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BOREHOLE SHEAR WAVE VELOCITY MEASUREMENTS OF CHAMPLAIN SEA SEDIMENTS IN THE OTTAWA-MONTREAL REGION

By
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Introduction

This report contains a compilation of borehole shear wave velocity information gathered over the past several years by the Terrain Geophysics Group of the Terrain Sciences Division, Geological Survey of Canada, Natural Resources Canada. The boreholes were drilled for several surficial geological and geotechnical projects in Champlain Sea sediments of the Ottawa Valley. Some studies were concerned with issues of sensitive “clay” and slope stability, and these boreholes were situated along the South Nation River north of Casselman Ontario, near Lefaivre Ontario and near Rigaud, Quebec. Other boreholes were drilled for stratigraphic information as part of a groundwater project in the Lachute-Oka area of Quebec. Another hole was drilled as a calibration hole for near-surface geophysics sonde-testing at Anderson Road, Ottawa. In total 18 boreholes were used for this study (locations are shown in Figure 1). The shear wave velocity data obtained in these boreholes have been collated, processed and interpreted as a guide for use by geotechnical engineers in the estimation of soil response to earthquake shaking.

Geological Background of the Ottawa-Montreal area

The Ottawa Valley, much of which is underlain by Paleozoic sedimentary rock, lies in a northwest-trending graben between uplifted Precambrian bedrock to the north, west and south. The base of the Late Quaternary sequence filling the valley consists of a generally thin sheet of till and, in places, thin to thick accumulations of glaciofluvial sand, silt and gravel. These sediments are overlain by a thin unit (commonly less than 2 m) of freshwater, rhythmically bedded, fine-grained lacustrine sediment which is in turn overlain by a thick marine sequence (Gadd, 1986). These marine sediments, which average 30 to 50 m thick, reach thicknesses of 100 m in the deepest parts of the basin adjacent to the Ottawa River (Gadd, 1986). The marine sequence records an upward change from a deep water, high salinity, marine environment to estuarine conditions. Massive to weakly stratified, gray marine clay and silty clay at the bottom of the marine sequence grade into a coarsening-upward sequence of rhythmically bedded red clay and gray silty clay with thin silt bands and occasional silt or fine sand layers. The red and grey clay rhythmites pass upwards from saline to estuarine conditions and represent the distal deposits of a large strip delta that prograded eastward through the Ottawa Valley as sea level fell. The marine clays are commonly overlain by interbedded silt and fine to medium sand which form the uppermost units of the strip delta. Subsequent fluvial action has eroded broad paleochannels into the marine sediments, and, in places, modern rivers are deeply entrenched.

The marine clay, informally known as Leda clay, is a clayey-silt or silty-clay composed of glacially-ground, non-clay minerals, held together in a loose structural framework capable of retaining a high water content. Marine salinity originally contributed to the bonding of the minerals, and salt leaching now influences structural strength (Torrance, 1988). In places, the clay is a geotechnically “sensitive” clay, vulnerable to large-scale, rapid, retrogressive earthflows and represents a serious hazard to the safety and property of the local population. If disturbed, these sediments can lose strength, collapse, and behave like a liquid. The resulting catastrophic earthflows can rapidly destroy large areas of flat land lying behind the unstable slope and the debris may flow great distances from the original failure.

Geotechnically sensitive sediments may liquefy during earthquake shaking. Evidence based on radiometric age dating and site investigation suggests that the lower Ottawa Valley experienced two geologically destructive earthquakes in the Holocene (Aylsworth et al., 2000). One, at 4550 yr B.P., caused widespread landsliding along the paleochannels in sensitive marine clays. The other, at 7060 yr B.P., caused irregular surface subsidence, lateral spreading, and sediment deformation in thick deposits of marine clay and sand infilling a small deep bedrock basin at Lefaivre, Ontario. Magnitudes of these earthquakes probably exceeded 6.5 (Aylsworth and Lawrence, 2003) and may have exceeded magnitude 7 (Adams, 2004; Aylsworth and Hunter, 2004). These new discoveries provide evidence that this region, which has experienced only small (magnitude <4) earthquakes during the historic period, may be subject to occasional high-magnitude earthquakes.

Geotechnical Applications of the Shear wave velocities and the 2005 National Building Code

Shear wave velocity (Vs) information is required as input data for several differing types of geotechnical model studies related to amplification and resonance of earthquake shaking in both soft cohesive clays and silts as well as fine sand soils of the Champlain Sea sediments. In general, these high-water-content sediments yield relatively low shear wave velocities (70-150 m/s) as measured at acoustic and sub-acoustic frequencies (20 to 150 Hz) and at low strains ($<10^{-4}$), compared to most other terrestrial Holocene fine-grained sediments. It is the authors' experience that only the Mexico City clays yield lower Vs velocities (~ 50 m/s).

The Ottawa-Montreal area has elevated earthquake hazard and risk (Adams and Halchuk, 2003, 2004) as delineated by historical earthquake activity. For the 2005 National Building Code (NBC), estimation of earthquake amplification effects at a construction site, is now based on average geotechnical properties of soils and rock to a depth of 30 m below ground surface (Finn and Wightman, 2003). Although standard penetration measurements as well as un-drained shear strength can be used to describe some soil conditions, the primary geotechnical measurement to describe all soil and rock site conditions is that of the average velocity of a shear wave travelling up from 30 m depth to ground surface (Vs_{30}). The range of site classifications given in the 2005 NBC are adopted from those recommended by the U.S. National Earthquake Hazard Reduction Program (NEHRP, 1994); these site classifications in terms of Vs_{30} are given in Table I.

TABLE I – Site Classification for Seismic Site Response (from NEHRP, 1994)

SITE CLASS	GENERIC DESCRIPTION	RANGE of Vs_{30}
A	Hard rock	Vs_{30} > 1500 m/s
B	Rock	760 < $Vs_{30} \leq$ 1500 m/s
C	Very dense soil and soft rock	360 < $Vs_{30} \leq$ 760 m/s
D	Stiff soil	180 < $Vs_{30} \leq$ 360 m/s
E	Soil profile with soft clay	Vs_{30} < 180 m/s
F	site-specific geotechnical investigations required: 1) soils vulnerable to failure or collapse under seismic loading (e.g. liquefiable soils, quick or highly sensitive clays, collapsible weakly cemented soils) 1) peats and (or) highly organic clays (> 3 m thick) 2) very high plasticity clays (> 8 m thick and with Plasticity index >75 3) very thick "soft-medium-stiff clays (> 36 m thick)	

As well, shear wave velocity-depth profiles are routinely used as input data to 1-dimensional "shake" analyses which model the response of thick soil sections. For such work, the complete velocity-depth profile from surface to (and including) the bedrock (or very firm ground) is required (Schnabel et al., 1972). Hence it is of interest to determine the variation in average shear wave velocities throughout the area so that geotechnical engineers may use these as a guide for model studies.

Shear Wave Velocity Measurement Techniques

For most boreholes in this study, down-hole shear wave velocities were obtained through PVC-casing using standard procedures as given by Hunter et al. (1998). The procedure is outlined in Figure 2. However, for one location (Rigaud), a data file of down-hole travel time information was obtained using a Seismic Cone Penetrometer (SCPT); the procedures and frequency bands with the SCPT equipment were similar to seismic equipment used in the other boreholes, hence these data obtained at Rigaud are equivalent to those obtained at the other sites.

Data were acquired at 1 m intervals down-hole for most sites. At some sites where detailed measurements were taken in support of stress-field anisotropy studies of hazardous slopes, measurements were taken at 0.5 m intervals. The polarized seismic source (a 7.5 Kg hammer struck against a loaded steel I-beam) was positioned at ground surface at either 3 m or 5 m offset from the borehole, depending on the site. The well-locked tool (or tools if a 3–pod array was used) were positioned vertically within an accuracy of 1 to 2 cm. Stacked three-component seismic records were taken for both polarities of the source. Usually the source was placed in the towards and away position to one component of the oriented 3-component array (Hunter et al, 1998; see also Figure 2). First arrival times were determined directly from the records or through the use of a hodograph plotting routine.

Average shear wave velocities (Vs_{av}) were determined from the travel times and source-receiver distances (after correcting for source offset). As well, interval velocities Vs were also computed using running least-squares fits of either 3 or 5 points (depending on the downhole sonde spacing).

Travel time-depth data, as well as interval velocities and average velocities, can be found in the digital data directory called “DATA” associated with this report.

The plots of Vs and Vs_{av} for individual boreholes and shown in Appendix A along with the generalized geological logs.

Compilation plots pertaining to data analyses are given in the main body of this report.

Data Compilation and Analysis

Both interval and average shear wave velocities vs depth for Champlain Sea sediments were compiled for all boreholes as shown in Figures 3 and 4 respectively. Similar compilations were made for interval and average velocities versus elevation as shown in Figures 5 and 6.

In general, interval velocities increase with depth (or effective stress) as might be expected for normally consolidated sediments (Hardin and Drnevich, 1972). It has been suggested that a surface “crust” of over-consolidated sediment can be found over most areas of the Champlain Sea deposits(Eden and Crawford, 1957) This could be manifested in a thin surface layer of higher shear wave velocity and some evidence of this can be seen in the plots in Appendix A. Further evidence can be seen from examination of the spread of values of the average shear wave velocities in Appendix A as well as in Figure 4 and Figure 6.

Eden and Crawford (1957) also suggest that pre-consolidation conditions of the Leda clay may be elevation dependent. As a result, interval and average shear wave velocities have been plotted versus elevation as shown in Figures 5 and 6. It is the authors’ opinion that in both cases where the interval and average velocities are plotted versus depth versus elevation, the scatter of the data is similar. Further discussions will therefore be confined to variations with depth.

Most of the anomalously high values are associated with three boreholes LV99-1, JA4 and JA4A, which were drilled to examine a “disturbed ground” area east of Lefaivre, Ontario. This area was thought to have suffered significant deformation during a significant earthquake dated at 7050 BP (Aylsworth et al., 2000), a conclusion supported by the evidence of sediment deformation within these boreholes, extending to a depth of 50 m in JA-4. As well, these boreholes encountered unusually thick layers of sand, a relatively rare occurrence within the marine clay sequence of the Champlain Sea sediments of the Ottawa Valley. Because of these geological and velocity anomalies, the data from these boreholes were removed from the composite plots.

Figures 7 and 8 show the edited composite plots of interval and average shear wave velocities plotted as a function of depth down to 60 m below surface, utilizing the remaining 15 boreholes. These figures show the spread of values possible within the Champlain Sea sediments. To obtain analytical expressions governing interval and average velocity vs depth, the following four approaches were considered:

<u>I - Down-hole Shear Wave Travel Time Analysis</u>

Figure 9 shows the composite travel-time versus depths (518 data points) for the 15 boreholes examined. A curve-fitting routine (TableCurve 2D, version 4.07) was utilized to fit various least-squares forms of equations to the data, and to rate best fitting equations in terms of minimizing the standard error of the fit. In this case, a power law function gave the best results. The shear wave down-hole travel time T (in ms) as a function of depth Z (in m) is given by:

$T = 10.40 * Z^{0.850}$ (1)

where 2 standard error (95% confidence limits) = +/- 34.3 ms

The average shear velocity (in m/s) is then given by:

$Vs_{av} = 1000*Z/(10.40*Z^{0.850})$ (2)

Figure 10 shows the curve of equation (2) and the 95% confidence limits of equation (1) plotted with the measured Vs_{av} of the composite data from 15 boreholes. Although the curve appears to fit the data well in the 7m to 30 m range, the near-surface portion (<7 m depth) deviates from the observed trend; as well, between 30 m and 60 m depth, the curve appears to be steeper than the observed trends from the data.

