Using HVSR measurements from ambient noise in Burwash Landing to determine bedrock depth and explore geothermal potential

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Introduction

As Canada advances towards net-zero CO_2 emissions, geothermal energy plays a crucial role for the country. Geothermal energy may be particularly useful in Northern Canada, where many communities rely on diesel fuel for power generation, including heating. The Yukon Geological Survey (YGS) leads a research program to assess the potential to produce geothermal energy in several Yukon communities. Following consultations with the Kluane First Nation, a location on the Denali Fault was identified as a promising target. Focussed exploration is carried out at this location near the community of Burwash Landing, to study whether favourable geological conditions exist that allow warm geothermal fluids to ascend near the surface where heat could be utilized (Witter, 2020).

With a mean annual temperature of -3°C, the Burwash Landing area is considered a favourable environment for geothermal energy due to an estimated geothermal gradient of 40°C/km, the presence of warm groundwater, and the proximity to the crustal-scale, dextral strike-slip Denali fault (Witter et al., 2018). For this project, continuous seismic data was recorded from 2021 to present using nine three-component broadband seismometers in the area (***Fig. 1***). We consider horizontal-to-vertical spectral ratio (HVSR) measurements of ambient seismic noise to estimate the fundamental resonance frequencies (f_0) of shear waves, which are used to infer the shallow seismic velocity structure. The results are interpreted in terms of bedrock depth beneath each station. Having constraints on the depth to bedrock is necessary to identify favourable locations for heat extraction from the subsurface and reduce exploration risks associated with drilling.

HVSR Method

The concept of utilizing the HVSR using a single station was initially presented by Nogoshi and Igarashi (1971). However, Nakamura (1989, 2008, 2019) advanced the method for earthquake hazard assessment. These works also proposed the use of the lowest frequency peak of HVSR curves to estimate the fundamental resonance frequency of a site and the amplification of ground motion influenced by a surface layer.

The resonance frequency, f_0, of shear waves in a low-velocity sedimentary column overlying higher velocity bedrock is defined as

$$f_0 = \frac{V_s}{4h},$$

where V_s is the average shear-wave velocity of the column, and h is its thickness.

