EVALUATION OF THE HORIZONTAL-TO-VERTICAL SPECTRAL RATIO (HVSR) PASSIVE SEISMIC METHOD FOR ESTIMATING THE THICKNESS OF QUATERNARY DEPOSITS IN MINNESOTA AND ADJACENT PARTS OF WISCONSIN

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ABSTRACT

Horizontal to vertical spectral ratios (HVSR) of ambient seismic noise may be used to estimate the thickness of sediment over bedrock, based on empirically-derived, power-curve relationships between sediment thickness and primary resonant frequency of shear-waves. The primary resonant frequency can be deduced from prominent peaks or troughs in the HVSR spectra, provided that the sediment-bedrock interface is reasonably flat, and is associated with a strong acoustic impedance contrast. Several recent geologic investigations in southern Minnesota have provided an opportunity to evaluate the HVSR method as a way to estimate the thickness of Quaternary sediments for a variety of bedrock and sediment conditions.

In most of the Twin Cities metropolitan area, a reasonably simple and young (late Wisconsinan), glacial sediment overlies a rigid substrate of Paleozoic sedimentary rocks. Primary resonant frequencies, which are evidenced by prominent (>3.5 amplitude) peaks in the HVSR spectra, were used at 41 control sites to derive a power-curve relationship with a correlation coefficient of 0.957 and an average percentage error of +/-13%. This relationship has proven useful for estimating sediment thickness in parts of the Twin Cities Metropolitan Area lacking geologic control. In the eastern part of the Twin Cities area the HVSR method has been very effective in mapping a buried bedrock ravine, whose narrow, winding trace was not effectively portrayed by existing well data.

In contrast, south central Minnesota presents more of a challenge for the HVSR method; here the bedrock surface ranges from rigid Precambrian rocks to much softer saprolith and Cretaceous strata and the glacial sequence can be complex and thick, with a significant Pre-Wisconsinan component. These complications can degrade or obscure the bedrock signature

in HVSR spectra. Analysis of 27 control sites where the glacial sequence is interpreted to rest directly on the rigid Precambrian rocks produced a power curve relationship similar to that from the Twin Cities metropolitan area and reasonable depths to the bedrock surface. In contrast, HVSR data from control sites where saprolith or Cretaceous strata form the bedrock are more likely to identify transitions between saprolith and fresh rock or the base of Cretaceous strata and the top of crystalline rock rather than the bottom of Quaternary sediments. This, at least in part, is due to the small impedance contrast between Quaternary sediments and saprolith or Cretaceous strata. Under these conditions, HVSR results do not always identify what is geologically classified as the bedrock surface in Minnesota (i.e., the top of Cretaceous sediments or saprolith), but instead are more likely to identify transitions to rigid or unweathered rock. As an added complication, some HVSR results from south-central Minnesota identify strong impedance contrasts within the glacial sequence. These horizons appear to correspond with dense tills in the Quaternary sequence that have been highly compacted by overriding glacial ice.

The floodplain and terrace deposits along major stream valleys in southeastern Minnesota and adjacent parts of Wisconsin are commonly associated with singular, high-amplitude (>5) HVSR peaks that are consistent with strong impedance contrasts at the bedrock surface. These valleys channeled enormous amounts of melt-water during the closing stages of the Wisconsinan glaciation, so that the valley bottoms were scoured down to fresh bedrock, and filled with poorly consolidated outwash, fluvial, and lacustrine deposits. The HVSR results at 37 control sites produce a power-curve relationship with a correlation coefficient of 0.952 and an average percent error of +/-20%. This relationship differs significantly from those observed over the glacial uplands of the Twin Cities Metropolitan area and south-central Minnesota, and most likely reflect lower shear-wave velocities for the unconsolidated fluvial-lacustrine deposits in the stream valleys.

Wherever Quaternary sediments cover the bedrock in Minnesota and adjacent areas, the HVSR method will be a useful supplement to geological and other geophysical investigations, provided that appropriate cautions are heeded. Although, the HVSR method does not match conventional seismic studies in the level of interpretive detail such as modeling a surface, it offers distinct advantages of rapid data collection, much lower equipment and staff costs, ease of data analysis and the large number of samples that can be collected within an area. The HVSR method can also be readily applied in areas of significant cultural noise, where conventional seismic data is difficult or impossible to obtain.

INTRODUCTION

Mapping the thickness of unconsolidated Quaternary deposits over bedrock can be a challenging problem in Minnesota. Glacial deposits of varying thicknesses cover over 90% of the state, and drill-holes that penetrate this sequence are very unevenly distributed (Figure 1). Most drill holes in Minnesota are water wells, and are concentrated in urbanized areas, where water demand is high. The density of wells decreases significantly in outlying rural areas and those wells drilled to bedrock decrease even more where the depth to bedrock exceeds 100 meters (328 feet) because most wells reach an adequate water supply within the glacial sediment, well-above the bedrock surface. In areas that are drilled for scientific or mineral exploration purposes the cost of drilling through such “overburden” precludes a large number of bedrock drill holes. Although conventional seismic sounding is a cheaper alternative to drilling, it can also become expensive in deep bedrock areas. It has been our experience that a seismic refraction crew typically involves 2-4 individuals, 2 vehicles, and a mechanical energy source, and can only acquire 2-4 soundings per day if bedrock depths exceed 100 meters (328 feet). Consequently, the thickness of glacial deposits, as well as the topography of the underlying bedrock surface, remains unknown over large areas of Minnesota. Because such information is pertinent to geologic framework studies, as well as long-term planning for groundwater use and protection, the Minnesota Geological Survey (MGS) has a growing need to improve upon this problem.

Over the last two decades considerable progress has been made elsewhere with passive seismic methods and their geologic applications. One of these, the horizontal-to-vertical

-spectral ratio (HVSR), has shown considerable potential for rapidly and inexpensively estimating the thickness of unconsolidated deposits over bedrock. In this paper we investigate the effectiveness and limitations of the HVSR method for mapping the thickness of Minnesota's Quaternary sequence. These findings have significant implications regarding use of the HVSR method elsewhere.

THE HVSR PASSIVE SEISMIC METHOD

The HVSR method was originally developed to assess seismic risk in Japan (Nogoshi and Igarashi, 1971; Nakamura, 1989). Surficial sediment is widely known to produce enhanced shaking during an earthquake, partially as a consequence of horizontally oscillating shear waves arriving from below at the fundamental resonant frequency of the sediment. At this frequency a significant part of the shear wave energy is trapped within the sediment in a state of constructive interference. As a result, the horizontal oscillations are amplified relative to the vertical oscillations. Thus, on a 3-component seismic record, the averaged spectra of the horizontal components divided by the vertical spectrum should produce a prominent peak at the fundamental resonant frequency of the sediment (Nogoshi and Igarashi, 1971; Nakamura, 1989). Although data can be collected during earthquakes, the method can sometimes work effectively with ambient seismic noise, increasing its value as a preemptive tool for earthquake risk assessment. Most HVSR applications record frequencies ranging between 0.1 Hz to 60 Hz. Signal from 1 Hz and above are largely due to cultural activities such as industrial, agricultural, and traffic noise. Signals below 0.3 Hz are primarily caused by oceanic waves, winds and other meteorological sources (Bonnefoy-Claudet and others, 2006).

Considerable controversy has existed regarding the type of seismic waves that actually produce results with the HVSR method. Nakamura (2000) suggested that the HVSR peak was caused primarily by shear wave resonance of the sediment and, as such, the maximum amplitude of the peak equates to an amplification factor. Others (Lachet and Bard, 1994; Fah and others, 2001; and Bonnefoy-Claudet et al. (2006) have argued that Rayleigh waves can be primary components of the seismic noise, and the HVSR peak occurred at the point of maximum horizontal ellipticity in the fundamental mode Rayleigh waves. If so, the peak amplitude would not equate in any simple way to an amplification factor. Airy phase Love waves may also contribute to some observed HVSR results (Konno and Omachi, 1998; Bonnefoy-Claudet and others 2006). Fortunately for the purposes of this paper and estimating sediment thickness, the HVSR method has emerged as a robust tool for collecting shear wave resonant frequency data in sediments, regardless of what types of waves are actually present (Konno and Omachi, 1998; Bonnefoy-Claudet and others, 2008; Tuan and others, 2011, Ibs-von Seht and Wohlenberg, 1999).

Assuming that the observed HVSR peak adequately represents the fundamental resonant frequency of sediment, and if the sediment-basement contact is flat with a strong acoustic impedance contrast (> 2.5), the HVSR peak frequency can be empirically related to sediment thickness (Ibs-von Seht and Wohlenberg, 1999; Lane and others, 2008). For the simplest case of a uniform sediment layer

(1) m=Vs/4fhv

where m=thickness of the sediment layer
Vz=shear wave velocity
fhv=HVSR peak frequency

Shear wave velocities actually tend to increase non-linearly with depth, due to compaction and other factors, and the distribution of shear wave velocities in an sediment layer can be more effectively approximated by a power law in the form (Bundy, 1984):

(2) Vs(z)=Vs0*(1+Z)^x

Where; z = depth
Vs0=shear wave velocity at the surface
Z=z/z0 with z0=1m
x=describes the depth dependence of shear wave velocity

And in this case, the thickness of the sediment (m) is:

(3) m=((Vs0(1-x)/4fr)^1/1-x)-1

In the absence of shear wave velocity information, Ibs-von Seht and Wohlenberg (1999) demonstrated that an empirical relationship could be established between m and the observed HVSR peak frequency as follows:

(4) m=a*fhv^b

Where parameters a and b are determined empirically by collecting HVSR data at control points (drill holes or seismic soundings) that span a wide range of thicknesses and include a sufficient number of points for reasonable statistics. For Tertiary and Quaternary fill in the Lower Rhine Embayment (Germany) Ibs-von Seht and Wohlenberg used HVSR results at 34 drill hole sites, and developed a calibration curve where a = 96, b = -1.388, and R = 0.9905. This relationship is shown as a power curve on a linear plot (Figure 2a), and as a straight line on a logarithmic plot (Figure 2b). This empirical relationship was used to map fill thickness in parts of the Embayment lacking geologic control. A similar empirical approach was used to map fill thickness elsewhere in the Rhine Embayment (Parolai and others, 2002; Hinzen and others, 2004), as well as in other Tertiary-Recent basins in Europe (D'Amico and others, 2008; LeRoux and others 2012).

GLACIAL GEOLOGY

During the Pleistocene Epoch (ca 1.8 -0.01 Ma) numerous episodes of glaciation occurred in the region (Knaeble, 2006; Meyer, 1986). Derived from multiple source areas, ice advanced and retreated along differing directions (Figures 3 and 4), depositing laterally and vertically heterogeneous till, outwash and lacustrine sediments. Along with erosion and compaction by ice and meltwater, long interglacial periods contributed to further erosion and mixing of sediments

Till is the primary deposit of a warm-based ice sheet and, being directly deposited by ice, consists of an unsorted mix of sands, silts, clays and pebble- through boulder-sized rocks. Retreat, and stagnation of an ice front is associated with melt-water-related outwash (sand and gravel) and glaciolacustrine (silt and fine sand) deposits. Inter-glacial episodes usually result in erosion and soil formation, although deposits of lacustrine and eolian sands and silts can occur locally. Adding to the complexity, each major episode may include minor advances and retreats of ice, with each contributing its own local suite of deposits. These variations have to be borne in mind when applying the simplifying assumptions of HVSR analysis to glaciated landscapes.

In addition to the lithological heterogeneity of the glacial sequence, the shear-wave acoustic impedance within the glacial sequence may be affected significantly by compaction, especially with regard to some of the older and deeper glacial tills. Added to the normal compaction by overlying glacial sediments, some older tills have been overridden at least once by glacial ice, resulting in an unusually dense (over-consolidated) layer of material. Although there are presently no direct measurements of physical properties from these over-consolidated sediments in Minnesota, they could feasibly produce an acoustic impedance contrast that would obscure the bedrock/till signature in HVSR spectra.

BEDROCK GEOLOGY

Much of Minnesota's bedrock surface consists of Precambrian age (Figure 5), crystalline igneous and metamorphic rocks or well-indurated early Proterozoic-to- Phanerozoic sedimentary rocks (Jirsa and others, 2011). These rocks should seemingly present a strong acoustic impedance contrast with the overlying glacial and post-glacial deposits. However, significant areas of the Precambrian surface are actually saprolith, a soft weathering residuum, much of which developed on the crystalline rocks during Cretaceous time (Setterholm and others, 1989; Figure 6). Saprolith is likely to decrease the impedance contrast with overlying sediments and possibly broaden out the frequency response over some indeterminate depth interval. Drill hole data indicates that the saprolith is generally a meter to 10's of meters in thickness, but it can be considerably more, especially near fracture systems.

Phanerozoic age rocks in southern and northwestern Minnesota (Figure 5) also present some challenges to the HVSR method. Paleozoic age rocks, which consist of carbonates, shales, and variably cemented sandstones, are generally rigid, and should be usually associated with strong acoustic impedance contrasts with the overlying glacial and post-glacial deposits.

However, Cretaceous rocks, generally which are poorly indurated, may not have a sharp acoustic impedance contrast with the overlying glacial sequence. Conventional (P-wave) seismic profiling in southwestern Minnesota (Berg and Petersen, 2000) demonstrated that Cretaceous rocks differ little in seismic velocity with the overlying glacial sequence, and neither seismic refraction nor seismic reflection could detect the Quaternary –Cretaceous contact, although both might sometimes recognize horizons within the lower Cretaceous sequence. The difficulties that saprolith and Cretaceous strata pose to the HVSR method will be treated in more detail below.

INSTRUMENTATION AND BASIC PROCEDURES

Following a pilot study using a Guralp CMG-3T broadband, 3-component, seismometer with accessory equipment (Chandler and Lively, 2009), all HVSR analyses in Minnesota have been conducted using Micromed\Tromino model TRZ Tromographs. These self-contained, broadband devices are compact (1 decimeter^3) and light weight (1 kg), and are designed specifically for a variety of engineering- and geology-related applications. The Tromino units have yielded HVSR results that are comparable to those acquired using more expensive and less portable vault-type seismometer systems, such as the Guralp (Castellaro and Mulargia, 2009a). Analysis of data collected is accomplished using software (Grilla) provided with the instrument by Micromed\Tromino.

At a field station, the Tromino was pressed into a flat area of ground (usually below grass root level) such that the three 5-cm-long spikes mounted on the underside of the unit penetrate the soil and form a solid anchor. A bubble level on top of the unit provides for leveling, but, priority is given to a solid ground connection over exact leveling. If vegetation, roots, or loose, rocky soil were part of the site, an area was cleared or deepened until the unit could be firmly implaced. In thick, loose sand this was not always possible, but as long as the unit was firm within the original spike holes it worked as desired. In clayey soil, if the unit had to be moved for leveling, spike holes were not reused as that was found to reduce the coupling between the ground and spikes. As a convention, the unit was oriented towards geographic north in order to assess any directional preference in the ambient noise. Wherever possible, stations were located away from trees or other tall objects that might impart significant ground movement in the presence of wind. A hot-wire anemometer was used to occasionally check wind speeds in the area of the readings. In general, winds above 10 mph (4.5 m/s) began to interfere significantly with the results, and useful subsurface data were not attainable if wind speeds exceeded 15 mph (6.7 m/s).

The sampling rate and recording interval depends on the expected range of frequencies in the HVSR spectra, which in turn depends on the expected range of thickness and shear wave velocity of the sediment. In Minnesota, glacial deposits range from a few meters to between 200 to 300 meters (656 – 984 ft.) in thickness. (Olsen and Mossler, 1982; Lively and others, 2006; Runkel, 2010). Velocity data from shear-wave studies of glacial deposits conducted elsewhere (Carr and others, 1998; Motazedian and others, 2008 and 2011; Crow and Hunter, 2012) can be used with Equation 1 to equate frequency with thickness. The sampling rate of 128 Hz, (Nyquist frequency, 64 Hz.), with a shear wave velocity range of 100-200 m/s, equates to a minimum thickness range of 0.4-0.8 meters, which is more than adequate. For large depth to bedrock values, 300 meters of glacial materials with an average shear wave velocity of 600 m/s would equate to an expected peak frequency of 0.5 Hz. and a 2 second recording time for one cycle. In practice, spectral estimates are statistical in nature, and several cycles of the lowest signal frequency should be recorded. We selected a standard sampling window of 20 seconds, which allows for 10 cycles of our lowest expected frequency. A field recording time of 16 minutes creates 48 sampling windows, further enhancing the statistical sampling.

