# Knowledge of in-slab earthquakes needed to improve seismic hazard estimates for southwestern British Columbia

**John Adams and Stephen Halchuk**
*Geological Survey of Canada, 7 Observatory Crescent, Ottawa, Ontario, K1A 0Y3, Canada*
*adams@seismo.nrcan.gc.ca, halchuk@seismo.nrcan.gc.ca*

## *ABSTRACT*

*In-slab earthquakes (earthquakes within the subducting Juan de Fuca plate) make the major contribution to seismic hazard for the Strait of Georgia region of British Columbia. These earthquakes dominate the hazard, despite their depth, because they have a higher rate and cause stronger shaking than the crustal earthquakes. Key knowledge of in-slab earthquakes needed to improve seismic hazard estimates for southwestern British Columbia includes the constraints on the spatial distribution, rate and maximum size of the earthquakes, the ground motions to be expected, the nature of the earthquake sources and the structure and properties of the lithosphere through which the waves propagate.*

## Introduction

Seismic hazard for the Strait of Georgia region of British Columbia (including Vancouver, Victoria and a substantial fraction of B.C.'s population) comes from three sources: crustal seismicity in the North American plate, great earthquakes of the Cascadia subduction zone on the interface between the North American and subducting Juan de Fuca plate, and deep earthquakes within the subducting slab ("in-slab" earthquakes). It is, however, dominated by the contribution from in-slab earthquakes. In Canada's fourth generation seismic hazard model (see *Adams et al*., 1999a, 1999b, 2000), these earthquakes dominate the hazard despite their greater depth, firstly because they occur at a rate up to five-fold higher per unit area than the shallower crustal earthquakes, and secondly, because their predicted shaking is stronger than crustal events of the same size (see below). Thus when attempts are made to improve the estimation of seismic hazard for southwestern B.C., a great deal can be gained by better understanding these earthquakes.

We raise the following series of questions to highlight the knowledge of in-slab earthquakes we believe is needed to improve seismic hazard estimates for southwestern British Columbia. Some of the differences that result from the current level of uncertainty are demonstrated on Figure 1, a comparison of the GSC and USGS deaggregated hazard for Bellingham, Washington. Clear differences are seen in the fraction of the hazard coming from in-slab versus crustal earthquakes, and in the contribution from earthquakes larger than magnitude 7.

## What is the spatial distribution likely for future earthquakes within the slab?

The GSC's fourth generation hazard maps use three source zones to model deep earthquake distribution, Georgia Strait (GEO) and Puget Sound (PUG) for one probabilistic model and Georgia Strait/Puget Sound (GSP) for the other, reflecting uncertainty in the future location of damaging deep earthquakes (Figure 2). What is needed are geological or geophysical reasons to constrain the updip, downdip, northern and southern extent of the deep seismicity. Although the two probabilistic models attempt to model the range of possible distributions, the level of hazard is strongly controlled by the active PUG zone. This is especially important for Vancouver, as the northern boundary of PUG lies under the city and generates a steep gradient in hazard across the city (Figure 3). Fairly large changes in hazard for communities in this gradient zone could result from slight adjustments to the source zone boundary, perhaps as the result of new significant earthquake activity outside the currently-defined PUG zone, or a recognition that certain regions within the boundary are (and will continue to be) aseismic. Improved geological/geophysical constraints might identify these regions and so refine the hazard estimates.

## What is the rate of activity?

The rate of large earthquakes is a function of the rate of activity for small earthquakes (a-value or alpha for the magnitude-recurrence curve) and the slope of the magnitude-recurrence curve (b-value or beta). Alpha is quite well determined in aggregate, but it is unknown whether it truly varies in space (as it appears to during the historical record), and if so, why it should vary. The GSC uses a source zone approach which assumes uniform rates within each source zone (which may not be valid); the USGS uses spatial smoothing of past activity, which assumes that the locations of future large earthquakes will

