Seismic Hazard Analysis In British Columbia

Where Have We Been?
Where Are We Headed?

Tim Little, P.Eng.

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Outline

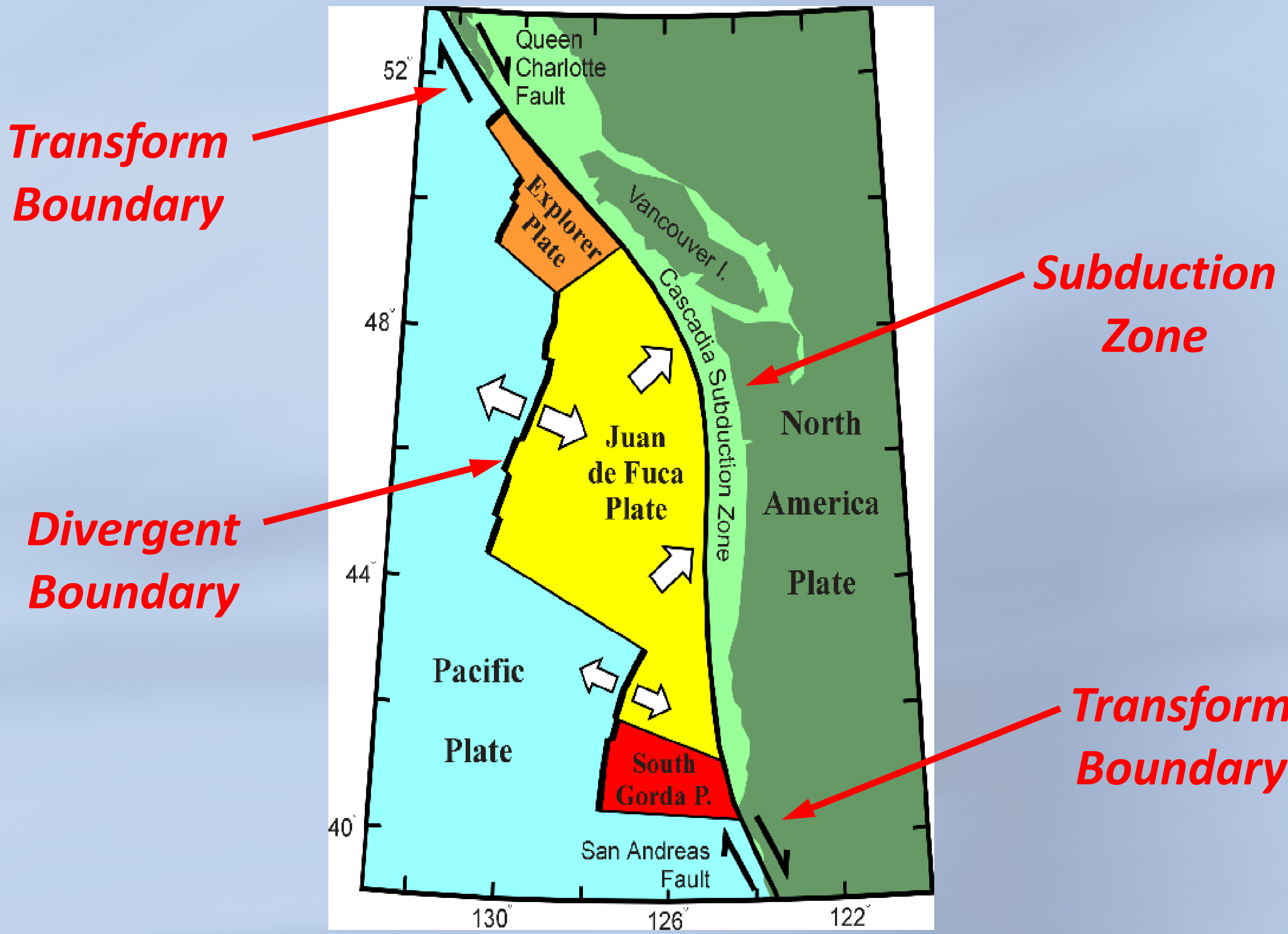
- Overview of B.C. seismotectonic setting
- Probabilistic seismic hazard analysis basics
- Evolution of the treatment of uncertainties in PSHA over the last 30 years.
- A look forward
- Closing comments

B.C. Seismotectonic Setting

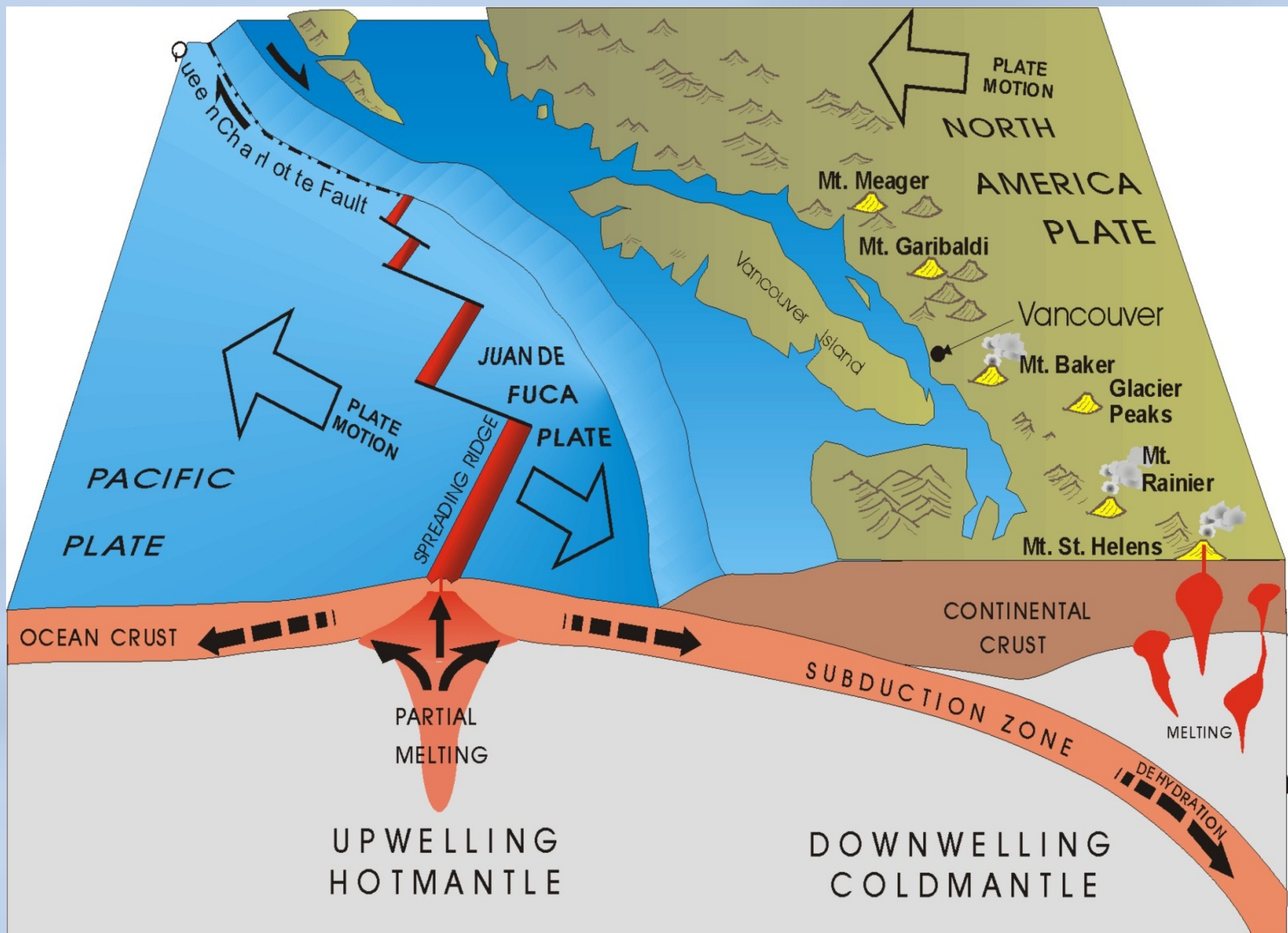
- The Cascadia region is one of the more tectonically complex regions in the world.
- B.C. is situated on the western edge of one of the world's largest tectonic plates
- Southwest B.C. is situated over an active subduction zone
- West of the subduction zone is a divergent plate boundary
- Northwest B.C. is situated adjacent to a transform plate boundary

Tectonic Plates of the World

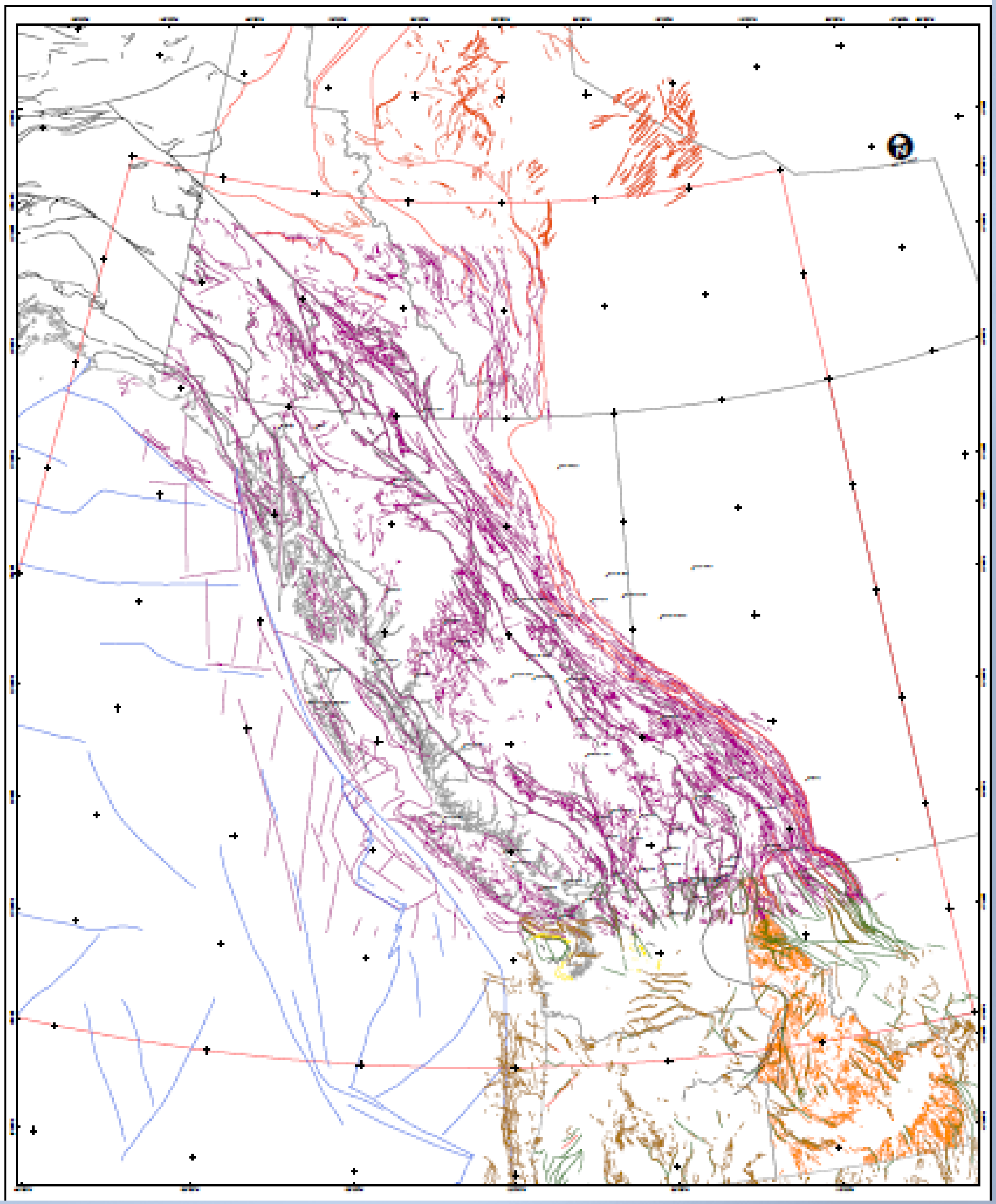
Cascadia Subduction Zone - Plan



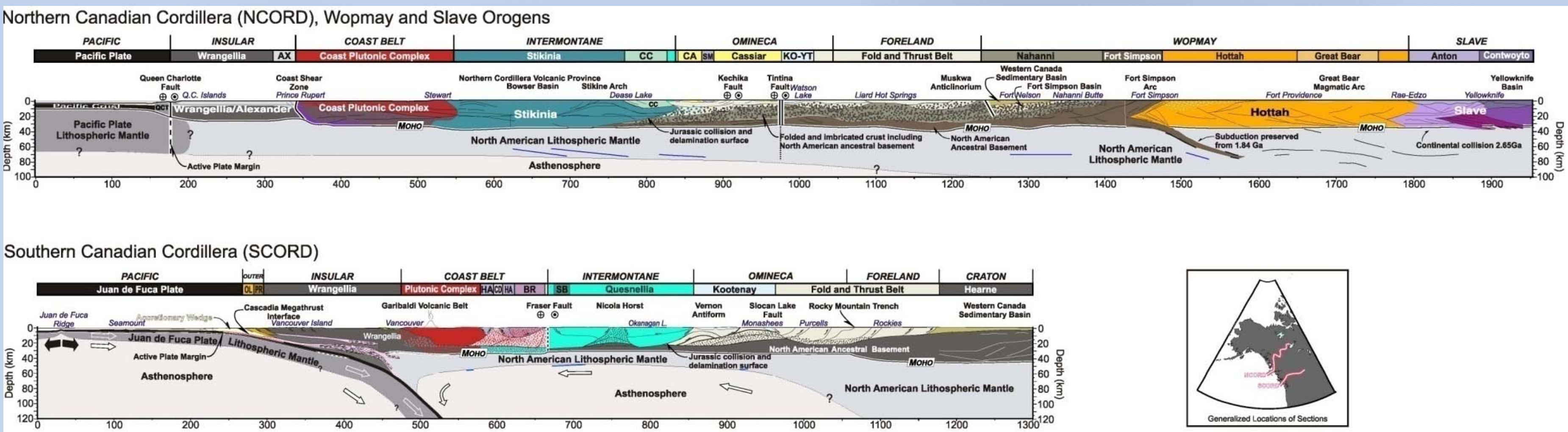
Cascadia Subduction Zone - Section



Major Mapped Faults

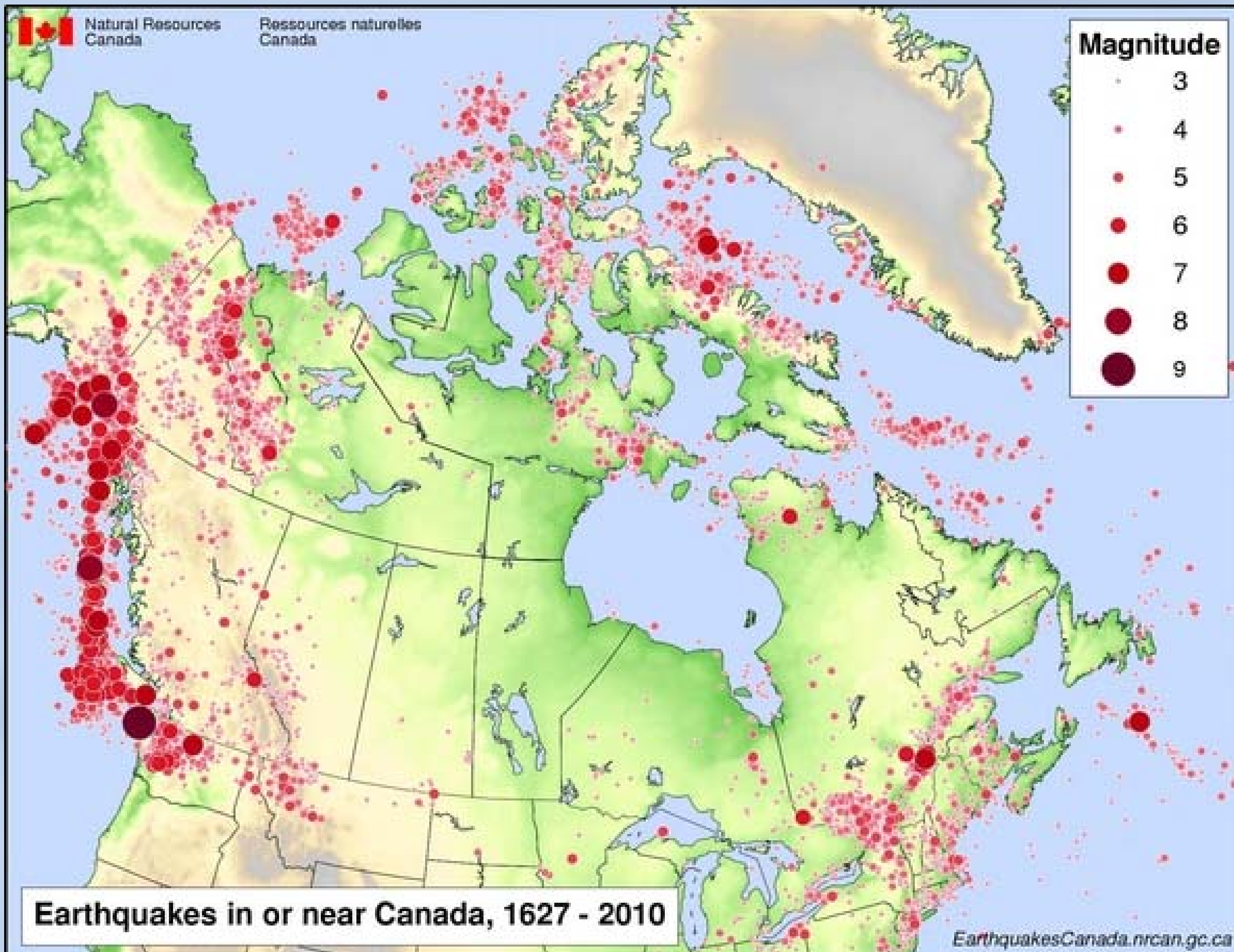


Geological Structure of B.C.