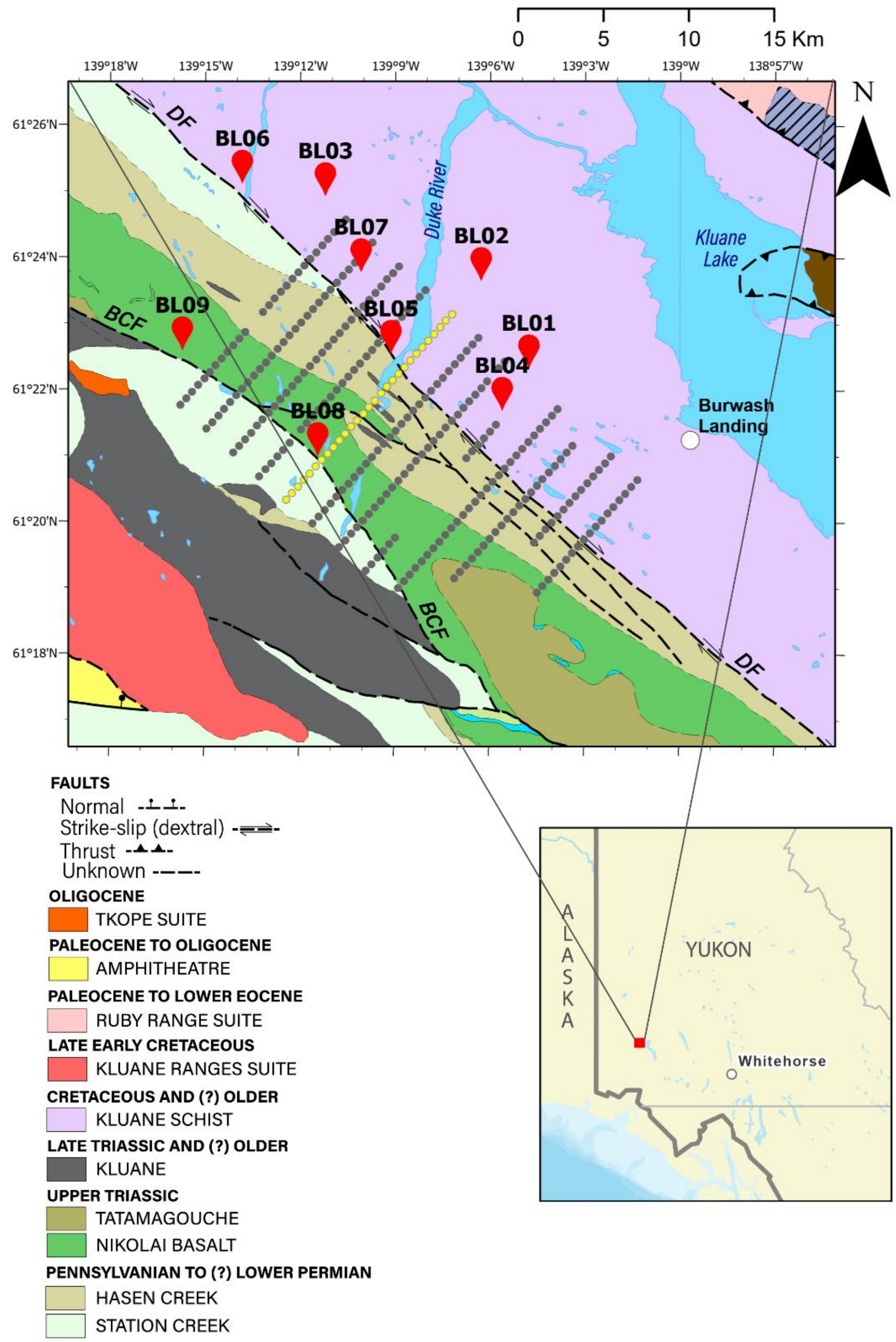

Figure 1. *Geologic map of the Burwash Landing area. (YGS, 2022). Faults are shown by black dashed lines. Three-component seismometers are shown as red pins. Gravity stations for which a profile section is available are shown as yellow circles. All other gravity stations are shown in gray circles. The community of Burwash Landing is denoted as a white circle. DF = Denali Fault; BCF = Bock's Creek Fault.*

The calculation of HVSR curves involves averaging the Fourier amplitude spectra of the north-south ($H_{NS}(\omega)$) and east-west components ($H_{EW}(\omega)$) and dividing by the Fourier spectrum of the vertical component ($V(\omega)$)

$$HVSR(\omega) = \frac{\sqrt{H_{NS}(\omega) \times H_{EW}(\omega)}}{V(\omega)}.$$

The close relationship between f_0 and HVSR curve peaks provides estimates of the shallow shear-wave velocity profiles in the upper crust. Therefore, if either the velocity or thickness of a layer can be constrained, the remaining parameter can be calculated using the spectral peak of an HVSR curve. For example, using the above equation for the resonance frequency, an observed $f_0 = 0.5\,Hz$ at a station atop a sedimentary layer with $V_s = 500\,m/s$ would predict a layer thickness of $250\,m$. For comparison, a higher resonance frequency of $f_0 = 5\,Hz$ for a station atop a layer with the same seismic velocity would correspond to a thickness of only $25\,m$.

Data Processing

To select a specific day to produce a simple representative HVSR curve we visually inspected multiple days of data and ensured that certain criteria were met. We selected timeseries where no large-amplitude impulsive signals (most likely of anthropogenic origin) were present. Having low-amplitude ambient noise enhances the signal-to-noise ratio of HVSR measurements. If anthropogenic noise is dominant near seismic stations, spectral peaks of stratigraphic origin could be masked. We then conducted individual analysis of the different components to ensure that HVSR spectral peaks originated from a local minimum in the vertical component. This behavior is characteristic of surface waves around the resonance frequency at a site (Fäh et al., 2003).

