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Shear Wave Measurements for Earthquake Response Evaluation in Orleans, Ontario

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Abstract

The Geological Survey of Canada and Carleton University collected shear wave data at 63 seismic sites in the Ottawa suburb of Orleans as part of the Eastern Canada Geohazards Assessment Project. Data collection techniques included reflection/refraction and landstreamer profiling. Previous collection and analysis of high-resolution borehole velocity logs in 18 borings in the Ottawa-Montreal area led to the definition of an average shear-wave velocity-depth function unique to these sediments. This formula, when applied to 835 borehole logs from within Orleans, was used to estimate a Vs_{30} value at each location, based on the soil type described in the log. The combined data from surface seismic sites and derived velocity-depth calculations were contoured to produce a Vs_{30} map of Orleans. Shear wave velocity and post-glacial thickness information was also used to produce a fundamental site period map.

High Vs_{30} values (>1500 m/s) were calculated in areas of thin overburden, and very low Vs_{30} values (<180 m/s) were obtained in areas underlain by thick deposits of post-glacial sediments. Of note is a buried bedrock valley with steep sides which extends in an elongate, NE-SW trend for approximately 2.5 km under Orleans. Borehole data alone did not clearly define the extent or depth of the clay-filled bedrock valley, which reached a depth of 95 meters in places. Due to the high velocity contrast between post-glacial sediments and bedrock in the Ottawa area, ongoing research is being carried out to address the unusually high soil amplification factors observed in the study area.

Introduction

Ground motions during an earthquake can be greatly amplified by the presence of thick accumulations of soft sediment overlying the bedrock. An understanding of subsurface geological conditions at a site can be used to predict the damage potential of incoming seismic waves and therefore, assess earthquake hazard. The 2005 National Building Code of Canada (NBCC, 2005) defines amplification at a site primarily in terms of a Vs_{30} value. Vs_{30} is defined as the travel time-weighted average shear wave velocity profile through the top 30 meters of the ground. The 2005 NBCC uses the descriptions of soils and rocks given by the National Earthquake Hazard Reduction Program (NEHRP) of the United States, wherein five zones (A through E) are classified based on ranges of Vs_{30} values (Table 1).

This report presents the findings of the 2005/2006 geophysical investigations and borehole database analysis in the Ottawa suburb of Orleans, where thick deposits of Champlain Sea sediments are known to overlie thin glacial deposits and bedrock. The data have been collected by the Geological Survey of Canada (GSC) and Carleton University using various geophysical techniques to obtain shear wave velocity measurements (V_s) in the near-surface within the City of Ottawa. The primary purpose of this report is to present hazard maps showing calculated Vs_{30} values and fundamental site periods in the Orleans area. A secondary purpose is to compare the Vs_{30} map computed exclusively from an existing borehole database, with the same map enhanced with data from the surface seismic surveys. Finally, this comparison will demonstrate the importance of geophysical data collection for cost-effective compilation of seismic hazard maps. This work represents a contribution to the Ottawa Earthquake Hazards Activity of the Eastern Canada Geohazards Assessment Project in the Reducing Risk from Natural Hazards Program of Natural Resources Canada (NRCan).

Site Class	Generic Description	Range of Vs_{30}
A	Hard Rock	>1500 m/s
B	Rock	760 - 1500 m/s
C	Very dense soil and soft rock	360 - 760 m/s
D	Stiff Soil	180 - 360 m/s
E	Soil Profile with Soft Clay	<180 m/s
F	Site Specific Geotechnical Investigations Required	

Table 1: Vs_{30} site classification for seismic site response as defined by NEHRP (1994) and adapted by the 2005 NBCC (see Finn and Wightmann, 2003). Class 'F' designation represents a special case of site class that requires site-specific geotechnical testing and can not be defined using Vs_{30}.

Study Area

Orleans is a suburb of Ottawa, located in the eastern area of the city (Figure 1a). The study area is situated within in the Ottawa-St Lawrence Lowlands, which were inundated by the Champlain Sea approximately 12000 - 10000 years ago (Figure 1b). The underlying bedrock is composed of Paleozoic sedimentary limestone, dolostone, shale and sandstone, which overlie Precambrian crystalline basement rock. Late Quaternary deposits generally consist of glacigenic gravel diamicton (till) that underlie glaciomarine silty clays and pro-delta silts deposited within the Champlain Sea. These Champlain Sea deposits are locally known as 'Leda clay' and are composed of glacially-ground, non-clay minerals held together in a loose structural framework (Torrence, 1988). These materials are geotechnically sensitive, and if disturbed, can lose strength and collapse. Within this report, all geologic materials have been classified as either 'post-glacial', 'glacial', or 'bedrock', based on the differing shear wave characteristics in each of these units.

The thickness of post-glacial sediment in the Orleans study area ranges locally from a thin surface veneer (<1m thick) to over 100 m thick where it has accumulated in bedrock depressions and valleys. Glacial sediments are generally thin (1-3 meters thick), but may be thicker (>5 m) within the bedrock depressions.

Seismic Setting

The Ottawa area is subject to local seismic activity originating from the Western Quebec Seismic Zone (Adams and Basham, 1989). The occurrence of two major paleo-earthquakes in the immediate Ottawa area at approximately 7060 and 4550 yr BP has been inferred by Aylsworth et al. (2000), based on the coincidental radiocarbon ages of a cluster of large-scale earthflows in the Bourget, Ontario area, and the presence of heavily disturbed fine-grained marine and sand deposits near Lefaivre, Ontario, 20 and 50 km east of Ottawa respectively. The disturbed deposits exhibit irregular surface subsidence, minor lateral spreading, and sediment deformation to a depth of 50 m. Although earthquakes measured in the Ottawa area between 1980 and 2000 generally recorded magnitudes between M2.0 and M4.0, the magnitudes of these paleo-earthquakes are estimated at M6.5 (Aylsworth and Hunter, 2004), indicating that the region has been subject to high magnitude earthquakes in the past.

Methodology

Borehole Database and Vs_{30} Calculation

Basic subsurface stratigraphic information was obtained from a Geological Survey of Canada digital borehole database of the National Capital Area, containing 2370 borehole engineering logs, 23000 water well logs, and 1600 seismic refraction sites (http://gsc.nrcan.gc.ca/urbgeo/natcap/index_e.php; Belanger, 1998). For each entry, the

online database contains a unique borehole ID, geographical co-ordinates, surface elevation (masl), bedrock depth, and basic stratigraphic information including soil units, lithology, depth, and layer thickness.

Within the Orleans study area, the database contains 775 water well records and 60 engineering logs (Figure 1c). Each borehole log was reviewed and the materials were classified as either 'post-glacial' or 'glacial', based on the deposit description, stratigraphic position, and inferred depositional environment using the GSC's Surficial Materials and Terrain Features Map (Richard et al., 1978; Figure 1d). This distinction between materials was made for the purpose of calculating a Vs_{30} value at each borehole location using a velocity-depth function for the post-glacial unit, and using uniform velocities for the glacial and bedrock units.

To predict shear-wave velocities from sediments, equations were previously derived from downhole velocity logs acquired in 18 widely separated boreholes drilled in the Champlain Sea sediments along the Ottawa-Montreal corridor (see Hunter et al., 2007). A compilation of travel-time weighted average shear wave velocities resulted in the derivation of an empirical linear equation for the Champlain Sea sediments, given by:

$$V_{s(av)}=135 + 1.1667*Z \quad (+/- 35 \text{ m/s}) \qquad (1)$$

where Z is the depth of post-glacial deposits. Equation (1) was used to calculate an average shear wave velocity for post-glacial sediments within the borehole records of the borehole database. Where present in the upper 30 meters of the borehole log, uniform average velocities applied to glacial materials and bedrock were 503 m/s and 2380 m/s, respectively. From these data and the velocity-depth function, a preliminary Vs_{30} map was created from the calculated Vs_{30} values at borehole locations in the Orleans area, prior to the inclusion of the surface seismic results.

Seismic Reflection/Refraction Methods

During the 2005 field season, seismic and borehole data provided evidence of a buried bedrock valley, prompting additional data collection in 2006 to better define the shape, depth, and orientation of the feature. Over both seasons, seismic data were acquired at 339 sites distributed across the National Capital Region. Of these sites, 63 lay within the Orleans study area, all of which were situated in city parks in densely urbanized areas or along roadsides in sub-urban areas.

At each location, a 24-channel array of 8-Hz horizontal axis geophones oriented in SH mode was laid out at either a 3 meter or 5 meter spacing. Geophone separation was influenced by the space available at each site, and the inferred depth to bedrock based on a review of available borehole logs in the vicinity. The data were recorded using a Geometrics Strataview or Geode seismograph. Source points were chosen 1 and 1½ geophone spacings off each end of the array, and one centre shot was taken between geophones 12 and 13 (Figure 2a). This configuration allowed for trace-to-trace correlation of wide angle reflections from the glacial or bedrock interface, while

permitting sufficient source-geophone spacing to detect the bedrock refractor at depths down to 30 meters. The seismic source consisted of a steel I-beam plate with one edge dug into the ground in SH orientation and a 10-lb hammer connected to an electronic trigger (Figure 2b).

