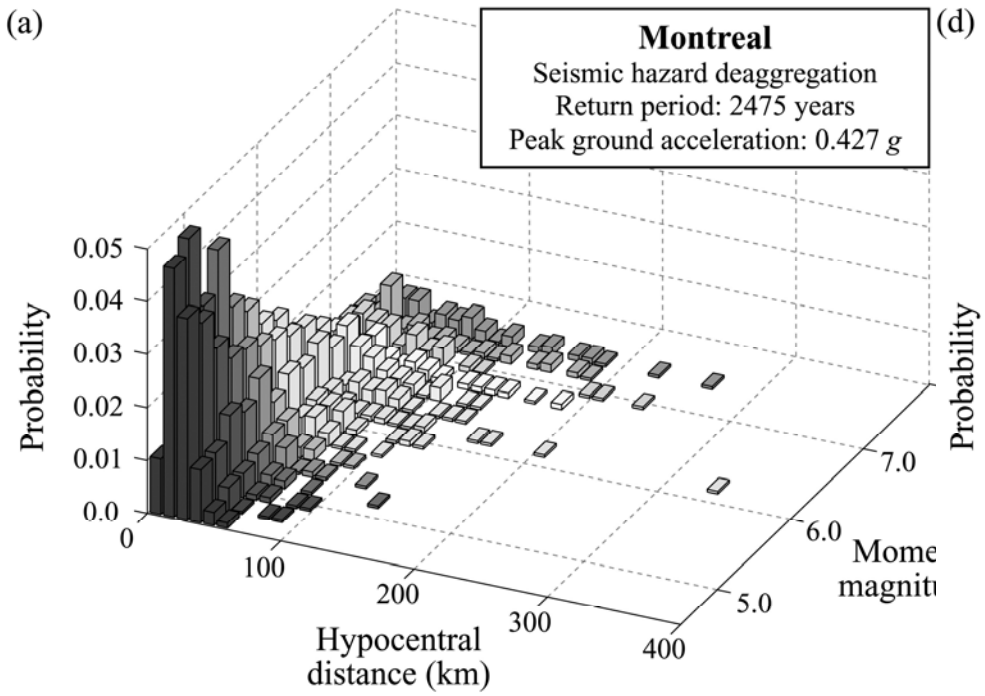
Updated Seismic Hazard Assessment – Vancouver (Atkinson and Goda, 2011)



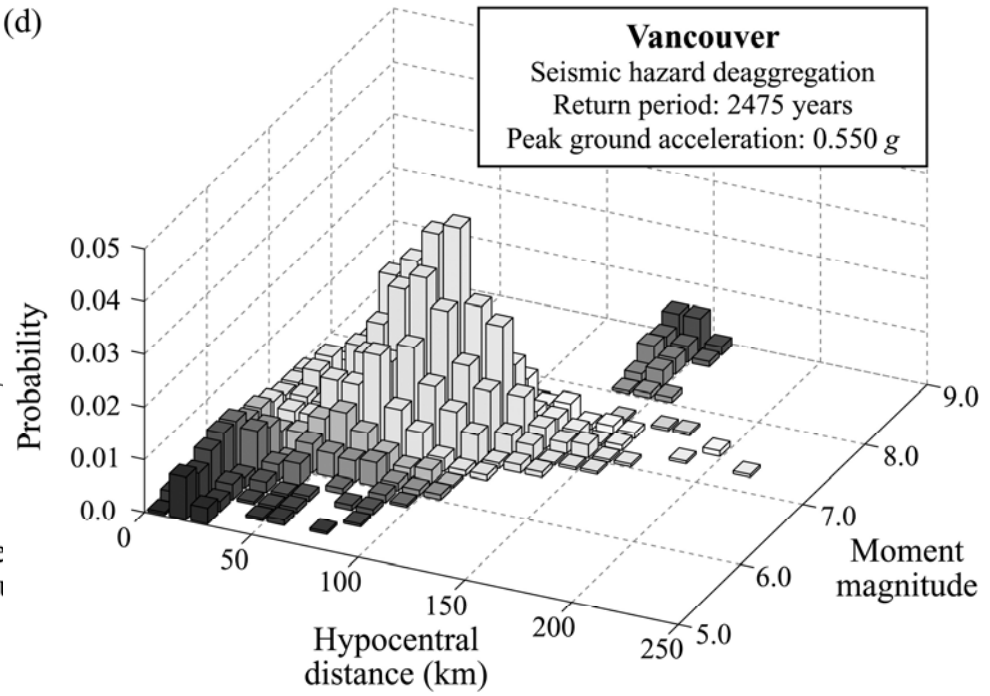
- Updated seismic hazard estimates for Vancouver (mean-hazard) exceeds 2005/2010 NBCC median by a modest amount
- But note it would not exceed NBCC if we had used median-hazard rather than mean-hazard

Deaggregation Analysis -

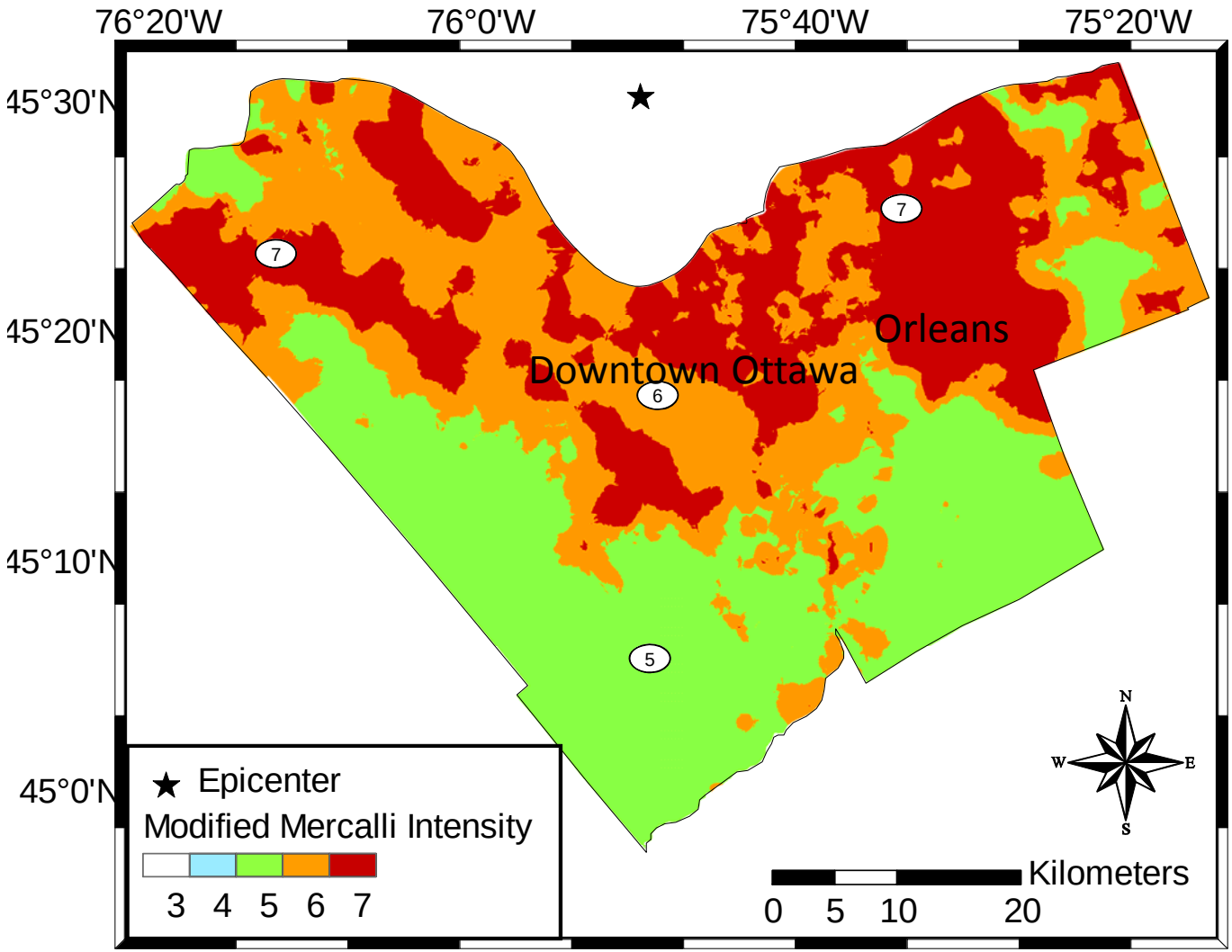
Montreal



Vancouver



- Seismic hazard deaggregation shows the characteristics of contributing seismic events at a selected probability level – PGA shown here
- For Montreal, seismic hazard (short periods and PGA) is dominated by M~5 to 6.5 at R<50 km
- For Vancouver in-slab events dominate for short periods (and PGA); crustal events also important