Once we had a selected day, we computed HVSR curves using two-hour-long traces (local hours 5 to 7 AM in the morning), cut into 60-second-long windows with no overlap. Time windows were smoothed in the frequency domain using a Konno and Ohmachi window with a bandwidth coefficient equal to 40. Forward models were calculated using Grilla software, developed by the company MoHo s.r.l. The theoretical assumptions adopted by the forward modeling code are that the seismic wavefield is equally partitioned between Rayleigh and Love waves, and that the seismic path is a 1-D layered viscoelastic solid (Castellaro & Mulargia, 2009).

Results

After computing HVSR curves for every station, we noted that all curves are characterized by a single peak. We have divided stations into three different groups based on the frequency of its HVSR peak (***Fig. 2***). The first group, with low-frequency peaks ($\sim 0.3 - 0.4\,Hz$) and varying amplitudes ($\sim 1.8 - 4.2$), corresponds to stations BL01, BL02, BL03, BL04, and BL07, located to the NE of the Denali Fault. A thick section of Quaternary sediments overlies the Kluane schist near these stations. The latter was determined by an early exploration well drilled entirely in sediments at Burwash Landing with a $384\,mMD$. Stations BL05 and BL06 comprise the second group, with HVSR peaks at 7.75 and $7.51\,Hz$ and amplitudes of ~ 2.5. These stations are located close to the Denali Fault, where Quaternary sediments overlie the Hasen Creek Formation. The thickness of the Quaternary sediments beneath stations in Group 2 is thinner than the sedimentary layer beneath stations in Group 1, as confirmed by drilling operations in late 2022. A well drilled close to station BL05 encountered bedrock at a depth of $\sim 50\ m$. The third and final group corresponds to stations BL08 and BL09, which lie near Bock's Creek Fault. These stations show HVSR peaks around $11\ Hz$ and amplitudes of ~ 2.5.