Interpretations of the first arrivals from the records were made using the Interpex IXSEG2SEGY software. This software allows the interpreter to use a variety of bandpass filters and gain enhancements, including AGC, trace max, and user specified constant gains to enhance different features in the record. On many seismic records in the Ottawa and Orleans areas, a thin high shear wave velocity exists on surface. This is due to over-consolidation caused by centuries of freeze-thaw cycles, or by man-made compaction on road bed or construction sites. This layer is visible only in the first few traces of the record and quickly dies off with distance from the source. The most prominent refraction event on the sections is generally the arrival through the Champlain Sea sediments, or 'post-glacial' materials. A bedrock refraction, if visible as a first arrival, can generally be brought out by increasing gain levels to heighten the trace amplitude (Figure 3a). At many sites in the Orleans area where thick deposits of post-glacial sediments exist, it was observed that higher velocity layers at depth (high velocity silts or glacial materials) occur as 'hidden' layers, due to the very high velocity contrast between the post-glacial and glacial or bedrock horizons. Evidence for this can be seen when the refraction tail from the post-glacial materials curves back in at wide angles, or where the bedrock refraction intercept time occurs later than the bedrock reflection intercept (Figure 3b). Forward and reverse arrival data were analysed separately and time-distance slopes were inverted to estimate interval velocities and t_o intercept times for each layer (Figure 3b).

To obtain time-averaged shear wave velocities required for the NEHRP zonation, prominent reflections in the record were fitted with hyperbolic curves using the IXSEG2SEGY software. The reflection fitting algorithm provides a t_o, average velocity, and depth value for each reflector fit (Figure 3c). The off-end shots, both forward and reverse, were used to interpret average velocities and reflector depths, and values were copied to a spreadsheet for depth-velocity analysis. If glacial materials were present at a site, two prominent reflections were generally observed in the sections at depth, interpreted as a thin veneer of glacial material overlying the bedrock surface. The sharp impedance contrast between the post-glacial soils and the glacial tills could cause this reflection to become more prominent than the reflection from the till-bedrock interface. Due to the compact nature of the glacial till and its high velocities (500 – 800 m/s), the glacial material is considered the 'firm' horizon and is not distinguished from the bedrock for the purposes of the site period calculation. The centre shot was used for the 'depth to firm' analysis and to estimate the average velocity from surface to the firm ground boundary (Figure 3d). Both depth and velocity parameters were used in calculating the fundamental site period.

Using the REFRACT program (Hunter, pers. comm. 2006), interval velocities and intercept times from the refraction interpretation were used to calculate layer thickness of the units lying above the bedrock. By applying a time-weighted average calculation over

these thicknesses, the interval velocities were converted to average velocities and combined with the reflection data to produce an average velocity vs. depth plot (Figure 3e). A best fit curve was drawn by hand and used to assign a Vs_{30} value to the site.

Shear Wave Landstreamer Lines

Landstreamer reflection techniques are well suited for collecting seismic data in urban environments (Pugin et al., 2007). Towing an array of geophones behind a vehicle avoids the need to plant geophones in busy urban areas, and data collection can be achieved more quickly than with conventional roll-along methods. Details of the landstreamer work in the Orleans area are summarized by Pugin et al., (2007). Briefly, 24 pairs of SH-oriented, 8-Hz geophones were sled-mounted and towed behind a vehicle which contained the seismograph. The source was either a truck-mounted hydraulic ram-loaded roller which was struck with a hammer in SH orientation (Figure 4a), or a Minivib swept-frequency source (Figure 4b). The Minivib vibrator mass was mounted in SH mode, swept from 10Hz to 100Hz over 6 seconds, and data were recorded over a period of 8 seconds. The streamer coupled with the Minivib source was found to be the optimal configuration for urban seismic studies, as it could work through significant traffic noise.

Two shear wave reflection lines were collected using the roller source in Heritage Park (Line A) and along Boyer Rd (Line B), and one line with the Minivib source along Belcourt Ave (Line C) (Figure 1c). Line A was used to delineate the structure of the valley above Heritage Park prior to the installation of a seismograph station (Figure 4c). Lines B and C were intended to delineate the steep southern side of the bedrock valley where it intersects the road alignment (Figures 4d and e). Due to the angle at which the lines cross the buried valley, the bedrock is not seen to rise on the northern end of the section.

The interpreted post-glacial and glacial material thicknesses along Lines A, B, and C were used to calculate Vs_{30} values in the same manner as the information derived from the borehole log database. Eq.(1) was used to calculate the average shear wave velocity of the post-glacial materials, and, if present in the upper 30 m, uniform average glacial and bedrock velocities of 503 m/s and 2380 m/s, respectively, were also used to calculate a Vs_{30} value at each point along the landstreamer line. Collectively, this dataset was gridded with the information from the borehole database and surface seismic sites to show the enhanced resolution brought by the landstreamer coverage across the sharp valley slopes.

Results

Stratigraphic Variation

Figure 5a presents the post-glacial sediment thickness derived solely from information found in the borehole database. Sixty-three additional seismic sites and 3 landstreamer lines provided greater definition in the south-west and central areas of the map (Figure 5b), where a steep-sided, NE-SW trending valley is found to be deeper than the borehole data alone suggests. Landstreamer lines indicate that the post-glacial deposits reach depths of 95 meters within the basin. Seismic data collected in a residential region on the south bank of the Ottawa River also indicate that a thick deposit (approx.101 m) of post-glacial materials is present, which was undetected in Figure 5a due to the lack of boreholes in this area. During the 2007 field season, additional seismic work will focus on this area to better understand trends in bedrock depressions.

Vs_{30} and NEHRP Classification

Figure 5c presents the preliminary Vs_{30} map computed from the borehole database and derived shear wave velocity function only. The borehole database and surface seismic datasets are combined to produce the most complete Vs_{30} map for the Orleans area, shown in Figure 5d. Vs_{30} maps are presented using contours based on the NEHRP site classification categories (see Table 1). Due to the improved definition of post-glacial soil thickness brought by the seismic surveys, Figure 5d shows that a greater area of the map falls under the lowest shear wave velocity category (<180m/s) than was previously identified by the borehole database dataset alone.

Fundamental Site Period Estimation

The fundamental period (T) of a soft soil site approximates the period of vibration at which the greatest soil amplification is anticipated (Kramer, 1996). The period is governed by the main seismic impedance contrast caused by the post-glacial-to-glacial or post-glacial-to-bedrock boundary, and is given by:

$$T=4*Z/V_{s(av)} \qquad (2)$$

where Z is the depth to the boundary, and $V_{s(av)}$ is the average velocity of the overlying post-glacial sediments. Figure 5e presents the results of the site period calculations. Site periods exceeding 1.0 second are generally found in areas of thick (>30m) post-glacial sediments, notably in the bedrock rock valleys overlain with thick post-glacial deposits. This should be a consideration in the design of tall structures constructed over thick accumulations of soft soil.

Discussion and Future Work

Amplified seismic ground motions from a modest- to large-scale earthquake are of concern in large, soft-sediment filled basins. The identification of the 'Orleans' bedrock valley and other isolated bedrock depressions highlight the importance of carrying out surface geophysical surveys when creating microzonation seismic hazard maps of cities in high and moderate earthquake risk zones. Shear wave seismic surveys fill in gaps between boreholes and provide broad coverage of geological trends in the soil and bedrock surface using non-invasive, cost-effective methods. The application of landstreamer technology with a Minivib source was found to be extremely effective in defining the bedrock surface in a continuous profile perpendicular to the axis of the bedrock valley. Landstreamer data were relatively quick to collect (approx 1.2 km/day) and acquisition was carried out on city streets with moderate traffic flow without compromising data quality.

In the coming year, data at an additional 150 seismic sites will be collected across the National Capital Region to create a larger NEHRP map for the City of Ottawa. Based on the success of the landstreamer profiles using a Minivib source, additional lines are proposed in areas of known bedrock depressions. In addition to active source seismic investigations, data from a passive-source seismograph station installed in Heritage Park in 2006 will continue to be analysed. Early results indicate amplification in the soft soils is much higher than predicted by NEHRP–based amplification factors when comparing Heritage Park microtremor measurements with those collected on bedrock outcrop by the Ottawa station of the Canadian National Seismograph Network. Due to the high velocity contrasts between the Champlain Sea deposits and bedrock in the Ottawa area, ongoing research is being carried out by the GSC and Carleton University to address the very high soil amplification factors observed in the St Lawrence Lowlands.

Disclaimer

Her Majesty the Queen in right of Canada, as represented by the Minister of Natural Resources ("Canada"), does not warrant or guarantee the accuracy or completeness of the maps and other data and information ("Data") contained in this report and does not assume any responsibility or liability with respect to any damage or loss arising from the use or interpretation of the Data.

The Data in this report is intended to convey regional trends and should be used as a guide only. The Data should not be used for design or construction at any specific location, nor is the Data to be used as a replacement for the types of site-specific geotechnical investigations recommended by the 2005 National Building Code of Canada.

