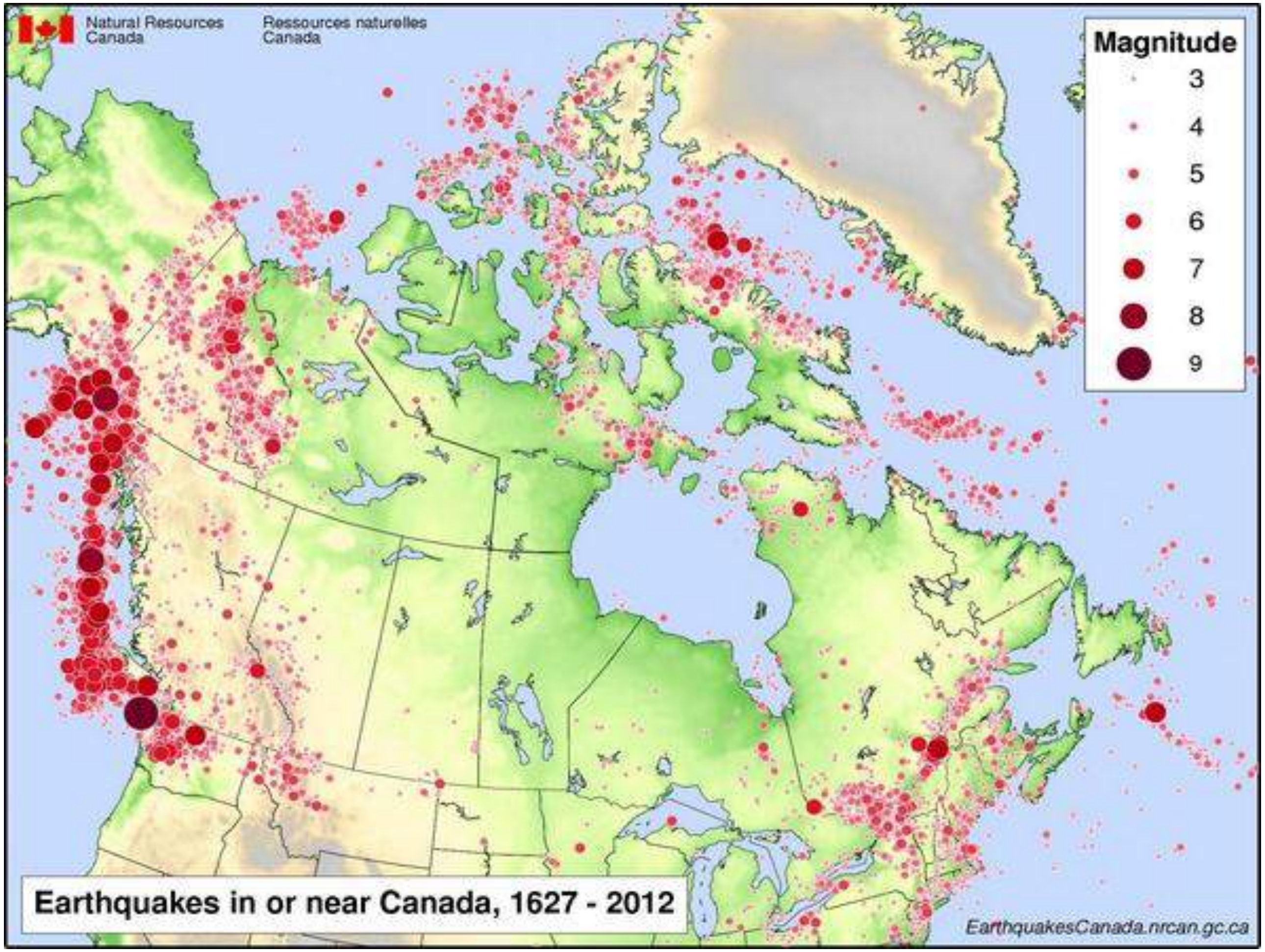
Earthquake Hazard Maps for the Area of Ottawa, Ontario and Gatineau, Quebec with Focus on Seismic Microzonation



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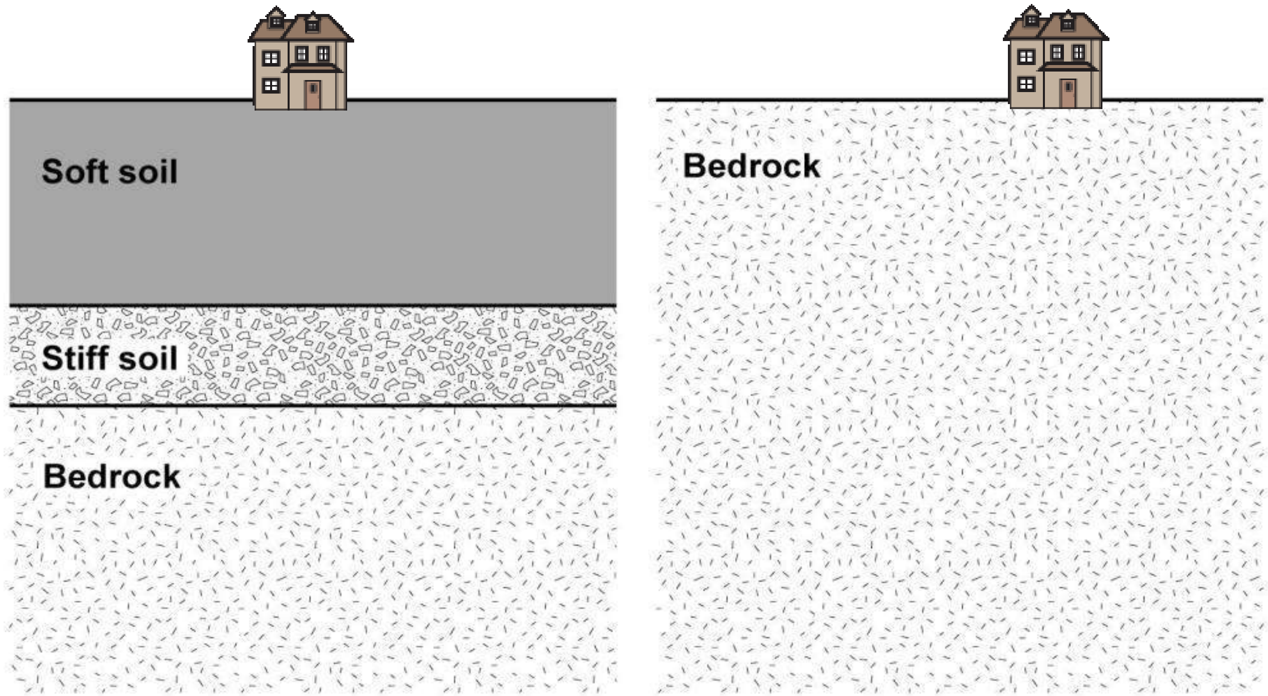
CANADA 1842 GEOLOGICAL SURVEY - COMMISSION GÉOLOGIQUE

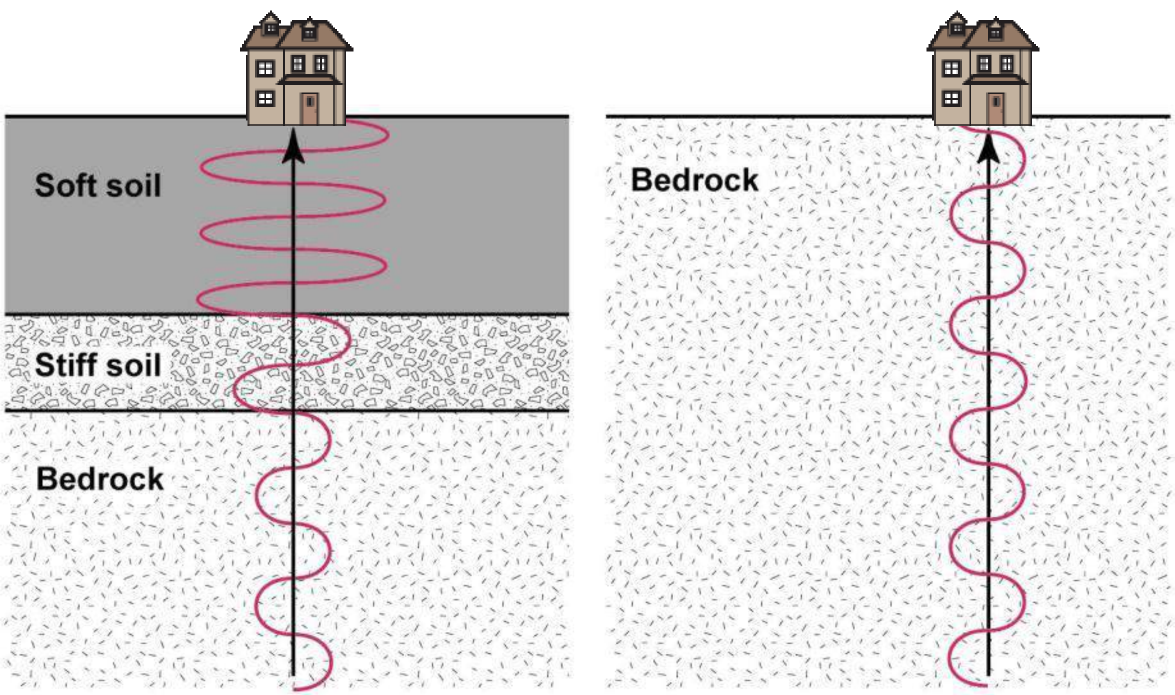
Basic Concept !
Soil amplification

- Consider two nearby sites (1000 m apart)
  - one on **rock(Vs~2700 m/s)**, typical bedrock in Ottawa)
  - and the other one on soil **(Vs~150m/s)** typical post-glacial soil in Ottawa)
  - The same seismic wave from a remote earthquake is approaching these sites



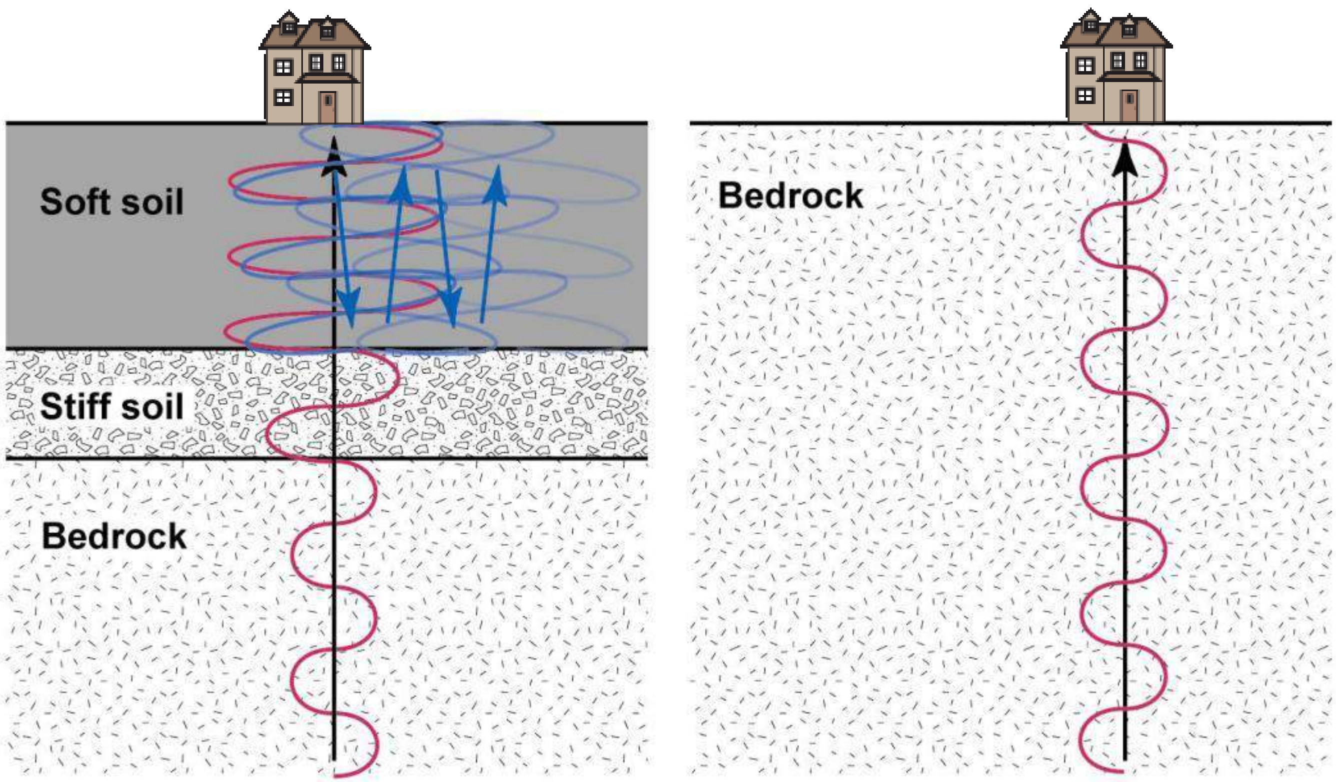
Velocity contrast amplification

- Consider a seismic wave
- To make it simpler consider **just one harmonic** of the seismic wave
- Now , a sine wave **with a specific amount of energy**, is entering a medium with lower velocity
  - **It slows down.**
- **To conserve the energy , the amplitude of sine wave has to increase because the velocity has gone down**



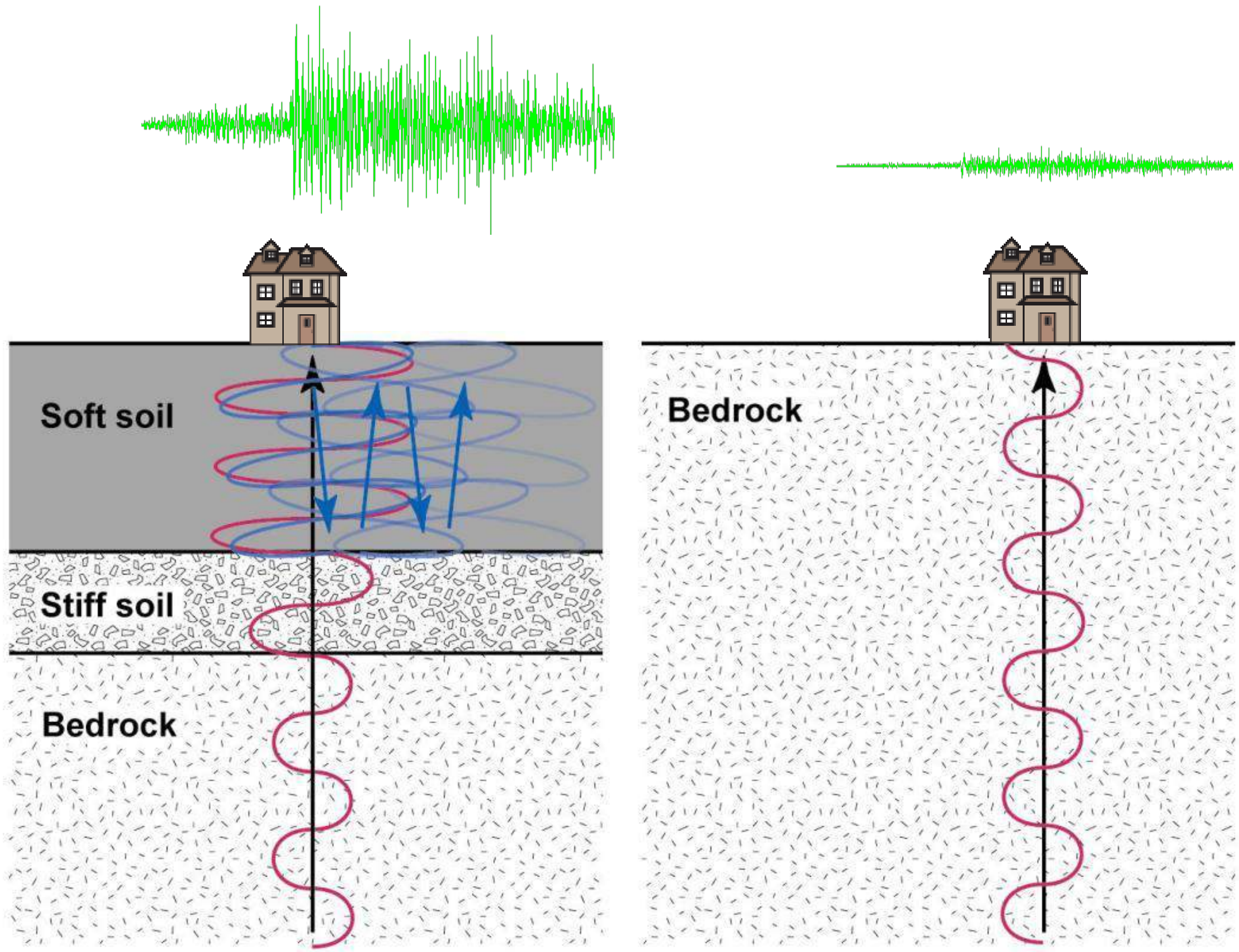
Resonance effects

- Caused by **discontinuity** in properties
- A number of **multiples** are produced in the top layer.
- **Trapped** waves reverberate due to multiple reflections.
- **Constructive interference causes resonance**,
- The **resonance frequency** depends on
  - **thickness** of layer and
  - **elastic properties**.



Velocity contrast amplification **Plus Resonance effects**

- Resonance effect is one of the main key phenomena affecting the level of ground shaking at a soil site.



Seismic Site Classification

In building code applications, soil amplification is based on shear-wave velocity averaged over the top 30 m and spectral period

Site CLASSIFICATION; **Used in National Building Code of Canada 2005**

Increasingly Severe thick soil site effects

CLASS	Vs_{30} (m/s)	
A	> 1500	(hard rock)
B	760 - 1500	(rock)
C	360 - 760	(soft rock or firm soil)
D	180 - 360	(soft soil)
E	< 180	(very soft)

Vs_{30} = thickness-weighted average shear wave velocity to 30 m depth

NBCC; Values of F_a as a Function of Site Class and T= 1 s Spectral Acceleration.

Reference class

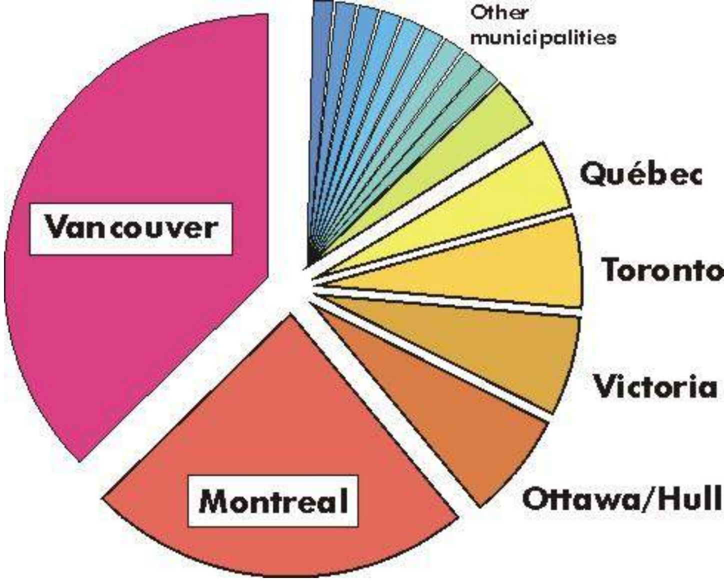
Non linearity

Ottawa

Montreal

Site class	Values of F_a				
	S_a (1.0) ≤ 0.1 g	S_a (1.0) = 0.2 g	S_a (1.0) = 0.3 g	S_a (1.0) = 0.4 g	S_a (1.0) = 0.5 g
A	0.5	0.5	0.5	0.6	0.6
B	0.6	0.7	0.7	0.8	0.8
C	1.0	1.0	1.0	1.0	1.0
D	1.4	1.3	1.2	1.1	1.0
E	2.1	2.0	1.9	1.7	1.7
F	Site specific investigation required				

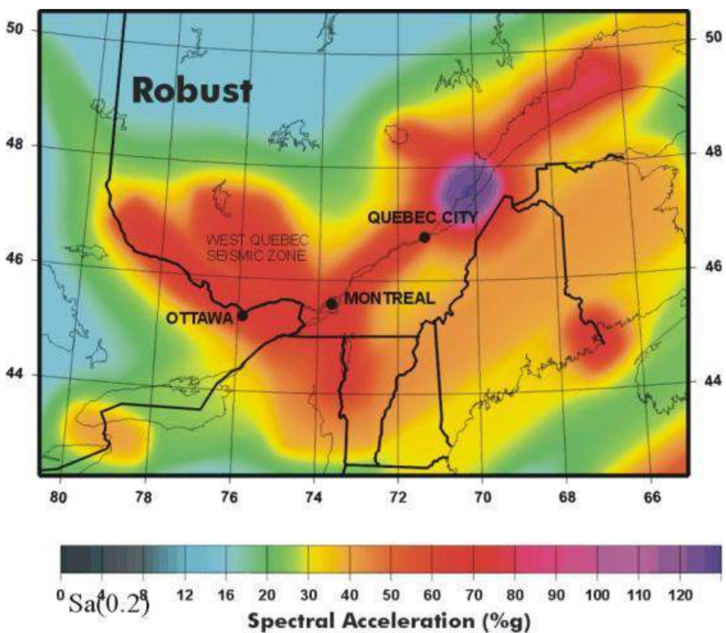
Motivations for Ottawa



- **NEHRP Site classification is a required** parameter in the new edition of the **NBCC** (National Building Code of Canada, 2005, 2010) for the seismic design load.

- Unfortunately, the basic information on the NEHRP site class in various parts of **Ottawa was not known and the majority of the area is not known yet.**

- On the other hand , in terms of cities with highest **seismic risk**, Ottawa is rated **third** in the country since it is located in the **Western Quebec Seismic zone,** which includes the Ottawa region (after Adams and Halchuk, 2003).

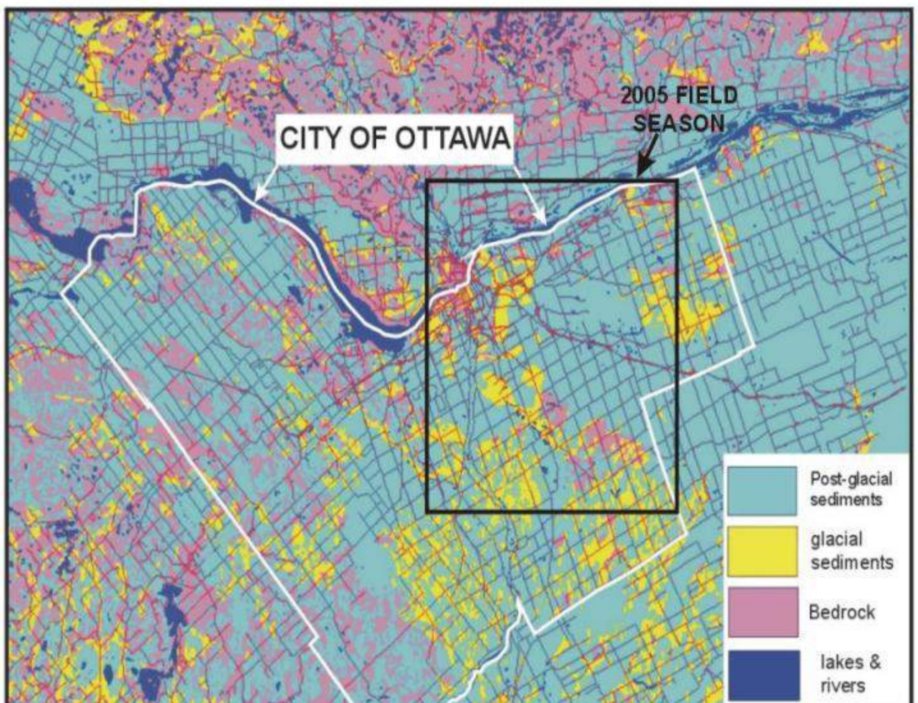


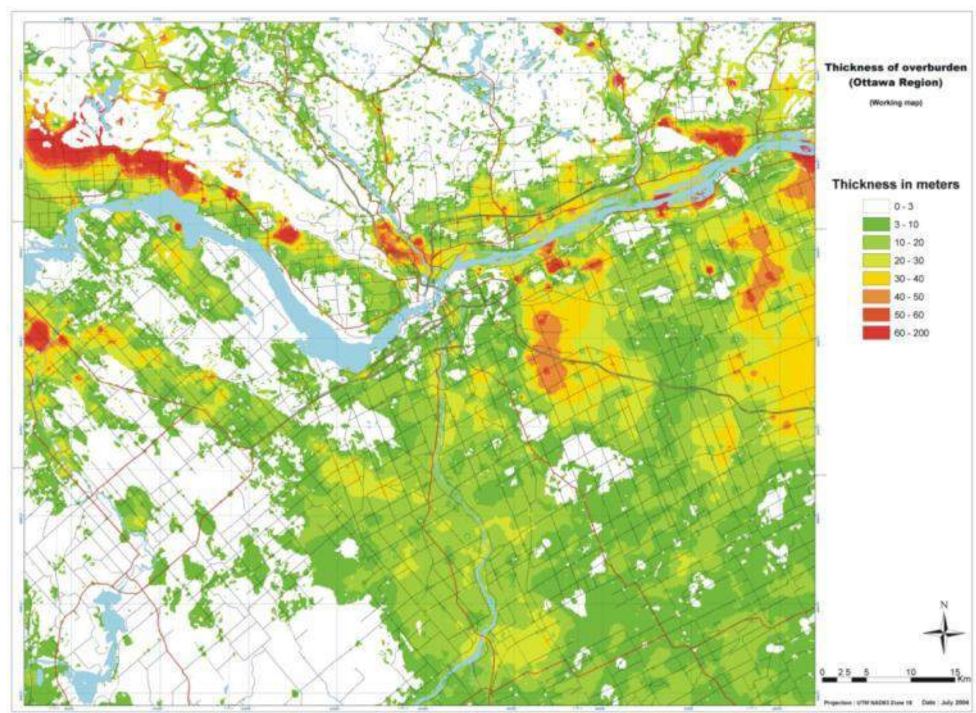
Motivations: Surficial geology and the thickness of overburden Ottawa-Montreal Area

- Champlain Sea 13,000-9,000 years ago
- Deposited soft soils: “Leda Clay”

Motivations: Surficial geology and the thickness of overburden

- Furthermore, Surficial geology of Ottawa shows that **most of the city is located on post-glacial sediments**, which are very loose sediments.
- In addition, there are many areas of Ottawa, especially in south-east, which are located on **relatively thick soils** with significant amplification potential.