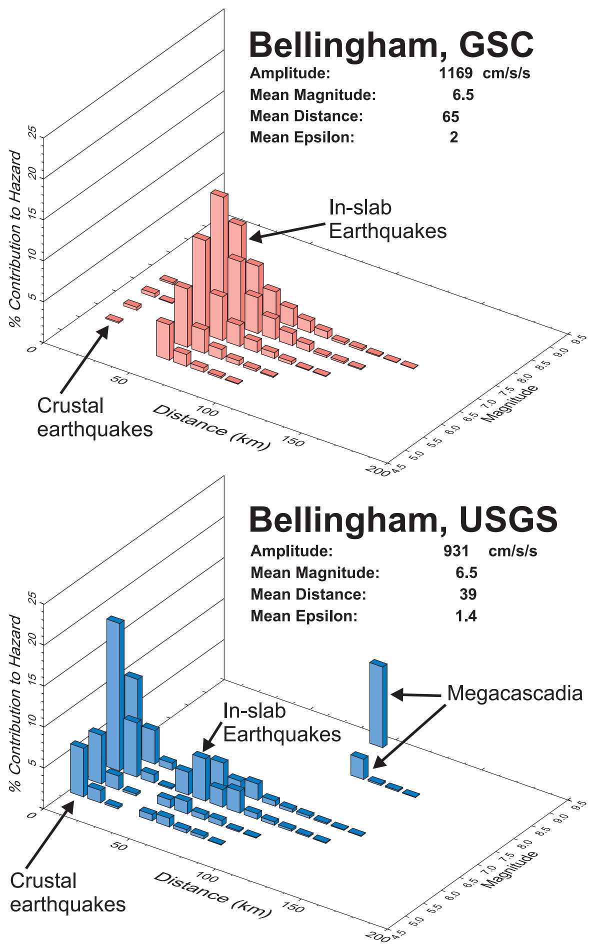

**FIGURE 1: Seismic hazard deaggregations of 0.2 second spectral acceleration values at 2%/50 years for Bellingham show the GSC results are dominated by the contribution from in-slab earthquakes, unlike the 1997 USGS results.**

precisely mimic the smoothed distribution of the small earthquakes (which may not be valid either).

The slope of the curve (beta) represents the relationship between the number of small and big earthquakes. For PUG, it is distinctively flatter than for most crustal source zones such as the crustal earthquake zone, Cascade Mountains R model (CASR), which overlies it (Figure 4). Two curves are shown for the crustal earthquakes (CASR), one representing the mathematical fit to the observed rates and the other—dashed —accommodating the observed higher rate of $M>6.5$ earthquakes. The value used in the Canadian hazard model is much lower (beta=1.01, b=0.44) than that used by the USGS (beta=1.5, b=0.65) for its deep earthquakes. No sound explanations exist for the different empirical values of beta, though a study of worldwide in-slab earthquakes might confirm the reasonableness of the value chosen, and provide insight into the reasons for such a low value.

Together, the magnitude recurrence parameters explain some of the difference in hazard. Figure 4 shows the activity rates of PUG and the overlying CASR crustal earthquake source. At magnitude 6, the predicted rate of in-slab earthquakes is three to ten times the rate of crustal earthquakes, thus accounting for the larger hazard contribution from the former. On Figure 4, the curve representing the USGS slope is drawn through the magnitude 4 data point on our PUG magnitude recurrence curve. As to be expected, the steeper USGS slope predicts a rate of M>6 earthquakes only one-third the GSC rate, and thus explains some of the hazard difference.

### How large can the in-slab earthquakes get?

The largest historical in-slab event occurred in 1949, of moment magnitude about 6.9. Compared with recent earthquakes, almost nothing is known about the rupture parameters of this earthquake, such as its depth extent, fault length or stress drop. Some geophysical constraints such as temperature in the slab are believed to limit the thickness of brittle rock thus restricting fault width; larger earthquakes therefore require greater fault lengths or greater slip (or both). The GSC model currently allows an upper bound magnitude of 7.3 for PUG (with an uncertainty range of 7.1–7.6) as shown on Figure 5, presuming that a future large earthquake could extend deeper into the slab, or have larger displacement, or rupture a longer fault (perhaps through cascading rupture segments as demonstrated during the Lander's earthquake). In 1997, the USGS adopted an upper bound magnitude of 7.0. Because of the high rate for these large earthquakes (due to the small b value), their contribution to the total seismic hazard is not trivial (for the GSC's results, about 14–24% of the seismic hazard, dependent on model, comes from earthquakes larger than the 1949 one). More work in understanding the 1949 and 1965 earthquakes together with the geological/geophysical conditions might allow tighter constraints on the largest possible earthquakes.