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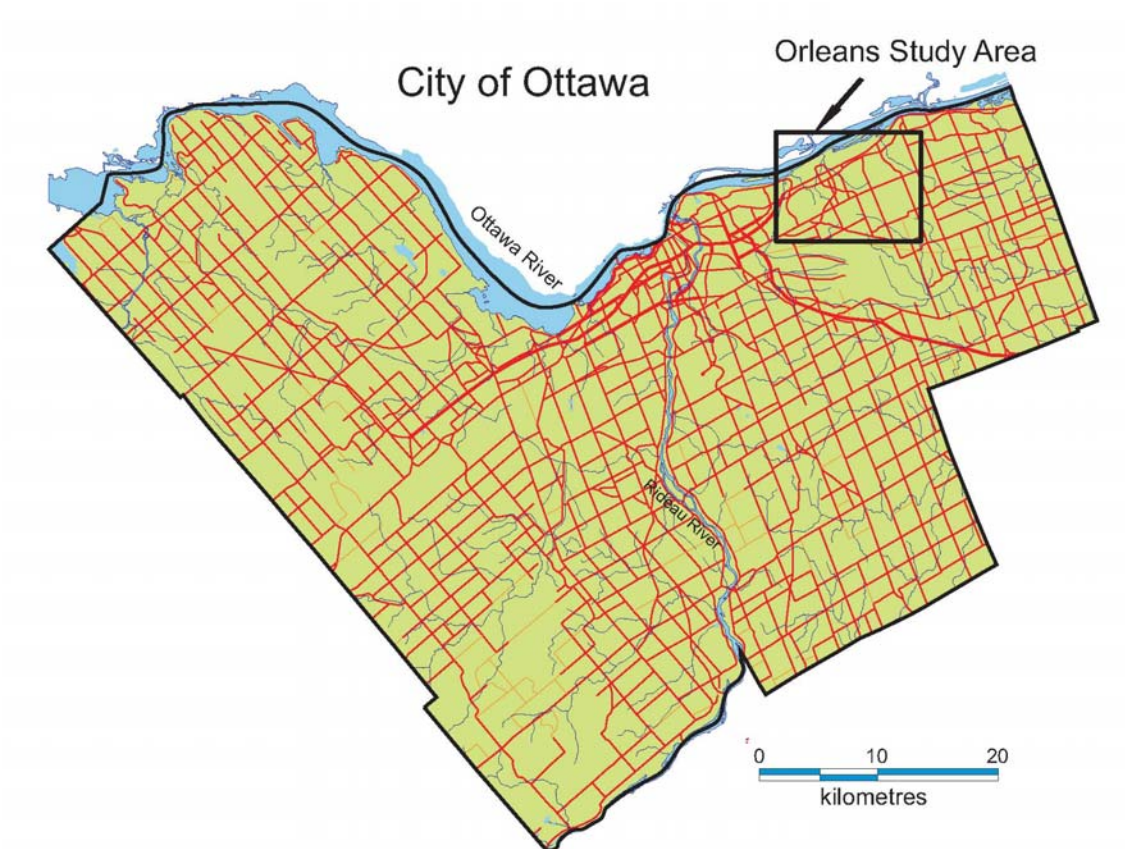

Figure 1a – Location of Orleans study area within the boundary of the City of Ottawa.

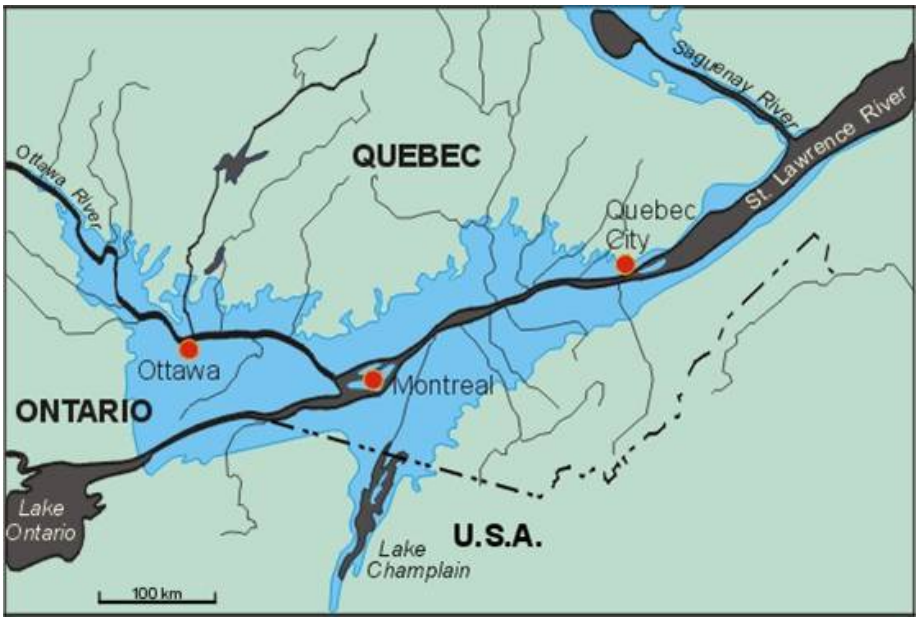

Figure 1b – Extent of Champlain Sea deposits within the St. Lawrence Lowlands.