After de-trending, tapering and padding with zeros (within the Grilla software) the amplitude spectra of the three components are computed for each 20-second window via Fast Fourier Transform, and smoothed with a triangular 10% window. The geometric average of the two horizontal spectra (the square root of the product) is divided by the vertical spectrum to obtain the horizontal to vertical spectral ratio (HVSR) ratio. Both the spectra of the components and the HVSR are then averaged for all sampling windows. The spectral contributions of each sampling window can be edited at this stage to remove the effects of transient spikes in the data (passing vehicles, oblivious pedestrians, passing trains, etc.), and the HVSR results are recalculated. These results were compared with 9 statistical criteria developed by the SESAME (**S**ite **E**ffect**S** assessment using **AM**bient **E**xcitations) consortium (SESAME, 2004) as guidelines for evaluating the reliability and clarity of HVSR data. These criteria test for adequate sampling of the selected HVSR peak, for statistical consistency of amplitudes and peak frequencies of averaged HVSR spectra, and for amplitude of the HVSR peak (for more information on these criteria see the SESAME, 2004 reference). If several criteria were unfavorable, the analysis was repeated using a larger window with greater smoothing, usually 40 seconds with 20% smoothing. In a few cases a 60 second window with 30% smoothing was tried, the smallest window that satisfied all or most of the criteria was selected as the best interpretation.

Figure 7 shows an example of an analysis processed with the Grilla software. Along with the HVSR spectrum (red) with standard deviations (black), Figure 7a), the results include the spectra of the individual components (Figure 7b), a time progression of the spectra in 20 second increments (Figure 7c), and a directional presentation of the spectra in 10 degree increments (Figure 7d). Note how the HVSR peak corresponds with an "eye" pattern (7b, centered at 1.5 Hz) where the horizontal and vertical spectra diverge, which is consistent with an interpretation that the peak represents a stratigraphic source (Castellaro and Mulargia, 2009a).

In addition to the HVSR peak, a "first trough", is often recognizable to the immediate right (up-spectrum) of the main peak (7a), that appears to relate to bedrock depth (Konno and Ohmachi 1998; Hinzen and others, 2004). In the shear-wave resonance model, this trough occurs in the region of maximum destructive interference within the sediment layer, and is twice the frequency of the HVSR peak. The first trough frequency, divided by two, could be substituted for the term fhv in Equation 4, to estimate depth to bedrock. In situations where HVSR peak quality is good, the first trough frequency is not usually used for depth estimates as it may be vulnerable to interference from higher-mode surface waves (Konno and Ohmachi, 1998,) In addition, the acoustic impedance contrast at the bedrock surface, as well as the Poisson Ratio of the sediment, can alter the 2:1 relationship of the first trough with the HVSR peak (Konno and Ohmachi, 1998; Tuan and others 2011). Nonetheless, in some deep-bedrock situations the first trough frequencies appear to produce more reliable depth-to-bedrock values than peaks (Hinzen and others, 2004), and they will be considered in some of the discussion to follow.

To evaluate the HVSR method in Minnesota, 280 passive seismic measurements were taken at control points where the bedrock depth was known (Figure 8). Drill holes constituted the vast majority of control points, and information on them was obtained from the Minnesota County Well Index (CWI). This database, maintained by the MGS and Minnesota Department of Health, contains information for over 452,000 water-wells and exploration drill holes in Minnesota. The majority of CWI wells used here have field-verified locations and drilling logs that have been reviewed and interpreted by an MGS geologist. In addition to drillholes, ten control measurements were obtained at seismic refraction soundings conducted by either MGS or Minnesota Department of Natural Resources (MNDNR). All control measurements were taken as closely as practical to the actual control location; the average distance from a control point for the data was 48 meters (158 ft.), and none exceeded 250 meters (820 ft.) distance. A trial using only stations within 50 meters (164 ft.) of control points did not significantly alter the results, and it was assumed that the allowed 250-meter distance limit did not lead to significant errors. Most of the control points are located in east central, southeastern, and south-central Minnesota and cover a range of sediment thickness, from near zero to 219.2 m (719 ft.), as well as a wide variety of sediment and bedrock stratigraphic conditions.

DISCUSSION OF RESULTS

General Observations

The linear and log-log plots for the HVSR peak frequency versus bedrock depth (thickness of glacial deposits) for all 280 control measurements are shown in Figures 9a and 9b, respectively. Figure 9c shows the correspondence between peak and one-half first trough. The points follow a general power curve distribution, similar to the relationship proposed by Ibs-von Seht and Wohlenburg (1996, Figure 2), but considerable scatter occurs. Much of this scatter likely reflects lateral variations in shear-wave velocities in the unconsolidated sediments, and it is probably best to derive power-curve relationships for depth estimates within specific study areas, where lateral continuity can be more safely assumed. Hinzen and others (2004) cautioned that relationships derived from empirical data should not be used blindly, because parameters derived from one area or geologic situation may not be applicable to another. Consequently we have developed three different calibrations for three distinctly different geologic situations, and there may eventually be others. The degree of scatter, possible causes and resolving power of these models form much of the following discussion. To save time and space, only the log-log plots of the HVSR peak frequency vs. depth relationships will be shown.

The Twin Cities Metropolitan Area

HVSR Analysis

The Twin Cities Metropolitan Area (Figure 10) presents several favorable conditions for an initial test of the HVSR method. Firstly, the region has an abundance of drill holes reaching bedrock (Figure 6), and the MGS is located within this region. The MGS has active mapping projects within the Metropolitan area where depth to bedrock is an important topic and, even with a general abundance of well data, there are still areas with limited information. The Twin Cities area is also a major market for groundwater and geo-engineering organizations that might find the HVSR method useful. The bedrock geology is also favorable, consisting of Paleozoic strata (Figure 5) that are likely to present a reasonably flat and fresh bedrock surface in many areas. Very little Cretaceous strata or saprolith are known in the Twin Cities region. Finally, the glacial stratigraphy is relatively simple over most of the region, being dominated by late-Wisconsinan sediments (Meyer, 1985, 2007).

A total of 61 HVSR control measurements were collected in the Twin Cities area, but for calibration, a sub-set of optimal observations was selected (Figure 10). These consisted of observations with single HVSR peaks and amplitudes of 3.5 or greater, and resulted in 41 controls. The selected measurements define a distribution along a linear trend on a signature plot (Figure 11a), resulting in a power-curve fit with a = 129, b = -1.295 and R (correlation coefficient) = 0.968. Examples the spectra are shown in Figure 12. Rejected control samples included HVSR spectra with low-amplitude, broad or flat top peaks, and multiple peaks packed closely together. Examples of the lower quality spectra are shown in Figure 12b. The variety of rejected samples is thought to reflect unfavorable subsurface conditions such as an uneven or sloping bedrock surfaces (Gueguen and others, 2007), or lateral variations in the sediment.

The percentage error for depth estimates using the parameters derived from the 41 control points, was calculated as follows:

((Estimated depth-well depth)/well depth)*100 = %

Out of 41 controls, 26 estimated depths (63%) were within +/-15% error and 37 (90%) were within +/-25% (Figure 12b). The largest errors are associated with depths of 75 meters (246 ft.) or less. The above parameters were also used for depth estimates at the 20 rejected control stations, and of these only 9 (45%) were within +/-15% error and 11 (60%) were within +/-25% error. Although the sampling is limited, the results indicate that depth estimates derived from low-quality HVSR peaks should be used with considerably more caution than those derived from high-quality HVSR peaks.

Figure 11c shows the relationship between the first trough frequencies and HVSR peak frequencies. Most of the points closely follow the 2:1 relationship line, indicating a general equivalency between peak- and trough-based depth estimates. The 2:1 ratios for the peak/trough couplets are also consistent with strong acoustic impedance contrasts at the bedrock interface (Konno and Ohmachi, 1998)

Average shear-wave velocity for the glacial sequence can be estimated at each control station by using the HVSR peak frequency and known depth with Equation 1. Such estimates represent linear averages of a function that is likely to be non-linear (Bundy, 1984), and therefore the velocity may not represent any specific unit in the glacial sequence. Nonetheless, such estimates provide at least some shear-wave velocity information in a region where very little shear-wave data are available, and they provide insights into the degree that shear wave velocities vary laterally and vertically within the glacial sequence. These estimates also provide a check on the validity of a control; for example, an extreme shear-wave velocity estimate may indicate that the selected HVSR feature does not reflect the bedrock surface. Figure 11d shows the average velocities derived at various depths from the selected control stations. In this form the error of the HVSR analysis manifests as scatter in velocity. A general trend of increasing average velocity with depth is apparent, starting with 240-300 m/sec near the surface and increasing to about 600 m/s at 150 meters, with the most scatter between 25 to 75 meters depth, where estimated velocities range between 330 to 540 m/s. This scatter likely reflects lateral variations in the glacial deposits. Geological cross-sections in the Twin-Cities area indicate that glacial stratigraphy can change significantly over a lateral distance of only a few km (Meyer, 1985; Hobbs and others, 1990; Lusardi, 2009; Meyer, 2010).

Buried Valley Test in Washington County

Recent HVSR work in the Twin Cities metropolitan area included an investigation of a narrow (400-650 m), deep (60-80 m) bedrock ravine that is largely concealed by glacial deposits in southern Washington County, near the border with Wisconsin. The valley, which is thought to extend in roughly a north-south direction is of interest because it is a local source of groundwater, and it is a potential path for pollutants to enter bedrock aquifer systems. Being fairly narrow in width, the valley has not been adequately defined by well data, and considerable conjecture is involved in mapping its location and extent. Seismic refraction was applied with some success on parts of this feature about twenty years ago (Swanson and Meyer, 1990), but further acquisition of these data would be expensive, slow and likely to be frustrated by a high traffic and other cultural noise that has come with subsequent development of the area. Using the HVSR methods, a reconnaissance profile was conducted across a segment of the ravine in the Cottage Grove area, where it is partially exhumed. The profile, consisting of 5 stations, was acquired by one individual in 2 hours. Near the profile, well control was good (Figure 13a), with one well indicating a depth to bedrock of 67 m (220 ft.), and nearby wells indicating much shallower bedrock. The HVSR peaks show a marked and systematic shift to lower frequencies near the projected axis of the valley (Figure 13a). Conversion of these peak frequencies to bedrock depth using the parameters derived for the Twin Cities Metropolitan Area yield estimates that appear to be compatible with surrounding well data (Figure 13b). The HSR method assumes a flat bedrock surface, and it is probable that the degradation of results at stations Wash 12 and Wash 13, signified by decreased peak amplitudes and double peaks, is caused by a sloping or uneven bedrock surface (Gueguen and others, 2007) at the western valley sidewall.

The success of the HVSR method in tracing the buried ravine at Cottage Grove, prompted further work to locate the ravine in an area several kilometers to the north where the ravine is completely concealed and well control is missing in critical areas. As with Cottage Grove, depths were estimated from HVSR peak frequencies using the Twin Cities Metropolitan Area parameters. The trace of the buried ravine is revealed by markedly deeper estimates in four locations (Figure 13b). Tracing the ravine using these points produces a nonuniform pattern suggestive of control by two or more joint sets.

South-Central Minnesota

General Considerations

The second test area was in south-central Minnesota (Figure 14), where bedrock and glacial sediment conditions are more complex. There, the bedrock surface consists primarily of less rigid materials, such as saprolith or Cretaceous strata (Figure 6), which do not favor a strong HVSR response relative to the overlying glacial sediment. In addition, the glacial sequence can be considerably thicker and more complex than that in the Twin Cities Metropolitan area.

Stratigraphic horizons may include Wisconsinan and pre-Wisconsinan sediments, some of which have been densely compacted (over-consolidated) (Knaeble, 2006; Meyer, 1986). As a result, the glacial sequence itself may contain acoustic impedance contrasts that could obscure or even preclude a HVSR signature from the sediment-bedrock interface, especially if softer saprolith or Cretaceous strata constitute the bedrock surface.

HVSR Analysis

HVSR data were collected at 77 control locations (Figure 14), where bedrock depth could be established from drill holes (73) or from seismic refraction lines (4). High quality peaks are shown in Figure 15a. Examples of the lower quality spectra are shown in Figure 15b, along with examples of trough frequencies. Initial analysis showed considerable variation in the quality of the HVSR peaks and in the peak frequencies for data from similar known depths. To eliminate the potential error that could be introduced with either saprolith or Cretaceous strata at the bedrock surface, a subset of 27 stations were selected where these relatively soft units appeared to be either thin or absent. An initial observation of peak-based values revealed considerable scatter, relative to the overall distribution for bedrock depths in excess of 100 meters (Figure 16a). Use of one-half the trough frequency for depths in excess of 100 meters created a better overall alignment of points (Figure 16a) and these values were used in forming the calibration curve. Hinzen and others (2004) implemented a similar selection of trough-based frequencies for deeper parts of the Lower Rhine Embayment, although there the transition depth was 500 m rather than the 100 m in Minnesota.

Thus fitted, parameters from the 27 control points from south-central Minnesota (Figures 16a and 16b), follows:

$a = 135$
$b = -1.248$
$R = 0.9532$ (correlation coefficient)

The percent error data for the 27 selected control stations are summarized in Figure 16c. Out of the 27 depth estimates, 21 (78%) are within +/-15% of the drill hole value and 26 (96%)

are within +/-25%. The minimum/maximum percentage errors are -23% and 26% respectively, and the average error is 10%. The results imply that reasonably accurate depth-to-bedrock estimates are possible in south-central Minnesota, provided that it is known ahead of time that saprolith and Cretaceous are absent. Unfortunately that is usually not the case, and no reliable criterion has yet been established from the HVSR results that unequivocally indicates the presence of such soft bedrock. However, comparing the rejected soft-bedrock controls with the hard-bedrock curve derived above can further assess the effect of saprolith or Cretaceous bedrock.

The rejected control stations were subsequently divided into two subsets, one where saprolith was reported at the bedrock surface and one where Cretaceous strata were reported. Both of these conditions were assumed to degrade the acoustic impedance contrast at the bedrock surface. A comparison of the hard-bedrock results with the data for the latter two subsets is presented in Figure 16b with different color dots representing the datasets. The percent error of the saprolith and Cretaceous stations, relative to curve derived from the 27 calibration stations, is included in Figure 16c.

In Figure 16c the 27 saprolith control stations are associated with percent errors ranging from -22% to 55%, and an average error of 17%. Fifteen lie within +/-15% and 6 lie outside of +/-25%. The largest percentage error for the saprolith stations appears to be greatest for depths less than 50 meters. For deeper bedrock depths the saprolith stations appear to be associated with errors that are no larger than those of the points used to make the hard-bedrock calibration curve (Figure 16b and 16c). The apparent reduction of error with depth may reflect thinning of the saprolith due to erosion in low spots, or it could simply reflect the saprolith becoming a smaller percentage of the total, low-velocity sequence, as compared with the thickening Quaternary deposits. In either case, saprolith does not appear to greatly affect HVSR depth estimates for bedrock surfaces deeper than 50 meters. Results from 9 control stations where wells passed through saprolith to fresh rock (Figure 16d), showed that in 5 cases, using the depth to fresh bedrock instead of depth to saprolith resulted in points that were closer to the hard-bedrock calibration curve, but in four cases, this substitution resulted in points further from the curve (Figure 16d). This implies that the HVSR results may in some cases be tracking the transition to fresh rock but in other cases may be tracking closer to the saprolith surface.

Compared with the saprolith stations the results from the 21 Cretaceous control stations depart severely from the hard-bedrock calibration curve (Figures 16b and 16c). The Cretaceous-bedrock results have errors that range from -6% to 673%, and the average error is 106%. Six of the Cretaceous-bedrock control estimates (29%) lie within +/-15% of the well data and nine (43%) lie within +/-25%. The greatest error appears to be associated with bedrock depths of 70 meters (230 ft.) or less. The implication is that in these areas, the HVSR data is not tracking the Cretaceous bedrock surface at all, but a significantly deeper interface. Cretaceous rocks were investigated in greater detail at 13 HVSR stations that were located at wells that penetrated the entire Cretaceous sequence (Figure 16e). Using the depth of the pre-Cretaceous surface instead of the depth to the Cretaceous strata significantly lessens the departure of the points from the calibrated curve in all but three cases. The results in Figure 16e indicate that the HVSR results derived over Cretaceous strata in Minnesota most likely reflect the depth to the pre-Cretaceous surface, which in most cases is saprolith derived from Precambrian crystalline rocks.

The estimated average shear-wave velocities at various depths in the glacial materials for south-central Minnesota are shown in Figure 16f. Similar to the Twin Cites data, the error around the calibration curve for the HVSR analysis manifests as scatter in the velocity estimates. A general trend exists of increasing velocity with depth, resulting in poorly defined 230-340 m/sec velocities near the surface, 425-585 m/sec velocities between 50-100 meters, 440-620 m/sec velocities for 100-150 meters, and 535-650 m/sec velocities between 150-200 meters depth. The average shear-wave velocities estimated here are generally higher than those observed for the Twin Cities metropolitan area, possibly reflecting the contribution of over-consolidated tills in the older glacial sequence.