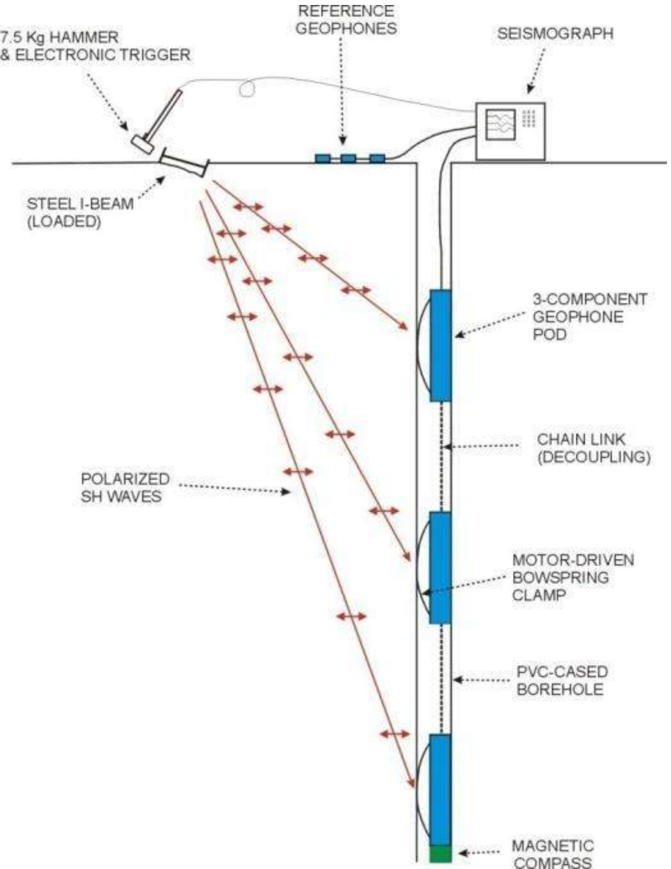
Objectives

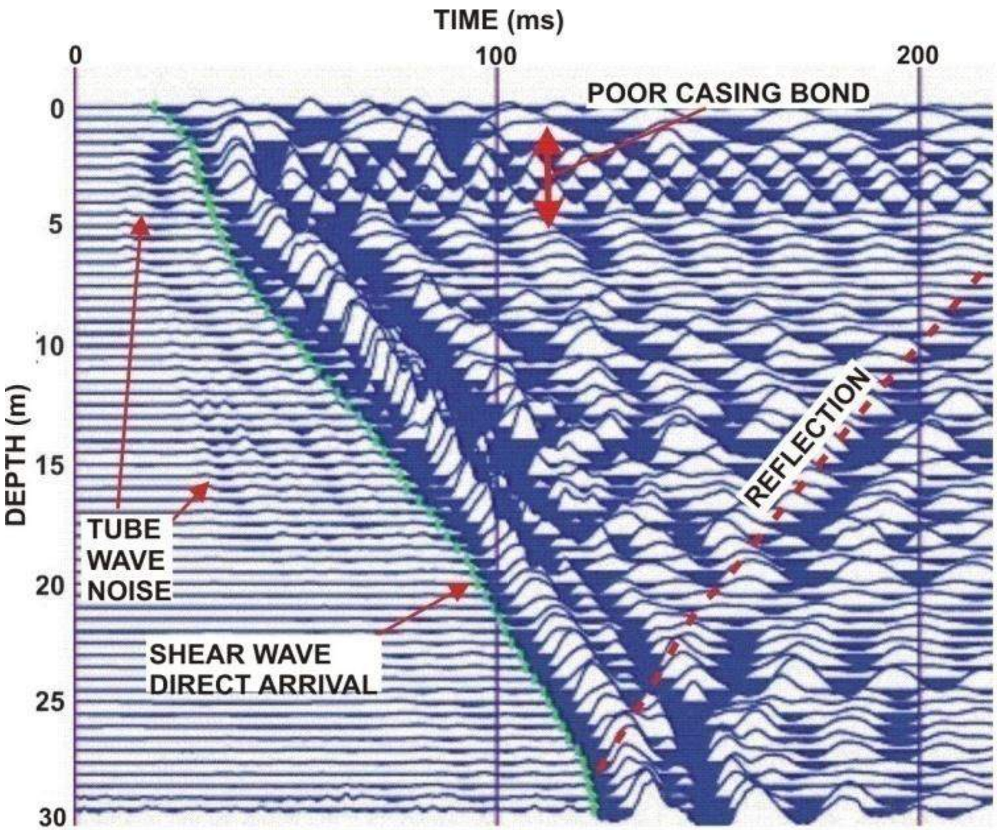
- **Short term:**
  - To identify the appropriate **NEHRP site classes in Ottawa region** using different techniques (refraction/reflection, Spectral ratio methods, MASW, etc).
  - To suggest **some modification factors for high contrast bedrock** in the application of NEHRP site classes in the Ottawa region , based on soil modeling (1-D and 2-D).
  - Provisional **site amplification digital maps** for selected areas of the City of Ottawa based on site classifications.
- **Long term:**
  - NEHRP maps for **Ottawa region and Saint Lawrence Valley**.
  - Long term: **Inclusion of liquefaction and slope stability** data in the microzonation maps derived from near-surface studies.
  - …

Methods

- **Analysis of the available borehole data**
- **Shallow reflection/refraction:** In-situ measurements of near-surface S-wave seismic velocities.
- **MASW:** In-situ measurements of near-surface S-wave seismic velocities using the MASW method in downtown Ottawa.
- **Spectral ratios** Background noise analysis: In-situ measurements of background noise using broadband seismometers and portable seismographs.
- **Correlation between geological data and Shear wave velocities**
- **1-D, 2-D and 3-D Soil modeling**

- **Downhole shear wave logging**
  - Survey configuration and
  - Time series
  - 18 boreholes in Ottawa area





➢18 borehole sites

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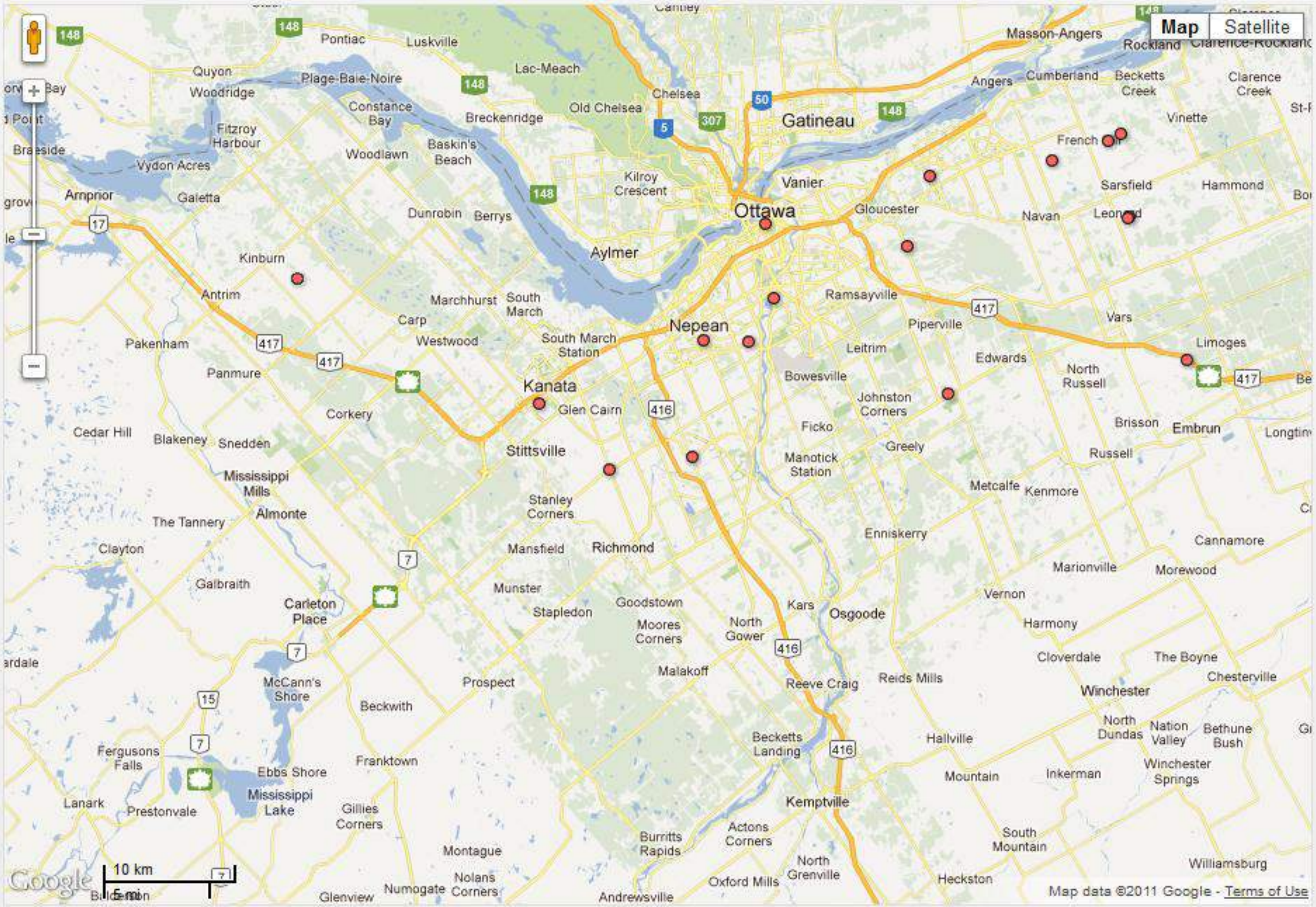
Interactive Vs30 Google Map for the City of Ottawa

GSC



Overlays:

Click to toggle layers:

- ☑ BH Geophys (18 Sites)
- ☐ HVSR (238 Sites)
- ☐ Boreholes (20716 Sites)
- ☐ Seismic Sites (1226 Sites)
- ☐ Vs30Class
  - Class A
  - Class B
  - Class C
  - Class D
  - Class E

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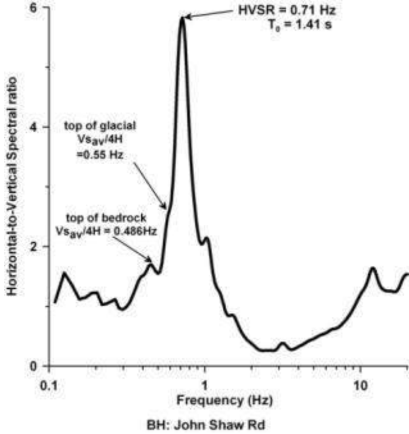
- **T_0 based on HVSR** of background noise analysis
- It is based on Spectral ratio of horizontal component to vertical component of background noise
  - ➢ **Spectral peak(s)** correspond approximately with
    - **F0 = Vs/4*H**
    - Vs = the average shear wave velocity of overburden layer
    - H = thickness of the overburden layer
  - ➢ It is very fast (30 min a site!)
  - ➢ Popular
  - ➢ **Accurate !**
- Because of **high impedance contrasts** between Leda clay and bedrock **~20**
- It works perfectly in providing a sharp peak!



➢ 2000 HVSR

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GSC
Map
Satellite
Overlays:
Click to toggle layers:
BH Geophys (18 Sites)
HVSR (238 Sites)
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Vs30Class
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Gatineau
Ottawa
Vanier
Aylmer
Nepean
Kanata
Gloucester
Stittsville
Richmond
Osgoode
Kemptville
Arnprior
Almonte
Carleton Place
Orleans
Cumberland
Rockland
Navan
Russell
Embrun
Metcalfe
Manotick
Winchester
10 km
5 mi
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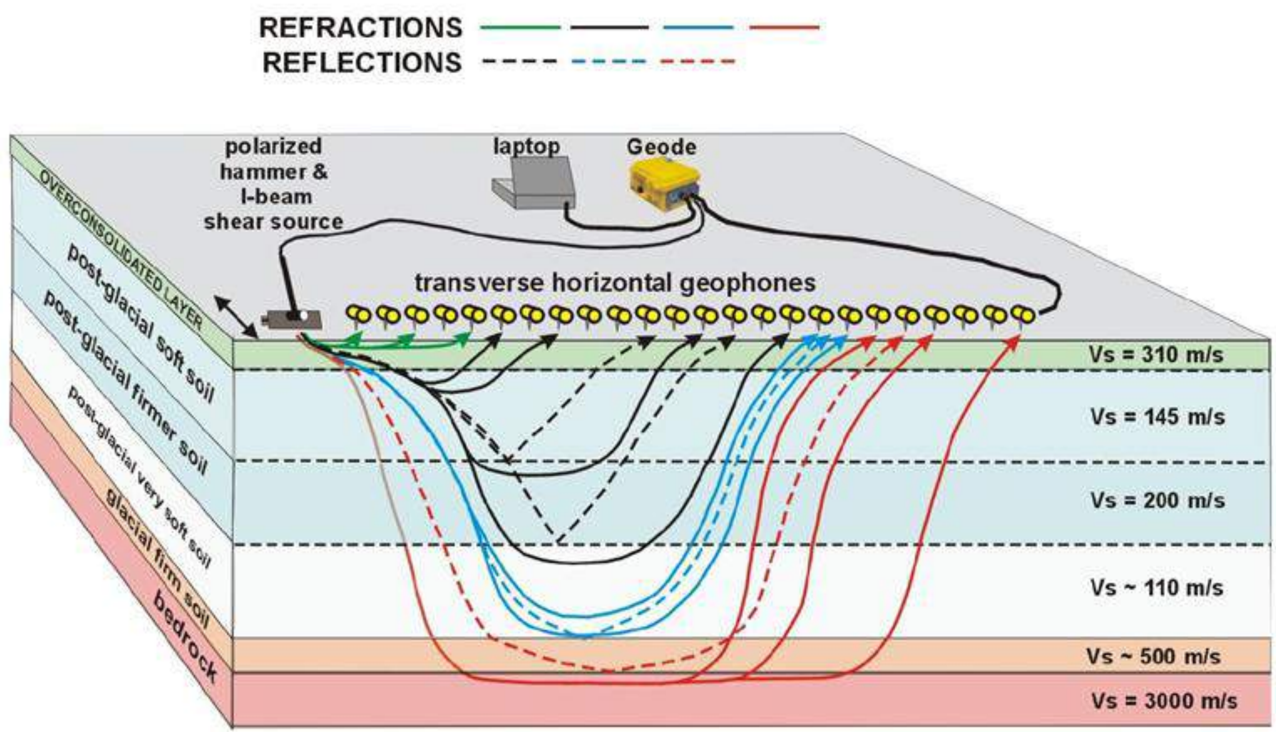
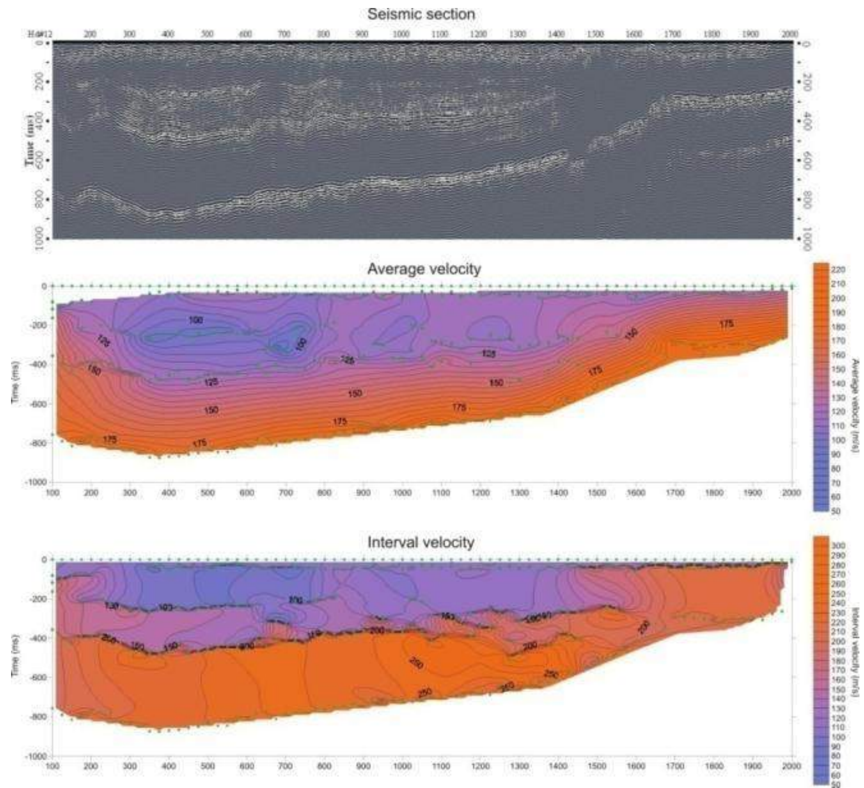
- **Seismic reflection/refraction sites Suitable for Ottawa**
    - Because of the very **high shear wave velocity contrast** between soil (**150 m/s**) and very hard bedrock (**2700 m/s**)
  - **Practical** and **fast** method for Ottawa (**3 sites a day**).

- 24 horizontal geophones, 3-5 m spacing, 2s Sampling duration, 5-10 stacks, 12 lb sledge hammer source.

- Data was acquired in **city parks**, green-space and **roadsides** with the permission of the city of Ottawa.



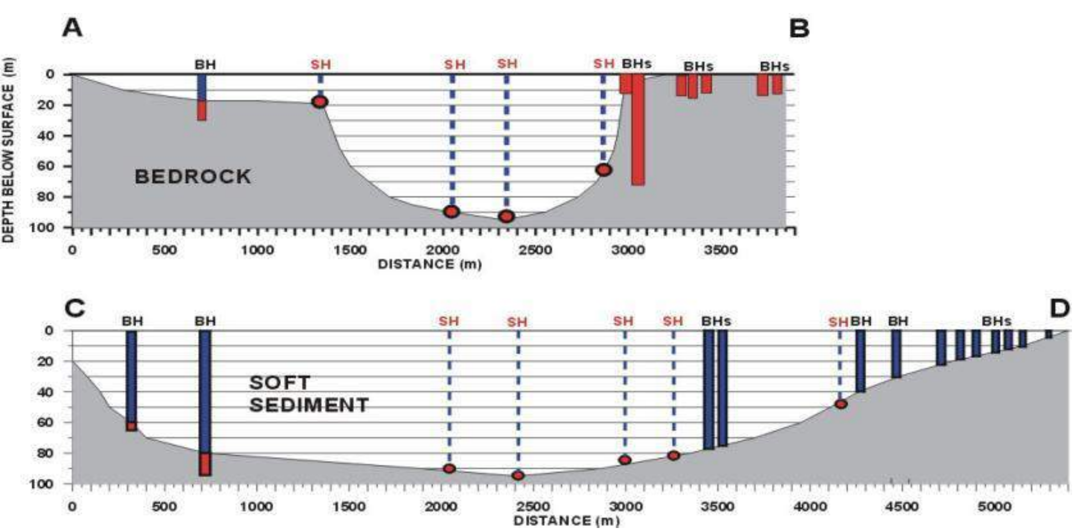
- **Landstreamer array with mini-vibe**
- Recently developed by **GSC** (Pugin *et al)*
- 3-cmpt geophones on 48 sleds
  - It can be used on pavement or asphalt
  - **A few kilometers per day**
- Processed landstreamer profile and average velocity model
- **50 line-km landstreamer profiling in Ottawa**



A buried Valley in the Orleans area

- A **buried Valley in the Orleans area.**

- We conducted a near surface seismic measurements to investigate the exact geometry of the buried valley.



- **700 seismic reflection/refraction sites**
- **50 line-km landstreamer profiling**
  43 MASW

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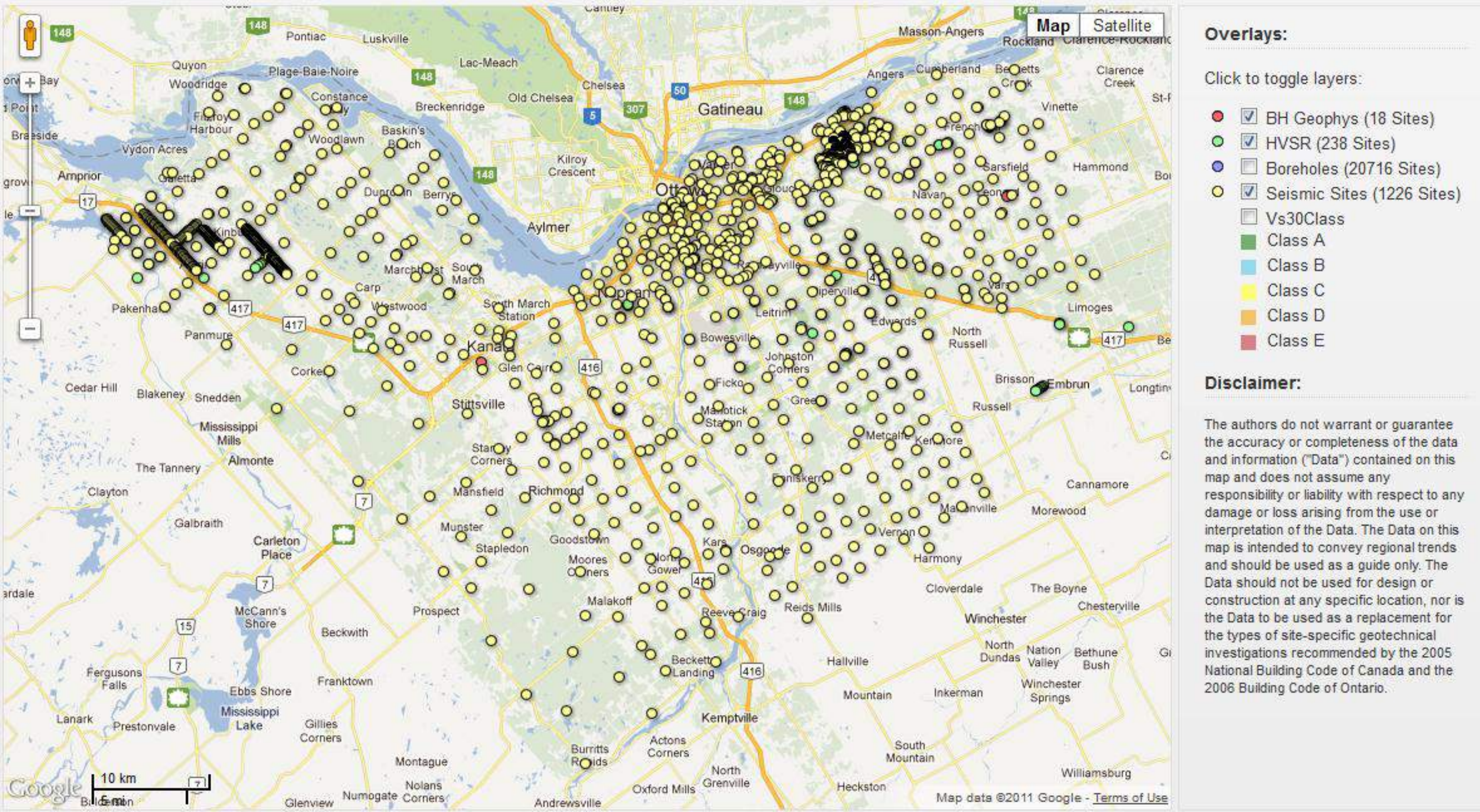
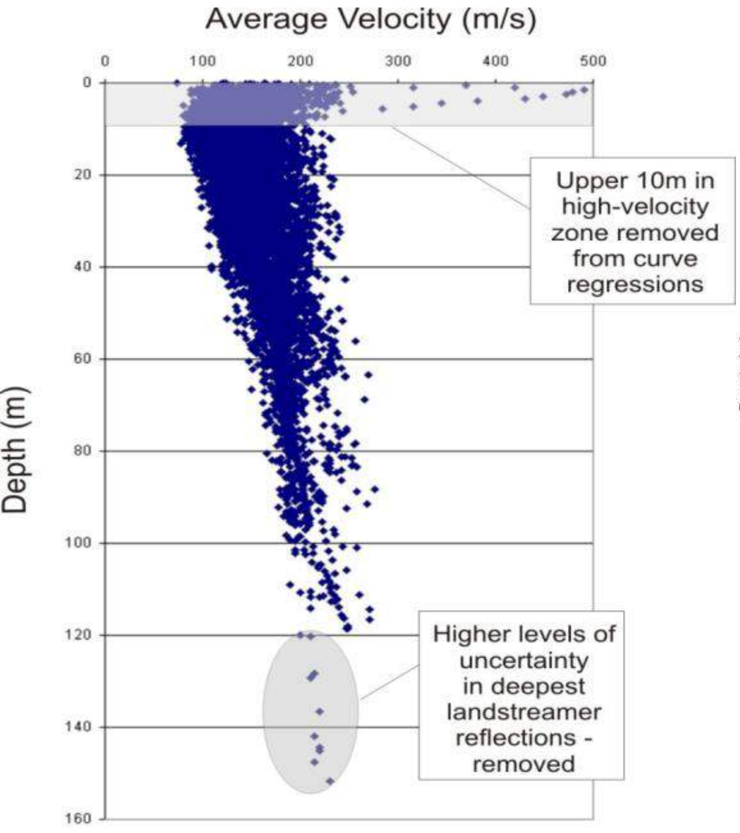
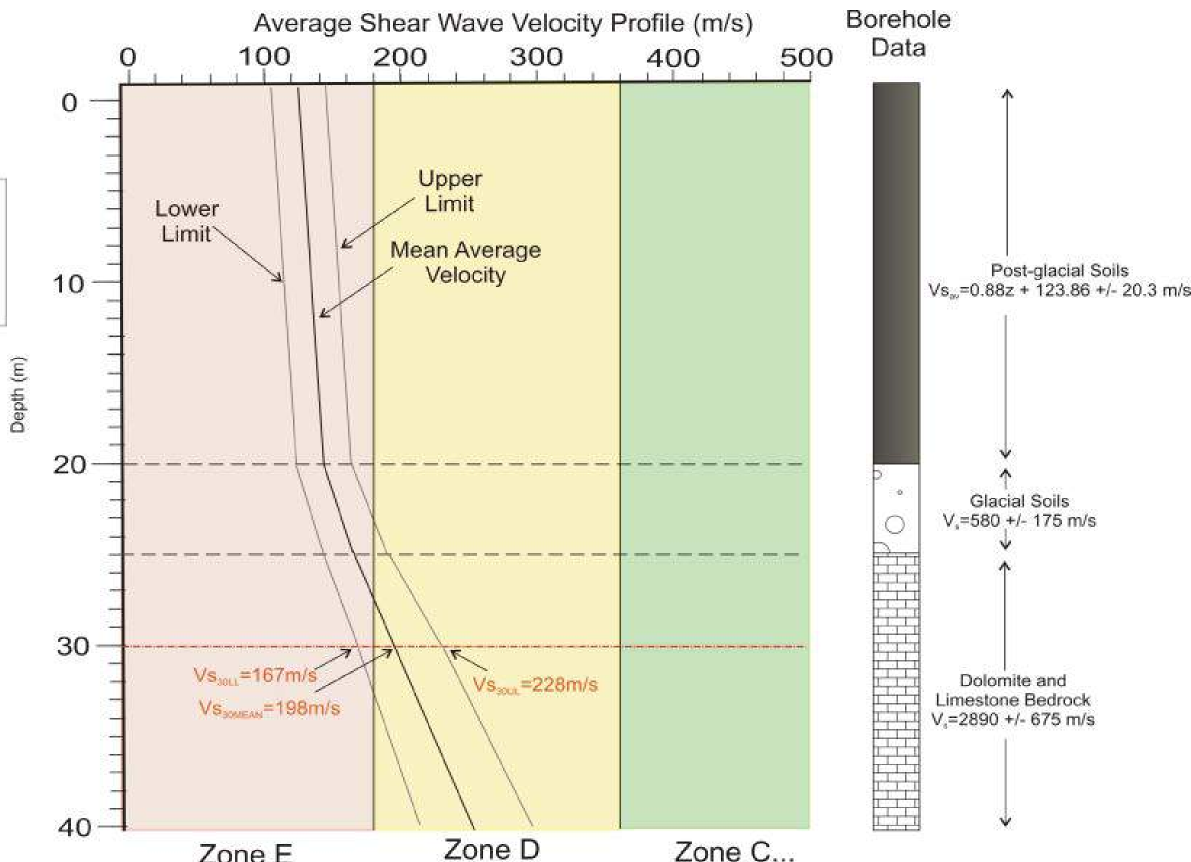


