Development of a 3D Shear Wave Velocity Model for Metro Vancouver Considering Geological Heterogeneity and Spatial Correlation

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ABSTRACT

Shear wave velocity (V_S) is a critical soil property in seismic microzonation, reflecting soil stiffness and influencing seismic wave propagation and ground shaking. Soil properties typically exhibit spatial correlation, where values at nearby locations are more similar than those farther apart, supporting V_S prediction at unmeasured locations. However, stratigraphic heterogeneity introduces non-stationarity, weakening spatial correlation and increasing spatial variability. Addressing this requires detailed knowledge of stratigraphic architecture and geotechnical properties. In Metro Vancouver, sequences of Quaternary post-glacial, inter-glacial and glacial depositions result in a complex stratigraphy that is simplified and grouped into four main geological units: Holocene post-glacial sediments (PG), Pleistocene and older interglacial/glacial sediments (G), Tertiary sedimentary rocks, and Pre-Tertiary Coast Mountain plutonic rocks. A three-dimensional (3D) geological model was developed using a comprehensive regional geodatabase that was developed over 6 years from a wide range of geodatasets to produce PG and G thickness maps. Passive-source seismic testing, including ambient vibration array (AVA) and microtremor horizontal-to-vertical spectral ratio (MHVSR) methods, was instrumental in delineating glacial and bedrock sub-topography. Spatial prediction of V_S within the 3D geological model is accomplished to generate a 3D Vs model. Depth-related V_S trends were removed to counter overburden stress effects. The normalized V_S values were analyzed to study spatial variability within each geological unit. Using geostatistical modeling, V_S values were predicted in 3D, addressing geological heterogeneity and preserving spatial correlation. The resulting detailed 3D V_S model provides a robust foundation for seismic microzonation in Metro Vancouver.

RÉSUMÉ

La vitesse des ondes de cisaillement (V_S) est une propriété critique du sol dans la microzonation sismique. Les propriétés du sol présentent généralement une corrélation spatiale, les valeurs à proximité étant plus similaires que celles à distance, ce qui appuie la prédiction de la V_S à des emplacements non mesurés. Cependant, l'hétérogénéité stratigraphique introduit une non-stationnarité, affaiblissant la corrélation spatiale et augmentant la variabilité spatiale. La prise en compte de ce phénomène nécessite une connaissance approfondie de l'architecture stratigraphique et des propriétés géotechniques. Dans la région métropolitaine de Vancouver, les séquences de dépôts postglaciaires, interglaciaires et glaciaires du Quaternaire donnent lieu à une stratigraphie complexe, qui a été simplifiée et regroupée en quatre grandes unités géologiques : les sédiments postglaciaires de l'Holocène (PG), les sédiments interglaciaires/glaciaires du Pléistocène et plus anciens (G), les roches sédimentaires du Tertiaire, et les roches plutoniques pré tertiaires de la chaîne Côtière. Un modèle géologique tridimensionnel (3D) a été développé à l'aide d'une base de données géographique régionale complète qui a été développée sur 6 ans à partir d'un large éventail d'ensembles de données pour produire des cartes d'épaisseur PG et G. Des essais sismiques passifs, incluant les méthodes par réseau de vibrations ambiantes (AVA) et le rapport spectral horizontal/vertical des microtremor (MHVSR), ont permis de délimiter la sous-topographie glaciaire et celle du substratum rocheux. La prédiction spatiale de la VS dans le modèle géologique 3D a permis de générer un modèle 3D de V_S. Les tendances de V_S en fonction de la profondeur ont été supprimées afin de corriger les effets liés à la contrainte de recouvrement. Les valeurs normalisées de V_S ont été analysées pour étudier la variabilité spatiale au sein de chaque unité géologique. Grâce à la modélisation géostatistique, les valeurs de V_S ont été prédites en 3D, en tenant compte de l'hétérogénéité géologique et en préservant la corrélation spatiale. Le modèle détaillé de V_S en 3D qui en résulte constitue une base solide pour la microzonation sismique dans le Grand Vancouver.
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1 INTRODUCTION

Local soil conditions significantly influence the amplitude and frequency content of seismic waves, a phenomenon known as the *site effect*. This effect plays a critical role in seismic hazard assessment and microzonation, as it governs the intensity and distribution of ground motion during earthquakes. Site effects depend on both geotechnical properties (e.g., shear wave velocity, shear modulus, damping ratio) and geometrical features (e.g., stratigraphy, basin geometry, soil thickness).