II – Best Fit Shear Wave Interval Velocity Curve

A similar approach was applied to the composite shear wave interval velocity data using least-squares Table Curve software and rating the best fitting equations in terms of minimal standard error of the fit. Figure 11 shows the resulting power-law fit along with the observed shear wave interval velocity and 95% confidence limits (2 standard error of the fit). The shear wave interval velocity Vs (in m/s) as a function of the depth Z (in m) is given by:

$Vs = 110.3 + 5.179*Z^{0.871}$ (3)

where 2 standard error = +/- 55.4 m/s

The average shear wave velocity Vs_{av} obtained from integration of this curve is given in Figure 12 along with the 95% confidence limits from equation (3). The curve does not fit the observed average shear wave velocity data at shallow depths (<10 m). As well, the curve does not follow the trend of observed data below 30 m depth.

III – Shear Wave Interval Velocities as a Function of Effective Overburden Stress

From laboratory testing of soils, Hardin and Drnevich (1972) established that the shear wave velocity was a function of effective overburden stress to the ¼ power; hence Vs would also be a function of $Z^{0.25}$. More recently, Japanese experience has suggested that the exponent be modified to 0.33 (Andrus and Stokoe, 1996). Utilizing this form of equation, a least-squares fit was made to the shear wave interval velocity data as shown in Figure 13. The interval velocity Vs (in m/s) as a function of depth Z (in m) is:

$Vs = 64.4*Z^{0.33} + 13.3$ (4)

where 2 standard error = +/- 58.6 m/s

The average shear wave velocity Vs_{av} derived from integration of equation (4) is given in Figure 14 along with the 95% confidence limits of +/- 58.6 ms. The curve does not fit the observed data well in the upper portion down to a depth of about 15 m. At depth however, the curve more closely follows the trend of the data.

IV – Observed Limits of Average Shear Wave Velocity Data

Although reasonable curve fits could be made to shear wave interval velocity data as given by equations (3) and (4), no clear fits of derived Vs_{av} curves have been found. In order to establish limits to Vs_{av} versus depth Z, as a reference for future work, we have assigned two parallel linear trends which bound the majority of the data, as given in Figure 15. For Vs_{av} (in m/s) as a function of depth Z (in m), the limiting trends are:

$Vs_{av} = 100 + 1.1667 * Z$ (5a)

and,

$Vs_{av} = 170 + 1.1667 * Z$ (5b)

From inspection of Figure 15, there is one borehole (LV97-2 near Lemieux, Ont.) that gives relatively high velocity values throughout. Removal of that data set could result in relatively closer spaced limiting equations. However, re-examination of the borehole geology as well as the first arrival down-hole records yields no reason to discount this data.

Observed Range of Vs_{30} for Champlain Sea Sediments

Since the 2005 National Building Code defines sites in terms of the NHERP zone classifications, it is of interest to note the range of Vs_{30} values obtained from each of the boreholes within the Leda Clay. Figure 16 shows the average shear wave velocities for 15 boreholes plotted down to 30 m depth. As can be seen, the variation in Vs_{30} lies between 135 m/s and 205 m/s. Most of the borehole data lies in NEHRP Zone E, whereas only one borehole (LV97-2) reaches beyond the 180 m/s boundary to NEHRP Zone D.

Shear Wave Velocities in Pleistocene Materials

Although the number of observations of downhole shear wave velocities in Pleistocene materials is quite limited (71 measurements), these data were collected and plotted with respect to depth, as shown in Figure 17. Despite the scatter in the data, there appears to be a trend towards increasing velocity versus depth for those data points in the lower portions of the velocity range between 225 and 425 m/s. This shear wave velocity trend line is given by:

$Vs = 225 + 1.333 * Z$ m/s (6)

Where Z is depth below surface in meters.

It is suggested that those data points in the high velocity range (600-1400 m/s) may be associated with over-consolidated tills containing cobbles and boulders. The data has also been plotted in histogram form for a bin size of 100 m/s as shown in Figure 18; the skewed distribution shows a peak centered at 350 m/s. The arithmetic mean value of all equally-weighted data is 503 m/s with a standard deviation of 277. The median value is 398 m/s

Conclusions and Discussions

Down-hole shear wave velocity measurements were made in 18 boreholes in Champlain Sea sediments in the Ottawa- Montreal area using standard near-surface geophysical techniques. From this data set, three holes in the Lefaivre Ont. area were excluded since their anomalous velocity-depth functions and geological surface and borehole sampling observations suggested that these sediments had been previously disturbed (with subsurface layering that may have been pre-consolidated) by significant earthquake shaking.

The down-hole shear wave travel-time and velocity data from the other 15 boreholes indicated that shear wave interval velocities in Champlain Sea sediments ranged between 85 m/s near surface to as high as 350 m/s at a depth of 60 m. Estimations of shear wave least-squares velocity-depth functions were computed using various approaches; the approach yielding minimal error was a power-law fit given as equation (3) of this report. Although the form of this empirical equation has no direct relation to geotechnical theory or to previous research in effective overburden stress (in contrast to the approach given by equation (4)) ***equation (3) is recommended for use as a guide for model studies (e.g. 1-D shake modeling).***

Average shear velocities for Champlain Sea sediments were also computed using various approaches of down-hole travel times and from estimates of best fitting curves of shear wave interval velocities. From the observed data for average shear wave velocities (as seen in individual boreholes shown in Appendix A) there appears to be a considerable variance from borehole to borehole. It is suggested that this phenomenon results from variation in near-surface shear wave velocities that can make considerable contributions to the offset travel-times. Because of this variance, ***the most conservative approach to estimating the average velocity-versus-depth function is to provide two linear plots which bracket the observed data; such limiting equations are given as (5a) and (5b).***

The wide variation in average shear wave velocity with depth for Champlain Sea sediments from this limited data set of 15 boreholes, suggests that no single empirical equation can be reliably developed. Perhaps this observation will be modified in future as more down-hole or surface seismic data is acquired. At present, such average velocity-depth functions, and hence ***Vs_{30}* estimates, must be considered to be site dependent. In turn, this suggests that to obtain an accurate *Vs_{30}* at a particular site, surface or borehole shear wave velocity measurements should be made.** **However**, as a **guide** to a **first-order estimate** of the range **of possible Vs_{av} values** for Champlain Sea sediments in the Ottawa-Montreal area**, limiting equations (5a) and (5b) could be used.**

Measurements of shear wave velocities in the underlying Pleistocene sediments, from this borehole data set, are limited. An observed velocity-vs-depth trend is described by equation (6) and is shown in Figure 17. A histogram of the data set is shown in Figure 18 with a peak value of 350 m/s, a median value of 398 m/s and an arithmetic mean value of 503 m/s. There appears to be an abrupt shear wave velocity boundary associated with the base of the Champlain Sea sediments. The associated seismic impedance is a significant one for "shake" modeling of soil response.

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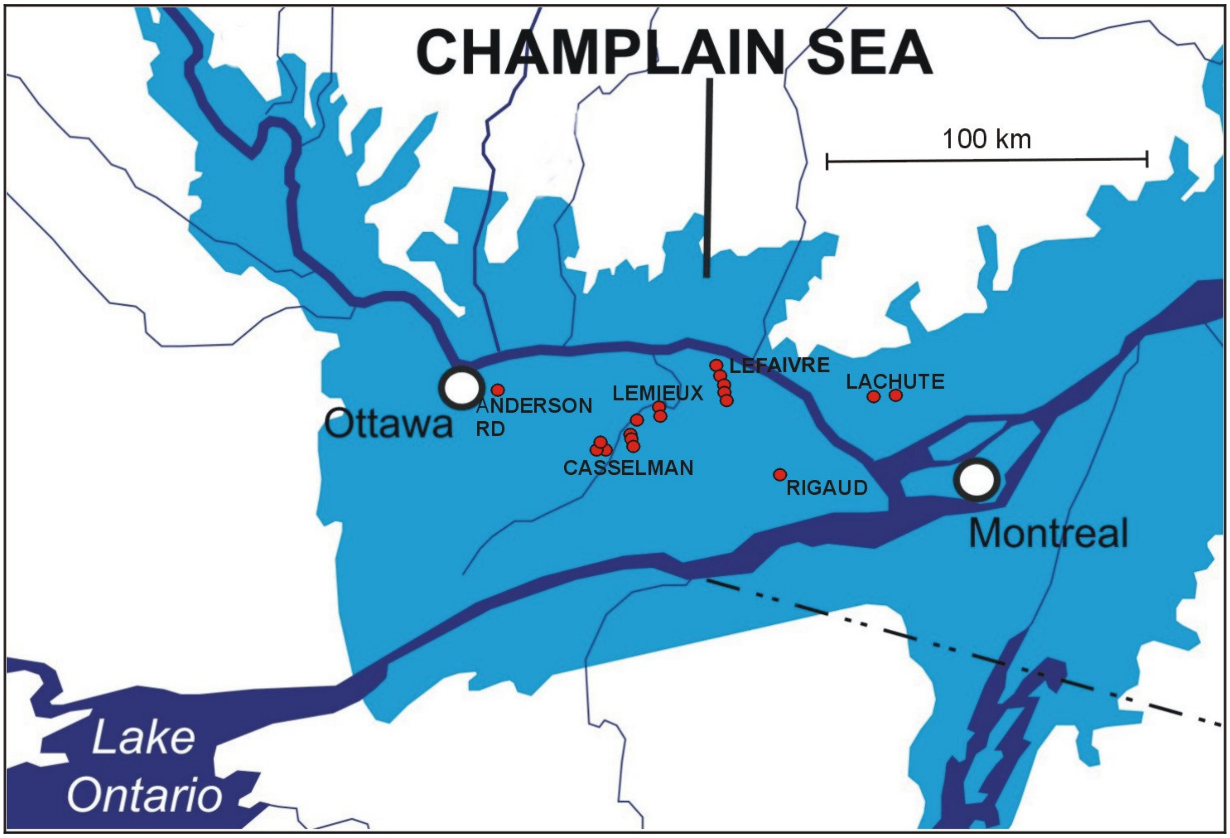

FIGURE 1 – Location of (18) GSC Boreholes discussed in this report.

