APPENDIX 1: HVSR passive seismic applications in Bayfield County

The horizontal-to-vertical-spectral ratio (HVSR) passive seismic method is a quick and inexpensive method for estimating depth to bedrock. The method was used in Bayfield County to supplement existing bedrock data for developing a countywide depth-to-bedrock map.

HVSR analysis relies on recording ambient ground vibrations in shallow geologic materials with a small seismometer. The movement of objects (such as trees and their root systems or car traffic on a road) at the surface causes ambient ground vibrations that penetrate down into the earth. The passive seismic recordings are analyzed to determine the frequency at which these ground vibrations resonate (known as the "fundamental resonant frequency"). The fundamental resonant frequency is inversely related to sediment thickness or depth to bedrock because the horizontally oscillating waves are constrained between bedrock on the bottom and land surface on the top. A higher resonant frequency corresponds to a shallower depth to bedrock or thinner sediment, and a lower resonant frequency corresponds to a greater depth to bedrock or thicker sediment.

The relation between the resonant frequency of ground vibrations and depth to bedrock depends on the stiffness and density of sediments. The relationship is mathematically determined through calibration by making HVSR measurements where bedrock depth is known.

This appendix summarizes the HVSR data collection and interpretation used in Bayfield County. All of the HVSR spectra images are provided in appendix 2. Measurement locations are included with the depth-to-bedrock GIS layer.

Passive seismic data collection

HVSR measurements were collected with a Tromino seismograph at 115 locations in Bayfield County. Data were collected using a sampling rate of 128 hertz (Hz) and a recording time ranging between 16 and 20 minutes.

Most of these measurements were collected where existing bedrock information was sparse and the depth to bedrock was expected to be less than 100 feet (ft) (30 meters (m)) (fig. 1). Data collection where sediment thickness exceeds 100 ft was not a priority because the primary purpose of this work was to improve resolution in areas with shallow bedrock. New data collection

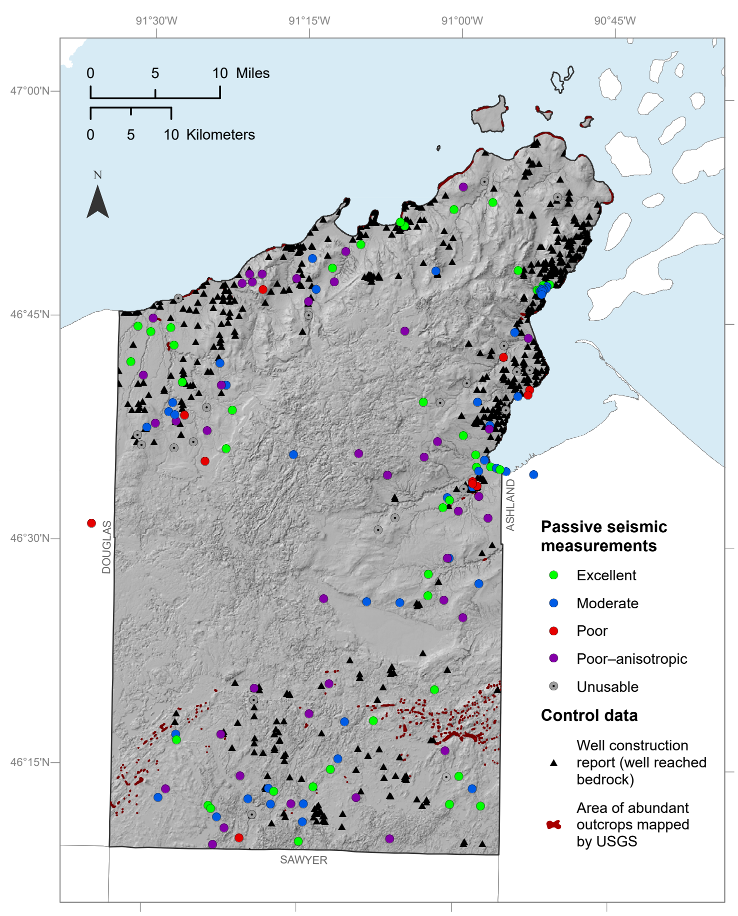

Figure 1. Locations and quality of 149 HVSR passive seismic measurements throughout Bayfield County. Outcrop locations extracted from bedrock maps by Cannon and others (1999) and Nicholson and others (2006). Base map from Bayfield County 5-ft lidar.