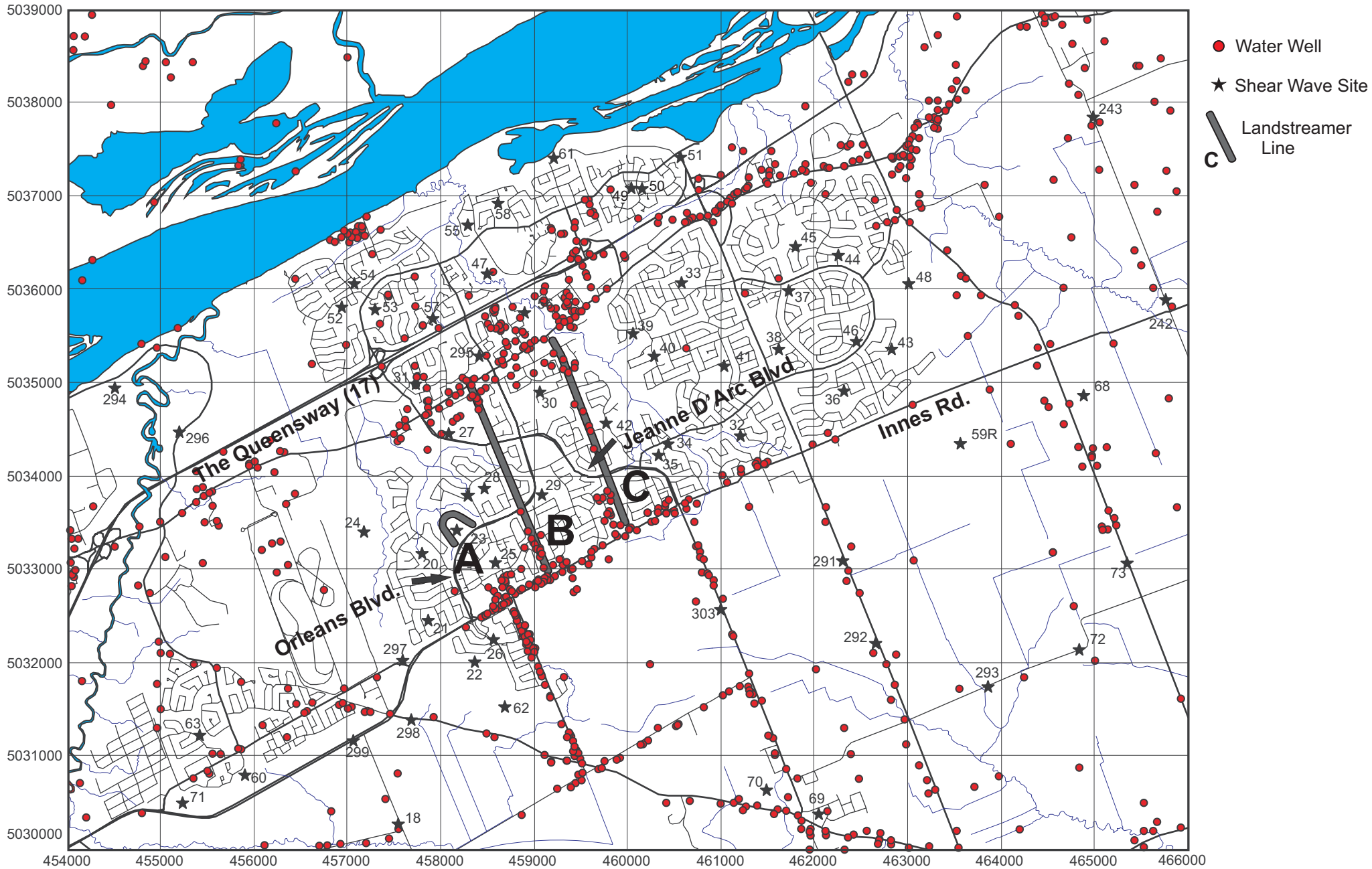

Figure 1c - Borehole and Seismic Site Locations

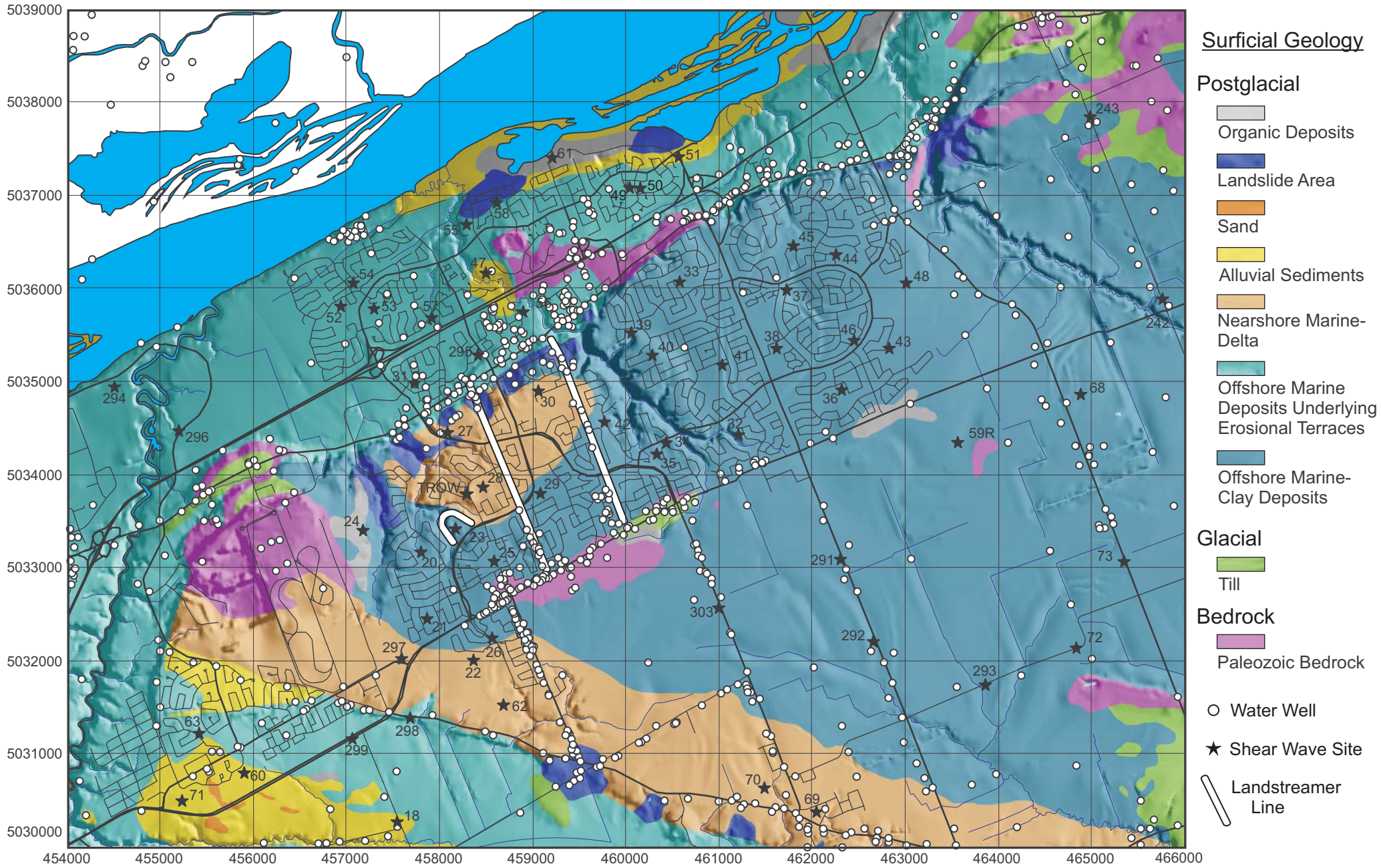

Figure 1d - Surficial Geology Draped Over 10m Digital Elevation Model

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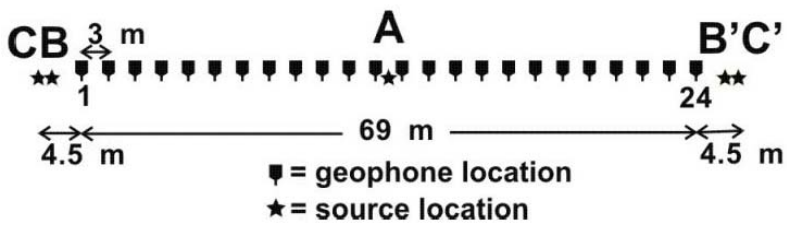


Figure 2a – Survey configuration for a 3m-spaced geophone array. Five shots were taken at each site; 1 and 1½ geophone spacings off each end (C, B, B', C') and a centre shot between geophone #12 and 13 (A).

Figure 2b – Sub-urban roadside shear wave site. Active source for the surface surveys consisted of a 10lb neoprene hammer connected to an electronic trigger, and a steel I-beam with one edge dug into the ground in SH orientation.

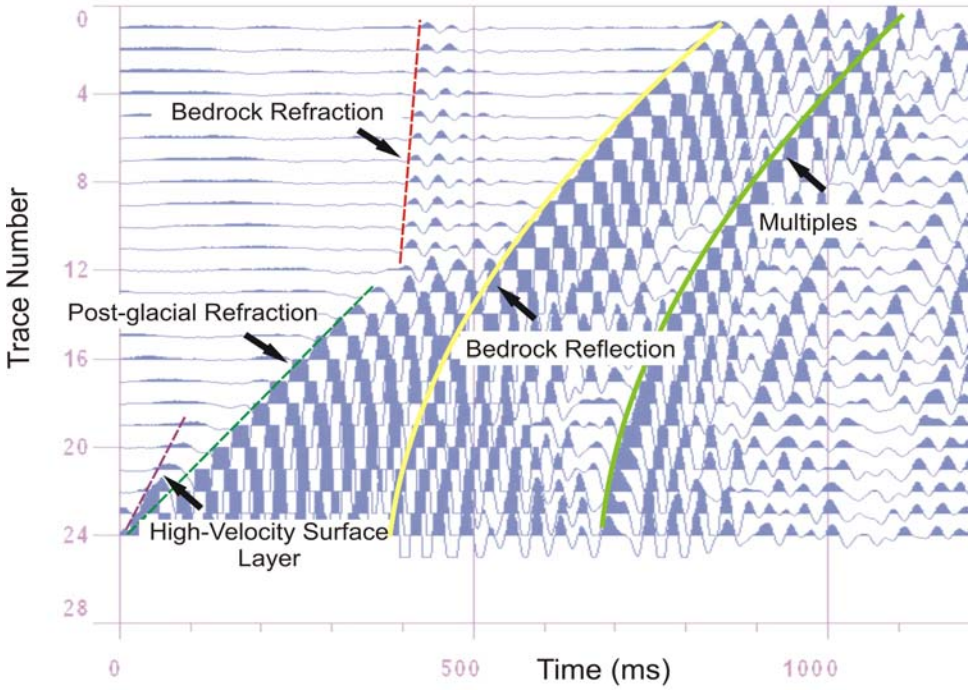


Figure 3a - First arrivals though the overconsolidated surface materials, post-glacial materials, bedrock, and the associated bedrock reflection and multiples.

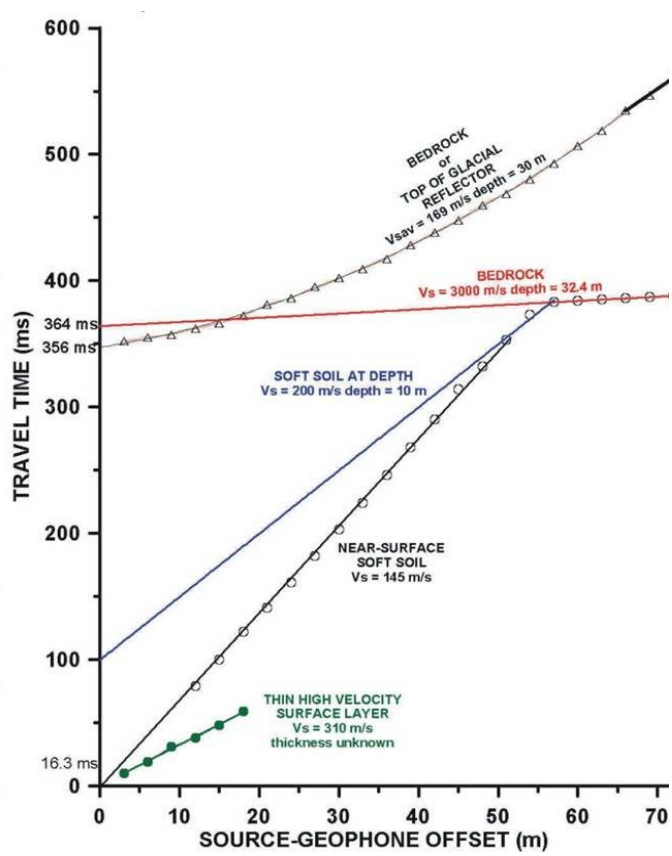


Figure 3b – Travel-time vs. source offset plot showing bedrock refraction intercept time arriving later than the bedrock reflection intercept, indicating the presence of 'hidden' layers.

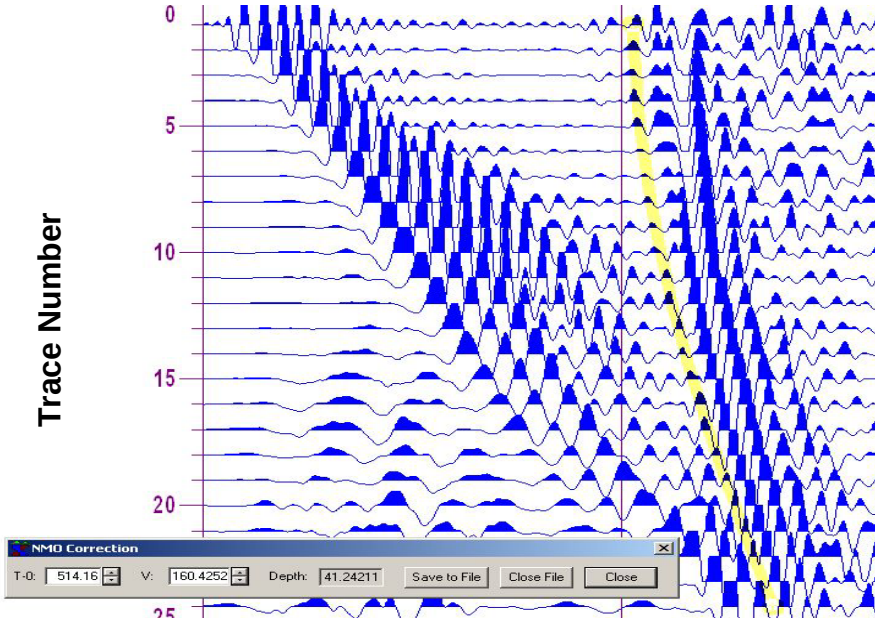


Figure 3c – To obtain average shear wave velocities, hyperbolic curves were fitted to reflections using IXSEG2SEGY software. The software displays the t_o, average velocity, and depth of the reflection in a dialogue box.