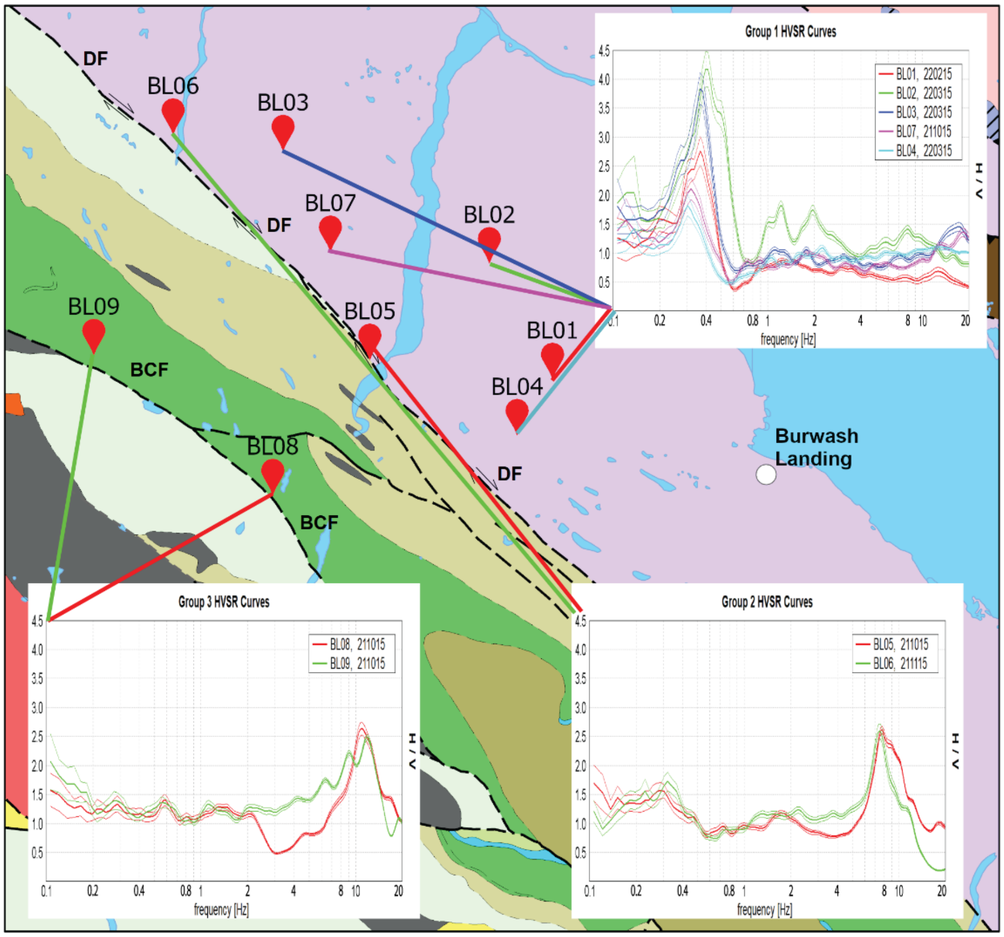

Figure 2. *HVSR curves for all stations shown on top of the bedrock geology map (YGS, 2022). Stations BL01, BL02, BL03, BL04 and BL07, all located to the NE of the Denali Fault, show a clear low-frequency peak (0.32 – 0.41 Hz). Stations BL05 and BL06, located near the Denali Fault, show peaks at 7.75 and 7.51 Hz, respectively. Lastly, BL08, and BL09, located near the Bock's Creek Fault show a high-frequency peak (10.94 and 11.06 Hz, respectively).*

Based on forward modeling the HVSR measurements produced here, we have developed preliminary 1-D shear-wave velocity models for a station taken from the first (BL02), second (BL05), and third (BL08) groups of stations. These three stations were chosen because they closely align with a cross section and density model constructed using gravity data collected by Aurora Geosciences (Witter, 2020). We computed three different models corresponding to a range in values for V_s in the upper layer based on reasonable bounds for the types of rocks present at the surface. We estimated the thickness of the shallow layer for a slow, intermediate, and fast model using f_0 observed on the HVSR curves. (***Fig. 3***).