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in southwestern and southeastern Bayfield County was limited due to restricted road access in those areas. Wet conditions around Bibon Swamp were incompatible with the use of the Tromino and thus limited the collection of data close to the swamp.

In addition to the 115 HVSR measurements acquired specifically for this project, measurements from other projects were obtained, for a total of 149 HVSR recordings for Bayfield County (included in figure 1). The Minnesota Geological Survey shared 16 HVSR measurements. Seventeen HVSR measurements collected by WGNHS in 2014 for an unrelated project also were available for this mapping effort.

Data analysis

HVSR data were analyzed using the software (Grilla) provided with the Tromino instrument. Irregular noise was removed from the analysis using the "automatically selected windows" function and a moving standard deviation/total standard deviation of 1.5. Recordings were divided into 20-second windows and horizontal and vertical amplitude spectra between 0 and 64 Hz were calculated for each window using 10 percent triangular smoothing. A higher smoothing rate was required for a few noisy recordings. This processing measures the intensities of different frequencies detected during each time window.

HVSR is the ratio between the average horizontal components (vibrations in sediment trapped between the land surface and the top of bedrock) and average vertical components (vibrations oscillating upward, theoretically not constrained) of the recording.

A high-quality recording may show a peak in the HVSR spectrum, signifying the frequency at which horizontal waves resonate. At this frequency, shear wave energy is trapped in a state of constructive interference, and horizontal oscillations are amplified relative to the vertical oscillations (Chandler and Lively, 2016). A high-quality HVSR reading also may show a trough at double the resonant frequency, explained by the destructive interference of out-of-sync resonant waves canceling each other out.

A level of confidence was assigned to each passive seismic recording on the basis of observations of the strength (or amplitude) and smoothness of the HVSR peak. The five qualifiers (excellent, moderate, poor, poor–anisotropic, and unusable) are defined below, and HVSR data representative of each category are provided in figures 2 through 5. The qualifiers describe how confident we are that the primary resonant frequency was selected for analysis. The quality of measurements ranged evenly among the geologic settings tested (for example, the clayey lowlands close to the Lake Superior shore, the rocky uplands in the south, and so on), with no apparent spatial pattern in distribution of recording quality (see figure 1). Of the 115 measurements made in 2017 and 2018, 27 were excellent, 26 were moderate, 8 were poor, 34 were poor–anisotropic, and 20 were unusable.

- **Excellent**: The primary peak had a high amplitude (>4) that was at least twice that of neighboring peaks, a defined trough was observed at a frequency double the primary peak frequency, and a corresponding eye was visible in the amplitude spectra.
- **Moderate**: The peak frequency was easily spotted but had weaker amplitude, or secondary peaks or other noise were present. North-to-south and east-to-west horizontal spectra may have had similar peak frequencies, but slightly different shapes and amplitudes.
- **Poor**: Frequencies were messy, had a weak signal, or multiple peaks. North-to-south and east-to-west spectra may have had slightly different primary peak frequencies. In some cases, the resonant frequency was calculated by halving the frequency of a more strongly defined trough.
- **Poor–anisotropic**: A strong signal was present in one horizontal amplitude spectrum, whereas the opposite direction produced a completely flat reading. If the directional spectrum independently had an otherwise "excellent" or "moderate" peak, the measurement was categorized as "poor–anisotropic."
- **Unusable**: Measurements were categorized as "unusable" if the signal was flat or irregular and a reliable feature in the horizontal-to-vertical spectrum was not discernable.