Three-dimensional (3D) geological models offer a powerful framework to define these geometrical properties and support spatial prediction of geotechnical parameters, particularly shear wave velocity (Adhikari & Molnar 2024; Salsabili et al. 2023). These models form the basis for estimating key seismic site parameters, including the average Vs in the top 30 m ($V_{S,30}$), the average Vs of the entire deposit, and the fundamental site period or frequency ($T_0 = 1/f_0$). In Canada, 3D geological and seismic wave propagation models have been applied in various contexts: for example, Molnar et al. (2014) used a 3D seismic model in western Canada to generate 3D synthetic ground motions at long spectral periods; Carter et al. (2019) developed a 3D Paleozoic bedrock model for southern Ontario.

While 3D modeling is well-established in mining and petroleum geological applications (Pyrcz and Deutsch 2014), its integration into high-resolution near-surface 3D *Vs* models referred to as a “geotechnical layer” *Vs* model remains limited. In Eastern Canada, Vs models have been developed using depth-based predictive functions, including layered and composite approaches for Montreal and typical profiles for post-glacial and glacial units in the Ottawa and St. Lawrence Valleys (Rosset et al. 2014, Nastev et al. 2016). These studies focused only on statistical uncertainty of V_S, while ignoring spatial heterogeneity and variability. Salsabili et al. (2023) introduced a methodology in the Saguenay region to incorporate both geological and V_S uncertainties, yet not fully address the 3D spatial variability of V_S values.

To fill this gap, a new 3D Vs modelling methodology was developed for the Metro Vancouver region, characterized by complex Quaternary stratigraphy. The subsurface is simplified into four major geological units: Holocene post-glacial sediments (PG), Pleistocene and older interglacial/glacial sediments (G), Tertiary sedimentary rocks, and Pre-Tertiary plutonic rocks. Thickness maps for each unit were produced using a comprehensive geodatabase built over a 6-year period by the Metro Vancouver seismic microzonation mapping project (MVSMMP) (Molnar et al., 2020; www.metrovanmicromap.ca) to build the geological model.

To spatially estimate V_S, depth-related trends were removed to address the effect of overburden stress, and residual V_S values were analyzed to explore intra-unit spatial variability. Using geostatistical techniques (Leapfrog Geo software), V_S was estimated in 3D, maintaining geological consistency and spatial correlation. The resulting 3D V_S model offers a basis for site response analysis and seismic microzonation in the Metro Vancouver area. The 3D model presented in this paper uses the same geodata sets and *Vs* database and block volume definition of the main geologic units using Leapfrog Geo as that of the earlier 3D seismic geology model developed by Adhikari and Molnar (2024). The 3D *Vs* model of this paper supersedes the 3D Vs model of Adhikari and Molnar (2024).

2 STUDY AREA

Metro Vancouver is situated at the northeastern limit of the Cascadia Subduction Zone, underlain by complex geological formations that strongly influence seismic site response. The region includes the Georgia Basin, a fore-arc basin developed within the basement rock assemblages of the Wrangellia Terrane, the Coast Plutonic Complex, and the Cascade Fold Belt (Armstrong 1990). The subsurface comprises four major geological units identified by seismic impedance contrasts: late Pleistocene to early Holocene post-glacial sediments (including Fraser River delta and Capilano sediments), Pleistocene interglacial and glacial deposits (notably Vashon drift and Quadra sands in western Metro Vancouver), Tertiary sedimentary rocks of the Georgia basin (e.g., sandstone and shale), and Pre-Tertiary granitic intrusions of the Coast Mountains (Armstrong 1990). These materials are distributed across diverse physiographic settings—lowlands, uplands, and the Coast Mountain foothills—resulting in substantial spatial variability in sediment thickness, stratigraphy, and material properties. Holocene deposits can reach up to 300 m thickness in the Fraser delta, with Pleistocene sediments below reaching up to 500 m (Britton et al. 1995). As in, Tertiary sedimentary rock is present at ~800 m depth below the southern Fraser River delta.