Fluvio-lacustrine Deposits along Major River Valleys

General Observations

It was noted fairly early in the development of HVSR calibration parameters in Minnesota that values derived for glacial deposits consistently overestimated bedrock depth when applied to HVSR data taken on floodplains or terraces along major river valleys. For example, measurements crossing the floodplain of the Mississippi River in southeastern Minnesota produced depth estimates on the order of 250 ft., although nearby wells indicated bedrock depths more in the range of 170 ft. (about a 47% overestimate). Considering the relationship between primary resonant frequency and sediment thickness (Equation 1), the overestimate implies that the average shear-wave velocities of the deposits in the river valleys are significantly lower than that of till and outwash on the glaciated uplands. Such a difference in shear-wave velocity can be explained by considering that the major valleys in the region served as primary drainages for melt-water during the waning stages of late-Wisconsinan glaciation (Wright, 1972; Blumentritt and others, 2009). One or more of these drainage events would tend to remove any previously existing soft bedrock and older glacial deposits, ultimately producing a relatively uncompacted sequence of outwash, fluvial, and lacustrine deposits on top of relatively fresh bedrock.

HVSR Analysis

For the fluvio-lacustrine calibration curve, 37 HVSR measurements were collected at well control points on floodplains and terraces along the Mississippi, Minnesota, St. Croix and Kettle Rivers (Figure 17). The HVSR analyses taken from the bottoms and terraces of the major river valleys yielded some of the cleanest, high-amplitude peaks observed in the region (Figure 18). These HVSR results are fitted by a calibration curve (Figure 19a) that yields the following parameters:

$a = 83$
$b = -1.232$
$R = 0.9515$ (correlation coefficient)

Using those coefficients, the fluvio-lacustrine stations have errors that range from -36% to 77%, with an average magnitude of error of 20% (Figure 19b). Of the 34 control stations that reach bedrock, 16 (47%) lie within +/-15% error and 28 (82%) lie within +/-25% (Figure 19b). The greatest error generally occurs at depths of less than 20 meters, and may in part reflect uneven bedrock surfaces, particularly near the valley walls where the bedrock surface is more likely to be sloping or contain talus. Although more accurate calibrations may be possible by focusing on specific river valleys or stretches of river valleys, the relationship derived above should provide rough estimates of bedrock depth along the bottoms and terraces of the major river valleys in the region.

The valley sample HVSR peak frequencies vs. one-half the first trough frequencies approximate a 1:1 relationship (Figure 19c), indicating that the first trough can be also used for depth estimates. Figure 19d shows the average shear-wave velocities at various depths for the 37 selected control stations described above. Although considerable scatter exists, a general trend for increasing velocity with depth is clear, with 100-280 m/sec velocities near the surface, 220-350 m/sec velocities between 30-50 meters depth, and 300-380 m/sec velocities to 70 meters depth. The overall distribution of velocity values for the fluvio-lacustrine deposits is conspicuously lower than that observed for the glacial uplands, a distinction that was not anticipated when first developing our regional models.

Intra-Glacial Horizons in HVSR Data

General Comments

HVSR studies over other glaciated areas indicate that acoustic impedance contrasts within the glacial sequence can produce HVSR peaks that can easily be misinterpreted as a bedrock signature (Gosar, 2008; Perret, 2012), and similar situations could clearly exist in Minnesota, especially with the presence of dense, over-consolidated tills. Likely candidates for intra-glacial picks are manifested in Figures 9a and 9b by those HVSR stations that produce points in that plot well above the main distribution of results. In other words, stations where the known depths are anomalously large for the observed HVSR frequencies. The results from two of these anomalous stations, those at CWI drill holes #243180 and #2101 are discussed below.

Site at CWI Well #243180 (Cored borehole, Sherburne County, Minnesota)

The drill hole encountered sand and gravely sand between 0 and 7.3 m (24 ft.,) sandy, relatively clay-free till of the Superior Lobe (Figure 3) between 7.3 m and 33.2 m (109 ft.) cobbly sand and gravel between 33.2 m and 37.5 m (123 ft.), saprolith between 37.5 m and 38.7 m (123-127 ft.) and fresh granite at 38.7 m. The HVSR results observed at this site (Figure 20a) showed a broad, skewed peak with a maximum at 6.17 Hz, a shoulder at 4.30 Hz, and a half-trough value of 5.71 Hz. Using the HVSR parameters derived for the Twin Cities metro area (a = 128.88, b= -1.2948), these equate to depths of 12.2 m (40 ft.) , 19.5 m. (64 ft.), and 13.4 m (44 ft.), respectively, none of which are close to the observed depth of the saprolith or granite. The Superior Lobe till in this hole has been described as “very dense” (Gary Meyer, MGS, oral communication), and it is likely that the acoustic impedance contrast of this dense sediment with the overlying sand (about 7 m depth) is the dominant response in the HVSR results.

Further analysis was conducted using a modeling program included with the Tromino/ Grilla software package. The model assumes flat layers and ambient tremors from randomly distributed sources that are composed of Rayleigh and Love waves (Castellaro and Mulargia, 2009b). To develop a model estimate, a number of layers are entered and the density, shear-wave velocity, and thickness values for each are adjusted until a suitable fit is achieved with the measured HVSR data interpretation. Density, which is not a crucial parameter, can be approximated from physical property investigations (Chandler and Lively, 2011). The ambiguity inherent to this modeling is reduced by the depth information from the well. Average shear wave velocities, calculated from Equation 1, at the station being modeled as well as from other sites, is helpful in selecting a reasonable range of velocities for the modeling.

The shear-wave model derived for station 243180 is shown in Figure 20b. The results indicate that Vs values are 200-230 m/sec to 9.1 m (30 ft.), where the velocity abruptly changes to a value of 600 m/sec, suggestive of the top of the compact till. Shear-wave velocities of

600-630 m/sec extend to a depth of 38.1 m (125 ft.), where they increase to 860 m/sec, a value consistent with saprolitic granite. This simple, but geologically and geophysically reasonable model yields a close fit to the observed HVSR spectral curve (Figure 20a). In this model a bedrock signature is present, but its peak has been shifted up-spectra, in response to the high till velocities, to become a side-lobe with the dominant, glacially derived HVSR peak. The results demonstrate that shear wave modeling can be a useful supplement to interpretation, provided that either depths or shear-wave velocities are adequately constrained.

Station at CWI Well #21001 (Mineral exploration borehole, Meeker County, Minnesota) BKV-81-1 CWI #21001. Driller's logs indicate that Well #21001 penetrates a thick sequence described as "glacial drift" before encountering sandstone at 187.1 m (614 ft.) and gabbro at 683 ft. (208.2 m). The HVSR spectrum displays a primary peak at 2.63 Hz and a secondary peak at 6.20 Hz (Figure 20 c), both of which are unrealistically high for a bedrock surface at such depths. For example, primary peak frequency of 2.63 Hz equates to depths of only 40.2 m (132 ft.) with the south-central parameters, and only 36.9 m (121 ft.) with the Twin Cities Metropolitan parameters. If the primary peak frequency of 2.63 Hz is combined with the 187.1 bedrock depth into Equation 1, the result would imply a shear-wave velocity of 1968 m/sec for the glacial sediments, which is well above velocity determinations from previous investigations (Carr and others, 1998) and this study (Figures 12d and 16f). It is far more likely that both the primary (2.63 Hz, and the secondary (6.20 Hz) peaks observed for station #21001 represent horizons within the glacial sequence. No stratigraphic information for the glacial sequence is available at CWI Well #21001, but a driller's log from a nearby well (CWI 133074, not shown) reports "hard gray clay" at a depth of 43.6 m (143 ft.), which could more feasibly be related to the primary peak.

Although a prominent bedrock signature is lacking, a weak peak at 0.74 Hz and corresponding first trough with half-frequency of 0.76 Hz (see arrows in Figure 20c) might represent bedrock. Using the south-central parameters an average value of 0.75 Hz equates to a depth of 193.2 m (634 ft.), which is certainly within a reasonable margin of error of the observed bedrock depth. These results imply that deep bedrock signatures may be recognizable, even when the signature is dominated by intra-glacial sources, but considerable caution is warranted. Away from control points such subtle features may be overlooked, and reasonably so; the amplitudes of the weak peak and trough in Figure 20c are less than the standard deviation of error (black lines). Furthermore, noise could completely obscure such subtle signatures in many situations. The potentially misleading results observed here underscores the importance of acquiring data at control points that span a wide range of probable bedrock depths, when moving into a new area. The noticeably high position of these two stations on the summary HVSR plots of all control stations (Figures 9a and 9b) implies that extreme underestimates of bedrock depth, due to intra-glacial sources, may be relatively rare, at least in the areas investigated so far.

DISCUSSION AND CONCLUSIONS

The HVSR method for calculating depth to bedrock has been evaluated for a variety of Quaternary sediment conditions, as well as a variety of bedrock conditions in Minnesota and adjacent parts of Wisconsin. Results from the evaluation indicate that it can perform reasonably well, but some caution is warranted in general usage. In general, application of the HVSR method relies on assumptions that a bedrock surface is flat and there is acoustic impedance contrast at the bedrock sediment interface that is generally 2.5 or greater. In the weathered and glaciated bedrock terrain of Minnesota, these assumed conditions are not always met, and adjustments must be made. The glacial sequence in Minnesota is a complex, multistage, depositional sequence, resulting in lateral and vertical variations that likely equate to an increase in the error of the empirically-based, power-curve approach to depth estimation (Equation 1). Additional complications arise in areas where saprolith and relatively soft Cretaceous rocks compose the bedrock surface. Consequently, the HVSR method in Minnesota may only be able to provide general estimates of bedrock depth (15-25% error) in glacial deposits and may have higher error when more adverse conditions are present. Nonetheless, for large areas of the state, these estimates are significantly better than no information at all and they provide useful data for geologic and topographic mapping of the bedrock surface. For example, the HVSR data was highly effective at locating the trace of a deep and narrow buried valley east of the Twin Cities metro area, by plotting peak frequencies independently from calculations of model depths (Figure 13). On a cautionary note, noticeably anomalous results should be crosschecked with additional HVSR stations, and, if necessary, with other geophysical methods.

The most reliable depth estimates were associated with single HVSR peaks that had a large (>3.5) amplitude. In contrast, HVSR results exhibiting broad, flat-topped peaks, tightly packed multiple peaks, or peaks with pronounced side-lobes, were associated with significantly higher errors for the depth estimates. In the Twin Cities metro area depth errors (residuals relative to the fitted curve) for 41 singular, high-amplitude peaks used in the HVSR calibration yield an average absolute percentage error of 13% with 90% of the estimates being within +/-25% of observed bedrock depths. These results should serve as a proxy for expected error at similar-quality HVSR peaks in areas lacking well control. By comparison, applying the same calibration curve to 20 other control stations with HVSR peaks that displayed some of the undesirable attributes mentioned above, resulted in an average percentage error of 26% with only 60% of the estimates being within +/-25% of observed bedrock depth. The less desirable peaks likely arise from a variety of causes, including uneven bedrock surface, low acoustic impedance contrast at the bedrock-sediment interface, and complex glacial stratigraphy. Currently no means of discriminating these possible causes has been discovered through any of the traits observed in the HVSR data.

In general, the heterogeneity of glacial deposits will likely prevent the HVSR method from consistently producing results that fall below a percentage error of +/-10%, a figure that is sometimes cited for conventional seismic refraction profiling under favorable conditions (Zohdy and others, 1974; Haeni, 1986). On the other hand, glacial stratigraphy also presents less-than-favorable conditions for conventional seismic profiling. This is evident from an error analysis of 34 seismic refraction soundings (P-wave) by the Minnesota Department of Natural

Resources and MGS that were collected within 250 meters of well control (Figure 21). The minimum depth, maximum depth and average depth for each interpretation were examined and the value closest to the observed bedrock depth of the well was selected. Of the 34 stations 24 (71%) are within +/-15% error and 58 (74%) are within +/-25%. Thus for this group of data, the errors in seismic refraction profiling are quite comparable with those from the HVSR method. Lateral variation in seismic velocity, which we believe is one of the major sources of error within the HVSR results, can also be a source of error with seismic refraction, along with thin layers, and velocity inversions, which cause under- or over-estimates of bedrock depth respectively. While this error analyses is not a rigorous comparison of HVSR versus seismic refraction data; the result does demonstrate that glacial deposits and bedrock variations create comparable challenges to conventional seismic profiling.

Of course multi-channel seismic methods provide additional information regarding seismic velocities and the form, if not the exact depth, of the bedrock surface, especially if reflection surveys are carried out. However, the cost and field logistics of conventional seismic profiling preclude its use for many organizations with limited staff and budgets. On the other hand, the ability to collect a large number of data points, quickly check and re-measure sites if necessary, and the low staff requirements make the HVSR method an attractive alternative, especially in many geologic mapping applications where high-precision may not be necessary. In addition, the HVSR method can operate effectively in developed areas that have a high background of cultural noise, a situation where use of conventional seismic methods can be severely restricted.

In conclusion the passive HVSR method is a potentially powerful tool for engineering and groundwater investigations in Minnesota and adjacent areas that are concerned with the thickness of Quaternary sediment. Although not always as precise or informative as conventional seismic methods, the HVSR method offers distinct advantages with regard to cost and speed, number of sample sites and wide range of usable locations. When encountering a new area, a preliminary investigation with measurements at carefully selected control points is necessary to confirm and evaluate the nature of the bedrock-sediment signature, after which the utility of the method for a given application can be assessed. In many applications and areas, the HVSR method can be used instead of conventional seismic methods, and where this is not the case, the HVSR method can be helpful in determining the best locations for analysis using conventional seismic methods.

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FIGURES

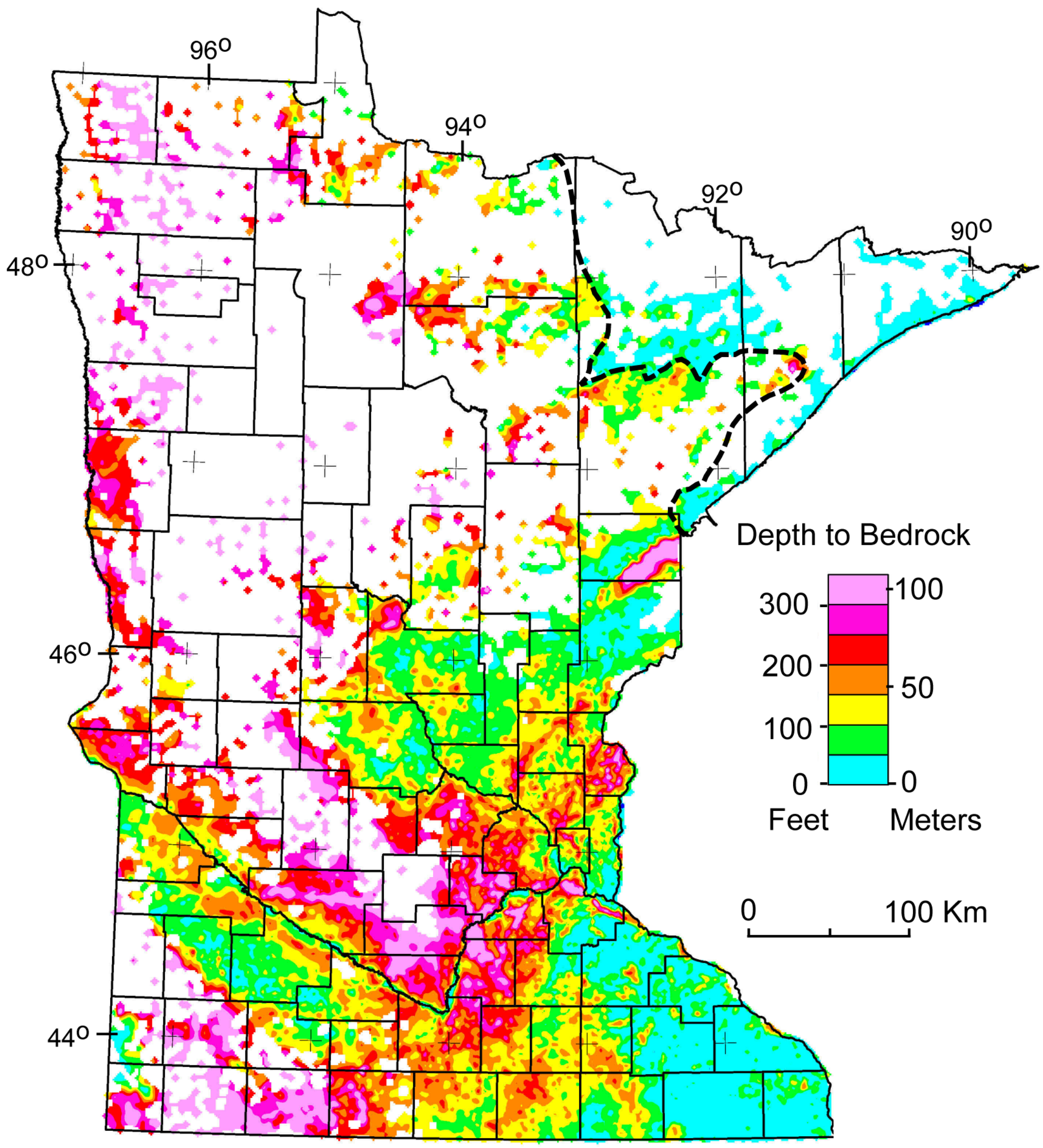

Figure 1. Glacial sediment thickness map of Minnesota, based on County Well Index (CWI) drill holes to bedrock. Areas not having a CWI control point within 2 km are blank and bedrock depths were inferred by interpolation (Lively and others, 2006). Bedrock is abundantly exposed in areas east and north of the heavy dashed line, northeastern Minnesota, and the land topographic surface approximates the bedrock surface