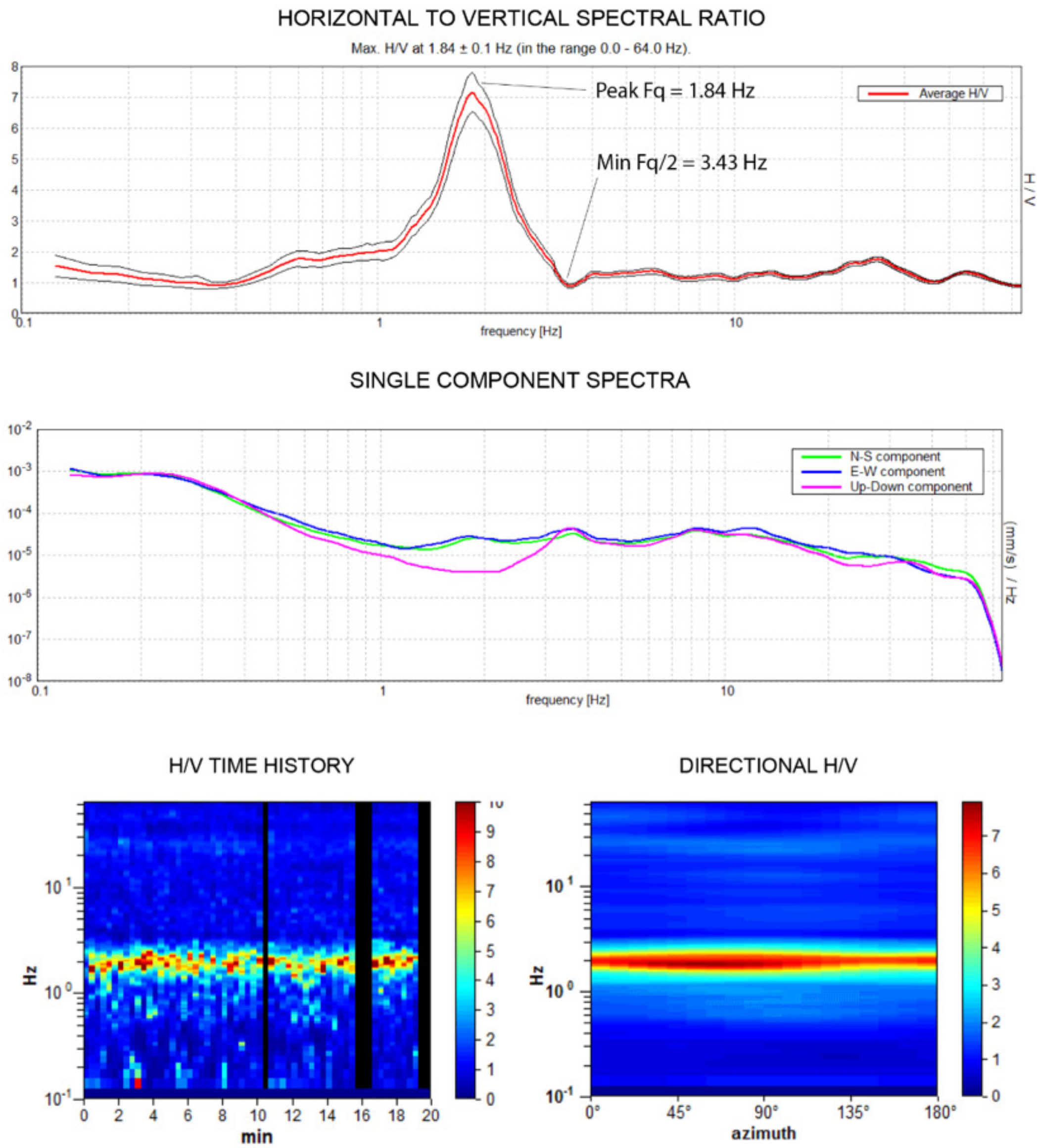

Figure 2. Results of measurements from location Eastern Bayfield 11, showing an example of an excellent HVSR peak. The HVSR shows a well-defined peak, and a trough (minimum frequency, labeled "Min Fq" on the figure) is present at about double the frequency of the peak. The plot of time history and directional H/V show, respectively, that this peak frequency was detected throughout the duration of the recording and from all horizontal directions.