Shear wave velocity (V_S) values vary widely across the region. Soft Holocene and Fraser River sediments typically exhibit Vs values between 75–270 m/s over the upper 100 m (Assaf 2022, Assaf et al. 2023), while Pleistocene deposits of the Vancouver and Burnaby uplands range from 480–800 m/s over the top 50 m (Assaf 2022) Click or tap here to enter text.. Tertiary sedimentary rocks are ~1000 m/s on average at shallow depths in Vancouver and at deep depths beneath the Fraser River delta (Assaf 2022), and Pre-Tertiary plutonic rocks are ~1350 m/s on average in the upper 10’s of meters (Assaf 2022)Click or tap here to enter text.. These lithologic contrasts produce major impedance boundaries of 1.5 between Holocene and Pleistocene units, and up to 3 between Pleistocene sediments and Tertiary bedrock (Hunter et al. 2016). The depth to these interfaces’ controls site resonance, particularly in the Fraser River delta, where their influence on earthquake ground motion has been documented Finn et al. 2003, Onur et al. 2004, Assaf et al. 2023).

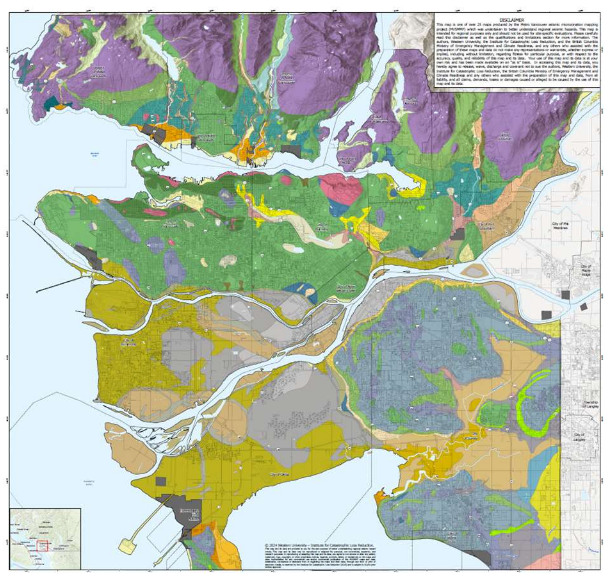

Figure 1. Quaternary and bedrock geological map of Metro Vancouver: Holocene post-glacial sediments (Fraser River lowlands) in yellow and grey shades; Pleistocene glacial/interglacial sediments (Vashon uplands and Capilano) in green and grey-blue; Tertiary Georgia Basin sedimentary rocks in pink; and Pre-Tertiary Coast Mountain plutonic rocks (North Shore) in purple; see

MVSMMP Map01 (Adhikari et al., 2024) for detailed legend.

3 DATABASE PREPARATION & ANALYSIS

A comprehensive Vs database was developed as part of the MVSMMP, combining geological, geophysical, and geotechnical data from ~15,000 locations (Molnar et al. 2020, Molnar et al. 2023). To date, 29 seismic microzonation maps and a CPT sub-database of the MVSMMP are published online with the full geodatabase to be published in future here: https://borealisdata.ca/dataverse/MVSMMP. The database includes 688 Vs depth profiles obtained through: (1) existing public and private subsurface datasets, notably over 500 profiles from Hunter et al. (2016), and (2) multi-method non-invasive seismic field testing (e.g., MASW, AVA, MHVSR) at over 120 sites, with joint inversion of Rayleigh wave dispersion and H/V peak frequencies (f_{0HV}, f_{1HV}). Additionally, 2,375 MHVSR spectra were acquired to characterize site amplification and resonant frequencies across the region (Assaf et al. 2022, Molnar et al. 2023).

3.1 Vs Database

Table 1 highlights total data samples, velocity range, and length of Vs measurements after processing and primary corrections (i.e., removing duplicate tests and outliers). Invasive methods, including SCPTs (Seismic Cone Penetration Tests), downhole and cross hole Vs profiling, provide high-resolution Vs data but are limited to short sampling intervals (typically ~1 m). Non-invasive methods, such as ambient vibration array (AVA), refraction surveys, and Spectral Analysis of Surface Waves (SASW) tests, yield the largest total survey length (e.g., 29,124 m for arrays), making them suitable for deeper or regional-scale investigations. Due to lower sampling density and differences in measurement length, non-invasive methods require resampling to ensure consistency in number of samples and length.

