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3D GROUND MOTION IN THE GEORGIA BASIN REGION OF SW BRITISH COLUMBIA FOR PACIFIC NORTHWEST SCENARIO EARTHQUAKES

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ABSTRACT

Long-period (> 2 s) ground motions in the Georgia basin region of SW British Columbia (BC) are investigated for Pacific Northwest scenario earthquakes using 3D finite-difference simulations of viscoelastic wave propagation. The simulations are validated by comparing synthetic surface waveforms with 36 selected strong- and weak-motion recordings of the 2001 M_W 6.8 Nisqually earthquake at sites spanning from Puget Sound, Washington, to southern BC. This is the first opportunity to validate the 3D geologic model of the Georgia basin region, such that the upper 1 km structure and the degree of anelastic attenuation are currently under development. Deep in-slab Juan de Fuca plate scenario earthquakes are investigated by initiating the Nisqually-model source in four different locations beneath Georgia basin in a NW-SE trending sense congruent with observed seismicity. For all deep in-slab earthquake simulations, the largest ground motions occur NW of the source location, dramatically altering the amplitude and pattern of the simulated ground motion with source location. In all cases, ground motion is predominantly amplified in the NW part of the Georgia basin as well as along a NE-SW trending velocity contrast that runs beneath the city of Vancouver. In Vancouver, the largest simulated ground motions (9.6 cm/s) from "Nisqually-type" deep in-slab earthquakes occurs when the source is located towards the southeast. Shallow crustal North America plate scenario earthquakes are being explored using slip distribution solutions from large shallow earthquakes elsewhere in the world.

Introduction

Earthquake waves can be altered by 3D basin structure due to S-wave focusing at basin edges and the generation of surface waves. Finite-difference modelling of ground motion from earthquake waves has been applied to many basins worldwide: the Seattle basin in Washington (WA) (Frankel et al. 2007), the Kanto basin in Japan (Sato et al. 1999), and the Wellington basin in New Zealand (Benites and Olsen, 2005). Basin-edge and 3D basin structure effects are path dependent phenomena, depending on both the direction of incoming seismic energy and the nature of the structure, predominantly steepness, at the edge of the basin. Thus, the seismic source coupled with the 3D basin structure will determine the simulated ground motion results.

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The Georgia basin is a NW oriented Cretaceous structural and topographic depression encompassing Georgia Strait, eastern Vancouver Island, the Fraser River lowlands, and the NW mainland of WA. The basin is one of several located along the Cascadia forearc; to the south are the smaller Everett and Seattle basins in Puget Sound, WA. The 3D structure of the Georgia basin is constrained by two major tectono-stratigraphic clastic sedimentary packages: western outcropping Upper Cretaceous Nanaimo Group marine rocks, and eastern outcropping Tertiary Huntingdon formation non-marine rocks (Groulx and Mustard, 2004; Monger, 1990). More than 2 million people and critical infrastructure (ocean ports, international airport, ferry terminals, etc.) are situated in the Georgia basin region.

The Georgia basin region is subject to three types of earthquakes: shallow (5 and 15 km) North America (NA) plate earthquakes, deep (40 to 70 km) Juan de Fuca (JdF) plate events, and large Cascadia subduction zone earthquakes that rupture along the thrust fault between the two plates. Olsen et al. (2008) simulated the Cascadia megathrust (M_W 9.0) event and determined a maximum peak ground velocity of 10 cm/s in Vancouver. In this paper, long-period (> 2 s) ground motions in the Georgia basin region of SW British Columbia (BC) are investigated for the first two types of Pacific Northwest scenario earthquakes using 3D finite-difference simulations of viscoelastic wave propagation.