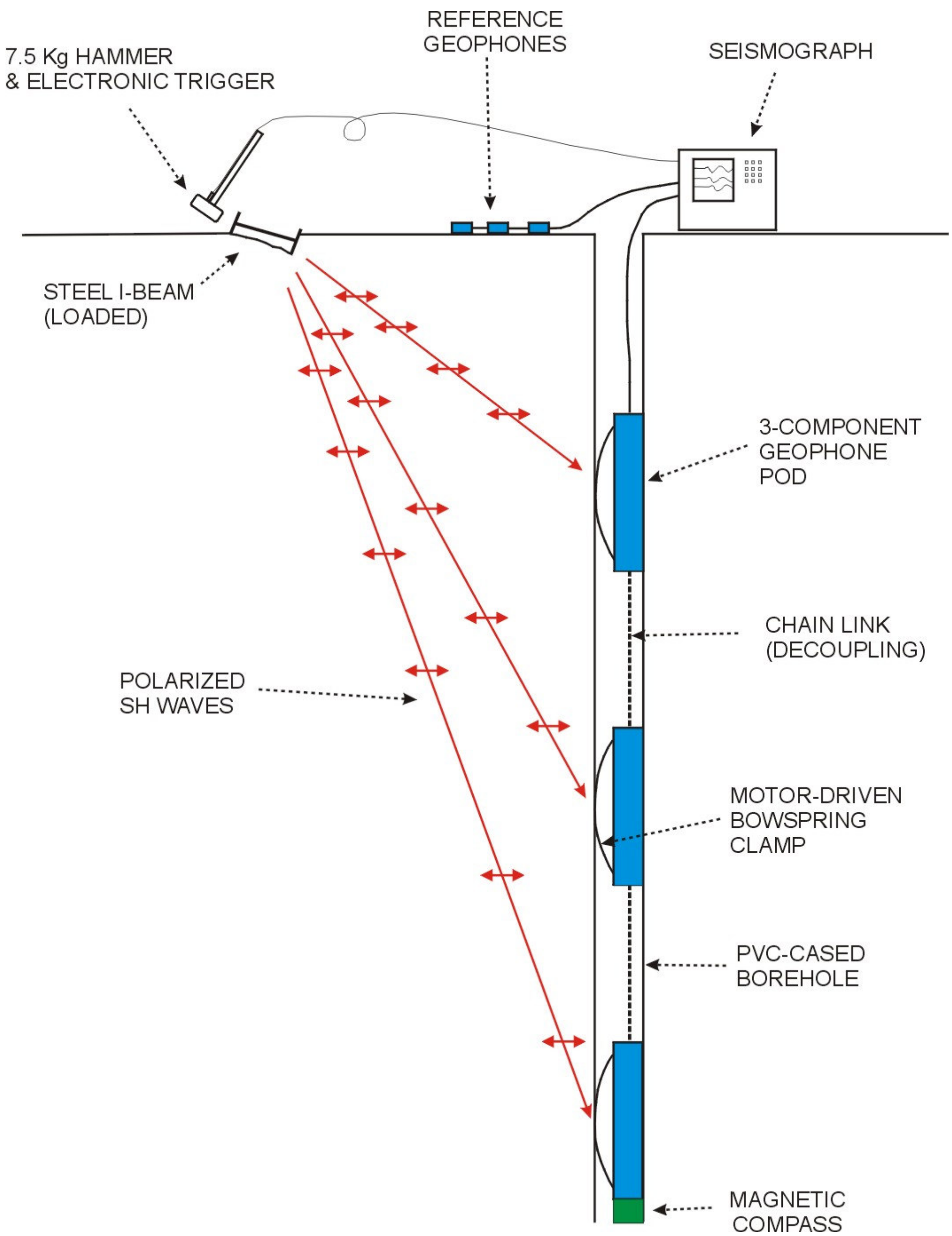

FIGURE 2 – Shear wave down-hole measuring technique. See Hunter et al., (1998) for detailed descriptions.

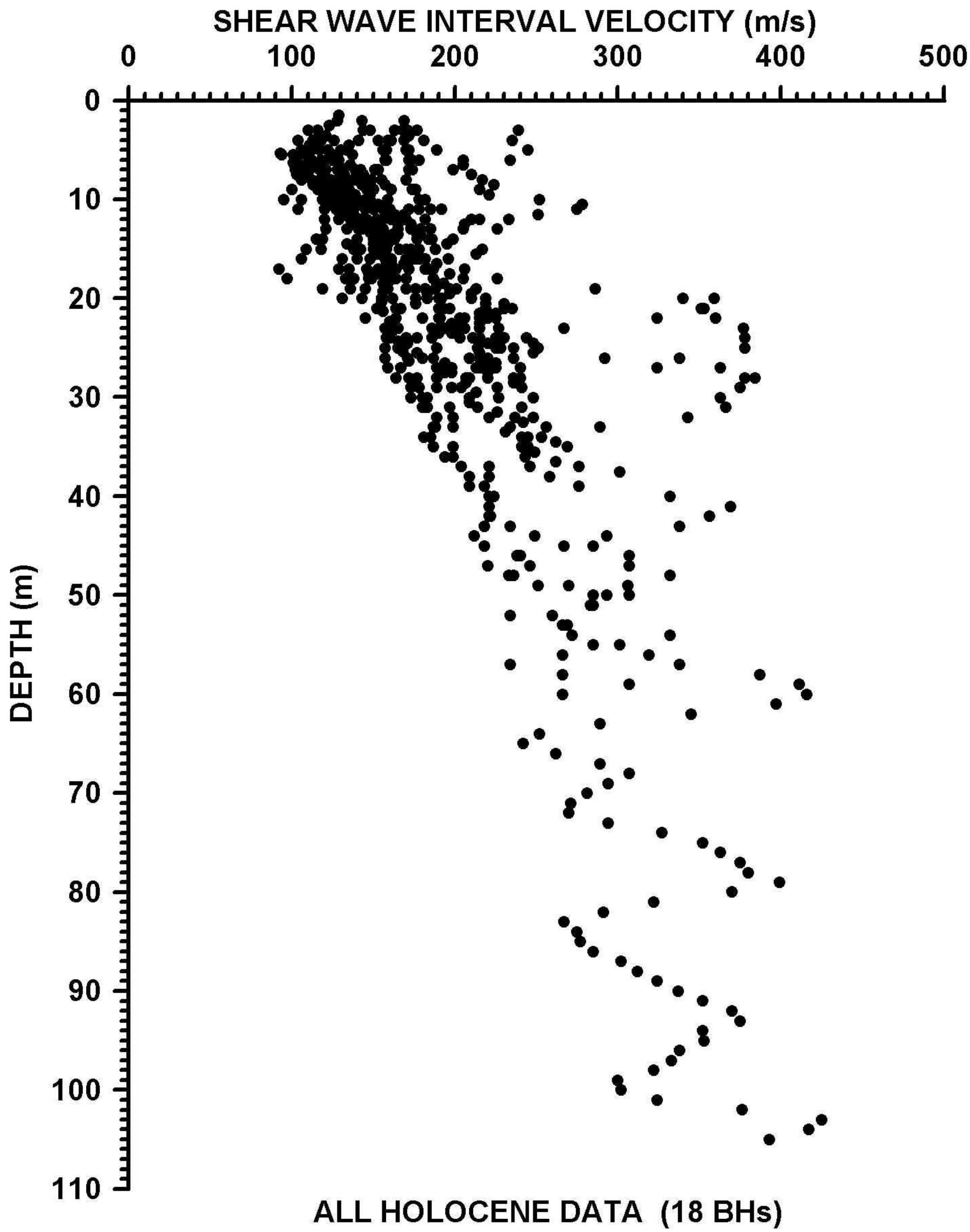

FIGURE 3 – Composite Champlain Sea shear wave interval velocities for all borehole data plotted as a function of depth below ground surface. Data obtained from the directory DATA (see also individual borehole plots in Appendix A).

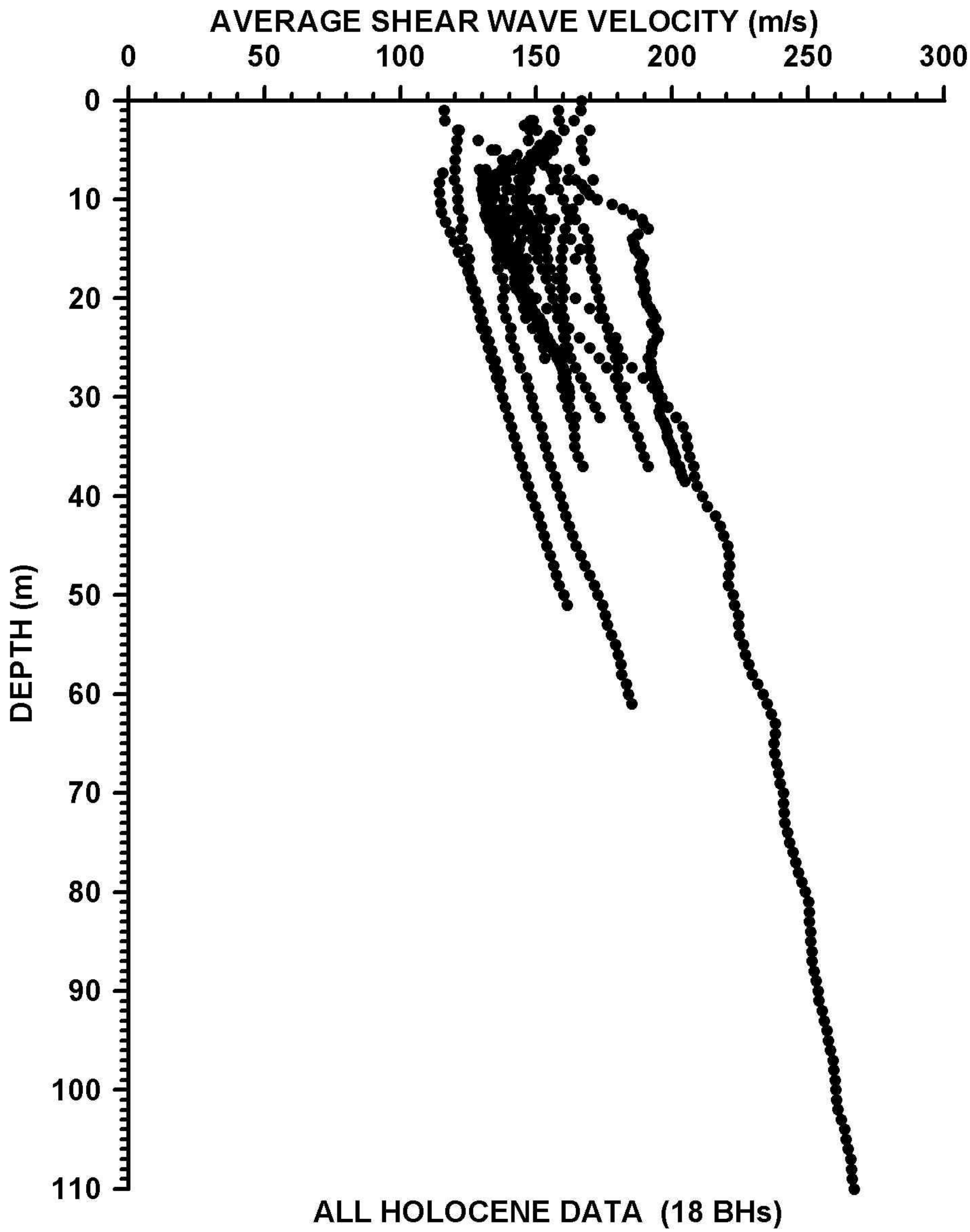

Figure 4 – Composite Champlain Sea average shear wave velocities from all boreholes plotted as a function of depth below ground surface. Data obtained from the directory DATA (see also borehole plots in Appendix A).