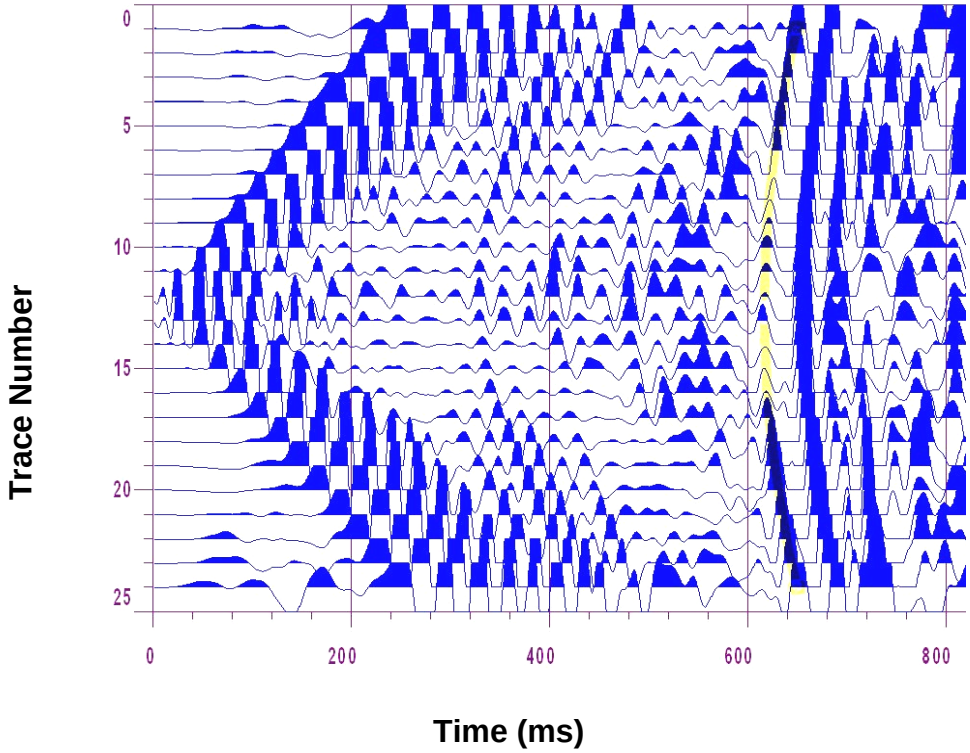


Figure 3d – Prominent reflections from interpreted glacial and bedrock boundaries. Highlighted reflection represents 'depth to firm' horizon

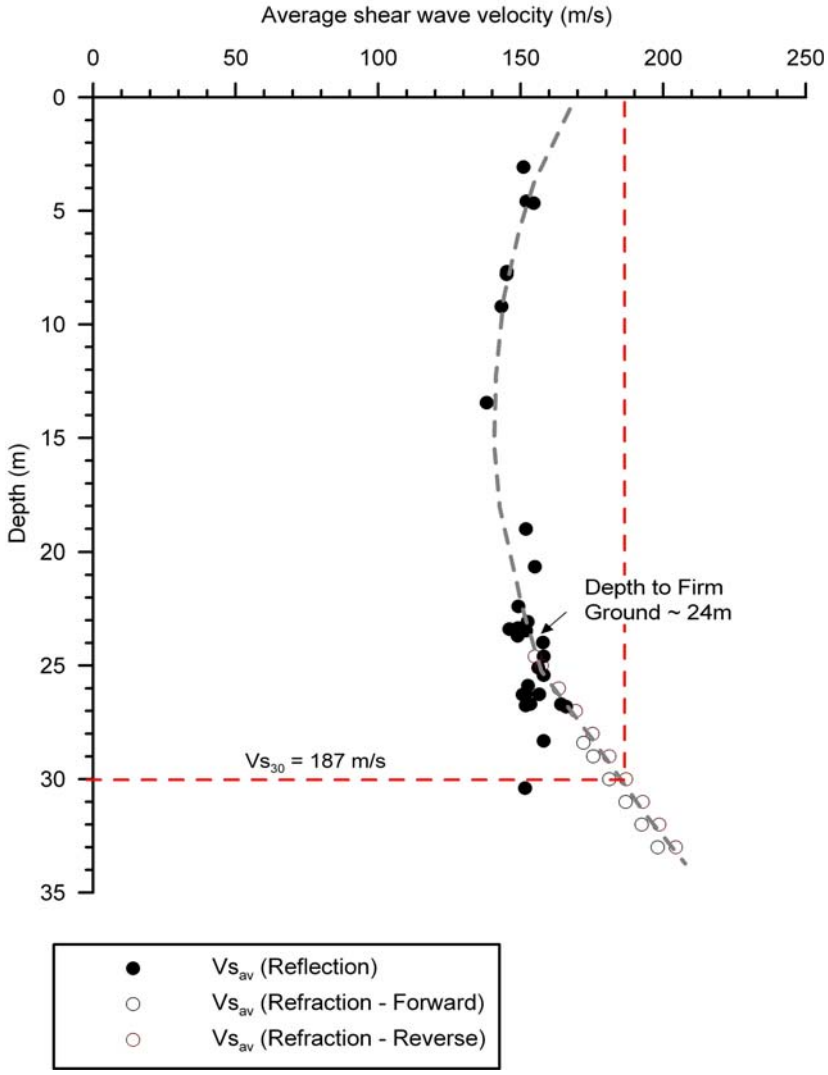


Figure 3e – Combined reflection and refraction data on a (time-weighted) average shear wave velocity vs. depth plot. Vs_{30} is derived from the *AVERAGE* velocity curve at 30 meters depth.

Figure 4a – Landstreamer configuration with hammer/roller source.

Figure 4b – Landstreamer in operation in Orleans with Minivib source.

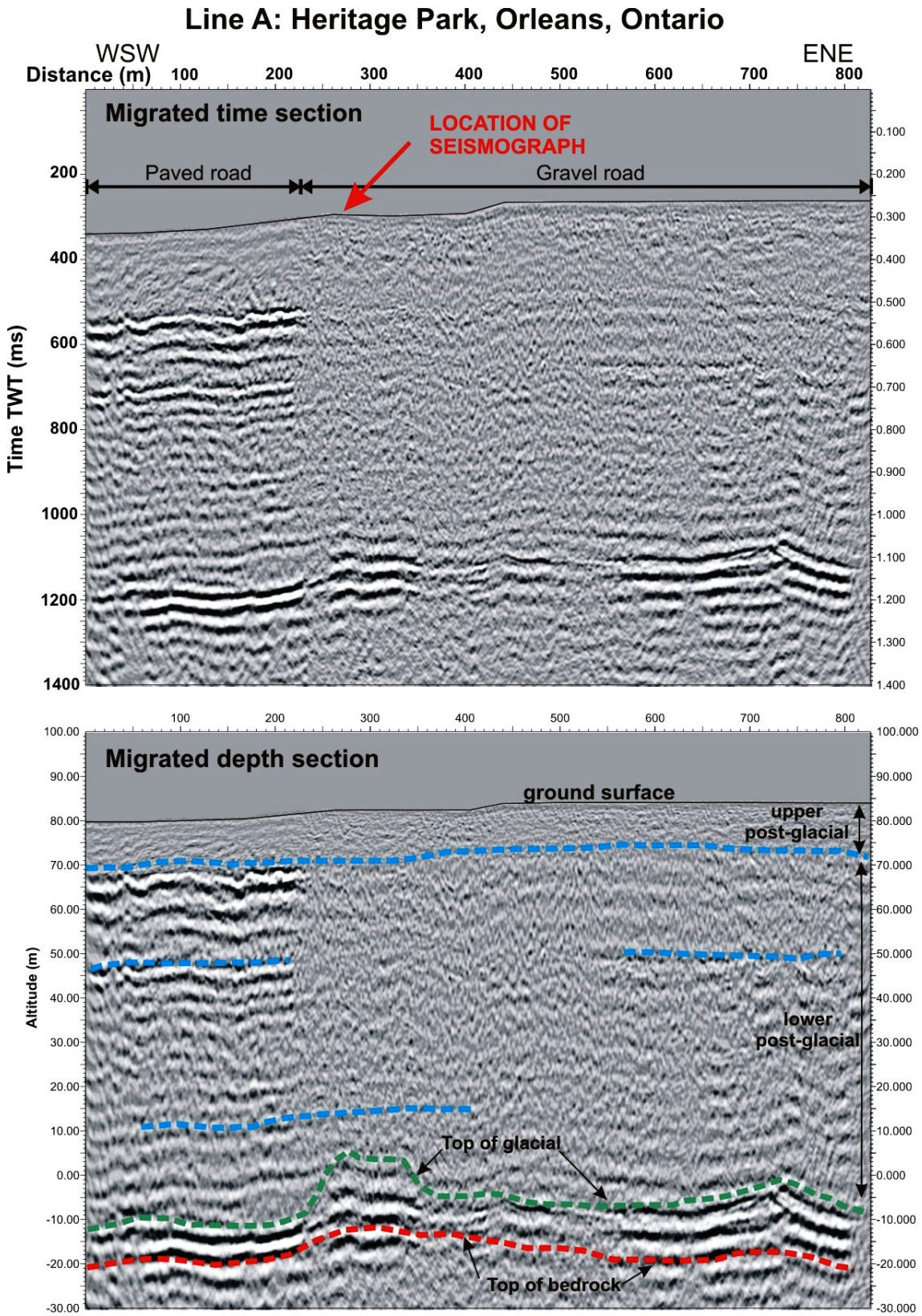


Figure 4c – Processed SH-wave reflection profile for Line A using the hammer/roller as the source. The upper panel shows the migrated section in two-way travel time, and the lower panel shows the depth section (plotted in masl) with interpreted soil/bedrock horizons. Both panels have 5X vertical exaggeration.