Numerical Modelling Parameters

Surface velocity values are simulated using a fourth-order staggered-grid finite-difference code (Olsen-AWM) run on the parallel supercomputer at the University of Victoria, which uses 64 processors communicating via the message-passing interface. The elastic models used in this paper includes different sized 3D models of the Pacific Northwest Community Velocity Model (CVM, version 1.3) that characterizes six geologic units by compressional-wave and shear-wave velocities (V_P and V_S, respectively) and density (Stephenson, 2007) set with a minimum V_S of 625 m/s (Olsen et al. 2008). Viscoelastic ground motion is calculated using anelastic attenuation (Q_P and Q_S) relations of Olsen et al. (2003). The largest model spans from northern WA to southern BC (Fig. 1) encompassing an area of 337.5 km (NS) by 200 km (EW) by 55 km (vertical) and is discretized with a uniform 250 m grid spacing resulting in 237.6 million grid points. The maximum resolvable frequency is 0.5 Hz (2 s) equivalent to 5 nodes per minimum shear wavelength of 1250 m. Due to computational constraints, the model does not include surface topography or the surficial low-velocity (< 350 m/s) Holocene Fraser River delta sediments, the latter of which are known to reach up to 300 m thickness and cause significant earthquake amplification at 1.5 to 4 Hz (Cassidy and Rogers, 1999). The surface velocities of the models used in this paper represent over-consolidated Pleistocene glacial sediments, such that actual shaking could be greater than the presented simulations. As technology advances and computational constraints decrease, a higher resolution model that includes the Holocene delta sediments should be generated to simulate higher frequency ground motions.

3D Geologic Model

Tomographic V_P models clearly delineate relatively low-velocity (2.5-4.0 km/s) sedimentary rocks of the Georgia basin (Dash et al. 2007; Ramachandran et al. 2006, 2004; Zelt et al. 2001). These are primarily comprised of conglomerate, sandstone, silt-stone, and shale of the Upper Cretaceous Nanaimo Group and overlying Tertiary Huntingdon Formation. The velocity of the base of Georgia basin sedimentary rocks is inferred to be between 5.5 km/s

(Ramachandran et al. 2006, 2004) and 6.0 km/s (Zelt et al. 2001). However, Stephenson (2007) uses the 4.5 km/s contour of Ramachandran et al. (2006) as the base of Tertiary sediments in northern WA and imposes a constant V_P/V_S conversion factor of 2 on the Tertiary subunit. The 3D model shown in Fig. 1 presents the spatial limits of the Seattle and Georgia basins at 750-1000 m depth, defined as the areas within the 4.5 km/s contour line, at the southern and northern extent of the model, respectively. The imposed rapid decrease in V_S will cause amplification wherever V_P is $\leq$ 4.5 km/s in the model (i.e. within the sedimentary basins). A linear NE-SW velocity contrast (0.5-1.0 km/s) that spans the width of the Georgia basin is present in the 3D model between 250 to 1000 m depth towards the NW end of the basin (Fig. 1). This feature separates lower velocities in the NW (3-3.5 km/s) from higher velocities in the SE (3.5-4.5 km/s) at the same depth, such that greater amplification will occur in the NW end of the Georgia basin.