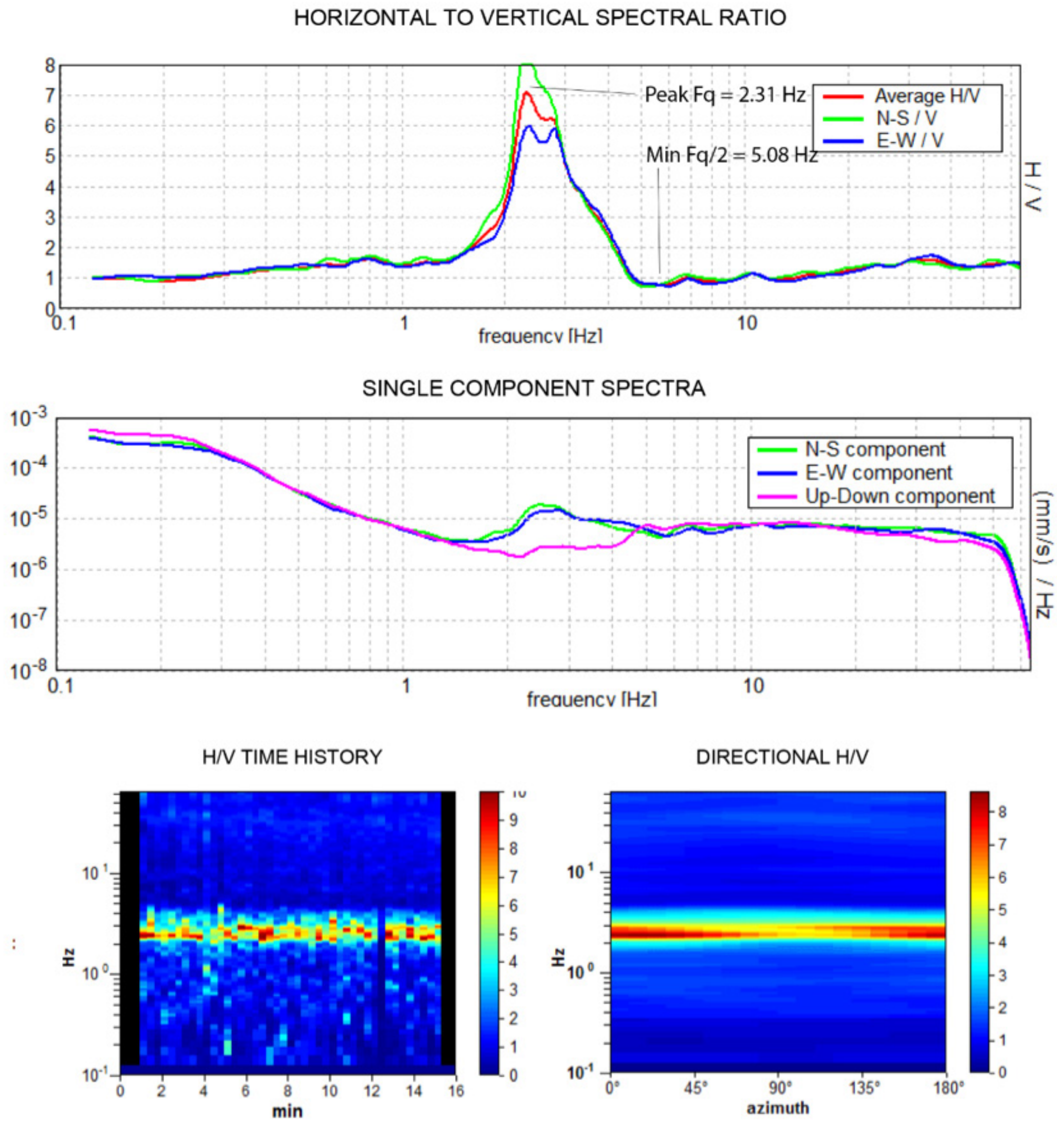

Figure 3. Results of measurements from location Southern Bayfield 3, showing an example of a moderate HVSR peak. The north-to-south (N-S/V) and east-to-west (E-W/V) horizontal spectra have slightly different shapes. The average H/V peak is more strongly influenced by the N-S spectrum, which has a better defined and prominent peak at 2.31 Hz.