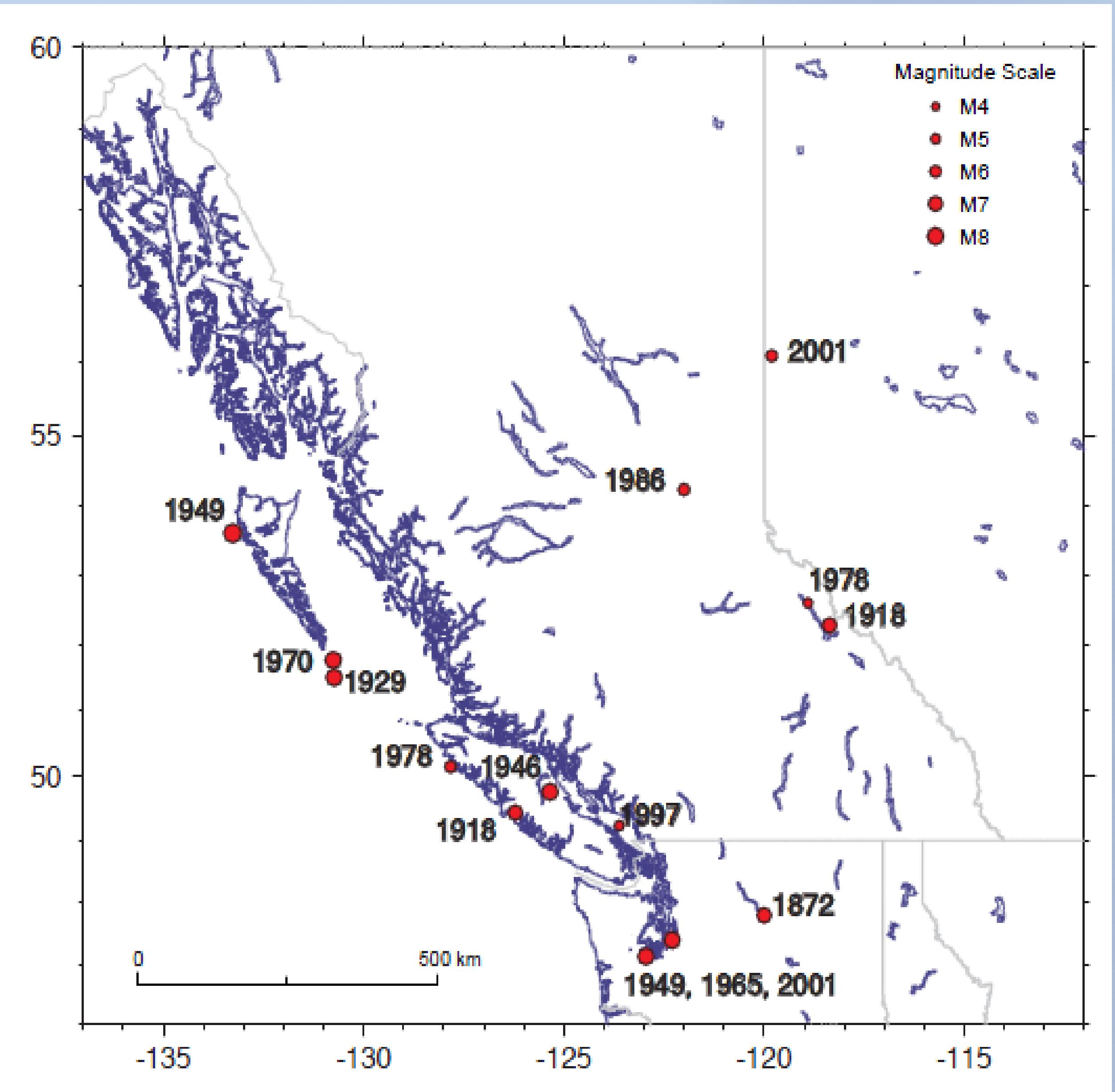


- Over the last 20 years, the LITHOPROBE Project has greatly advanced the level of knowledge of the 3D structure & geological evolution of Canada’s continental landmass and its margins.

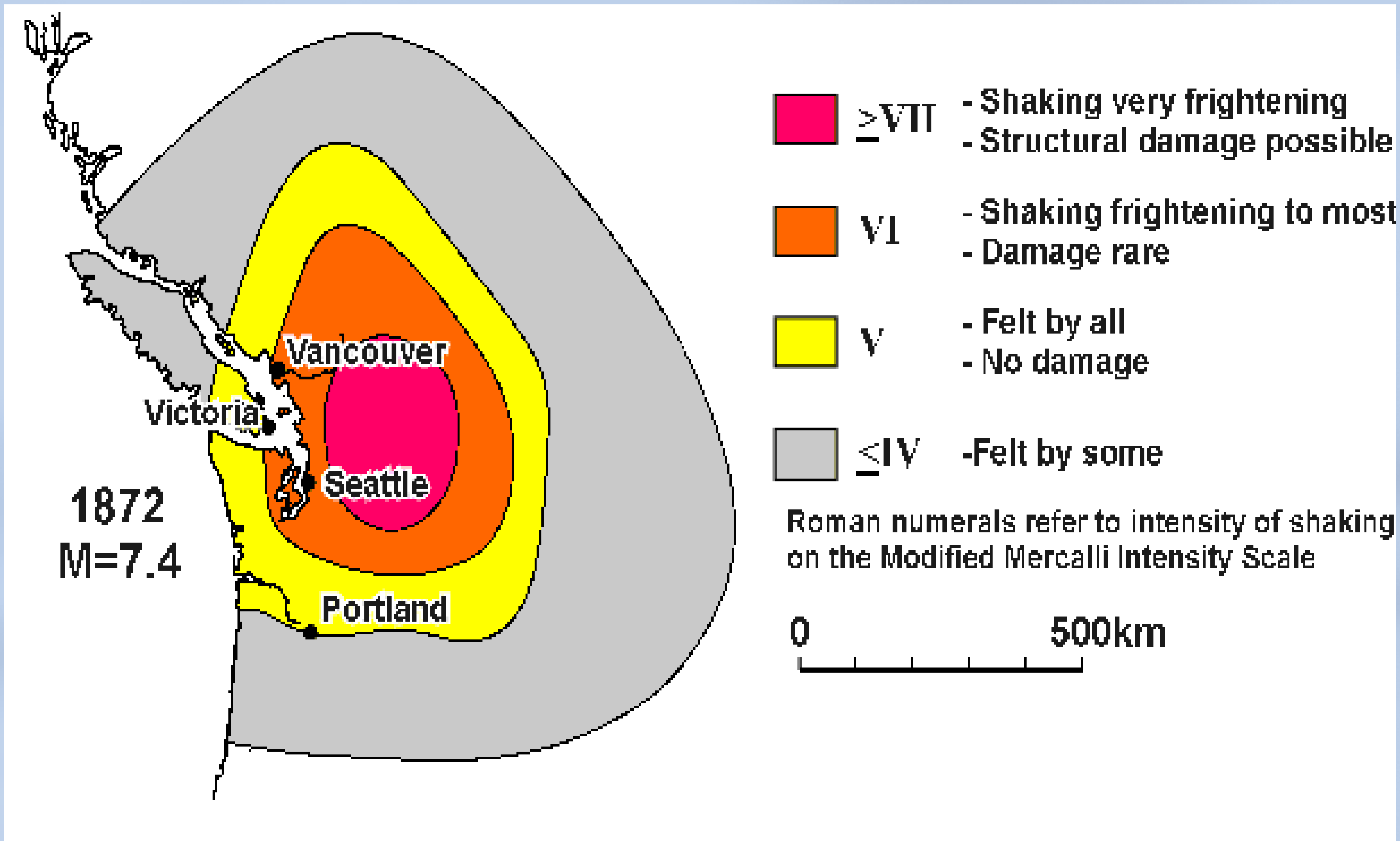
Canadian Seismicity



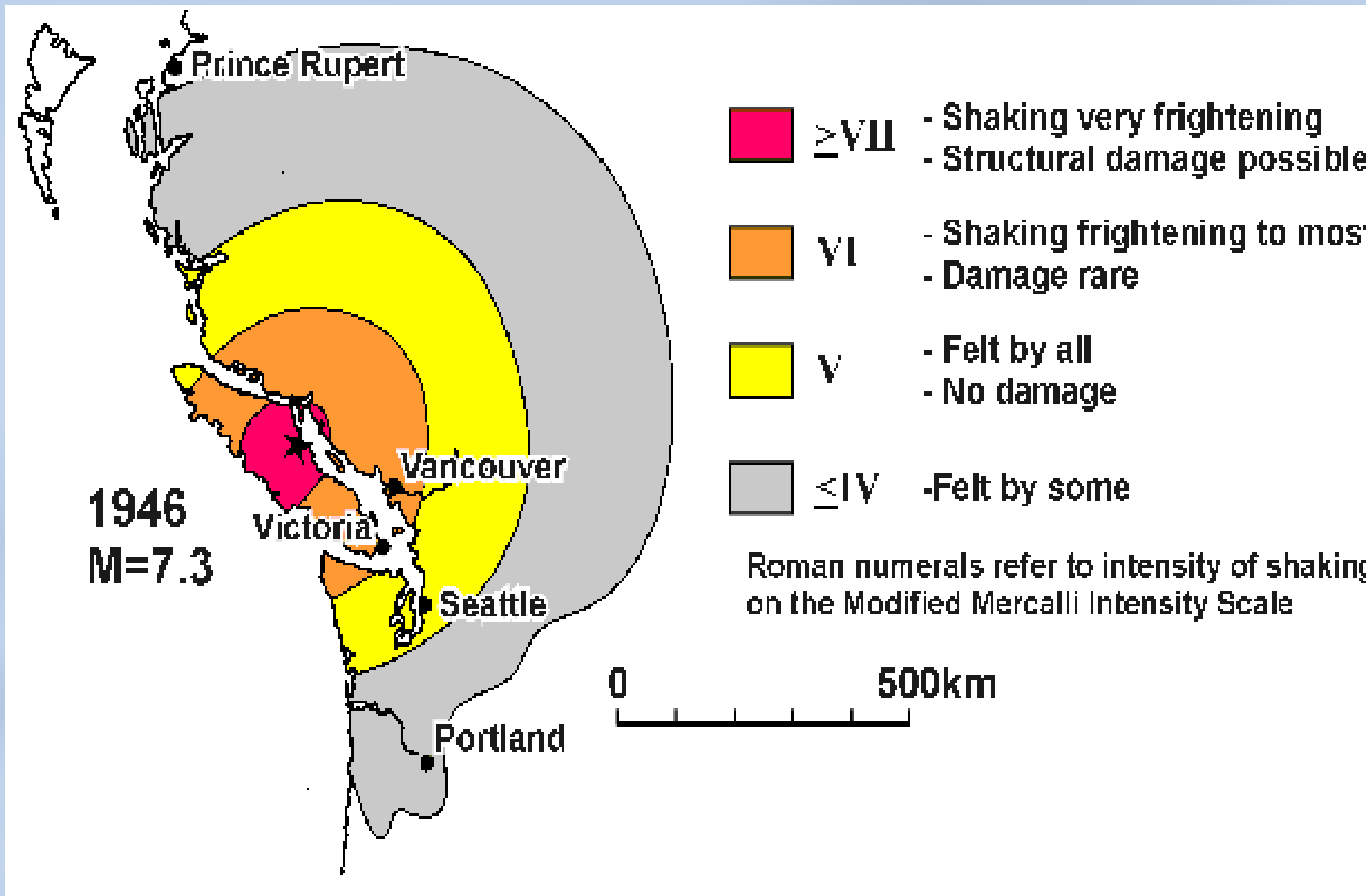
Some Significant Historical Earthquakes



1872 Northern Washington EQ



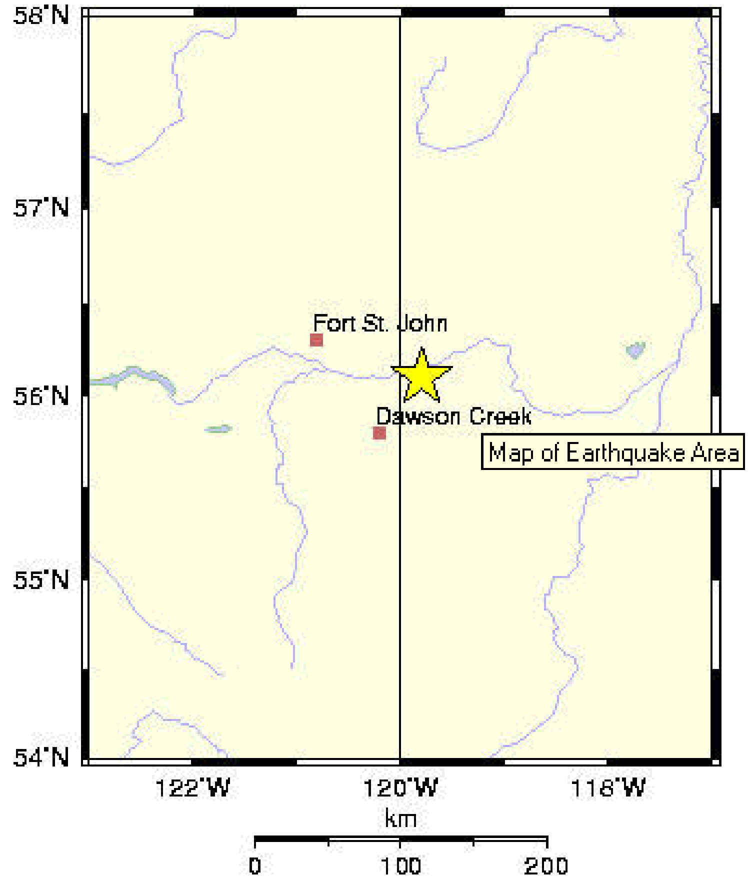
1946 Campbell River EQ



1949 Queen Charlotte EQ

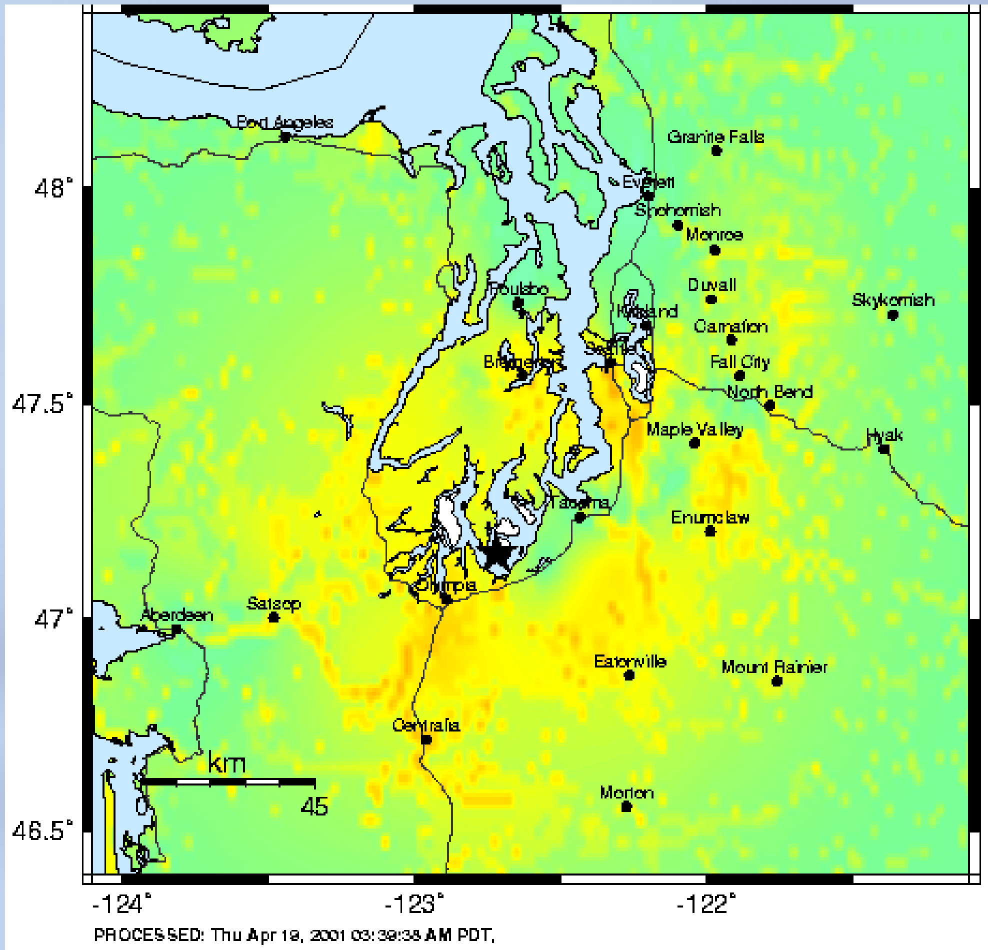
2001 Dawson Creek EQ

Earthquake Information (PGC)	
Friday April 13, 2001	
Time:	8:20 PM MDT
Magnitude:	$5.4\ M_L$
Latitude:	56.1° N
Longitude:	119.8° W



This earthquake was felt throught northeast British Columbia and northwest Alberta, as far away as Edmonton. Items were knocked from shelves at Tumbler Ridge, B.C. Dawson Creek, B.C., and Grande Prairie, Alberta. There have been no reports of structural damage. This is the largest earthquake in the region since 1986 when a magnitude 5.5 earthquake occurred to the northeast of Prince George, B.C.