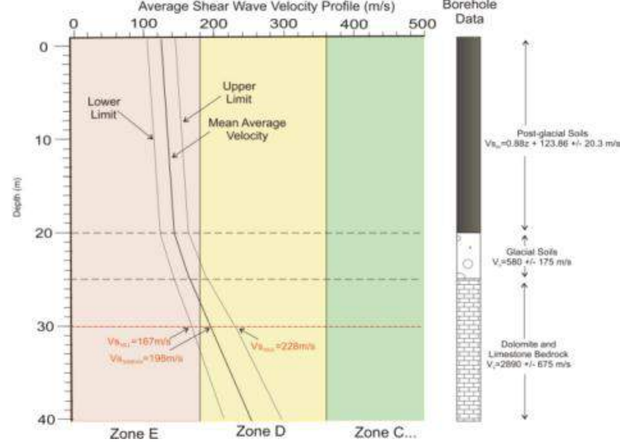
- **Velocity-depth database** for **Champlain Sea sediments** was compiled
- Typical average shear wave velocity profile for the Ottawa region.
- Error associated with the mean velocity

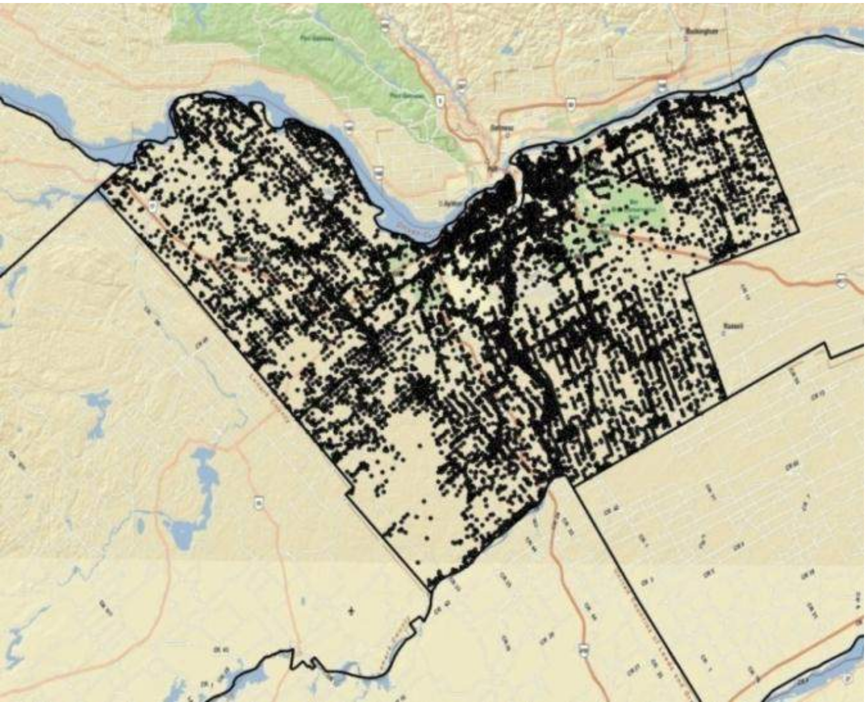
- Post glacial sediments : **Vs_{av}=124 + 0.88z ± 20 m/s for 10m ≤ Z ≤ 100m**
- Glacial soils : **580 ± 175 m/s**
- Typical bedrock : **2700 ± 675 m/s**

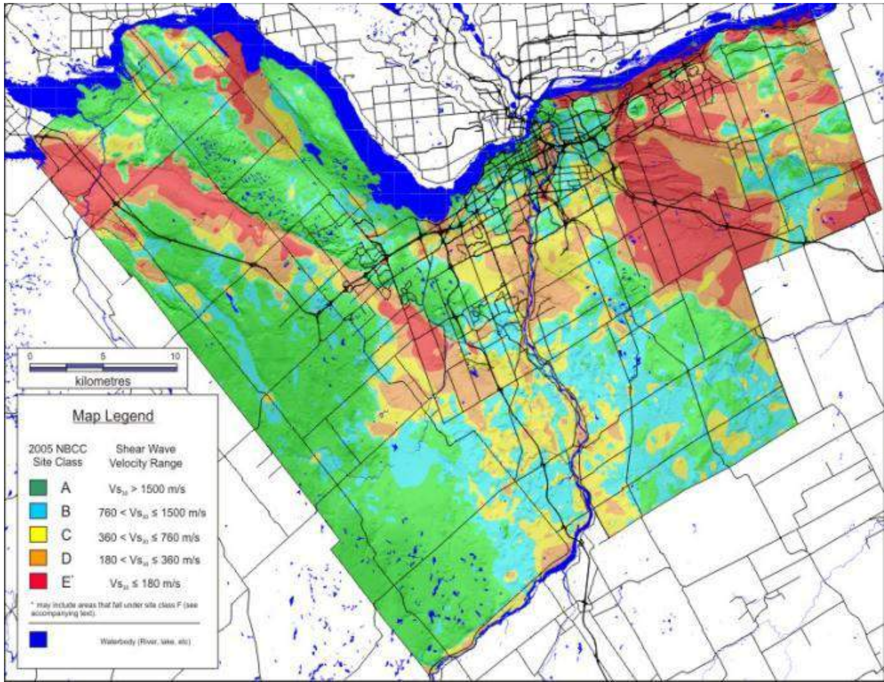




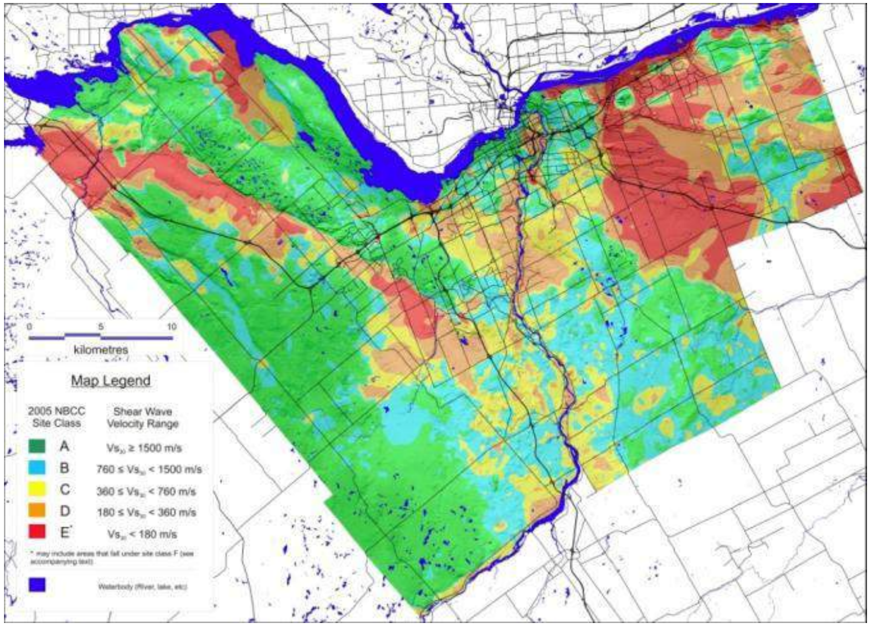
- **The velocity-depth function**
- **~21,000** GSC borehole database
- Then, the velocity-depth functions were applied to all boreholes !
- **V_{s30} map (2005 NBCC)**
- Eastern part of Ottawa is mainly site **class E or F** (very loose soft soil)
- In just a few hundred meters you can see **dramatic changes in Vs30**
- City now is one of the **end users** of our Vs30 map

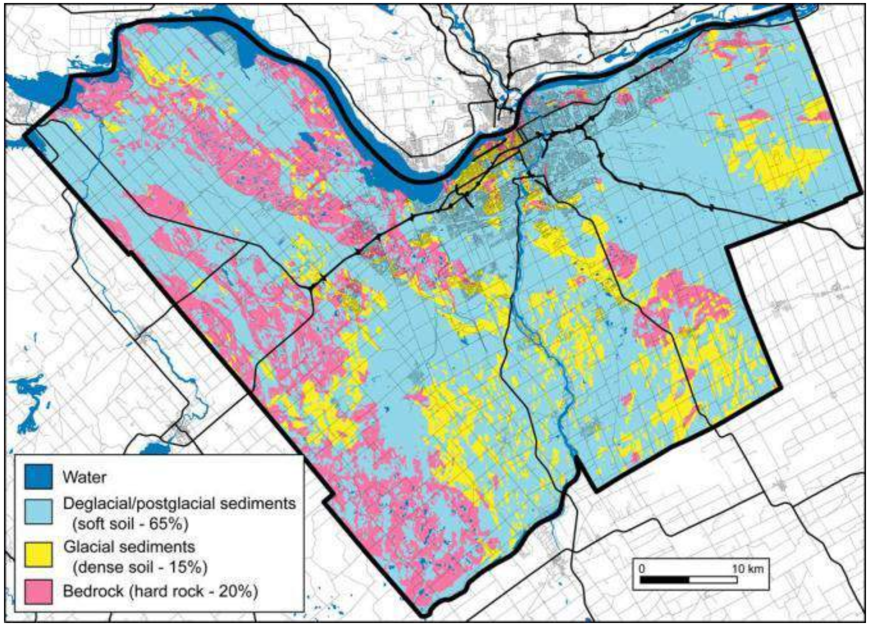






Ottawa





- Areas of site class E or F (NBCC 2005)
- Large areas of post-glacial “soft sediments”, surrounded by bedrock

- **Seismic Hazard map of Ottawa**
- Seismic Hazard map for before microzonation studies
- V_{s30} map
- **amplification factor given by NBCC 2005**
- Map 1 * Map 2 =Seismic Hazard map → corrected for site classes

➢ **These can be used for**
  - **Early warning system Or Shakemap**
  - **Scenario earthquakes**

➢ UWO is using our Vs30 map

Site class	Values of F_a				
	$S_a(1.0) \le 0.1$ g	$S_a(1.0) = 0.2$ g	$S_a(1.0) = 0.3$ g	$S_a(1.0) = 0.4$ g	$S_a(1.0) = 0.5$ g
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C	1.0	1.0	1.0	1.0	1.0
D	1.4	1.3	1.2	1.1	1.0
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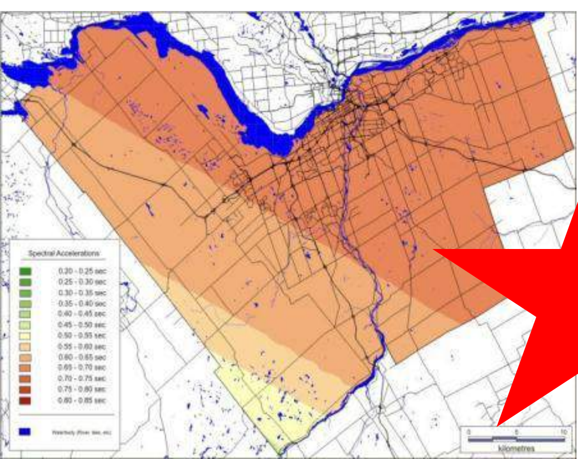
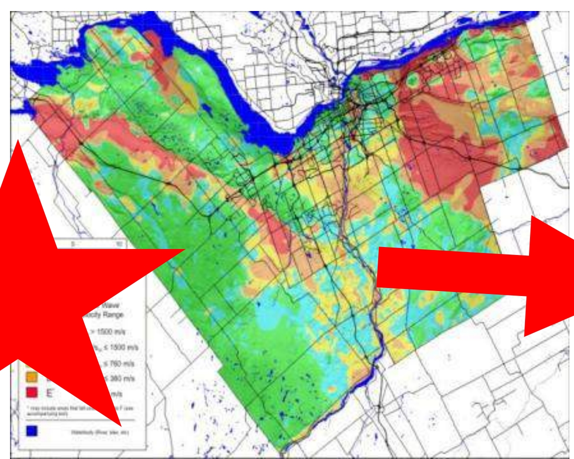
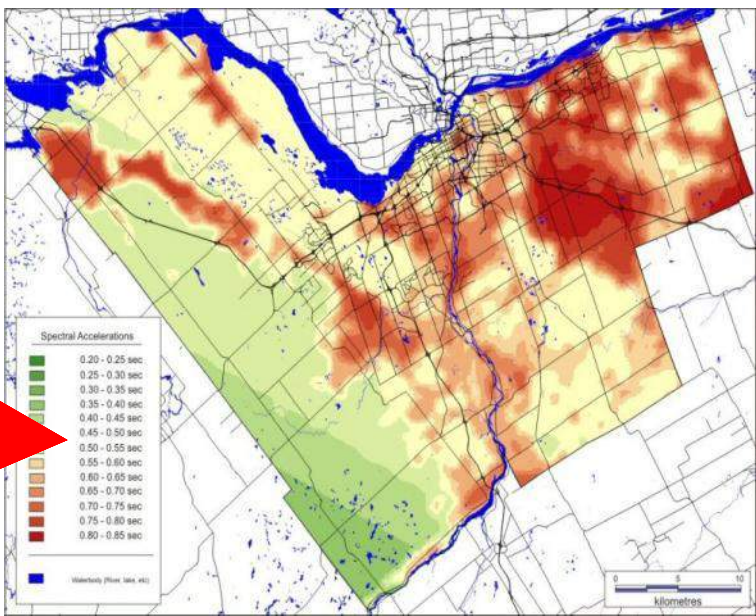
F	Site specific investigation required				







- More information
  - **GSC Open File Report 6273 (2010)**
  - **Canadian Geotechnical Journal paper (2011).**
  - **Interactive Google map http://http-server.carleton.ca/~dariush/Microzonation/main.html/**

Development of a Vs_{30} (NEHRP) map for the city of Ottawa, Ontario, Canada

D. Motazedian, J.A. Hunter, A. Pugin, and H. Crow

Abstract: Four different seismic methods were used extensively to evaluate the shear wave velocity of soils and rock in the city of Ottawa, Canada, from which the travel-time weighted average shear wave velocity (Vs) from surface to 30 m in depth (Vs_{30}) and the fundamental frequency (F_0) were computed. Three main geological or geotechnical units were identified with distinct shear wave velocities: these consist of very loose thick post-glacial fine-grained sands, silts, and clays (Vs <150 m/s, thickness up to 110 m), firm glacial sediments (Vs ~580 m/s, thickness ~3 m), and very firm bedrock (Vs ~1750–3550 m/s). The seismic methods applied were downhole interval Vs measurements at 15 borehole sites, seismic refraction–reflection profile measurements for 686 sites, high-resolution shear wave reflection "landstreamer" profiling for 25 km in total, and horizontal-to-vertical spectral ratio (HVSR) of ambient seismic noise to evaluate the fundamental frequency for ~400 sites. Most of these methods are able to distinguish the very high shear wave impedance of and depth to bedrock. Sparse earthquake recordings show that the soil amplification is large for weak motion when the soil behaves linearly.

Key words: seismic site classification, shear wave velocity, seismic refraction–reflection, downhole.

Résumé : Quatre méthodes sismiques différentes ont été grandement utilisées afin d'évaluer la vitesse des ondes de cisaillement des sols et roches dans la ville d'Ottawa, Canada, à partir desquelles la vitesse moyenne des ondes de cisaillement pondérée selon le temps de parcours (Vs) de la surface jusqu'à une profondeur de 30 m (Vs_{30}) et la fréquence fondamentale (F_0) ont été calculées. Trois unités géologiques ou géotechniques principales ont été identifiées selon des vitesses des ondes de cisaillement distinctes : des sables, silts et argiles post-glaciaires fins, lâches et épais (Vs <150 m/s, jusqu'à 110 m d'épaisseur), des sédiments glaciaires fermes (Vs ~580 m/s, ~3 m d'épaisseur) et du substratum rocheux très ferme (Vs ~1750–3550 m/s). Les méthodes sismiques appliquées étaient des mesures de Vs par intervalle en fond de forage pour 15 sites de forage, des mesures du profil de réfraction–réflexion sismique pour 686 sites, du profilage de la réflexion des ondes de cisaillement à haute résolution « landstreamer » pour 25 km linéaire au total, et le ratio spectral horizontal–vertical (RSHV) du bruit sismique ambiant pour l'évaluation de la fréquence fondamentale sur environ 400 sites. La majorité de ces méthodes sont capables de distinguer l'impédance très élevée aux ondes de cisaillement et la profondeur jusqu'au substratum rocheux. Quelques mesures de séismes montrent que l'amplification du sol est grande pour des mouvements faibles lorsque le sol de comporte de façon linéaire.

Mots-clés : classification sismique des sites, vitesse des ondes de cisaillement, réfraction–réflexion sismique, fond de forage.

[Traduit par la Rédaction]

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Interactive Vs30 Google Map for the City of Ottawa

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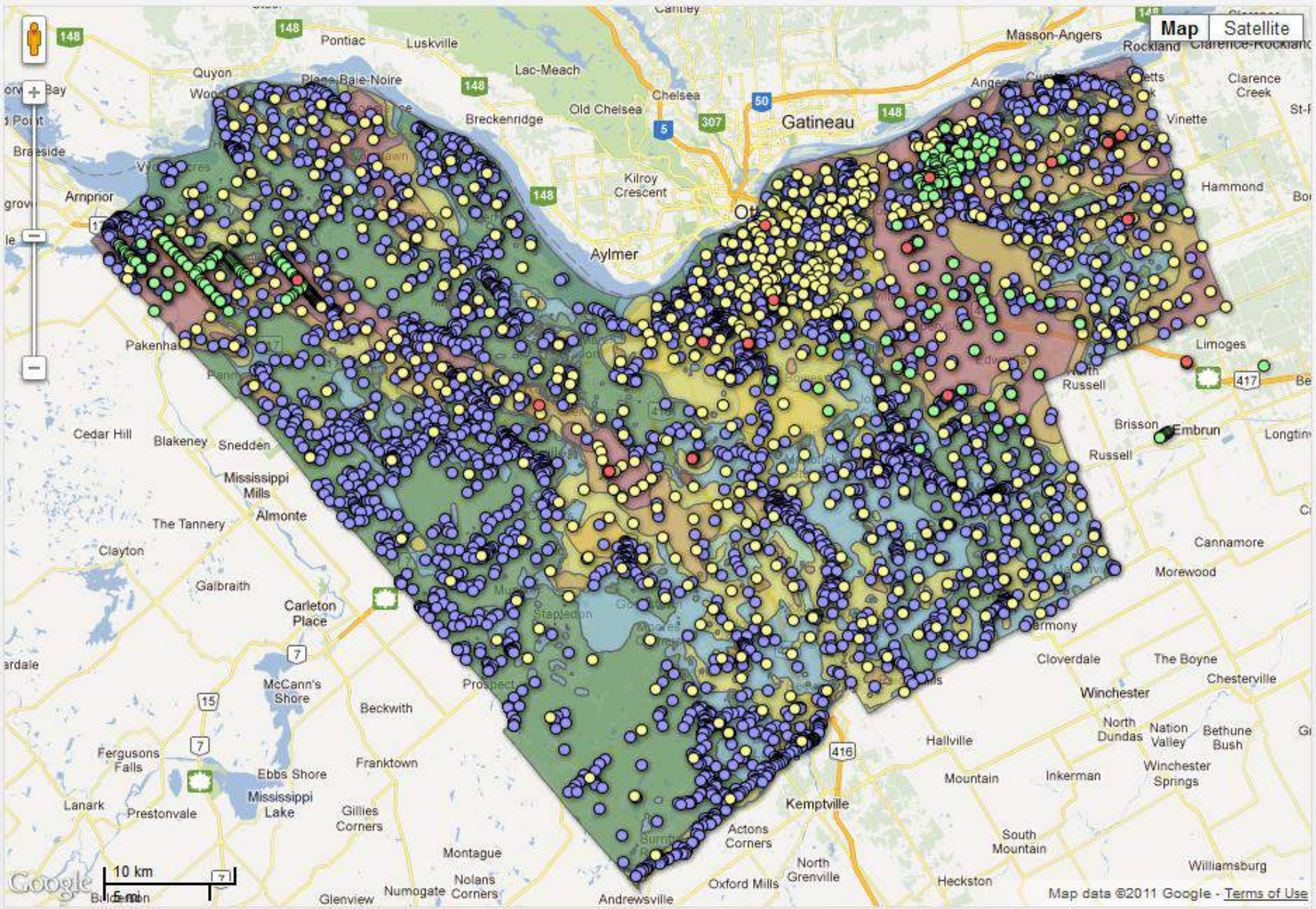

Overlays:

Click to toggle layers:

- BH Geophys (18 Sites)
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- Boreholes (20716 Sites)
- Seismic Sites (1226 Sites)
- Vs30Class
  - Class A
  - Class B
  - Class C
  - Class D
  - Class E

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SUMMER MOVIES

Jay Stone's guide, J1

GO DAD!

The Senators' Chris Phillips is gone on a 23-day trip to the worlds, but his family isn't complaining

SPORTS, C1

YARD SALE

10 great tips, E2

EXCLUSIVE: Data confirm why earthquakes are felt more in Orléans than in other areas

Scientists map Ottawa quake risk

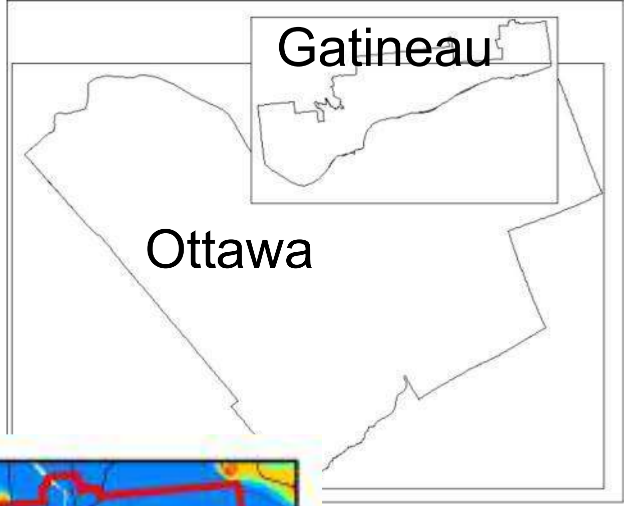
Areas built over Leda clay more prone to shaking, damage in big earthquake

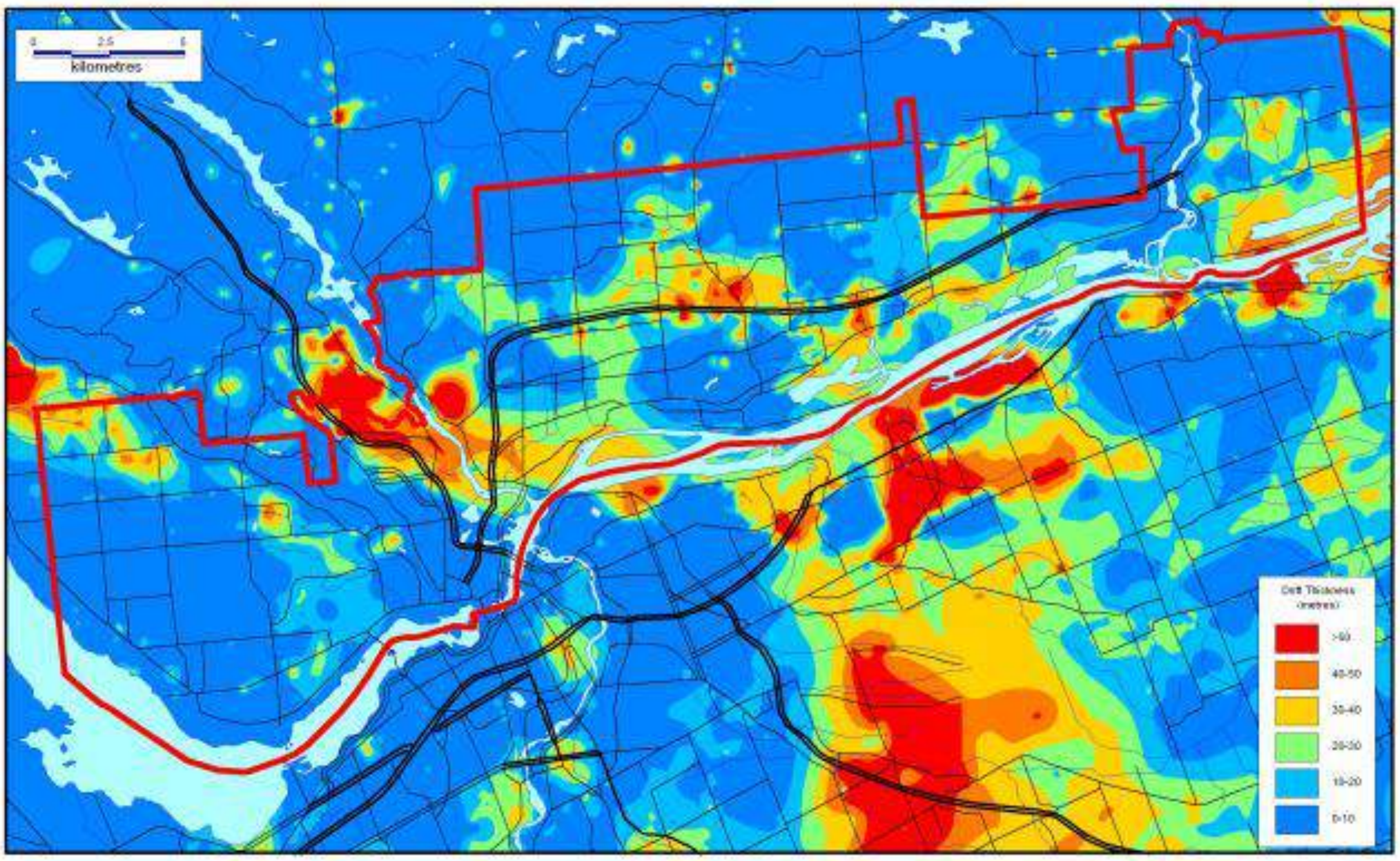
BY ANDREW DUFFY

Earth scientists have produced an earthquake "hazard map" for Ottawa that charts those parts of the city most at risk from seismic shaking.