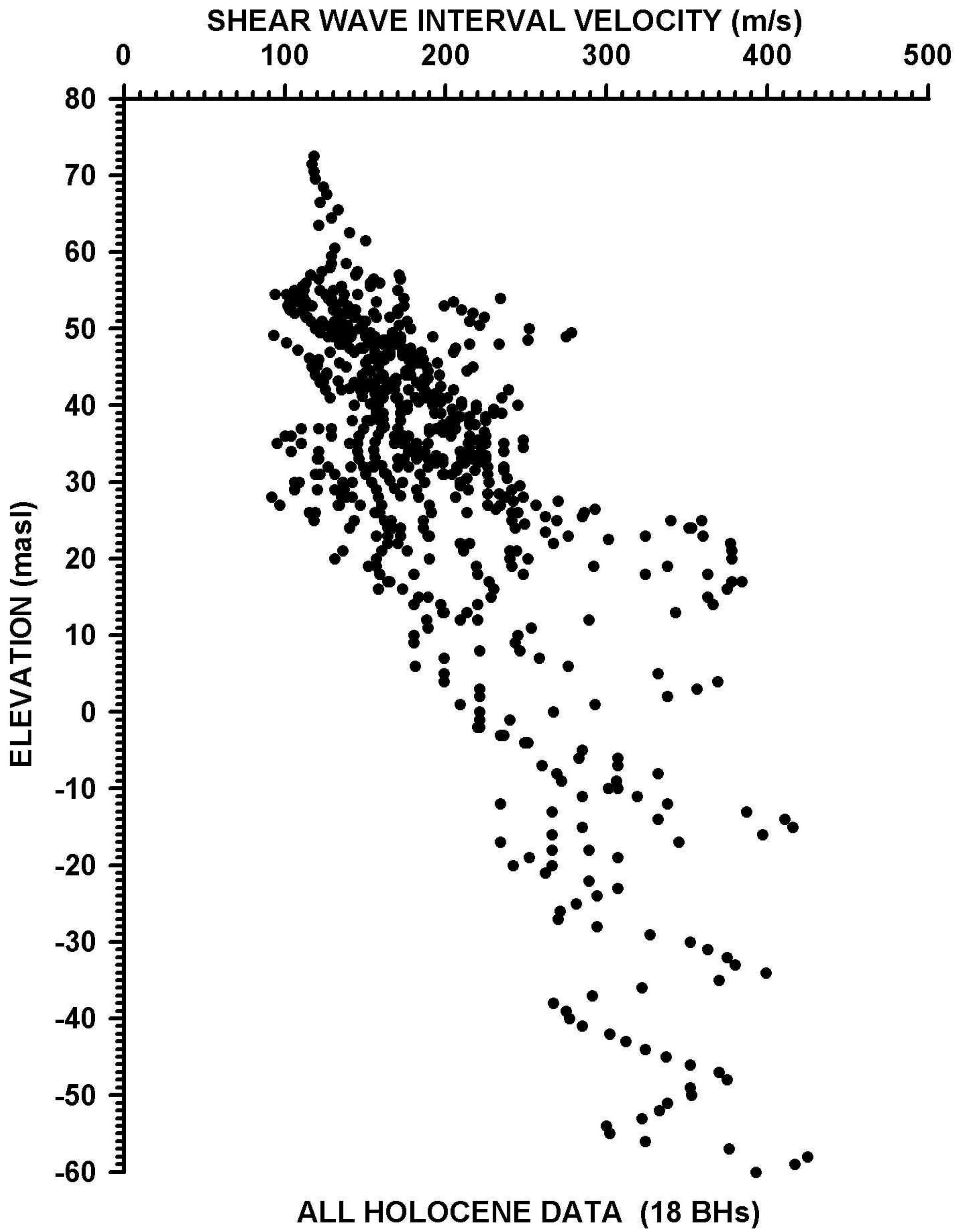

FIGURE 5 – Composite Champlain Sea shear wave interval velocities for all borehole data plotted as a function elevation above mean sea level. Data obtained from the directory DATA (see also individual borehole plots in Appendix A).

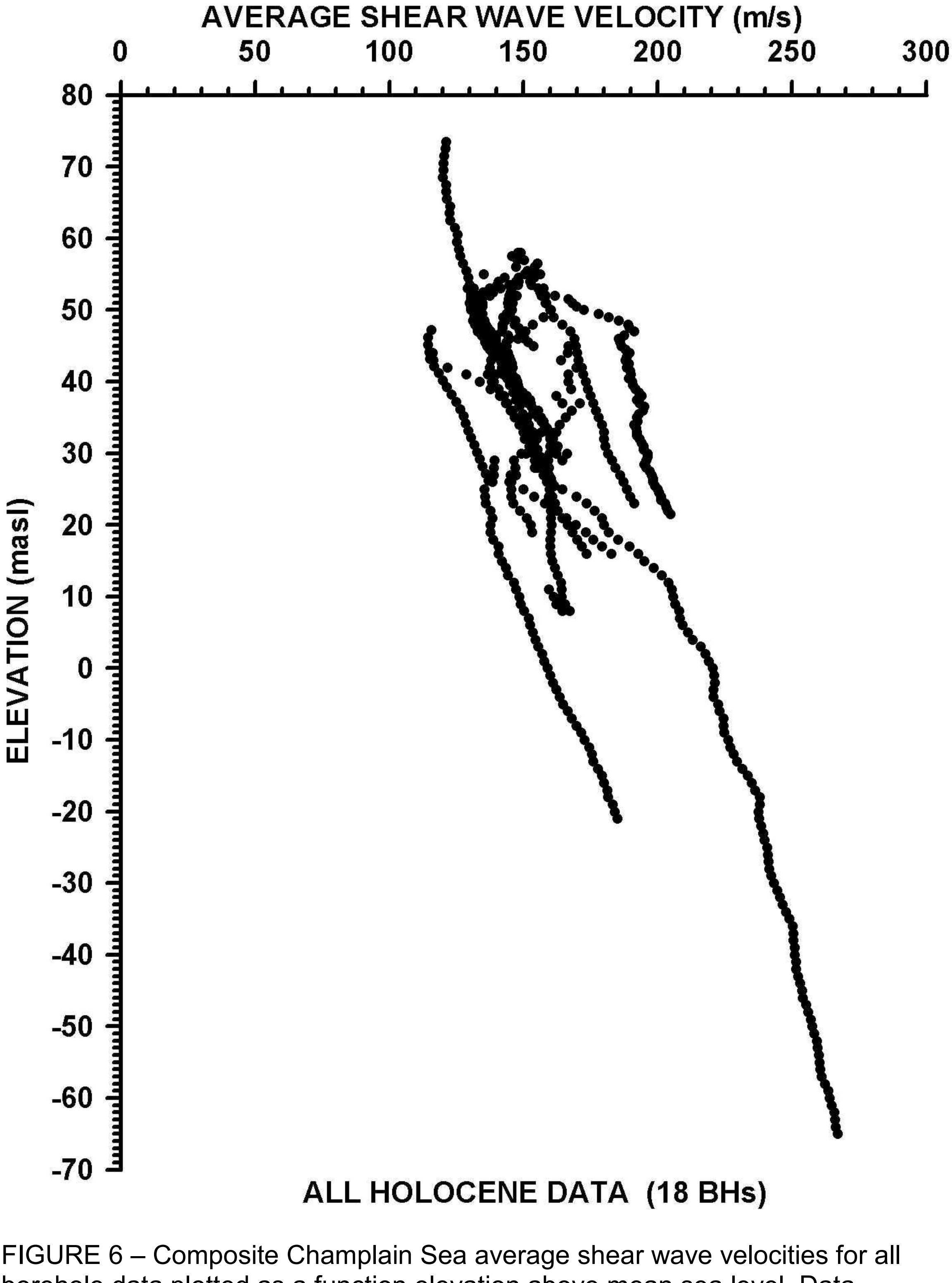

FIGURE 6 – Composite Champlain Sea average shear wave velocities for all borehole data plotted as a function elevation above mean sea level. Data obtained from the directory DATA (see also individual borehole plots in Appendix A).

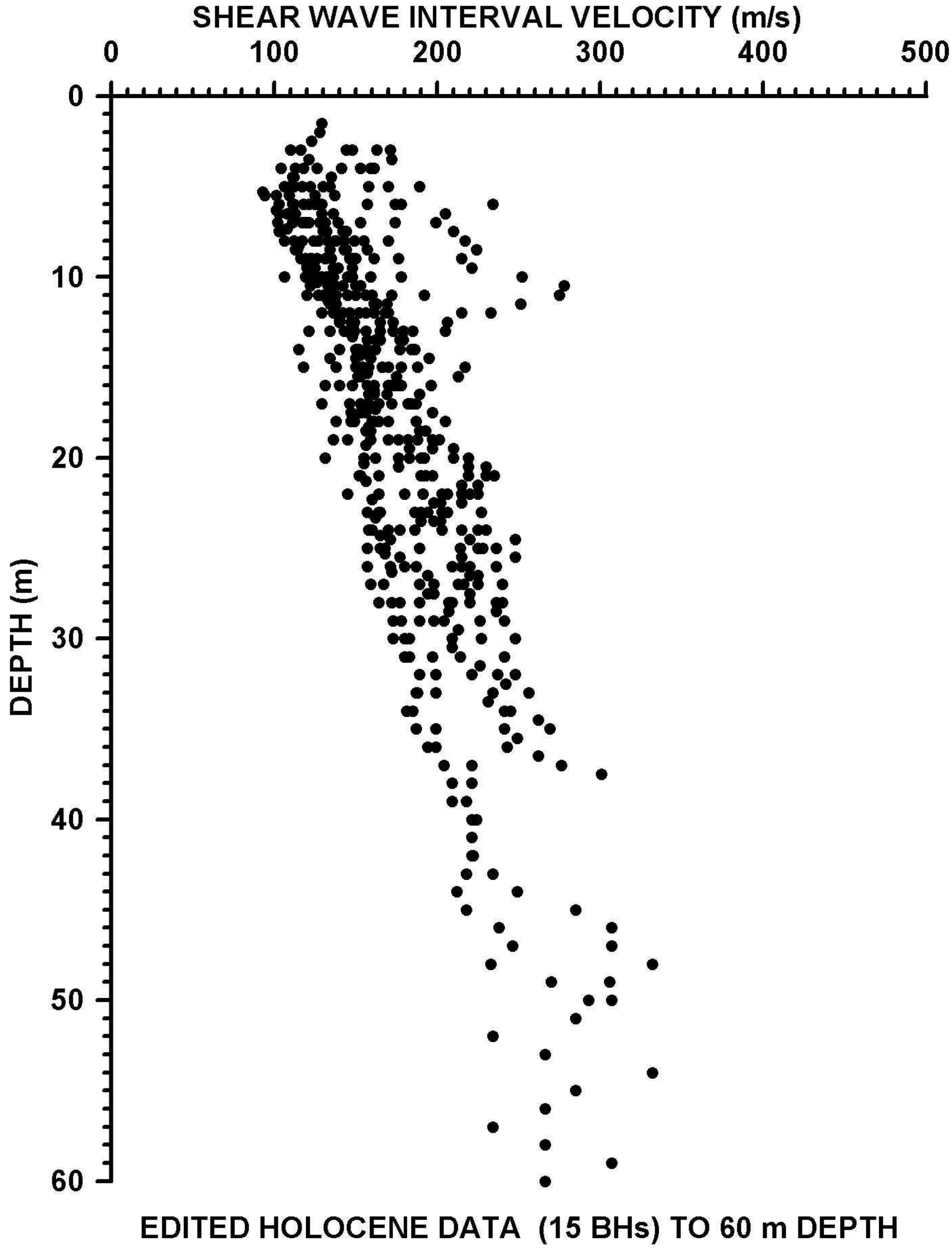

Figure 7 –Edited composite shear wave interval velocity data for Champlain Sea sediments plotted as a function of depth to 60 m.