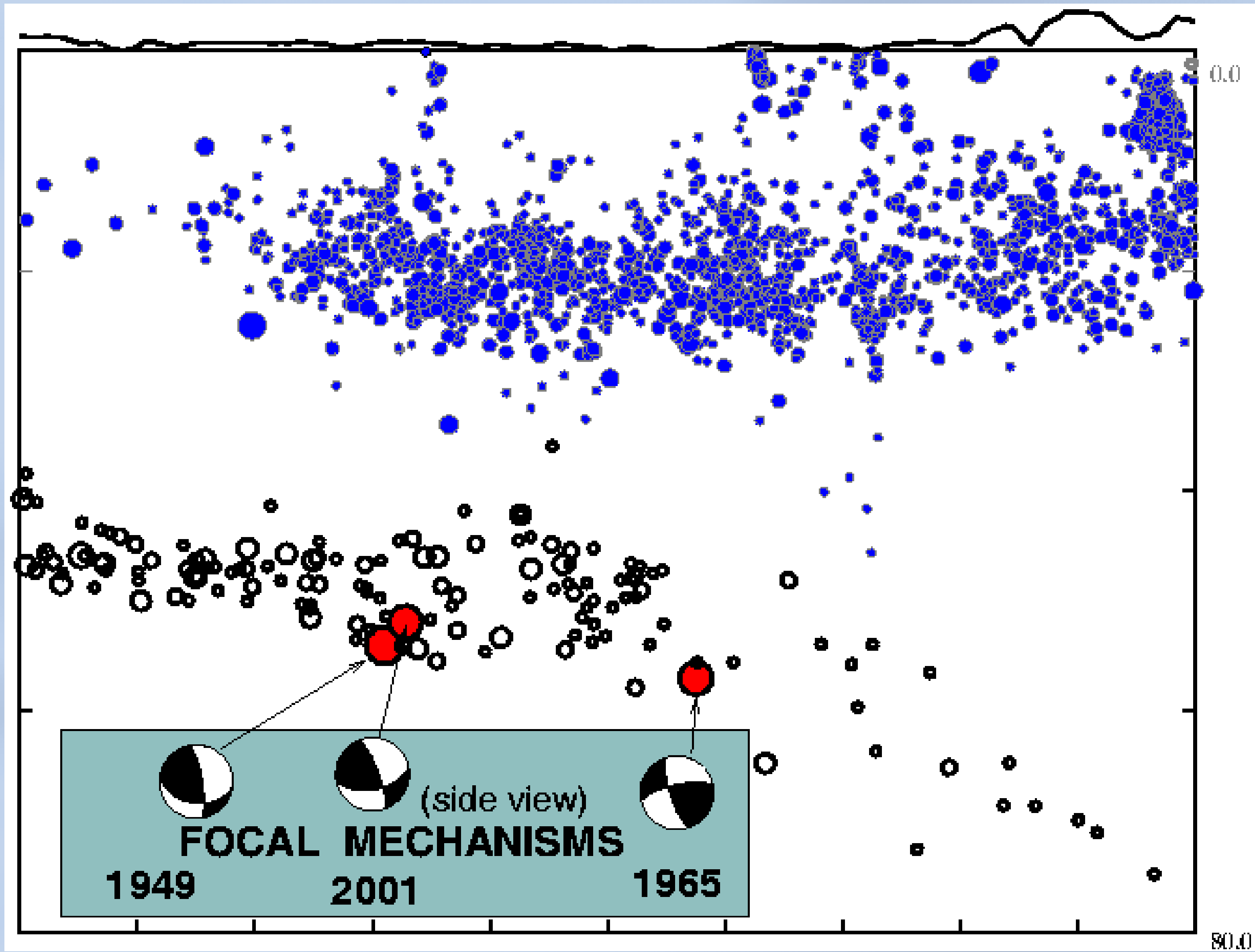
2001 Nisqually EQ



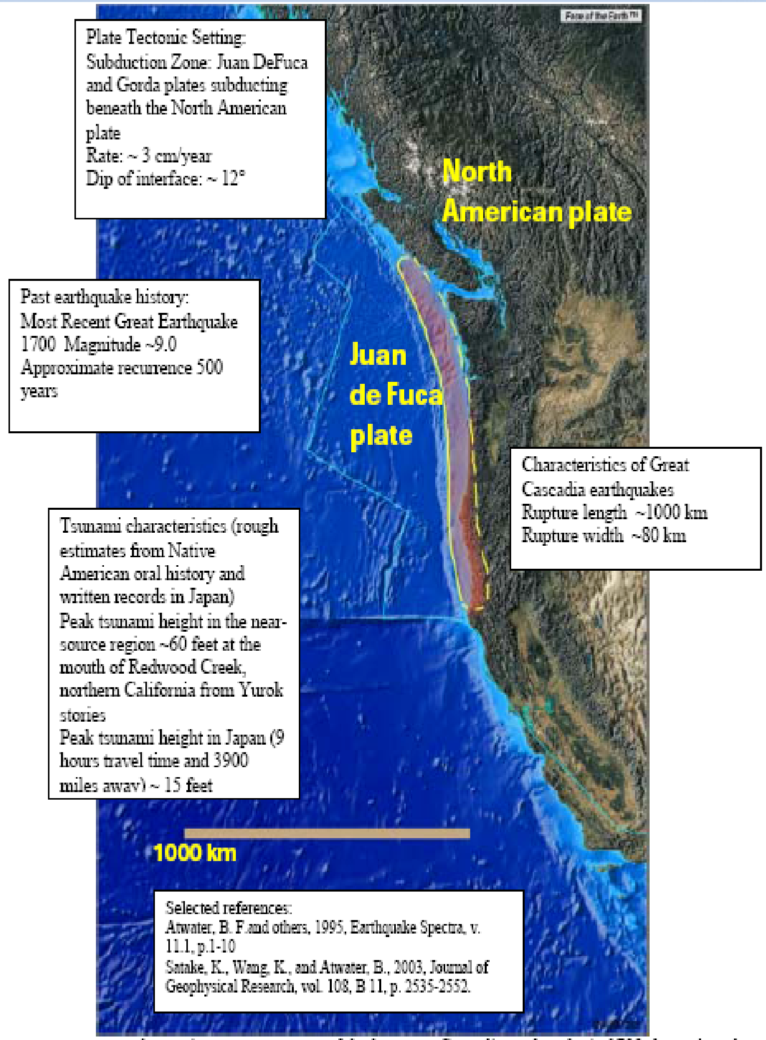
PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<.17	.17-1.4	1.4-3.9	3.9-9.2	9.2-18	18-34	34-65	65-124	>124
PEAK VEL.(cm/s)	<0.1	0.1-1.1	1.1-3.4	3.4-8.1	8.1-16	16-31	31-60	60-116	>116
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

M6.9
28 Feb 2001

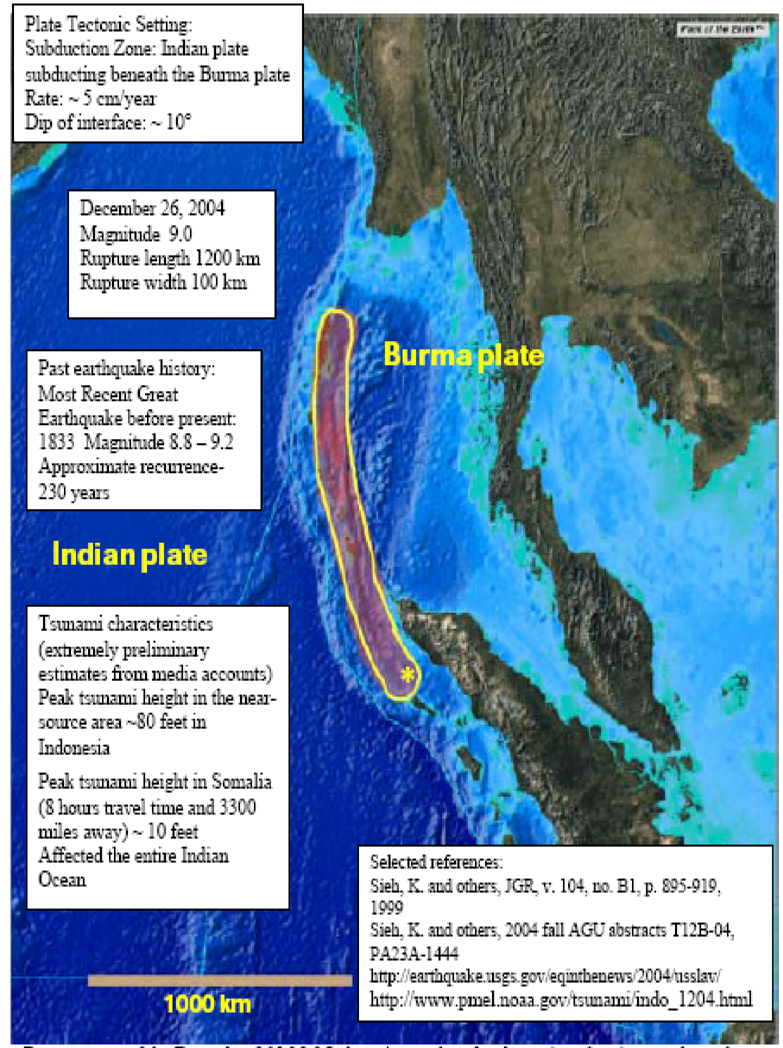
2001 Nisqually EQ - Hypocentre



Cascadia 1700 vs. Sumatra 2004



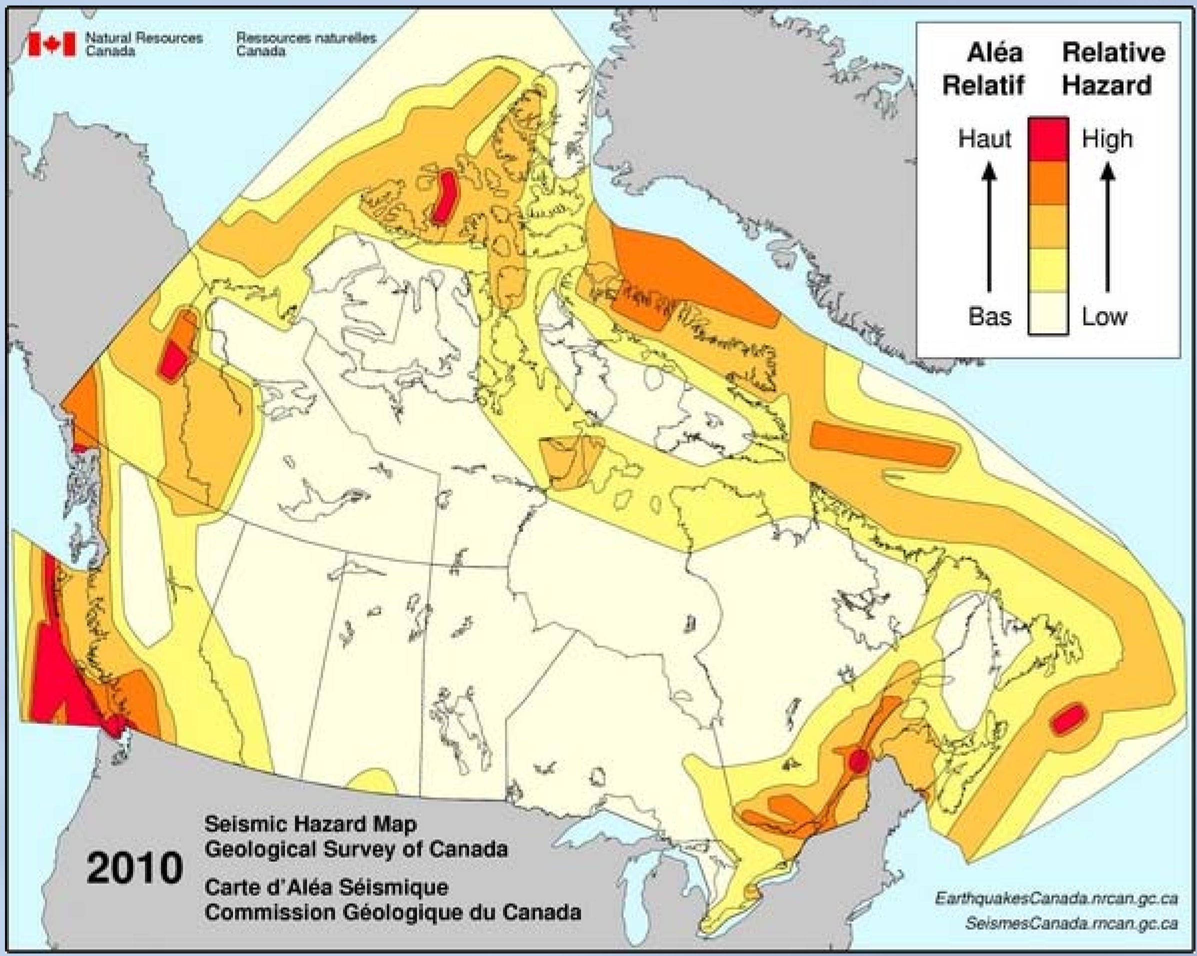
Approximate rupture zone of the last great Cascadia earthquake in 1700 shown in red.



Rupture zone of the December 26 M 9.0 Indonesian earthquake shown in red, epicenter shown by star.

Information compiled by Lori Dengler, Humboldt State University 1/07/05. Base image from the Jules Verne Voyager project: http://jules.unavco.org/

Seismic Hazard in Canada



Spectral maps available for PGA and Sa at T = 0.2, 0.5, 1.0, 2.0 secs

Seismic Hazard Analysis

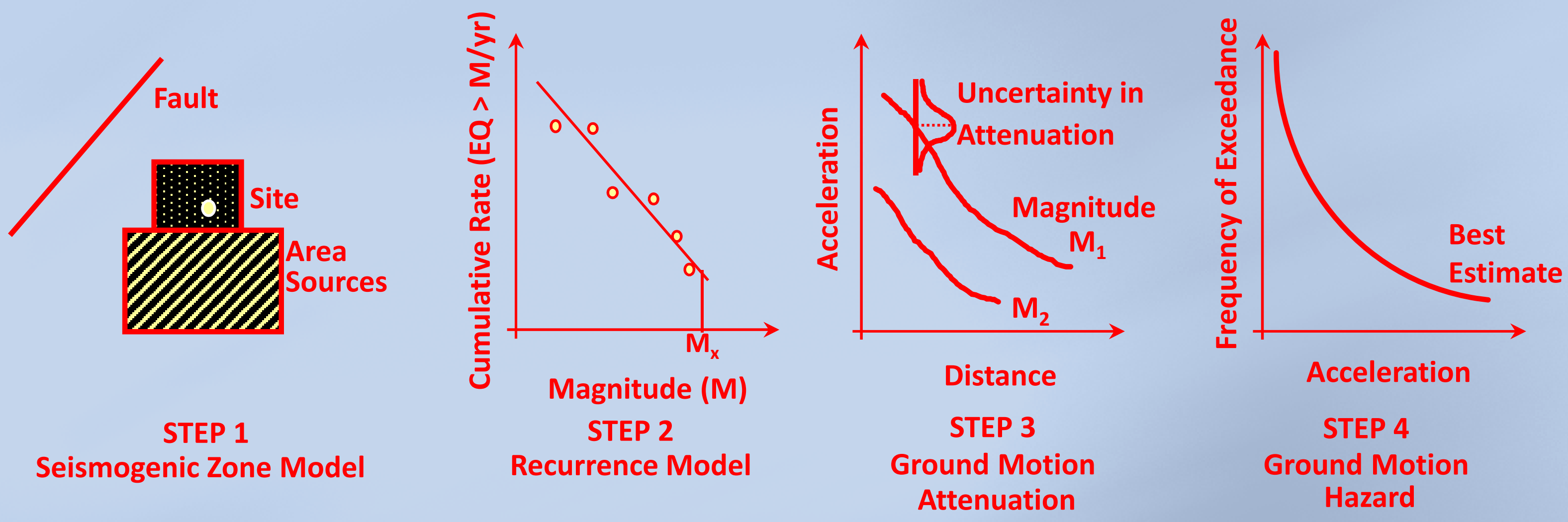
Definitions

- **Seismic Hazard** - A physical effect associated with an earthquake, such as ground shaking, that MAY produce adverse effects.
- **Seismic Hazard Analysis** - An evaluation of the seismic ground motions that may occur at a site due to potential earthquakes in the region of the site.
- **Seismic Risk** - The probability that consequences of an earthquake, such as structural damage, will equal or exceed specified values in a specified period of time.

Seismic Hazard Analysis Requirements

- A Seismic Source Model that represents the characteristics of the potential earthquake sources.
- A Ground Motion Prediction Model that estimates the ground motions resulting from an earthquake of a specific magnitude located at some distance from the site of interest.
- If the seismic hazard is to be expressed in terms of rates or frequencies (i.e. Probabilistic Seismic Hazard Analysis - PSHA), then a Recurrence Model is also required for each seismic source.

PSHA Basics



- **Define source zones (areas or faults) based on historical seismicity, tectonics and geology**
- **Determine an upper limit magnitude (M_x) for each source zone**
- **Develop a magnitude-recurrence relationship for each source zone**
- **Using an appropriate computer program and appropriate ground motion prediction model, compute probability distribution of ground motion at the site**
- **Select the design value at the appropriate probability level**

PSHA Formulation

- The "Cornell method" (1968):

$$P(Y > y) = \int_{M\,\min}^{M\,\max} \int_{0}^{D\,\max} \int_{-X\sigma}^{+X\sigma} f_M(m) f_D(d) f_\varepsilon(\varepsilon) P(Y > y | M, D, \varepsilon)\, dm\, dd\, d\varepsilon$$

P(Y > y) = Probability that ground motion > y

$f_M(m)$ = Magnitude Probability Density Function

$f_D(d)$ = Distance Probability Density Function

$f_\varepsilon(\varepsilon)$ = Attenuation Randomness Density Function

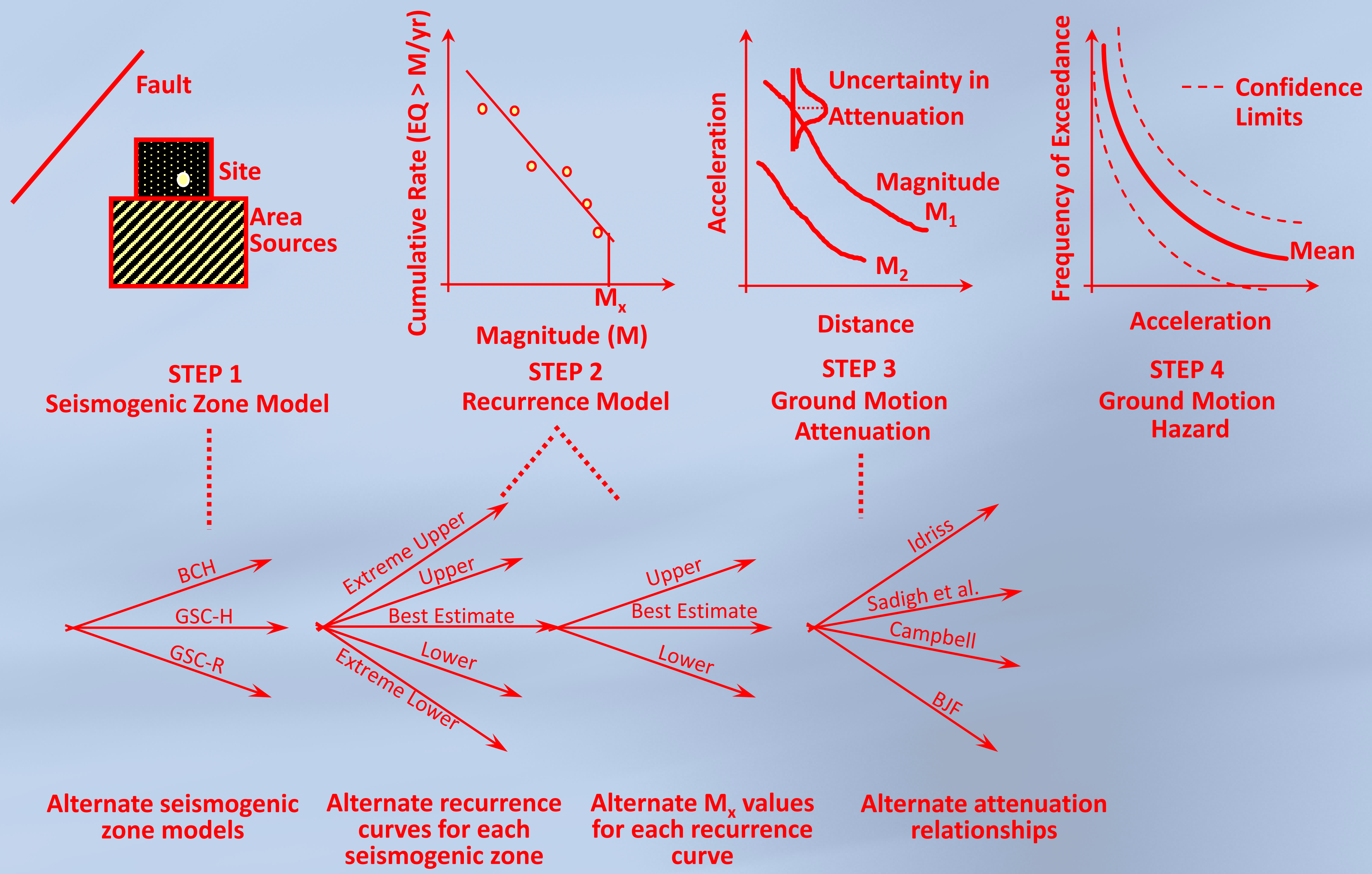
PSHA Uncertainties

- Inputs to a PSHA are not single-valued estimates; for instance:
  - Uncertainty in whether a seismic source is active
  - Range of estimates of the maximum size earthquake that could occur in a seismic source
  - Uncertainty in the estimate of earthquake recurrence rates
  - Alternative ground motion prediction models
- Available information often supports multiple, credible, scientifically sound interpretations.
- One goal of a PSHA is to develop inputs that represent the composite distribution of the informed scientific community.