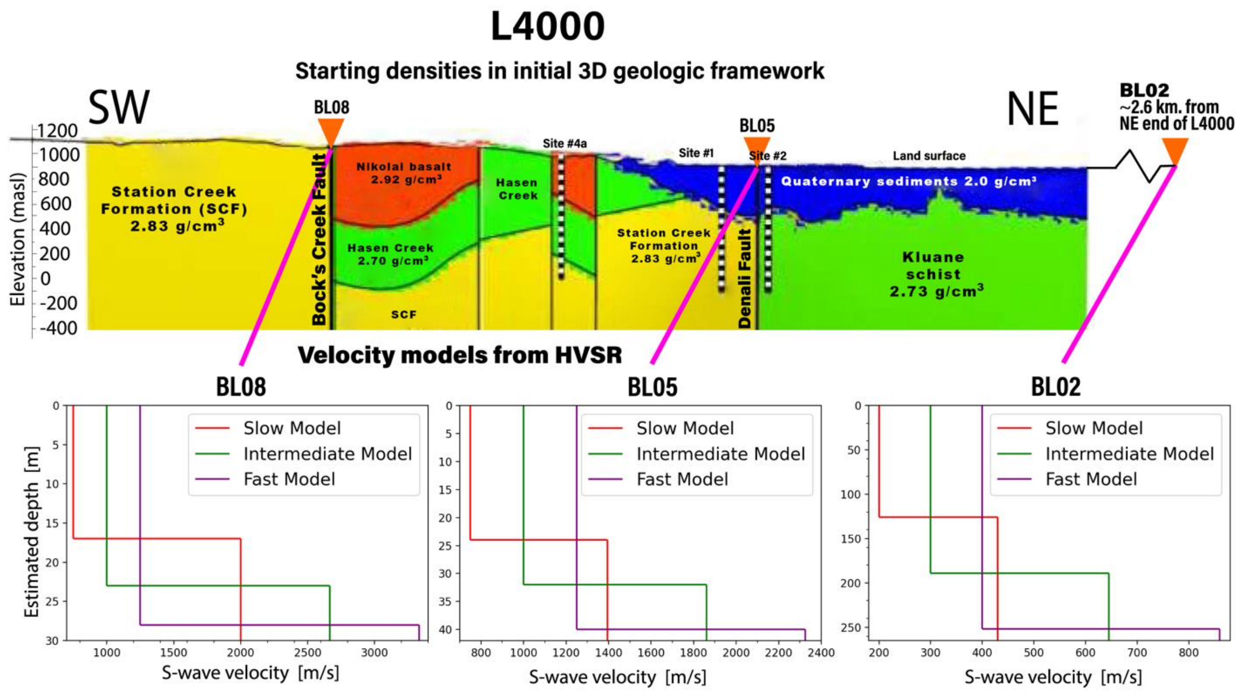

Figure 3. *Three 1-D shear-wave velocity models computed for three different stations along the starting density profile L4000 by Aurora Geosciences (top figure modified from Witter, 2020). Sites #1, #2, and #4a are three of the seven proposed drilling targets resulting from the early-stage exploration at Burwash Landing. Station BL08 is located near the Bock's Creek Fault, BL05 is located atop of a layer of Quaternary sediments near the Denali fault, and BL02 is located to the NE of this density profile and closer to Kluane Lake where a thicker sedimentary column is expected. Models for stations BL05 and BL08, representing Group 2 and 3 respectively, contain a shallow low-velocity layer with thicknesses in the range of* ~ 20 *to* $40\,m$*. overlying bedrock. Station BL02 has a significantly thicker low-velocity layer with thicknesses between* ~ 120 *to* $250\,m$*. Note differences in the range of depths and velocities in the Vs models presented for BL08, BL05, and BL02 at the bottom of the figure.*

The lower frequency HVSR peaks around 0.3 and $0.4\ Hz$ that characterize HVSR curves in Group 1 can be fit with models comprised of a low velocity shallow layer with thickness between ~ 120 and $\sim 250\ m$ (***Fig. 3***). These estimates are reasonable given the fact that the sedimentary layer is at least $384\ m$ thick at Burwash Landing, closer to the Kluane Lake. Models that fit HVSR curves for stations in Groups 2 and 3, exhibiting higher frequency peaks between 7.5 and $11\ Hz$, possess significantly thinner shallow layers in the range of 20 to $40\ m$ (***Fig. 3***). The constraints on the thickness of sedimentary columns beneath stations provided here can be used to further improve the inversion of other data, including gravity and magnetic observations, previously acquired in the region. Current geophysical models have overestimated the thickness of the Quaternary sediments layer at $\sim 200\ m$ around the drill site near BL05. On the other hand, we have estimated a thickness between ~ 25 to $40\ m$, closer to the observed bedrock depth of $50\ m$.

Due to limited constraints on the seismic structure of the upper crust near Burwash Landing, little is known about the thickness and distribution of low velocity shallow layers. The non-uniqueness of HVSR forward modelling means that a wide range of velocity models can fit the observed HVSR curves. Despite uncertainties in the shallow seismic velocities, models presented here constrain the shallow seismic structure near Burwash Landing. Moreover, our results show a strong correlation with the shallow geology with an increase in the thickness of the sedimentary column to the NE of the Denali Fault.

Acknowledgements

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