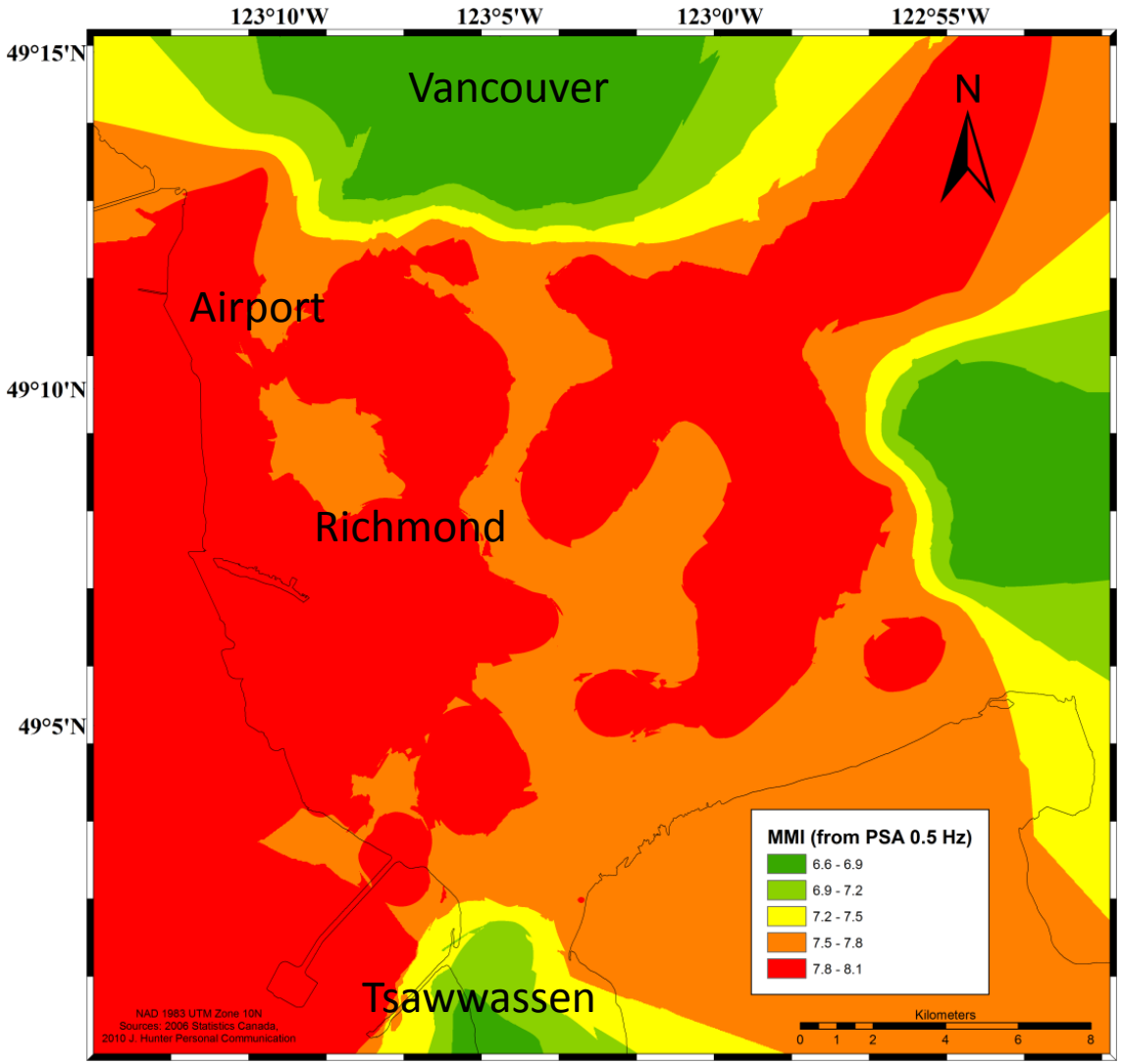
Predicted intensities for hypothetical M6 event north of Ottawa (star). Motions are code-level for design.

Max. MMI=7: Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable damage in poorly built or badly designed structures

Scenario ShakeMap for Ottawa (based on deaggregation)

(soils range from hard to soft)

Pal and Atkinson, BSSA, 2012)



Map of expected intensity (MMI), for an M9 Cascadia subduction zone. Max. MMI=8: Damage slight in properly designed structures; considerable damage in substandard buildings with partial collapse.

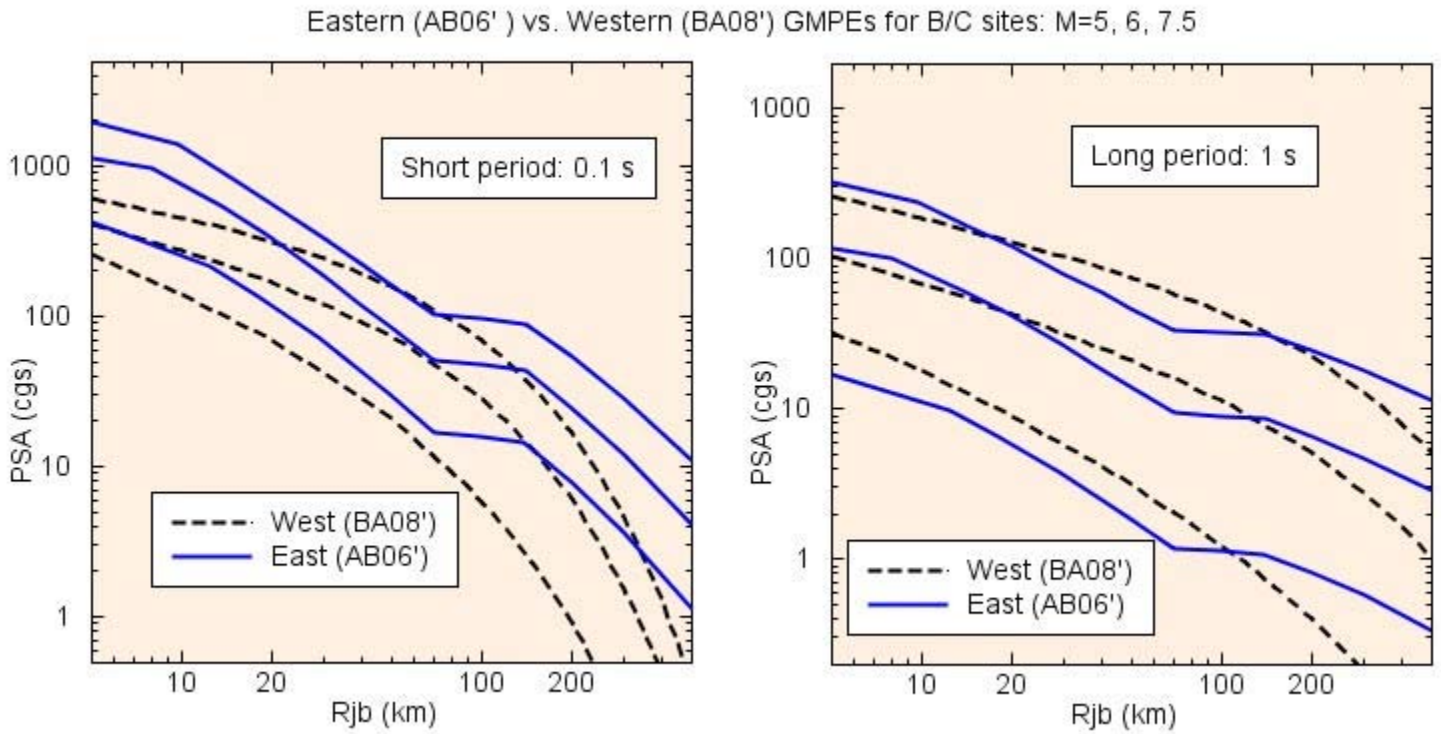
Damage great in poorly built structures.

Scenario ShakeMap for Fraser Delta, south of Vancouver (on deep soil deposits): M9 Cascadia

Ground-motion Prediction Equations (GMPEs)

- GMPEs are a key input to seismic hazard models that drives the output ground motion maps (or scenario ShakeMaps)
- They describe the shaking intensity as a function of earthquake magnitude, distance and site condition
- GMPEs based on empirical and analytical modeling of recorded ground motions from past earthquakes
- The database for GMPEs has increased a hundred to a thousand-fold since the maps for NBCC last updated
- Newer GMPEs routinely used in site-specific hazard analyses in Canada

Note on eastern vs. western ground motions and hazard: Ground motion characteristics different in stable continental regions (such as ENA) than in the west



Eastern motions have higher frequency content, and attenuate more slowly with distance.

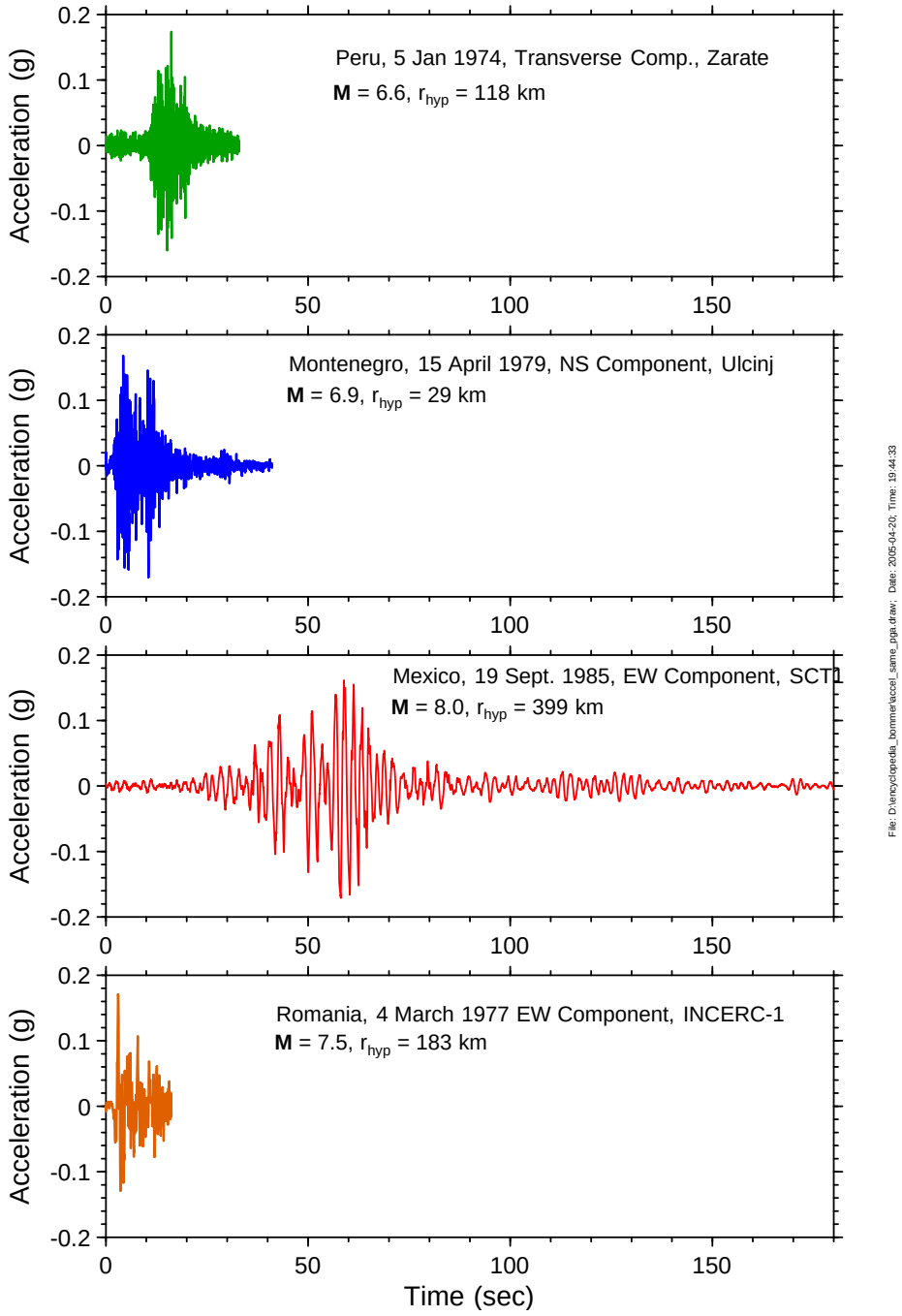
Thus nature of eastern and western hazard (and time histories) may be different