Types of Uncertainties

- As part of a PSHA, we are seeking to identify and model sources of:
  - **Epistemic Uncertainty** - Due to incomplete knowledge about a phenomena or parameter, which affects our ability to model it.
  - **Aleatory Uncertainty** - Inherent randomness which arises from physical variability in a natural process.

PSHA with Uncertainties Included - Example



Seismic Hazard Analysis Examples

- The Geological Survey of Canada (GSC) performs seismic hazard analyses that provide the basis for seismic design provisions of the National Building Code of Canada (NBCC).
- GSC seismic hazard models and estimates are frequently referred to by designers of non-NBCC facilities.
- BC Hydro is an example of an owner/designer that has performed its own seismic hazard analyses, which have been influenced by GSC models.

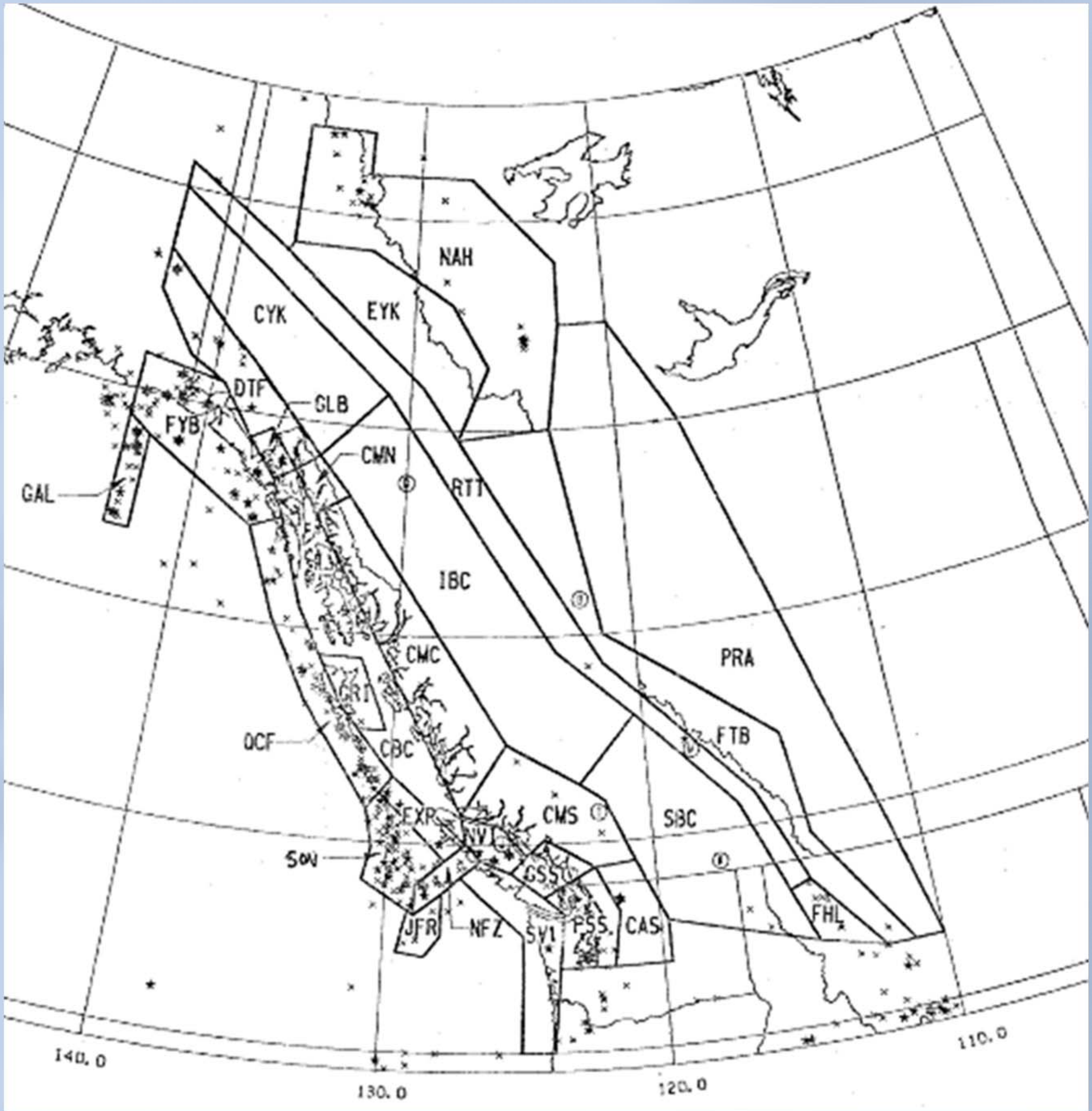
GSC/BCH PSHA Evolution - 1

- 1983 – GSC's first PSHA based on Cornell method
  - Single seismic source model; area sources only.
  - Single ground motion prediction model for all western Canada sources.
  - Only uncertainty included was aleatory ground motion model uncertainty.
  - Cascadia subduction zone not modeled.
  - Adopted for 1985 to 1995 NBCC.
  - Computed PGA and PGV.
  - NBCC design based on AEF = 1/475 (10%/50 yrs).

GSC/BCH PSHA Evolution - 2

- 1984 – BCH's first PSHA
  - Adopted GSC seismic source model.
  - Performed analyses with two alternate ground motion prediction models.
- 1991 – BCH's first regional seismic source model
  - Area sources only; some narrow zones along faults.
  - Overlapping "shallow" and "deep" sources to model seismicity within crust and subducting JDF slab.
  - Different ground motion prediction models for shallow and deep sources.

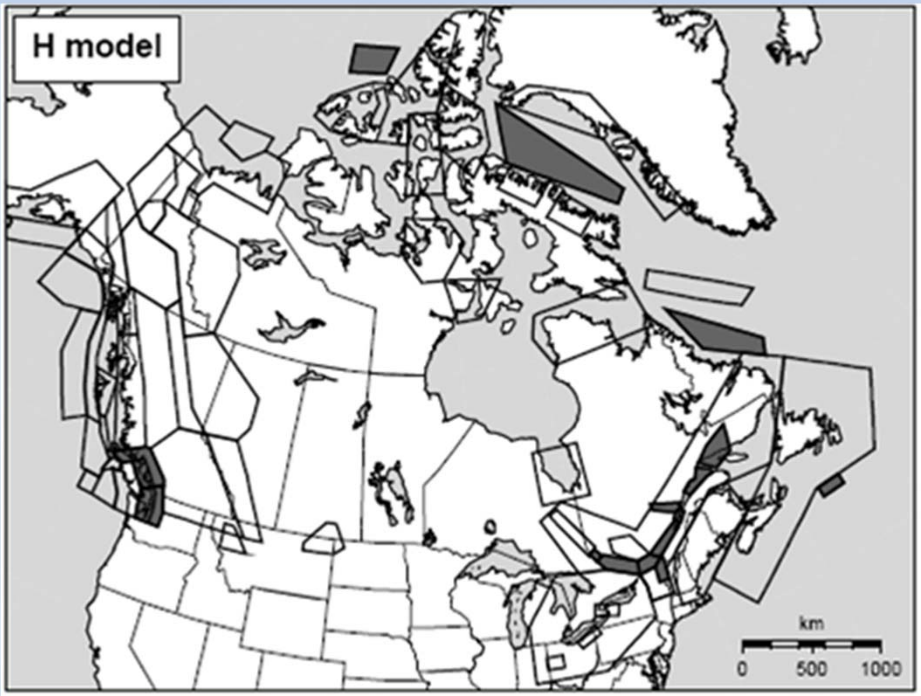
BCH Seismic Source Zone Model

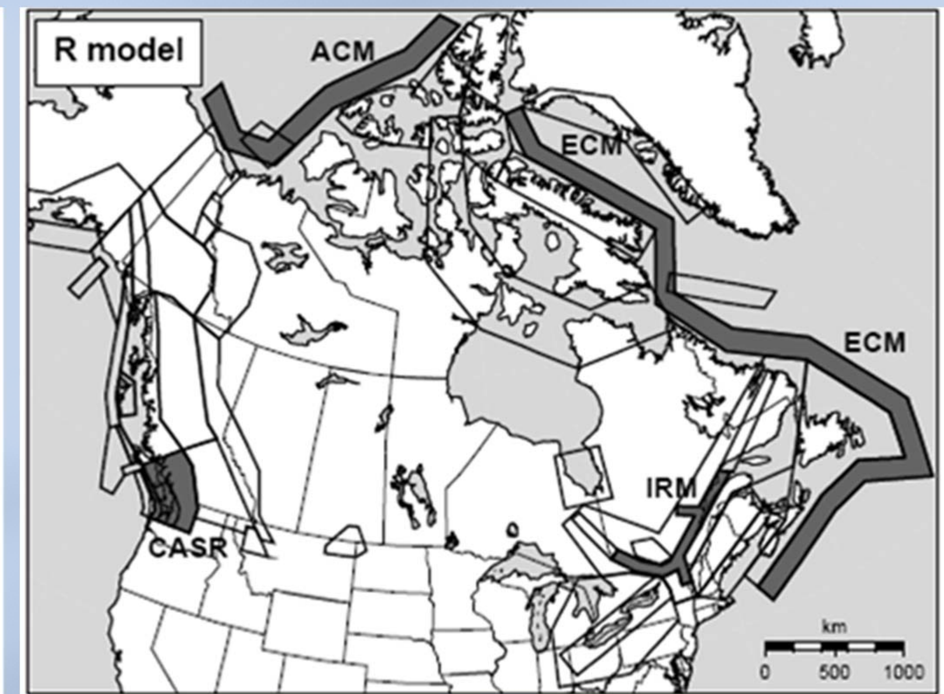


GSC/BCH PSHA Evolution - 3

- 1994 – GSC introduced "H" & "R" source models; intended for 2000 NBCC application.
  - H & R models intended to address epistemic uncertainty of modeling seismic sources.
  - Both models still included only area sources.
  - Overlapping "shallow" and "deep" sources to model seismicity within crust and subducting JDF slab.
  - Different ground motion prediction models for shallow and deep sources.
  - Cascadia subduction zone not included; modeled deterministically assuming M8.2.

GSC – H & R Models





GSC/BCH PSHA Evolution - 4

- 1997 – BCH expanded treatment of uncertainties:
  - Revised BCH source model to include uncertainties for earthquake depths, maximum magnitudes & magnitude recurrence for each source.
  - Included BCH, GSC-H and GSC-R source models as equally-weighted alternates.
  - Included sets of weighted alternative ground motion prediction models for shallow and deep sources.

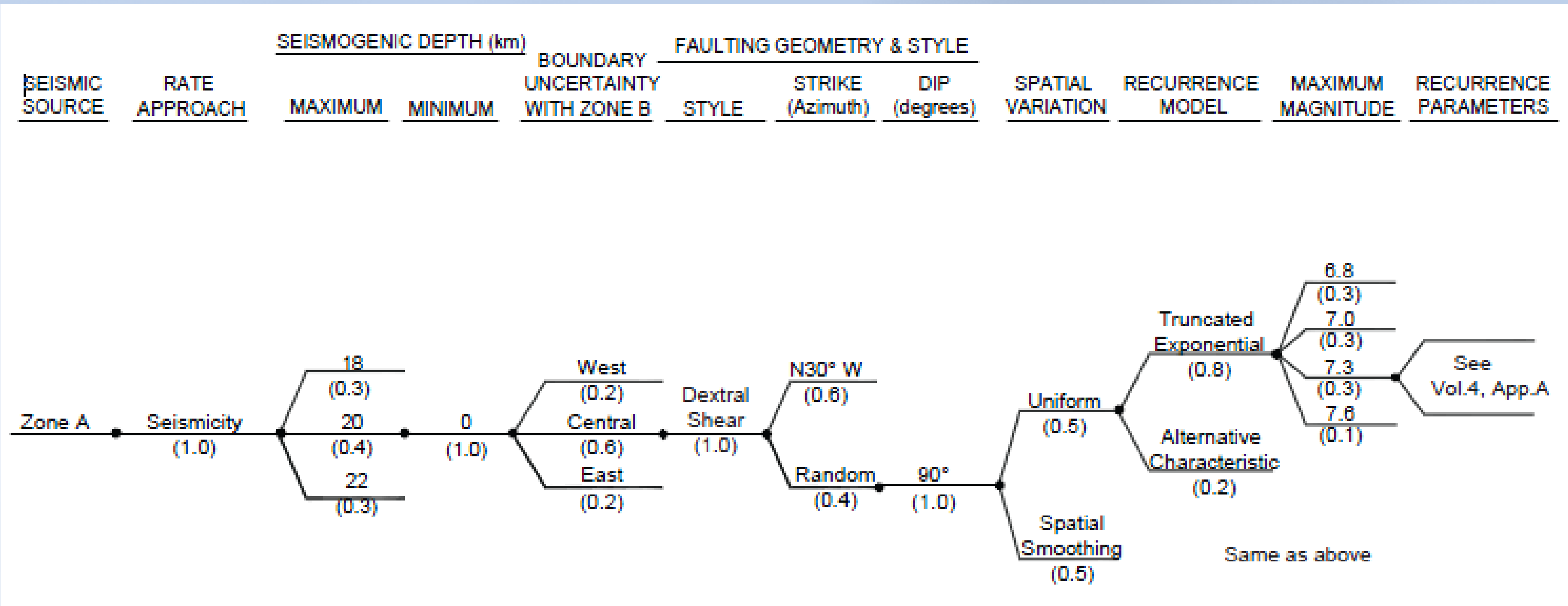
GSC/BCH PSHA Evolution - 5

- 2005 – First application of GSC “H” & “R” source models in NBCC
  - “Robust” analysis – PSHA run separately for each model & DSHA run for CSZ scenario. Largest ground motions selected for design.
  - Computed PGA and 5% damped spectral response for T = 0.2, 0.5, 1.0 and 2.0 secs, which define a simplified Uniform Hazard Response Spectrum.
  - NBCC design based on AEF = 1/2475 (2%/50 yrs).

GSC/BCH PSHA Evolution - 6

- 2008–2012 – BCH SSHAC Level 3 PSHA
  - Magnitude catalogue adjusted to common scale.
  - Seismic source model includes both area and fault sources; Cascadia subduction zone incorporated.
  - Different sets of ground motion prediction models for different tectonic regions.
  - New ground motion prediction model developed for subduction zone.
  - Uncertainty included for numerous source and ground motion model parameters.