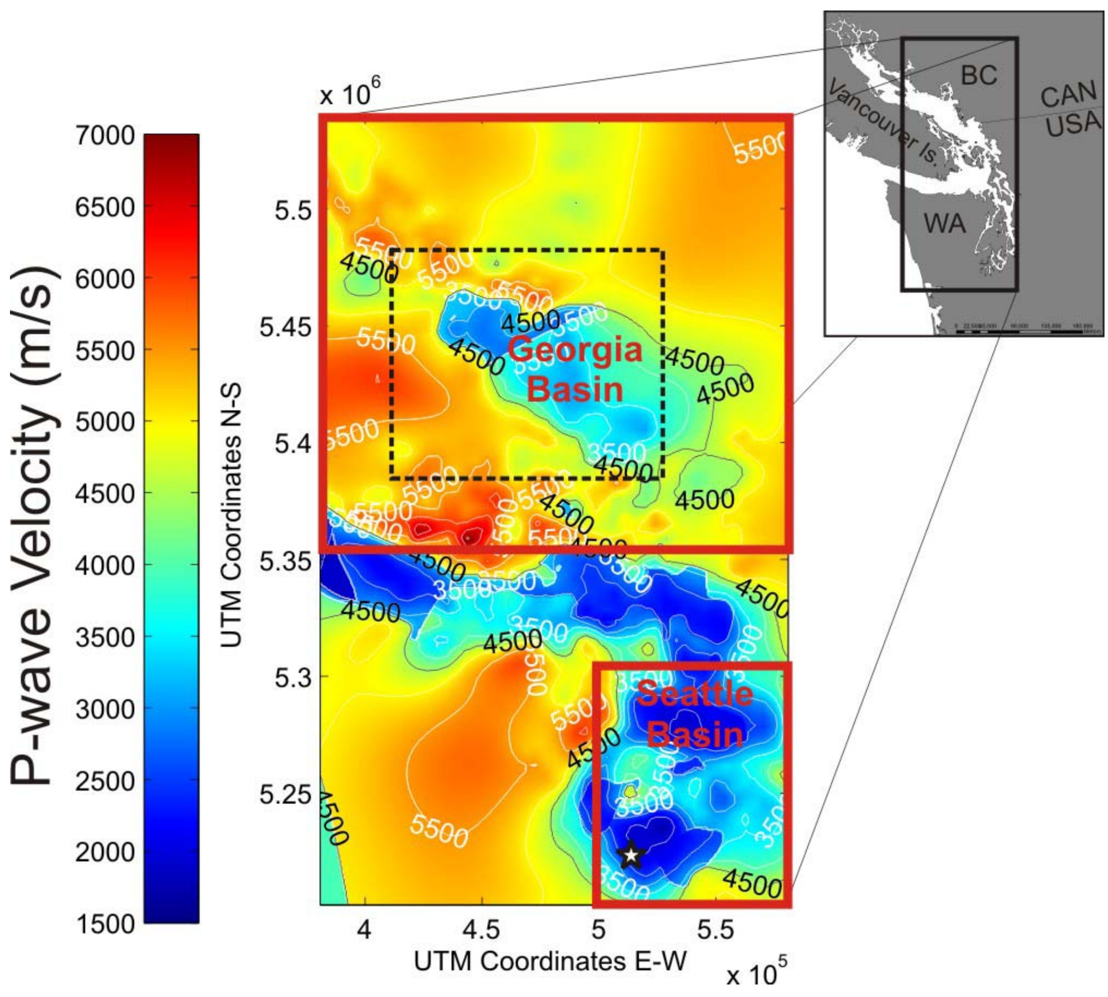

Figure 1. Pacific Northwest Community Velocity (V_P) Model at 750-1000 m depth between northern WA and southern BC (contour intervals are 500 m/s). Limit of Tertiary sedimentary basins inferred as 4500 m/s velocity contour (black line). White star denotes epicentre of M_W 6.8 Nisqually earthquake. Red boxes represent the spatial limits of the Nisqually earthquake simulation maps shown in Fig. 2. Black dashed box shows the spatial limit of the "Nisqually-type" earthquake simulation maps shown in Fig. 3.

Model Validation

The 2001 M_W 6.8 Nisqually earthquake was the largest earthquake to strike the Pacific Northwest in over 50 years, and has not been surpassed in the nearly 10 years since. Similar to large magnitude events in 1965 (M_W 6.5) and 1949 (M_W 7.1), the Nisqually earthquake was a normal-faulting event at 52 km depth within the subducting JdF plate. Similar agreement between synthetic and observed waveforms in northern Washington was achieved using either the Frankel et al. (2007) or Pitarka et al. (2004) Nisqually source functions (Molnar et al. 2008). In this paper, the Nisqually earthquake is simulated by initiating the Pitarka et al. (2004) moment-tensor rate function, equivalent to a M_W 6.8 event, at the epicentral location of the earthquake and at 47.5 km depth within the model.

The results presented here from a 130 s simulation of the M_W 6.8 Nisqually earthquake are the first opportunity to validate the 3D model in the Georgia basin region. As the model cannot resolve frequencies higher than 0.5 Hz, only agreement in the arrival time and in the amplitude of the initial S-waves and basin surface waves with Nisqually earthquake recordings are appropriate for validation. Fig. 2 presents resulting peak ground velocity maps in the Georgia basin and Seattle basin regions for the EW direction of motion. Ground motion is amplified within the basins, and along their edges (i.e. yellow to red areas are within the $V_P < 4.5$ km/s regions of the model at 750-1000 m depth). In the Georgia basin, ground motion is also amplified along the linear NE-SW velocity feature near the NW end of the basin. The same pattern of amplified ground motion in the Georgia basin is observed for motion in the NS direction but with reduced amplitude due to the Nisqually earthquake source character (Molnar et al. 2008).