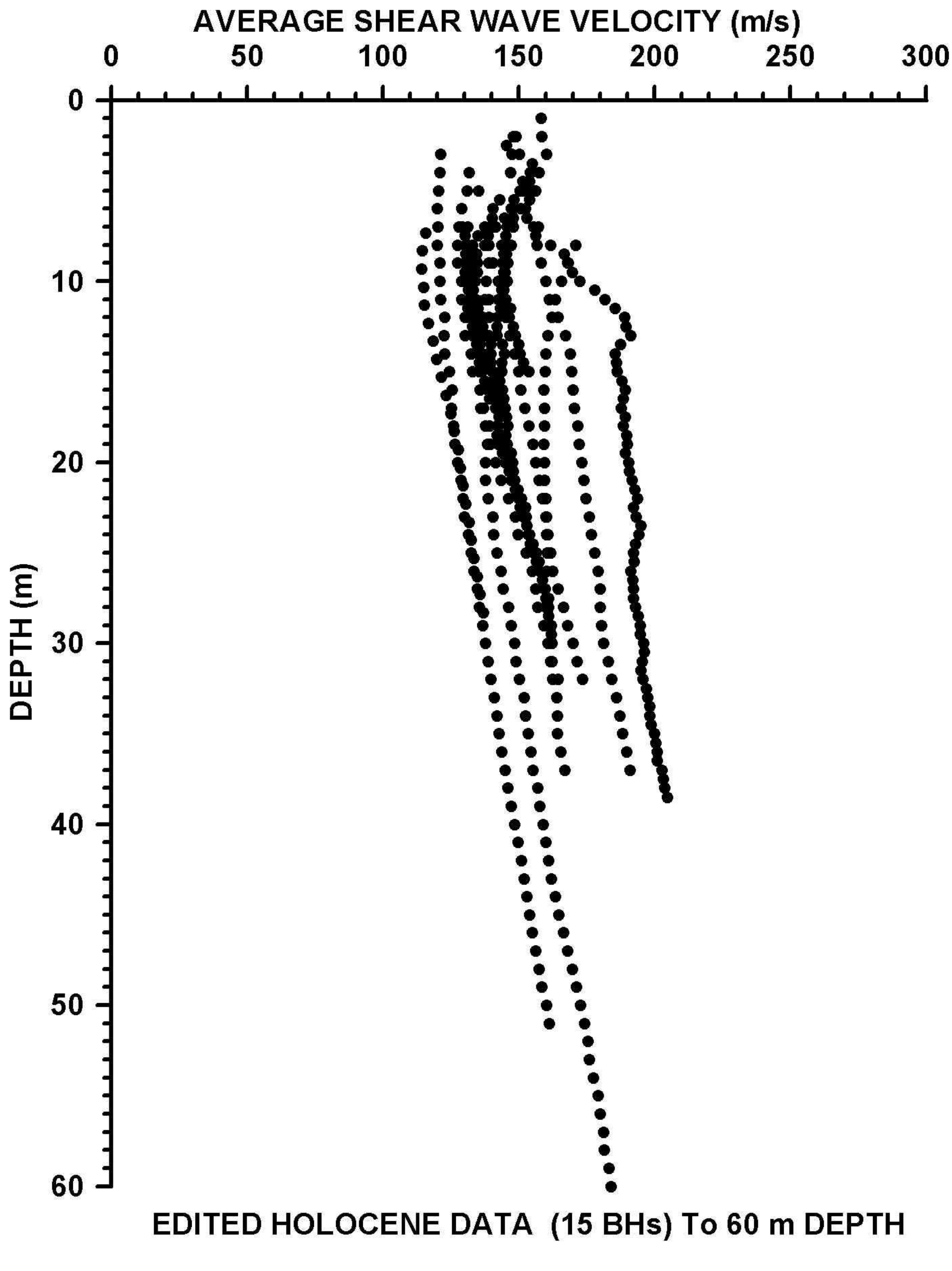

Figure 8 – Edited composite average shear wave velocities for Champlain Sea sediments plotted as a function of depth to 60 m.

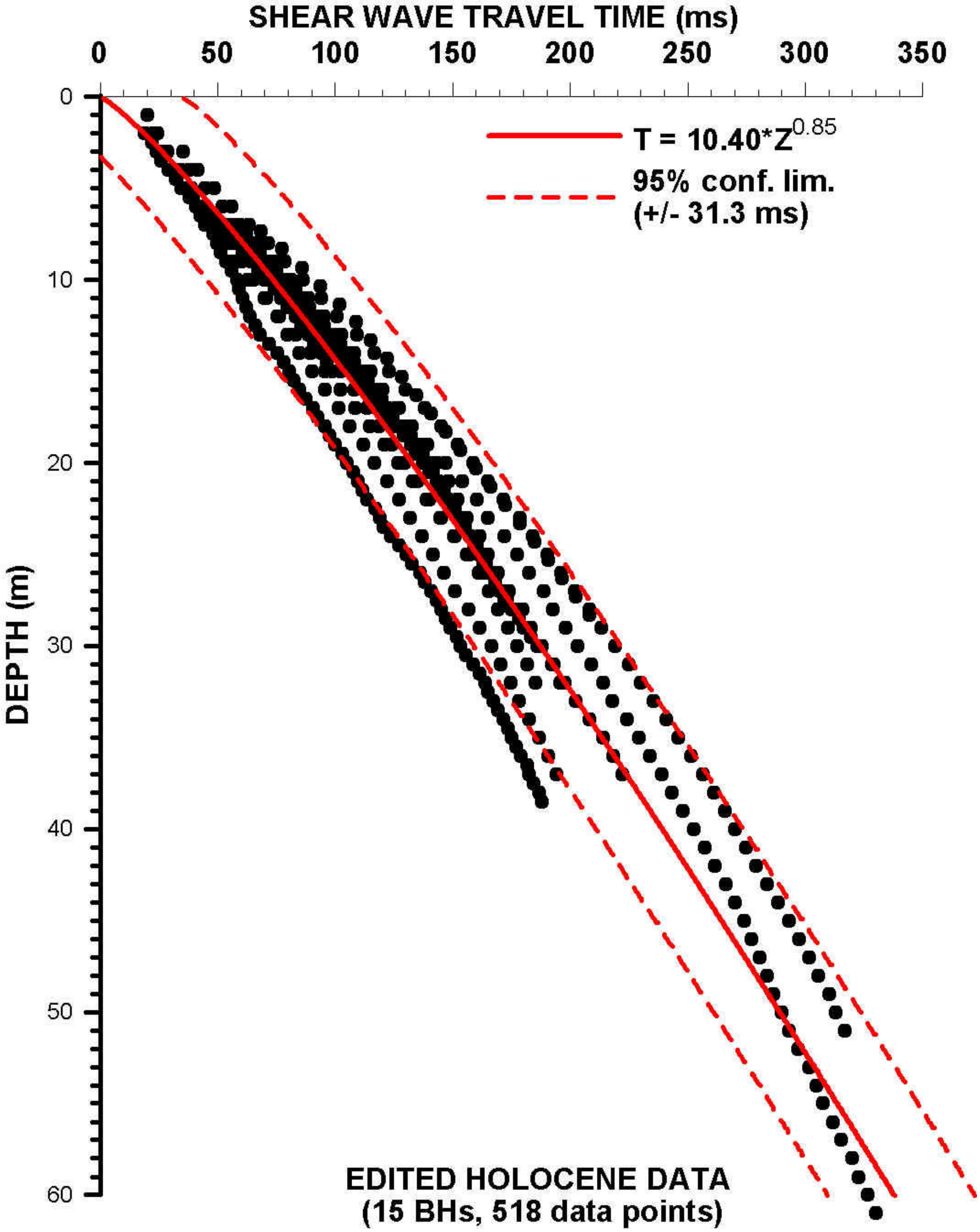

Figure 9 – Edited, composite shear wave travel-time versus depth for Champlain Sea sediments showing the “best-fit” power-law function.