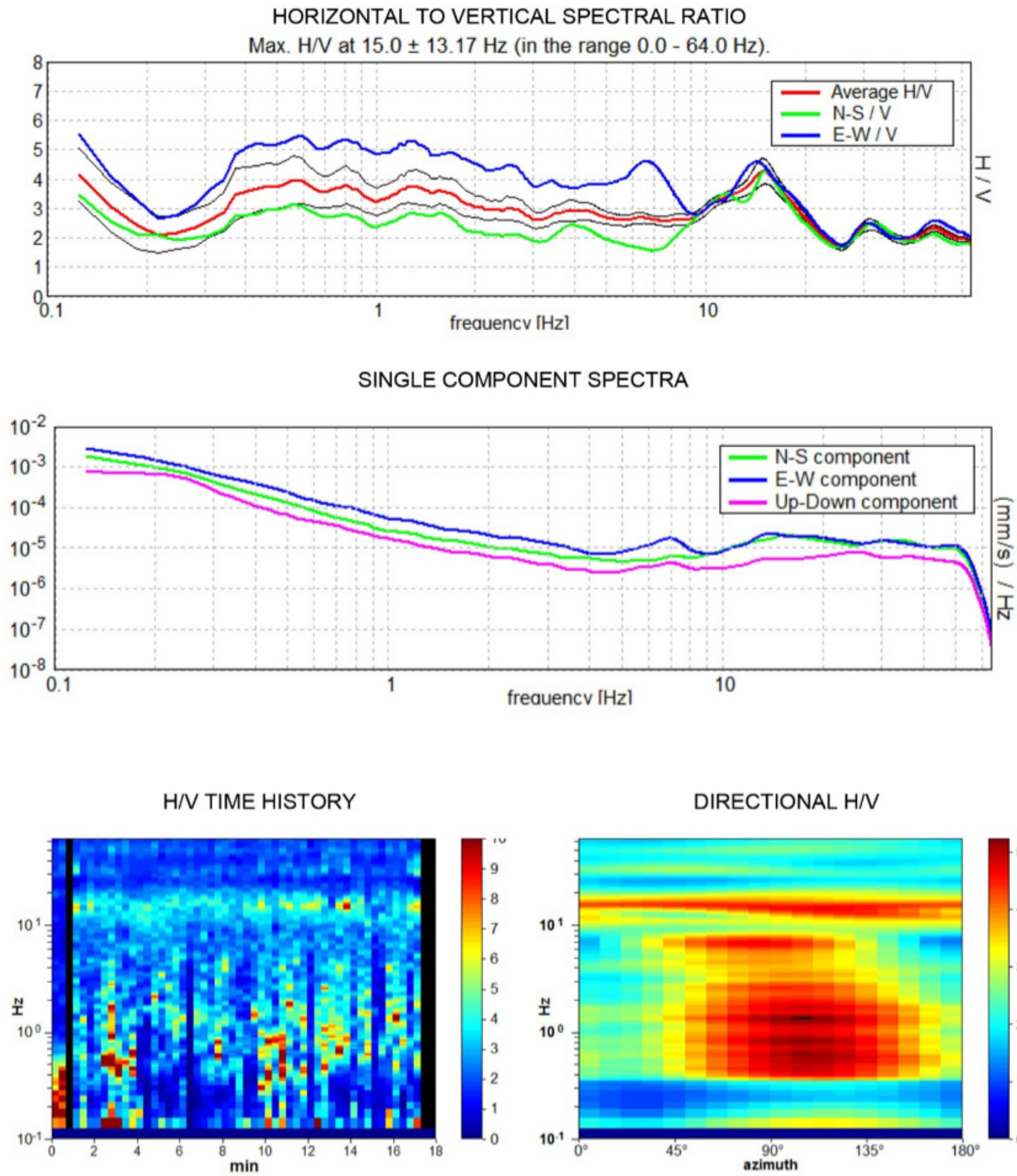

Figure 4. Results of measurements from location NW Bayfield 3, showing an example of a poor HVSR reading. The recording is noisy at low frequencies. The amplitude of the dominant peak at 15 Hz is relatively low compared with higher-quality recordings.