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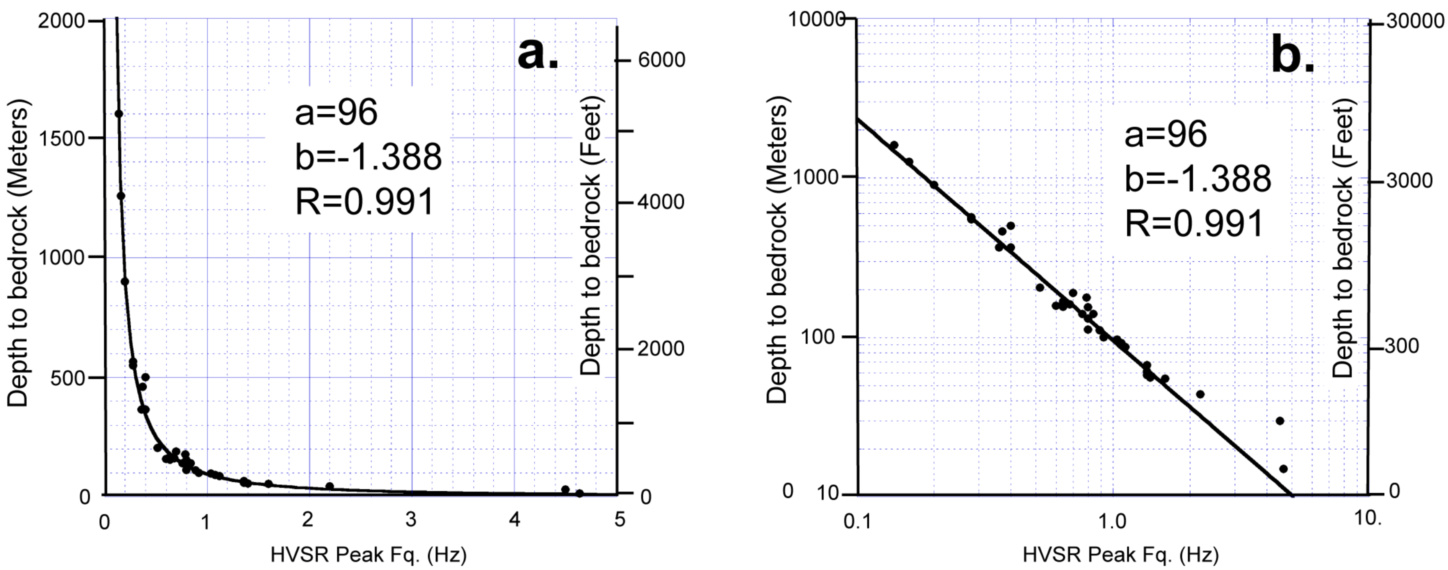

Figure 2 Ibs-von Seht HVSR relationship for the Lower Rhine Embayment. (a) linear plot of HVSR peak frequency vs. observed depth to bedrock. (b) log (signature) plot of HVSR peak frequency vs. observed depth to bedrock. Parameters are described in text.

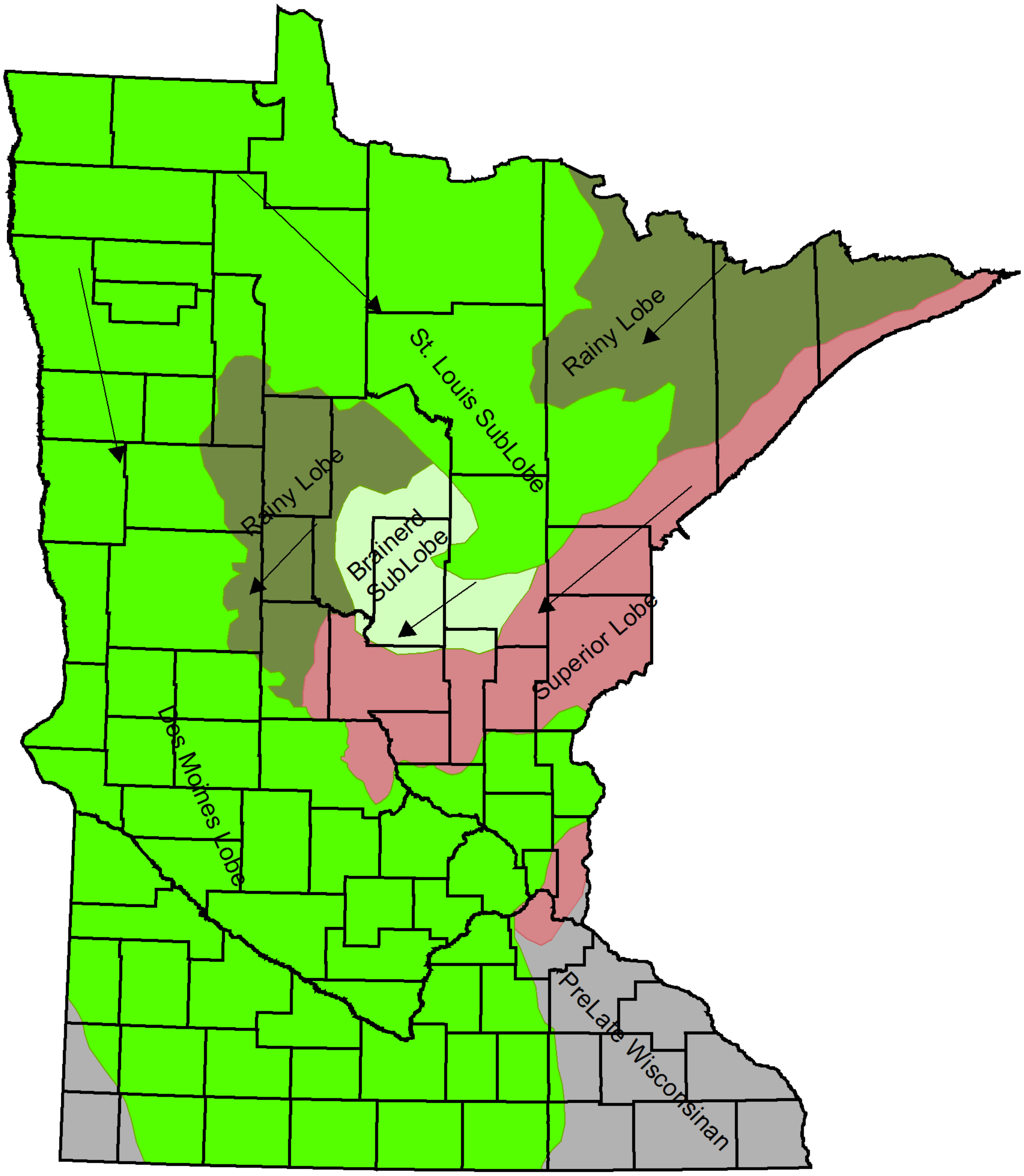

Figure 3 Map of Minnesota showing the major late Wisconsinan glacial advances (modified from Knaeble, 2006.)

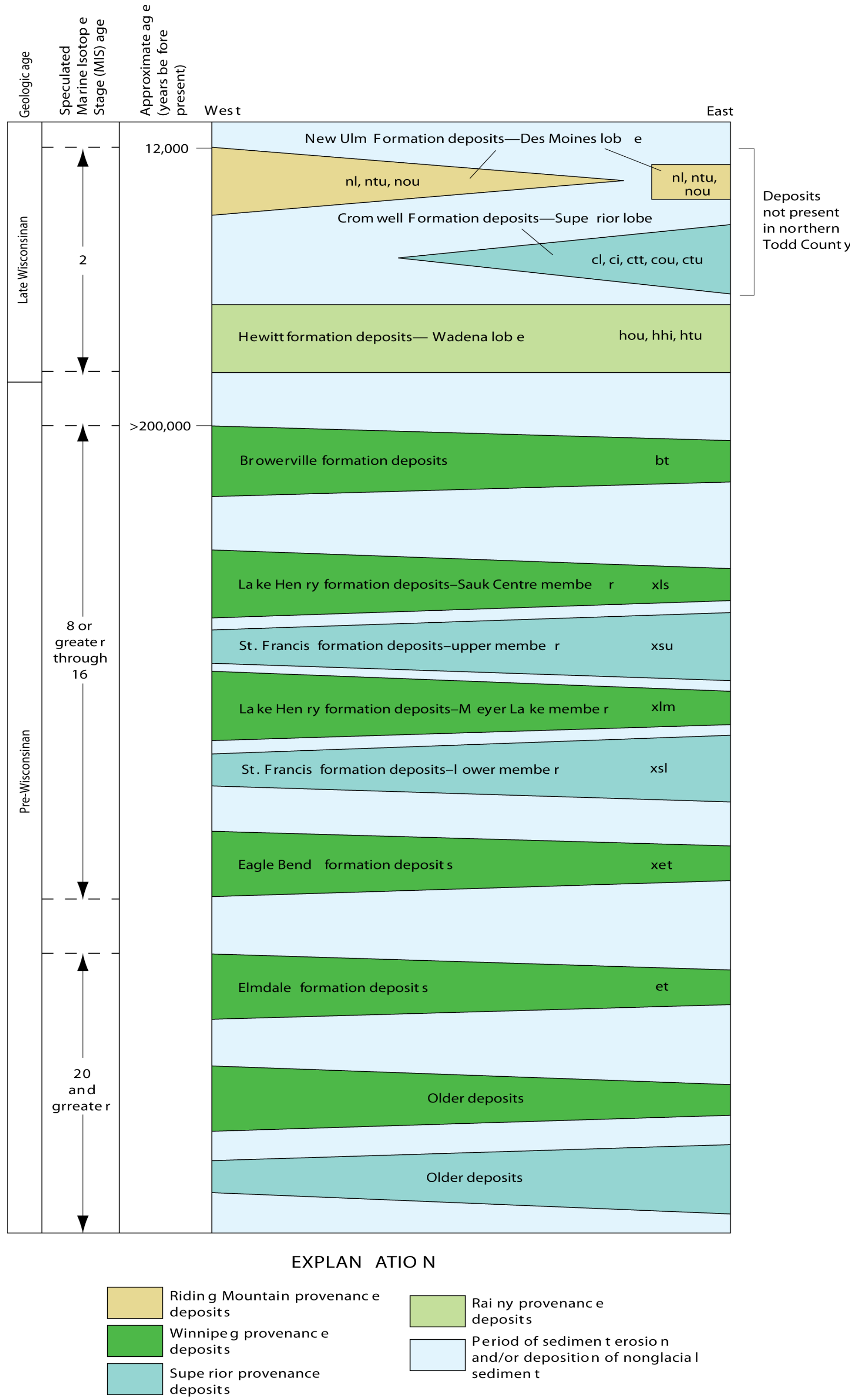

Figure 4 Till source stratigraphy of central Minnesota (Todd County), showing major till units from recognized late Wisconsinan (see Figure 3) and Pre-late Wisconsinan ice advances. (Knaeble and Meyer, 2007)

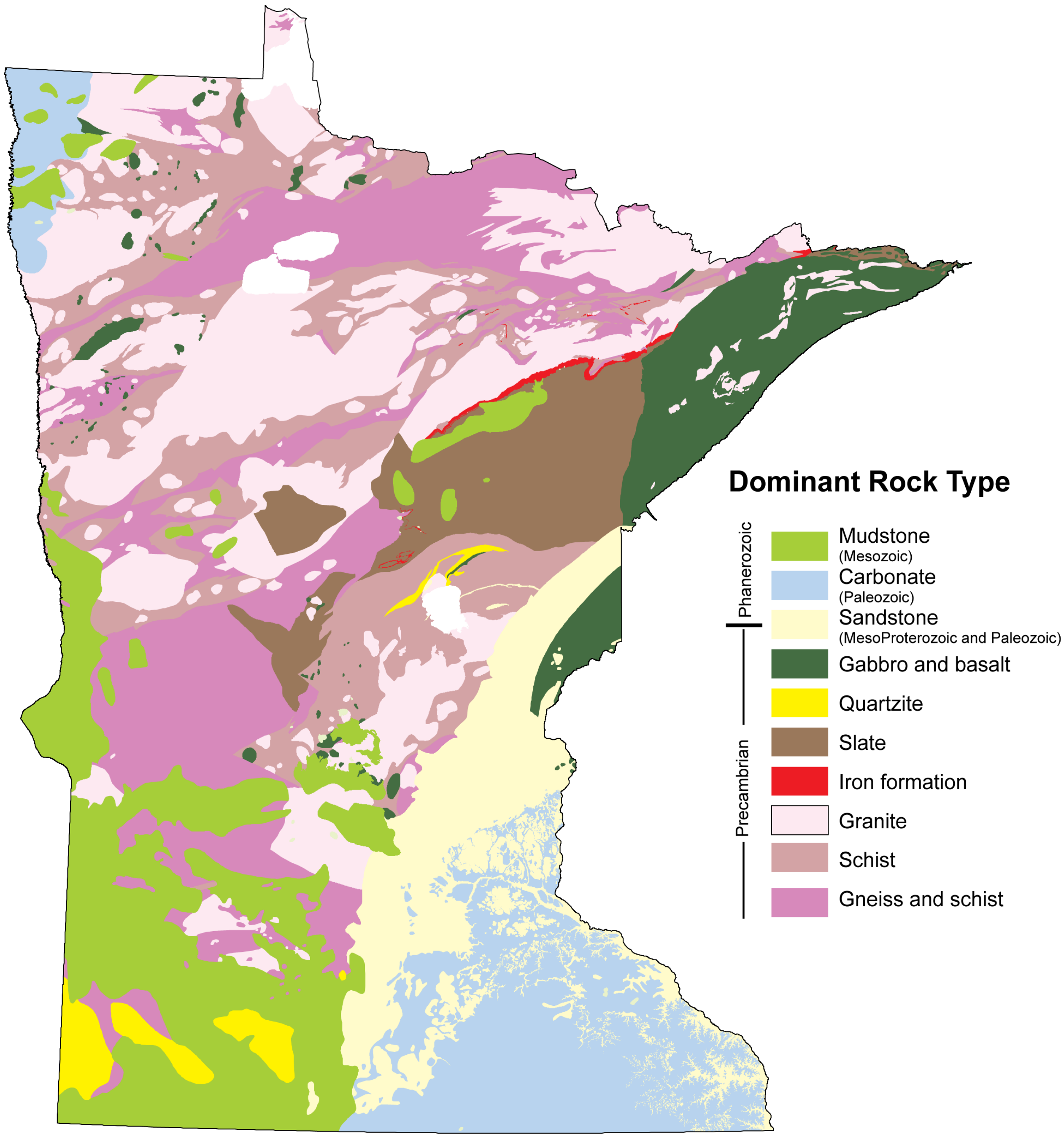

Figure 5 Geological map of Minnesota showing the major bedrock types (generalized from Morey and Meints, 2000). Except for a few outliers of Jurassic deposits in extreme northwestern Minnesota, all Mesozoic rocks are Cretaceous.