Overall, synthetic waveforms from the 3D simulation (Fig. 2) show reasonable agreement with observed Nisqually earthquake recordings at 36 select strong- and weak-motion instrument sites between northern WA and southern BC. The best agreement occurs at the northern WA strong-motion sites. As noted by Frankel et al. (2009) for the Seattle basin, more complex longer duration waveforms are observed within the basin, with large phases following the S-waves, whereas waveforms outside the basin have simpler shorter duration S-waves. This is true of the waveforms examined in the Georgia basin region as well. The results presented here for the northern WA sites agree with other 3D finite-difference simulations of the Nisqually earthquake for the Seattle basin region by Frankel et al. (2009, 0.4 Hz maximum) and Pitarka et al. (2004, 0.5 Hz maximum).

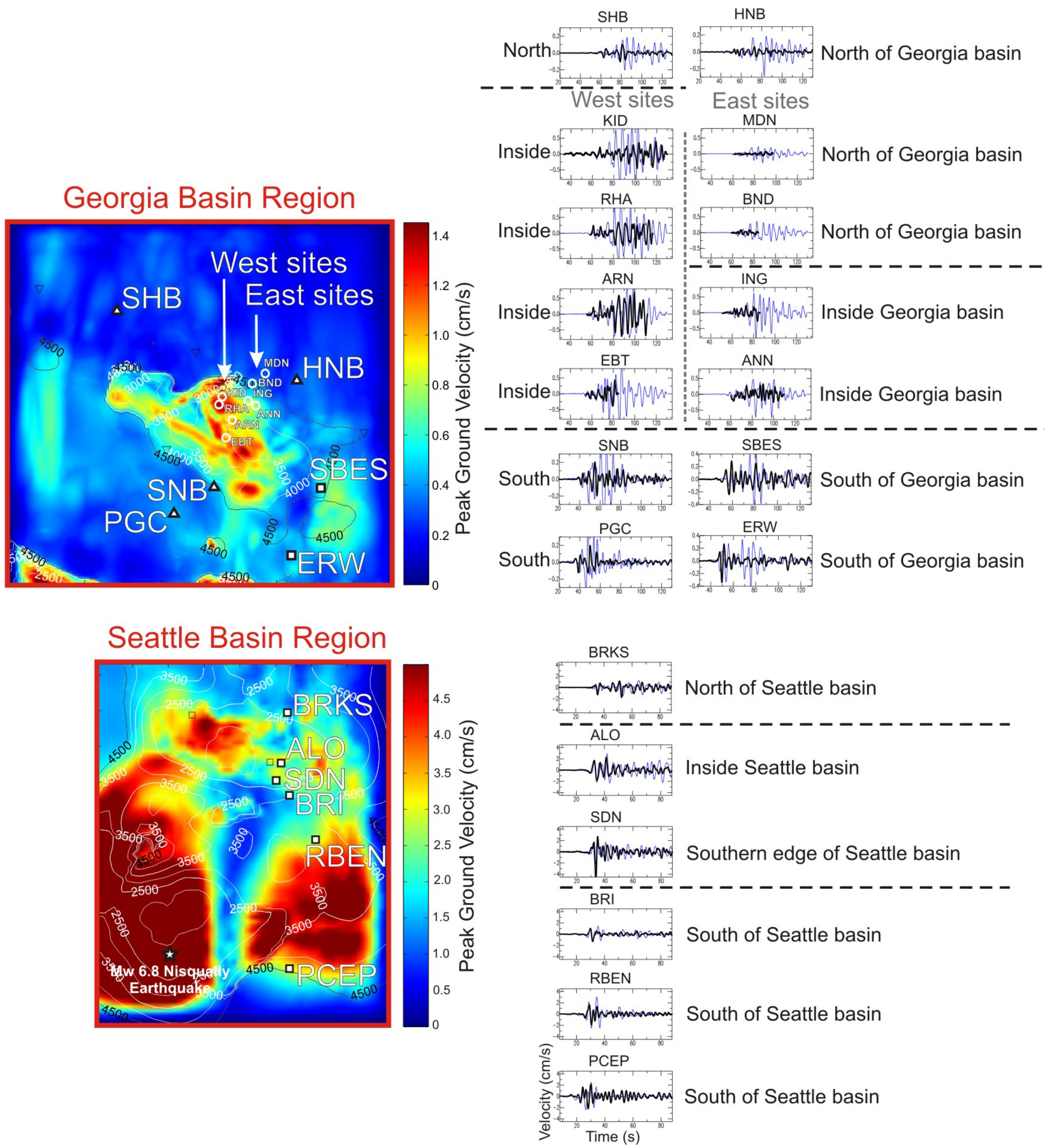

Figure 2. Peak ground velocity maps of the Georgia basin (max. 1.5 cm/s) and Seattle basin (max. 5 cm/s) regions from simulation of the M_W 6.8 Nisqually earthquake overlaid with V_P contours of the 3D model at 750-1000 m depth as in Fig. 1. Synthetic waveforms (blue) are compared with 20 observed Nisqually earthquake recordings (black) at strong-motion instrument sites in WA (squares) and BC (circles), and weak-motion instrument sites in BC (triangles). Only results for the EW direction of motion are shown. Sites labelled in/outside the Seattle basin as in Pitarka et al. (2004). Sites labelled in/outside the Georgia basin based on shown 4500 m/s contour.

Deep JdF Plate Earthquake Scenarios

In-slab JdF plate earthquakes occur in a NW-SE sense beneath Georgia basin at 40 to 70 km depth. To investigate the scenario of a “Nisqually-type” earthquake occurring beneath Georgia basin, the Nisqually source is initiated at four locations within the model at 47.5 km depth beneath the basin in a NW-SE trending sense congruent with the observed seismicity. A smaller sized model, centred on the Georgia basin (116 km EW and 99.5 km NS), is used for 70 s simulations of deep in-slab earthquakes. Fig. 3 shows that the largest simulated ground motions always occur NW of the source location due to the Nisqually source character (Fig. 2), causing a significant difference in the amplitude and pattern of the resulting ground motion with source location. However, ground motion is always predominantly amplified in the NW part of the Georgia basin, and along the NE-SW velocity contrast, regardless of source location. The maximum ground velocity occurs in the EW direction of motion; the same amplification patterns are observed for the NS direction of motion but with reduced amplitude.