Measures of ground-motion intensity for engineering purposes

- Peak Ground Acceleration (PGA), Velocity (PGV)
- Response spectra (elastic)

  (typical output of probabilistic hazard analysis – this is what is plotted on a Uniform Hazard Spectrum)
- Time series (typical input to dynamic analysis)

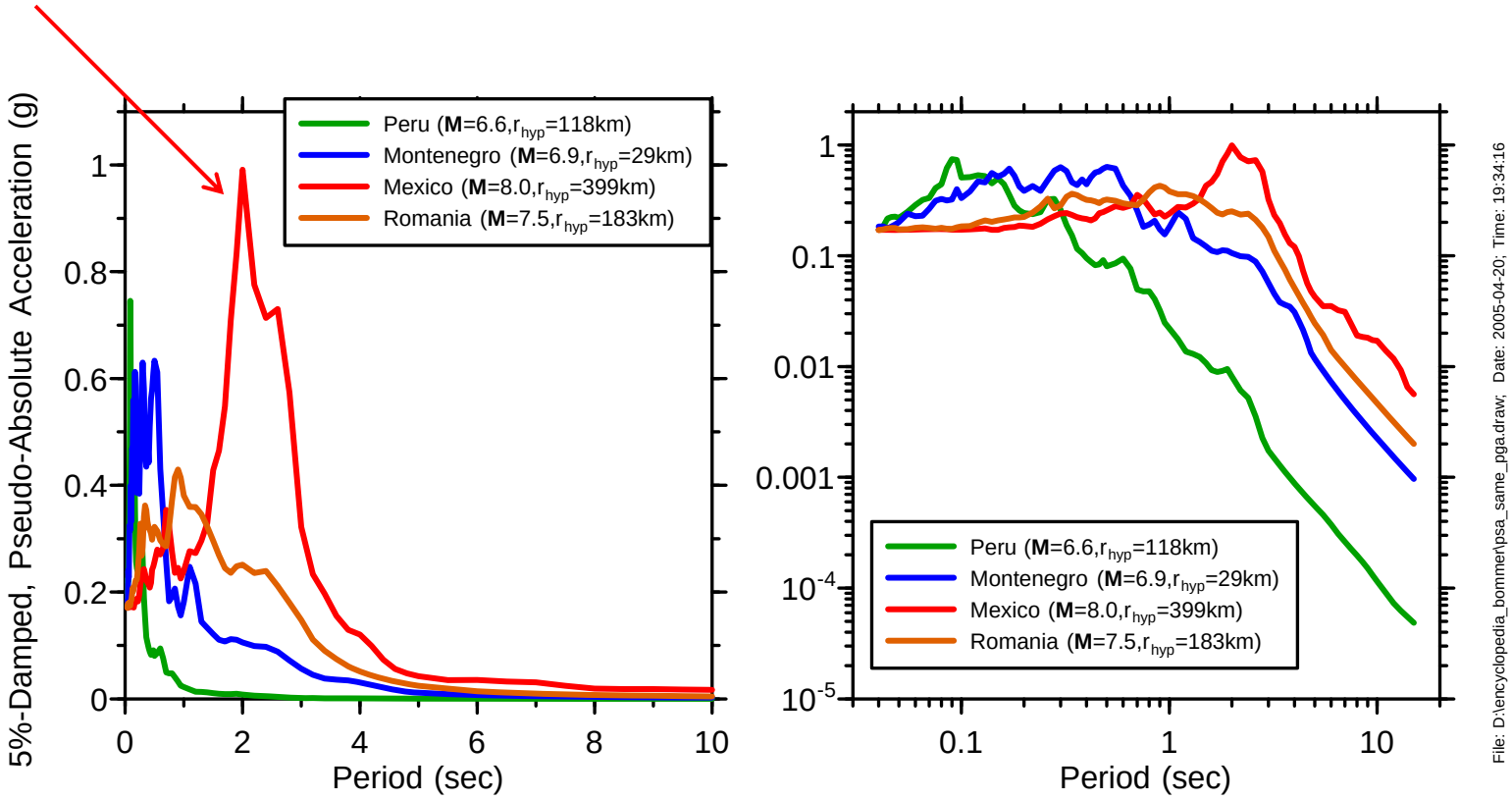
- Response spectrum is a handy way of describing both the amplitude and frequency content of earthquake records
- Single parameters like PGA are too limited
- All of these time series have the same PGA (0.18g)



D. Boore, USGS

Response of 2s SDOF oscillator to ground motion record

But the response spectra (and consequences for structures) are quite different (lin-lin and log-log plots to emphasize different periods of motion):



Linear scale at left

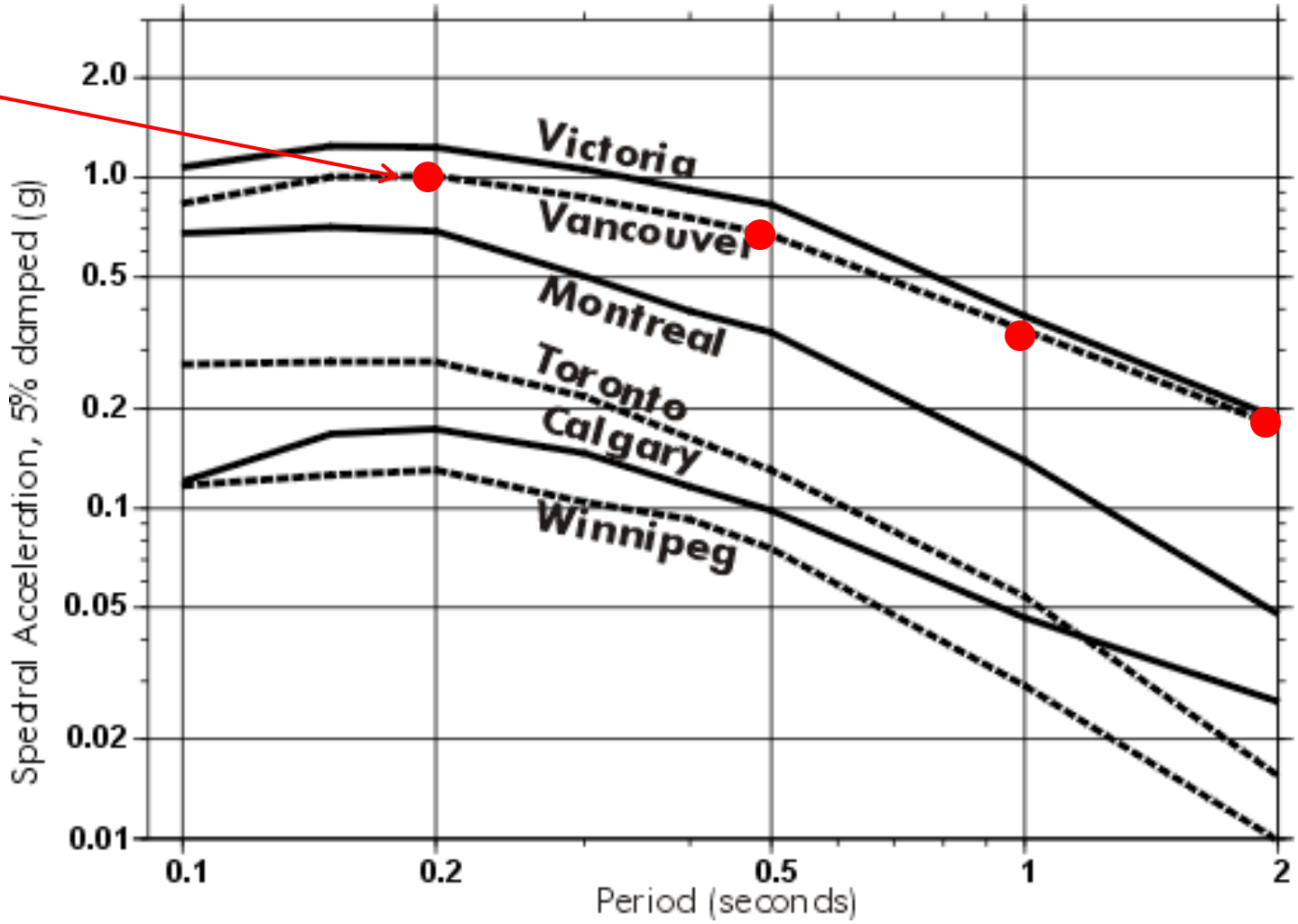
Log scale at right

D. Boore, USGS

To obtain the Uniform Hazard Spectrum: expected response spectrum for specified probability, is calculated (from the PSHA) and plotted vs. period

(the UHS is not the response spectrum from a single earthquake, but a composite of the response spectrum amplitudes for a specific probability)