Table 1. Summary of Vs Database

Field Method	Count of Profiles	Count of V_S samples	Average of V_S (m/s)	Sum of Length of samples (m)	Average of Length of samples (m)
SCPT	193	5780	192	6091	1
Cross Hole	3	218	264	283	1
Downhole	95	4503	361	5307	1
Refraction	104	446	240	5420	12
SASW	3	34	242	75	2
MASW & AVA	128	636	559	29124	46

Another source of V_S data particularly for shallow surfaces comes from conversion of ~600 CPT(z) to Vs(z) using the CPT-to-Vs relationship developed for the MV region by Assaf et al. (2023). Due to their short sampling intervals (< 0.5 m), these profiles were resampled at 2-meter intervals for better agreement with other invasive and non-invasive Vs data.

Figure 2 presents the frequency distribution of V_S values binned in 50-m intervals from < 50 to > 1000 m/s. The major geologic unit that corresponds to invasive Vs measurements are known from the invasive method's stratigraphic logging associated in the MVSMMP parent geodatabase. For non-invasive measurements, V_S is used to determine the associated major geologic unit. Post-glacial (PG) sediments correspond to the lowest Vs values and reach up to 400 m/s, Vs of glacial sediments spans from 400–1000 m/s, and Vs of bedrock exceeds 750 m/s. Impedance boundaries are also identified where significant jumps in each V_S profile occurs.

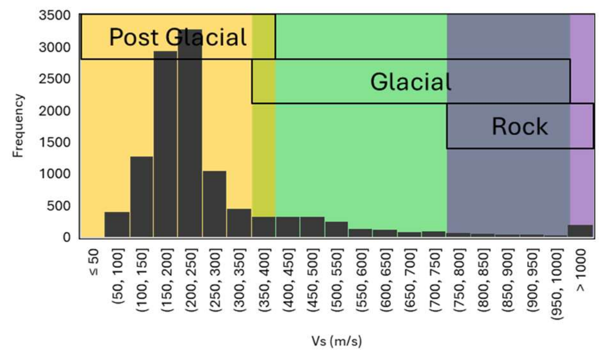

Figure 2. V_S frequency distribution and corresponding major geologic unit Vs ranges.

3.2 Vs Resampling in Post Glacial Sediments

To ensure consistency with invasive data sampled at 1-meter intervals, non-invasive V_S data and converted CPT-to-Vs data were resampled at 2-meter intervals. A power-law curve-fitting method ($Vs = a$ * Depth ^ $b + c$) with a positive intercept (c ≥ 50 m/s) is used to model the V_S – depth relationship for postglacial soils, where velocity increases with depth. This method is suitable in lowland areas with thick PG sediments but would be less applicable in Upland areas with thinner PG layers (< 20 m), where uniform resampling of Vs is used. Out of 128 multi-method Vs and 104 Vs refraction profiles, 76 were resampled using a power-law fitted model based on acceptable R^2 values. When acceptable R^2 values are not obtained, the remaining Vs profiles were resampled in 2-meter uniform intervals.

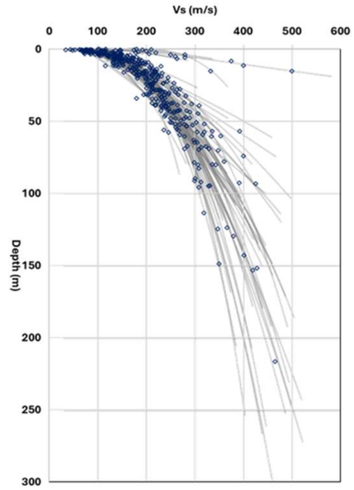

Figure 3. Demonstration of power-law Vs functions (grey lines) fit to each Vs profile's data (blue circles) in PG sediments.

3.3 Statistical Vs Trend Analysis of PG Sediments

After resampling, Figure 4 and Table 2 present summary statistics for the 14,548 postglacial Vs data: 9,358 invasive and 5,190 non-invasive Vs data. V_S values show high variability with a coefficient of variation of 0.34: means of 200 m/s (invasive) and 266 m/s (non-invasive), and standard deviations of 68 m/s and 89 m/s, respectively. This reflects both increasing stiffness with depth due to greater confining stress and heterogeneity in shallow soils, with a positive Vs skewness.