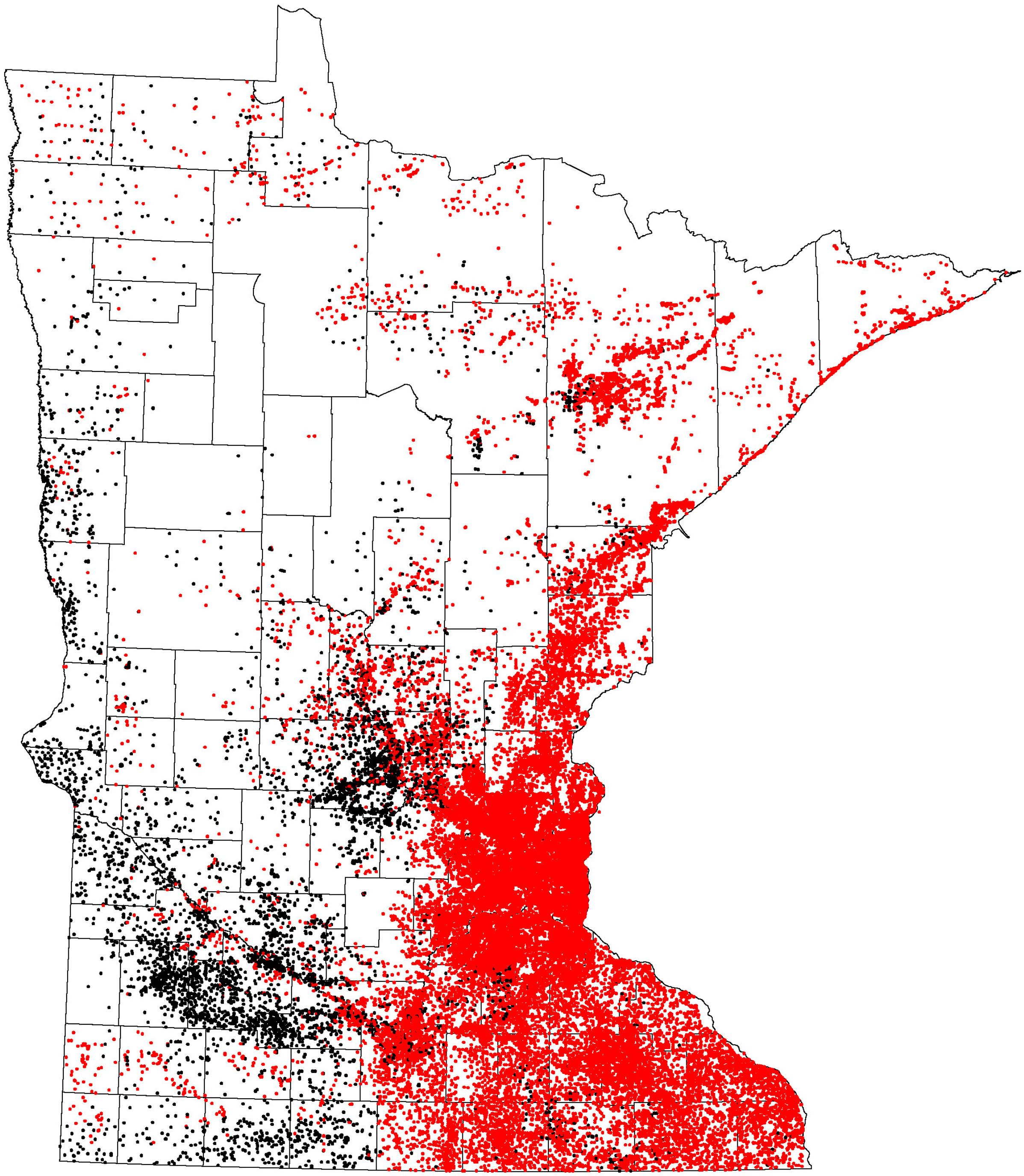

Figure 6 CWI drill holes in Minnesota that reach bedrock. Black dots designate wells reported to encounter either saprolith or Mesozoic strata at bedrock surface, and red dots designate wells reported to encounter presumably harder Paleozoic or Precambrian rock at the bedrock surface.

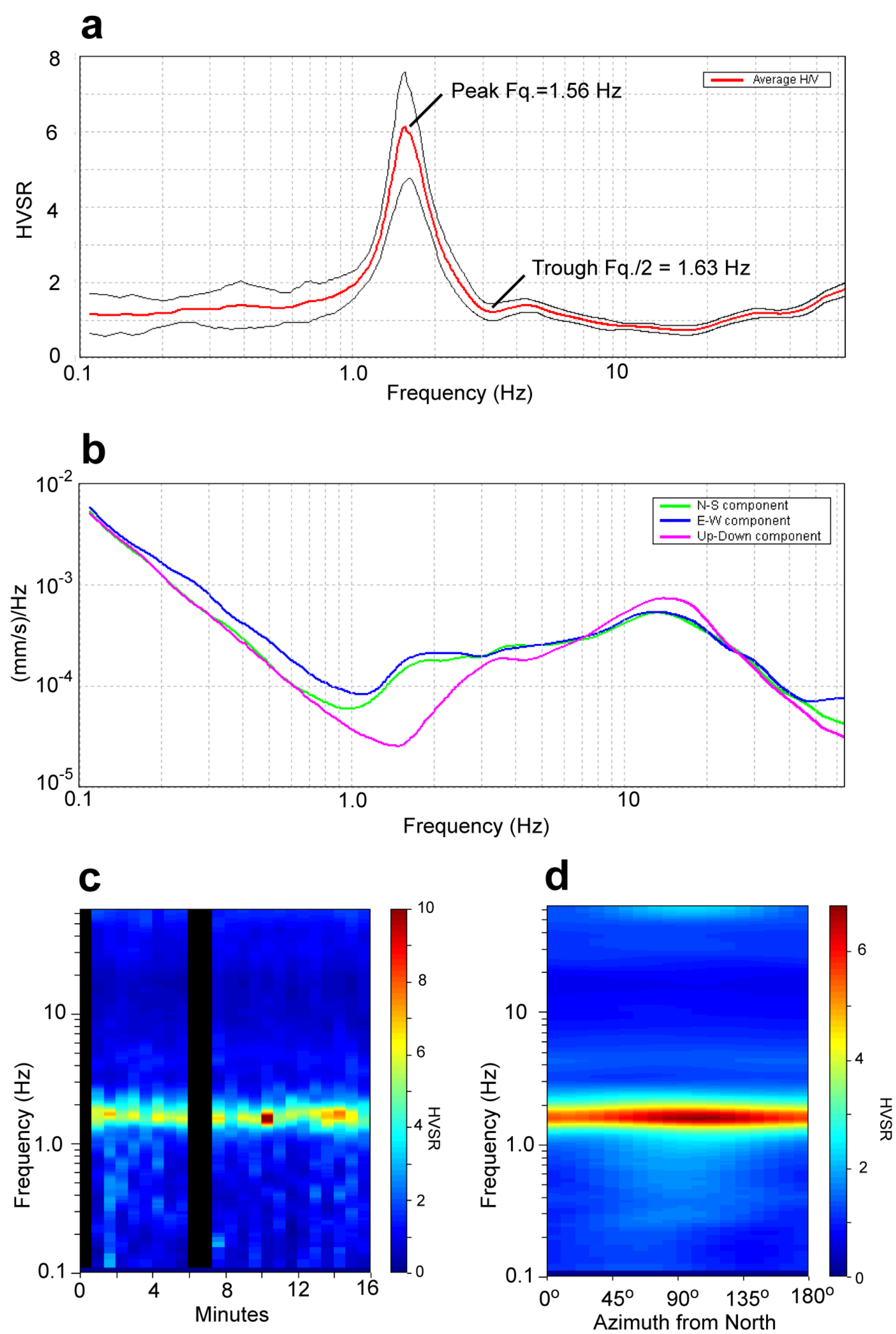

Figure 7 HVSR analysis for station located near bedrock well CWI 206721 ("Mounds View", see Figures 10 and 11). (a) HVSR spectra, (b) individual component spectra (note the "eye" feature corresponding to the HVSR peak), (c) time progression spectra, showing the spectra of the individual 20 second time segments that were used to compute average spectra shown in a and b, (d) directional component spectra, with north-south indicated as 0 and 180 degrees. The red line on the HVSR spectrum represents the average value, the black lines designate the standard deviation (Figure 7a).

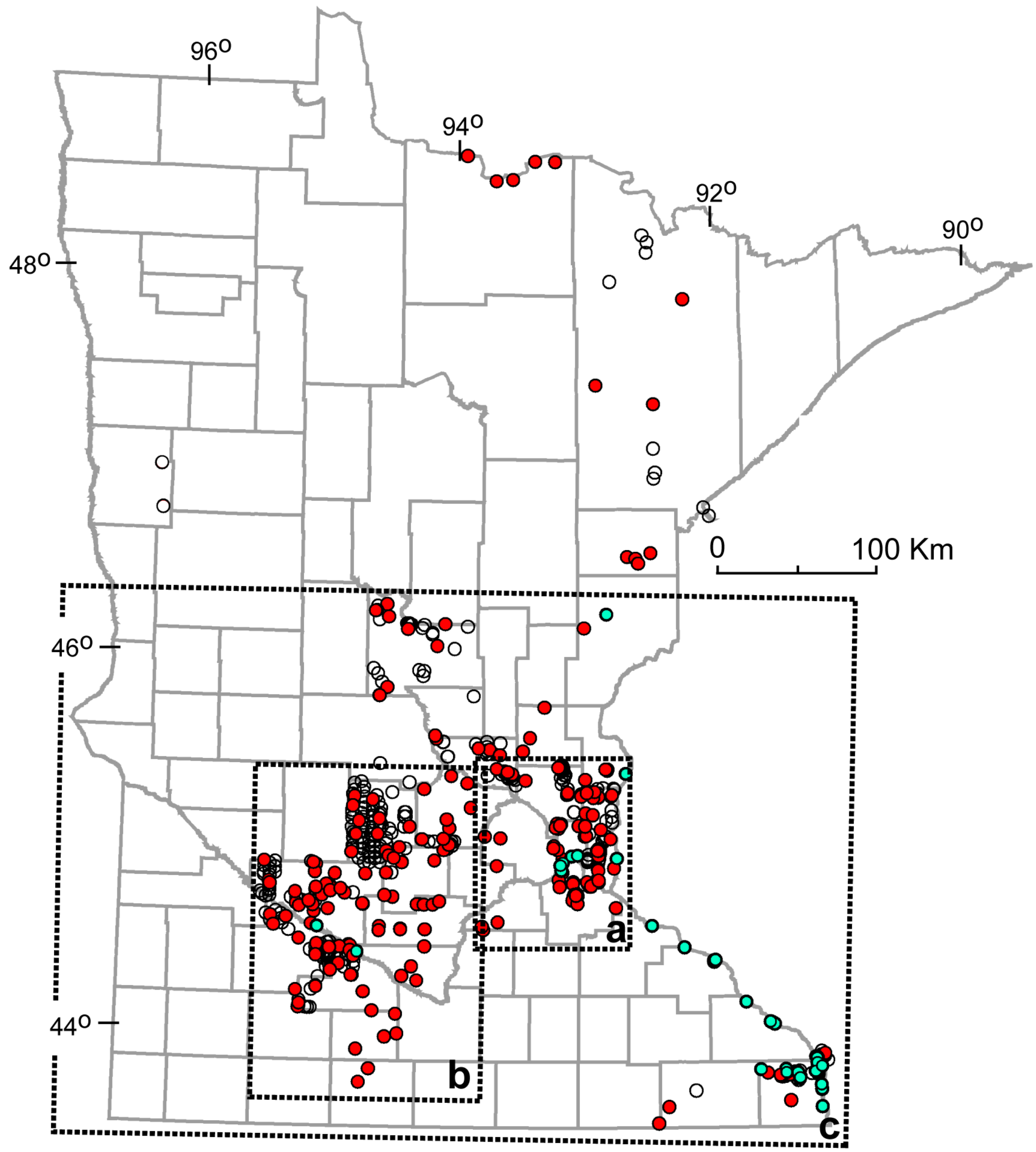

Figure 8 Map showing all HVSR stations acquired in Minnesota through 2012. White open circles designate exploration stations (no bedrock control), red circles designate control stations (wells or seismic soundings to bedrock) located on glacial deposits, and Blue circles designate control stations located on terrace and floodplain deposits of major rivers. Boxes in dotted lines designate study areas discussed in text, consisting of (a) the Twin Cities Metropolitan Area, (b) south-central Minnesota area, and (c) the fluvio-lacustrine area, encompassing floodplain and terrace deposits along the Minnesota, Mississippi, Root, St. Croix, and Kettle Rivers (see Figure 17).

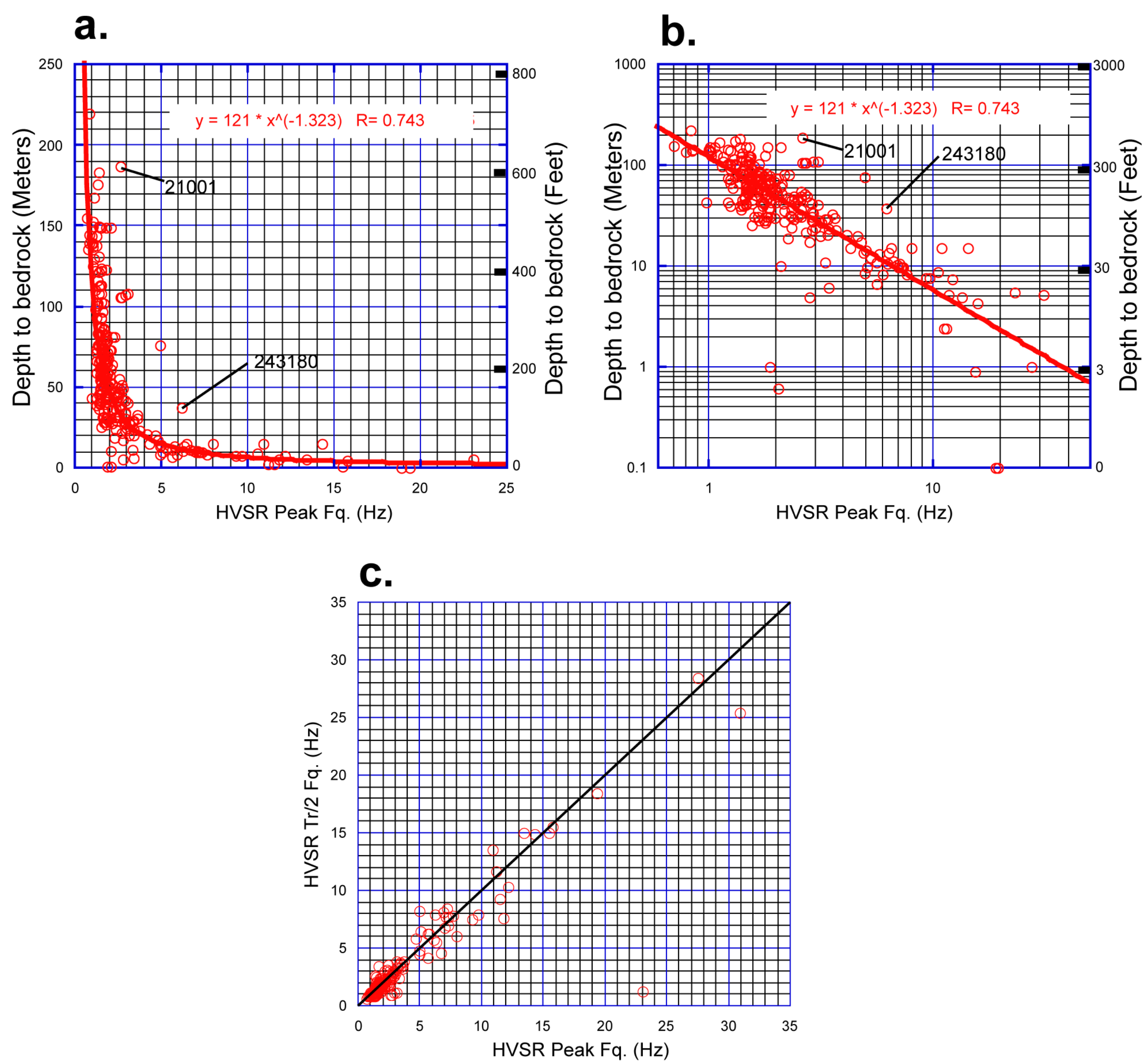

Figure 9 Relationship between HVSR peak frequency and bedrock depth at all control points; (a) linear plot of HVSR peak frequency vs. observed depth to bedrock, (b) log (signature) plot of HVSR peak frequency vs. observed depth to bedrock, and (c) linear plot of HVSR peak frequency vs. the first-trough frequency-divided by 2.