Response of SDOF oscillator of T=0.2s to ground motion



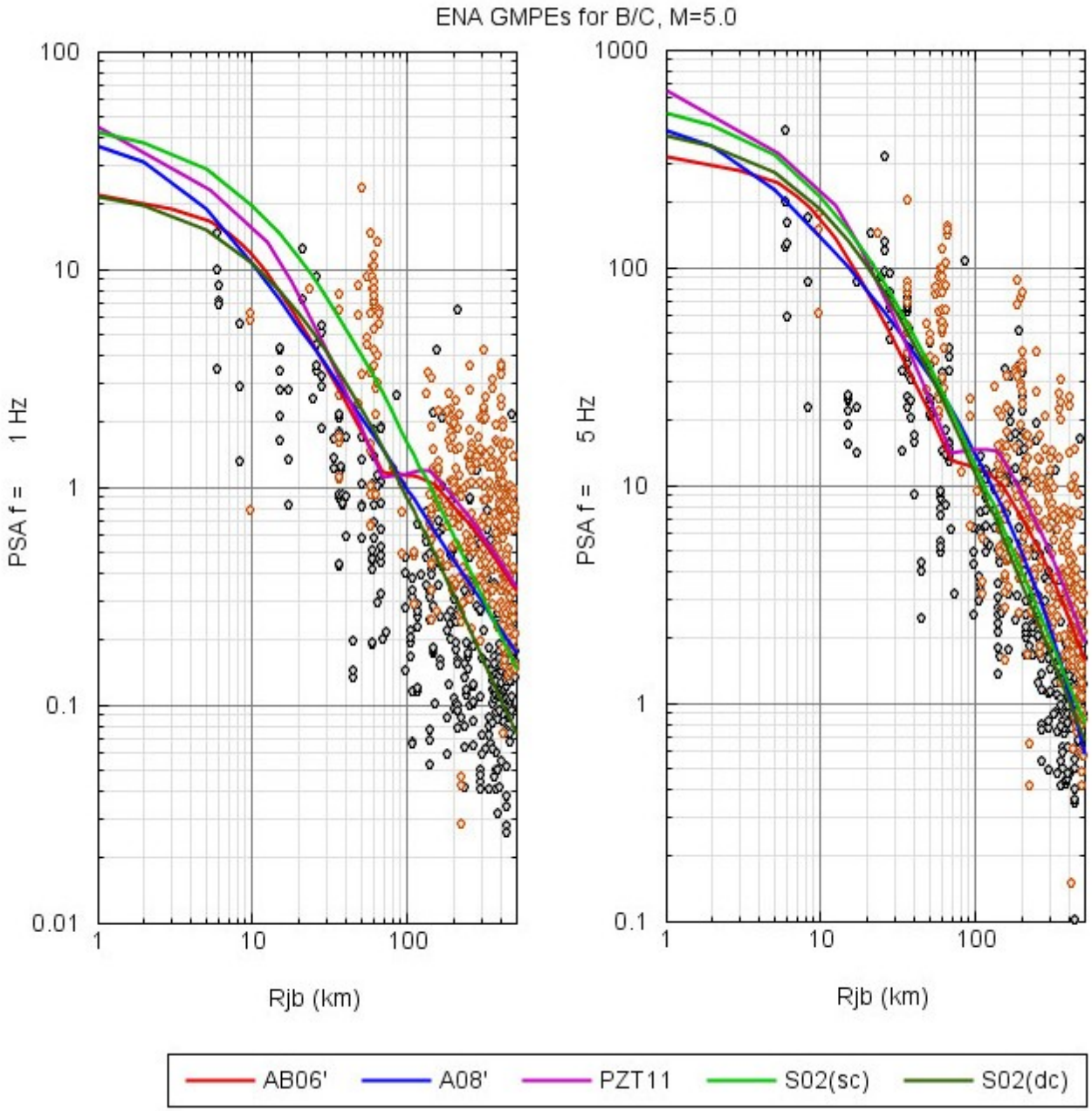
(J. Adams, GSC)

Selecting ground motion prediction equations for response spectra:

- Median GMPEs should be selected from published (or peer-reviewed) equations for appropriate region.
- Epistemic uncertainty in median GMPEs may be modeled by the use of alternative equations
- The GMPEs will typcially be given for the reference B/C condition (Vs30=760 m/s) for input to the hazard model – any modifications for soil can be done later.
- The magnitude measure for the GMPEs is moment magnitude (**M**); distance metrics vary (e.g. Rcd, Repi, etc.) but can be converted to a common equivalent.
- A set of 3 or more alternative weighted GMPEs is often used to describe the epistemic uncertainty

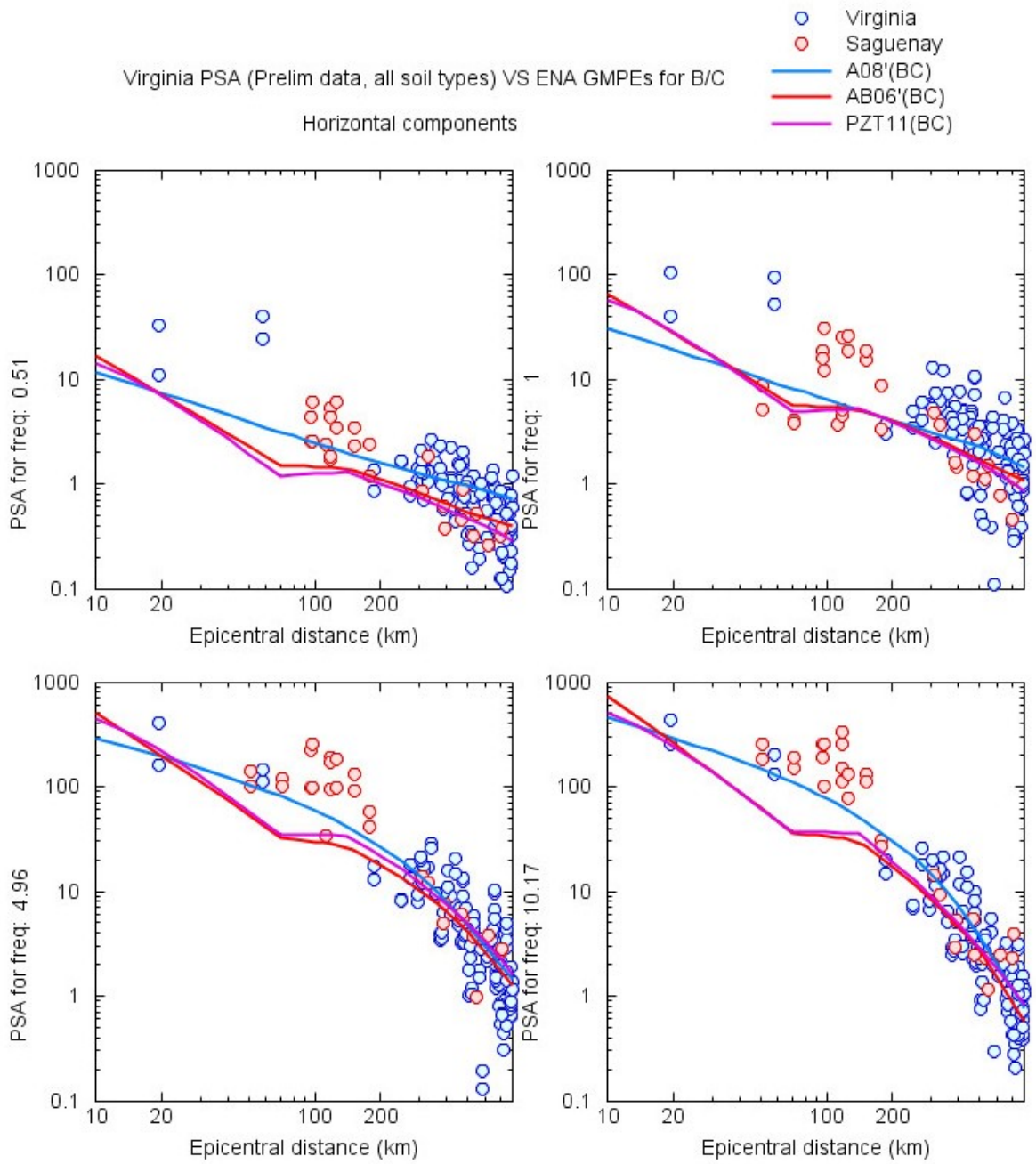
Eastern GMPEs

- Considered 5 alternative GMPEs that are commonly used in site specific studies in ENA, and used by USGS in their maps
- *PZT11: Pezeshk, Zhandieh and Tavakoli, 2011* - based on the hybrid empirical approach developed by Campbell (2003); updated model for both the ENA parameters and the WNA reference equations.
- *AB06': Atkinson and Boore, 2006 (as revised in Atkinson and Boore, 2011)* - based on a stochastic finite-fault approach, which is a simulation approach with key parameters calibrated based on ENA ground-motion data. Recently updated (Atkinson and Boore, 2011) to agree better with recent moderate-magnitude earthquake data. Updated version referred to as AB06'.
- *A08': Atkinson, 2008 (as revised in Atkinson and Boore, 2011)* - based on a referenced empirical approach, which uses ENA data directly to derive adjustment factors to WNA GMPEs. Updated version referred to as A08'.
- *SGD02S: Silva, Gregor and Daragh, 2002, Single-corner (variable stress)* - not been formally published (except on the authors' website) but has been very widely used; it is recommended for inclusion for this reason, as an 'industry-standard' model
- *SGD02D: Silva, Gregor and Daragh, 2002, Double-corner (with saturation)* - another variant of the SGD02 model, to address uncertainty in ENA source



Comparison of eastern GMPEs with data: M~5

Figure notes:
M*4.5-5.0 data in black,*
M*5.0-5.5 data in orange.*



Comparing Saguenay 1988 to Virginia 2011 (both M5.8) – Virginia record at 50km has strong site resonance 0.5 to 1 Hz