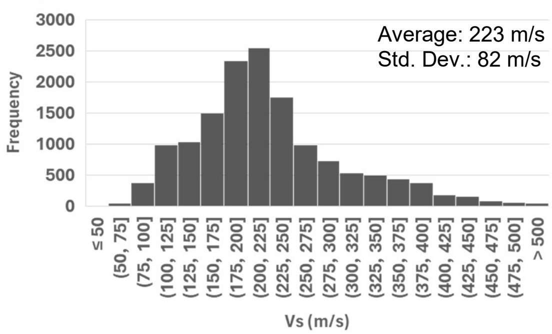

Figure 4. V_S distribution of PG sediments (resampled Vs data).

Table 2. Summary statistics of resampled Vs in PG soils

Field Method	Count of V_S Samples	Average V_S (m/s)	Std. Dev. V_S (m/s)	Min. V_S (m/s)	Max. V_S (m/s)
Invasive	9358	200	68	27	616
Non-invasive	5190	266	89	56	575

Spatial variation in shear wave velocity is typically separated into a deterministic trend, reflecting systematic changes like increasing overburden stress with depth, and a stochastic residual capturing local variability. Once the deterministic trend is removed, the remaining residuals capture small-scale, spatially correlated variability, which is analyzed using a variogram in geostatistical interpolation. In this context, the normalized shear wave velocity (Vs_1) is essential for comparing soil stiffness across sites and depths (Robertson 2009). However, computing Vs_1 requires input parameters such as soil unit weights and groundwater table (GWT) depth. Uncertainties in estimating these parameters can introduce significant variability into Vs_1, especially in shallow profiles, where GWT fluctuations have a greater impact on effective stress. To minimize the propagation of uncertainty into the estimation, we used raw V_S values and applied statistical detrending (Figure 5) to isolate deterministic variability. Figure 5 presents the power-law regression equation, while Figure 6 shows the histogram of the detrended V_S data (residuals) for PG sediments. The residuals closely follow a normal distribution.

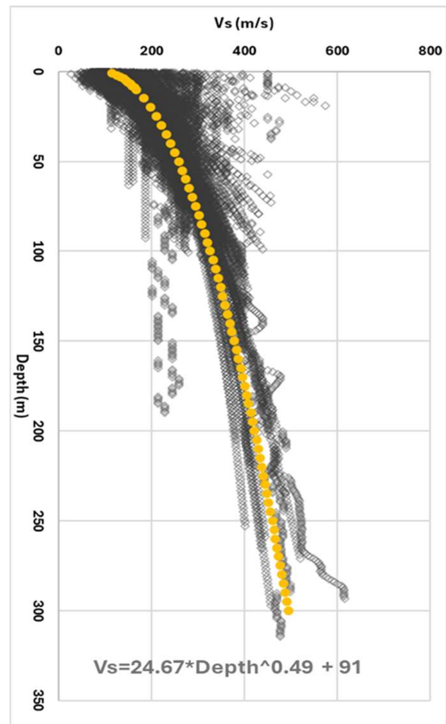

Figure 5. V_S –depth relationship in post-glacial soils and power-law regression equation used for detrending the V_S data.

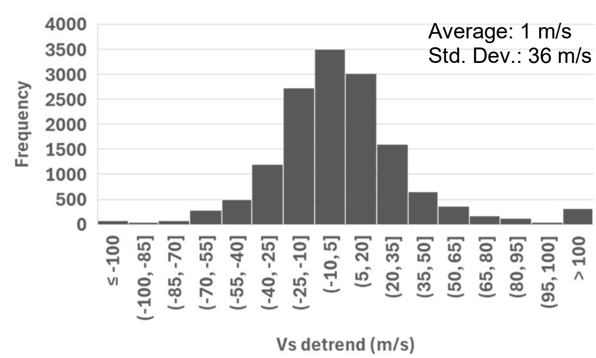

Figure 6. Histogram of detrended V_S data of PG sediments.