Schematic Source Zone Logic Tree



- Alternative input parameters and their relative weights can be portrayed in logic trees
- Full logic trees can have thousands of branches

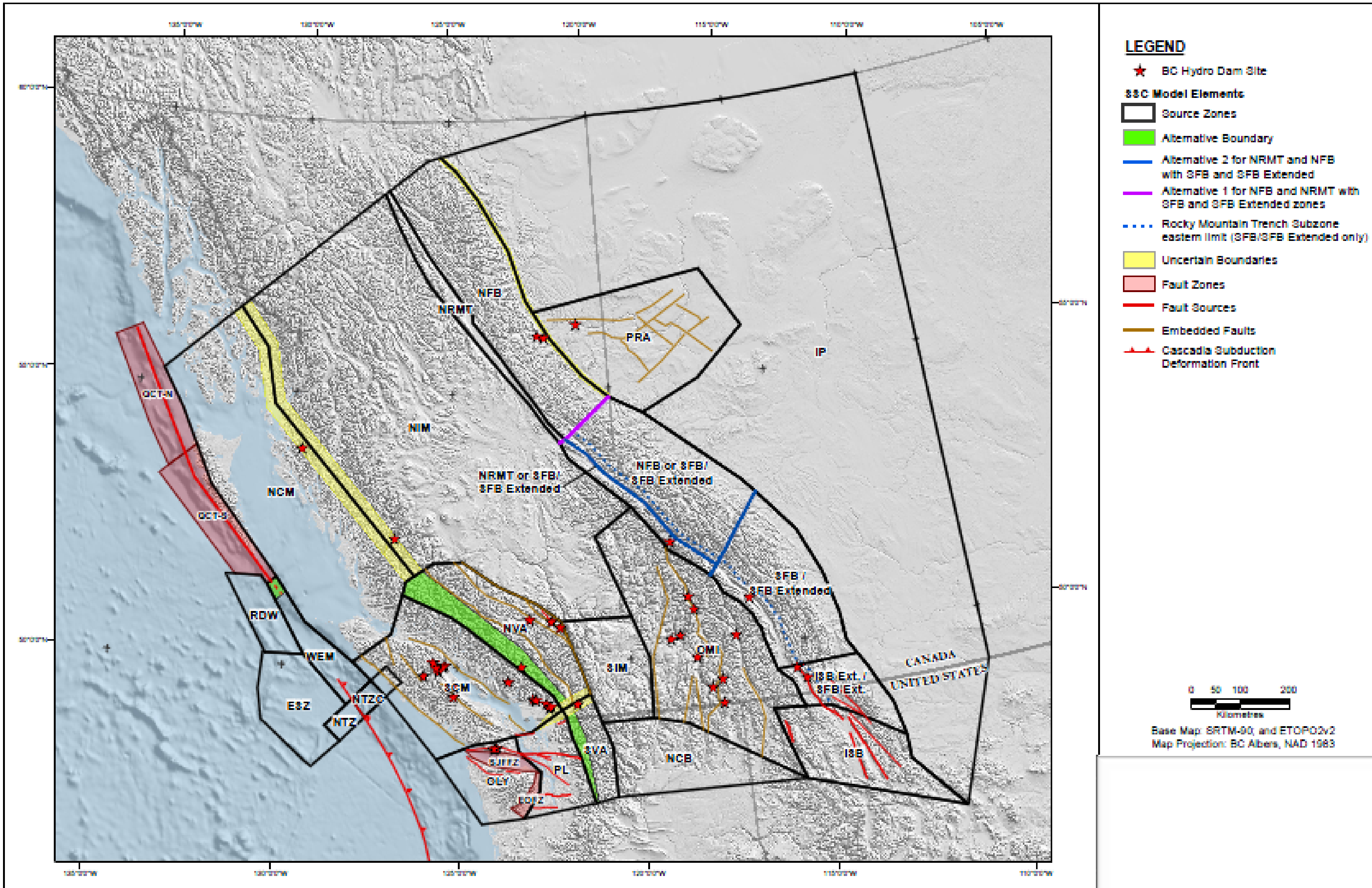
Seismic Source Modeling Challenges

- Incomplete understanding of seismotectonic setting & processes; multiple interpretations.
- Numerous mapped faults, but lack of identified active faults.
- Relatively short period of seismic monitoring; incomplete seismic record.
- Uncertainties in recorded epicentres and depths.
- Low seismicity areas have limited data for estimating maximum magnitudes and for computing magnitude-recurrence relations.

Source Zone Boundaries

- Delineate areas of contrasting seismogenic properties such that within an individual source zone, expected future earthquake behaviour is assumed to be relatively uniform.
- Boundaries may separate differences in recurrence rate, orientation & style of faulting, seismogenic depth, maximum magnitude, or the spatial distribution of seismicity.
- Boundaries are typically simplified for modeling purposes and have inherent uncertainties.

BCH 2012 Seismic Source Model



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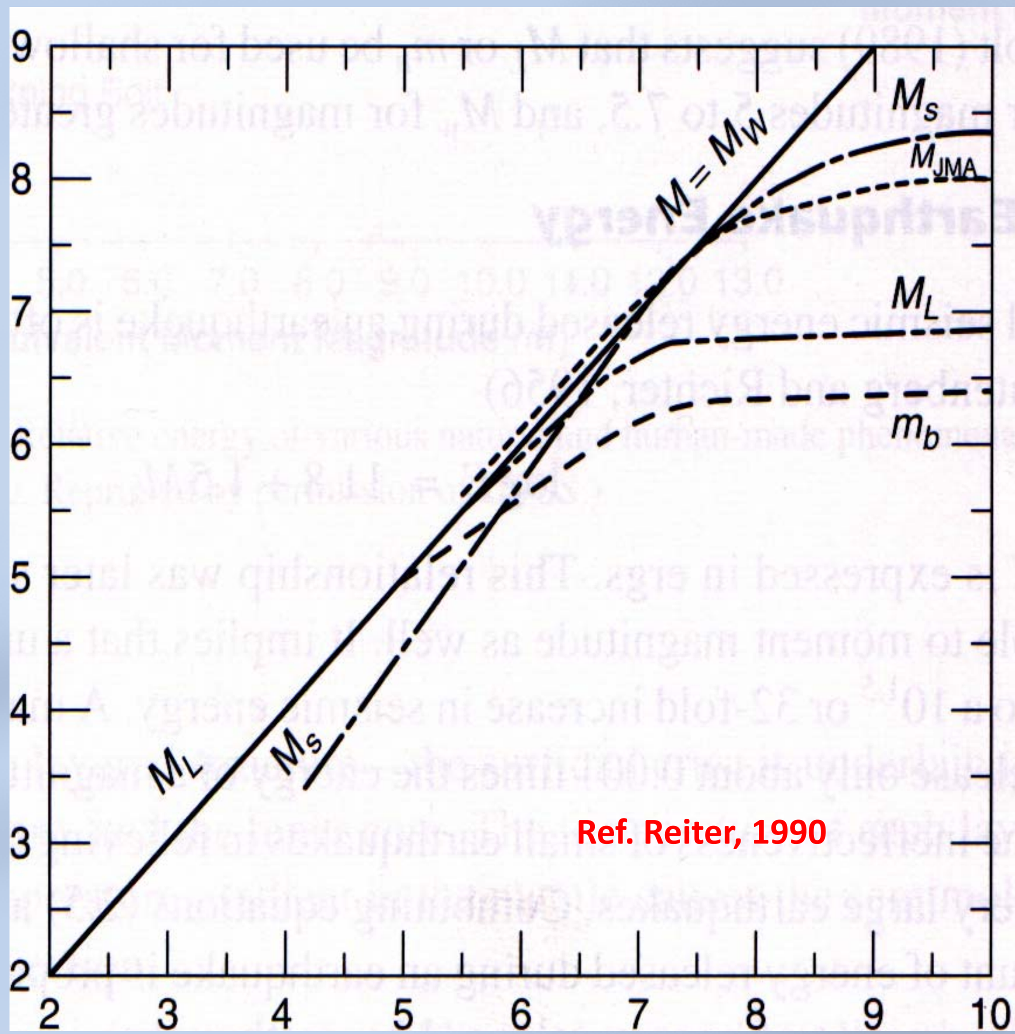
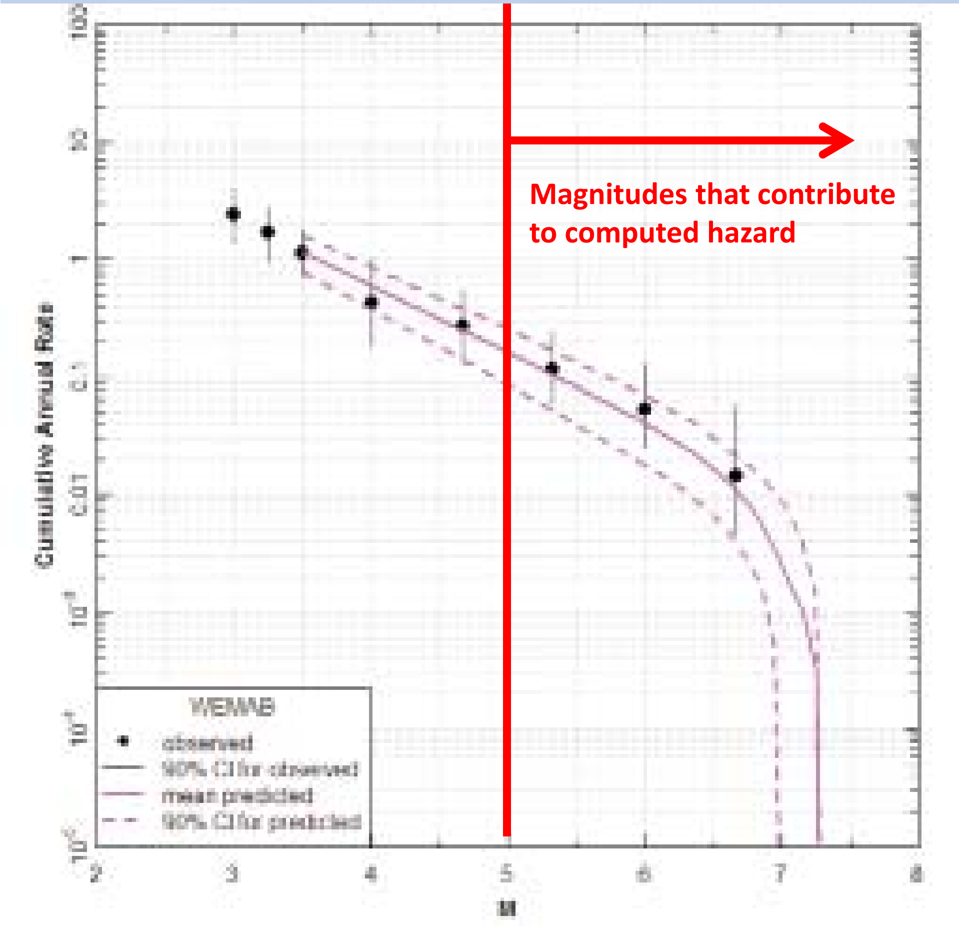
Magnitude Scaling

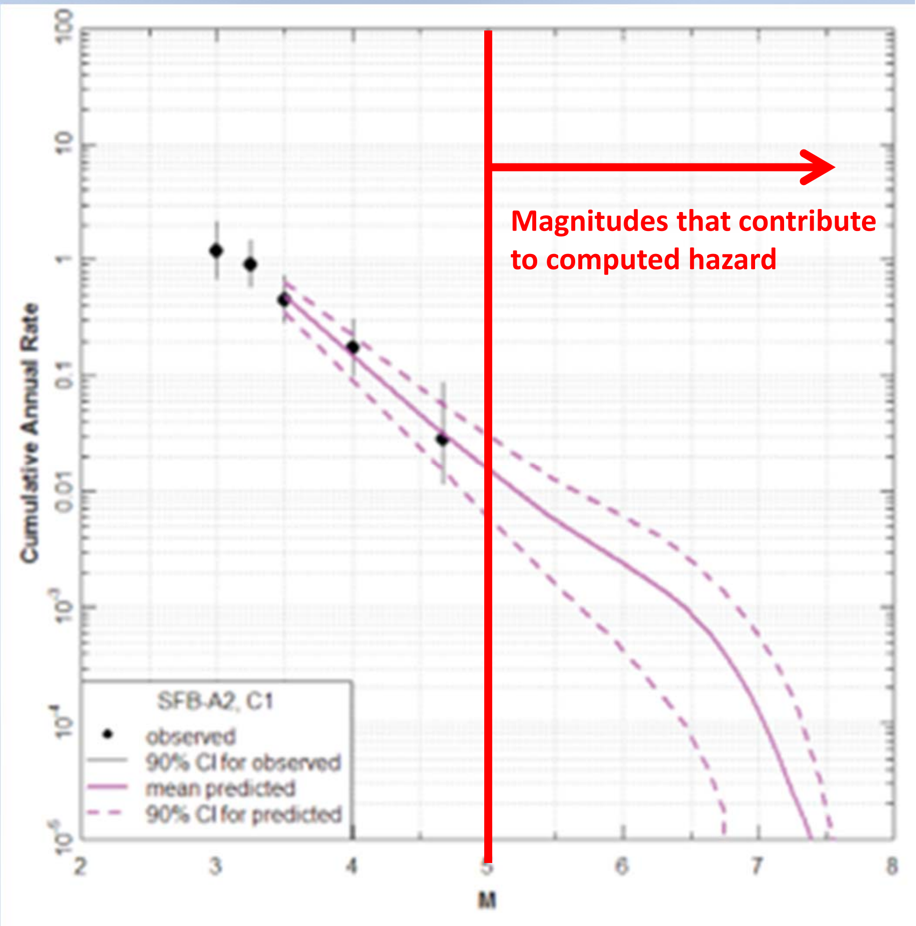
Magnitude



Moment Magnitude (M_w)

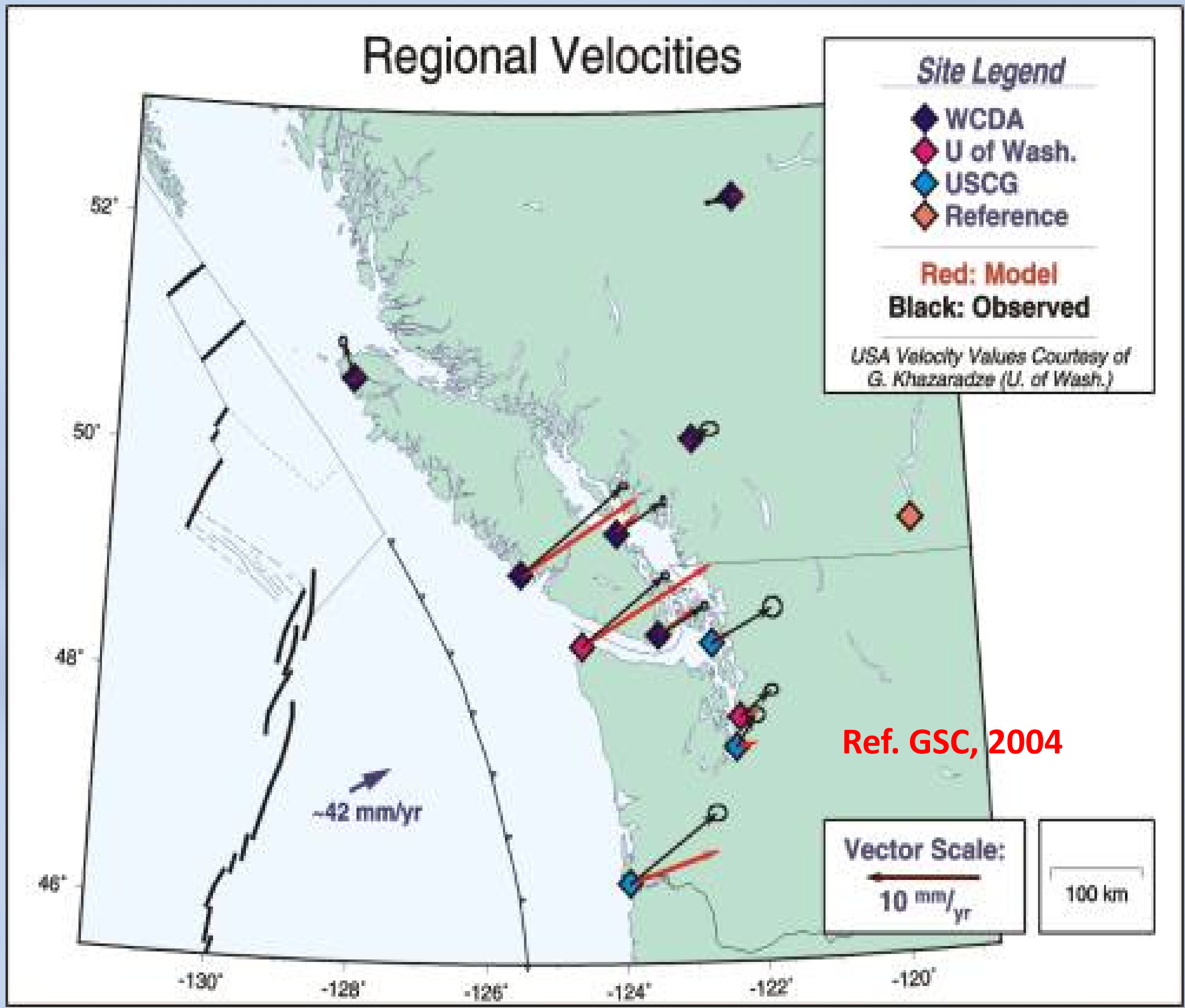
Recurrence Modeling Challenges





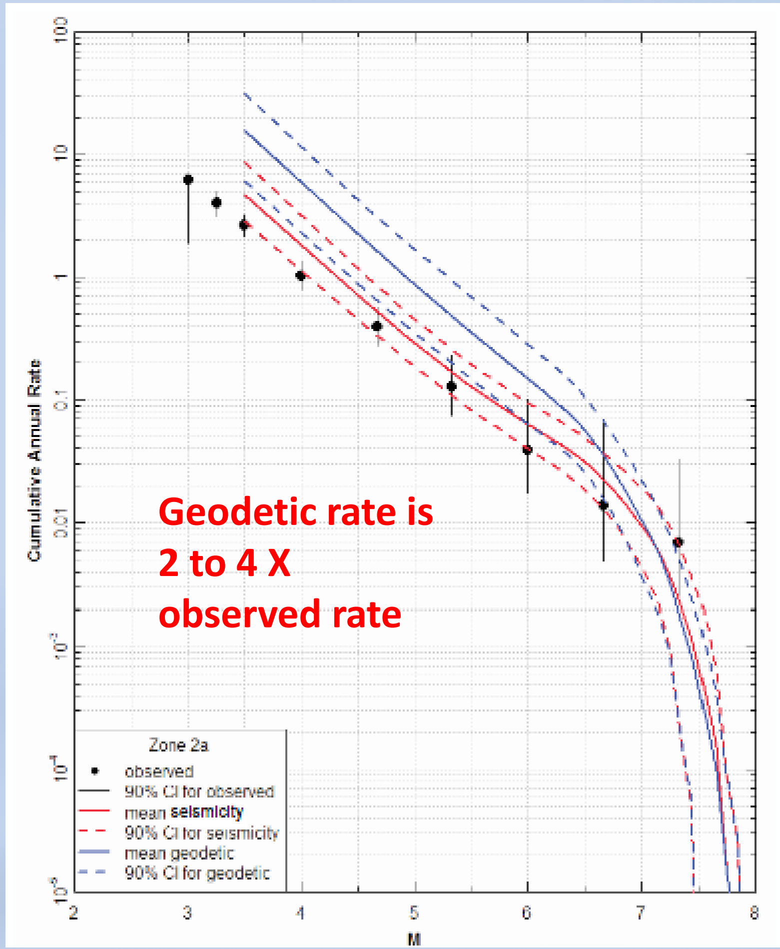
Geodetic Deformations

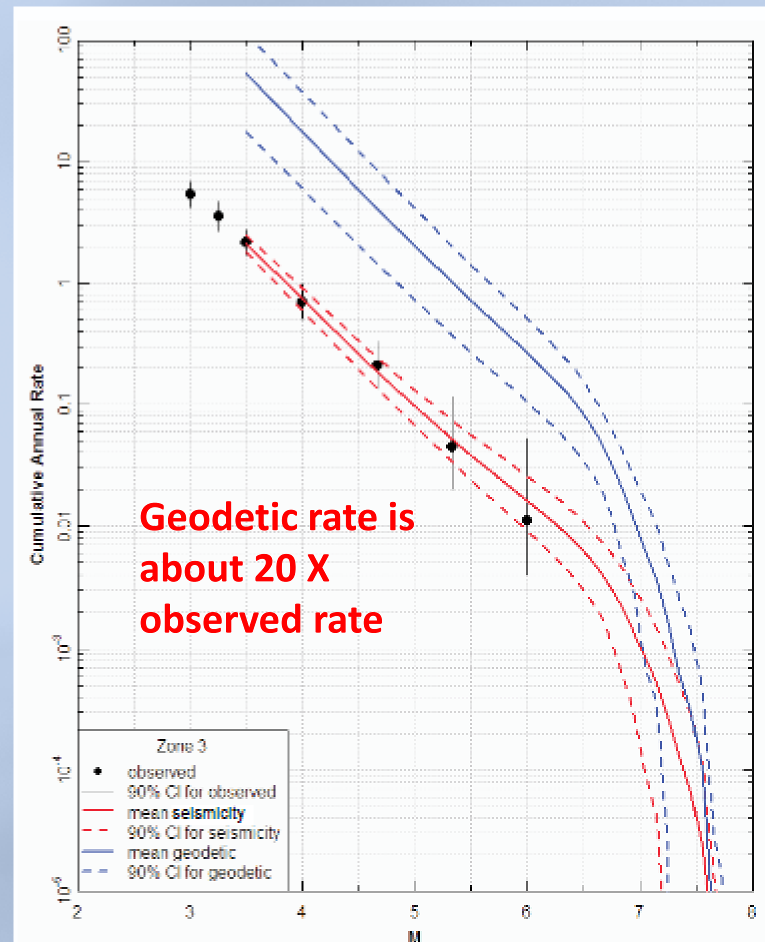
- Can strains recorded by regional GPS network be converted to seismic recurrences?