The map, based on data collected from 28,000 boreholes, suggests parts of Orléans

- We moved our studies to the north side of the river
- Surficial geology similar to Ottawa
- Soil thickness ; there are many areas with relatively thick soils
  - late/post-glacial sediments, Leda Clay(Vs~150 m/s)
  - bedrock outcrop (Vs~2700 m/s)
  - glacial sediment (Vs~580 m/s)





In addition to shear wave velocity-depth function gathered for the city of Ottawa, in Gatineau we covered extra

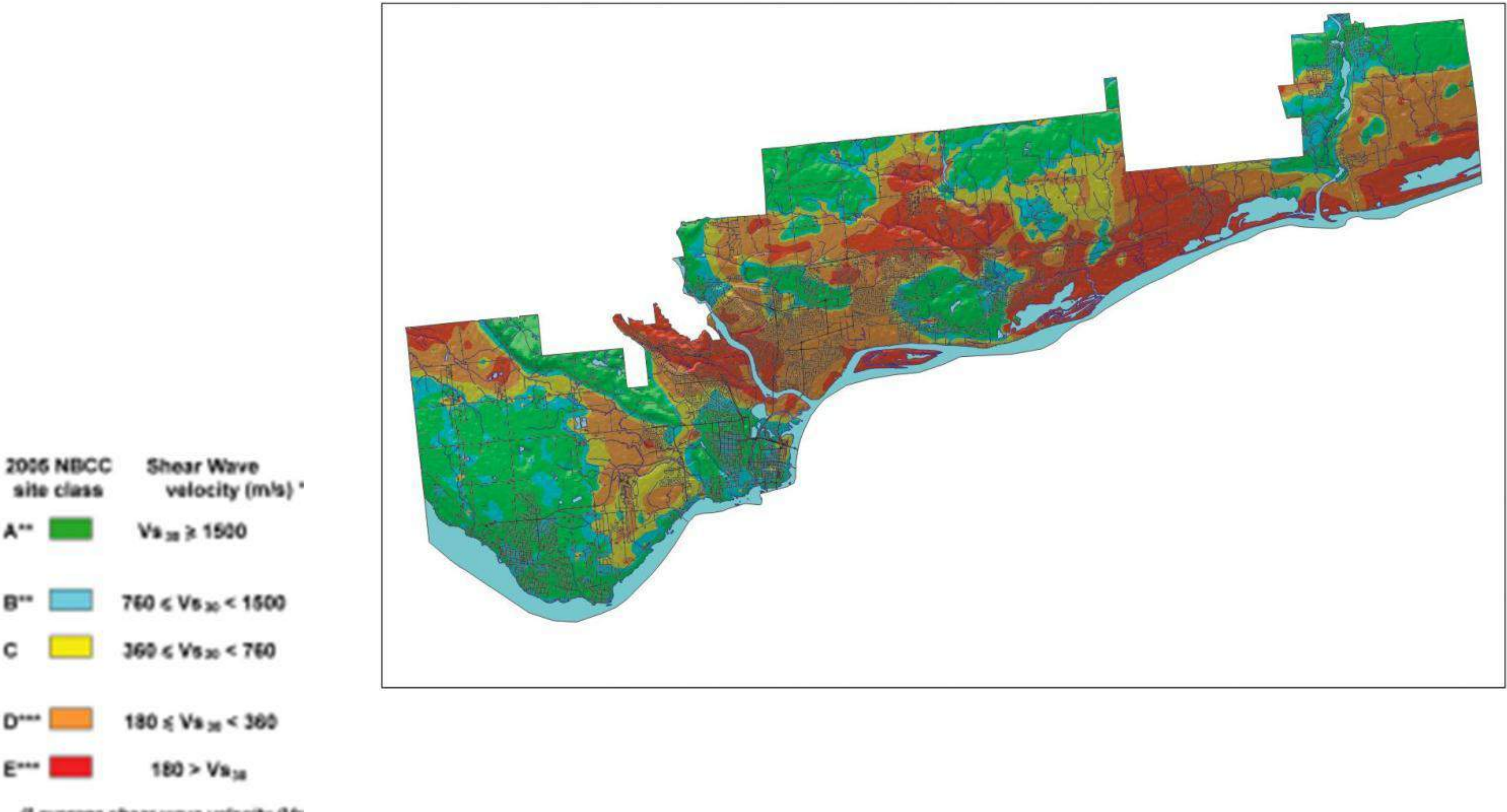
- **67** Seismic reflection/refraction sites
- **~100** HVSR sites

Using geological information for **1076** boreholes the Vs30 map has been provided.

- **A vs30 map** was compiled using sub - surface geological data obtained from **borehole records and measurements of shear - wave velocities** using shallow geophysical techniques.

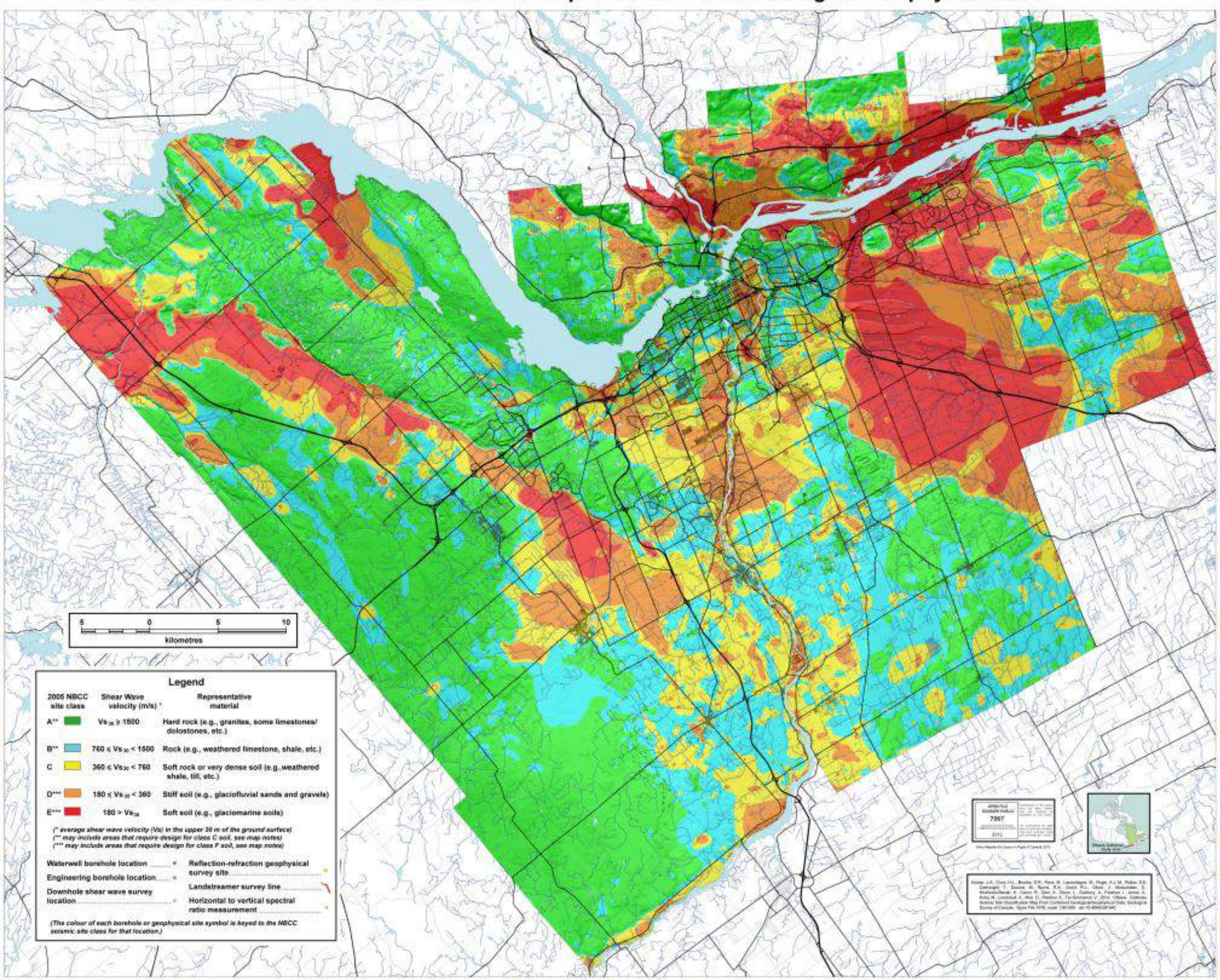
- The site classes were defined exclusively by using the **travel-time-averaged shear-wave** velocity over the upper 30 m of the ground (Vs30).

- The borehole data consist of **1075 water well and engineering boreholes** that were compiled from the Urban Geology of Canada's National Capital area website, Geological Survey of Canada (Belanger, 1998), and from the Ontario Ministry of Environment water-well database.



Putting all together !

Ottawa - Gatineau Seismic Site Classification Map From Combined Geological/Geophysical Data



Canada

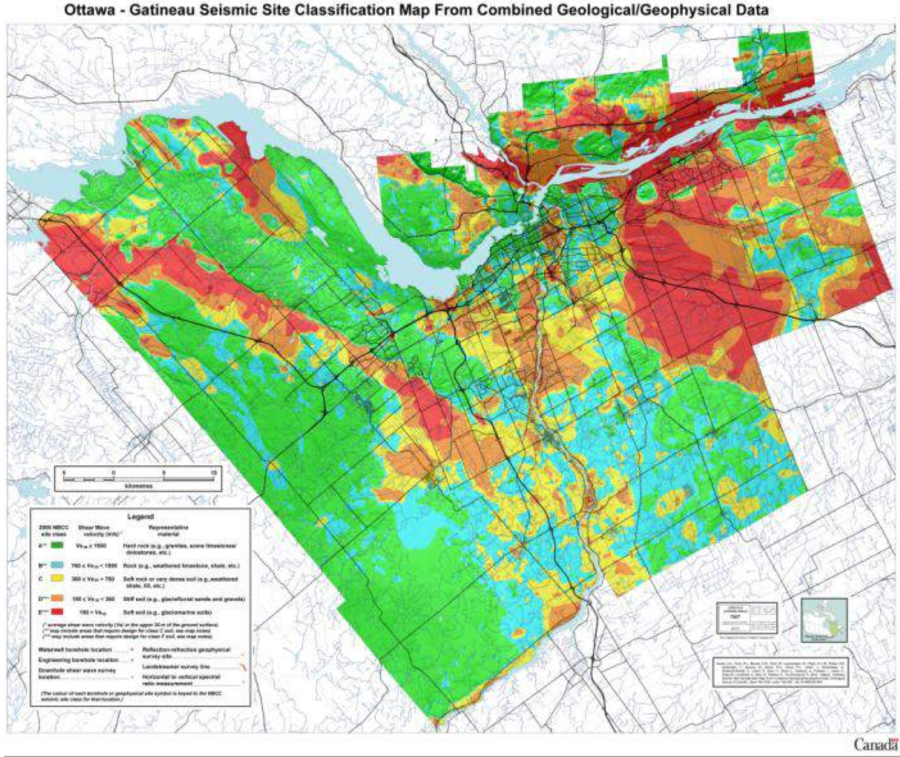
Uncertainty

- The **boundaries between site classes** are subject to **uncertainty** in position, especially where few data points occur.

- In some areas where **data density is high**, these seismic site classification boundaries are **accurate to within a few hundred meters**.

- In other areas, where **data are sparse**, the uncertainty in the mapped boundary might be **2 km or larger**.

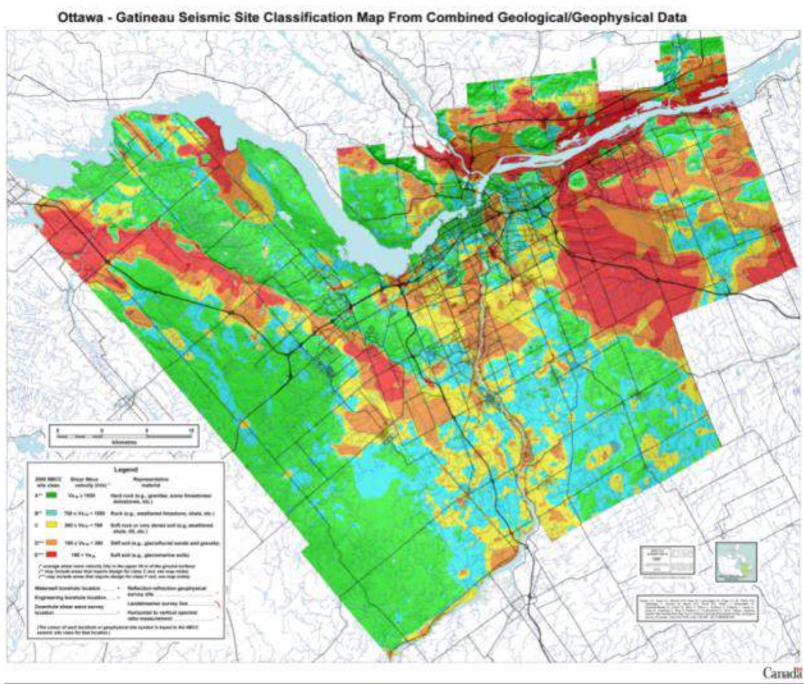
Ottawa - Gatineau Seismic Site Classification Map From Combined Geological/Geophysical Data



Uncertainty

- The final mapped **boundaries** between site classes were edited to respect **borehole and surface geophysics data po**ints as well as known surficial geological boundaries.
- To
  - ➢ reflect the **uncertainty in the contouring**,
  - ➢ the **variability in data density**, and
  - ➢ to show the **complexity of local geology**,

data points are displayed on the map and keyed by a symbol for the data type and by the colour of the associated seismic site class.



- It should be noted that it is possible that **class F site conditions** may be found within the areas mapped as C through E, as Vs30 alone does not allow class F conditions to be identified.

F	Other *soils*[(1)]	Site-specific evaluation required

(1) Other *soils* include:

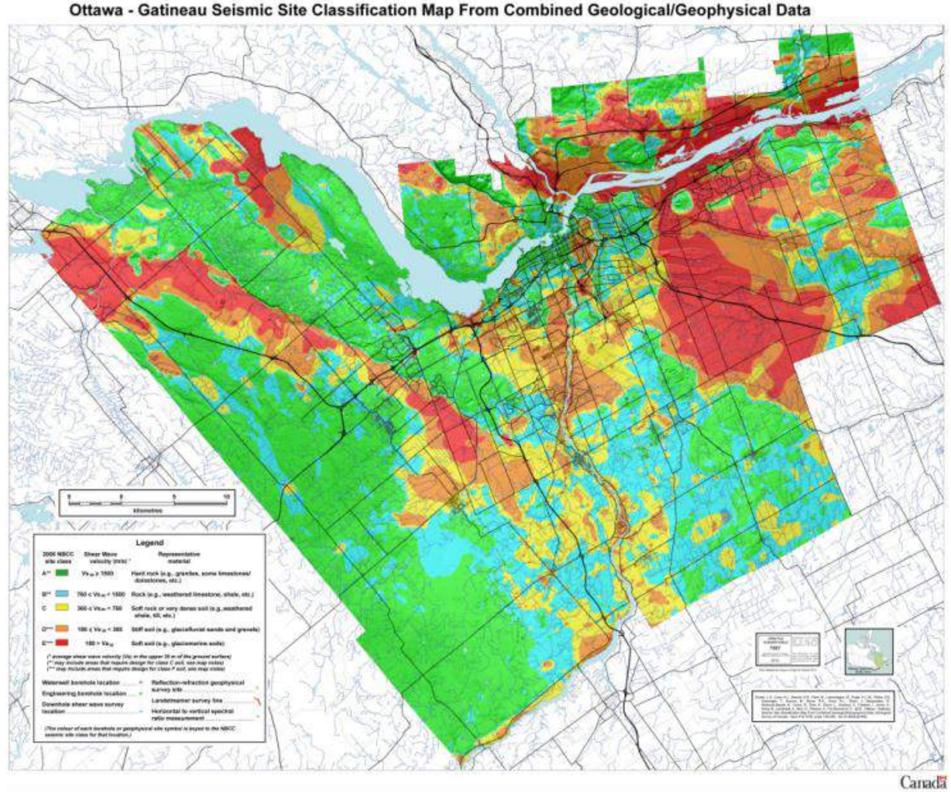
(a) liquefiable *soils*, quick and highly sensitive clays, collapsible weakly cemented *soils*, and other *soils* susceptible to failure or collapse under seismic loading,

(b) peat and/or highly organic clays greater than 3 m in thickness,

(c) highly plastic clays (PI > 75) more than 8 m thick, and

(d) soft to medium stiff clays more than 30 m thick.

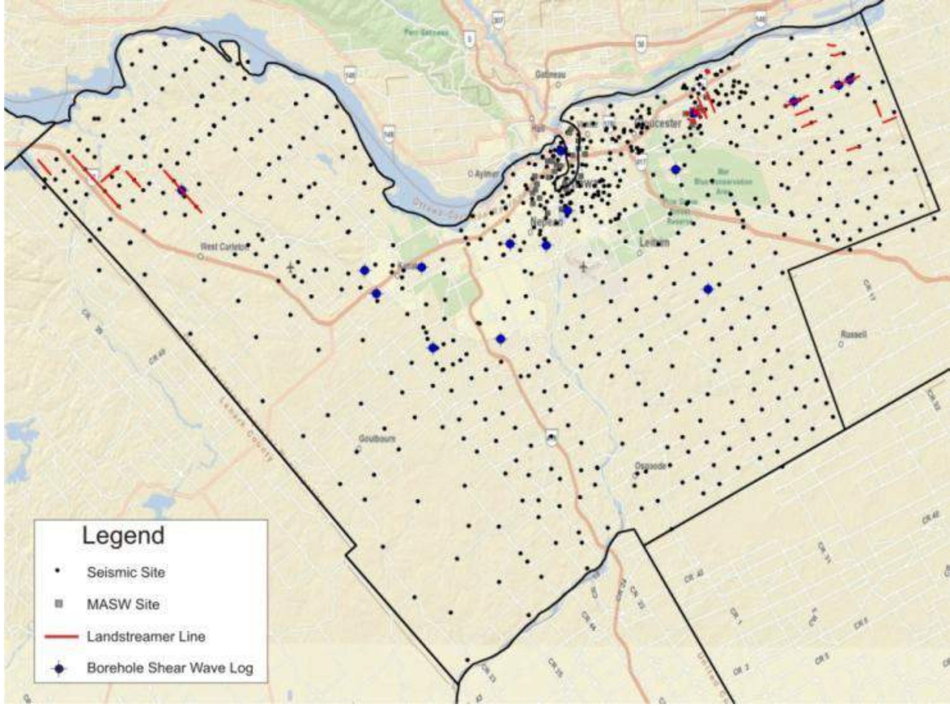
Ottawa - Gatineau Seismic Site Classification Map From Combined Geological/Geophysical Data

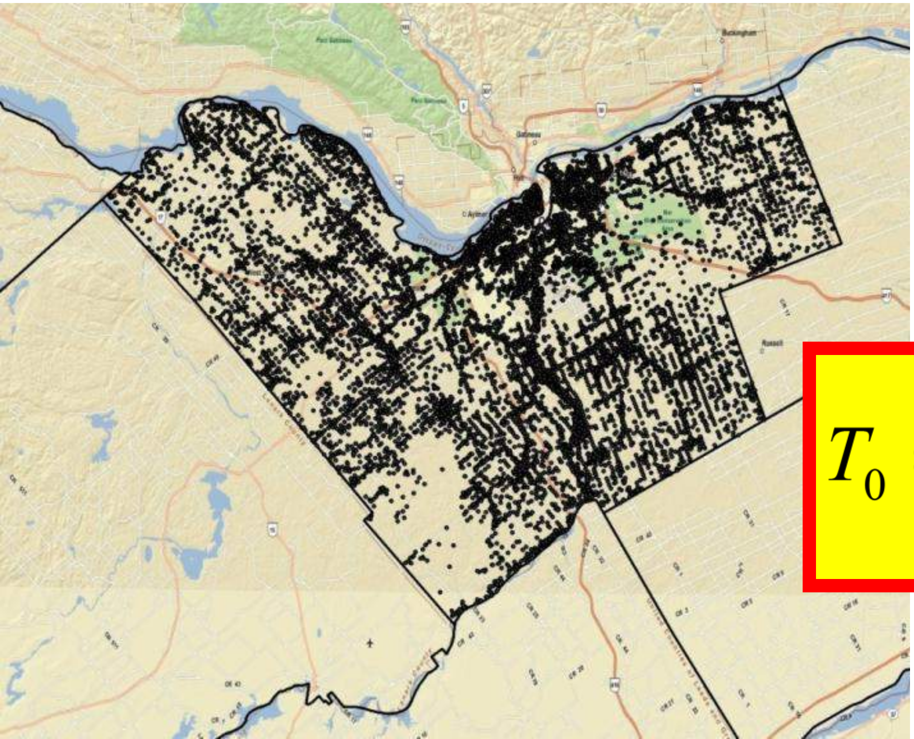


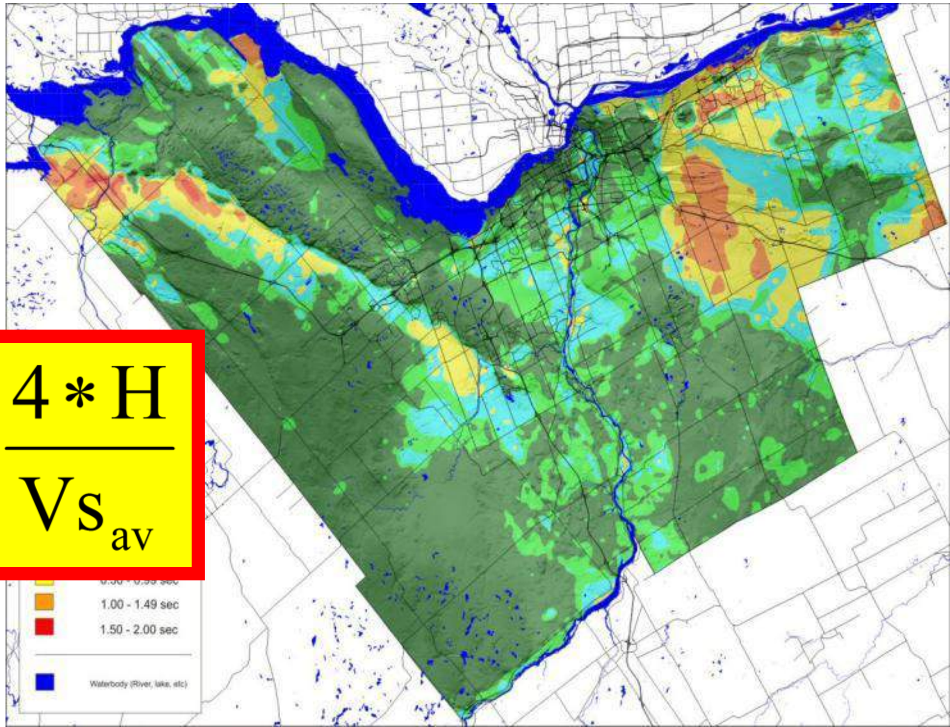
- **Fundamental Site Period**
- Recently, it has been recognized that **V_{s30} MAY not** represent the entire seismic soil amplification phenomenon (Abrahamson, 2009)
- There is a trend towards **inclusion of T_0** in the site classification
- Thus, we added the evaluation of Fundamental Site Period (T_0)
- **T_0 based on**
  - HVSR using **background noise analysis**
  - HVSR using **earthquake recordings**
  - **Equivalent single-layer** (ESL) modeling (NBCC 2005)
  - Multi-layer soil modeling
  - Finite element modeling for linear and nonlinear soil.

- **T_0 map**
- Based on NBCC 2005 guidelines

- **T_0=4H/Vsav** was applied to all sites and **~21,000** boreholes



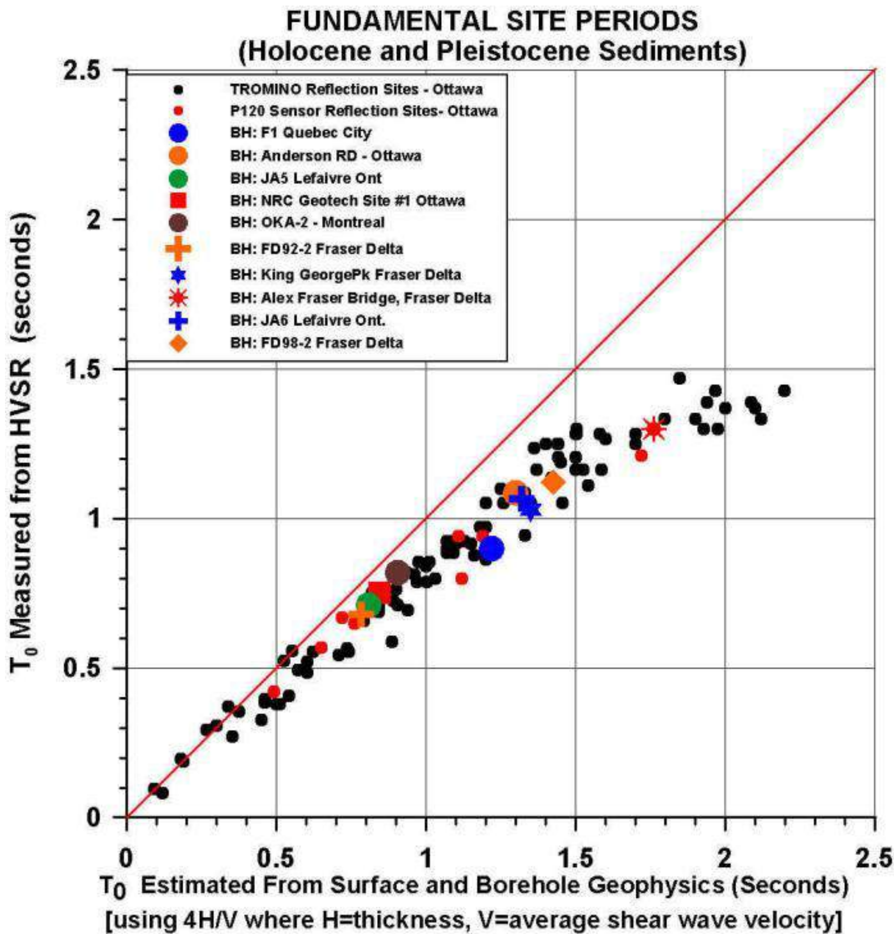




$$T_0 = \frac{4 * H}{Vs_{av}}$$

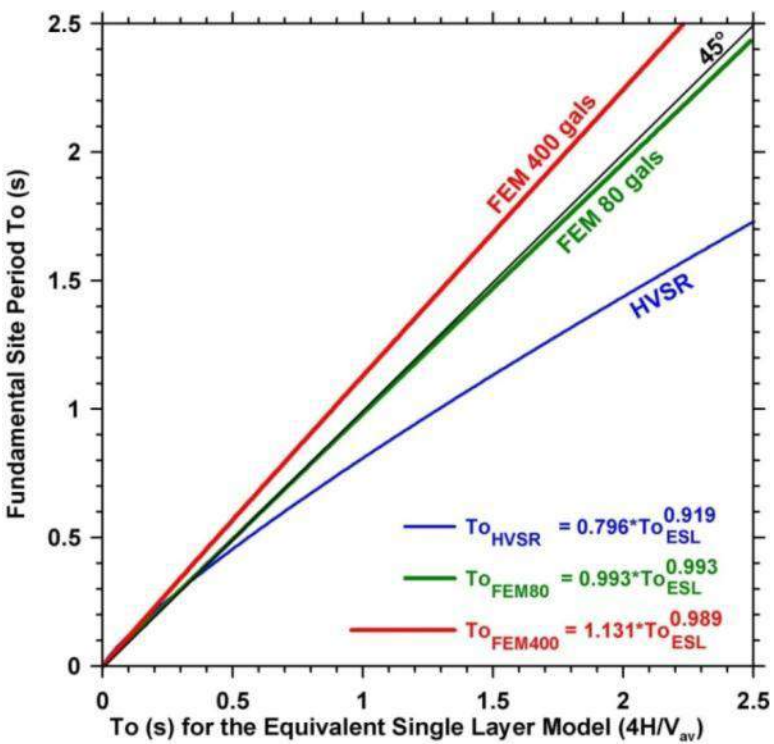
- **However a calibration is needed!**
- Comparison between
  - T_0 based on HVSR and
  - T_0 based on NBCC 2005 (4H/Vsav)
  - Boreholes **(very accurate Vs)** locations from:
    - Ottawa
    - Quebec City
    - Eastern Ontario
    - NW Montreal
    - and Richmond BC

- **They do not match!**
- **Which one is right?**



- **We applied many methods to obtain T_0**
  - NBBC 2005
  - HVSR using background noise analysis
  - Finite element modeling for **80 gal**
  - Finite element modeling for **400 gal** (**design earthquake for Ottawa**)
  - **They do not match!**
  - The relationships between all are obtained.