### How reliable are the current strong ground motion relations?

Both the GSC and USGS use the *Youngs et al.* [1997] relations to compute seismic hazard from the in-slab earthquakes. These relations concluded that in-slab earthquakes produce ground motions 40% larger than ground motions from adjacent subduction interface earthquakes (Figure 6), but this is not completely accepted. On the one hand, the *Youngs et al.* [1997] relations have been criticized as being based on rather sketchy data and upon no long period data at all [*Atkinson and Boore*, 2002]; on the other, the qualitative differences in damage between interface and in-slab earthquakes [e.g., *Okal and Kirby*, 2002] argue that there is almost certainly a quantitative difference in excitation, perhaps even larger than 40%. Considerable work is needed to determine if the

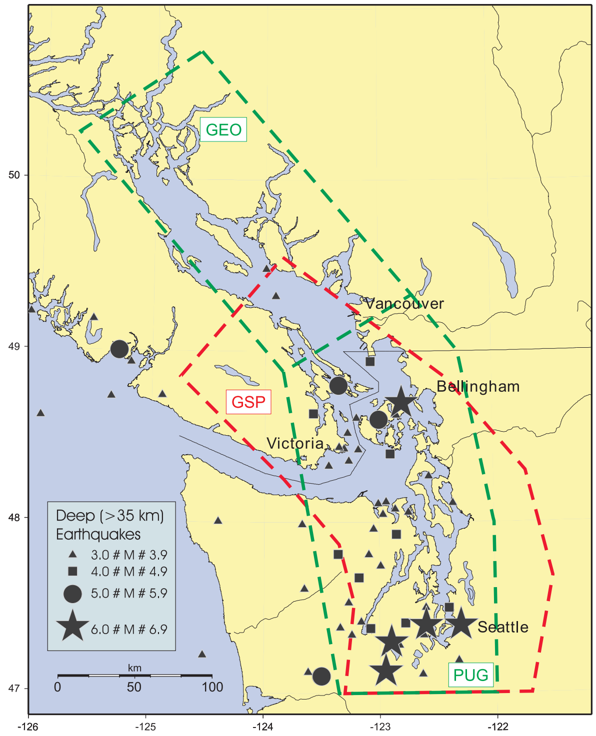

**FIGURE 2: Selected in-slab earthquakes (>35 kilometers) in the Puget Lowlands/southwestern B.C. and the alternative source zones used to model them for the GSC's fourth generation seismic hazard maps.**

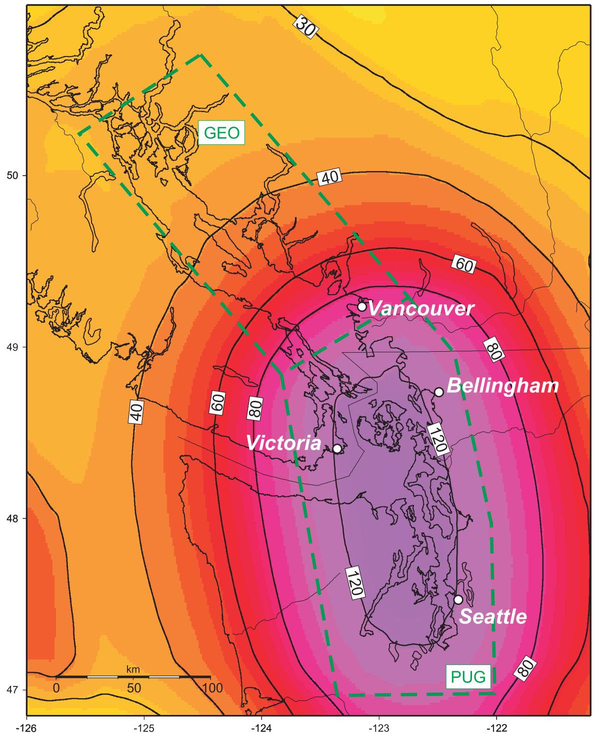

**FIGURE 3: Hazard map from the GSC model ('H') using the Puget Sound (PUG) source. Contours, for 0.2 second spectral acceleration and 2%/50 year probability, are in % g. Note how the steep gradient near Vancouver is dependant on the position of the PUG boundary.**