Ref. GSC, 2004

Observed vs Geodetic Recurrence



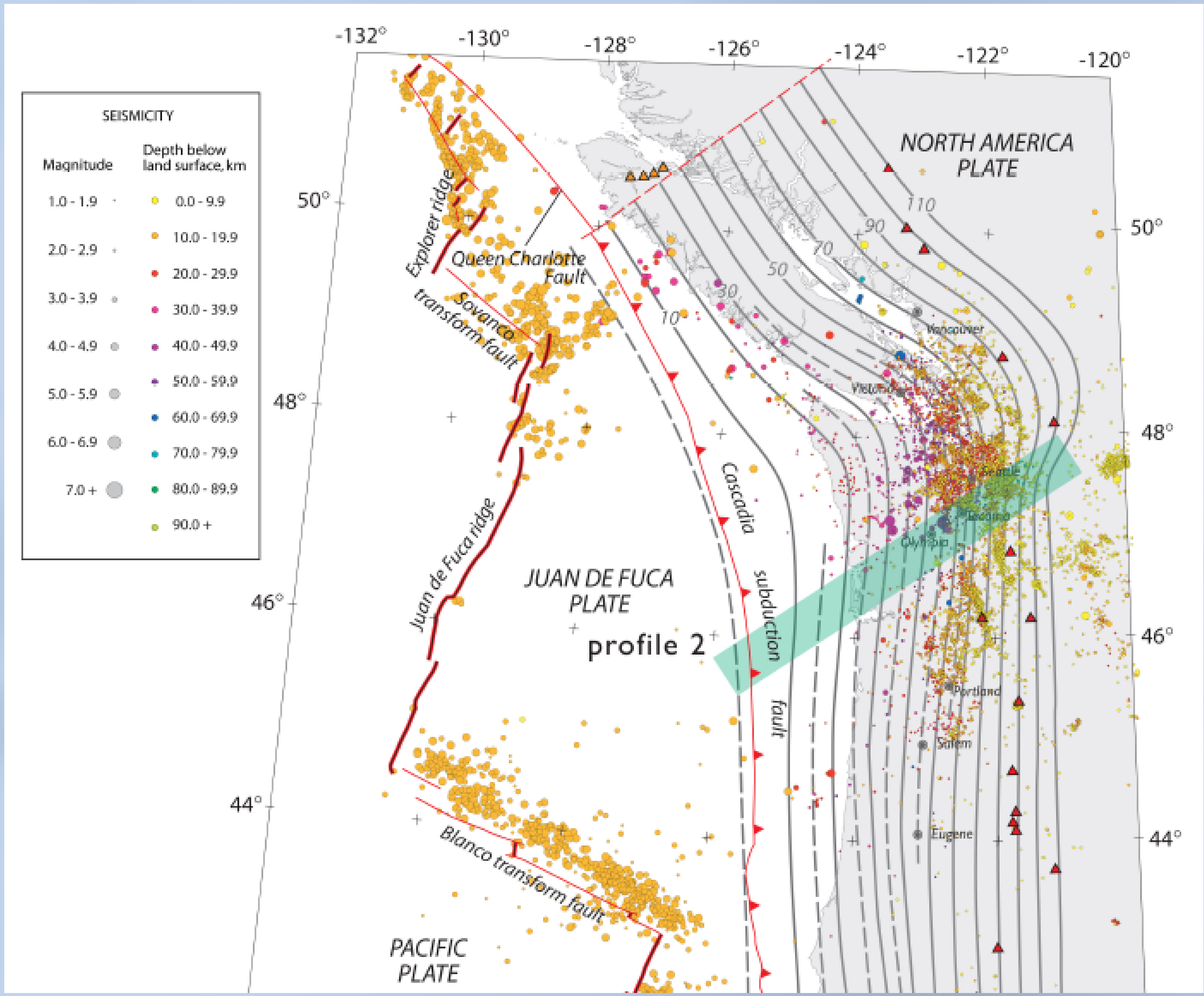


- Our understanding of seismic efficiency is incomplete (i.e. what percentage of geodetic strain gets converted to earthquakes?)

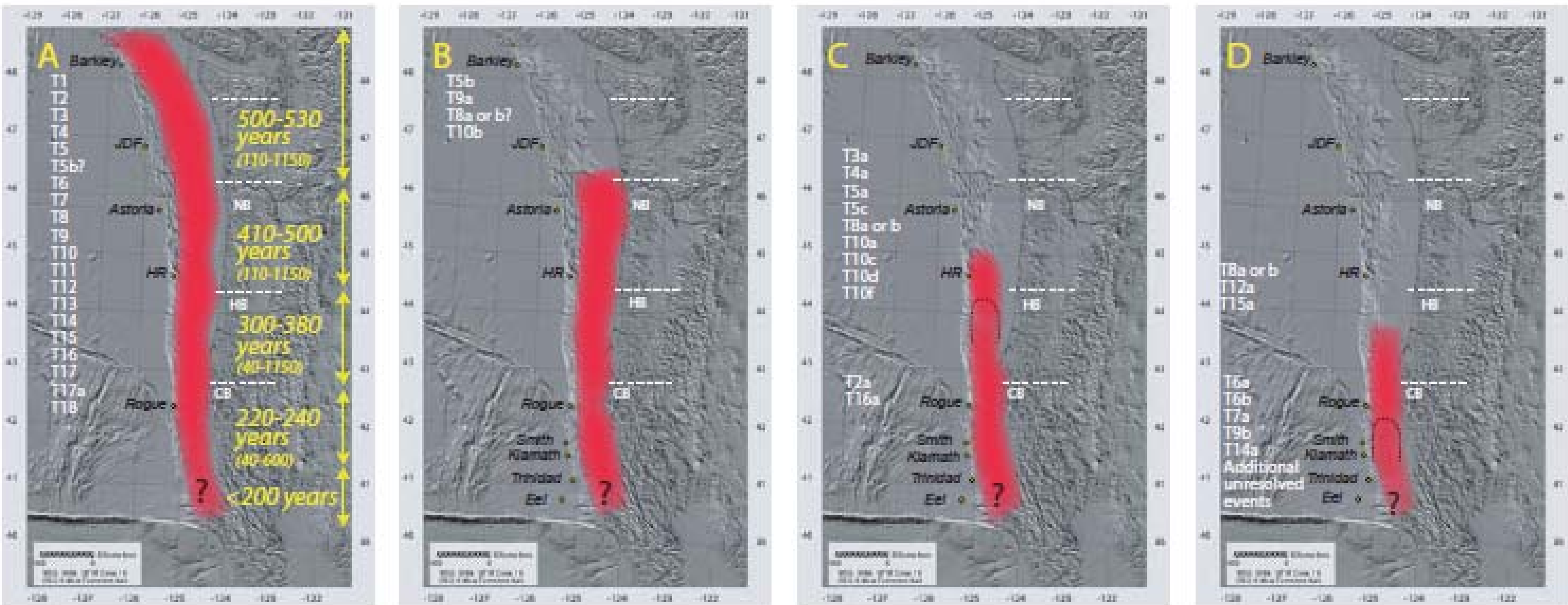
Cascadia Subduction Zone Modeling

- Complex geometry – variably dipping, curved interface.
- Interpreted to include both “locked” and “transition” zones down-dip.
- Northern extent uncertain.
- Ongoing intraslab earthquakes, but no confirmed interface earthquakes recorded.
- Paleoseismic evidence interpreted to show that last interface earthquake occurred in 1700, and there have been 18 such earthquakes in the last 10,000 years. Rupture lengths have varied.

CSZ – McCrory et al (2006) Model

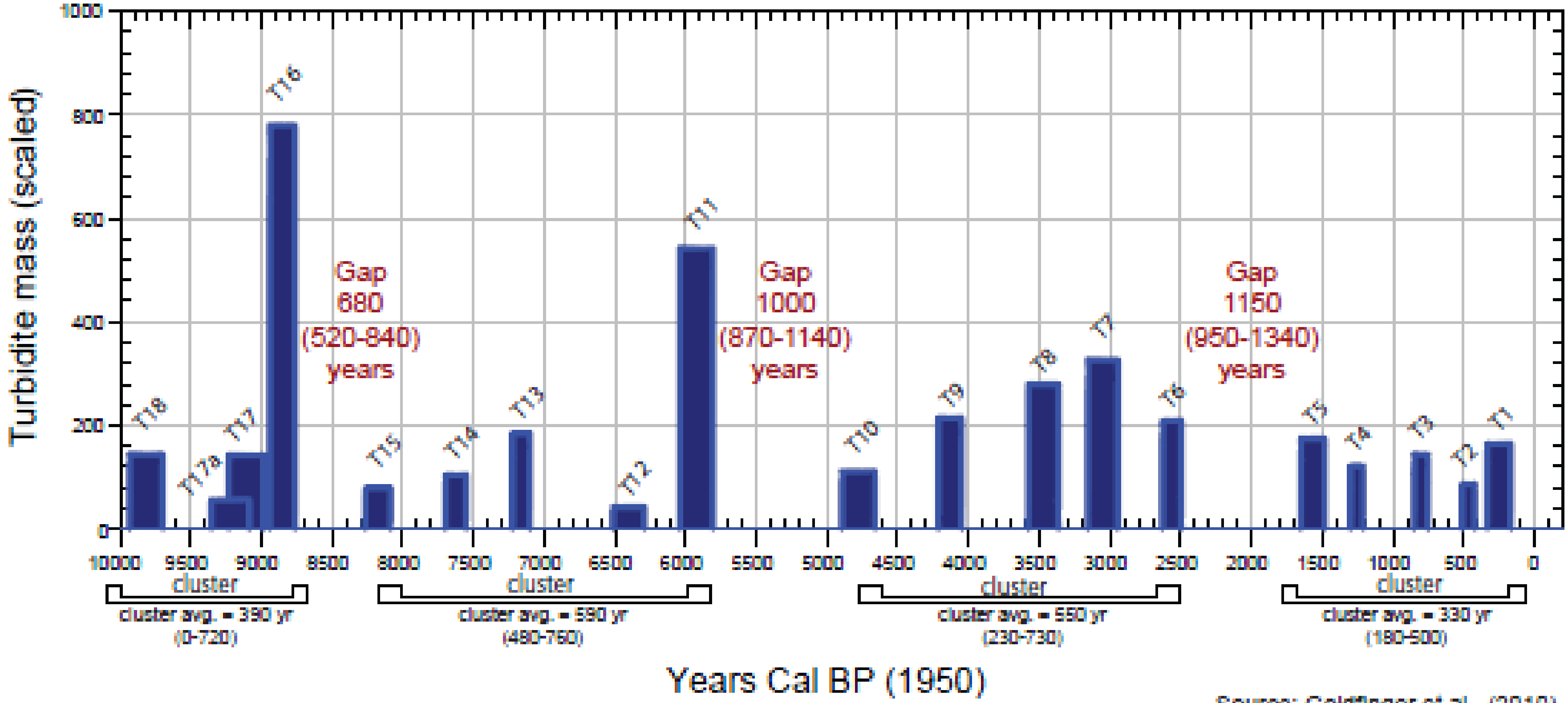


CSZ Rupture Lengths



Source: Goldfinger *et al.* (2010)

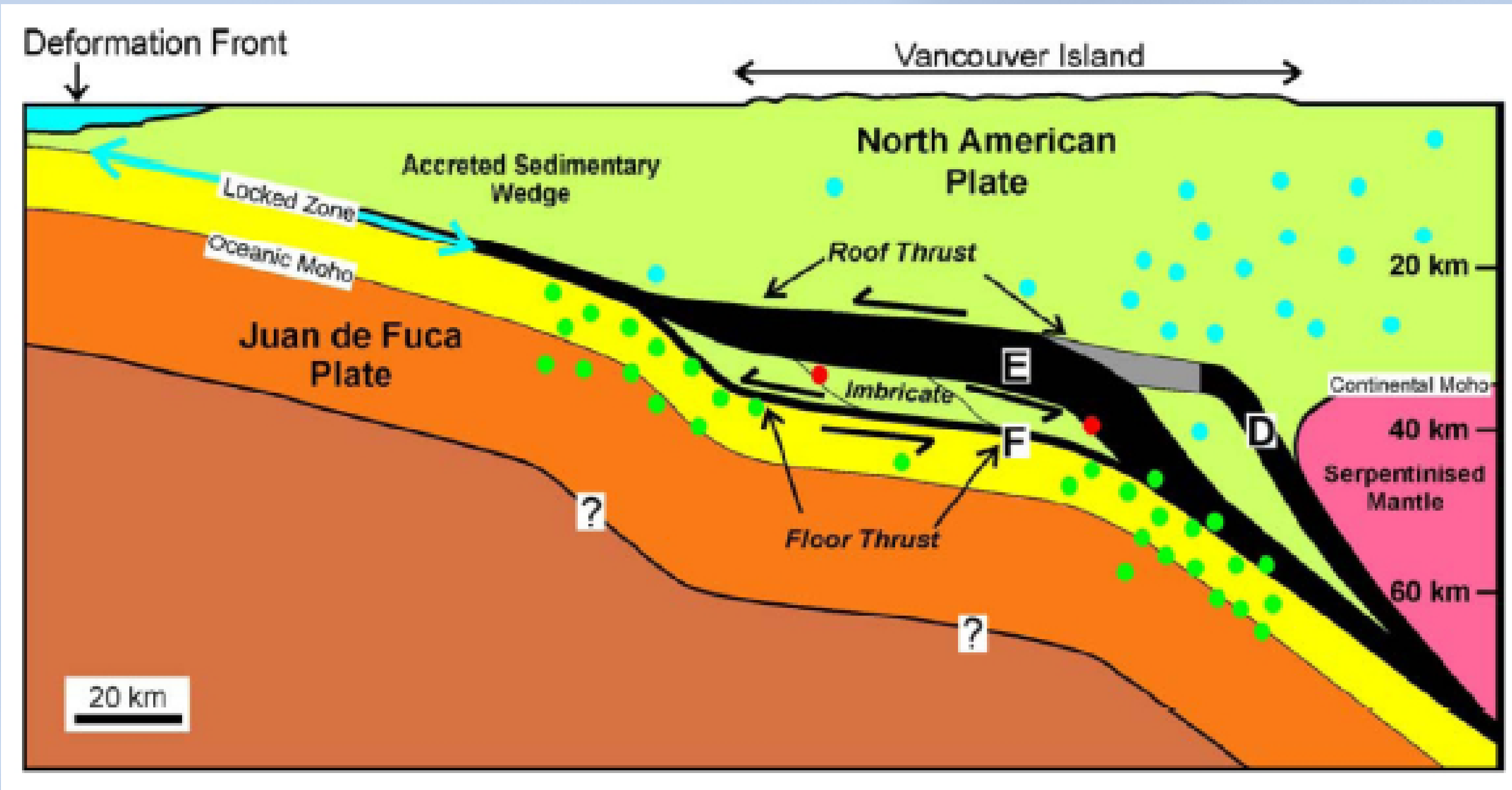
Clustering Model - Example



Source: Goldfinger et al., (2010)

A. Bars are scaled with height representing turbidite mass (taller bars are larger turbidites). Bar widths are the 2σ error range from Oxcal combines for each event. Turbidite mass calculated from gamma density data for cores 12 PC (Juan de Fuca Channel) and 23 PC (Cascadia Channel). The time series suggests a history of clusters of earhquakes (average repeat times shown), separated by gaps of ~750 - 1150 years. Gaps appear to have a tendency to conclude with a large event.