The city of Vancouver is located at the NE limit of the linear NE-SW velocity contrast (Fig. 3), resulting in amplified ground motions from S-wave focusing. The most hazardous scenario to Vancouver from a “Nisqually-type” earthquake occurs when the source is located SE of the city (location #4 in Fig. 3). The maximum peak horizontal velocity reaches 9.6 cm/s in Vancouver, or Modified Mercalli Intensity (MMI) VI (perceived strong shaking, light damage). Again, these are not true estimates of surficial ground motion as the Holocene Fraser River delta sediments are not included in the 3D model ($V_S < 625$ m/s) and frequencies higher than 0.5 Hz (2 s), or wavelengths shorter than 1250 m, are not resolved. For comparison, the highest 0.5 Hz amplifications from the Nisqually earthquake in Washington occurred at soft soil sites on the southern portion of the Seattle basin with amplification factors of 3.5 to 7.7 (Frankel et al. 2002). At these sites, the peak ground velocity reached just over 4 cm/s (Fig. 2; site SDN), or a MMI V (perceived moderate shaking, very light damage). Ground shaking levels in WA from the Nisqually earthquake are over 40 % less than those predicted in Vancouver for the most hazardous deep in-slab earthquake scenario, yet shaking from the M_W 6.8 Nisqually earthquake still managed to cause ~2 billion US dollars worth of damage in Washington.

Shallow NA Plate Earthquake Scenarios

The most poorly understood earthquakes in the Georgia basin region are the crustal NA plate events. Moderate and smaller events occur predominantly beneath the Strait of Georgia and show no obvious correlation with mapped surface faults, nor with large (M7+) historical crustal earthquakes (1872, 1918, and 1946) that have occurred in WA and on Vancouver Island. Crustal NA plate events occur in a bimodal depth distribution where moderate events in 1975, 1990, 1996 and 1997 have occurred at shallow depths (< 5 km), whereas the smallest events are concentrated at depths of 15-25 km (Mulder, 1995). Crustal NA plate events exhibit a mixture of strike-slip and thrust faulting with a margin parallel (N-NW) maximum compressive stress direction (Ristau et al. 2007). In ongoing work, shallow NA plate scenario earthquakes in the Georgia basin region are being explored by using slip distribution solutions from large shallow earthquakes elsewhere in the world (e.g. the M_W 6.9 Kobe, Japan, strike-slip event and the M_W 6.7 Northridge, California, blind thrust event). Results were not available at the time of writing.