---

40% "premium" for in-slab earthquakes is realistic, implausible, or too small, and whether the premium applies to all periods or just to the shorter ones. The comparison of the in-slab and crustal (using the *Boore et al.*, [1997]relations) earthquake motions (Figure 6) indicates that at essentially all the distances significantly contributing to the hazard, the ground motions from a 50 kilometer deep in-slab earthquake are expected to exceed those from a similar sized ten kilometer deep crustal earthquake.

## What are the typical seismic sources we have to contend with?

Our knowledge of the seismic source can affect our decision on which strong ground motion relations to use. Most earthquakes will probably have normal faulting mechanisms, but undetermined is the degree to which rupture directivity effects are important, particularly if ruptures tend to rupture upwards from their nucleation point (Figure 7).

If as a first approximation, the in-slab earthquakes are described as Brune sources, what are their stress drops? If as a refinement, they are described as realistic, elasto-dynamic sources, what are the key parameters (e.g. rupture velocity, source elongation, complete or fractional stress drop, source complexity/episodic rupture, fault roughness, etc.) that affect the spectral shapes of the source as radiated towards the overlying urban areas? Do in-slab source acceleration spectra have intermediate (omega$^{-1}$) slopes, and if so, over what frequency band? *Haddon* [1996] showed that typical $M_w$=6 eastern earthquake sources have omega$^{-1}$ slopes for about one decade of frequency above a lower corner, and that the high frequency (f>1 Hz) levels exceed those associated with a Brune model for a $M_w$=6, 100 bar stress drop event by a factor of three, and approach those for a Brune model source a full magnitude larger (see the velocity spectra on Figure 8). The intermediate slopes are consequent on high rupture velocities, rupture directivity effects involving asymmetrical ruptures, episodic ruptures and partial stress drop events. Therefore, given records of small earthquakes, source scaling parameters correctly incorporating these factors are needed to synthesize the ground motions for potentially damaging earthquakes.

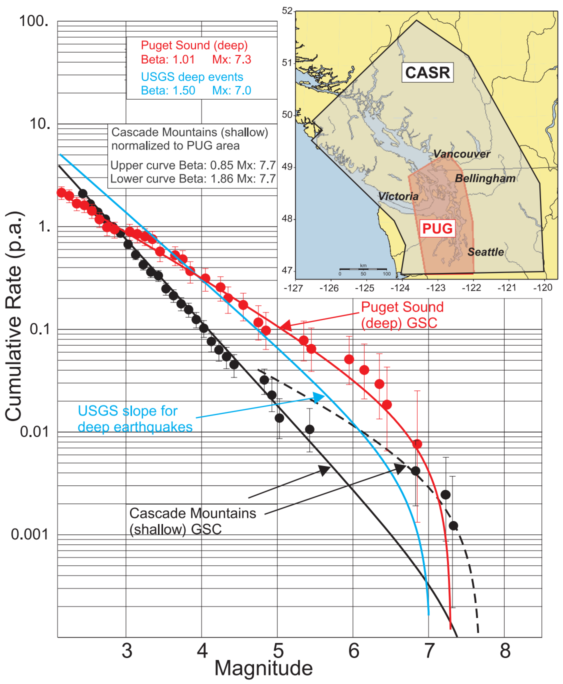

**FIGURE 4: Magnitude-recurrence curves and observed activity rates (dots with error bars) for in-slab (red) and crustal (black) earthquakes for the Puget Sound. Both CASR curves have been reduced by a factor of 6.2 to account for the larger area of CASR relative to the PUG (see inset). The scaled USGS relation (blue) for deep earthquakes is also shown.**