- **HVSR is fast and its T0 can be used to obtain T0 for the design EQ!**



- More information
  - **GSC Open File Report 6273**
  - **BSSA Journal paper (2011)**
  - **Interactive Google map** http://http-server.carleton.ca/~dariush/Microzonation/main.html/

Bulletin of the Seismological Society of America, Vol. 101, No. 6, pp. –, December 2011, doi: 10.1785/0120100344

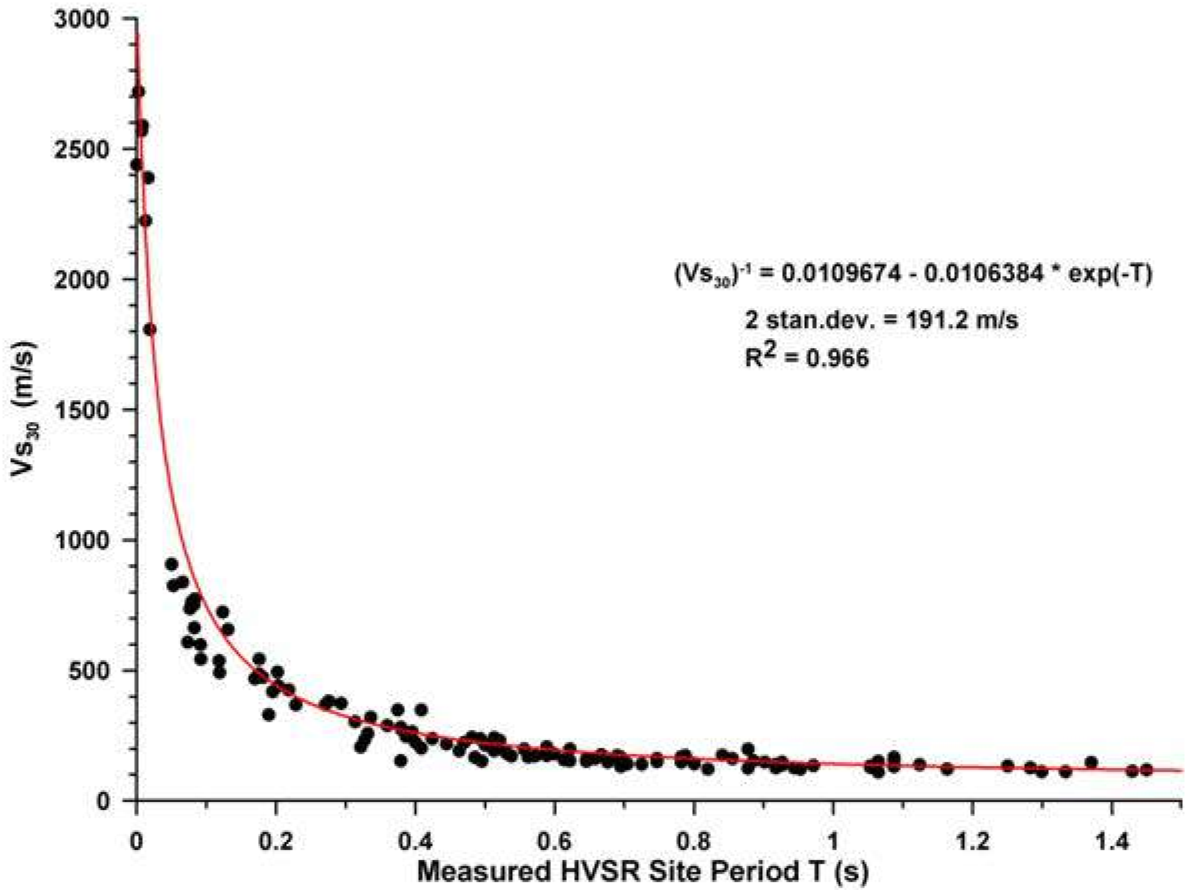
Comparison of Site Periods Derived from Different Evaluation Methods

by D. Motazedian, K. Khaheshi Banab,* J. A. Hunter, S. Sivathayalan, H. Crow,† and G. Brooks

Abstract As a part of our microzonation research activities for the city of Ottawa, the fundamental site period, T_0, was investigated based on different methods, including (1) the horizontal-to-vertical spectral ratio (HVSR) using microtremor ambient-noise measurements; (2) equivalent single-layer (ESL) modeling, as noted in the current National Building Code of Canada (2005); (3) earthquake weak motion observations; (4) multilayer soil modeling; and (5) finite element modeling for linear and nonlinear soil. The differences between these methods are discussed. We have discovered that T_0 based on the HVSR method systematically deviated from T_0 based on the equivalent single-layer modeling method. The variance was more than 30% for periods longer than 2 s, corresponding to impedance boundary depths of more than 75 m in the study area. The effect of the shear-wave velocity gradient on T_0 was investigated by applying multilayer soil modeling, which confirms that the actual velocity-depth gradient shifts the evaluated T_0 to shorter periods compared to equivalent single-layer modeling. The effects of soil nonlinearity on T_0 were examined using a finite element method analysis. The dependency of T_0 on the level of shaking is well defined at higher levels of shaking when the peak ground acceleration (PGA) exceeds 80 Gal because the soft soil behaves nonlinearly. It has been concluded that, for the case of nonlinear soil response, damping plays an important role in reducing the fundamental frequency. These findings will be used in our future research activities directed at providing fundamental period maps for the city of Ottawa, including fundamental period maps for the strong motion design earthquake.

- **Using HVSR to get Vs30!**
  - HVSR is fast (quite a few sites per day)
  - Can be used as a **screening tool to estimate Vs30!**

  - Vs30 versus T0 for Ottawa area



More information in Journal of Soil Dynamics and Earthquake Engineering paper in 2011

Soil Dynamics and Earthquake Engineering ■ (■■■■) ■■■–■■■

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

journal homepage: www.elsevier.com/locate/soildyn

Monofrequency *in situ* damping measurements in Ottawa area soft soils

Heather Crow [a,*], J.A. Hunter [a], D. Motazedian [b]

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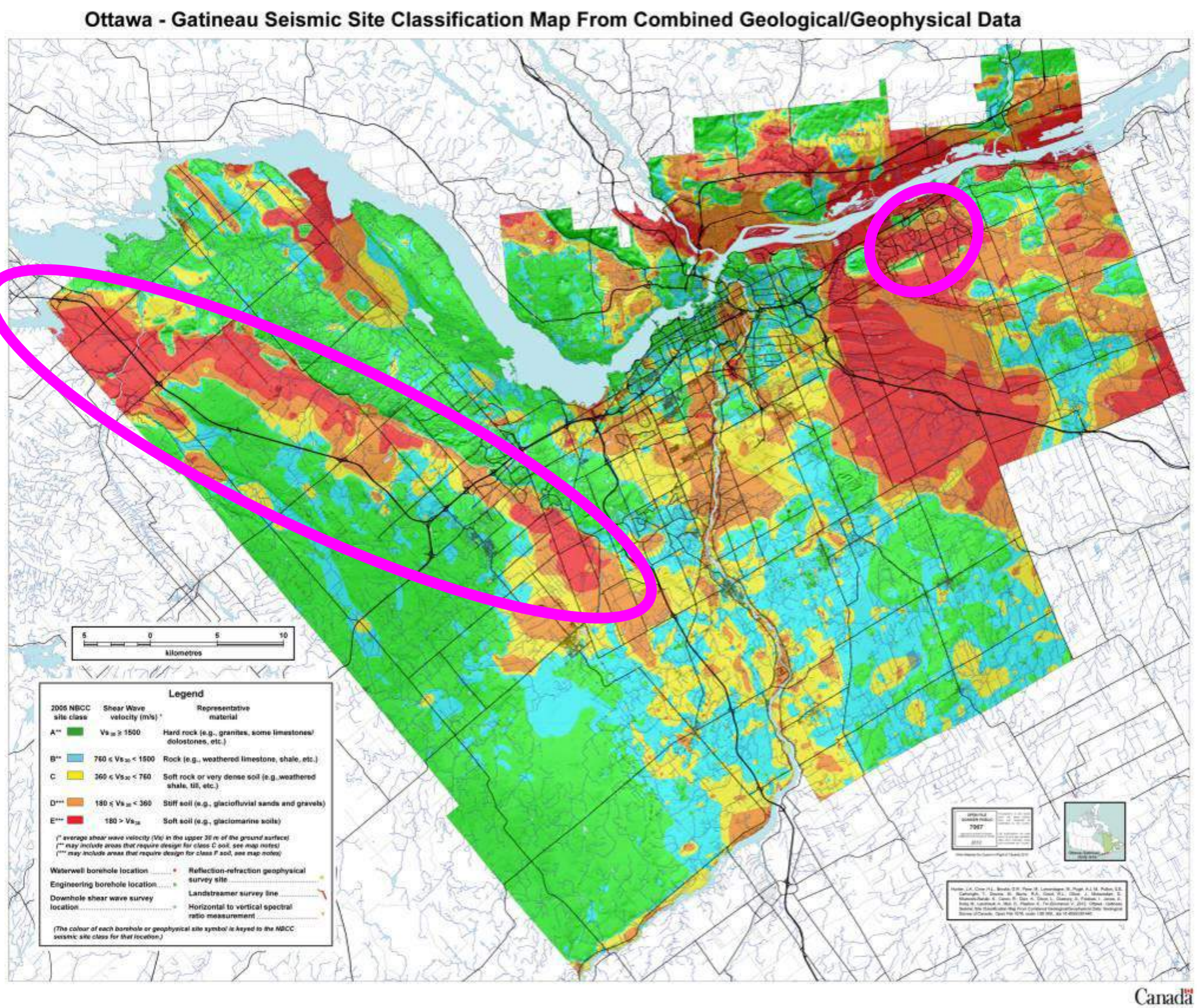
ABSTRACT

In Ottawa, Canada, unusually high amplification ratios have recently been measured in clayey silts (called 'Leda Clays') at low levels of earthquake-induced ground shaking. However, the contribution of seismic Q, or material damping ($\xi = 1/2Q$), to the overall ground motion at soft soil sites across the city is not well understood. This research investigates attenuation measurements in soft soils ($V_s < 250$ m/s) for ongoing seismic hazard evaluation in the Ottawa area. The work focuses on *in situ* measurements of damping in two deep boreholes drilled into Leda Clay. To investigate the possibility of frequency-dependent dynamic properties of these materials at low strains, a new approach to the spectral ratio technique has been developed for the measurement of Q_s in the field using a mono-frequency vibratory source (generating signals between 10 and 100 Hz), and two identical downhole 3-component geophones. Monofrequency signals also allowed for the measurement of dispersion (variation of velocity with frequency). Analysis of the data show that dynamic properties are, for the most part, independent of frequency in the homogenous silty soils, yielding negligible variation in shear wave velocity (< 2 m/s) across the frequency test band, and small strain Q_s's ranging from 170 to 200 (damping of 0.25–0.30%) over soil thickness intervals ranging from 10 to 60 m. At intervals within 20 m of the ground surface, laminated silt and clay beds of elevated porosity are found to have slight influence on the frequency dependence of damping for frequencies greater than 70 Hz (damping increase to 0.6%).

Earthquake Observations in Ottawa Area

Broadband stations in three Basins

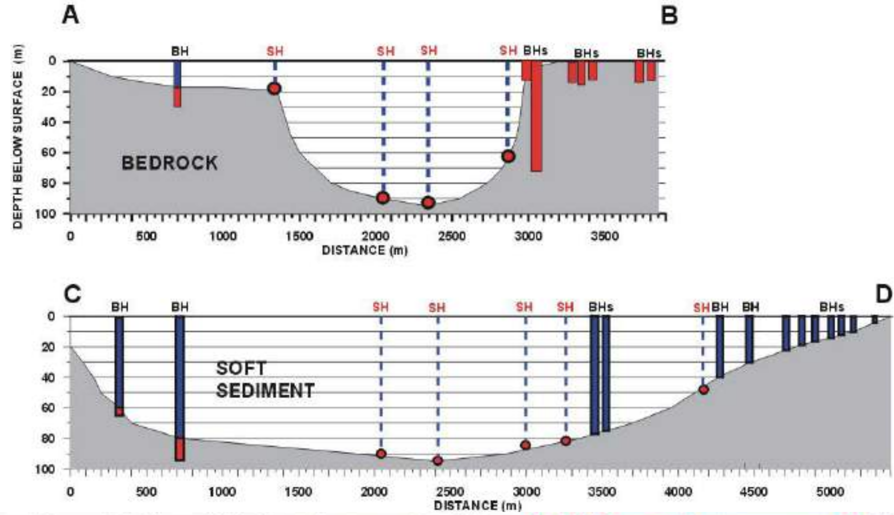


- We have three pairs of weak motion broad band station in Ottawa Valley

- Kinburn
- Orleans
- Alfred
- Each pair (one on soil one on bedrock)
- Instrumented by identical seismometers and digitizers

Orleans stations

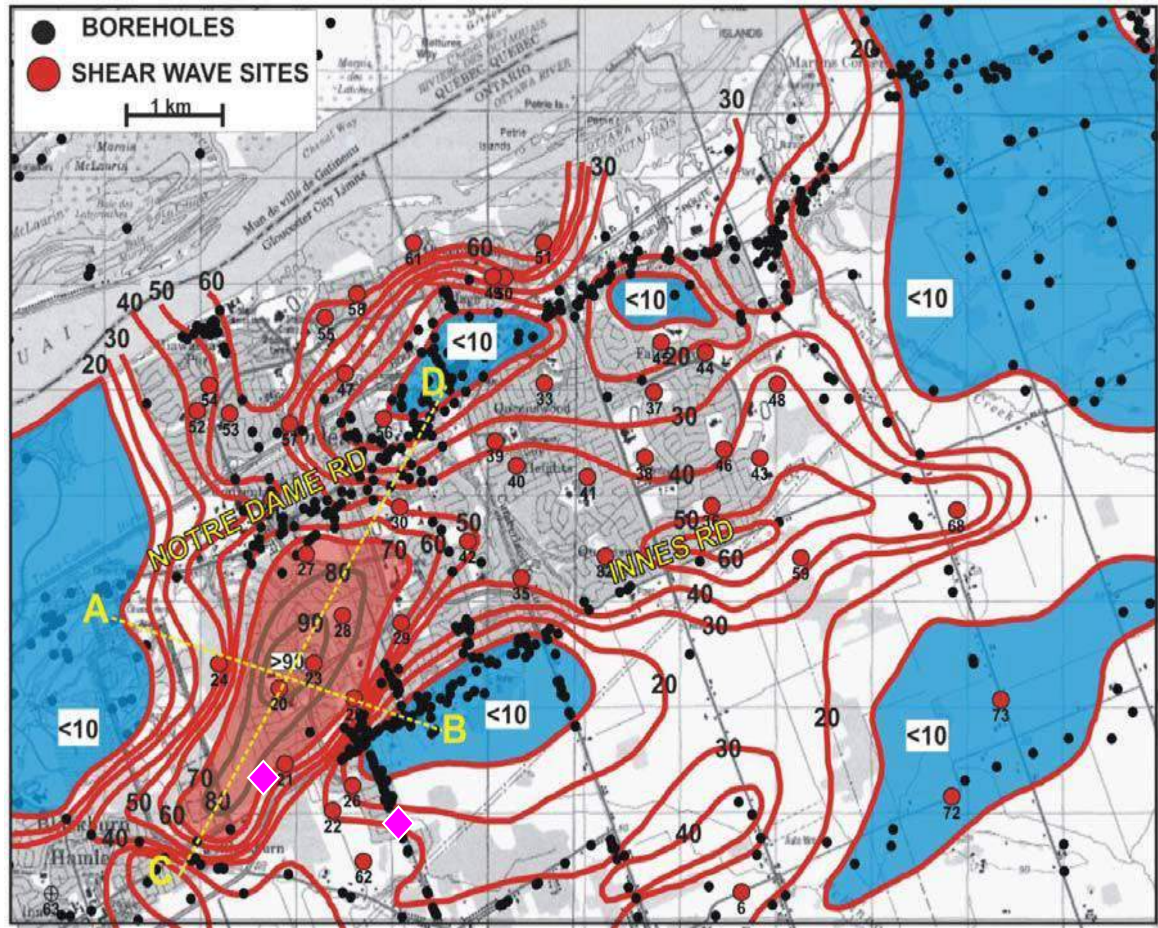
- by **two nearby broadband stations**
- One on 90m of soil (ORHO) and
- one on bedrock (ORIO)
- 1.5 km apart



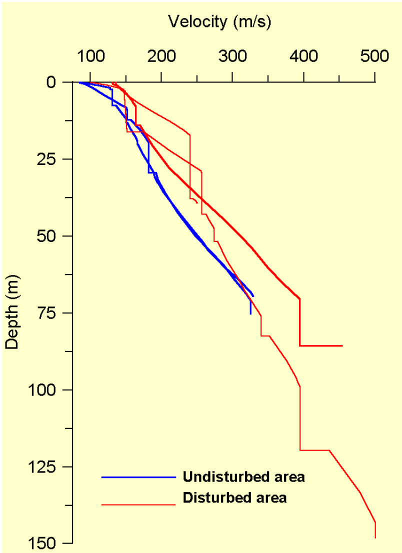
Overburden thickness (metres)

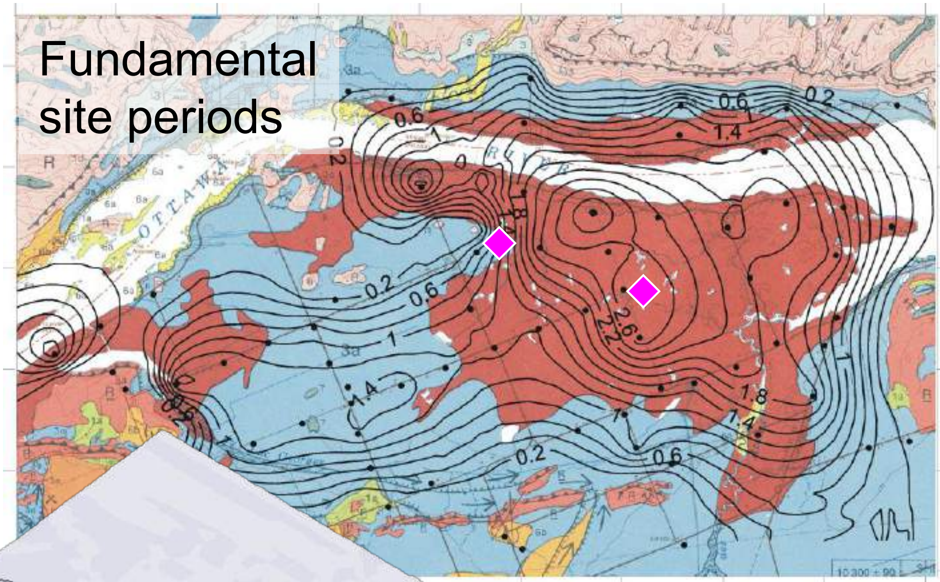
Motazedian and Hunter , 2008

Seismic stations

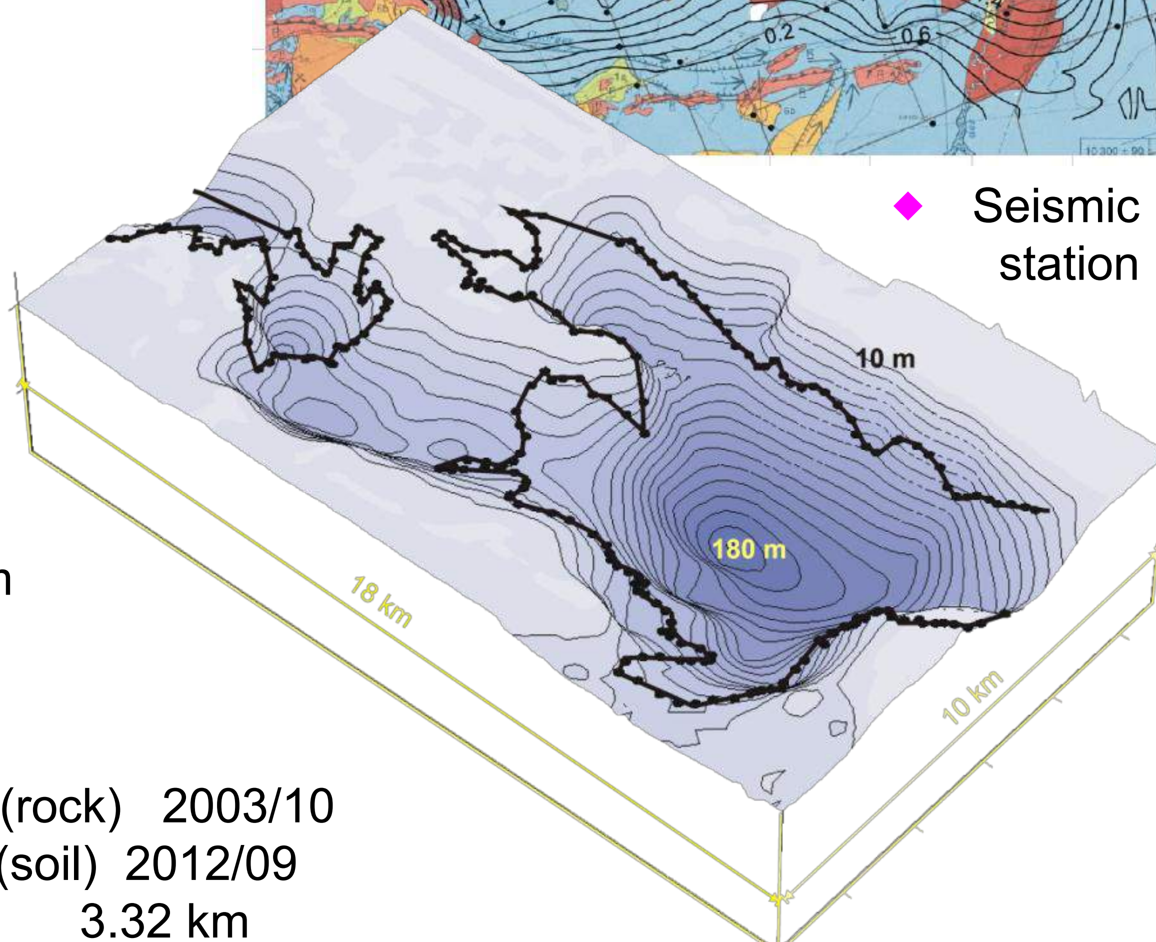


Alfred stations (Lefaivre) basin





◆ Seismic station



Basin properties:

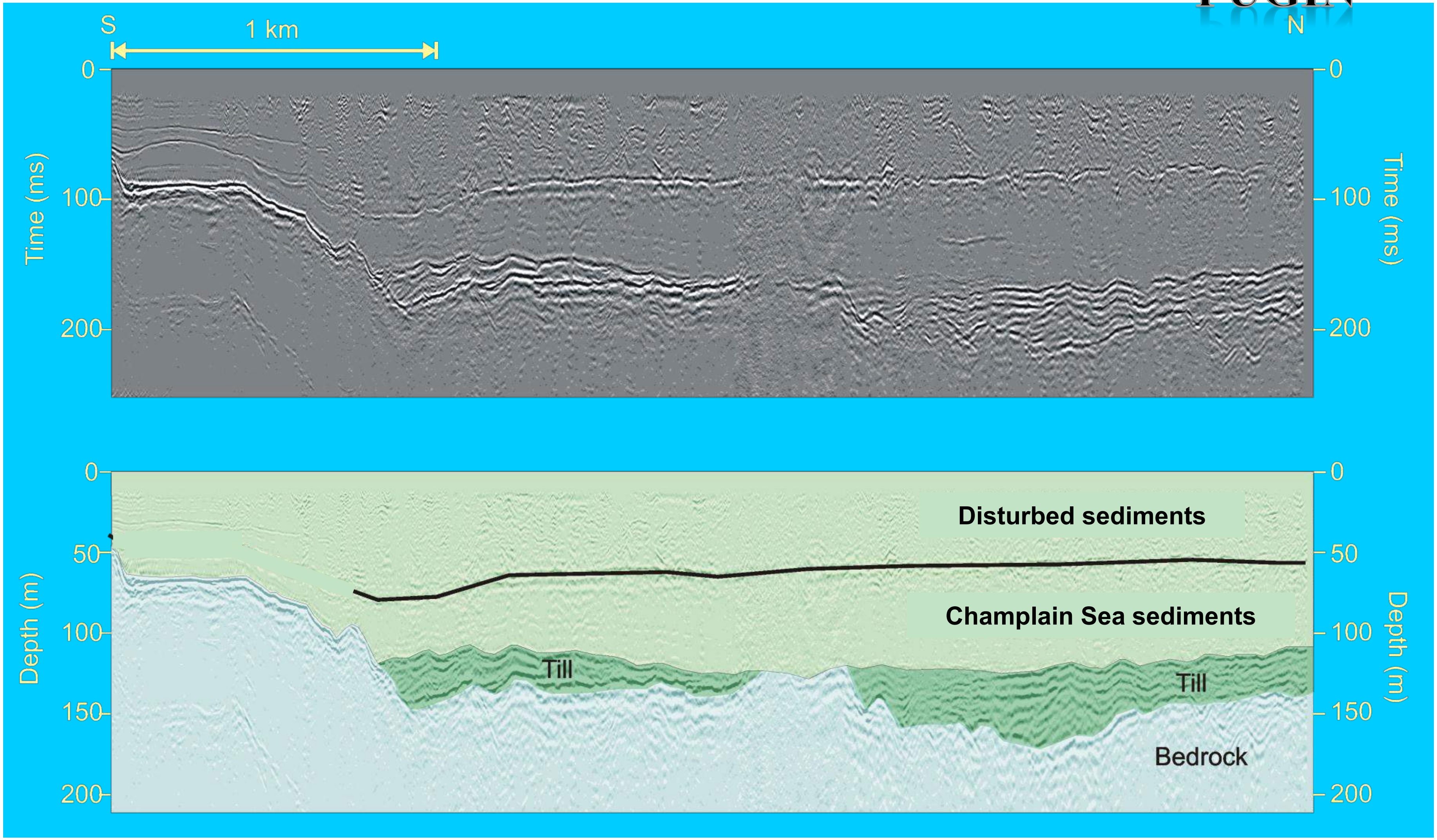
- Depth of ~180 m
- Non-sensitive clay
- Sand layers in upper 50 m
- Disturbed ground overtop
- ~18 km by 10 km

ALFO (rock) 2003/10
ALFS (soil) 2012/09
distance 3.32 km

Alfred-Lefaivre basin

GSC
PUGIN

P-wave seismic profile (disturbed area)



Basin properties:

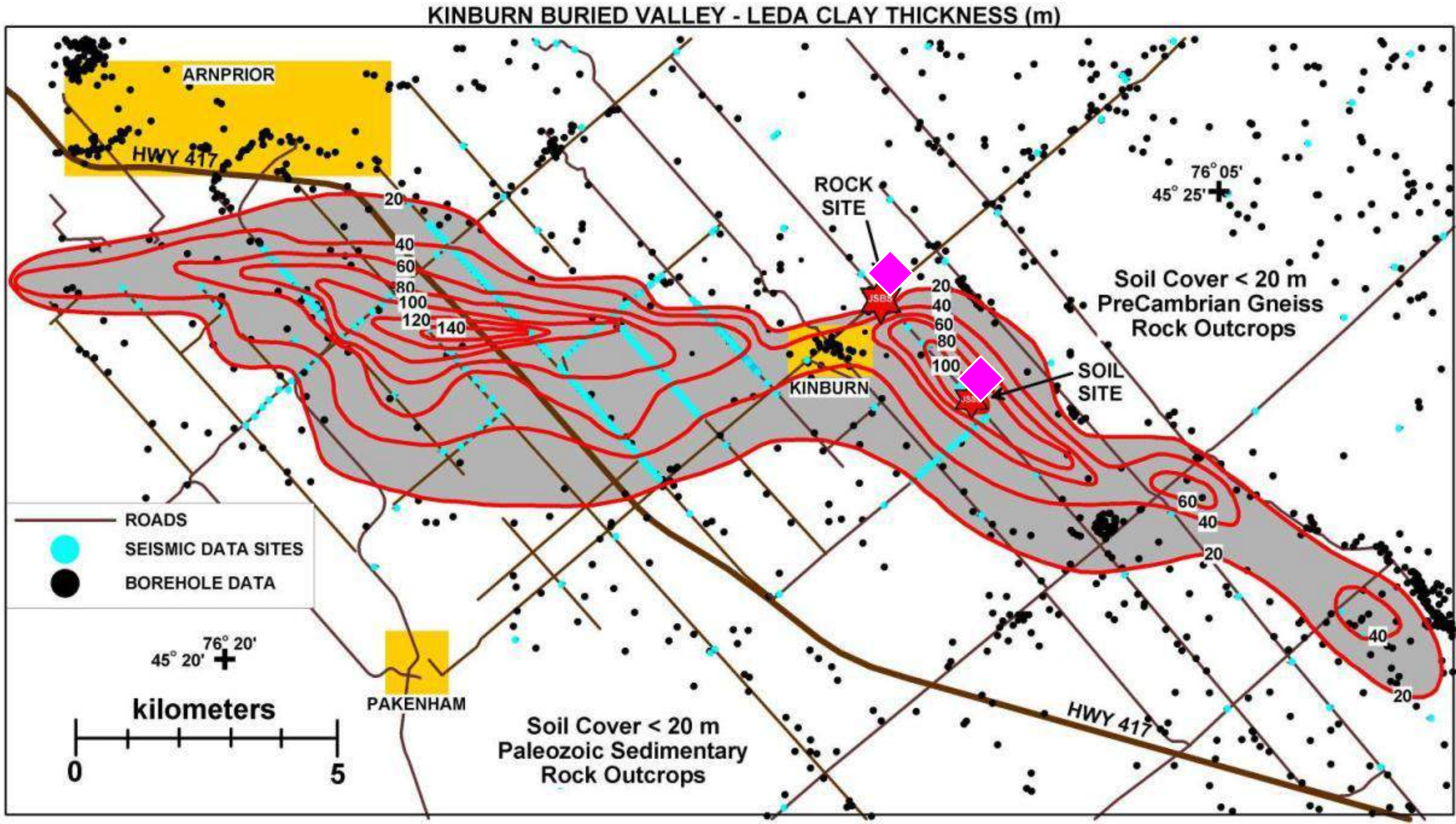
Kinburn Stations

- Made of several interconnected basins in a NW-SE direction;
- Approximately 5 by 20 km
- Depth ~140 m

- A few hundred HVSR measurements have been done this year
- **Many sites per day (Hunter)**

◆ Seismic stations

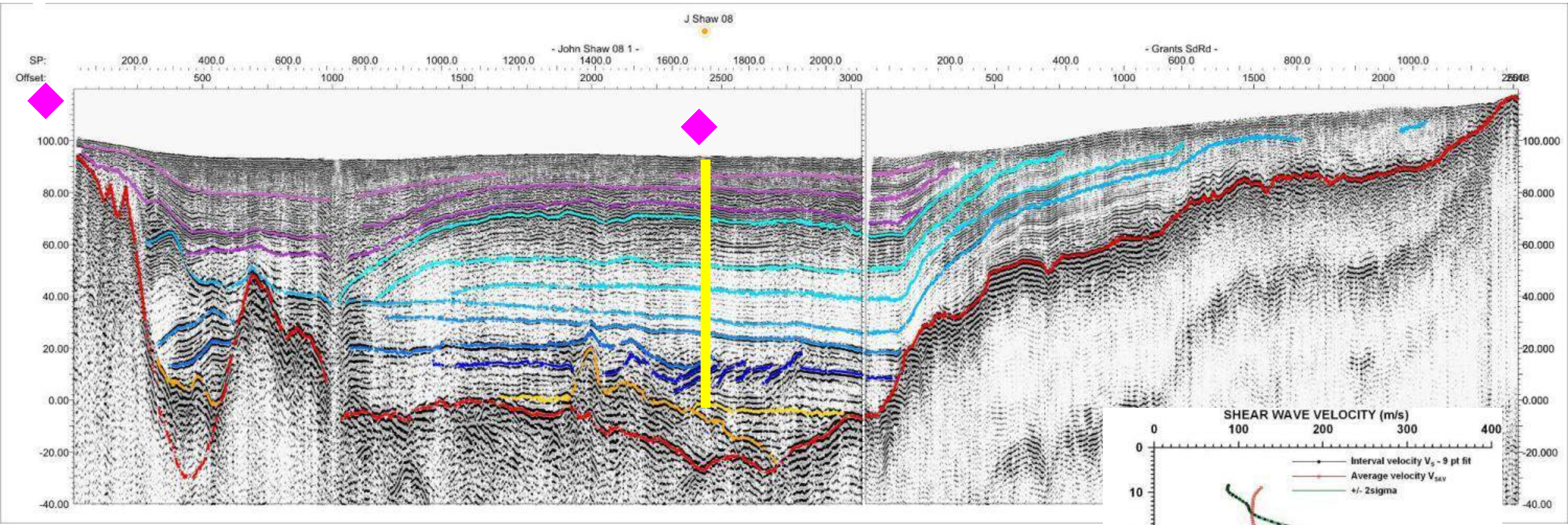
distance 2.12 km

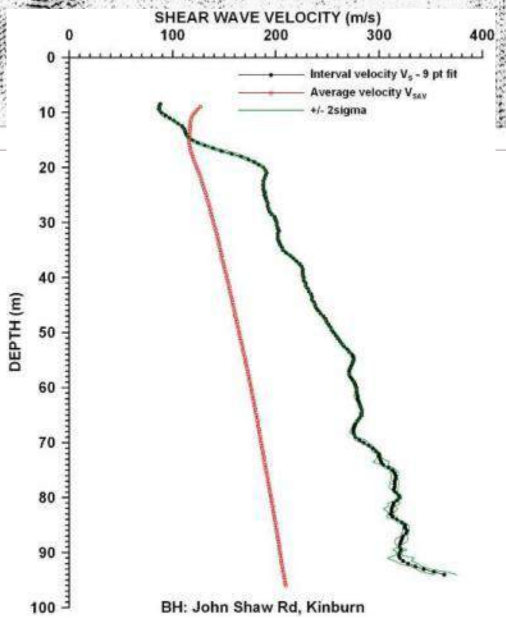


Kinburn Basin

Seismic station (rock)

Seismic station (soil)





- Bounded along NE side by fault
- SW side gentle slope
- No disturbed ground
- Non-sensitive clay
- Borehole logs indicate low Vs

Some Earthquake recordings by those broadband stations

Local and teleseismic

Weak motion

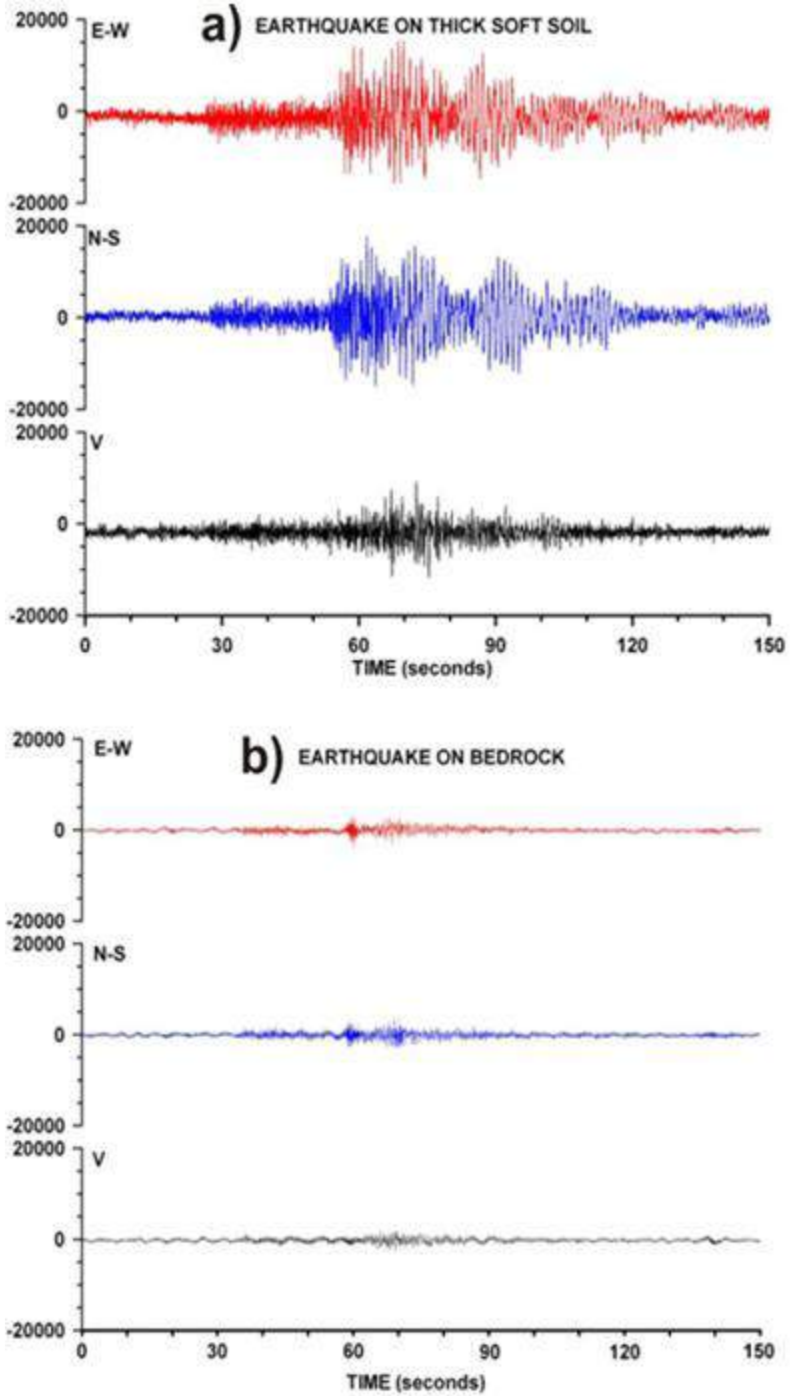
Just a few good ones!

- Cochrane earthquake on Dec. 7, 2006
- **M4.2**
- **R> 600 km ;**

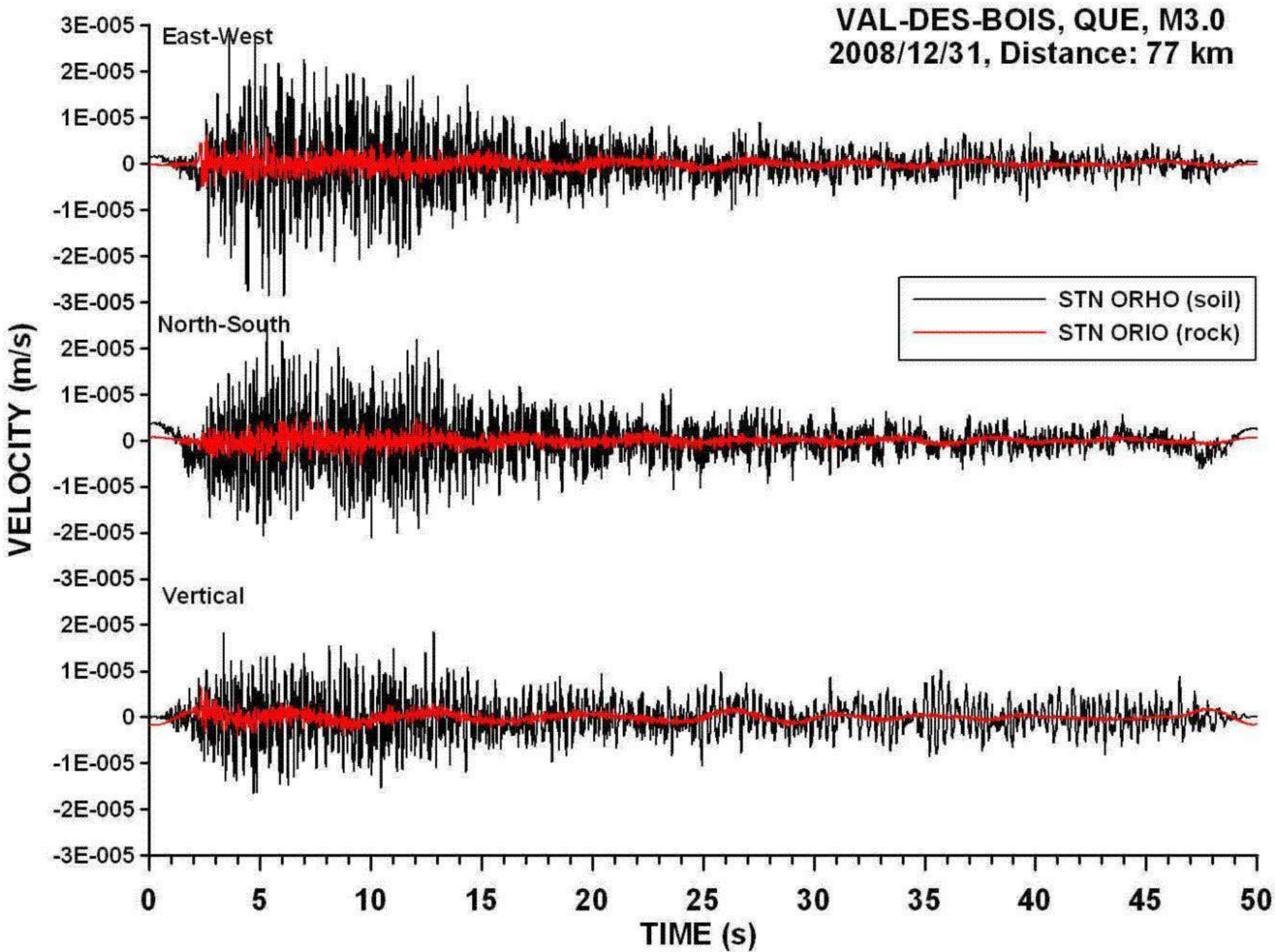
- Soil station

- Bedrock station

- Earthquake ground motion recorded on soil is much stronger than rock



a)

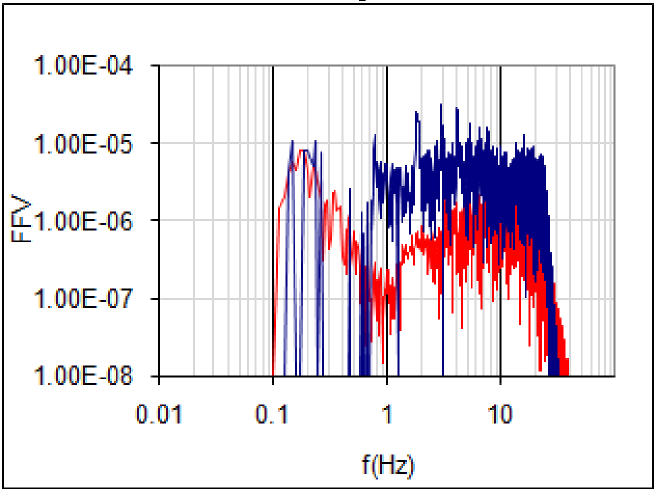


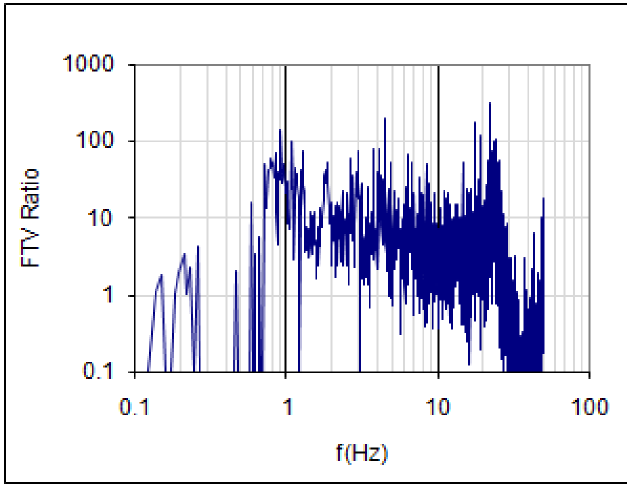
VAL-DES-BOIS, QUE, M3.0
2008/12/31, Distance: 77 km
East-West
North-South
Vertical
STN ORHO (soil)
STN ORIO (rock)
VELOCITY (m/s)
TIME (s)
3E-005
2E-005
1E-005
0
-1E-005
-2E-005
-3E-005
0
5
10
15
20
25
30
35
40
45
50