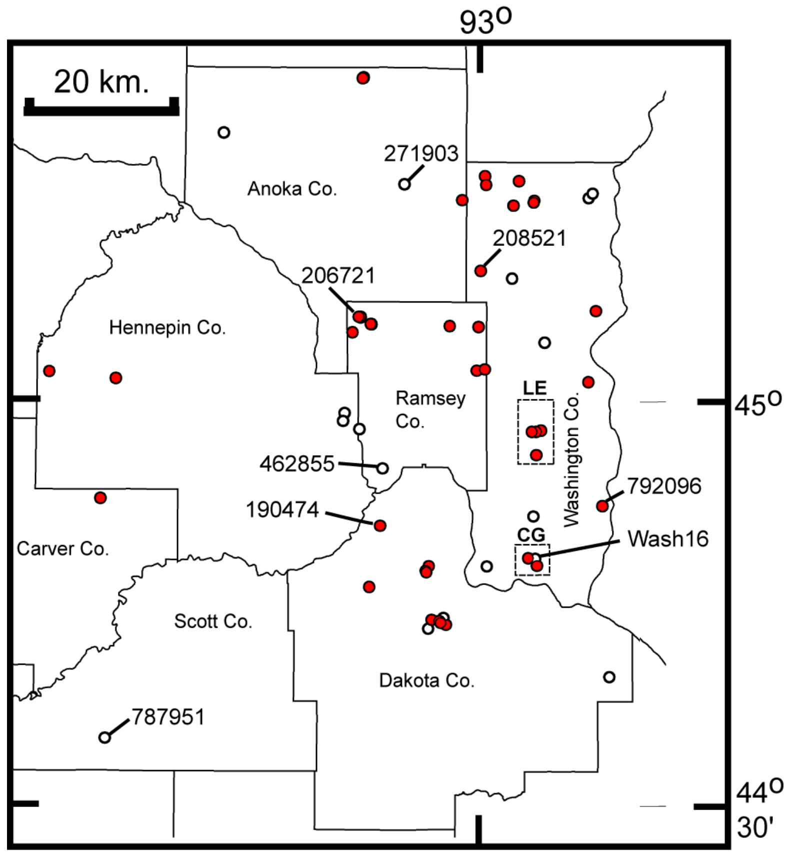

Figure 10. Map of the Twin Cities Metropolitan study area showing HVSR control stations, located at wells reaching bedrock. Red circles represent the 41 stations selected for bedrock depth calibration, using criteria described in the text. White circles represent control stations that were rejected for this calibration, based on irregularities in the HVSR spectra as described in text. Labels locate individual HVSR spectra shown in Figure 11. The small rectangles labeled CG and LE represent the Cottage Grove and Lake Elmo detailed study areas, shown in greater detail in Figure 13.

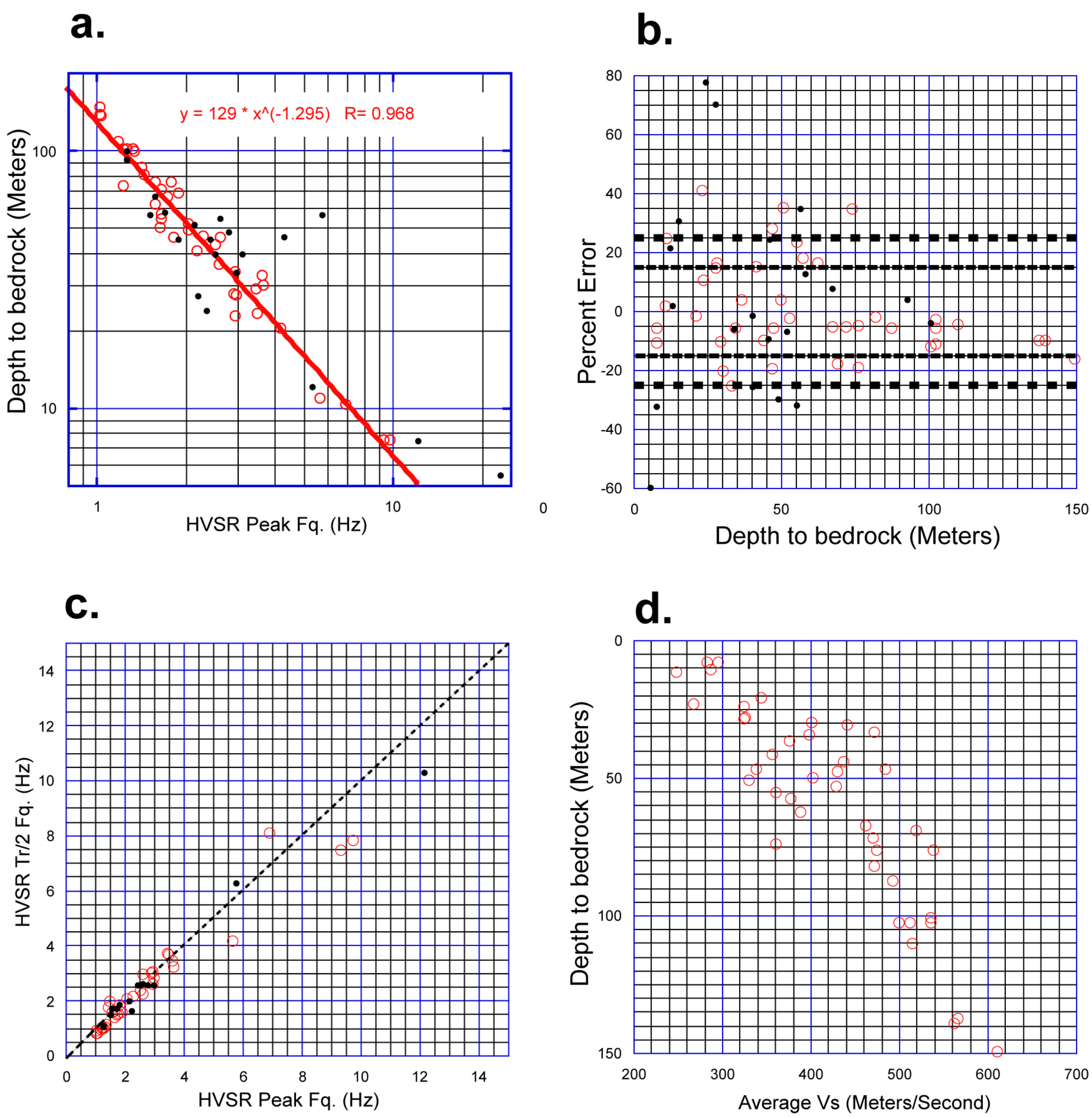

Figure 11 HVSR results for control stations in the Twin Cities Metropolitan area. (a) Log (signature) plot of HVSR frequency vs. observed depth to bedrock, Red circles represent the 41 selected calibration stations, and the red line with the annotated equation represents the power curve relationship fitted to these selected points. In the equation y is bedrock depth, 128.88 and -1.2948 are the a and b values, respectively, of the fitted power relationship, and R is the correlation coefficient. Black dots represent the control points that were rejected from the depth to bedrock calibration. (b) Percent error plot of the control points selected for the power-curve calibration, shown as red circles. Black dots represent the control points that were rejected from the depth to bedrock calibration. Light dashed lines delineate +/-15% error, and heavy dashed lines delineate +/-25% error. (c) Linear plot of HVSR peak frequency vs. the first-trough frequency-divided by 2. Red circles represent control points that were selected for the depth to bedrock calibration, and black dots represent control points that were rejected. (d) Plot of average shear wave velocity estimates based the observed bedrock depth and the HVSR peak frequency.. Results shown only for the stations used in the depth-to-bedrock calibration.

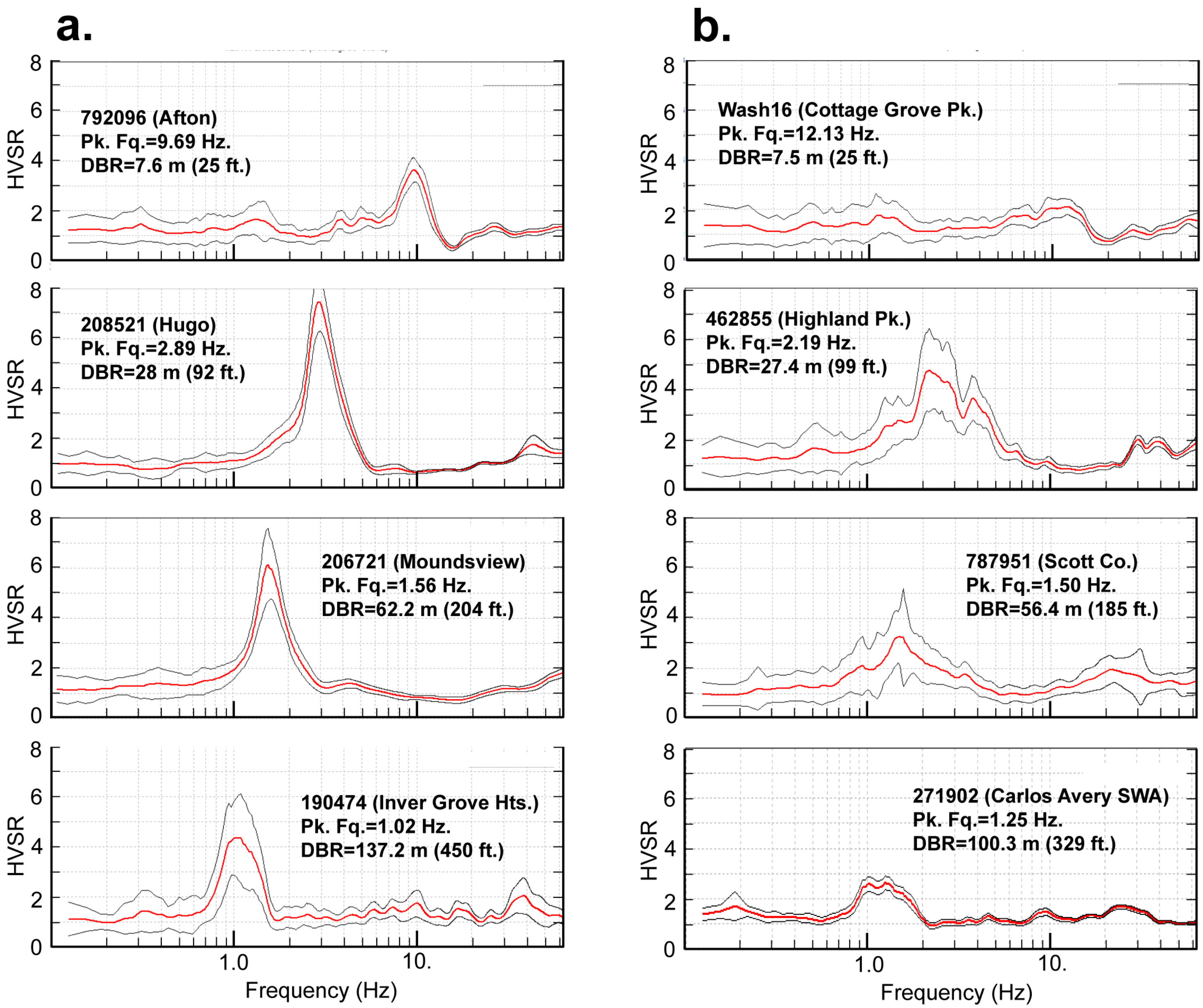

Figure 12. Examples of HVSR spectra observed in the Twin Cities Metropolitan area. (a) HVSR spectra typical of the 41 stations used for bedrock depth calibration. (b) HVSR spectra typical of stations rejected for bedrock depth calibration, that likely reflect unfavorable subsurface conditions.

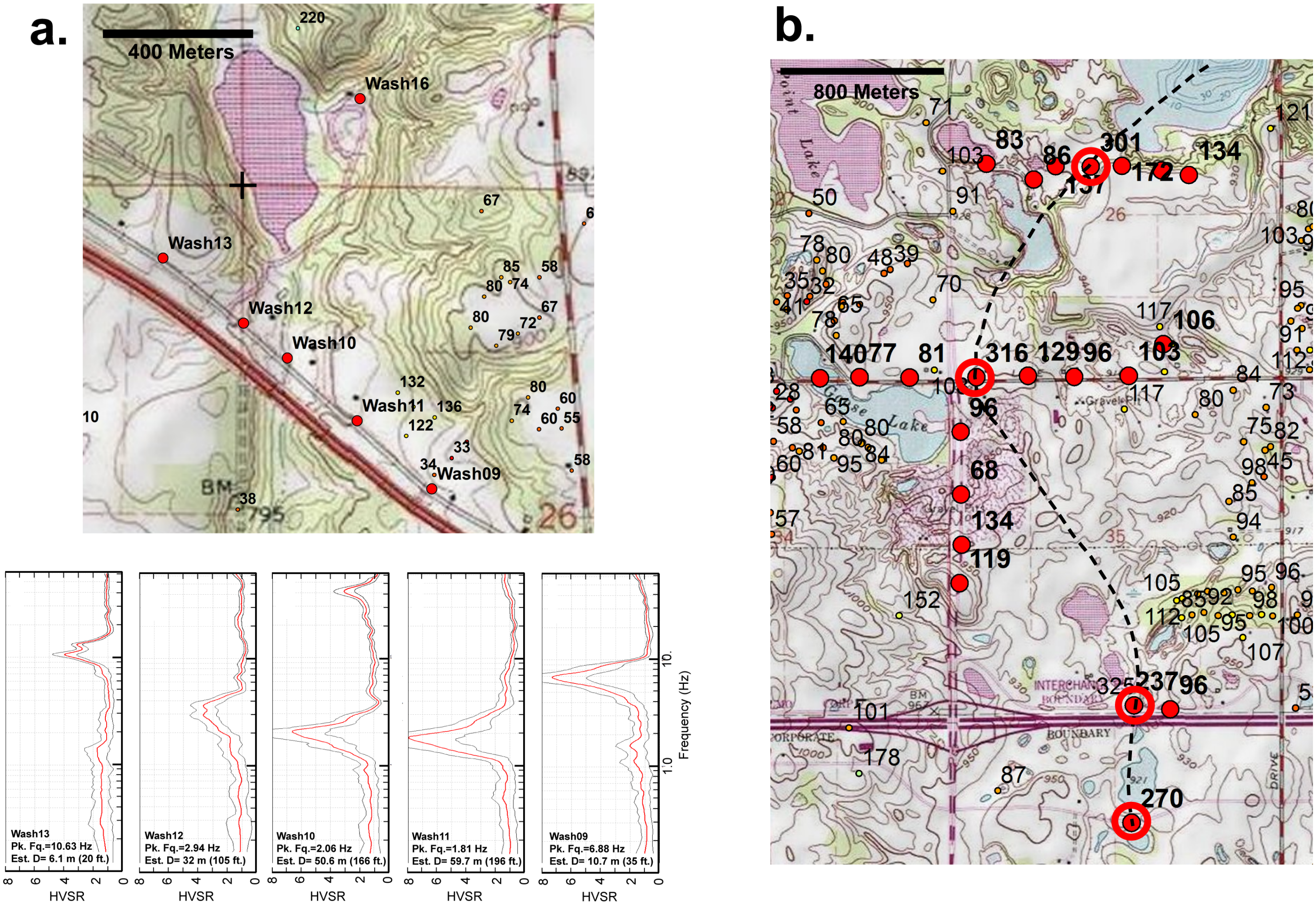

Figure 13 Detailed study areas of a buried bedrock ravine in Central Washington County, Minnesota (Figure 10). (a) HVSR in the Cottage Grove study area. Topographic contours in feet. Multi-colored dots are bedrock wells with depth to bedrock posted in feet. HVSR stations are represented by labeled red circles, and the respective HVSR spectra are presented vertically, below the map. Each spectrum includes its peak frequency (Pk. Fq.) and the estimated bedrock depth (Est. D), based on the calibration relationship shown in Figure 12a. (b) HVSR in the Lake Elmo area. Topographic contours are in feet. Multi-colored dots are bedrock wells with depth to bedrock posted in feet. HVSR stations are represented by labeled red circles with estimated depth (in feet) given in bold numbers. HVSR stations highlighted by large, open red circles represent the position of the buried ravine, based on the relatively large depth estimates at these stations. Dashed heavy line is the interpreted trace of the buried ravine, based on the HVSR results.