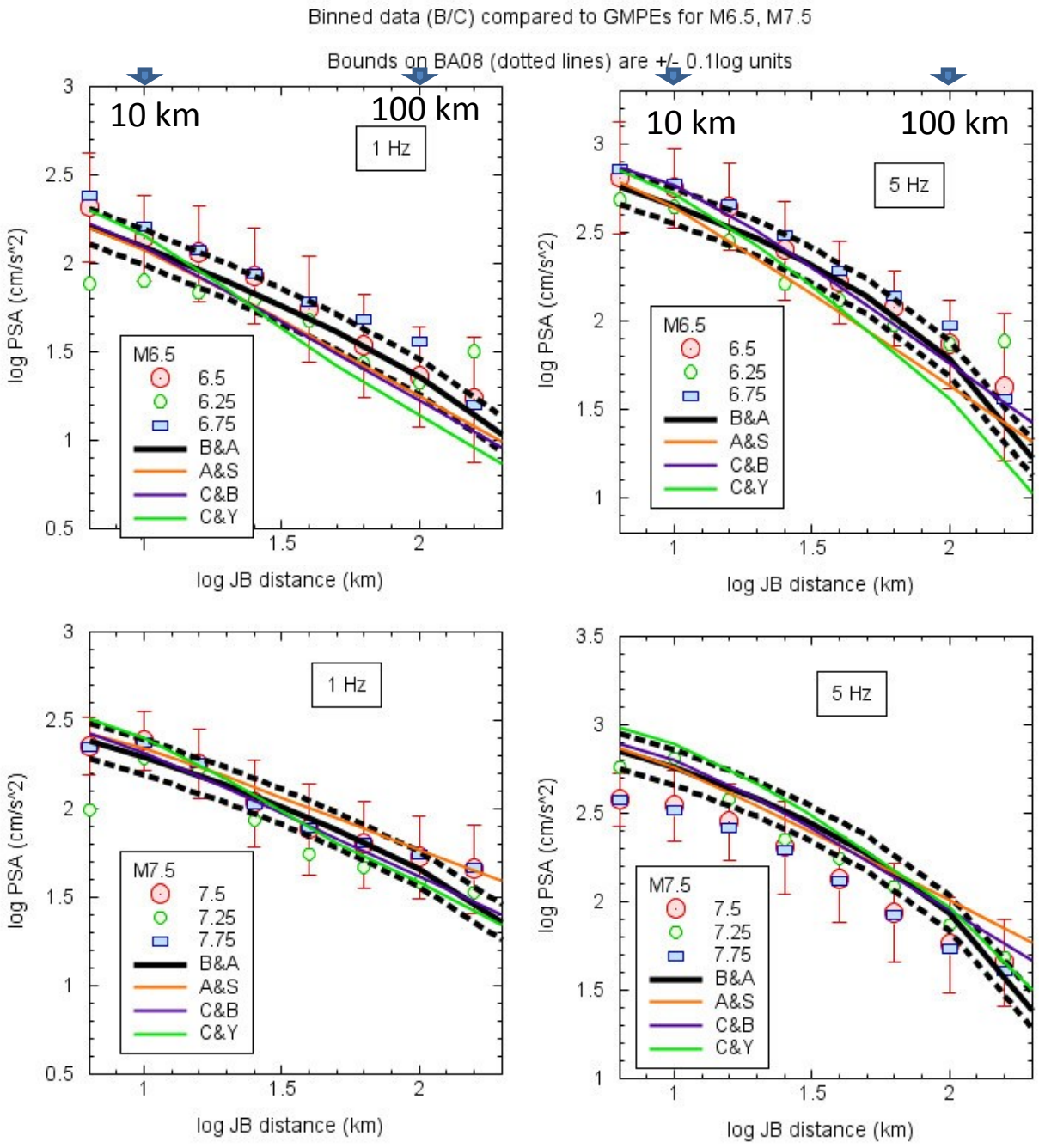
- Saguenay motions have strong Moho bounce near 100km (all in Chv)

Western crustal GMPEs

- Suite most commonly used now is PEER-NGA suite of 5 alternatives (only 4 if include just those developed with site condition as variable)
- Many involve level of detail/parameters that are unknown/not available for western Canada
- All known to overestimate motions for small events (M<6) but only 2 have been adjusted for this
- GMPEs agree fairly closely with each other and may not represent full uncertainty

Suggested approach

- Use one of the equations as representative, and use the other equations and data to define uncertainty about it
- Representative eqn is BA08’ (Boore and Atkinson, 2008), as adjusted for moderate magnitudes (Rationale: simplest fuctional form, fewest parameters, includes adjustment for moderate magnitudes)
- Use data constraints to bound uncertainty



Western crustal GMPEs for M6.5 (top) and M7.5 (bottom)

– compared to data constraints

Figure notes: Solid lines show NGA equations (10 to 200km). Dashed black lines are BA08 ± 0.1 log units. Note that for these magnitudes (M>6), BA08=BA08'. Symbols show mean data amplitudes for 0.5 unit magnitude bins; error bars show standard deviation for central magnitude bin.

Western in-slab GMPEs – from published studies using in-slab data

- Atkinson and Boore (2003) (AB03) – uses Nisqually data and addresses differences in in-slab motions between Cascadia and Japan
- Zhao et al. (2006) (Z06) – best current in-slab GMPE in terms of data, but focused on Japan
- Goda and Atkinson (2009) (GA09) – recent GMPE that includes depth, Vs30 as predictive variable (similar to Kanno, 2006)
- Note B.C. Hydro has new in-slab GMPEs that are expected to be released soon

Comparison of in-slab GMPEs: M7.0

(also shows Youngs et al. 1997 for reference)

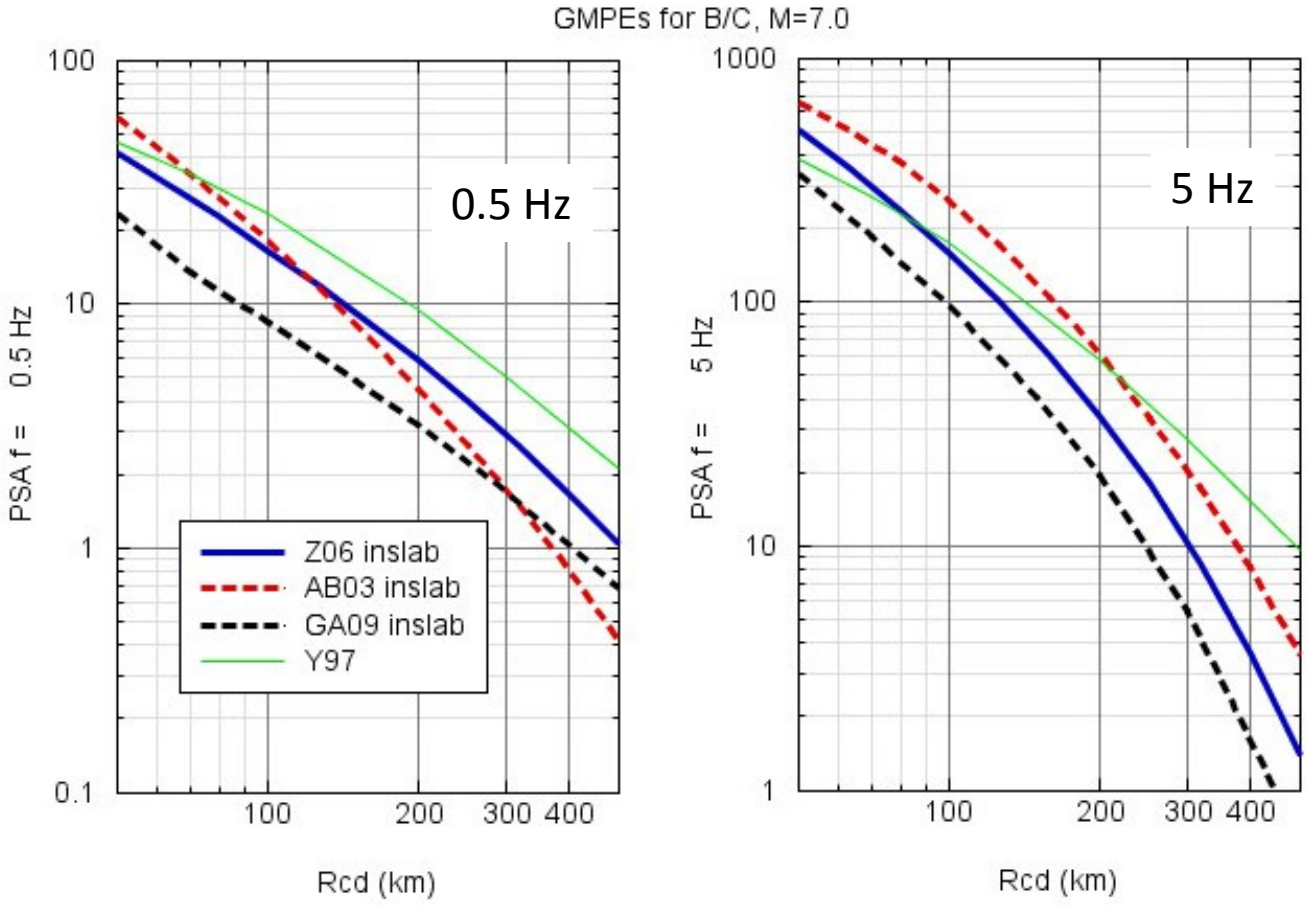


Figure notes: Comparison of in-slab GMPEs: AB03(Cascadia), Zhao09 and GA09. Note the Youngs et al. 1997 equation (Y97) has a different slope because in-slab attenuation was not considered at the time of that study (early 1990s). (see Atkinson and Goda, 2011)

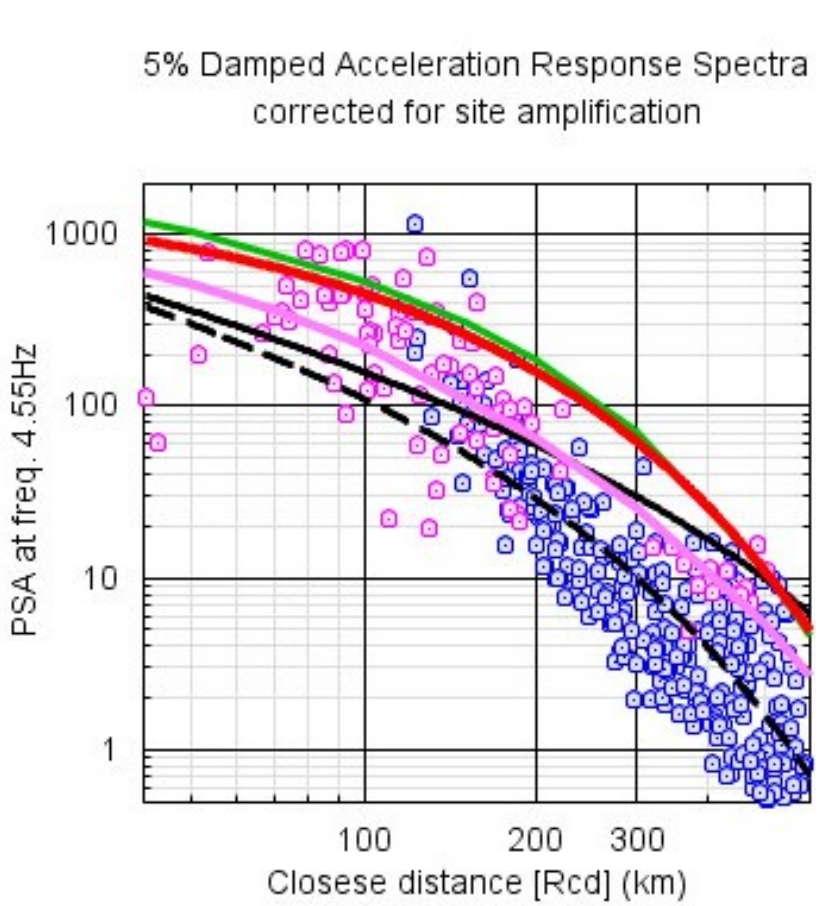
Western interface GMPEs

- Both empirical and simulation-based GMPEs may be used
- Recent data from Tohoku M9 2011 important in guiding choice (as this is largest well-recorded event and similar to expected Cascadia in magnitude)
- Note the interface GMPEs influenced by other large subduction events