4 SPATIAL CORRELATION

Spatial variation refers to the dissimilarity of the pairs of values of a random variable as a function of their distance (Isaaks and Srivastava 1989). Modelling the spatial variation assists in predicting the soil attributes at unsampled locations. After removing the deterministic Vs-z trend from V_S data, if the residuals exhibit stochastic spatial correlation, this spatial structure can be used to enhance the accuracy of *Vs* estimation at unsampled locations by geostatistical methods. An experimental variogram, $\hat{\gamma}(h)$, is used to statistically determine the ratio of the average dissimilarity between data separated by their distance vector *h* (Isaaks and Srivastava 1989) and is assumed as a measure of spatial variability:

$$\hat{\gamma}(h) = \frac{1}{2\,N(h)} \sum_{\alpha=1}^{N(h)} [z(u_\alpha) - z(u_\alpha + h)]^2 \quad [1]$$

where $z(u_\alpha)$ and $N(h)$ are the values of the variable of interest at location u_α and the number of data pairs within distance *h* in the respective direction. Key variogram parameters (nugget, sill, and range) describe the scale and strength of spatial continuity (Isaaks and Srivastava 1989). Table 3 presents the detailed variogram models, including anisotropy directions and two nested structures. Figure 7 shows the fitted variogram along the major axis (22.5°), consisting of a nugget effect and two structures with ranges of R_1 = 830 m and R_2 = 6140 m, capturing both short- and long-range spatial variability.

Table 3. Details of variogram parameters.

Variable	**Structure**	**Model Properties**		
		Model Type	Anisotropy Axis (a_{max}, a_{med}, a_{min})*	Model Parameters
Vs (detrend)	1	Ex.*	(22.5°,112.5°,90°)	Nugget: 80 R_1: (830,380,50) $Sill_1$ *: 456
	2	Sp.*	(22.5°,112.5°,90°)	R_2: (6140,4760,100) $Sill_2$ *: 390

*Partial sill, R: range (meter), Sp.: spherical, Ex.: exponential, a_{max}, a_{med} and a_{min} refer to the azimuths of the three principal axes of the anisotropy.

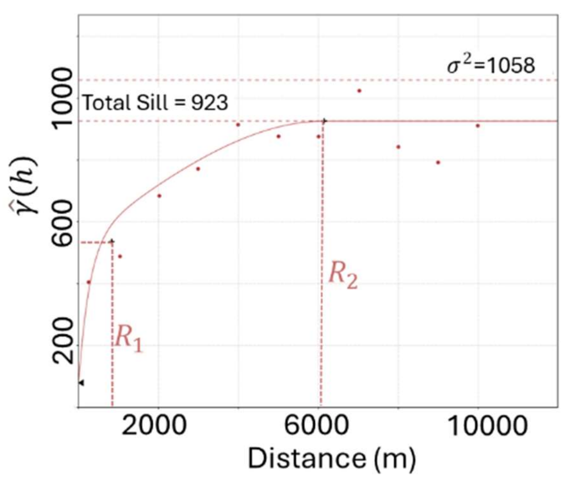

Figure 7. Variogram modeling along the major axis (22.5°) includes a nugget and two nested spherical structures, with R1 and R2 representing their respective ranges.

4 3D V_S MODEL

A full 3D volume is required to determine the V_S of post-glacial and glacial soil deposits. The block model fills this volume, and each block represents the smallest unit of V_S using geostatistical interpolation. For this purpose, the maps of bedrock and till (glacial) sub-topography surfaces are created by combining digital elevation modelling with total post-glacial and glacial sediment thickness or post-glacial thickness maps, respectively (Figure 8 a & b).

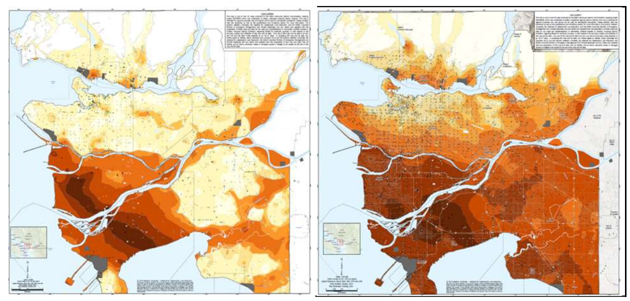

Figure 8. MVSMMP maps of (a) post-glacial thickness (H_{PG}) and (b) total PG & G sediment thickness (H_{soil}). Darker shades indicate greater thickness; see MVSMMP Maps 05 & 06 (Salsabili et al. 2024a, 2024b) for detailed legends.