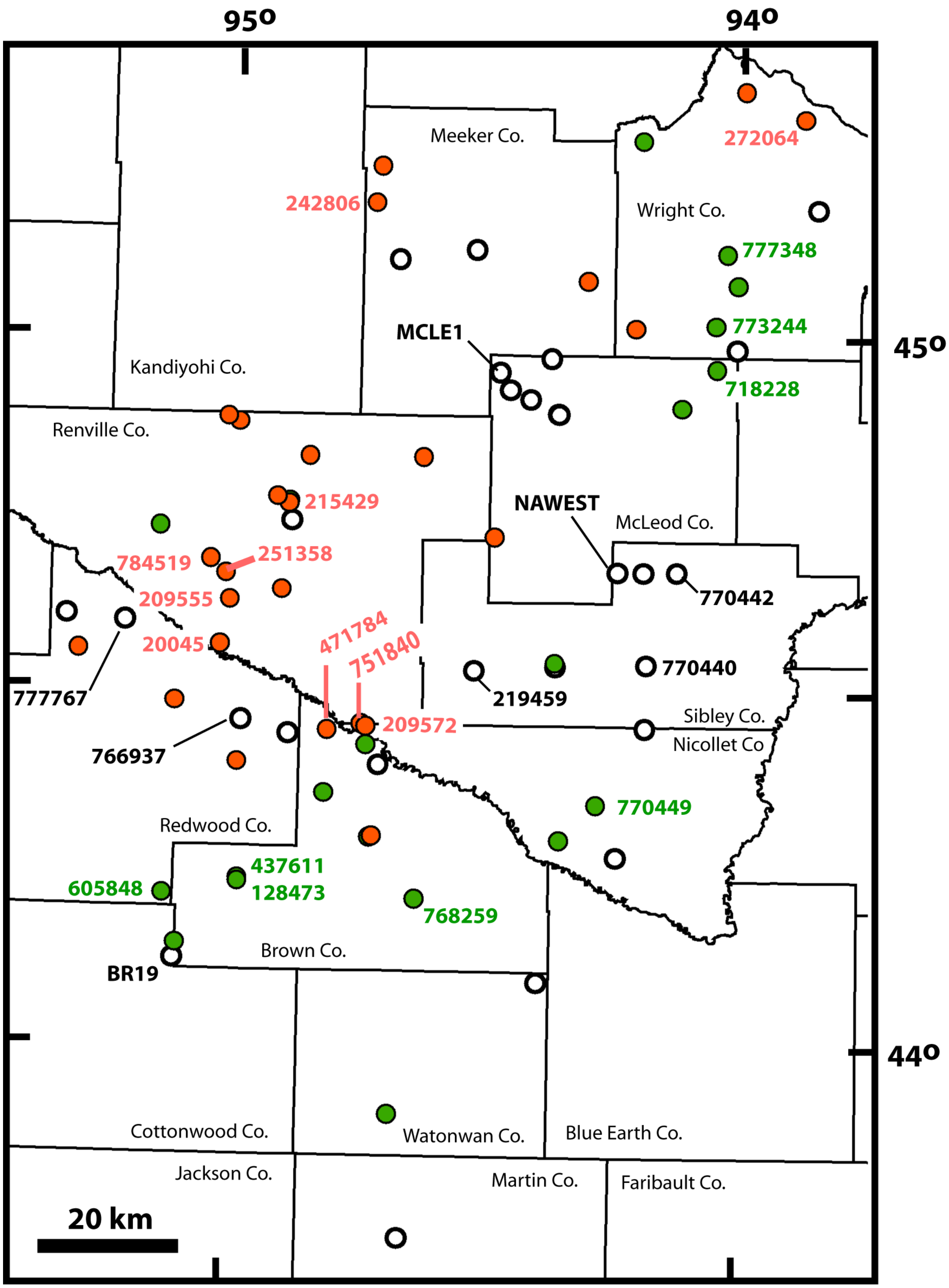

Figure 14. Map of the south-central study area showing HVSR control stations, with known depth to bedrock. White circles highlighted in black represent "ideal" control stations and labels locate individual HVSR spectra shown in Figure 15. Orange circles represent control stations where saprolith is reported at the bedrock surface, and labels locate wells that are interpreted to penetrate to fresh rock (Figure 15d). Green circles represent control stations where Cretaceous deposits are interpreted at the bedrock surface, and labels locate wells that are interpreted to penetrate to the Pre-Cretaceous surface (Figure 15e).

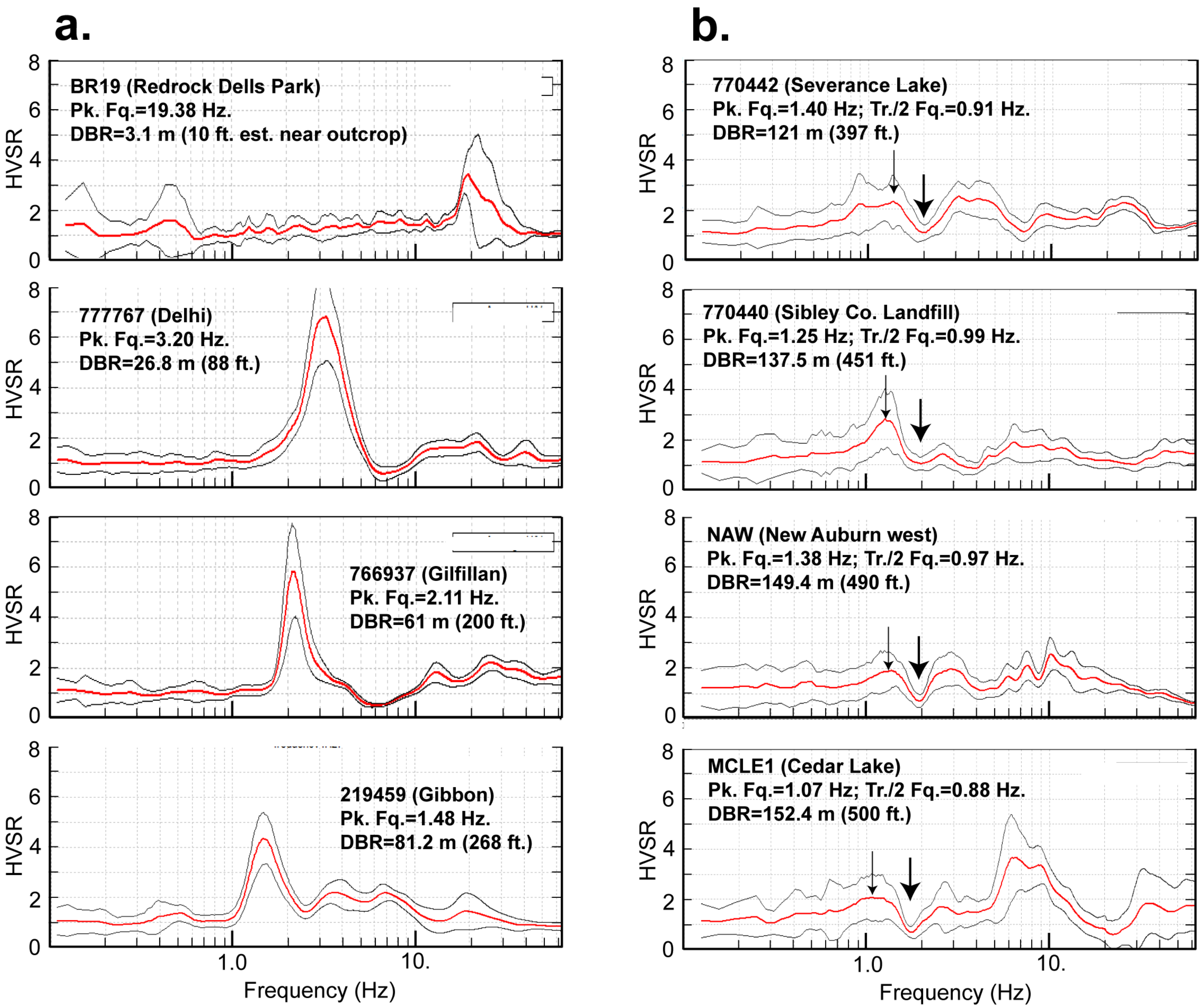

Figure 15. Examples of HVSR spectra observed at control points in the south-central study area. (a) HVSR spectra displaying a singular peak. (b) HVSR spectra for areas where bedrock depth is greater than 100 meters (328 ft.). Light arrows indicate HVSR peaks that are inferred to represent bedrock, based on their low-frequency position on the spectra, bold arrows indicate the interpreted “first” troughs that lie immediately up-spectra from these peaks. Pk. Fq. refers to the frequency of the HVSR peak inferred to represent bedrock. Tr/2 Fq. refers to the frequency of the first trough that is up-spectra from the primary HVSR peak, divided by two. DBR is depth to bedrock as reported at the control point.

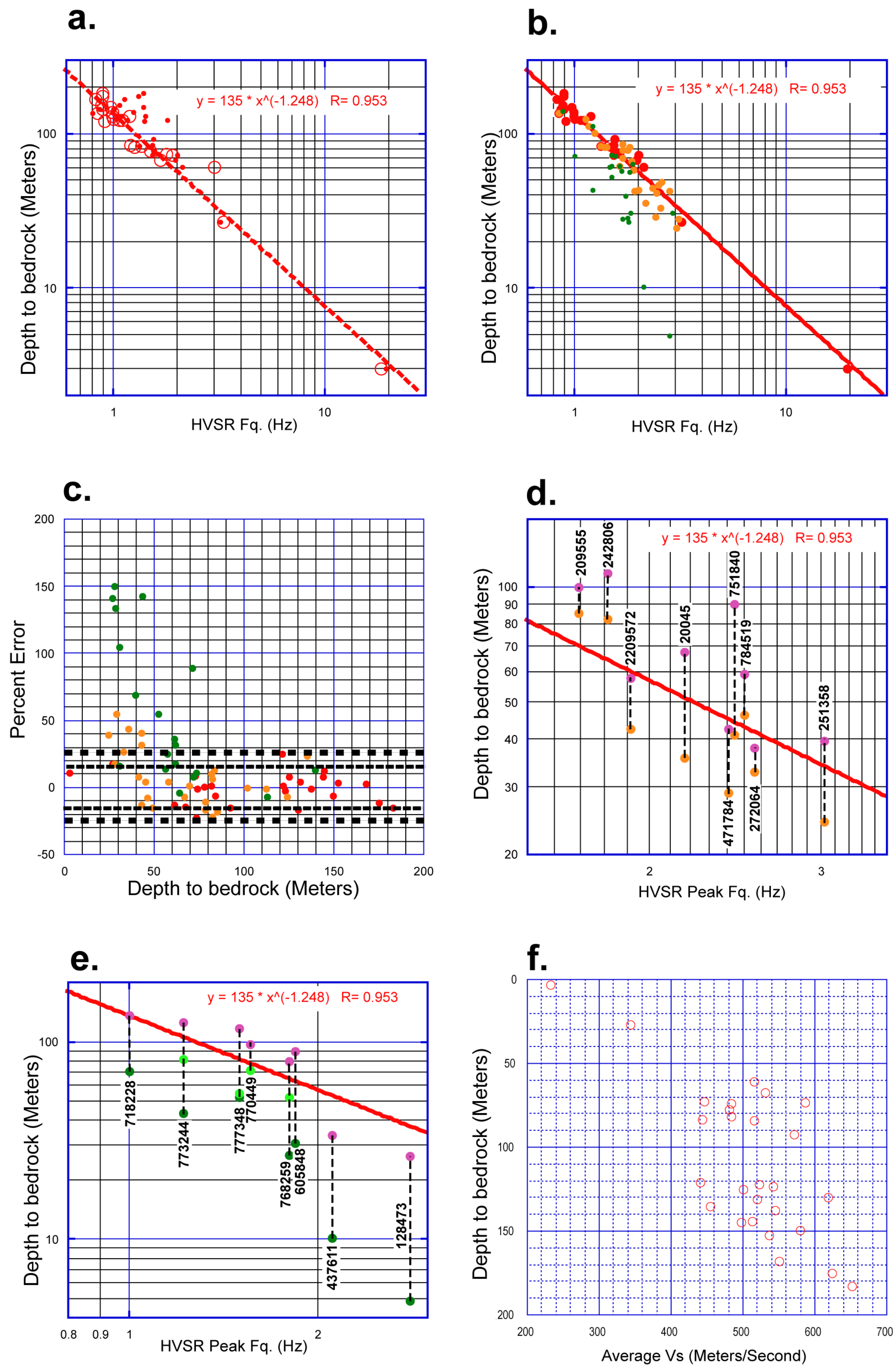

Figure 16. HVSR results for control stations in the south-central study area. (a) Log-log (signature) plot of HVSR frequency vs. observed depth to bedrock for the 27 "idealized" stations. Solid small circles represent HVSR peaks selected to represent bedrock, and open larger circles represent the frequencies of the first-troughs that lie up-spectra from the selected HVSR peaks, divided by

two Dashed line is the power relationship fitted to a combination of HVSR frequencies, consisting of peak-based frequencies for depths above 100 meters and trough-based frequencies for depths below 100 meters. . In the annotated equation y is bedrock depth, 134.82 and -1.2481 are the a and b values, respectively, of the fitted power relationship, and R is the correlation coefficient. (b) Log-log (signature) plot showing the HVSR points and the fitted power relationship from Figure 16a, along with HVSR results from control points where either saprolith (orange circles) or Cretaceous deposits (green circles) for comparison. (c) Percent error plot of the control points selected for the power-curve calibration, shown as red circles. Red circles represent the combined HVSR results that were selected for the power relationship calibration. (Figures 16a and 16b), orange circles represent HVSR peak results for control points where saprolith was reported at the bedrock surface, and green circles represent HVSR peak results for control points where Cretaceous deposits were reported at the bedrock surface. Light dashed lines delineate +/-15% error, and heavy dashed lines delineate +/-25% error. (d) Log-log HVSR vs bedrock depth plot showing the fitted power relationship presented in Figures 16a and 16b, with results from saprolith drill holes that penetrated to fresh rock (see Figure 15 for locations). For each drill hole the orange end point represents the depth to the top of the saprolith, whereas the magenta end-point represents the depth to fresh bedrock. (e) Log-log HVSR vs. bedrock depth plot showing the fitted power-law relationship presented in Figure 16a and 16b, with results from Cretaceous drill holes that penetrate to the Pre-Cretaceous surface (see Figure 15 for locations). Green end points represent depths to Cretaceous surface. Light green points represent depths to a recently recognized Cretaceous unit that is slightly older than Cretaceous deposits that were previously recognized in the region (Jirsa and others, 2011). (f) Average shear wave velocity estimates based the observed bedrock depth and the HVSR peak frequency. Results shown only for the stations used to construct the power-law calibration curve presented in Figure 16b.

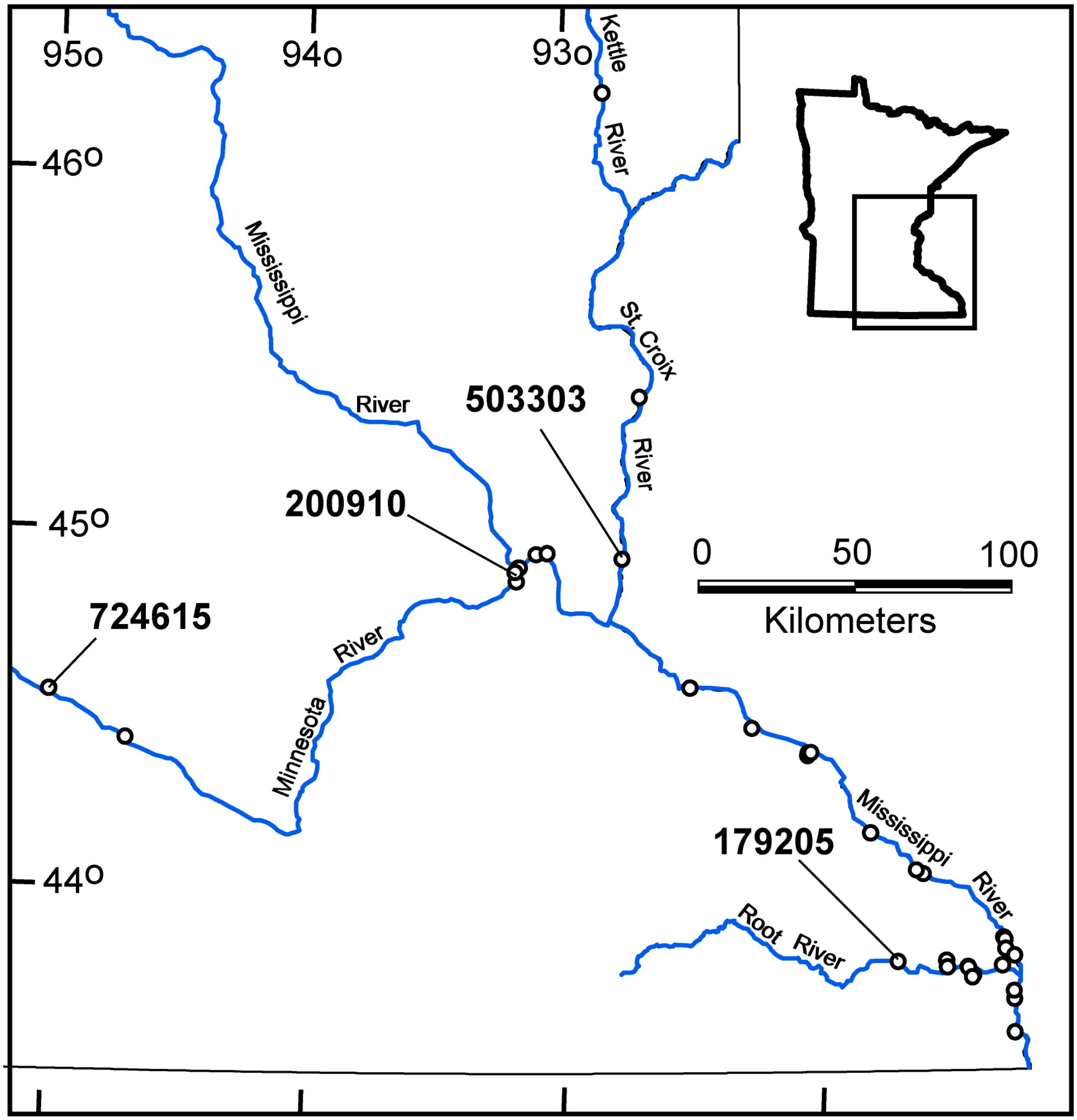

Figure 17. Map of southern Minnesota showing locations of the 37 fluvio-lacustrine control points that were used in depth calibration (circles), and labels locate individual HVSR spectra shown in Figure 18. Figure also includes locations and numbers of the intra-glacial HVSR stations (solid triangles), whose results are presented in Figure 20, and the locations of the seismic refraction soundings (diamonds) that are used in the error analysis presented in Figure 21.