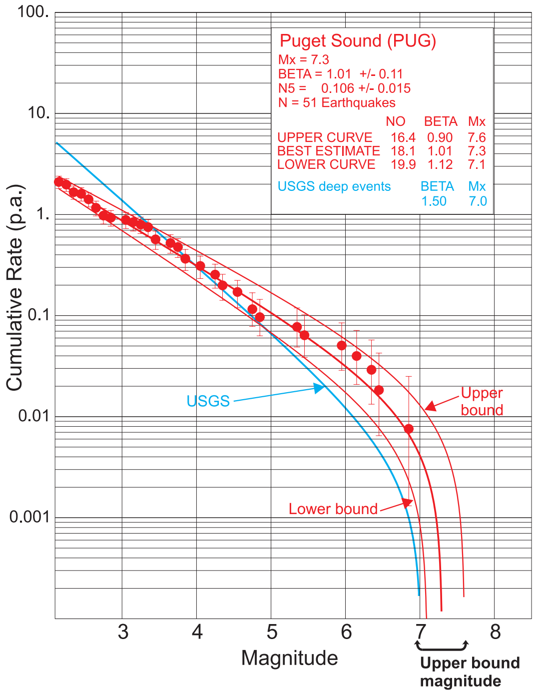

**FIGURE 5: Magnitude-recurrence curve for PUG (like Figure 4), showing the upper and lower uncertainty bounds and range of upper bound magnitudes. For comparison, the curve used for the USGS calculations is shown in blue.**

---

## What are the crustal/mantle properties (e.g. Q, velocity layering, dipping layers) that affect the radiated energy between the source and the site where hazard is needed?

A reliable interpretation of crustal and mantle properties is needed to assess and adjust the strong ground motion relations and to perform forward modeling to determine the consequences of scenario earthquakes. For example, if crustal conditions differ significantly from Mexico, a source of much in-slab earthquake data, how do we adjust strong ground motion parameters derived from a worldwide dataset?

## What earthquake scenario should be adopted for Vancouver and Victoria? How can the use of empirical Green's functions improve hazard estimates?

Deaggregations like Figure 1 indicate the magnitude and distance of the earthquakes contributing to the seismic hazard and are the starting point for design earthquake scenarios. Use of empirical Green's functions can improve hazard estimates (by effectively accounting for all path complexity), but still require much knowledge about the seismic source so that the source scaling can be done appropriately. Hence, future improvements will depend critically on our ability to understand what will happen during the larger earthquakes, and our best insight to that will come from analysis of the past large Puget Sound earthquakes.

## Conclusions

Different assumptions were adopted by the USGS in 1997 and the GSC in 1994–1999 and resulted in different estimates of seismic hazard for the U.S. and Canadian territory overlying these in-slab earthquakes. Reconciling these estimates and refining them towards the true hazard will involve better answers to the questions raised above.

## References

Adams, J., D.H. Weichert, and S. Halchuk, *Trial seismic hazard maps of Canada 1999: 2%/50 year values for selected Canadian cities, Geological Survey of Canada Open File 3724*, 107 pp., Geological Survey of Canada, 1999a.

Adams, J., D.H. Weichert, and S. Halchuk, Lowering the probability level—fourth generation seismic hazard results for Canada at the 2% in 50 year probability level, in *Proceedings 8th Canadian Conference on Earthquake Engineering, Vancouver 13–16th June*

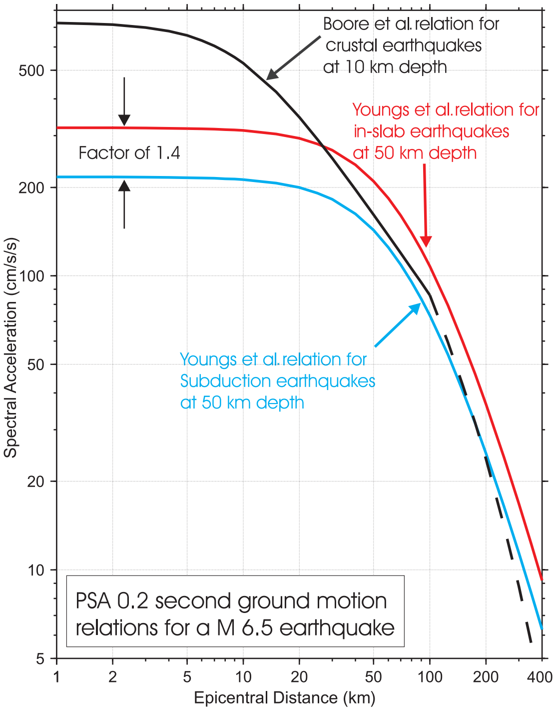

**FIGURE 6: A comparison of expected ground motions from adjacent interface and in-slab earthquakes, to those from similar-sized crustal earthquakes (black).**