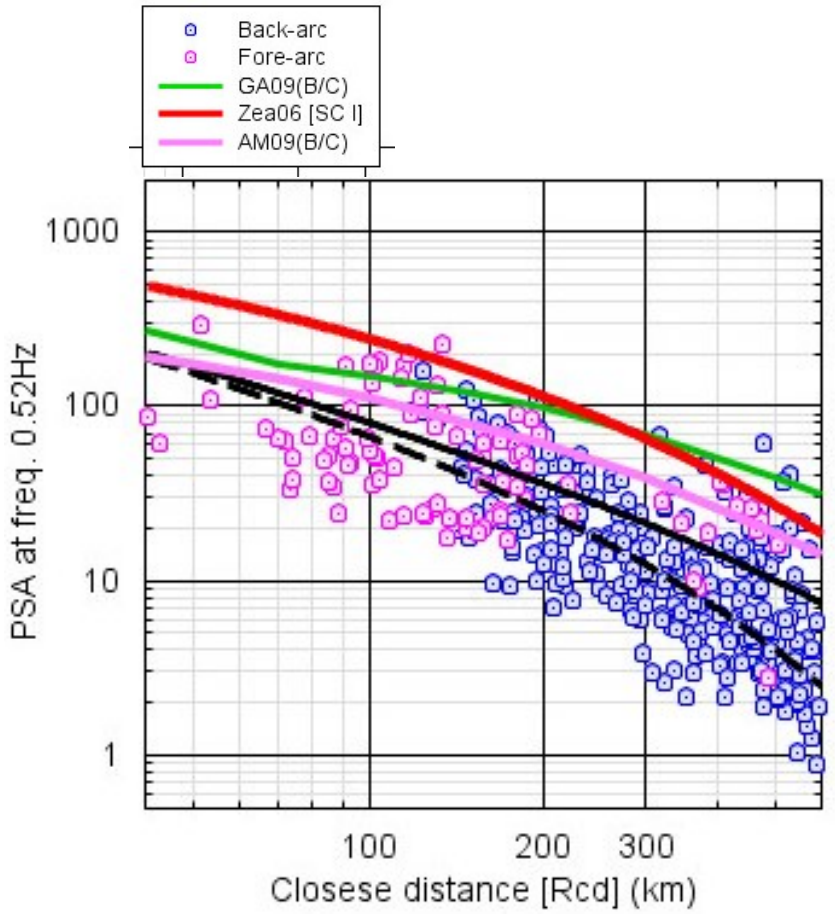
Regression model of M9 Tohoku motions (black lines)

(compared to GMPEs for M=9, **after correction for site effects**)

$$\log Y + \log(R_{eff}) - \text{site\_effect} = c_0 + c_1.F.R_{cd} + c_2.B.R_{cd}$$

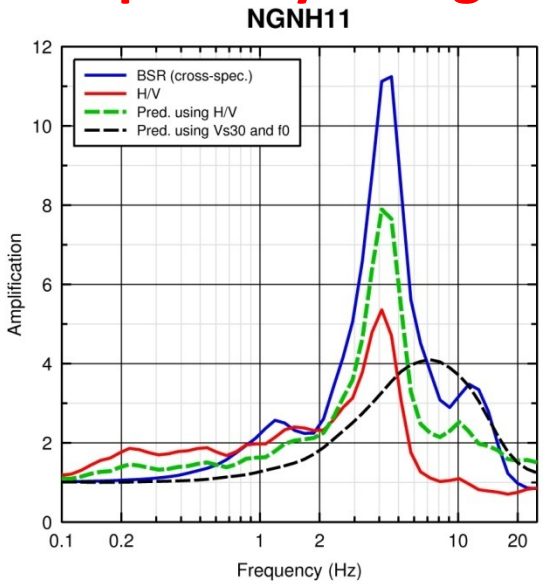


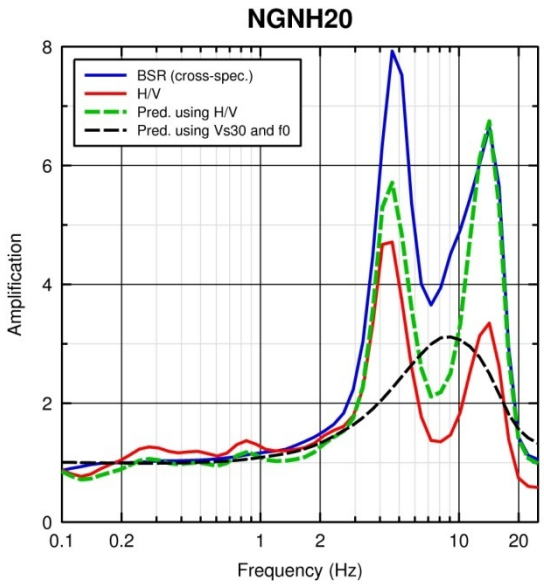
5Hz

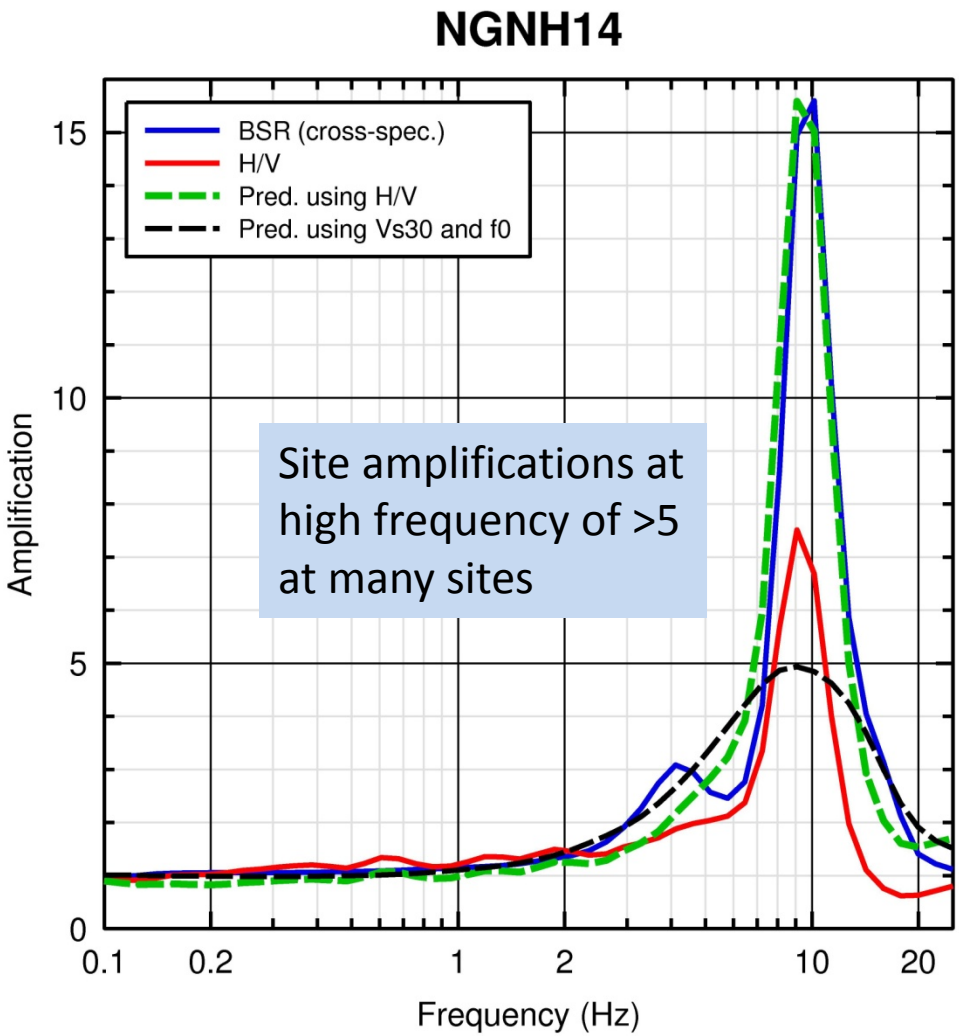


0.5Hz

Site Amplification – was very important in Tohoku motions, especially at high frequencies (characteristic of Japan)