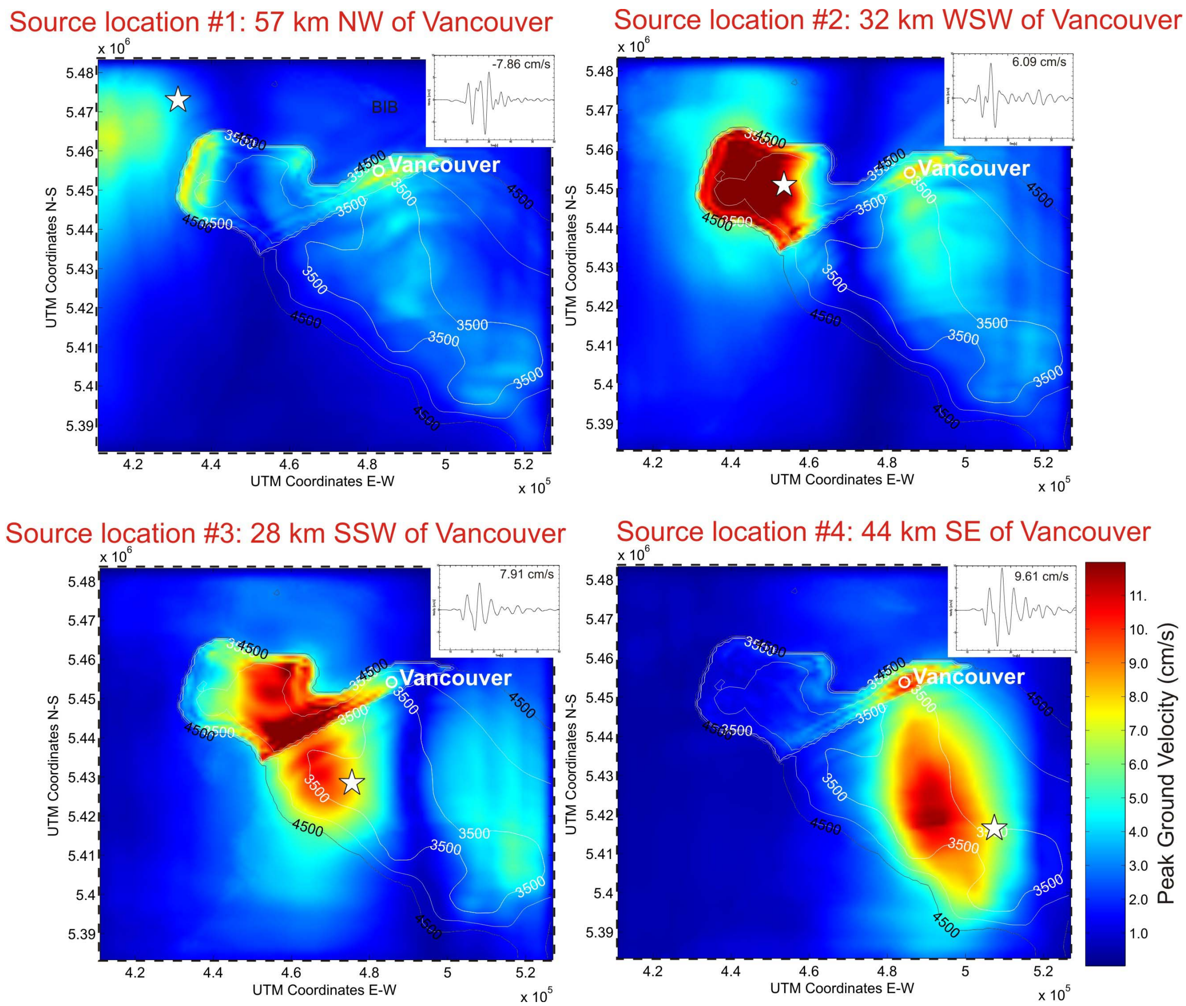

Figure 3. Peak ground velocity (EW motion) maps of the Georgia basin region from simulation of a M_W 6.8 in-slab event at four different positions (white stars) within the 3D model overlaid with velocity contours of the 3D model at 750-1000 m depth as in Fig. 1. Synthetic waveforms in upper right of each map represent simulated ground motion in Vancouver (open white circle). The largest ground motion simulated in Vancouver (9.6 cm/s) occurs when the source is located to the SE (location #4).