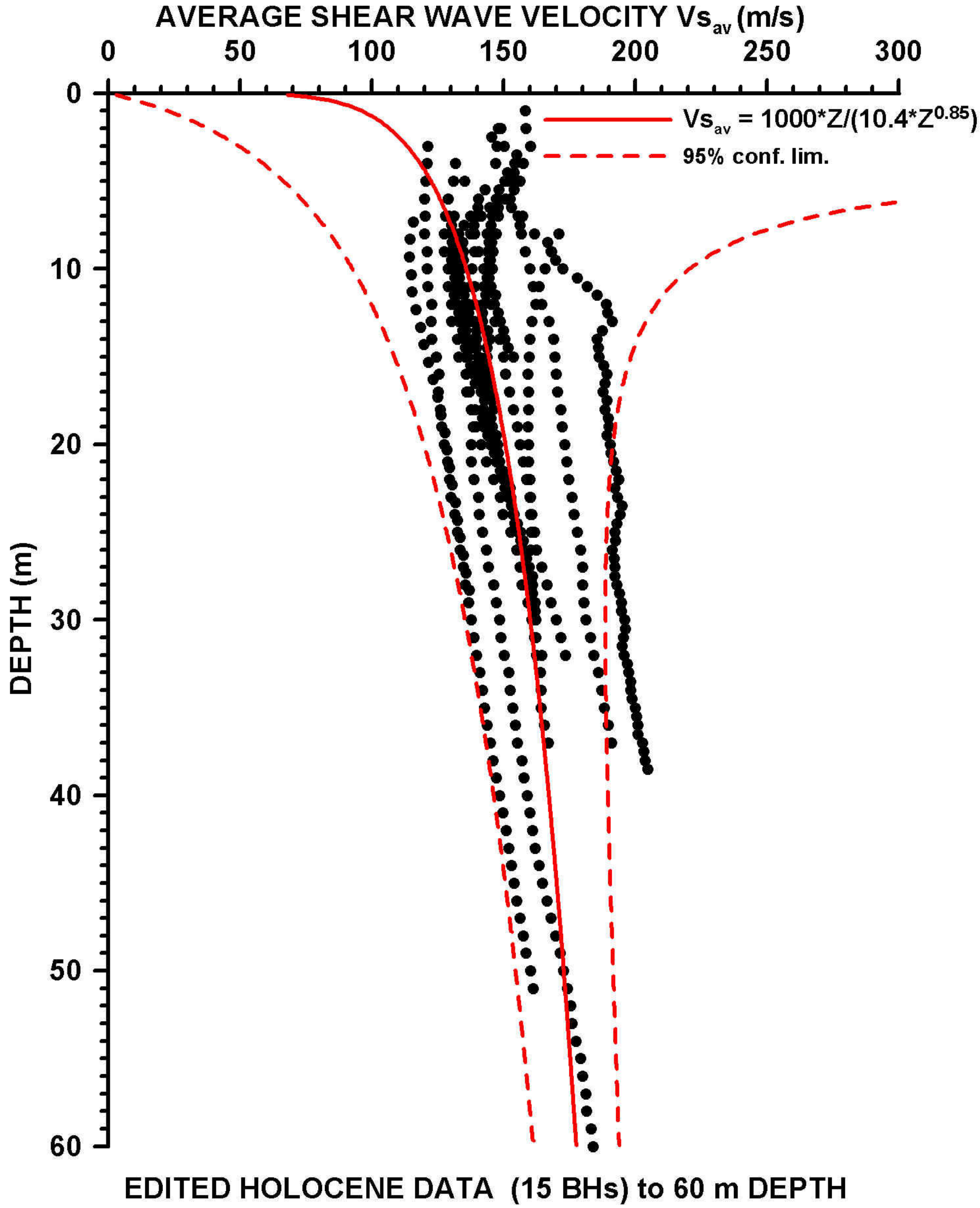

Figure 10 – Curve of average shear wave velocity versus depth derived from the travel-time curve fit of Figure 9 along with the composite of observed data points.

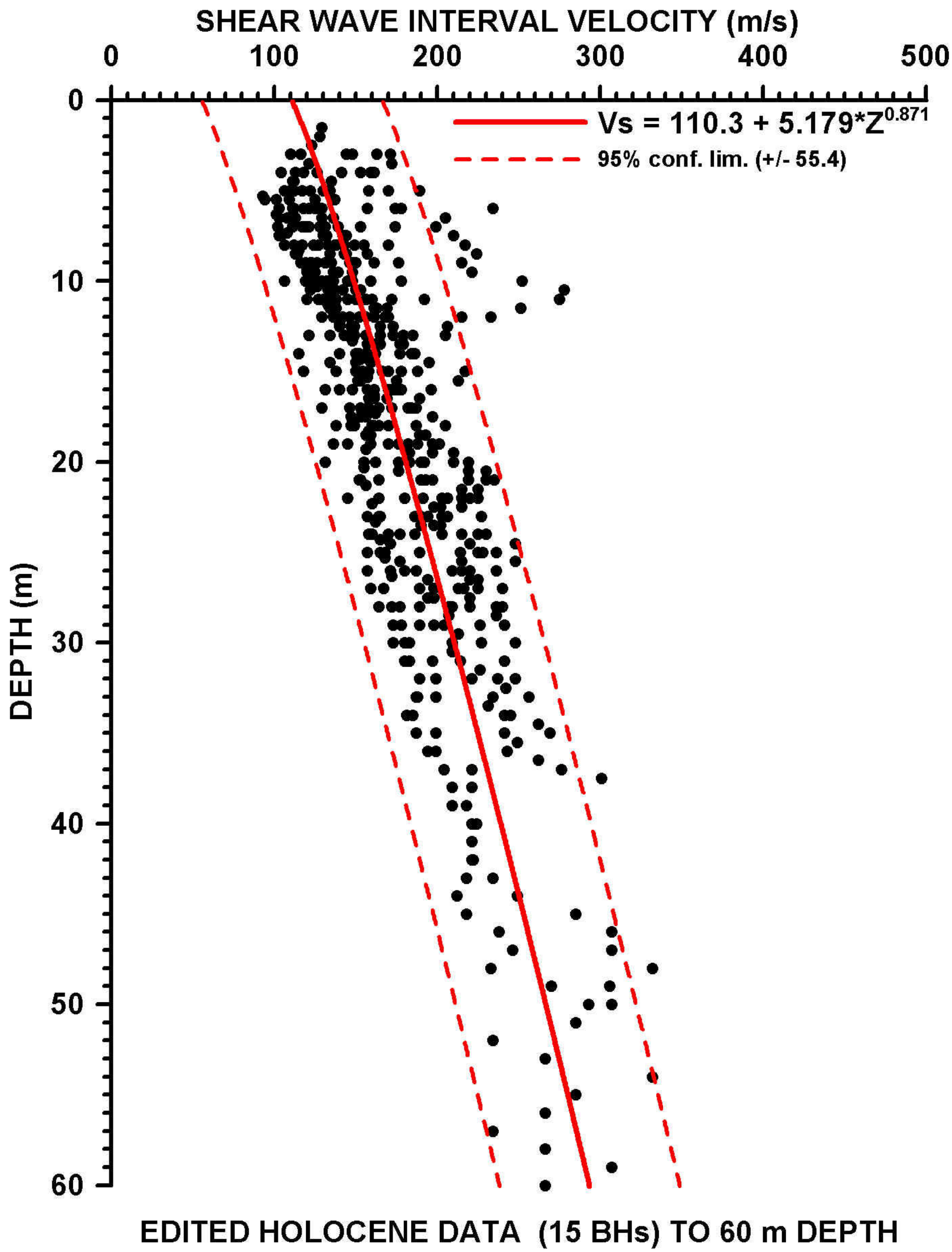

Figure 11 – Curve of “best-fit” (power law) of composite shear wave interval velocity versus depth for the edited Champlain Sea sediments data.

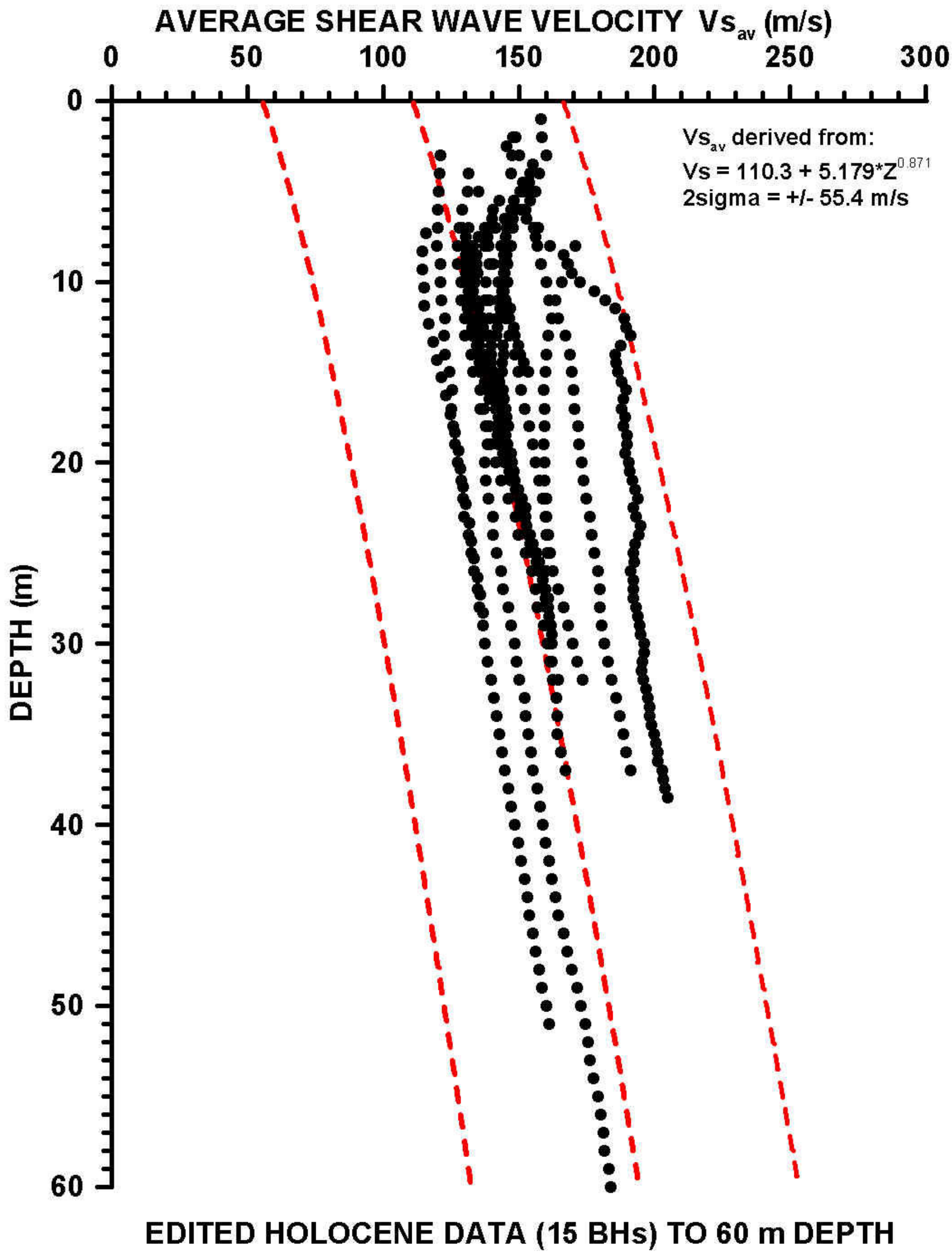

Figure 12 – Curve of average shear wave velocity versus depth derived from the interval velocity curve fit of Figure 11.