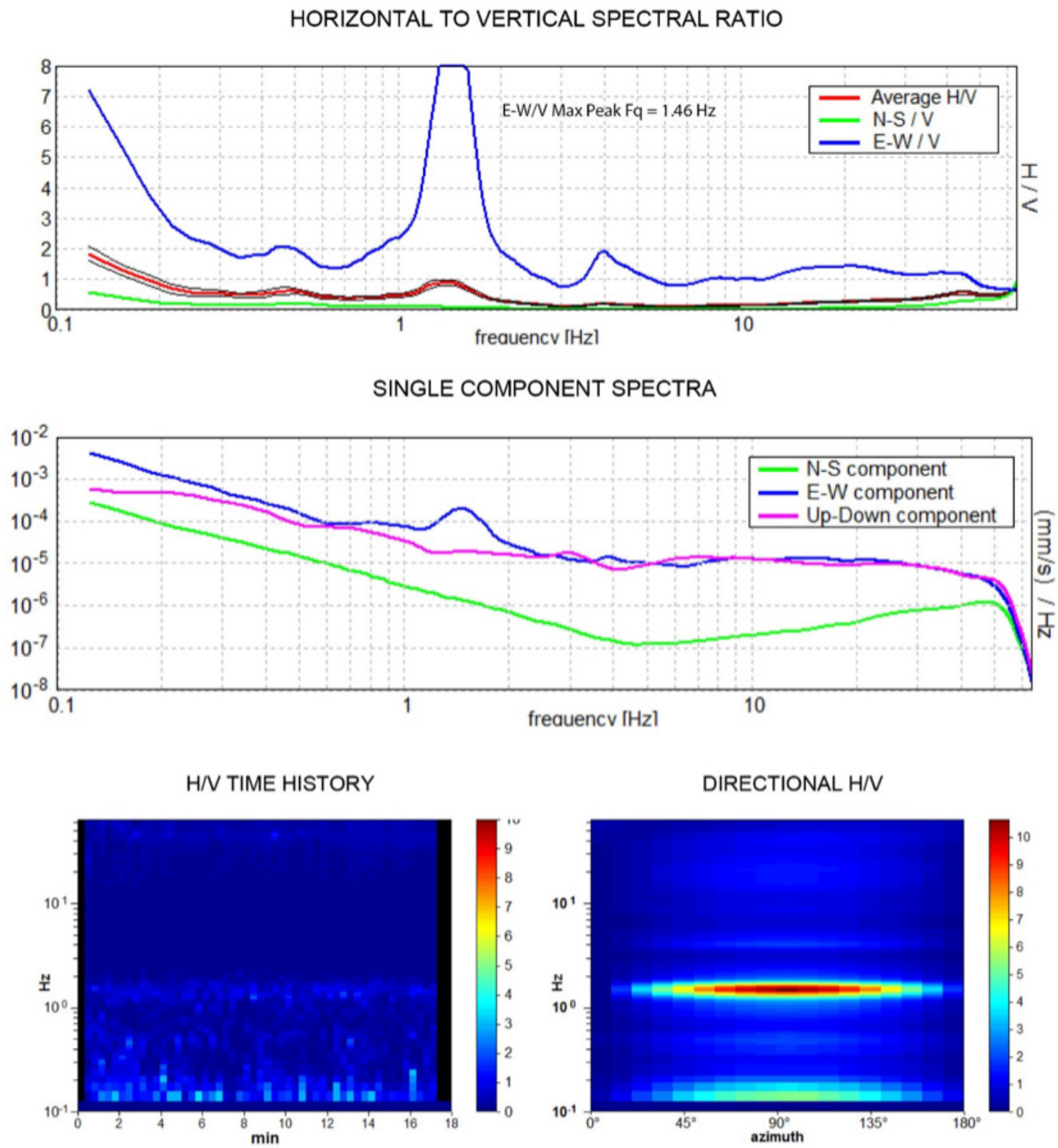

Figure 5. Results of measurements from location NW Bayfield Co. 18, showing an example of a poor–anisotropic HVSR reading. The east-to-west horizontal spectrum has a strong signal with a sharp peak and trough, but the north-to-south spectrum is flat.

Calibration

The primary resonant frequency, or HVSR peak frequency, is exponentially related to sediment thickness according to the following equation:

Sediment thickness =
a (peak frequency)^b (1)

where the variables *a* and *b* are determined empirically by collecting measurements at control points where the depth to bedrock is known (Chandler and Lively, 2016). This empirical relation is dependent on the type or stiffness of sediment at a location.

To calibrate the HVSR analysis for sediments in Bayfield County, 17 passive seismic measurements were taken close to wells where construction records were available and indicated the depth to bedrock (fig. 6). Control locations were intentionally selected to encompass a range of depths to bedrock, from 7 to 375 ft (2 to 114 m). Permission to make measurements within the immediate vicinity of a well was sought at some locations, but about half of the control measurements were taken in the right-of-way areas alongside roads and within 330 ft (100 m) of the well. The HVSR peak frequencies were plotted against the known sediment thickness (fig. 7), and an exponential equation was fit to the data, giving values a= 150.29 and b=–1.266 for equation 1.

The error between the data and the best-fit line appear log-normally distributed with an R^2 value of 0.9455. Confidence intervals based on standard error of the log-normal distribution show that the accuracy of the HVSR method decreases with increasing sediment thickness. The uncertainty in the estimates is lowest where bedrock is shallow. Ranges of uncertainty were taken into consideration while drafting the depth-to-bedrock map.

This calibration appeared to overestimate the depth to bedrock in northwestern Bayfield County where the sediment is rich in clay. We conducted a separate calibration for the northwestern region by making an additional six control measurements close to wells in clay environments (fig. 8) to identify the relation sediment thickness = 49.759 (peak frequency)$^{-0.69}$. This calibration was applied to the HVSR measurements primarily in the Port Wing area.

Depths to bedrock estimated by the second calibration were considered, but not applied, in eastern Bayfield County, where clay is also prevalent. The range of uncertainty in the passive seismic interpretation is substantial in eastern Bayfield County, where depth to bedrock exceeds 80 ft (25 m), because there is not enough information to know which calibration is more representative at specific locations. Future research focused on characterizing grain-size distributions of glacial deposits may improve the application of this method in such locations. One aspect to explore is whether the Miller Creek Formation's clay content is highest on the western side of the peninsula; this pattern was broadly observed within the Lake Superior region by Clayton (1984).