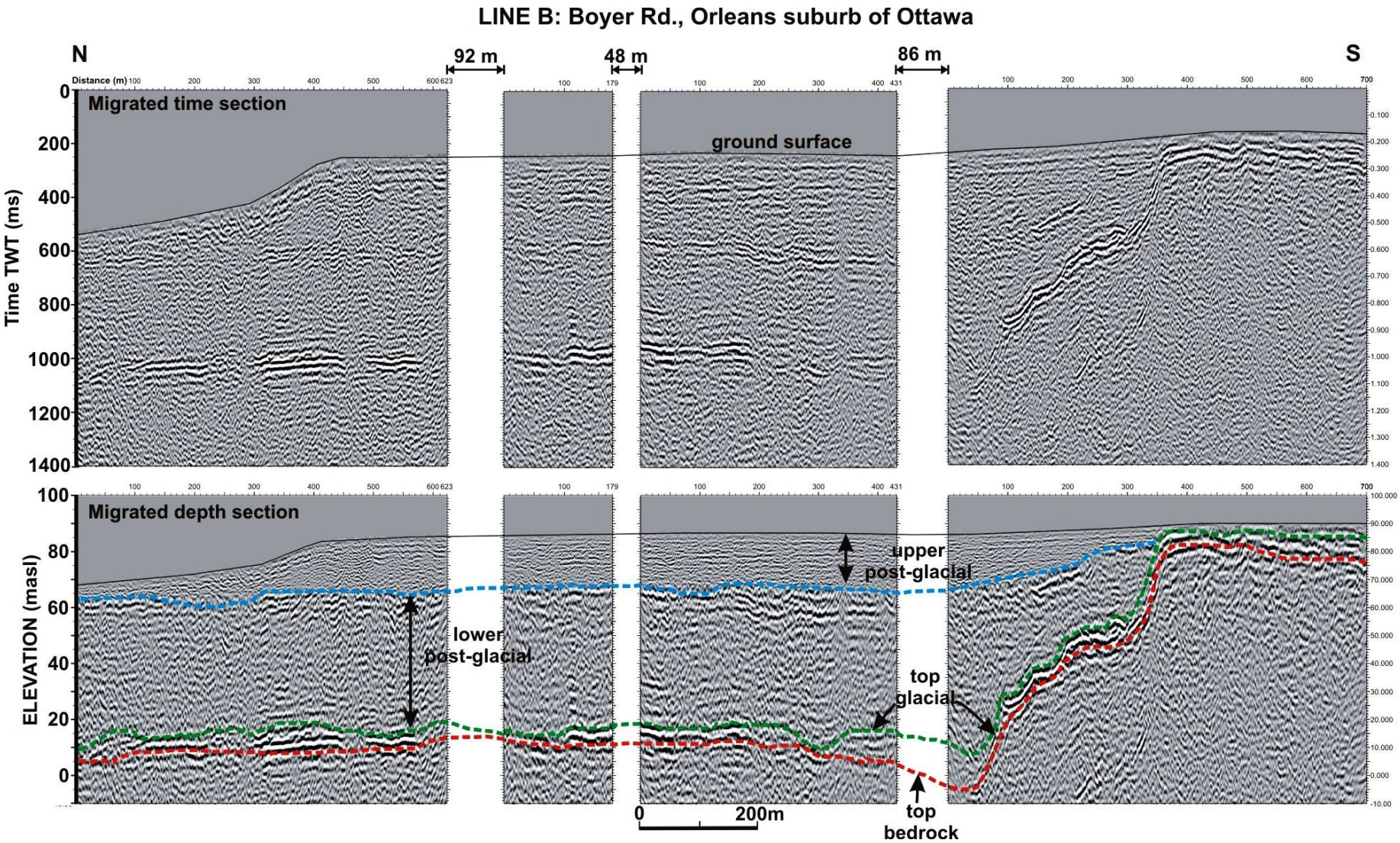


Figure 4d – Processed SH-wave reflection profile along Line B using the hammer/roller system as the source. The upper panel shows the migrated section in two-way travel time. The lower panel shows the depth section (plotted in masl) with interpreted soil/bedrock horizons. Both panels have a 5X vertical exaggeration. Breaks in the profiles represent roadway intersections where data could not be collected.

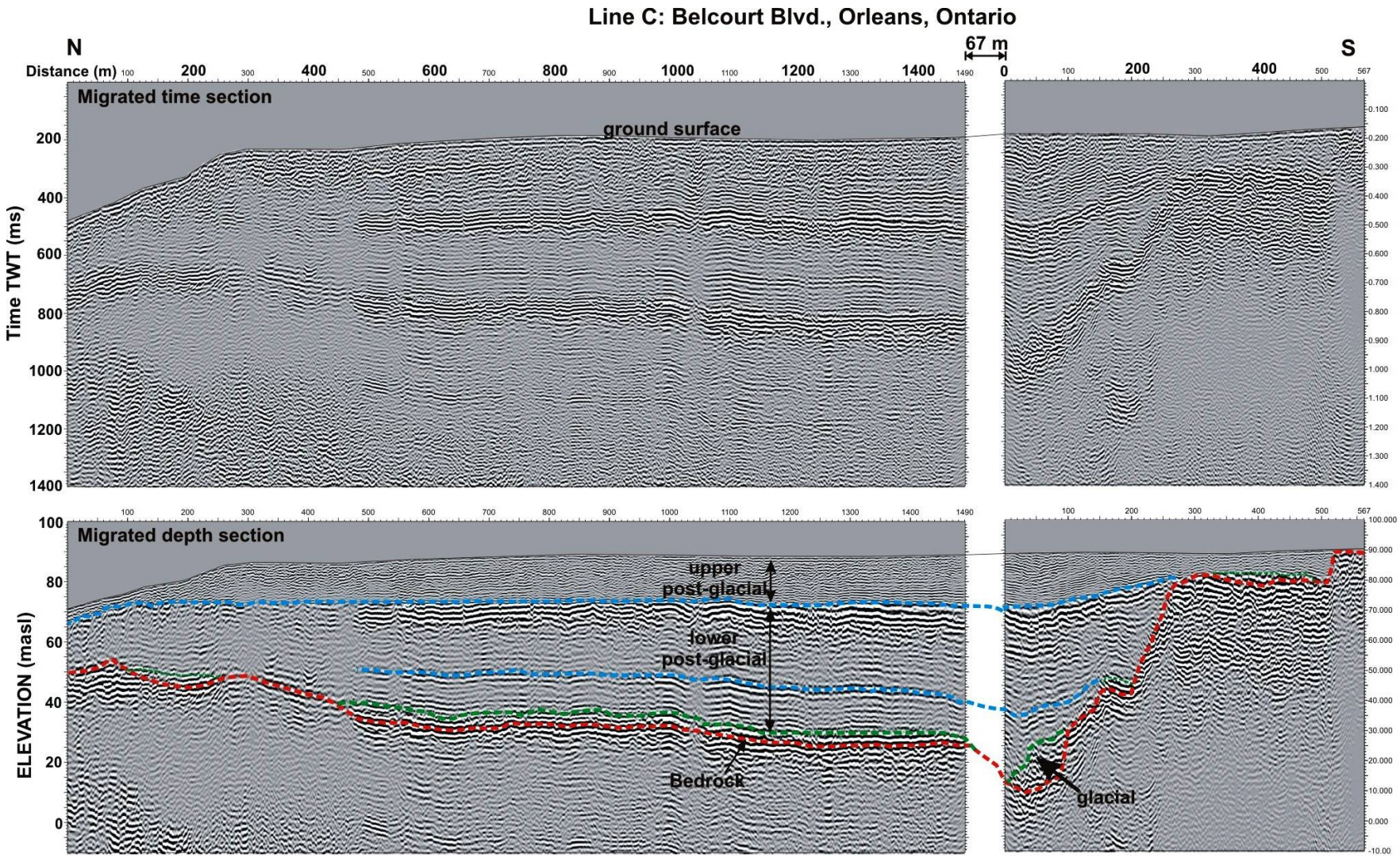
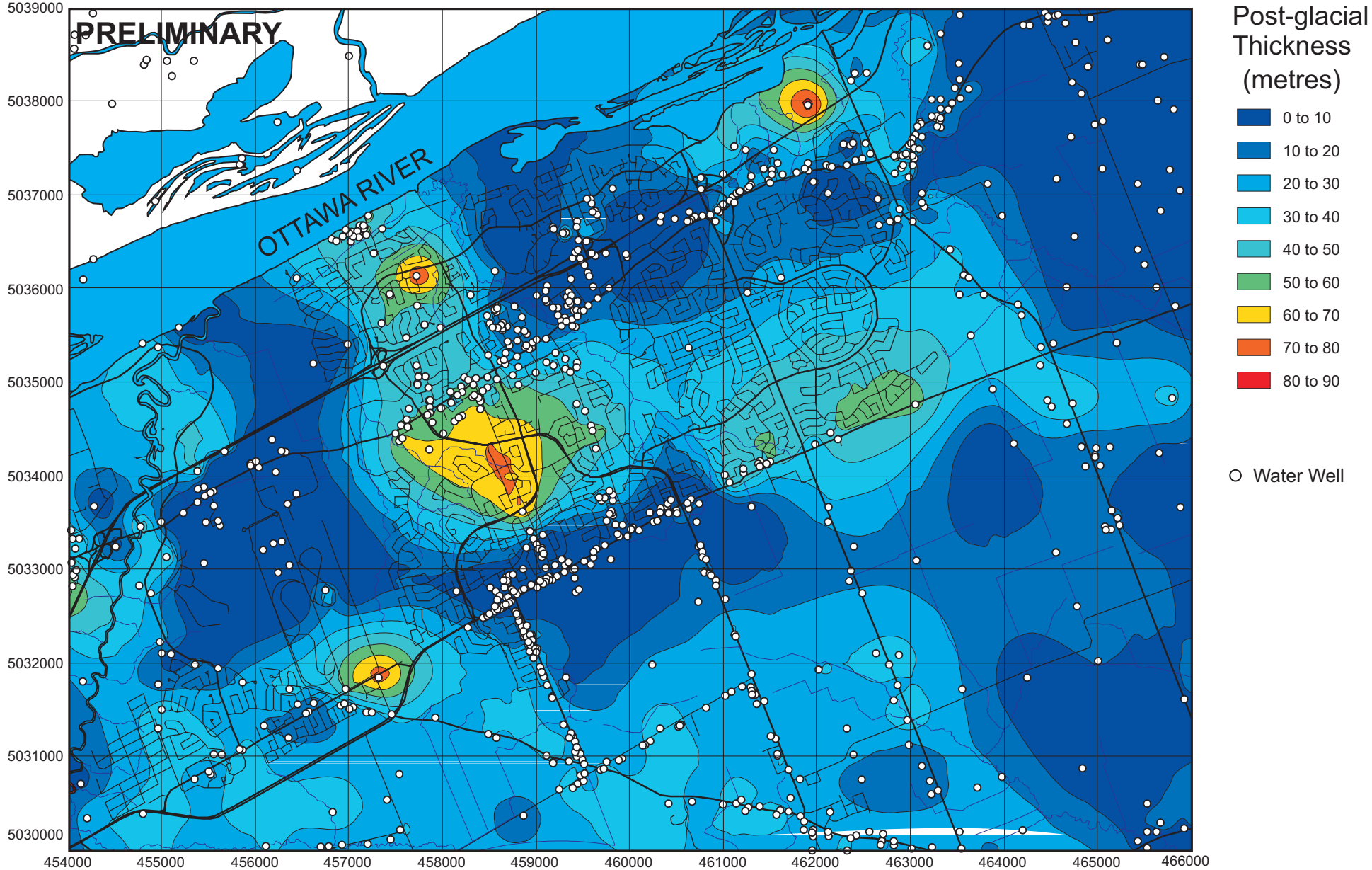