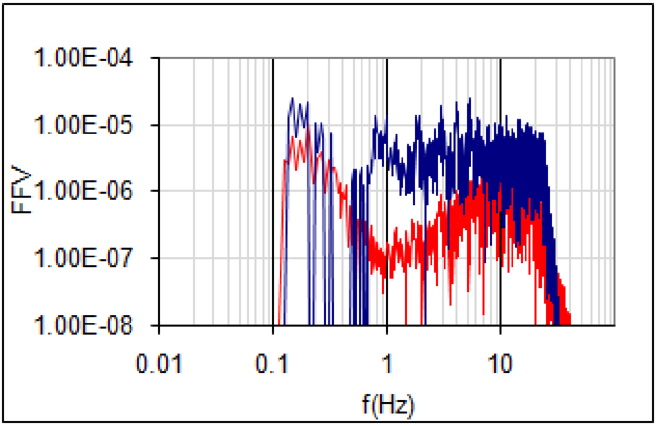
- Fourier spectrum

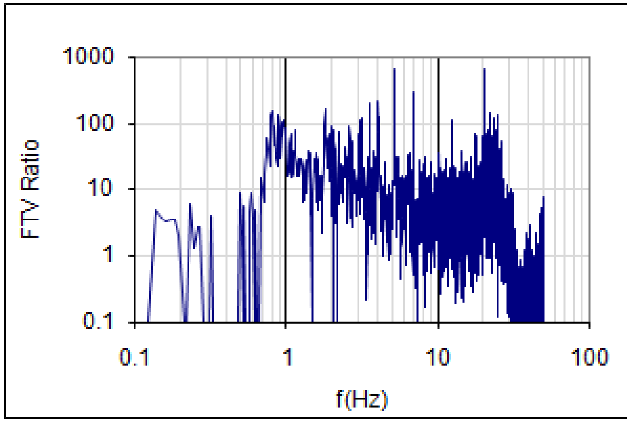
Amplification

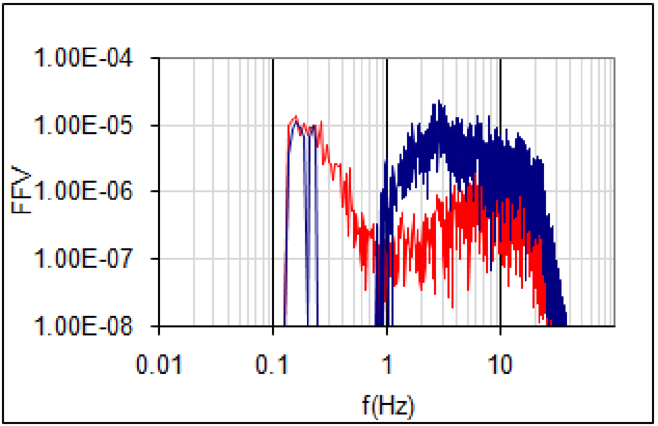
2008/12/31 06:54:48
73.45 46.14 2.9 MN

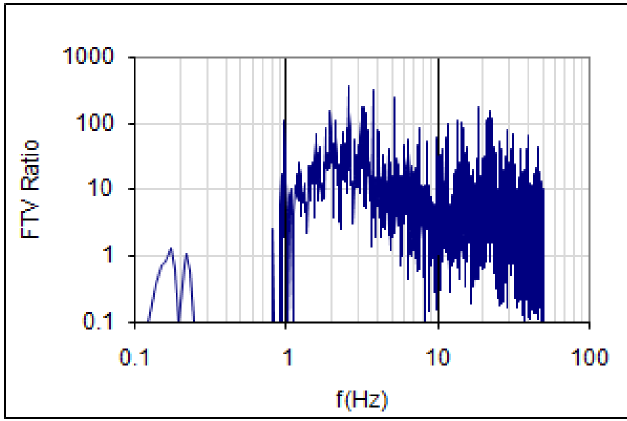




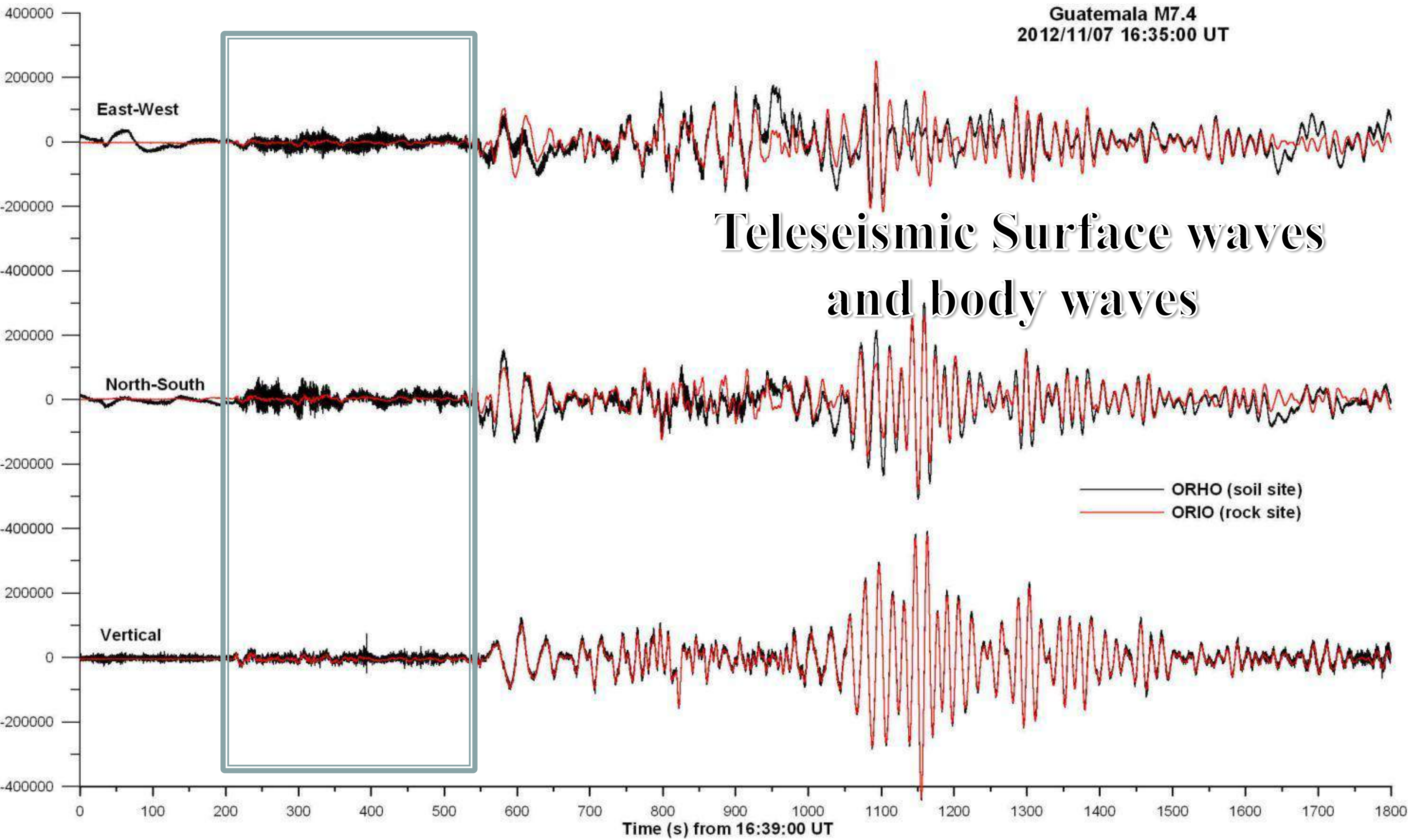




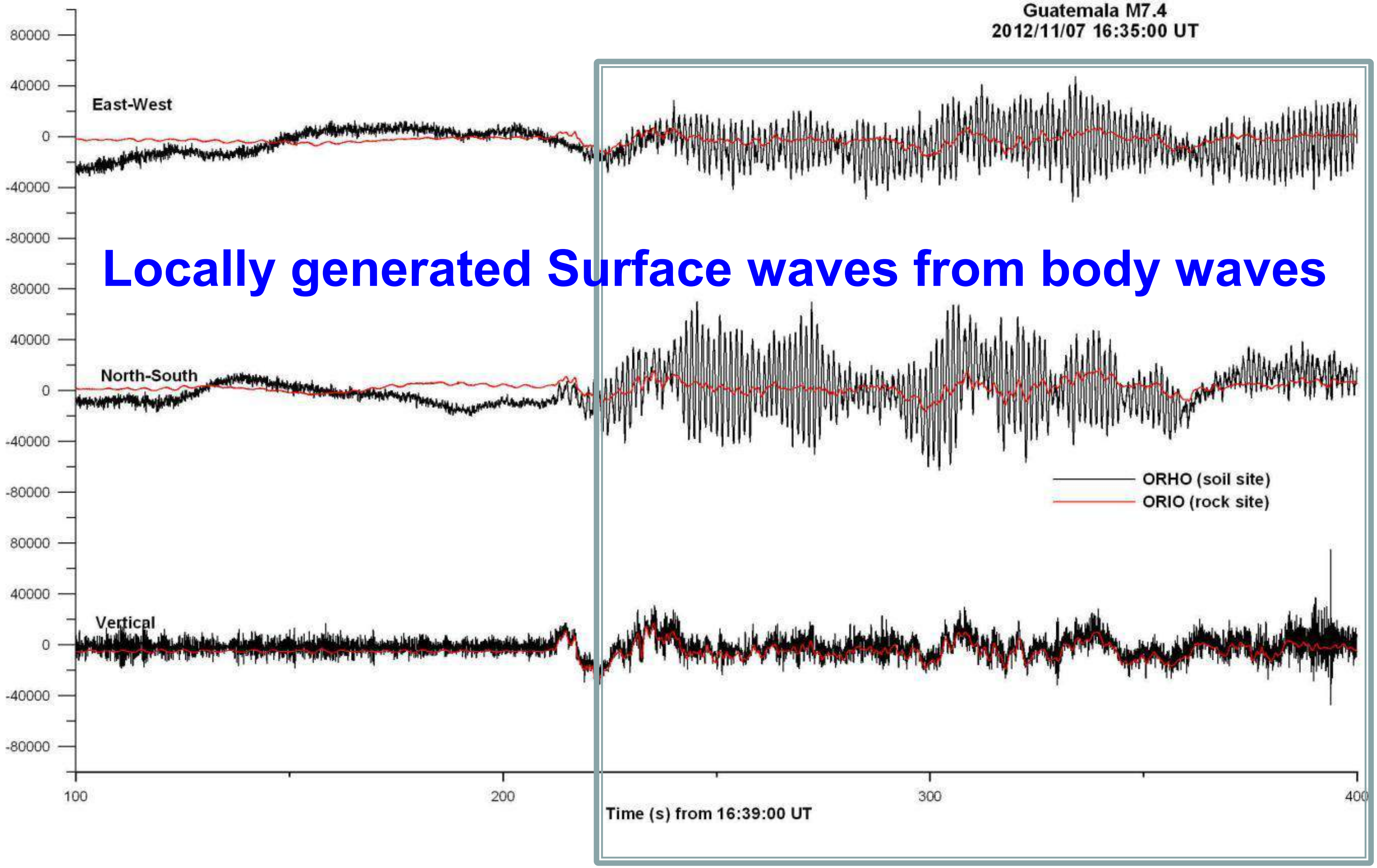




Guatemala, M7.4 , 2012,11,07
Orleans stations



Locally generated Surface waves from body waves

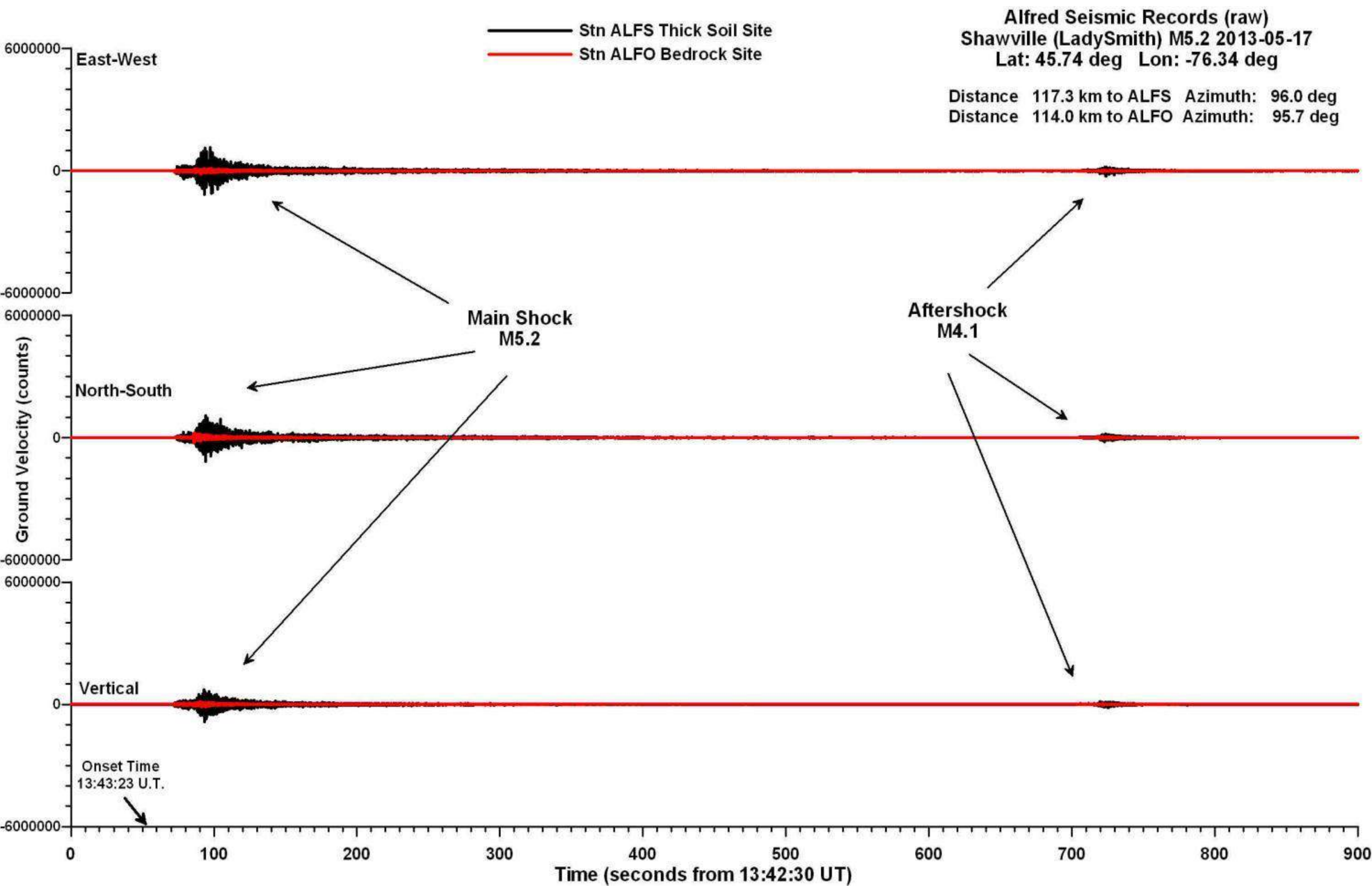


2013, 05, 17, M5.2, Shawville (Ladysmith)

Weak motion but recorded by strong motion sensors!

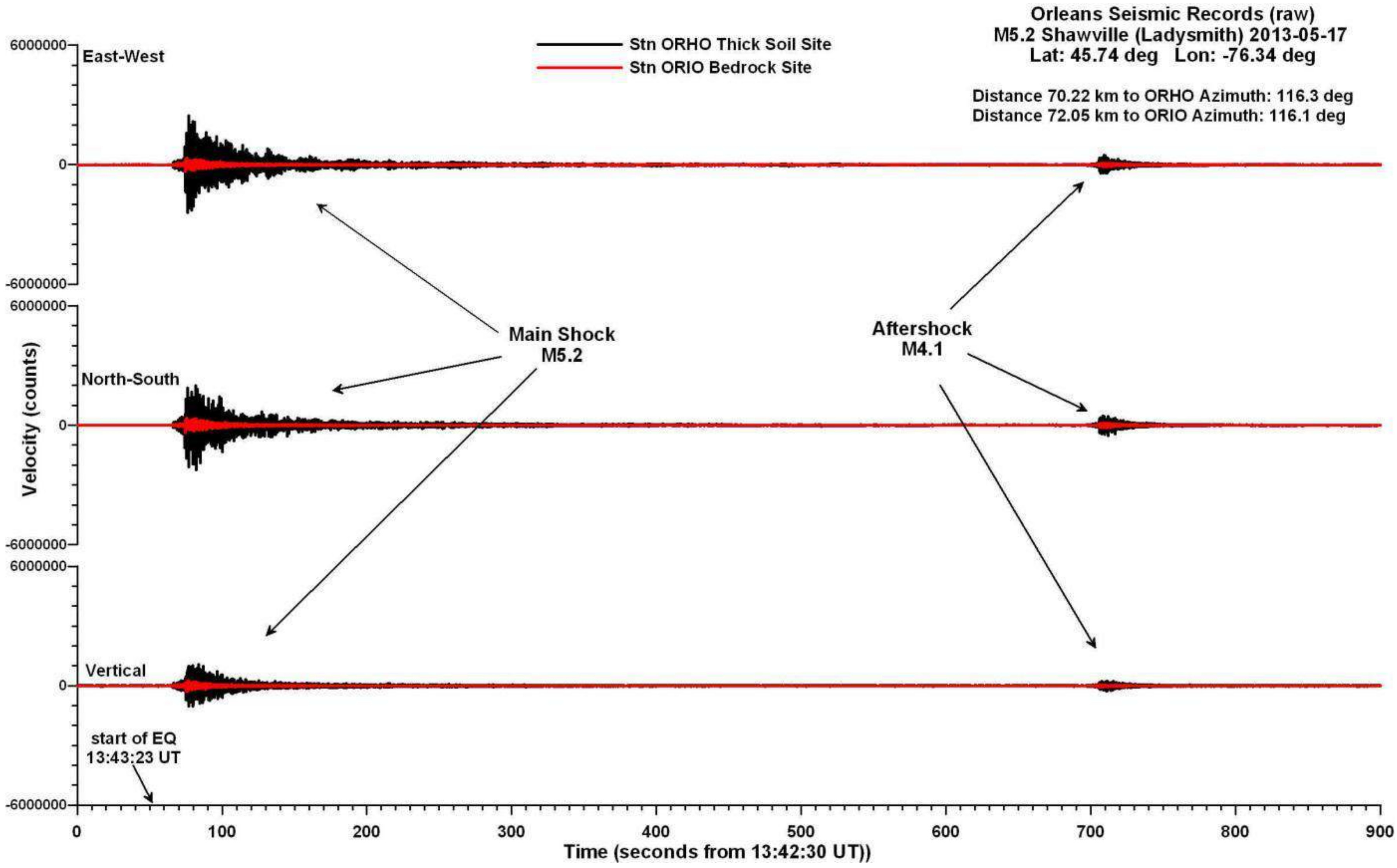
2013, 05, 17, M5.2, Shawville (Ladysmith)

Alfred Stations



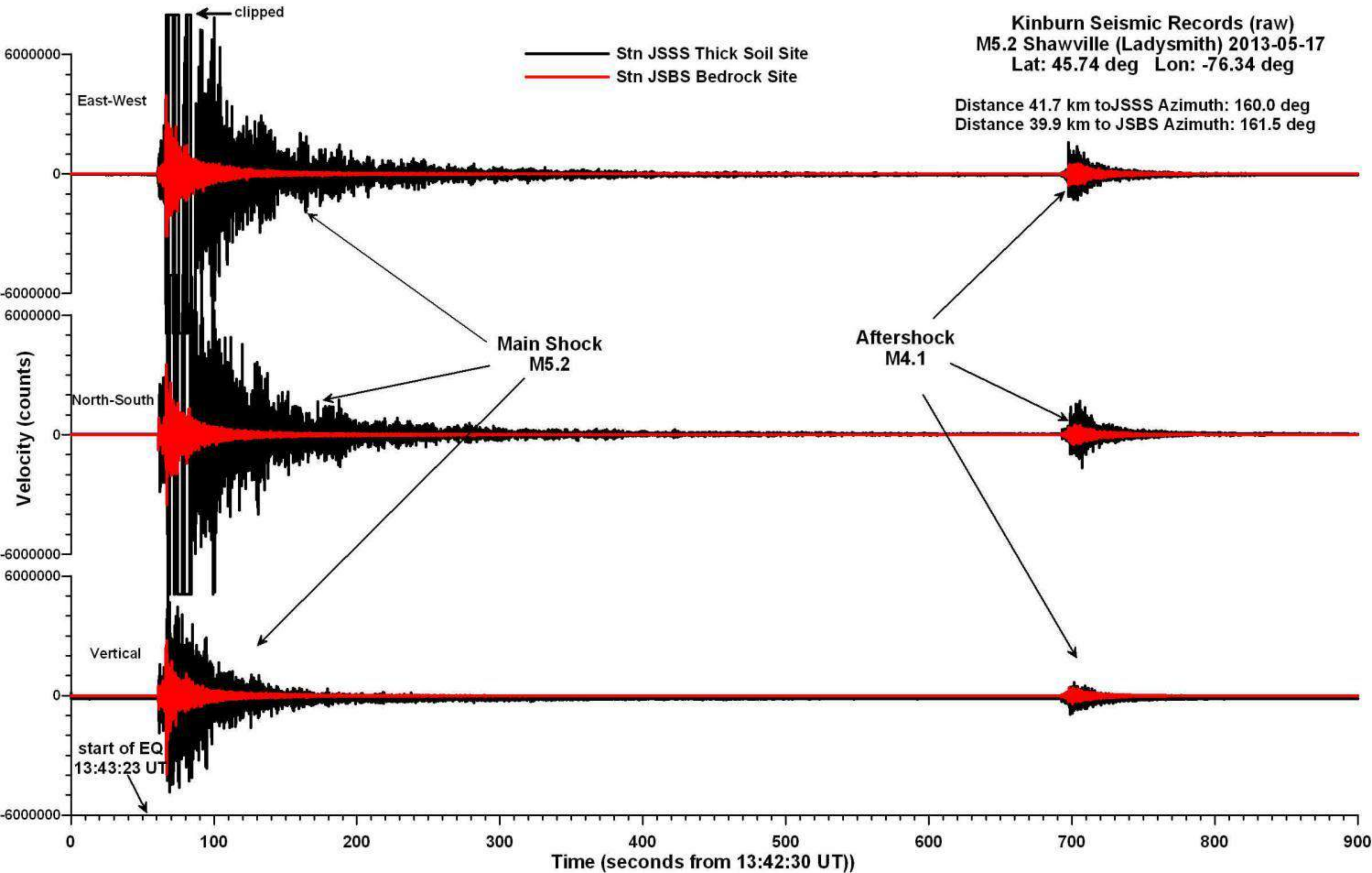
2013, 05, 17, M5.2, Shawville (Ladysmith)

Orleans Stations



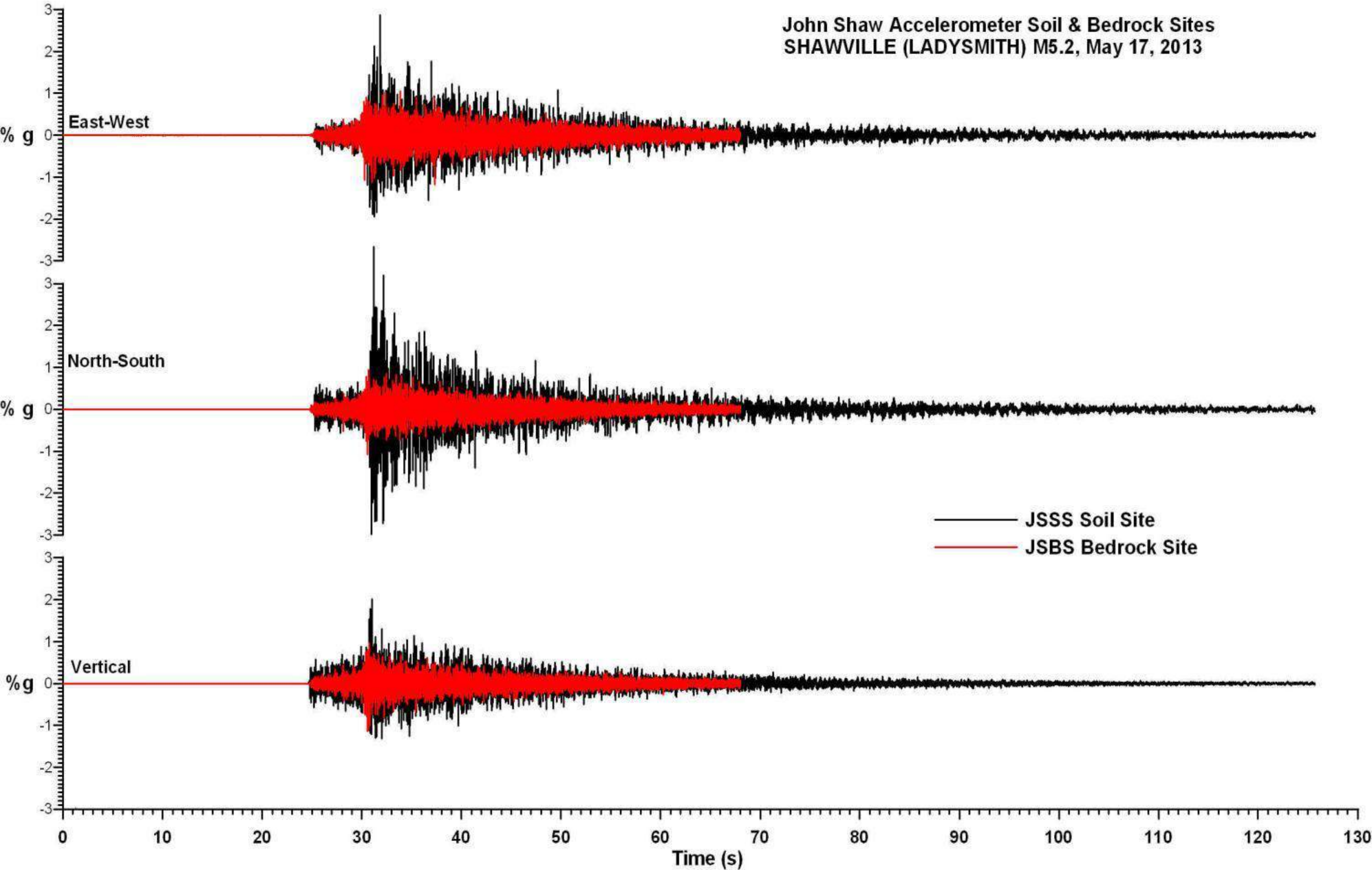
2013, 05, 17, M5.2, Shawville (Ladysmith)

Kinburn Stations



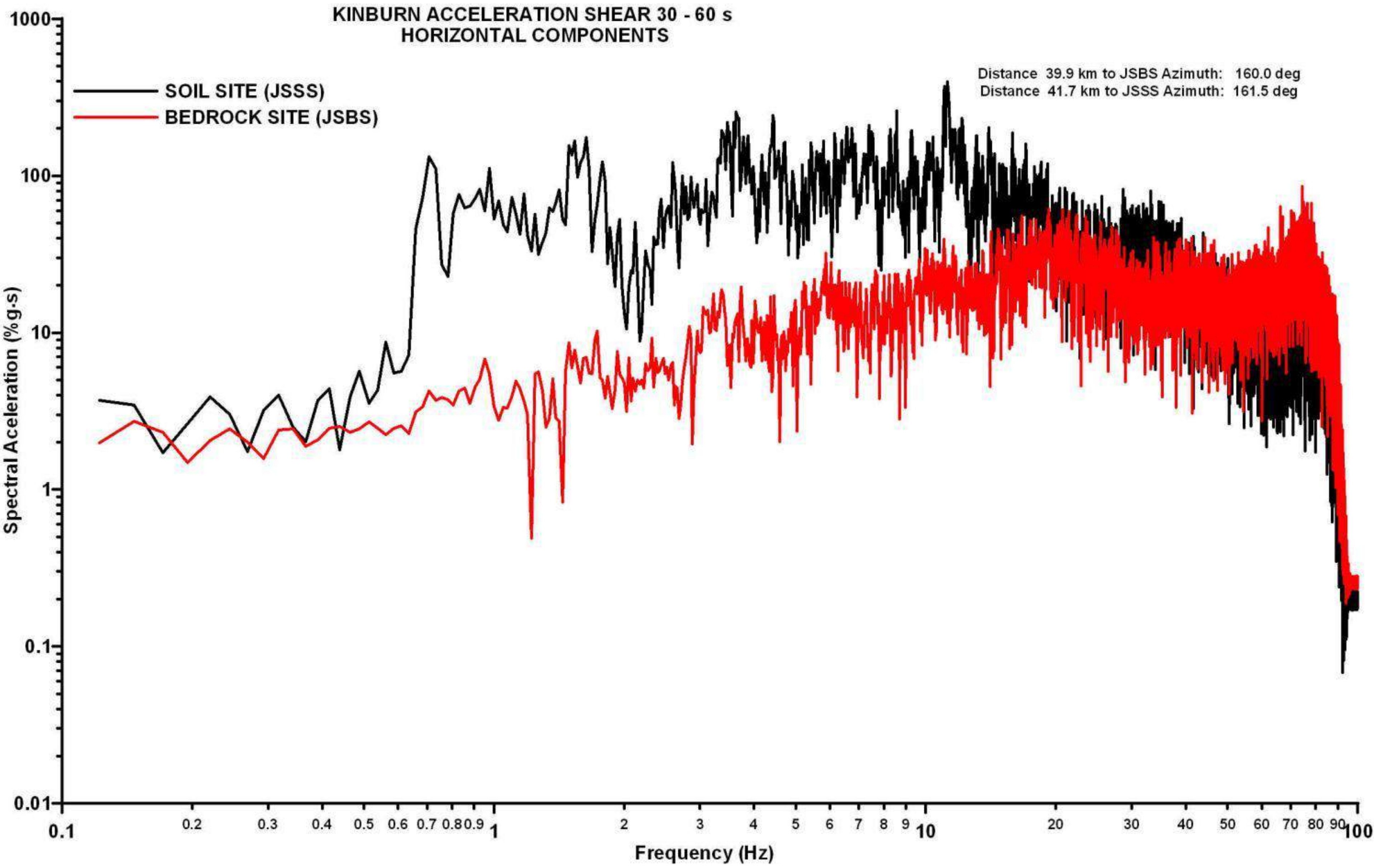
2013, 05, 17, M5.2 Shawville (Ladysmith)

Strong Motion



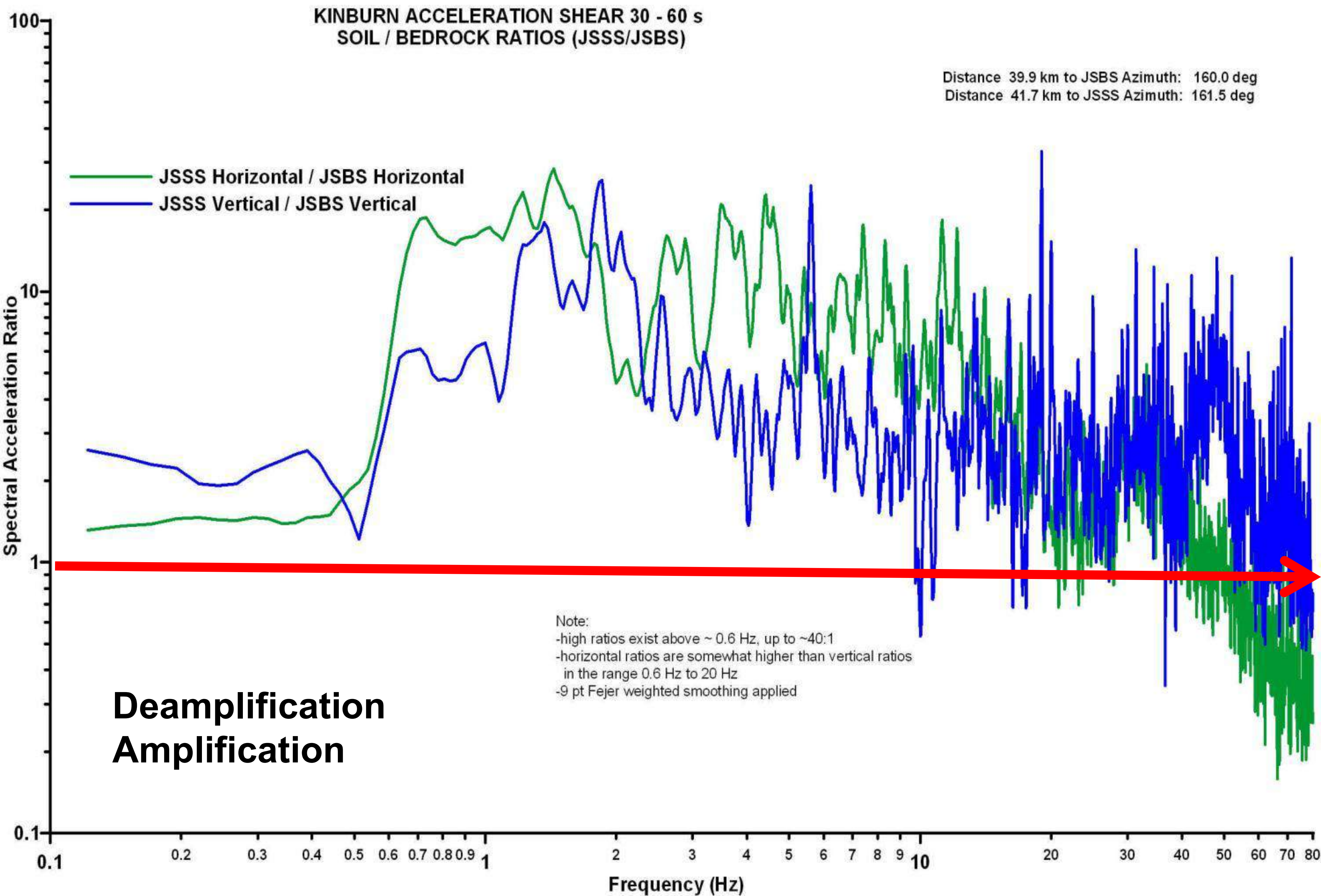
2013, 05, 17, M5.2, Shawville (Ladysmith)