Current Velocity Model Development

This paper presents the first examination of 3D finite-difference simulations of long-period (2 s) ground motion in the Georgia basin region from Pacific Northwest scenario earthquakes. The simulation results presented here are the first opportunity to validate the 3D geologic model of the Georgia basin region. In contrast, structural and geophysical detail has been added to the Puget Lowland area of WA in the Pacific Northwest community velocity model (version 1.3) from ~500 simulations of local and regional earthquakes conducted in the development of the Seattle Urban Hazard Maps (Frankel et al. 2007). During construction of the model, Stephenson (2007) either did not have access to, or did not pursue, detailed geologic information in the Georgia basin region. Simulations of earthquake ground motion (Figs. 2 and 3) demonstrate that areas of amplification in the Georgia basin region are strongly dependent on low-velocity ($V_P < 4.5$ km/s) regions in the upper 1 km of the model. To update the upper 1 km structure of the geologic model in the Georgia basin region, local velocity data has been collected and assembled. Resources of velocity information include: higher resolution tomographic inversion results (Dash et al. 2007), marine seismic surveying (Hamilton, 1991), oil well logs (Hannigan et al. 2001; BCMEMPR reports), and inferred velocity structure from seismic reflection data at borehole, seismic cone penetration test, and surface refraction sites on the Fraser River delta (J. Hunter, pers. comm.). Velocity changes to the model will cause the presence or disappearance of particular wave arrivals and alter their timing and amplitude in the synthetic waveforms.

The degree of viscoelasticity or anelastic attenuation affects the amplitude of the synthetic waveforms. The results presented in this paper use the same viscoelastic model as Olsen et al. (2008), which is the elastic (velocity and density) model of Stephenson (2007) with Q relations of Olsen et al. (2003) determined for near-surface sediments in the Los Angeles basin. Frankel et al. (2009, 2007) uses the same elastic model but with higher Q relations determined for the Santa Clara Valley, which provided good agreement with amplitudes of local and regional earthquake recordings at sites in northern WA. The surface sediments of the Georgia basin model represent over-consolidated Pleistocene glacial sediments and should have higher Q values than near-surface sediments of the Los Angeles basin. More appropriate (higher) Q values are being tested in order to reduce ground motion amplitudes in the Georgia basin region in accordance with amplitudes of the 2001 M_W 6.8 Nisqually earthquake.

Conclusions

This paper presents the first 3D simulations of long-period (2 s) viscoelastic ground motion in the Georgia basin region from Pacific Northwest scenario earthquakes. Olsen et al. (2008) simulated the Cascadia megathrust (M_W 9.0) event from northern California to southern BC, in which the long-period (2 s) peak ground velocity reached a maximum of 10 cm/s in Vancouver. However, no validation of the 3D model or the degree of anelastic attenuation in the Georgia basin region was carried out. Recordings of the 2001 M_W 6.8 Nisqually earthquake at 36 selected sites from northern WA to southern BC are used to validate the model in the Georgia basin region. The best agreement is found for strong-motion sites in northern WA where detailed structure has been added to the model from previous studies (Frankel et al. 2007). Current work to improve the fit of synthetic waveforms with the M_W 6.8 Nisqually recordings in the Georgia basin region (southern BC) includes: (1) updating the upper 1 km velocity structure of the model with more detailed local information, and (2) adjusting the degree of anelastic attenuation to more regionally appropriate values.

Shallow crustal North America plate events are being explored by using slip distribution solutions from large shallow earthquakes elsewhere in the world. Deep in-slab Juan de Fuca plate events are simulated using the Nisqually earthquake source at four different locations beneath the Georgia basin. Ground motions are predominantly amplified within the NW part of the Georgia basin, as well as along a NE-SW velocity contrast that runs beneath Vancouver. The largest ground motions in Vancouver (9.6 cm/s) from a deep in-slab event occurs when the source is located SE of the city.

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