Figure 4e – Processed SH-wave reflection profile along Line C using the Minivib as the source. The upper panel shows the migrated section in two-way travel time. The lower panel shows the depth section (plotted in masl) with interpreted soil/bedrock horizons. Both panels have a 5X vertical exaggeration.

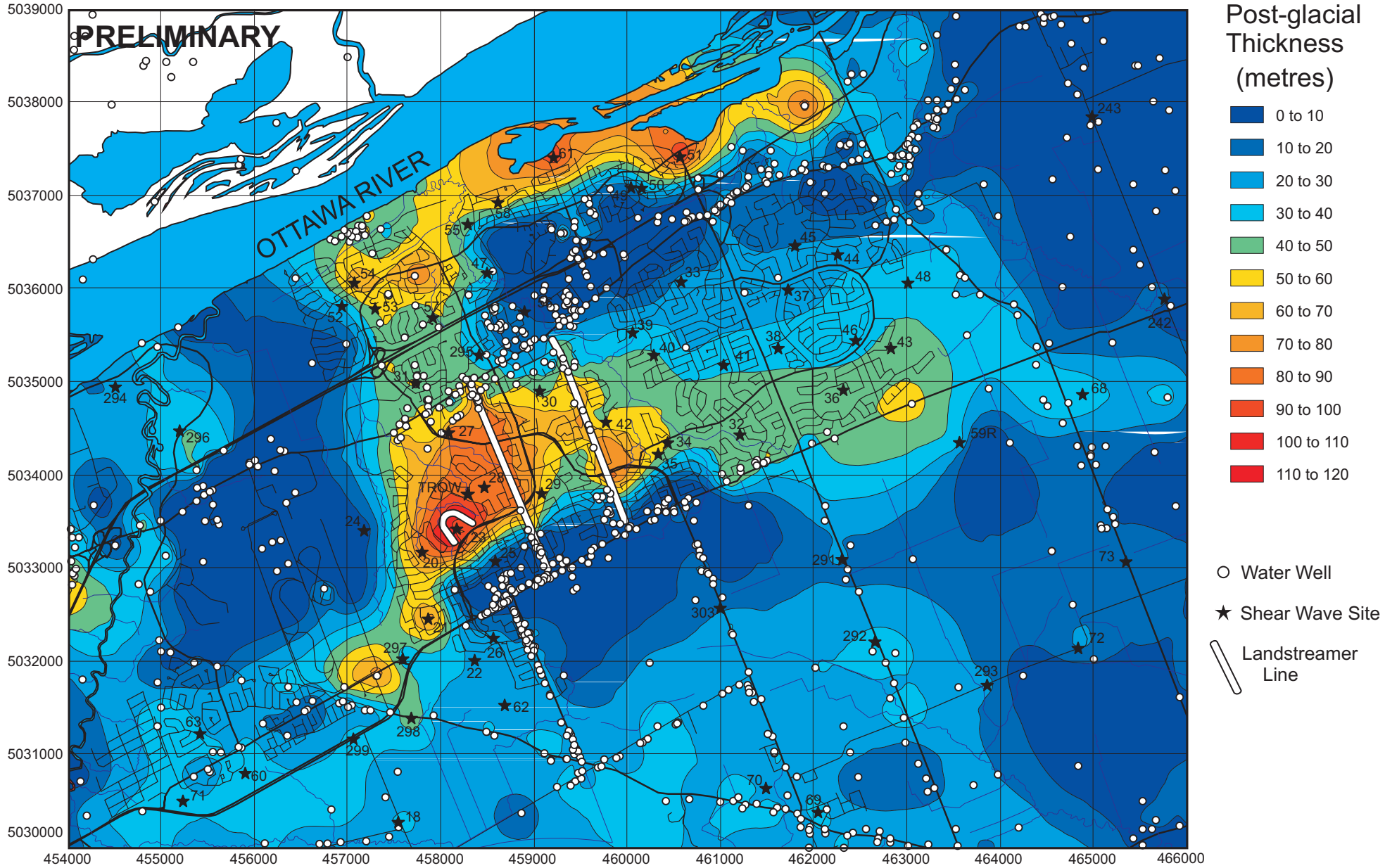
Figure 5a
Thickness of Post-glacial Materials Using Borehole Database Information



NOTE
See disclaimer on page 8 of accompanying report.

0 .5 1 1.5 2
kilometres

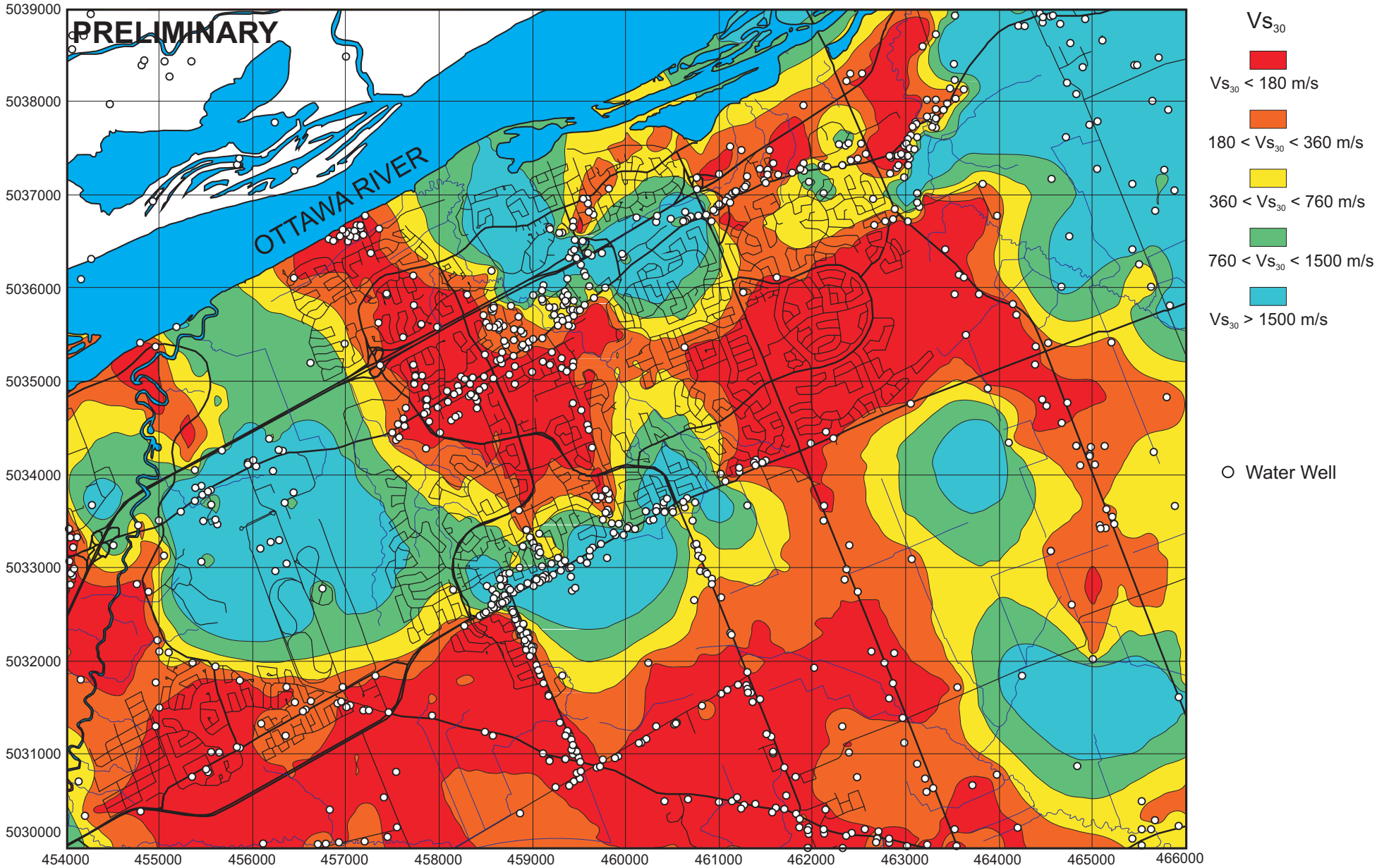
Figure 5b
Thickness of Post-glacial Materials Combining Borehole Database and Seismic Information



NOTE
See disclaimer on page 8 of accompanying report.