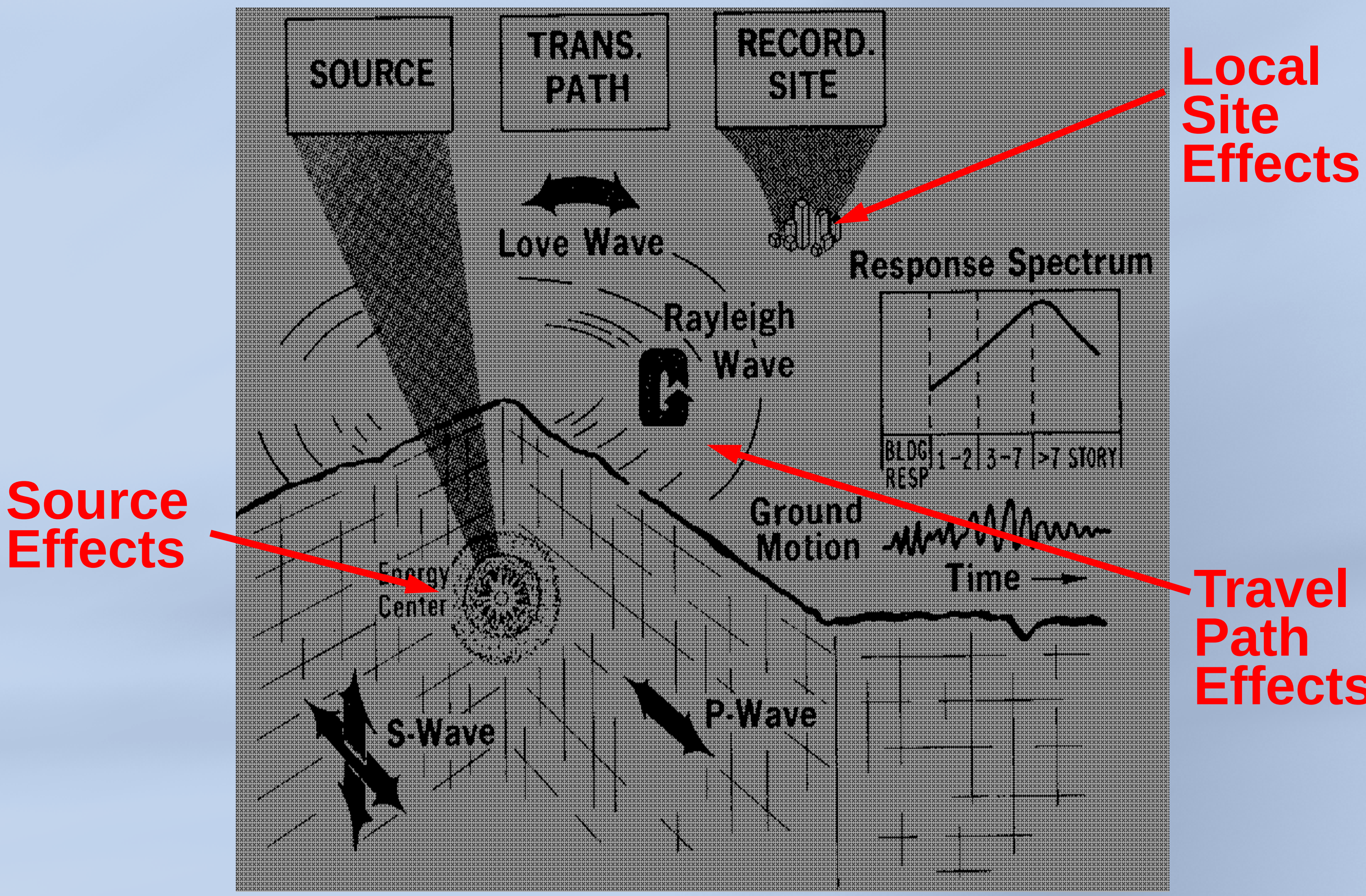
E Layer vs F Layer Interface



Note: The E and F reflectors define the roof and floor thrusts respectively of a 100-km-wide duplex structure, beneath which the Juan de Fuca plate subducts. The D reflectors may also be part of the roof thrust, but have not yet been shown to be continuous with the E reflectors, as indicated by the grey region. Seismicity in the subducting slab occurs primarily where the top of the plate is inferred to steepen.

Calvert et al, 2006

Ground Motion Modeling

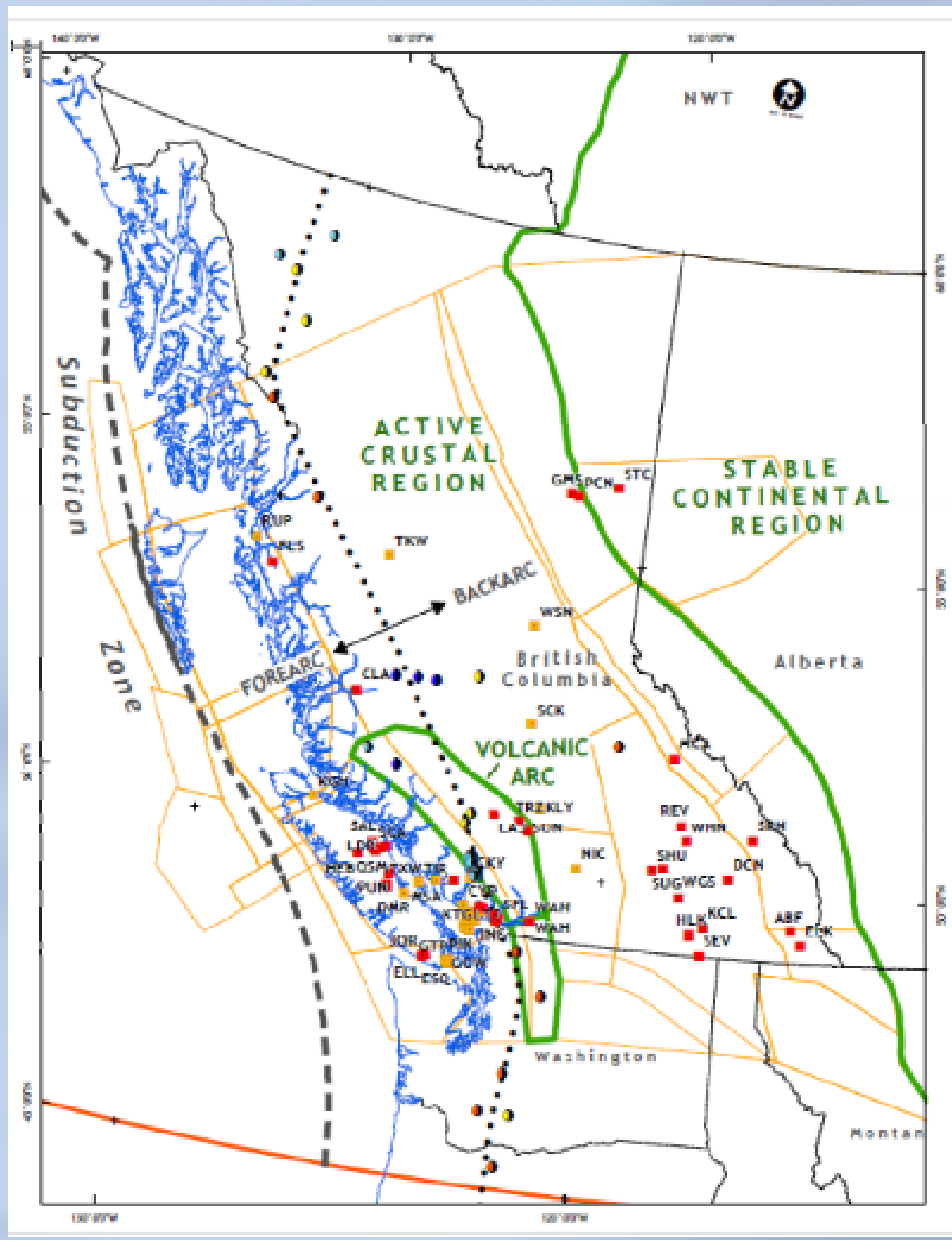


Hays et al, 1975

Ground Motion Prediction Models

- Numerous candidate models to choose from
- Candidate models are typically based on different earthquake data sets and include:
  - Different input parameters
  - Different mathematical modeling approaches
  - Different distance measures
  - Different reference ground conditions
- Limited B.C. strong motion data are available for validation

Tectonic Regions for GM Modeling

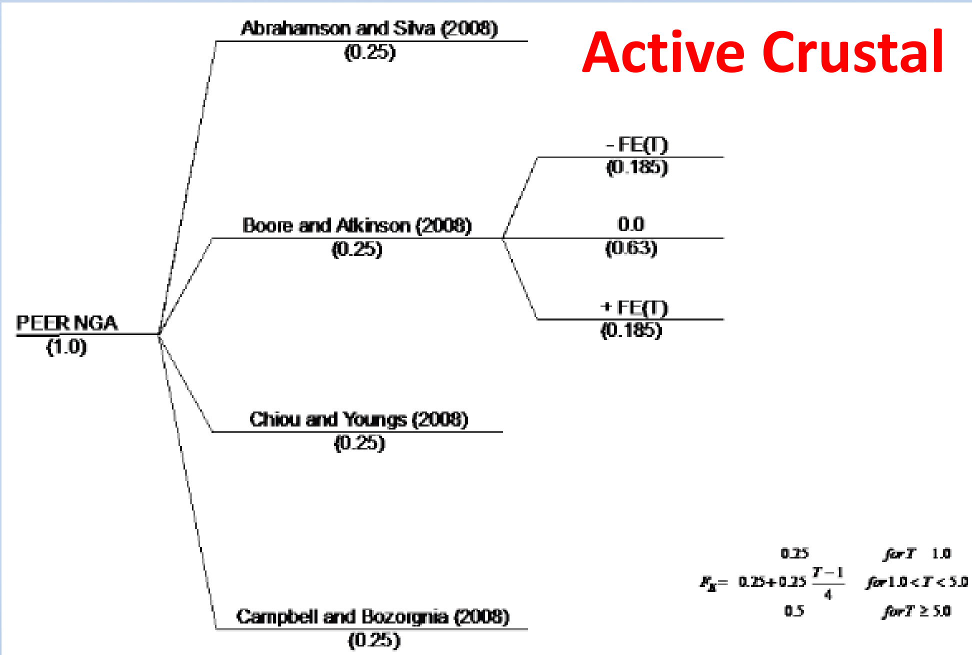


Adopted Ground Motion Models

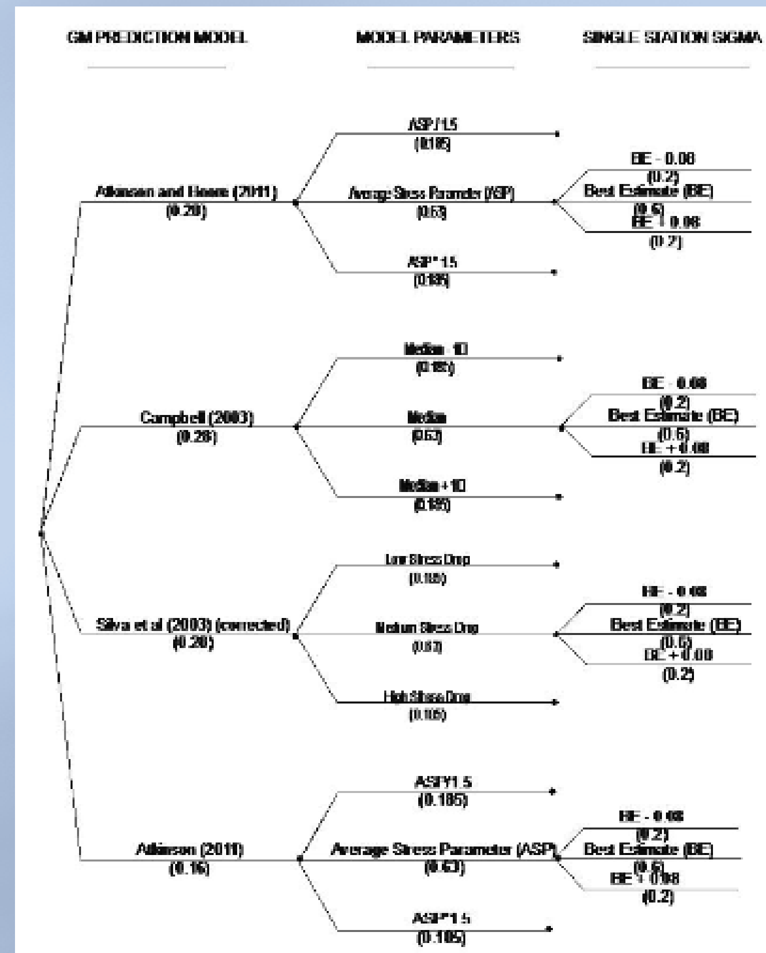
- Active Crustal Region
  - Abrahamson & Silva (NGA -2008)
  - Boore & Atkinson (NGA – 2008)
  - Chiou & Youngs (NGA – 2008)
  - Campbell & Bozorgnia (NGA – 2008)
- Stable Continental Region
  - Atkinson & Boore (2011)
  - Campbell (2003)
  - Silva et al (2003)
  - Atkinson (2011)
- Subduction & Volcanic Arc
  - BC Hydro (2010)

Ground Motion Logic Trees

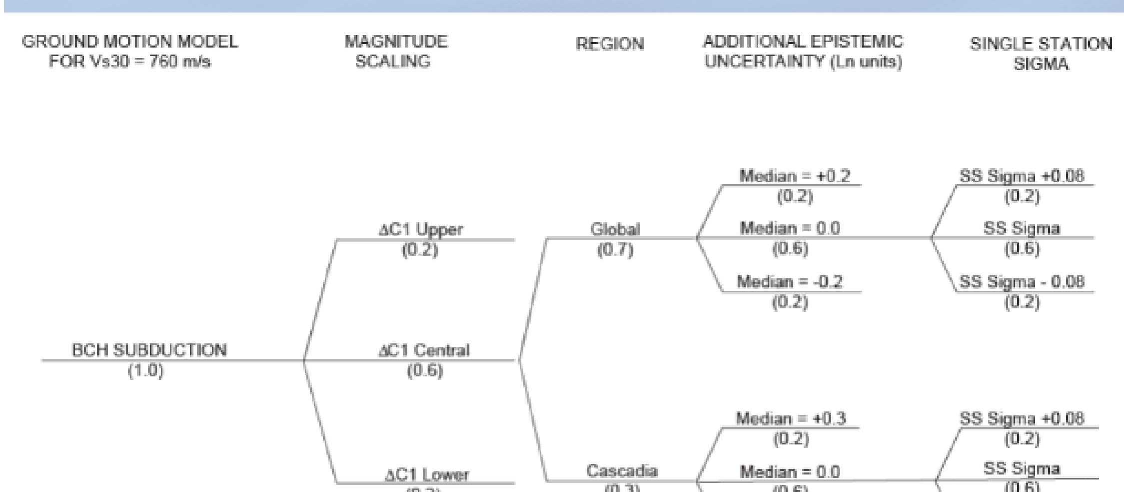
Active Crustal



Stable Continental



Subduction



What Next?

- GSC working on models for 2015 NBCC
- BCH expects its SSHAC project should provide technical stability of the model and hazard results for 10 to 15 years
- There will be continued focus on addressing (& reducing) uncertainties in PSHA
- Expectations of regulators with respect to level of effort will likely increase

Some Opportunities for Improvement

- More communication between engineers, scientists and seismologists.
- Identification & characterization of active faults
  - LIDAR/other remote sensing tools
  - Paleoseismic investigations
- Improved seismic monitoring
  - Increased density of seismographs
  - More strong motion accelerographs
- Research into geodetic strain/seismic efficiency.
- Reducing uncertainties in ground motion prediction models (more complexity).

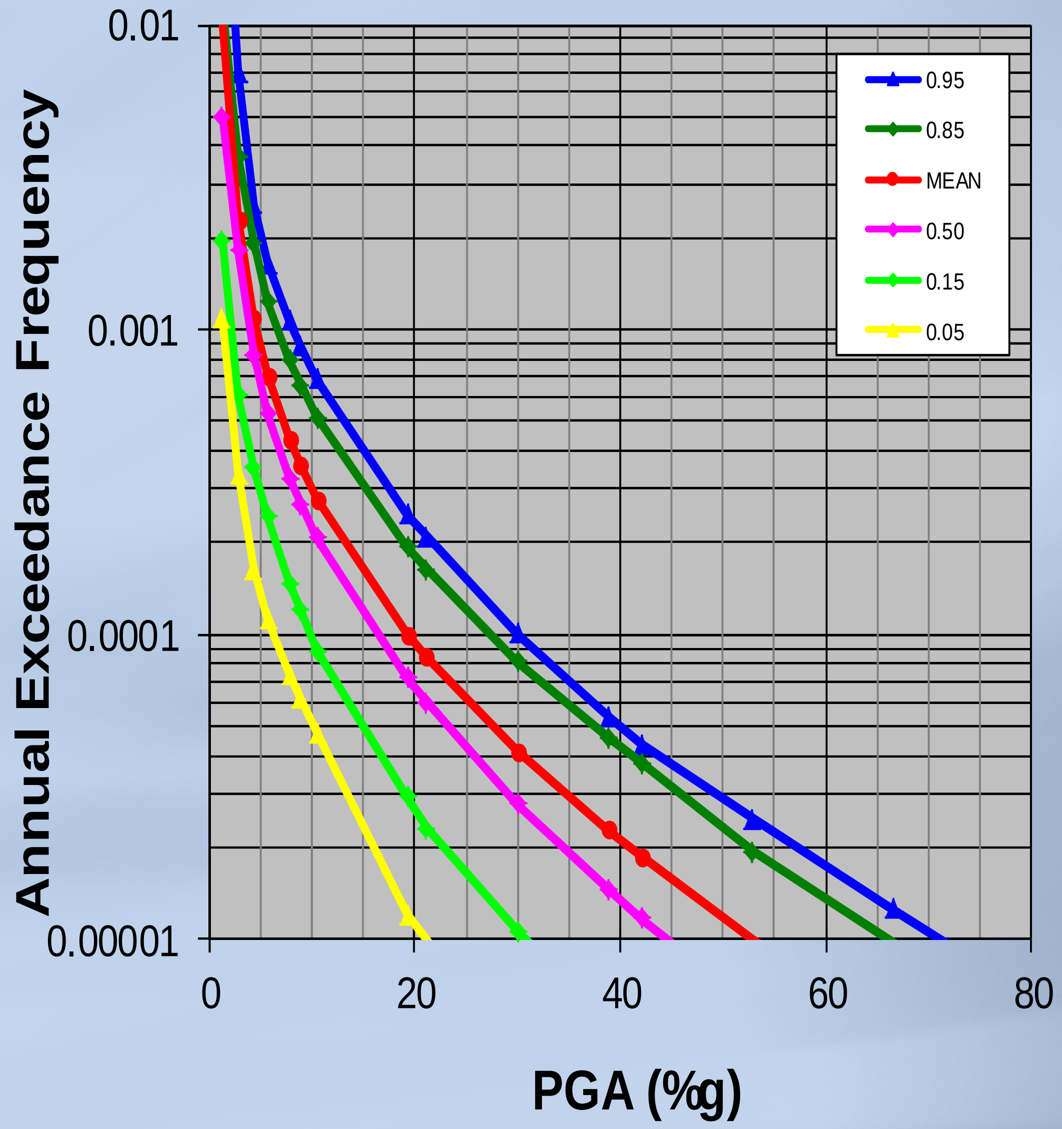
Long Term Future

- Is it possible to have a common set of seismic source and ground motion models that appropriately represent the ranges of informed technical community opinions and which everyone could use?
- Who would manage and maintain such models?
- How would such models be funded?