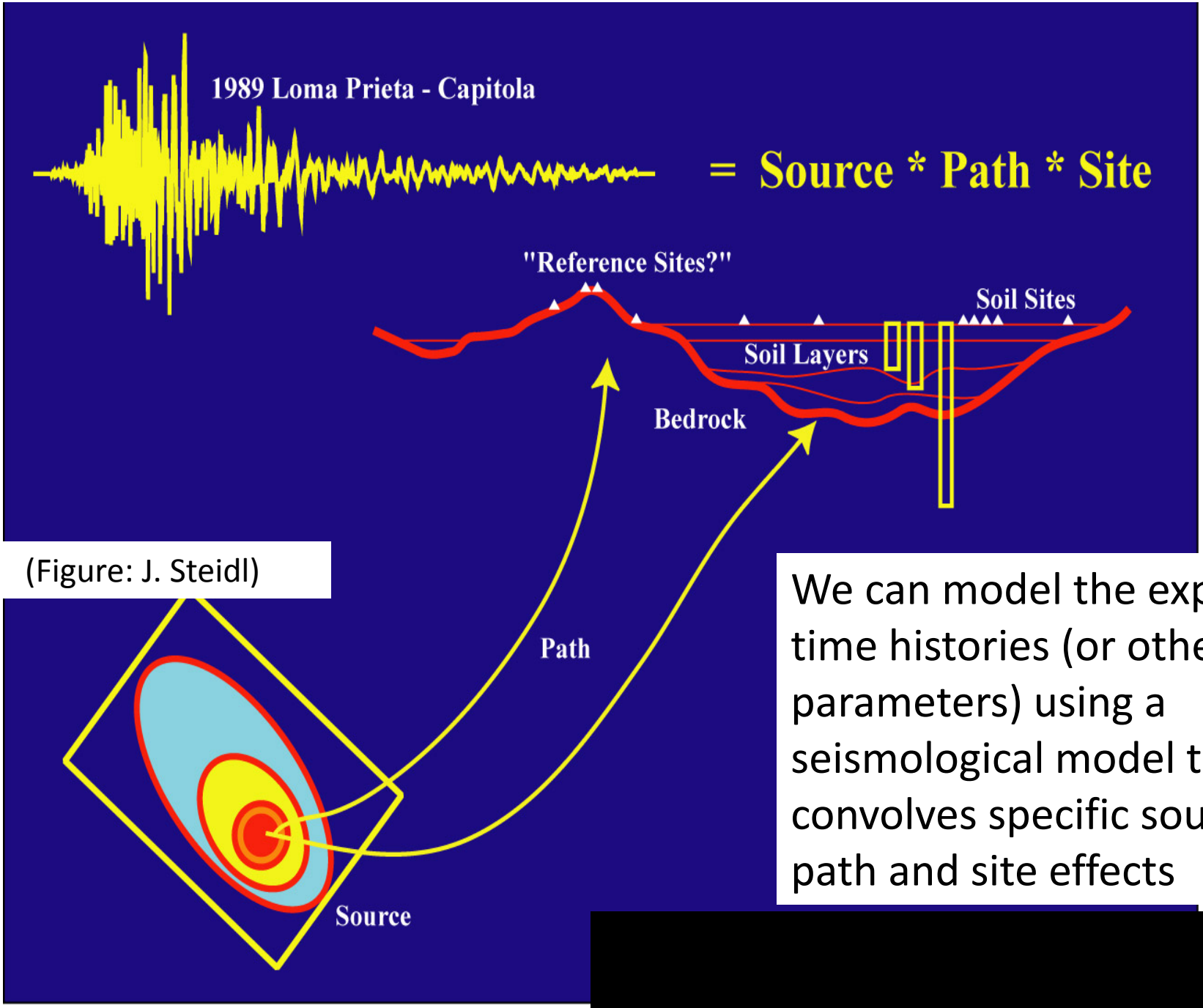


Simulated time histories compatible with 2005 (or 2010) NBCC UHS

Atkinson, CJCE, 2009

www.seismotoolbox.ca

Note: other types of time histories, such as scaled or spectrally-matched, may also be used



(Figure: J. Steidl)

We can model the expected time histories (or other parameters) using a seismological model that convolves specific source, path and site effects

[redacted]

Basics of Atkinson (2009 CJCE) simulations

- Realistic records for the typical magnitudes/distances that contribute to 2005 NBCC UHS for Canadian cities, for several generic site conditions (A, C, D, E)
- Simple finite-fault stochastic model encapsulates basic seismological parameters for east, west Canada
- User picks records from time history library and scales/matches as per study needs
- Note that other time history procedures are equally useful, such as scaling and/or modifying actual recordings to match a target spectrum on average over frequency range of interest

What is generated: East

East: For each site condition (A, C, D, E)

- M6 Set 1: 3 random components at 15 random locations about 10 to 15 km from fault (=45 records)
- M6 Set 2: 45 records about 20 to 30 km from fault
- M7 Set 1: 45 records about 15 to 25 km from fault
- M7 Set 2: 45 records about 50 to 100 km from fault

Download from www.seismotoolbox.ca

What is generated: West

West: For each site condition (A, C, D, E)

For Crustal/Inslab Events:

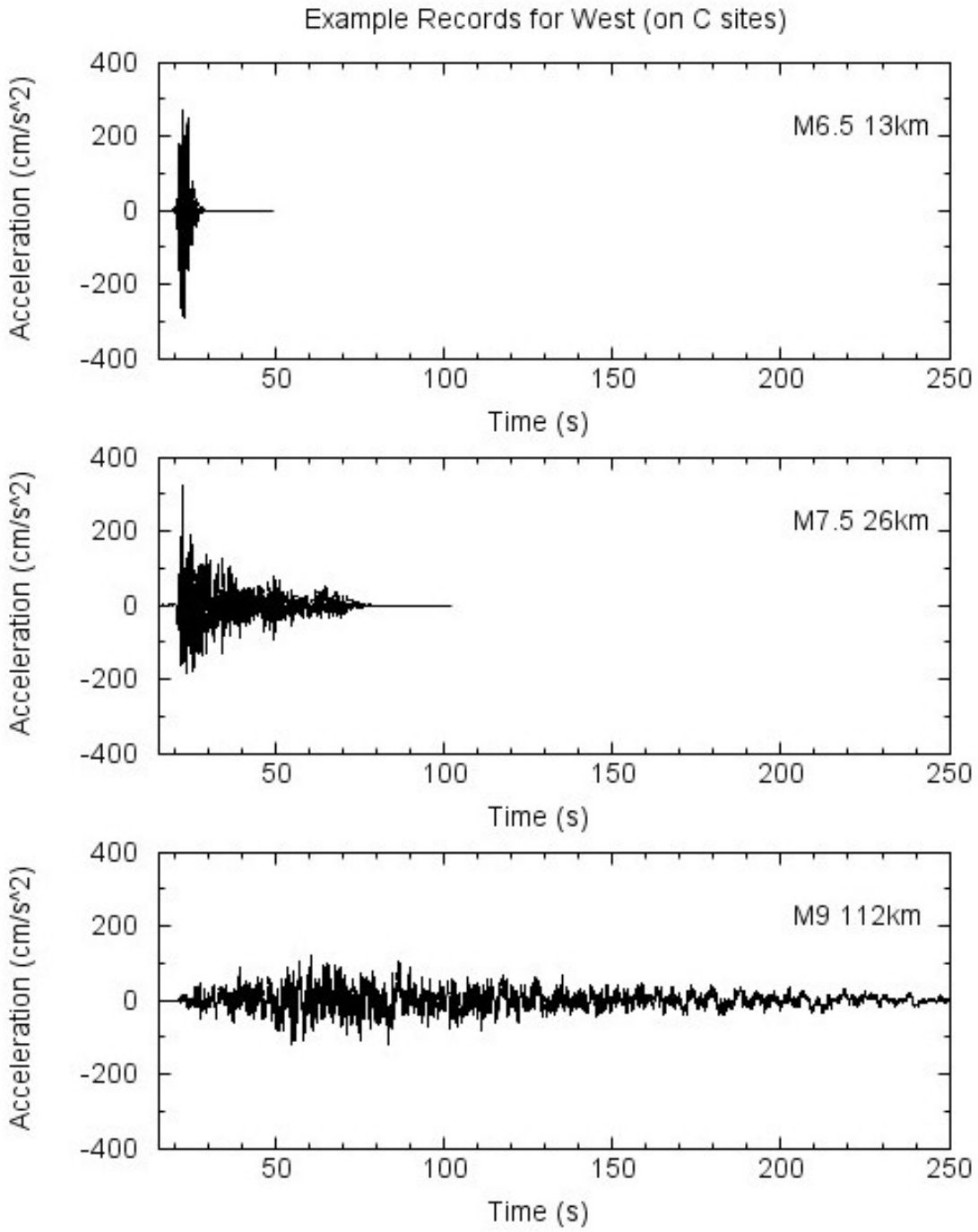
- M6.5 Set 1: 3 random components at 15 random locations about 10 to 15 km from fault (=45 records)
- M6.5 Set 2: 45 records about 20 to 30 km from fault
- M7.5 Set 1: 45 records about 15 to 25 km from fault
- M7.5 Set 2: 45 records about 50 to 100 km from fault

For Interface Events:

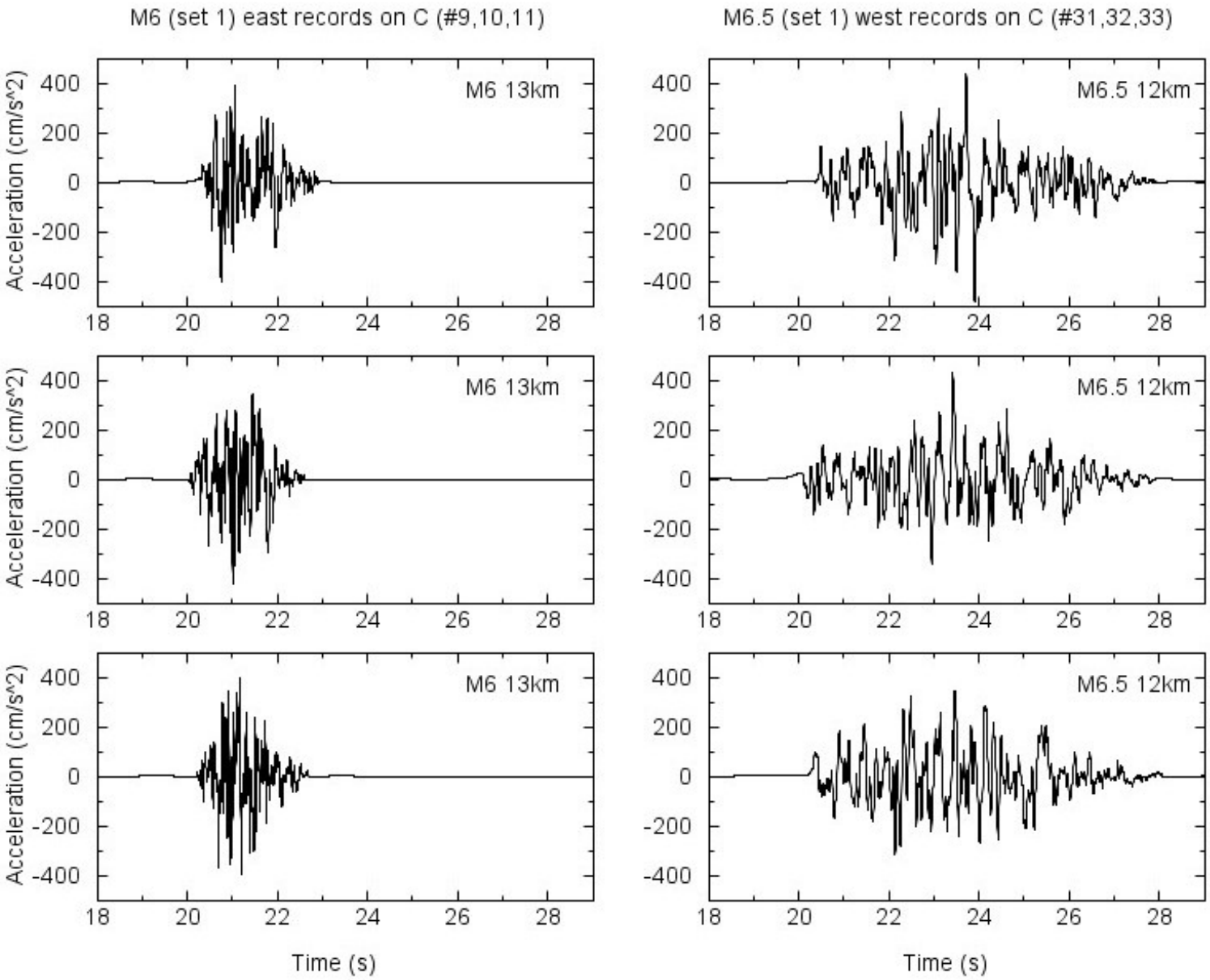
- M9 Scenario (Atkinson and Macias, 2009 BSSA for details): 45 records at distances 100 to 200 km from fault (eg. Victoria is at about 100 km)

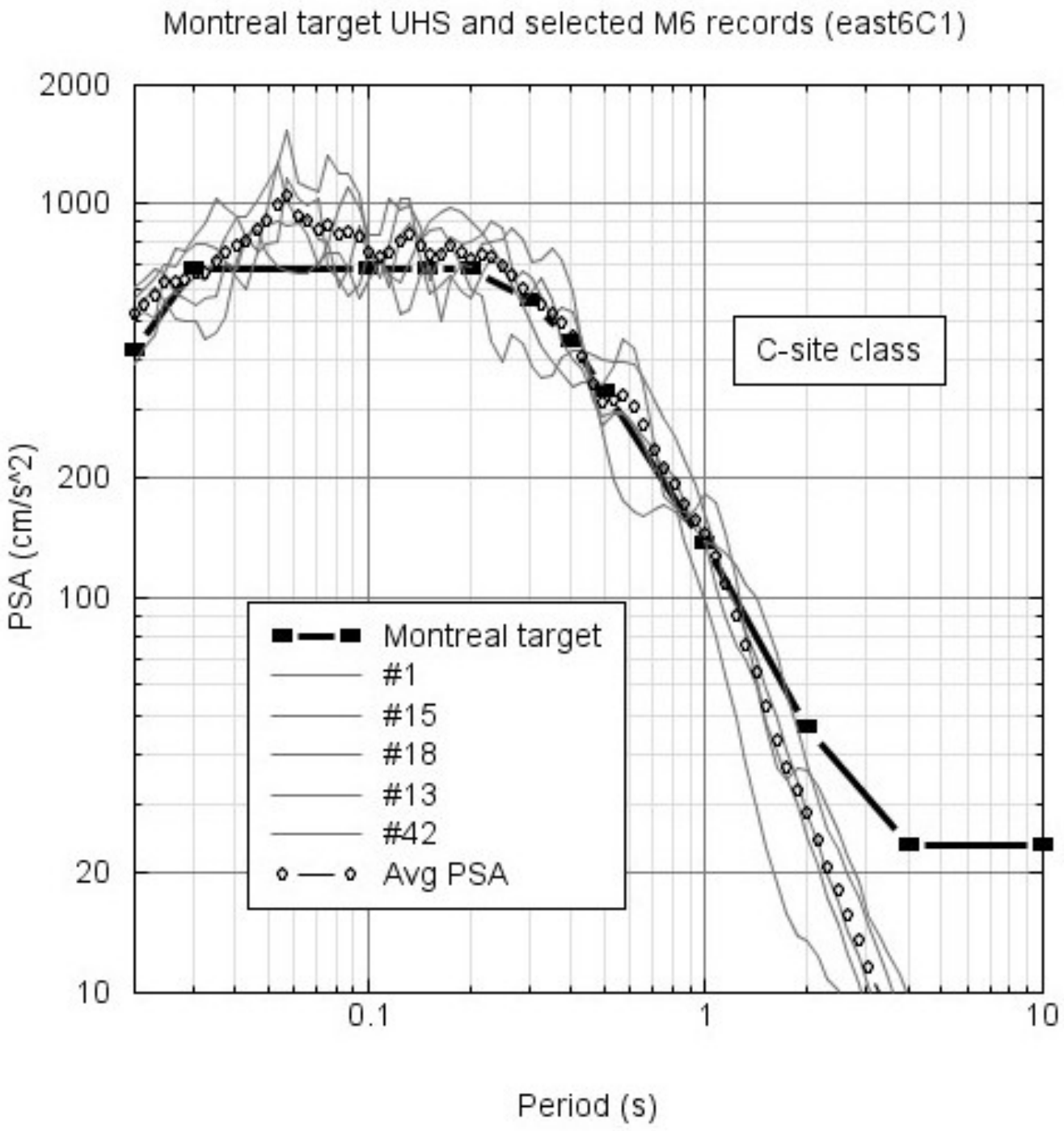
Download from www.seismotoolbox.ca

Example western records: note low PGA but long duration for M9 Cascadia

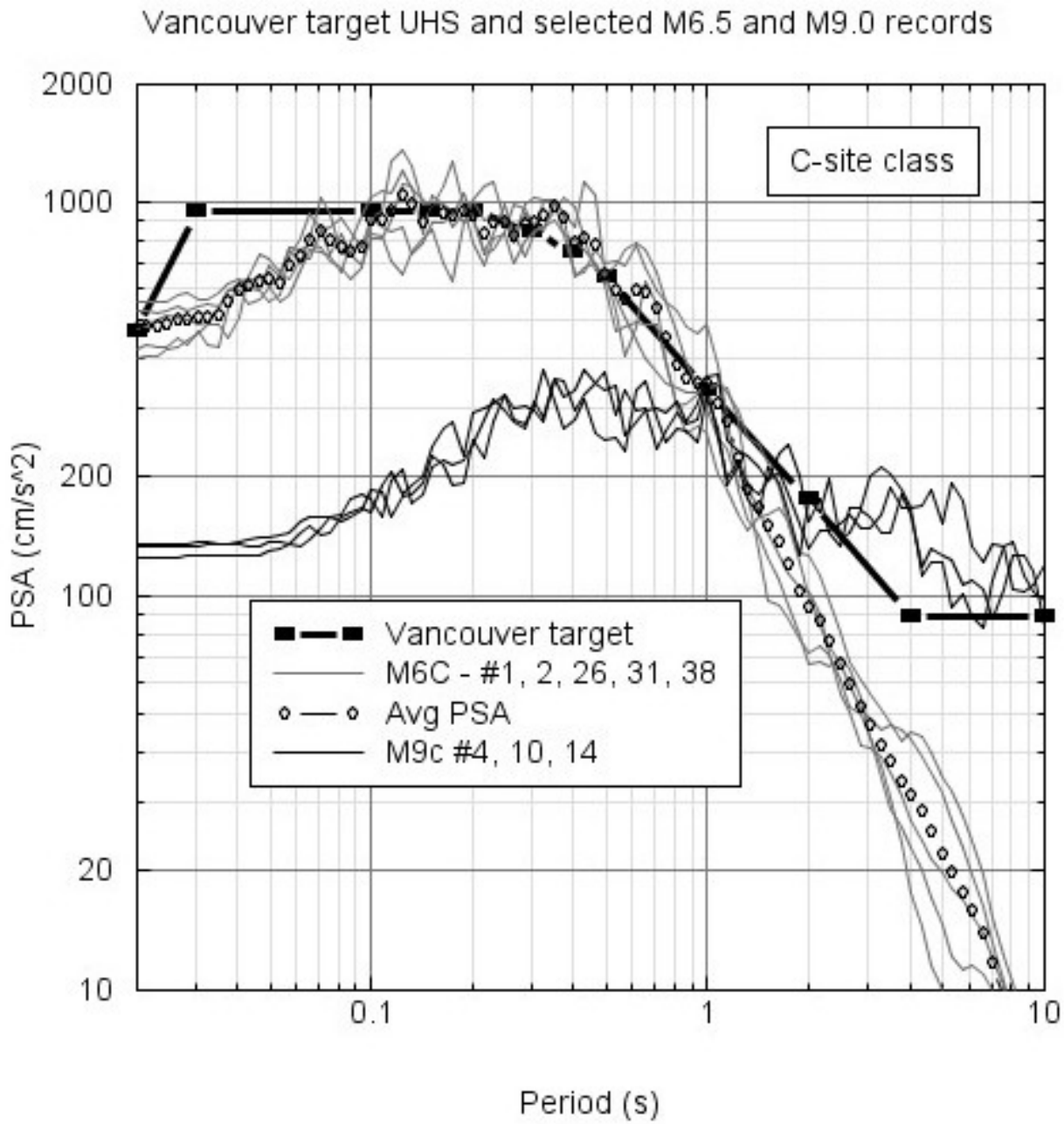


Example of east vs. west records (higher frequency content in east)





Example of 5 records of M6 selected/scaled to approximately match Montreal UHS on C-class site, 0.1-1 sec



Example of 5 M6.5 records selected/scaled to match Vancouver UHS at 0.1-1 sec

+ 3 M9 records (unscaled) selected to approximately match UHS at 1 to 2 sec.

Questions?

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