0 .5 1 1.5 2
kilometres

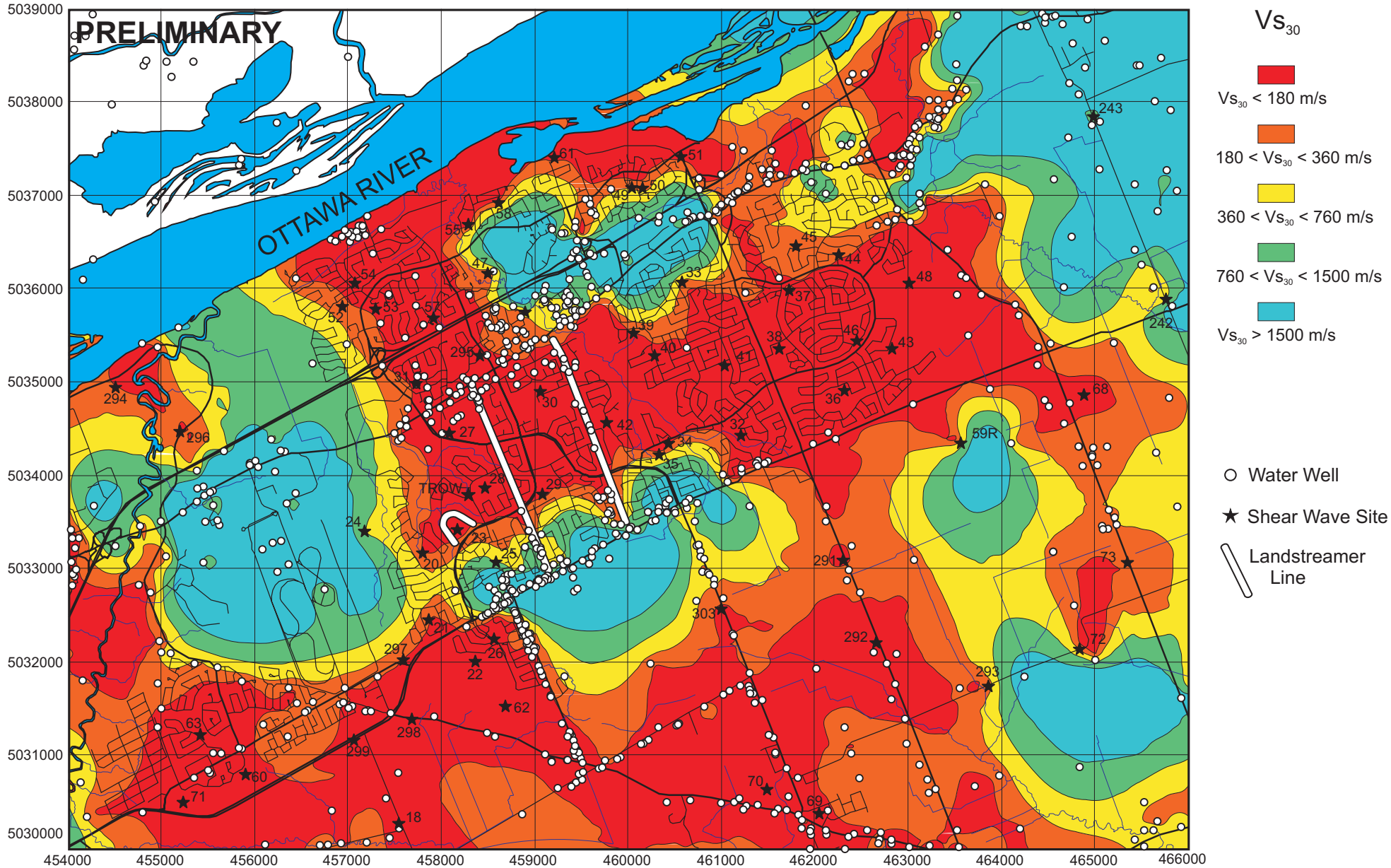
Figure 5c
Vs_{30} Calculated From Velocity-depth Function and Borehole Logs



NOTE
See disclaimer on page 8 of accompanying report.

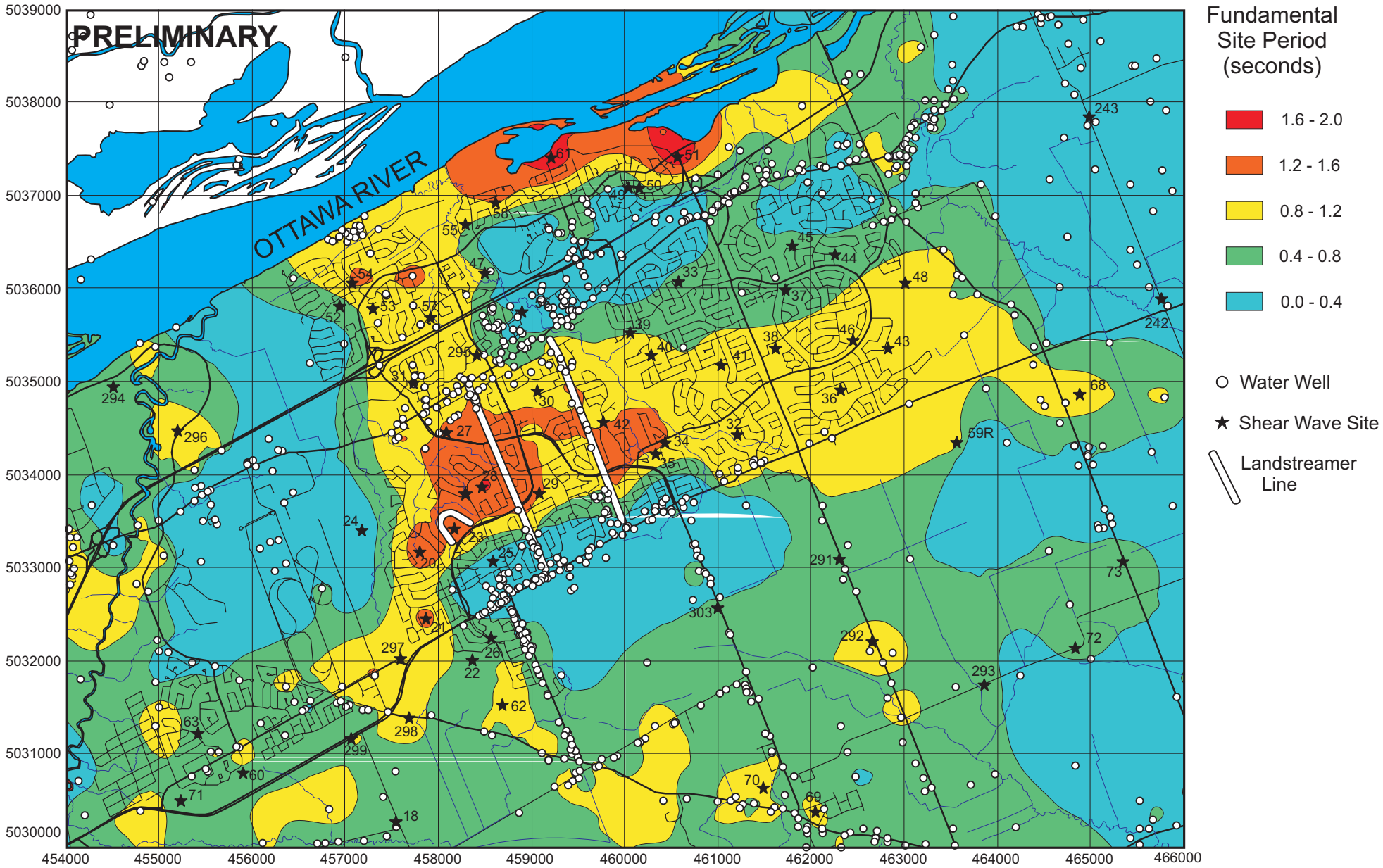
0 .5 1 1.5 2
kilometres

Figure 5d
Vs_{30} Calculated From Borehole Logs and Seismic Data



NOTE
See disclaimer on page 8 of accompanying report.

Figure 5e
Fundamental Site Period



NOTE
See disclaimer on page 8 of accompanying report.

0 .5 1 1.5 2
kilometres