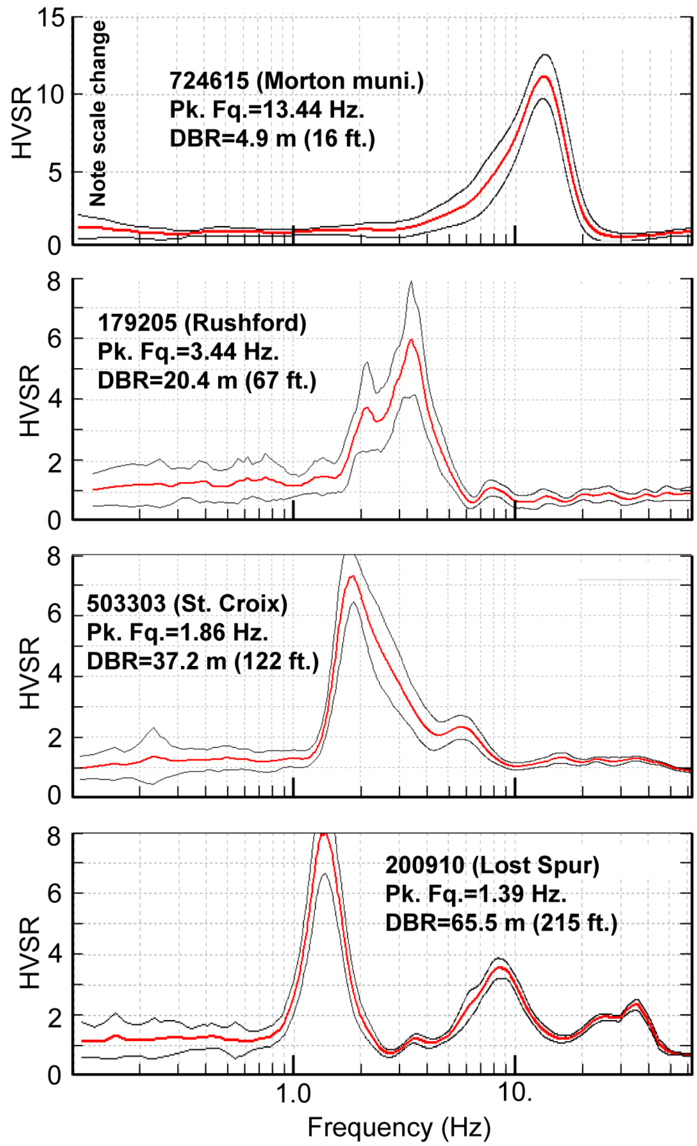

Figure 18. Examples of HVSR spectra observed along floodplains and terraces of major River Valleys. See Figure 17 for locations.

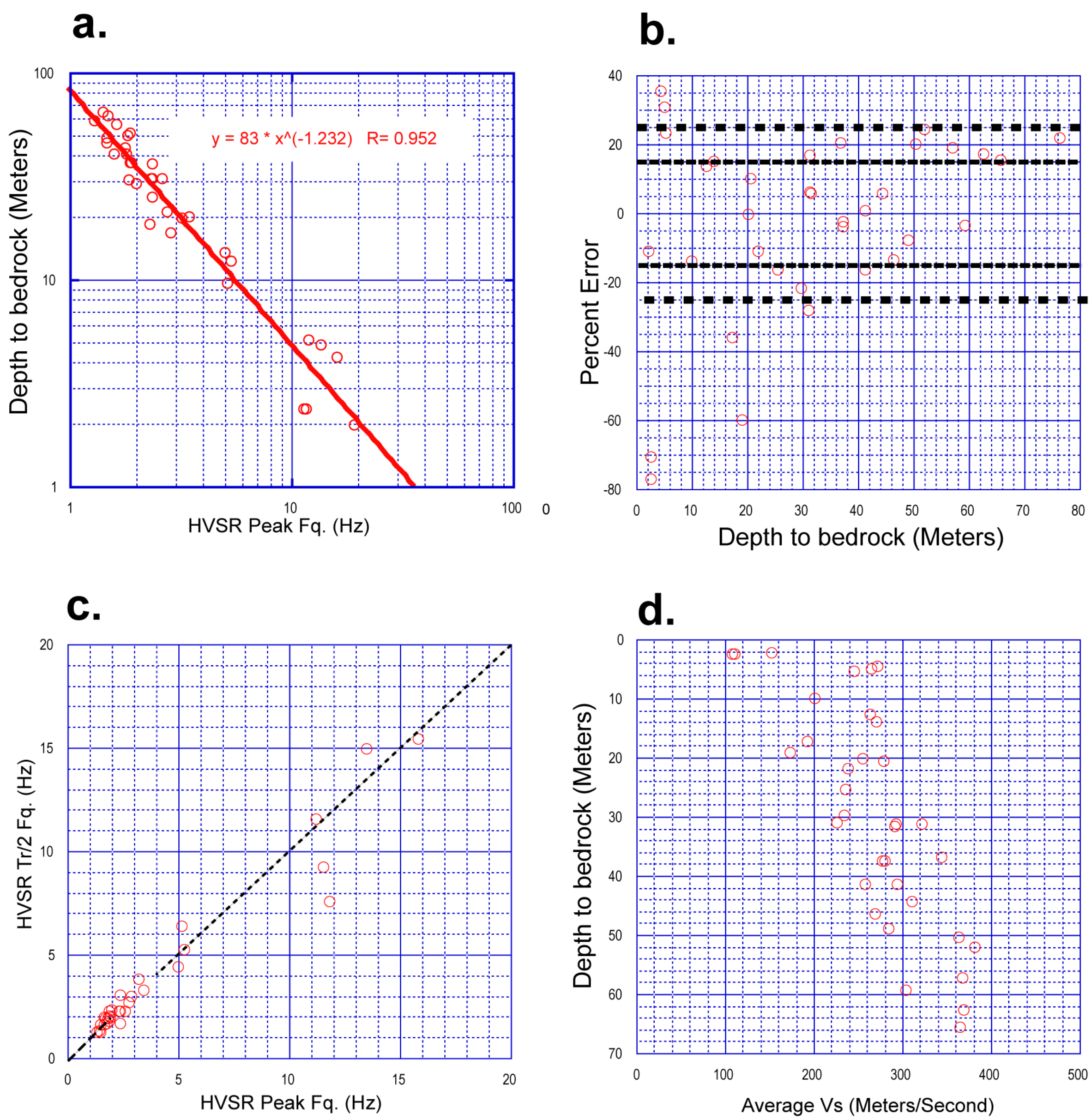

Figure 19. HVSR results for control fluvio-lacustrine stations, located along floodplains and terraces of major river valleys (Figure 17). Red circles represent the 37 selected calibration stations, and the red line with the annotated equation represents the power curve relationship fitted to these selected points. In the equation y is bedrock depth, 82.761 and -1.2315 are the a and b values, respectively, of the fitted power-law relationship, and R is the associated correlation coefficient. (b) Percent error plot of the control points selected for the power-law calibration, shown as red circles. Light dashed line delineates +/-15% error, and heavy dashed lines delineate +/-25% error. (c) Linear plot of HVSR peak frequency vs. the first-trough frequency divided by 2. (d) Average shear wave velocity estimates based the observed bedrock depth and the HVSR peak frequency. Results shown only for the stations selected for the power-law calibration.

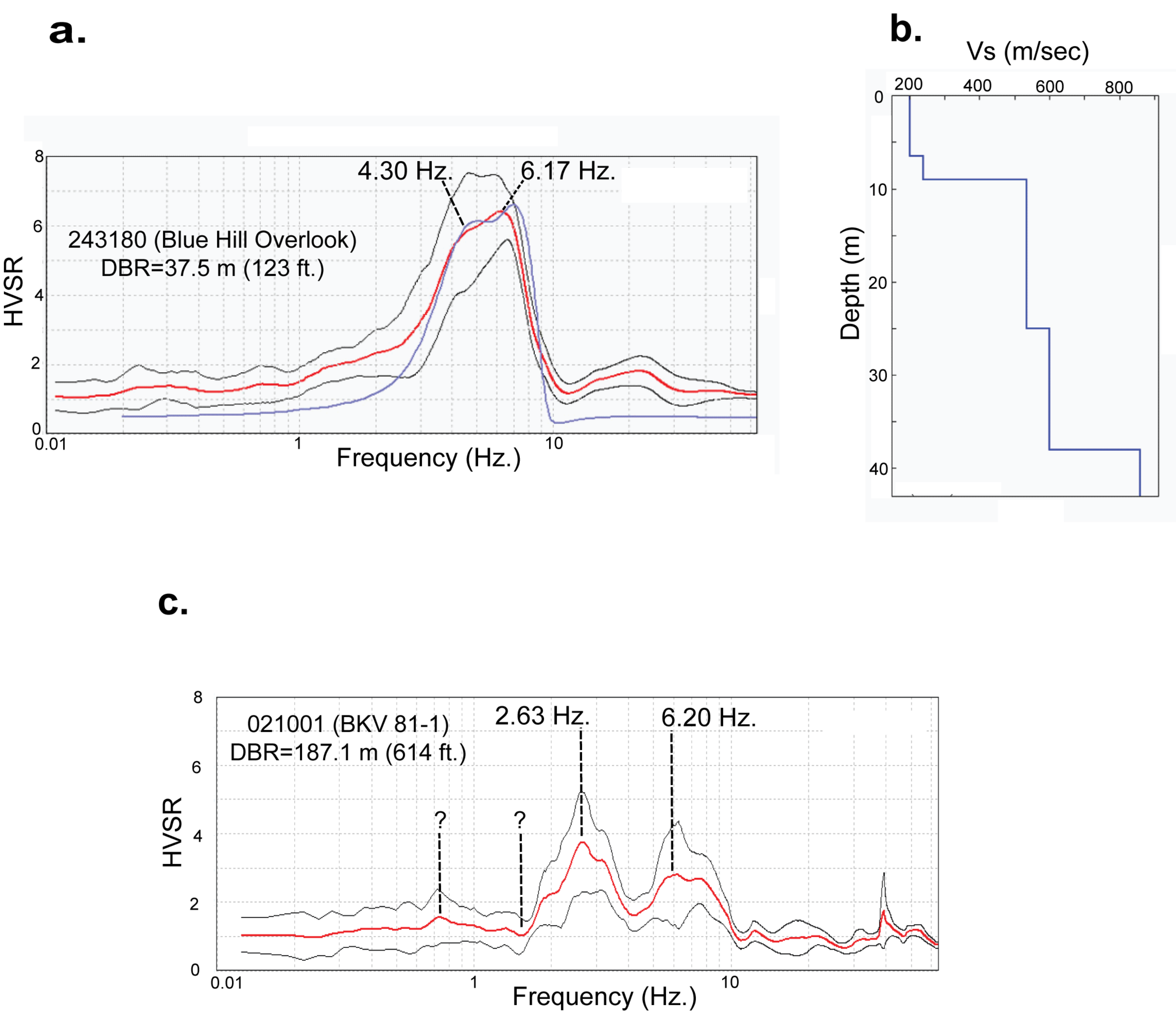

Figure 20 Examples of intra-glacial horizons dominating HVSR results. DBR is observed depth to bedrock. (a) HVSR spectra observed at CWI well #243180. Blue line is calculated spectra of shear-wave model shown in part b. (b). Shear wave model used to approximate HVSR spectra observed at CWI well #243180. Horizontal layers are assumed. (c) HVSR spectra observed at CWI well #021001.

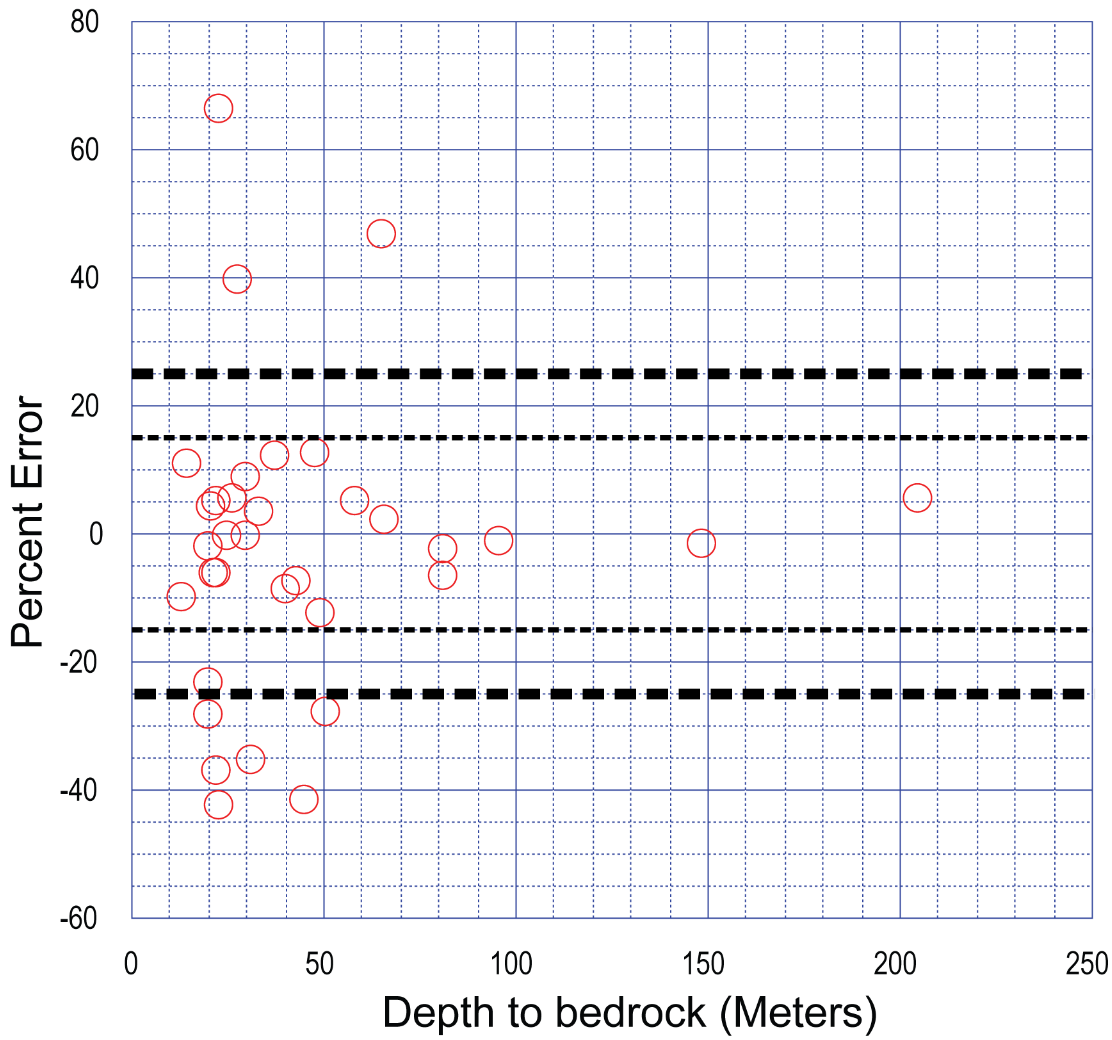

Figure 21. Percent error plot of bedrock depth estimates from seismic refraction profiling, based on soundings taken within 250 meters of a control well. Light dashed lines delineate +/-15% error, and heavy dashed lines delineate +/-25% error.