4.1 Geological model

When the bedrock and till sub-topography maps are created, the space between the top and bottom of each surface is filled with 200 × 200 × 2 m blocks for PG and 200 × 200 × 4m for Glacial layer volumes using Leapfrog Geo which are selected to balance computational efficiency with regional coverage. To improve the resolution in areas with complex surface morphology, particularly, topographic features, sub-blocking was implemented. Each parent block was subdivided into smaller blocks of 50 × 50 × 1 meters which is applicable in the top 5 or 10 m (near sub-topographic surfaces) of the full model.

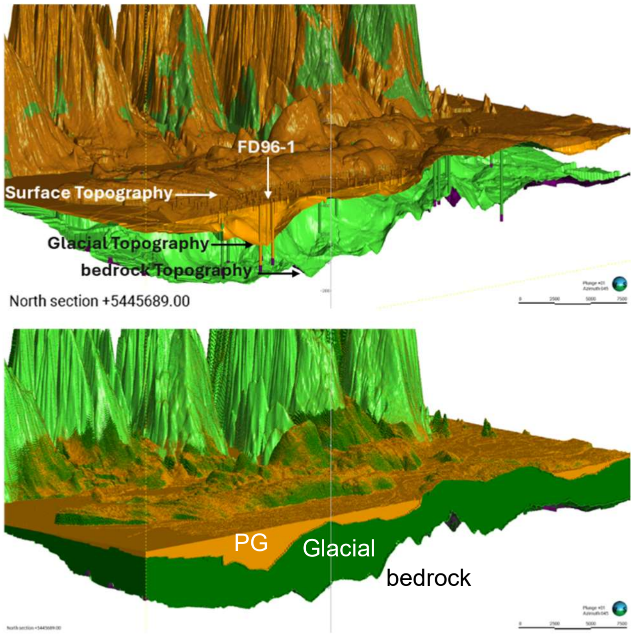

Figure 9. East-West cross section at Geological Survey of Canada downhole FD96-1 of the (a) input sub-topography PG and G surfaces, and (b) 3D geologic block model; vertical exaggeration is 10×.

4.1 Post-Glacial V_S modelling

Spatial correlation in V_S data was identified through geostatistical variographic analysis. Based on the variogram ranges, ordinary kriging, an effective and commonly used method for spatial interpolation across various disciplines, is used to predict detrended Vs values within the defined 3D block model volume (Passeri et al. 2020, Thompson et al. 2007, Goovaerts 1997).

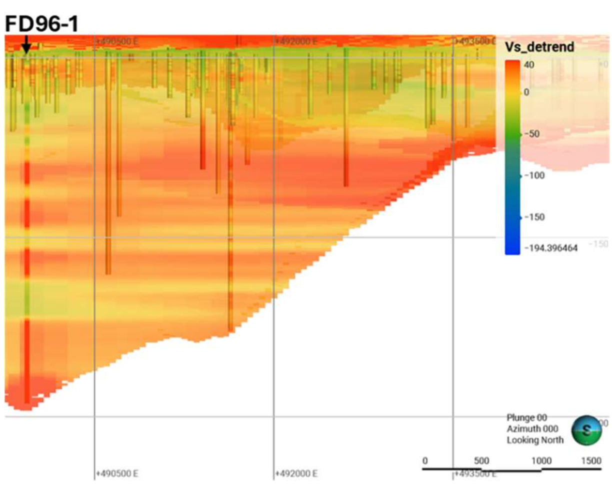

Figure 10. V_S prediction (light shading) of the de-trended Vs data (shown as boreholes) in the PG domain. Same east-west cross section view at GSC downhole FD96-1and 10x vertical exaggeration as Figure 9.

After Vs-z trend removal (Section 3.3), kriging was applied to the residuals (Figure 10), that are then transformed back to the original V_S scale in m/s (see transformed function, power-law equation, at Figure 5). In the post-glacial volume domain, V_S variability was found to be partially location dependent, likely due to depositional heterogeneity and lateral changes of PG sediment types, which may challenge the assumption of second-order stationarity (Isaaks & Srivastava 1989). This is reflected in the variogram, where the sill (965 m^2/s^2) was slightly lower than the total statistical variance (1024 m^2/s^2) as shown in Figure 7, indicating that some spatial variability is not fully captured by the model. To address this and avoid over-smoothing, we restricted the kriging neighborhood to the variogram ranges (~ R_2: 6140 m, 4760 m, 100 m), which is a common strategy for reducing the influence of distant or weakly correlated samples in non-stationary settings (Isaaks and Srivastava 1989)

4.2 Glacial V_S modelling

After detailed geostatistical variogram analysis, *Vs* data within the glacial sediments did not exhibit spatial correlation, due to high heterogeneity, variability in the lumped-together Pleistocene and older glacial and interglacial sediment types, and limited *Vs* data at greater depths, as indicated by a flat experimental variogram. Consequently, inverse distance weighting (IDW) was employed as a deterministic alternative for interpolating *Vs* within the glacial volume domain (Figure 11).