Back to the Present – Closing Comments

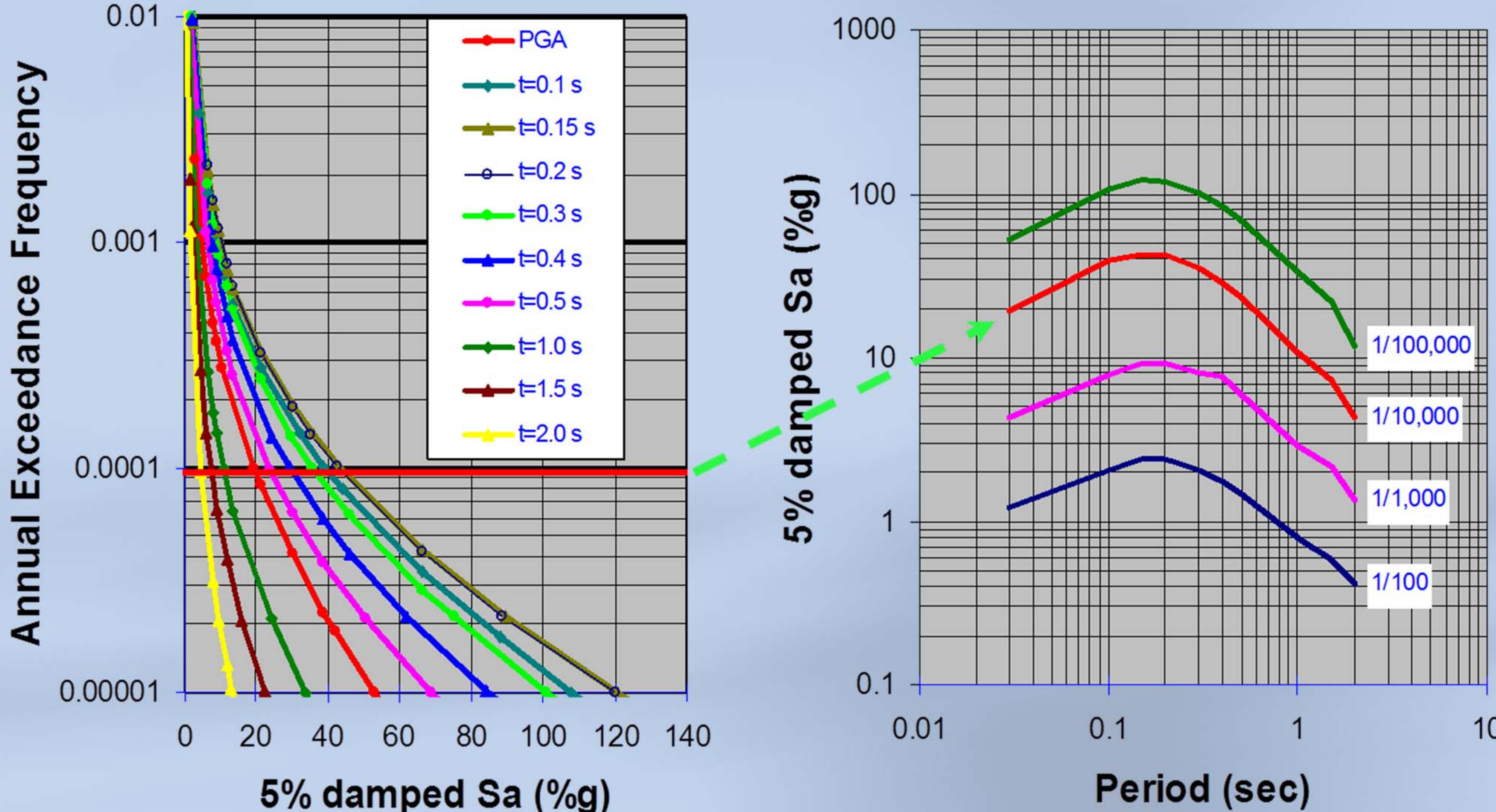
- Before starting on a seismic hazard analysis, the analyst and the user/designer both need to clearly understand what output is required, and for what purposes, e.g.
  - Is the design a routine NBCC application and can the seismic hazard analysis be done using readily available models?
  - If a non-NBCC design, does another code/guideline apply?
  - What design parameters are required (e.g. PGA, UHRS)?
  - Is a primary purpose of the analysis to provide information for selection of appropriate time histories for dynamic analyses?
  - Is information about uncertainties required (e.g. mean, median, fractiles)?
  - Will a risk analysis be performed?

Uncertainty in PGA Hazard - Example

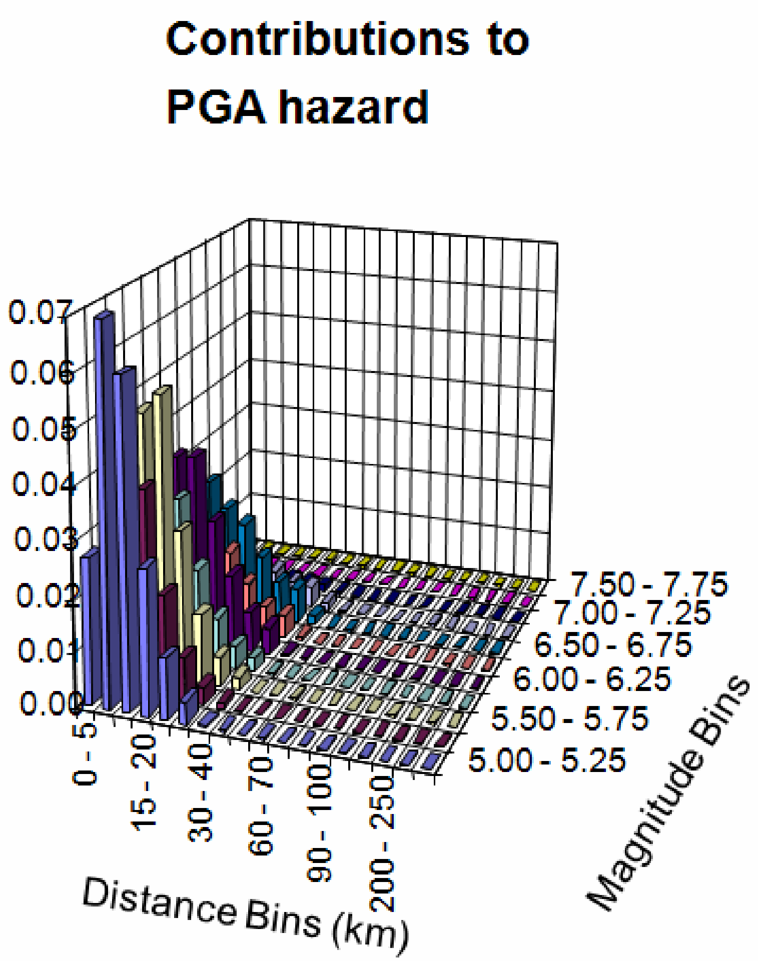


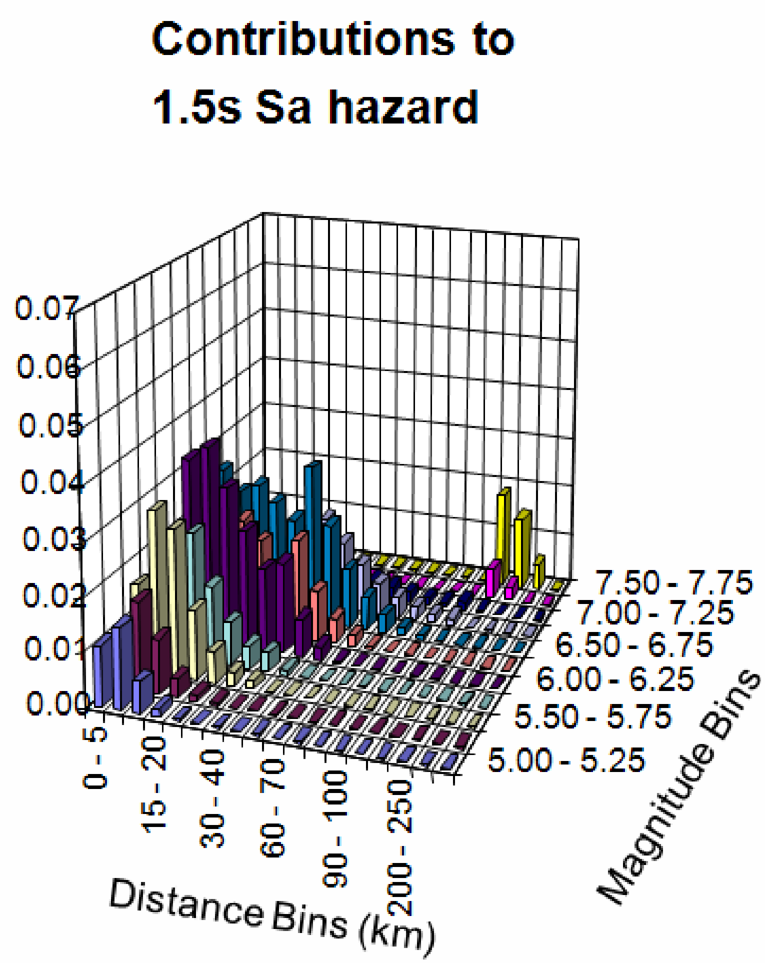
Note:
GSC/NBCC adopts medians
CDA recommends means

Uniform Hazard Response Spectra - Example



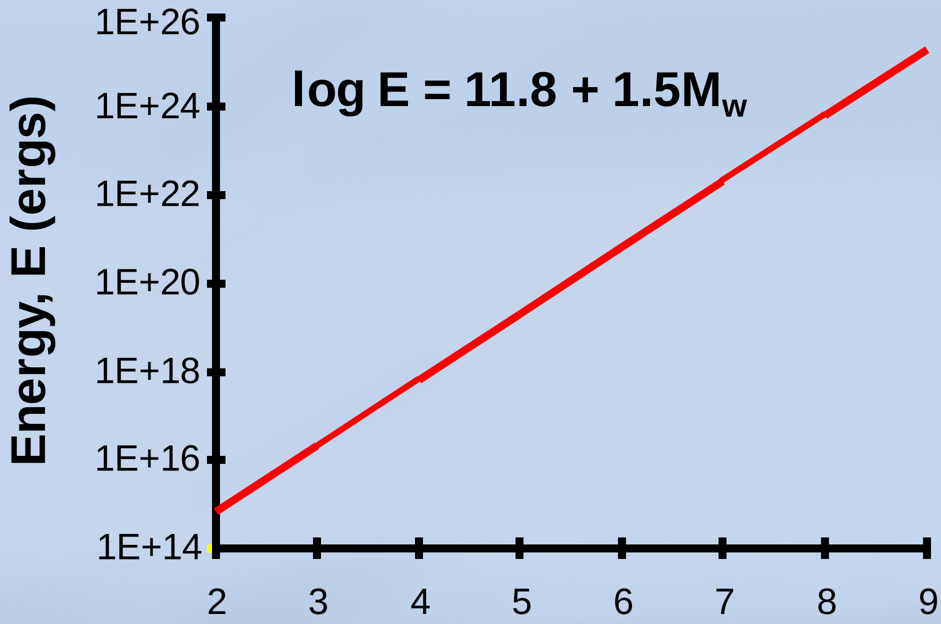
Period-Dependent De-aggregations - Example





Example from SE B.C.

Why Scenario Magnitude is Important



An increase of one unit of magnitude is equivalent to:

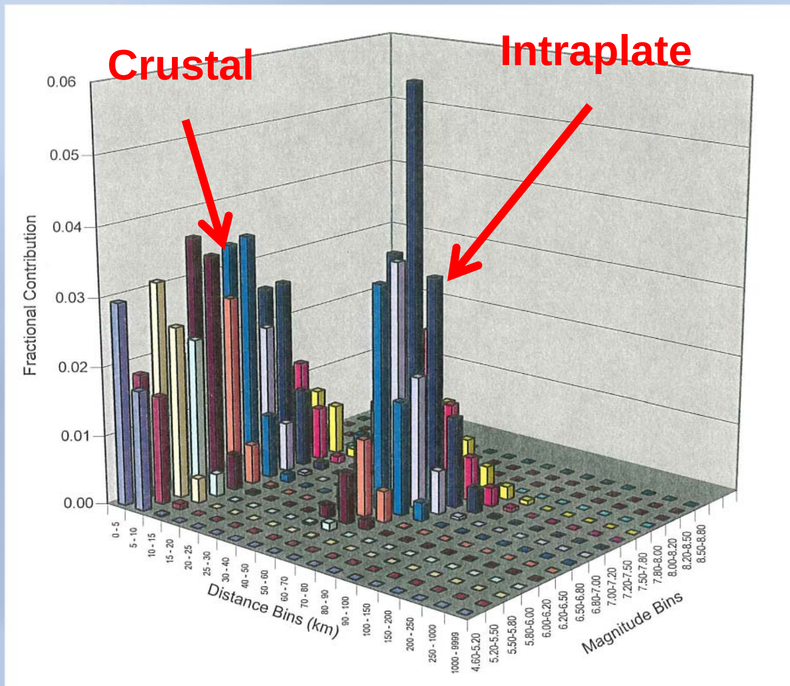
- A 10X increase in ground motion
- A 32X increase in released energy

Magnitude	Approx. Duration of Strong Shaking (sec)
4.0 to 4.9	**<5**
5.0 to 5.9	**2 to 15**
6.0 to 6.9	**10 to 30**
7.0 to 7.9	**20 to 50**
8.0 to 8.9	**30 to 90**

Seismic Design Requirements - Example

- Dam site in southwest B.C.
- Dynamic analyses required for concrete dam, powerhouse and soil slope, each with different fundamental vibration periods.
- Design AEF = 1/10,000; design PGA = 0.7g.
- Contributions to hazard from both crustal and intraplate earthquakes. A single “average magnitude/distance scenario” makes no sense.

Period	Crustal Earthquakes		Intraplate Earthquakes	
	M_bar	D_bar (km)	M_bar	D_bar (km)
PGA	6.3	6	7.0	57
T=0.15 sec	6.3	6	7.1	56
T=0.5 sec	6.7	8	7.1	60
T=1.0 sec	6.9	9	7.2	59
T=1.5 sec	7.0	10	7.2	61



Some Things to be Aware of

- Creating new seismic models that truly represent informed technical community opinion is not a small task. Input from multiple parties with appropriate expertise is required. Models need to be supported by evidence & rationale, not just opinion.
- At low probabilities typical of critical facility designs, computed hazard is typically driven by contributions from near-site sources.
- Extreme model scenarios/alternatives that are assigned low weights in a PSHA may become important at low probabilities.
- Although we spend large amounts of time & effort refining source models, ground motion prediction models are often even more important.
- Fully incorporating uncertainties in a PSHA may (but not necessarily) increase hazard over that previously computed with more simplified models.

An Opinion………….

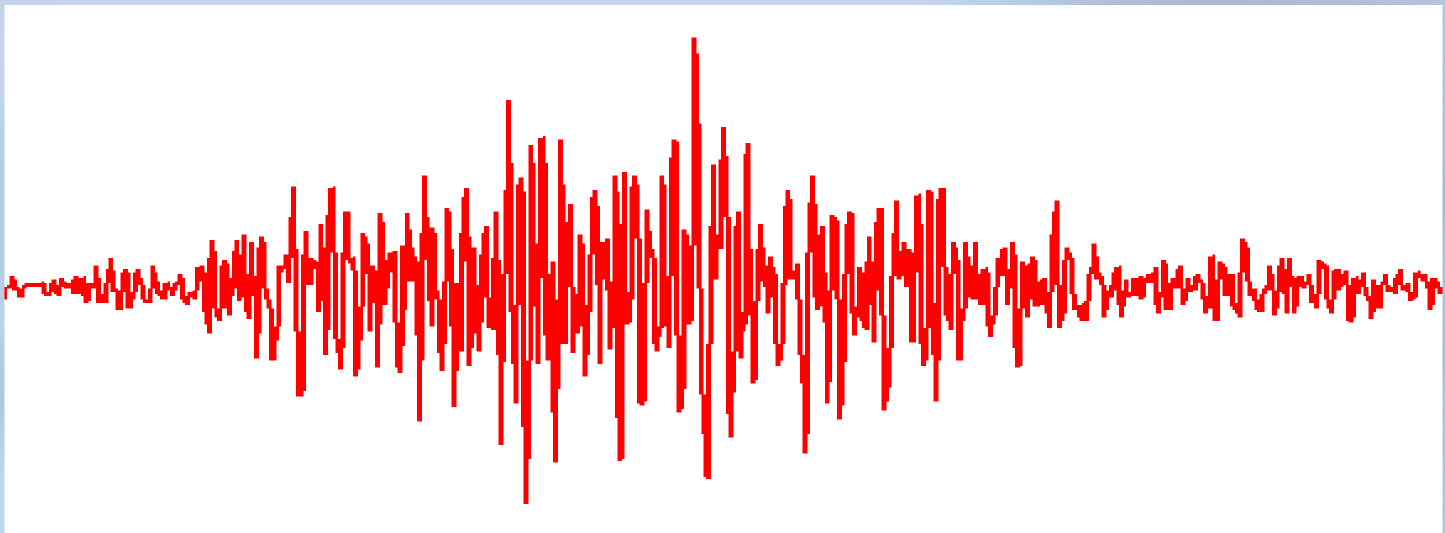
"….the increased hazard estimates resulting from modern probabilistic studies are entirely appropriate, and regardless of the costs and technical challenges it may present, the solution lies in engineering design or acceptance of greater risk and not in attempts to invalidate the new PSHA results." (Bommer and Abrahamson, 2006).

When it comes to seismic hazard analysis:

- A little knowledge is a dangerous thing.....
- .....and so is a lot.

(With apologies to Alexander Pope and Albert Einstein)

Thanks for your attention



Acknowledgements

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  - Geological Survey of Canada
  - US Geological Survey
  - USGS National Earthquake Information Centre
- ….and from BC Hydro project reports.

Comments & opinions expressed in this presentation are those of the author and do not necessarily represent the policy or position of any company or agency.