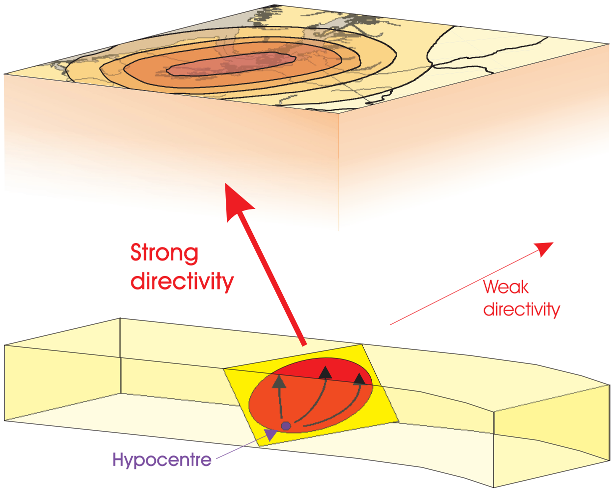

**FIGURE 7: Ground motions above a typical in-slab normal faulting earthquake may depend critically on the rupture plane location, rupture plane dip direction and the asymmetry of the rupture relative to the hypocenter, all contributing to directivity effects.**

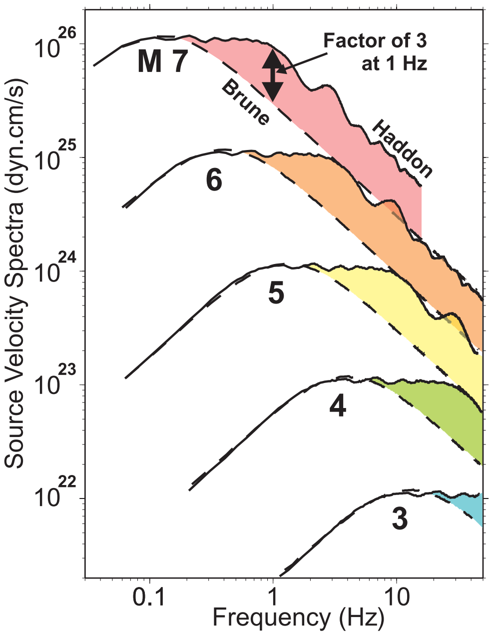

**FIGURE 8: According to Haddon, the velocity spectra of typical eastern earthquake sources are flat for about one decade of frequency above their lower corner, and their high frequency (f>1 Hz) levels exceed those associated with the corresponding Brune model event by a factor of three, approaching the shaking of a Brune event one magnitude larger (redrawn from *Haddon,* [1996]).**

*1999,* pp. 83–88, 1999b.

Adams, J., S. Halchuk, and D.H. Weichert, Lower probability hazard, better performance? Understanding the shape of the hazard curves from Canada's Fourth Generation seismic hazard results, *Paper 1555, 12th World Conference on Earthquake Engineering, Auckland, 30th January–4th February 2000*, 8 pp., 2000.

Boore, D.M., W.B. Joyner, and T.E. Fumal, Equations for estimating horizontal response spectra and peak acceleration from western North America earthquakes: a summary of recent work, *Seism. Res. Lett., 68,* 128–153, 1997.

Haddon, R.A.W., Earthquake source spectra for Eastern North America, *Bull. Seism. Soc. Amer., 86,* 1300–1313, 1996.

Okal, E., and S. Kirby, Energy-to-moment ratios for damaging intraslab earthquakes: preliminary results on a few case studies, this volume, 2002.

Youngs, R.R., S.-J. Chiou, W.J. Silva, and J.R. Humphrey, Strong ground motion relationships for subduction zone earthquakes, *Seism. Res. Lett., 68*, 58–73, 1997.