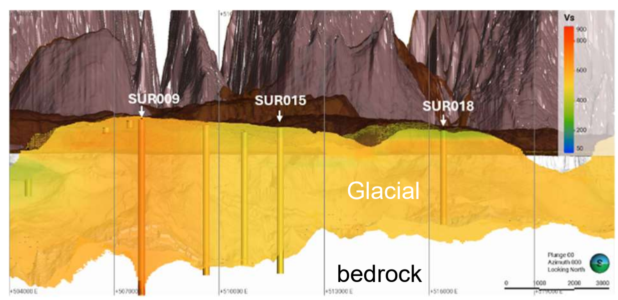

Figure 11. V_S prediction (light shading) of the Vs data (shown as boreholes) in the glacial domain. East-west cross section view at Surrey uplands; vertical exaggeration is 10×.

4.3 3D *Vs* Model of western Metro Vancouver

The 3D V_S model was constructed by integrating the post-glacial (PG) and glacial (G) block models. For sites with rock present at ground surface, Vs_{rock} for crystalline Mesozoic rock sites in the North Shore is set to 1777 m/s and for Georgia basin Tertiary sedimentary rock sites in upland areas is set to 797 m/s. Vs_{rock} at deep depths beneath the Fraser River lowland areas is set to 960 m/s (Assaf 2022). For grid blocks located outside the kriging search radius, V_S values were predicted using deterministic V_S–z profiles applicable to each PG or G geology as determined by Assaf (2022). For detailed calculation procedures, see MVSMMP Map 07 (Salsabili et al. 2024).

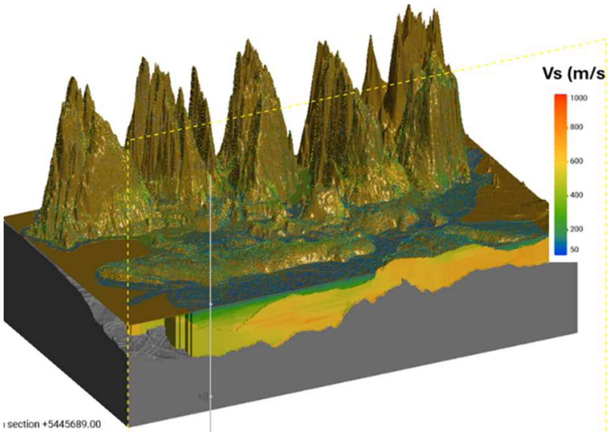

Figure 12. View of the 3D Vs model of western Metro Vancouver within Leapfrog Geo software.

5 CONCLUSION

A high-resolution 3D shear wave velocity model was developed for Metro Vancouver using a comprehensive geodatabase integrating geological, geophysical, and geotechnical data developed for the region over a 6-year timeframe.
Thickness maps of post-glacial (PG) and glacial (G) sediments were used to construct the geological model and define the 3D model's volume domains.

To isolate spatial variability, V_S data in PG soils were detrended to remove depth-related trends caused by overburden stress.

Ordinary kriging was applied to predict Vs of post-glacial (PG) sediments, where spatial correlation was evident, with variogram ranges extending up to ~6 km. In contrast, glacial sediments showed no spatial correlation due to high heterogeneity and sparse deep data. Hence Vs of glacial sediments were interpolated using inverse distance weighting (IDW). Deterministic V_S –depth profiles of PG and G geologies were used for regions beyond the estimation neighborhood.

The resulting 3D V_S model captures both stratigraphic and local variations in soil stiffness, providing a robust basis for seismic microzonation and site response analysis across western Metro Vancouver.

Future work should focus on co-simulation approaches to integrate invasive and non-invasive V_S datasets, modeling spatial variability, and inclusion of uncertainty analysis of predicted V_S.

6 ACKNOWLEDGEMENTS

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