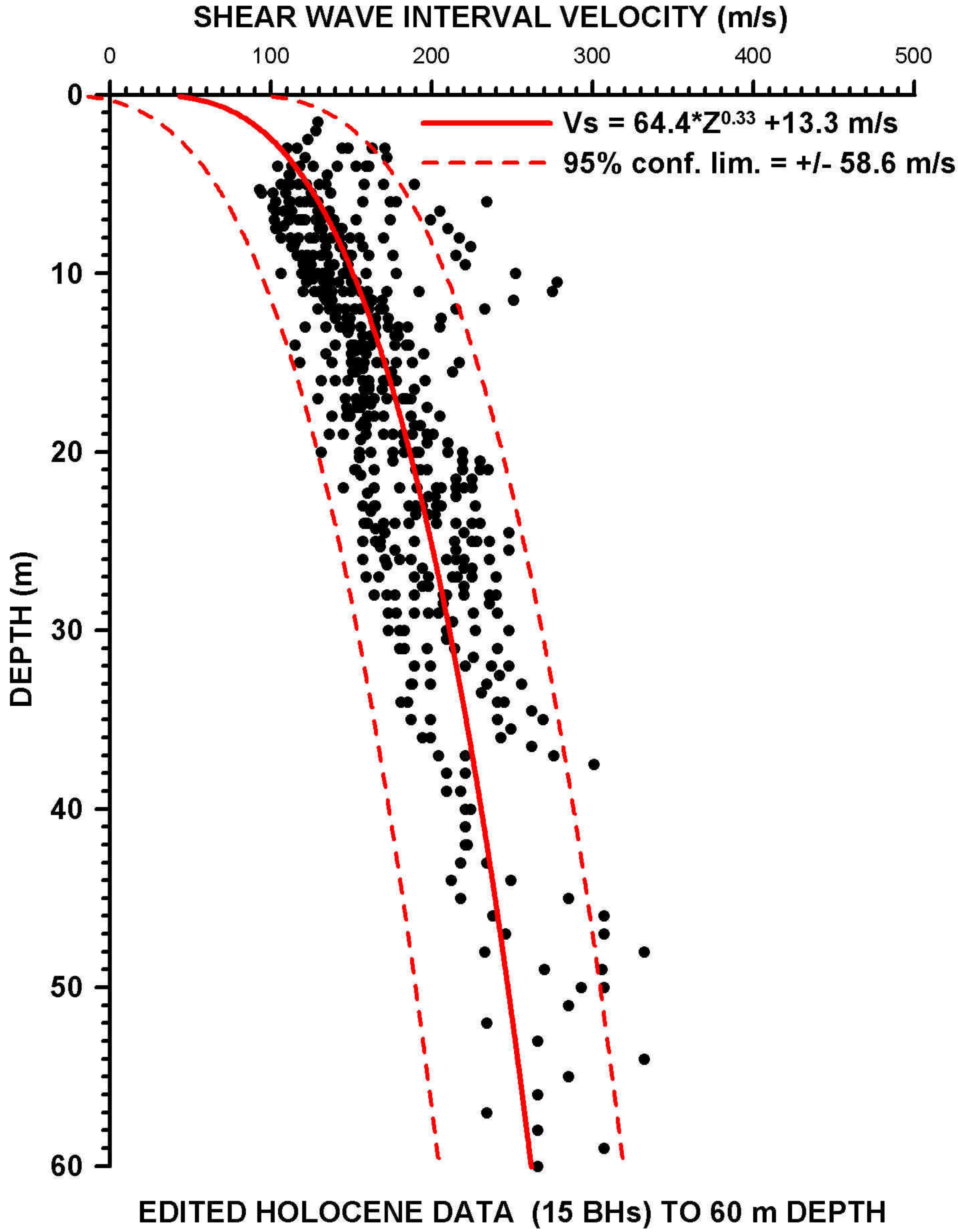

Figure 13 – Curve fit of composite Champlain Sea sediments shear wave interval velocities versus depth based on an empirical equation form related to effective stress in soils (see text).

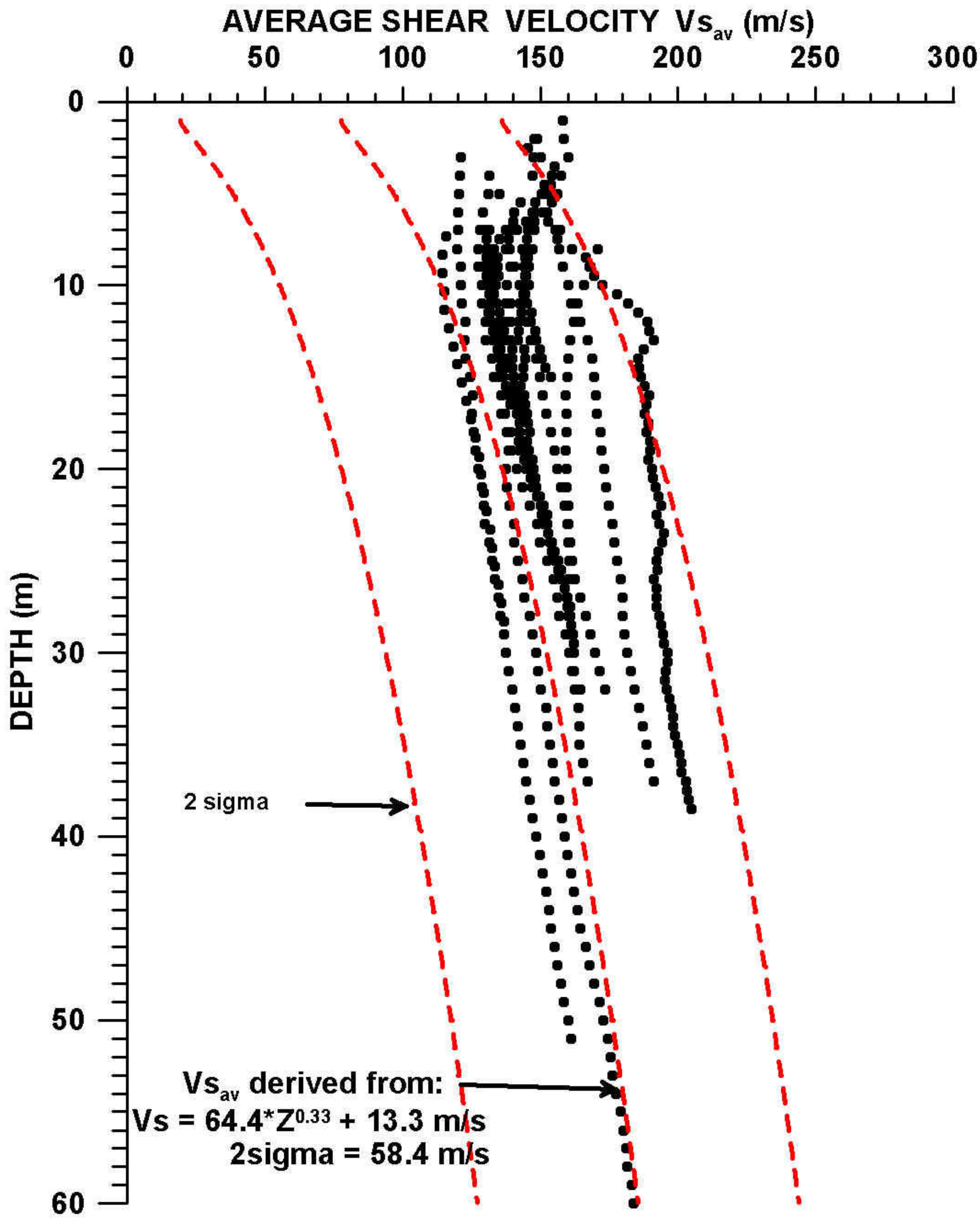

Figure 14 – Curve of average shear wave velocity versus depth derived from the curve-fit of Figure 13 plotted with composite observed data for Champlain Sea sediments.

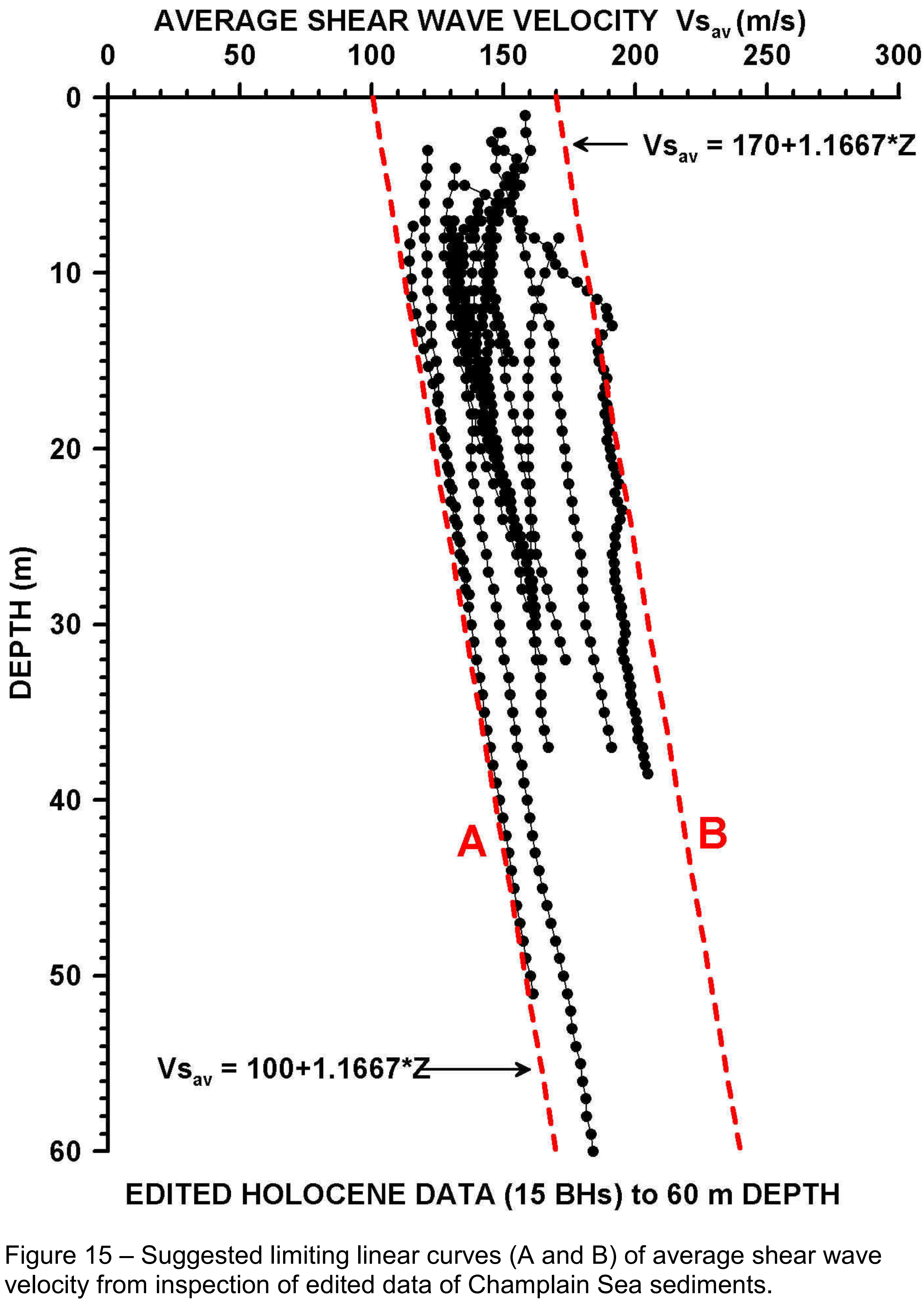

Figure 15 – Suggested limiting linear curves (A and B) of average shear wave velocity from inspection of edited data of Champlain Sea sediments.