Figure 6. Example of control measurement used for HVSR calibration. The Tromino seismometer is placed directly next to a well where depth to bedrock is indicated by driller's well records.

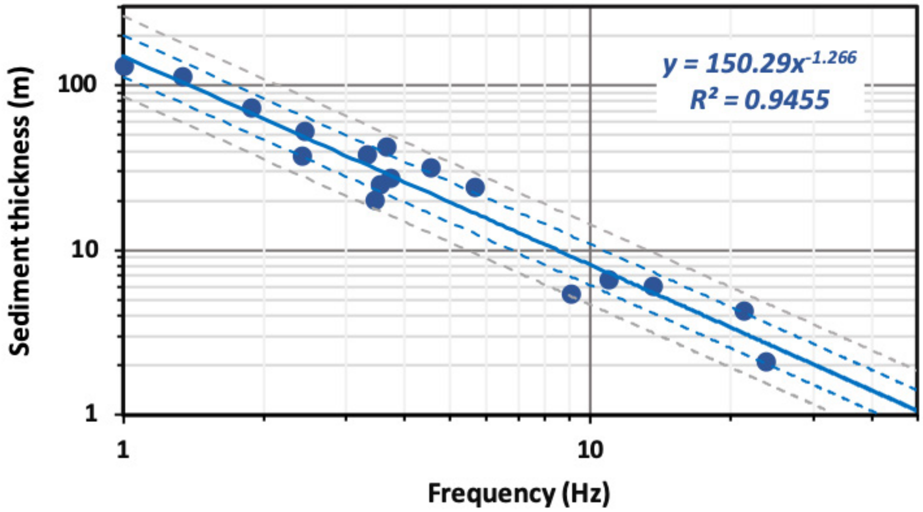

Figure 7. HVSR calibration for 17 control stations. The 68% and 95% confidence interval plot bounds are also shown as blue and gray dashed lines, respectively. Bounds are determined from standard error. Note that because the graph uses a logarithmic scale, the range of uncertainty is significantly wider where sediments are thickest.

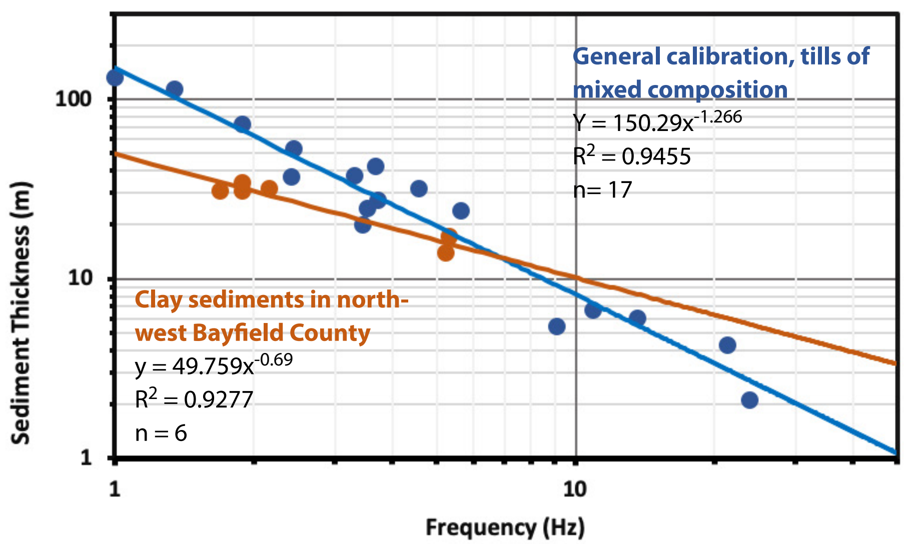

Figure 8. HVSR calibration for measurements made in clays in northwestern Bayfield County. The clay is shown in orange and the countywide, general calibration is shown in blue. The general calibration includes measurements made in sand and gravel and glacial tills of mixed composition.