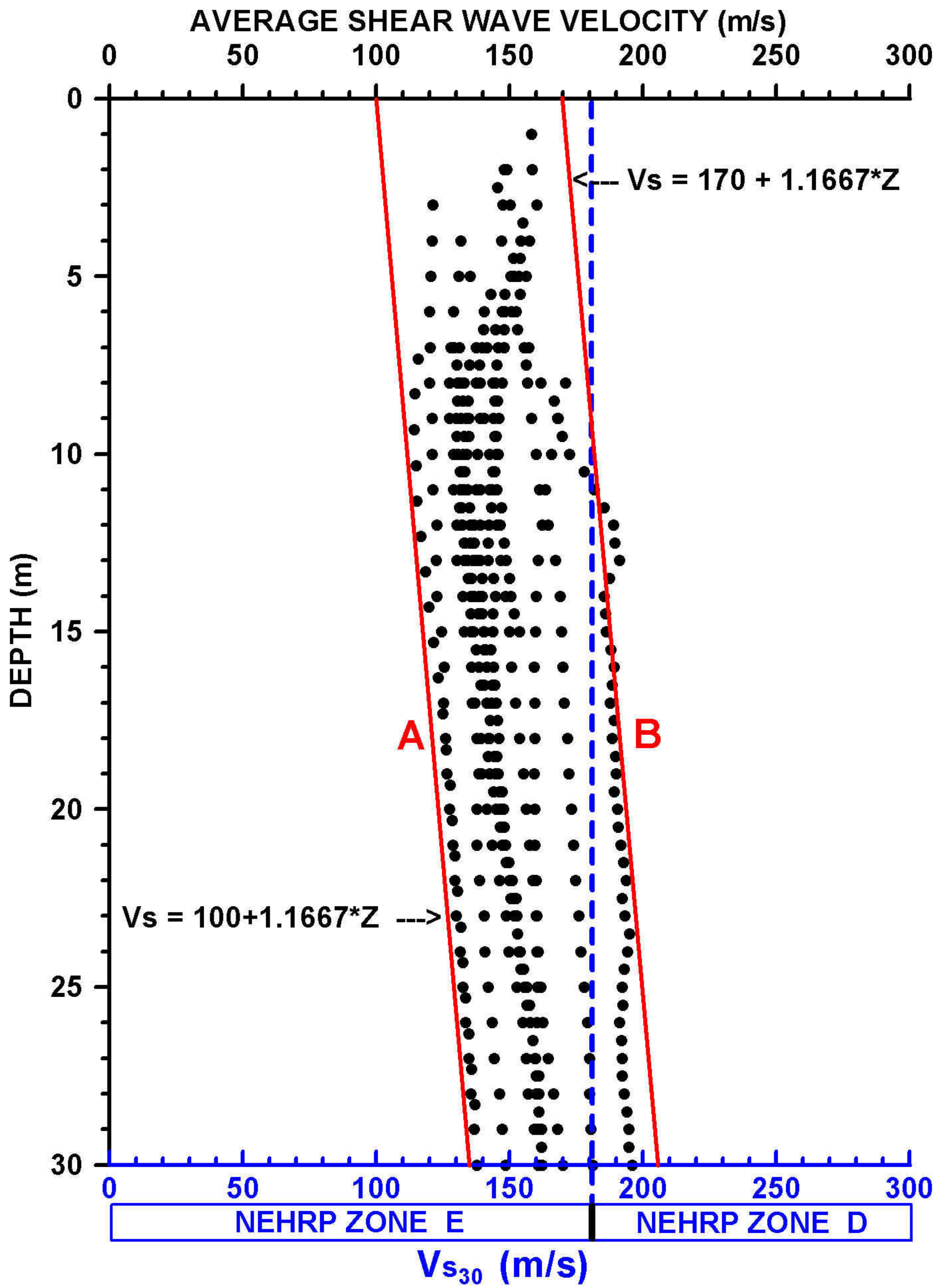

FIGURE 16 – Observed values of average shear wave velocity of Champlain Sea sediments to a depth of 30 m where limiting curves A and B indicate a Vs_{30} range between 135 and 205 m/s. Note that the NEHRP boundary between zones D and E occurs at 180 m/s.

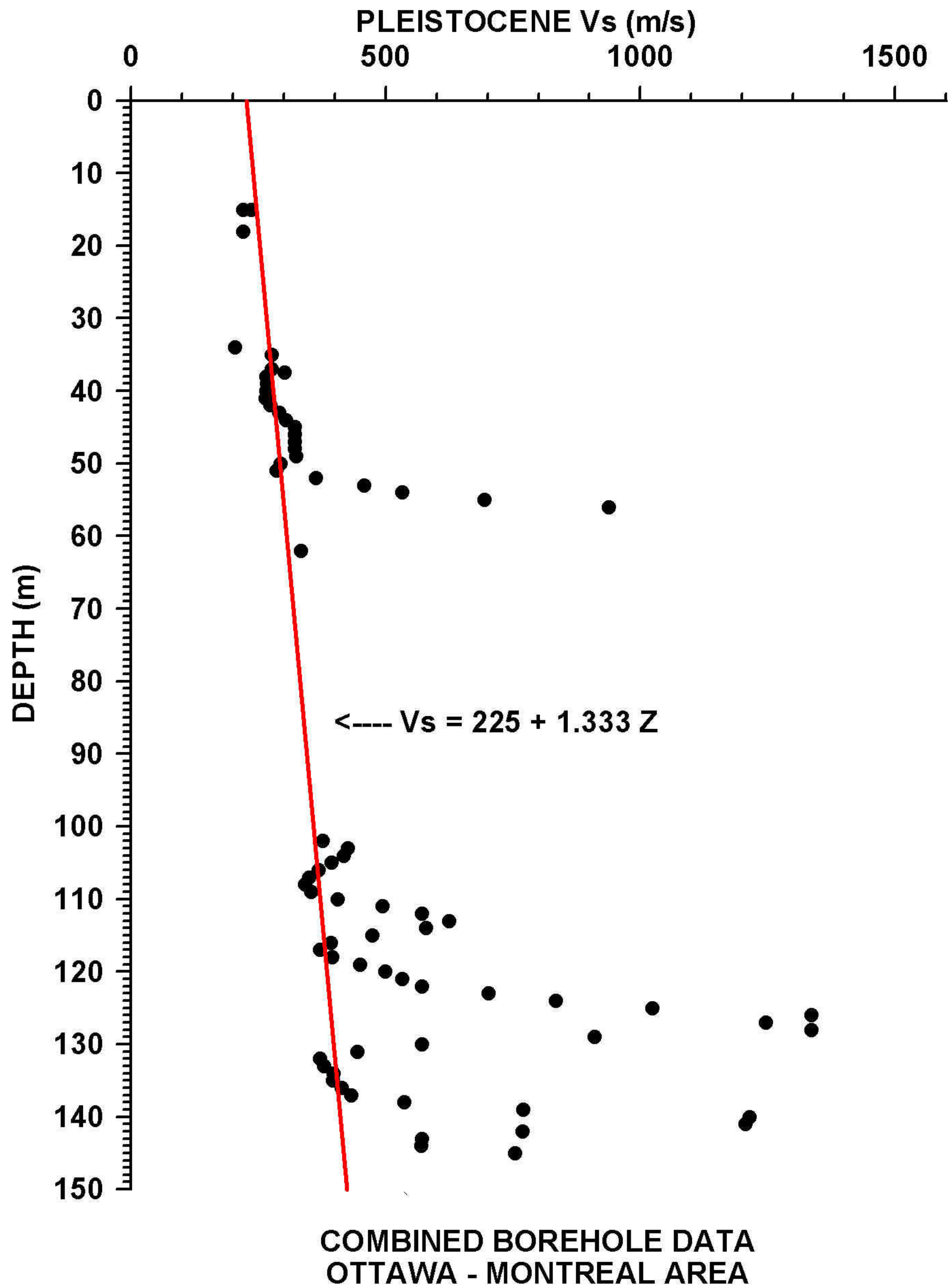

Figure 17- A compilation of shear wave interval velocity measurements in Pleistocene sediments – 71 observations.

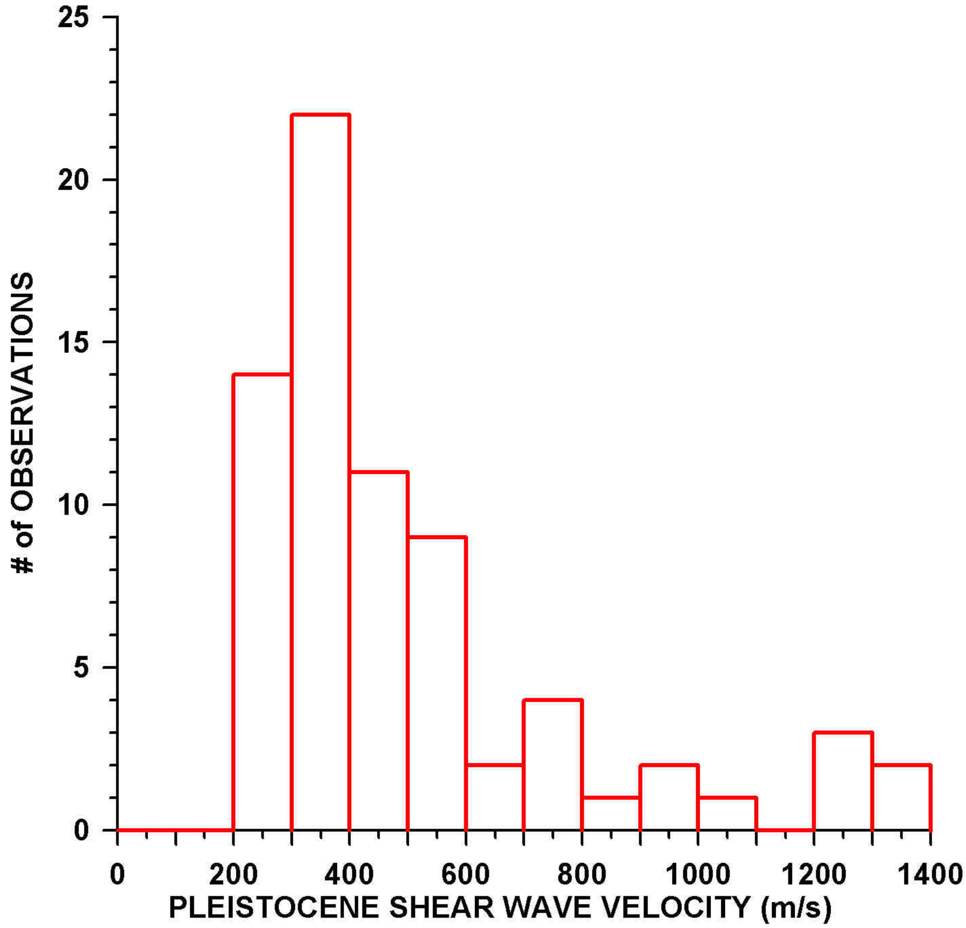

Figure 18 – A histogram of shear wave interval velocity measurements in Pleistocene materials from a compilation of all boreholes (71 observations). The peak is centered at 350 m/s, the median value is 398 m/s and the arithmetic mean is 503 m/s.