We applied the coefficients a=83 and b=–1.232 for HVSR measurements made in fluvial sediments close to the Lake Superior shore. These parameters resulted from a HVSR calibration by Chandler and Lively (2016) in similar sediments in eastern Minnesota. As in Chandler and Lively (2016), we also observed that the calibration parameters based on control points in upland environments overestimated the thickness of fluvial sediments. This is apparent near Chequamegon Bay (fig. 9), where HVSR data interpreted using a=150.29 and b=–1.266 implied bedrock elevations hundreds of feet lower than that suggested at nearby wells.

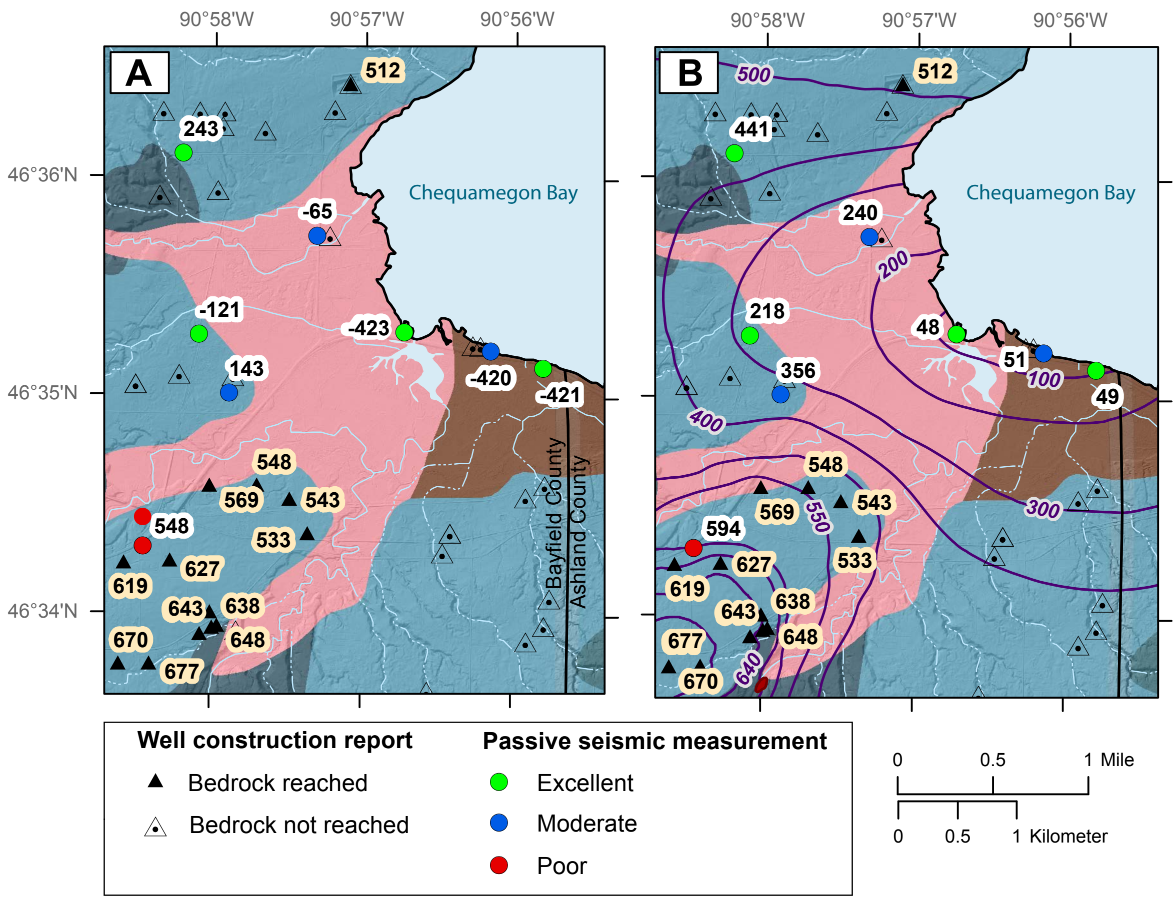

Figure 9. Comparison of bedrock elevations (feet above sea level) estimated using different HVSR calibrations. HVSR estimates of depth to bedrock were subtracted from surface elevations to determine the estimated elevation of the bedrock surface. The base layer shows Quaternary sediments (Clayton, 1984); stream sediments are shown in pink. Bedrock elevations derived from well data (triangles) are highlighted in tan, and bedrock elevations calculated from HVSR data (circles) are highlighted in white. (A) Calculated using HVSR calibration parameters a=150.29 and b=–1.266. (B) Calculated using HVSR calibration parameters a=83 and b=–1.232. Structure-contour lines (purple) show the interpreted elevation of the top of the bedrock.