Strong Motion, Horizontal component



2013, 05, 17, M5.2 Shawville (Ladysmith)

Strong Motion, ratio



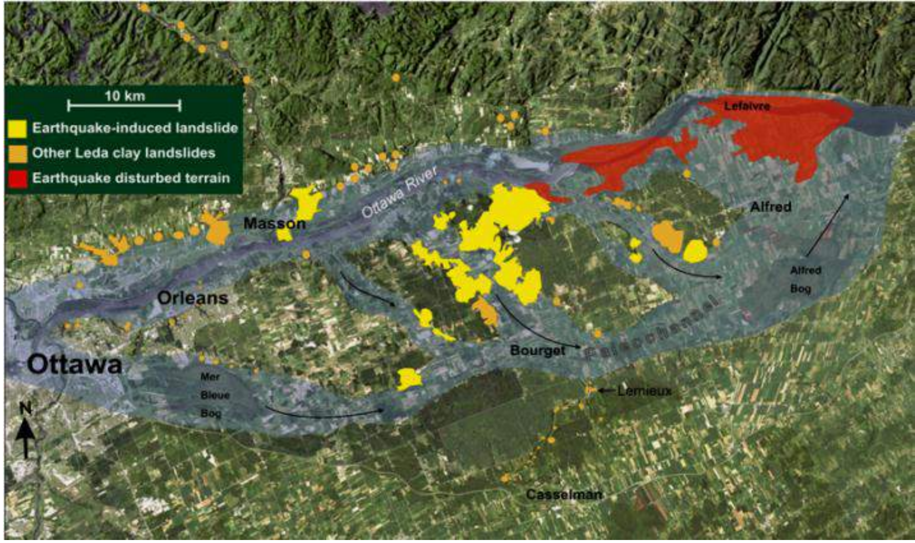
VAL-DES-BOIS June 23rd ,2010, M5; GSC recordings

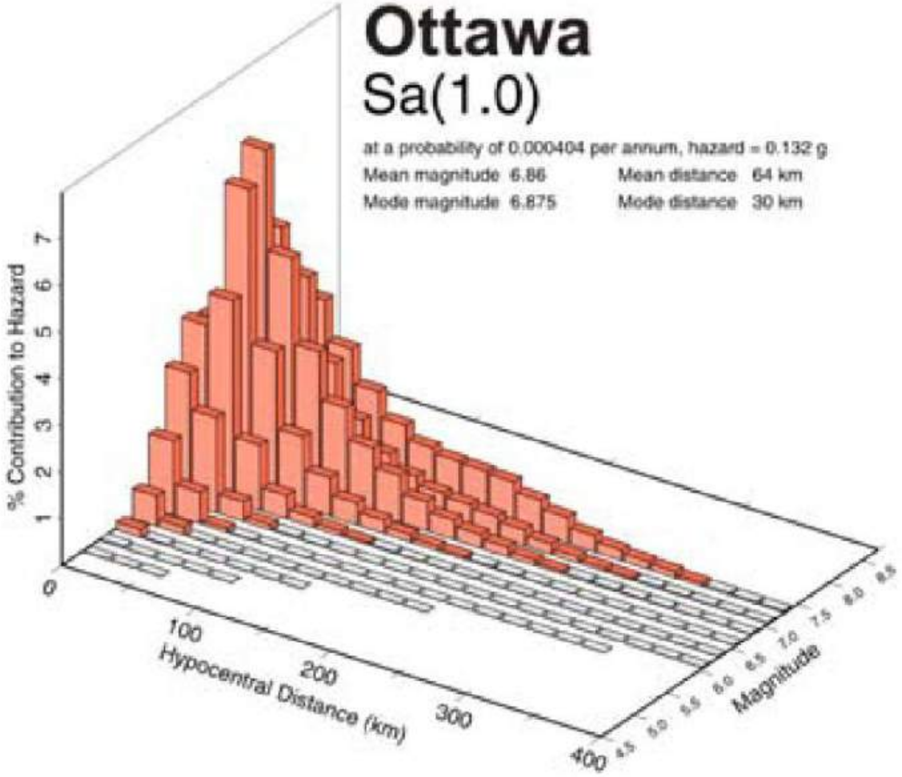
- PGA (B/A)
  - **VAL-DES-BOIS ~2**
  - NBCC~1.1
- PGA (C/A)
  - **VAL-DES-BOIS ~2-3**
  - NBCC~2
- A (D/A)
  - **VAL-DES-BOIS 1-3**
  - NBCC~4
- **Sparse Data**
- **Not enough!**

Site class	Values of F_a				
	S_a (1.0) ≤ 0.1 g	S_a (1.0) = 0.2 g	S_a (1.0) = 0.3 g	S_a (1.0) = 0.4 g	S_a (1.0) = 0.5 g
A	0.5	0.5	0.5	0.6	0.6
B	0.6	0.7	0.7	0.8	0.8
C	1.0	1.0	1.0	1.0	1.0
D	1.4	1.3	1.2	1.1	1.0
E	2.1	2.0	1.9	1.7	1.7
F	Site specific investigation required				

PGA (g)			Soil Class (NEHRP classification)
N-S component	V component	E-W component	
0.033	0.024	0.032	A
0.036	0.024	0.049	A
0.042	0.065	0.089	C
0.062	0.070	0.061	E
0.048	0.053	0.067	D
0.049	0.064	0.061	B
0.041	0.032	0.061	B
0.059	0.041	0.060	C
0.033	0.025	0.032	A
0.009	0.009	0.007	D
0.008	0.004	0.004	D
0.005	0.003	0.004	D
0.003	0.003	0.003	D

- Those are small earthquakes
- However, **paleoseismology** of the Ottawa area suggests that **two large earthquakes** occurred in Ottawa region (GSC, Jan Aylsworth)
  - **4550 B.P. Event**; Evidence of several very large landslides covering areas much larger than any landslides in recent history
  - **7060 B.P Event;** Three large areas with severely disturbed sediments
- **Seismic hazard** deaggregation for city of Ottawa
  - M6, M7
- **The return period is a few thousands years!**





- **Two Questions**

- **Development of Regional Site Amplification Models for Eastern Canada**
- The soil amplification factors are based on the analysis results of records mainly form Loma Prieta earthquake, 1989.
    - $F_a = (1050/ Vs_{30})^a$
    - $F_v = (1050/ Vs_{30})^b$

- Note : **1050** (in m/sec) is the average shear wave velocity for bedrock **(Franciscan bedrock in California).**

- Eastern Canada
    - ➢ A very high **Vs contrast close to 20**
    - ➢ Very loose soil (**150 m/s**)
        - At the low level of shaking
            - Leda Clay behaves **linearly (elastic)**
            - **Basin effetcs**
        - At the **higher level of shaking** soil behaviour is **nonlinear (anelastic)**

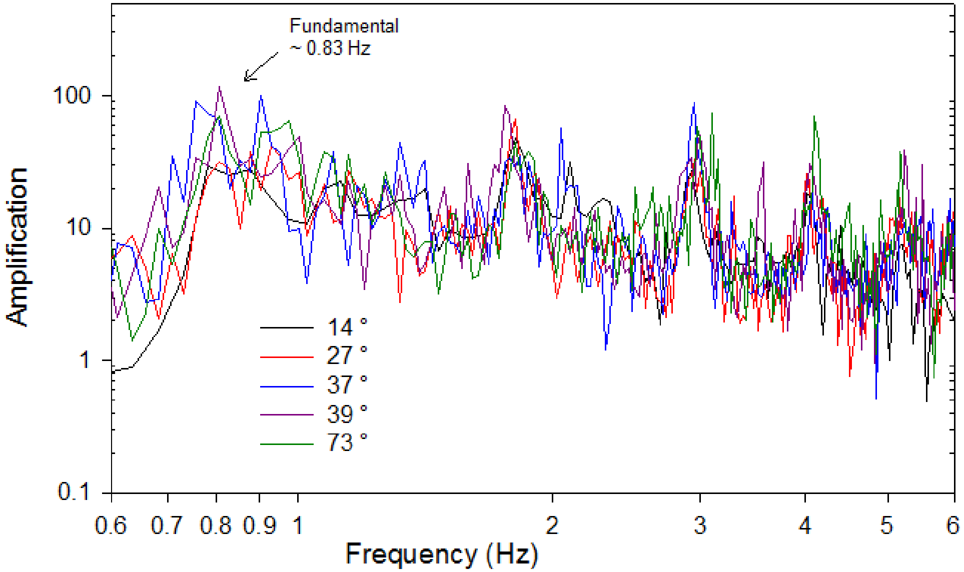
- **NBCC 2005 Site amplification factors**

Site class	Values of F_a				
	$S_a(1.0) \le$ 0.1 g	$S_a(1.0) =$ 0.2 g	$S_a(1.0) =$ 0.3 g	$S_a(1.0) =$ 0.4 g	$S_a(1.0) =$ 0.5 g
A	0.5	0.5	0.5	0.6	0.6
B	0.6	0.7	0.7	0.8	0.8
C	1.0	1.0	1.0	1.0	1.0
D	1.4	1.3	1.2	1.1	1.0
E	2.1	2.0	1.9	1.7	1.7
F	Site specific investigation required				

- **Spectrum on soil/ Spectrum on rock**
  - ➢ fundamental frequency ~0.8Hz
  - ➢ higher harmonics
- **Unusual** soil amplification factors for weak motions

- **These are weak motions!!**
- Need to consider
  - ➢ **soil damping**
  - ➢ **Vs contrast ~ 20**

- But Strong motion recordings in Ottawa are sparse!



- **Measuring damping of Leda clay for soil modeling**

Weak ground motions

1. **Small strain soil-to-bedrock amplification Ottawa (This year research activity)**
2. Comparison: seismic data with 1-D engineering
3. FEM and Shake models calibrated for Leda clay

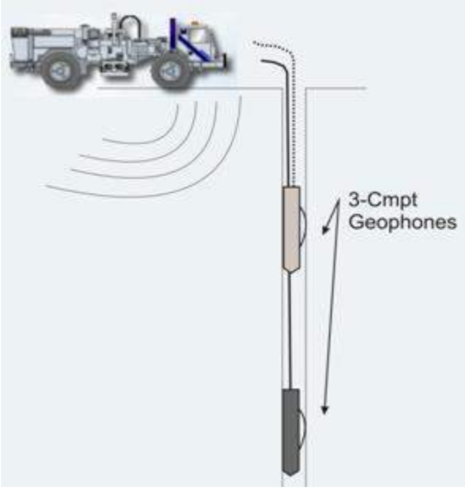
Strong ground motions

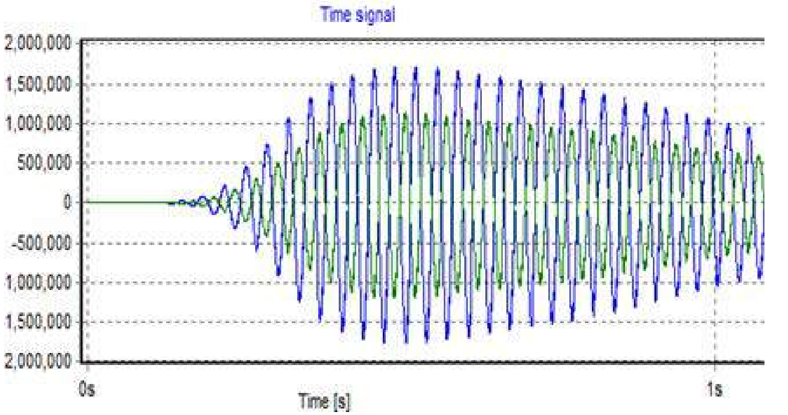
1. Application of (FEM and Shake) to Leda clay profiles
2. Production of time series using EXSIM for large earthquakes
3. Dynamic response for Leda clay deposits
4. Parametric study of site amplification (Fa-Fv)
5. Practical recommendations

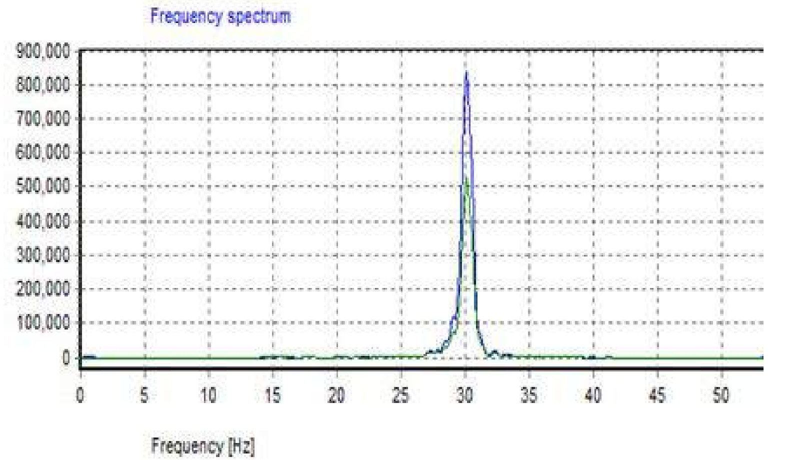
- **To address the damping !**
- **Measuring Q, or Soil Damping, In Situ**
- **Spectral Ratio Method for Mono-frequency Source Approach:**
  - 10Hz, 15 Hz, 20 Hz...120 Hz
- Example 30 Hz Vibe Input
- It is recorded by **two geophones** at different depths
- Some spectral analysis
  - the peak of spectrum recorded by upper geophone
  - the peak of spectrum recorded by lower geophone
  - The difference leads you to the Quality factor of soil between two geophones

- **Field tests indicate low damping levels of shear body waves in soft soils at low strains**

- Monofrequency tests indicate Q and Vs do not vary significantly with frequency in 10-100Hz range

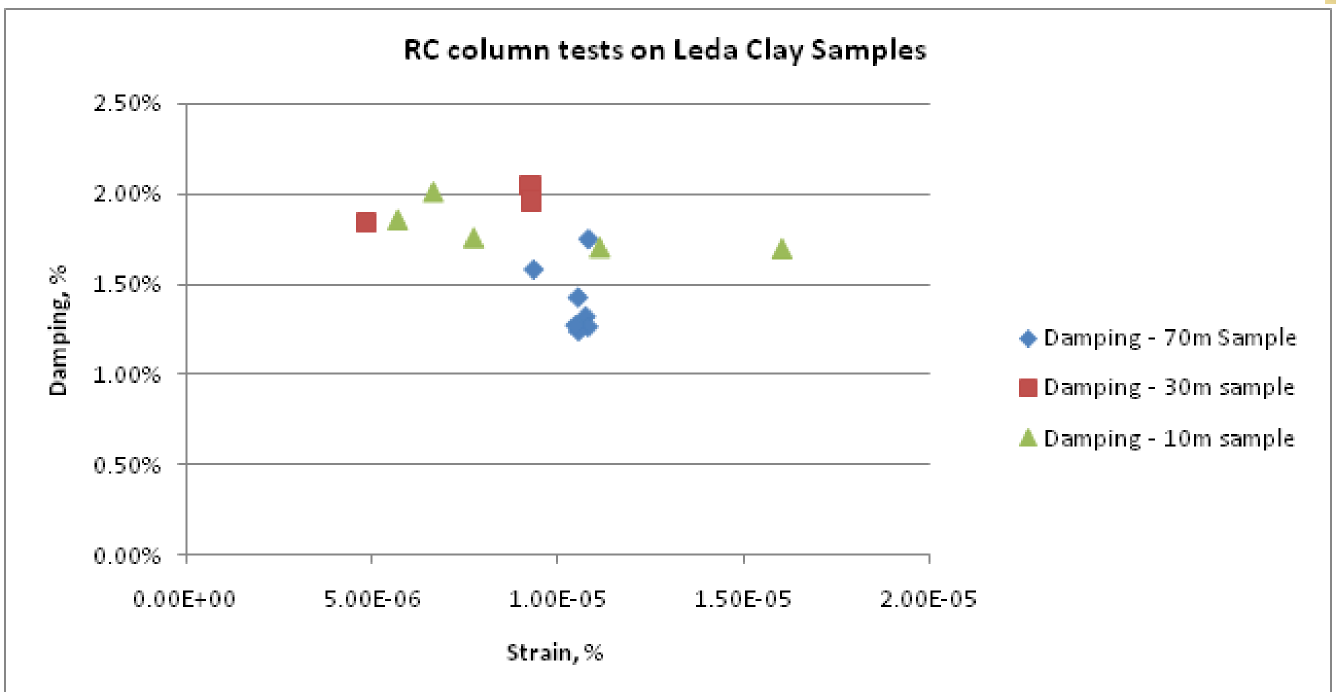







FRAGILE
FRAGILE

- **Lab tests**
- In collaboration with U Waterloo, Civil Eng
- Resonant Column Testing
- Prelim results
  - Integrity of lab samples imperative – but results do indicate low damping



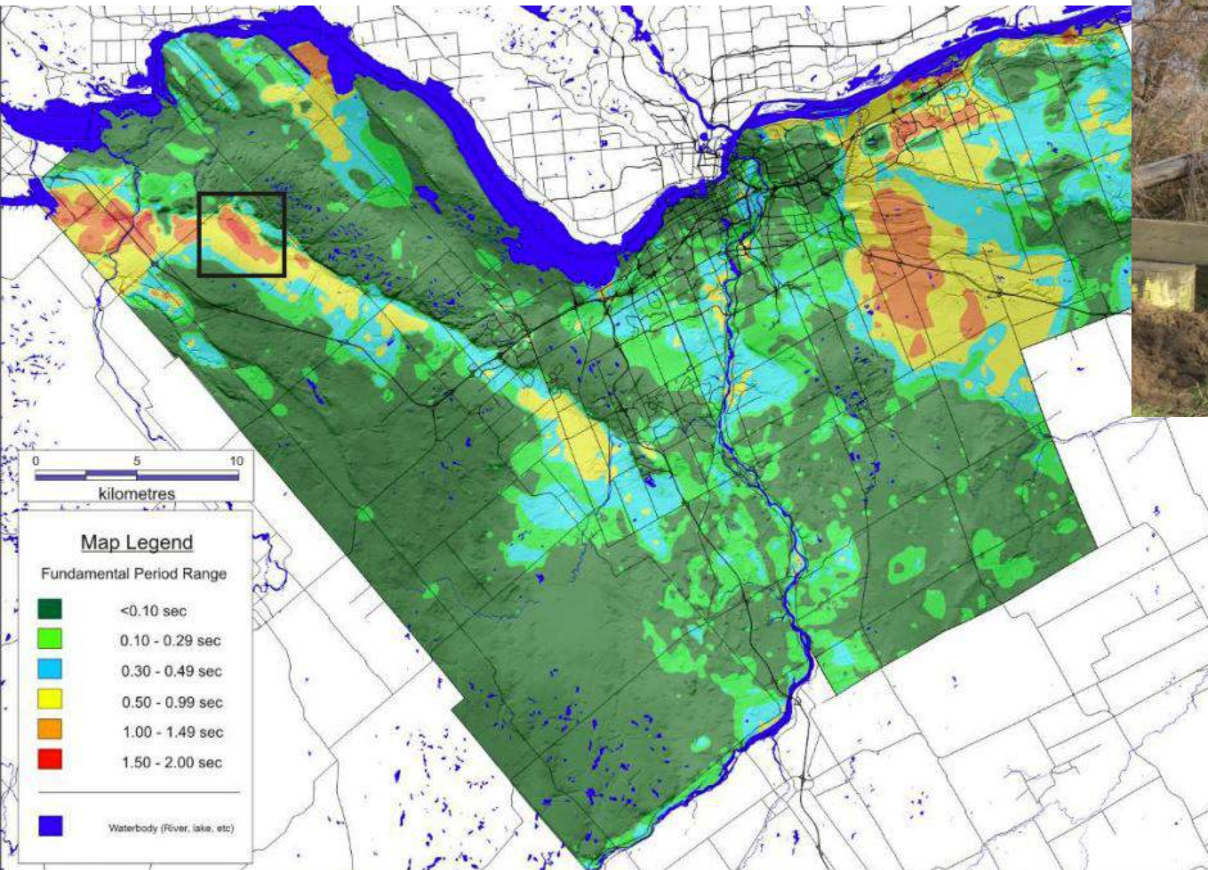
- We also need to measure and **understand the basin effect as well**

- first for the **weak motion**
- then the **strong motion**!

- We have been working on the **installation of a small array** to observe and model the basin effects

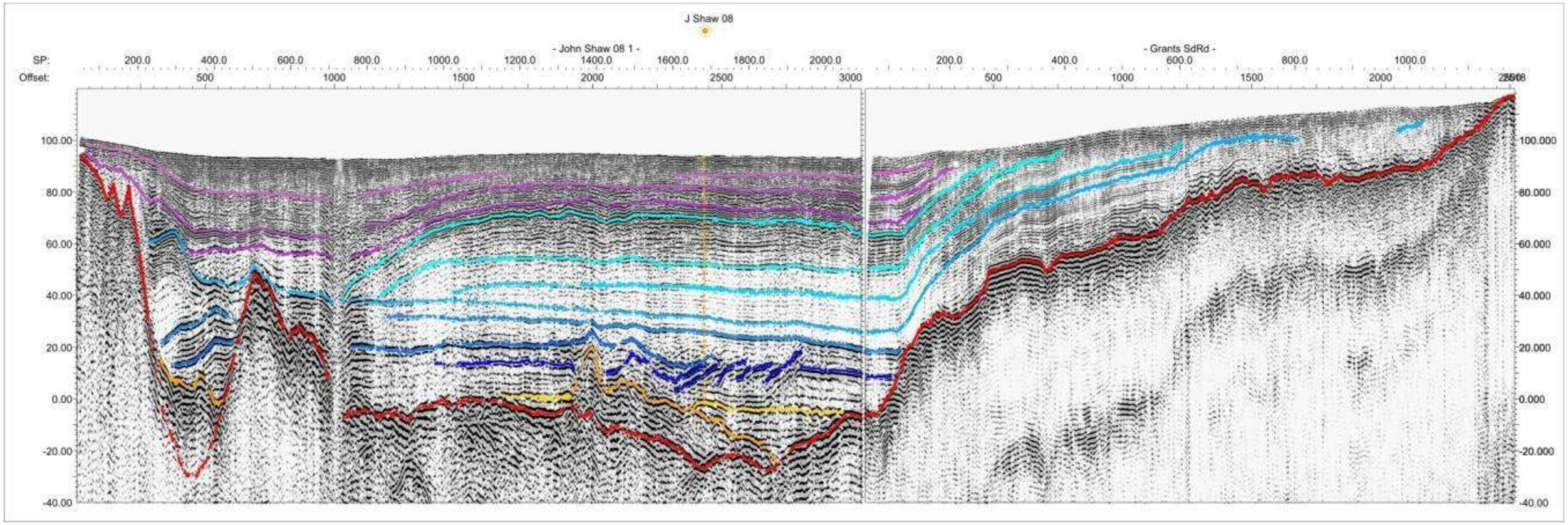
A new Seismic Array!

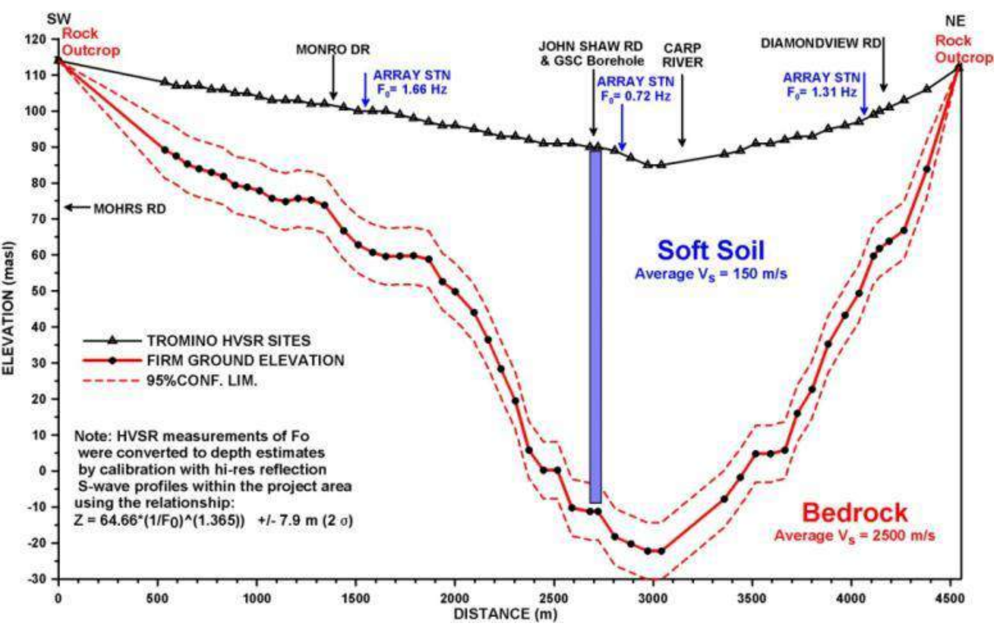
- We installed (September-December 2013) six broadband seismic station in Kinburn Area, which is a well-studied basin in Ottawa area
- All data archived at GSC



- Kinburn Array
- What are we doing?
  - **Measuring soil depth in the basin**
    - ~900 City of Ottawa water wells
    - 286 HVSR measurements
    - 2 High resolution Landstreamer sections
      - Along John Shaw Rd. And Grants Side Rd.
    - 1 Geological Survey of Canada logged borehole
  - **Creating a model** based on these measurements
  - Using this model to **simulate the response**
  - Comparing simulations to recordings from array
  - *Students*
    - M.Sc.; Sylvia Hayek (MSc , observation and interpretations)
    - Ph.D., Steve Crane (3-D basin modeling; Linear)
    - Ph.D., Amin Esmaielzadeh (3-D basin modeling; nonlinear!)
    - Undergrad

Soil Depth Cross Sections

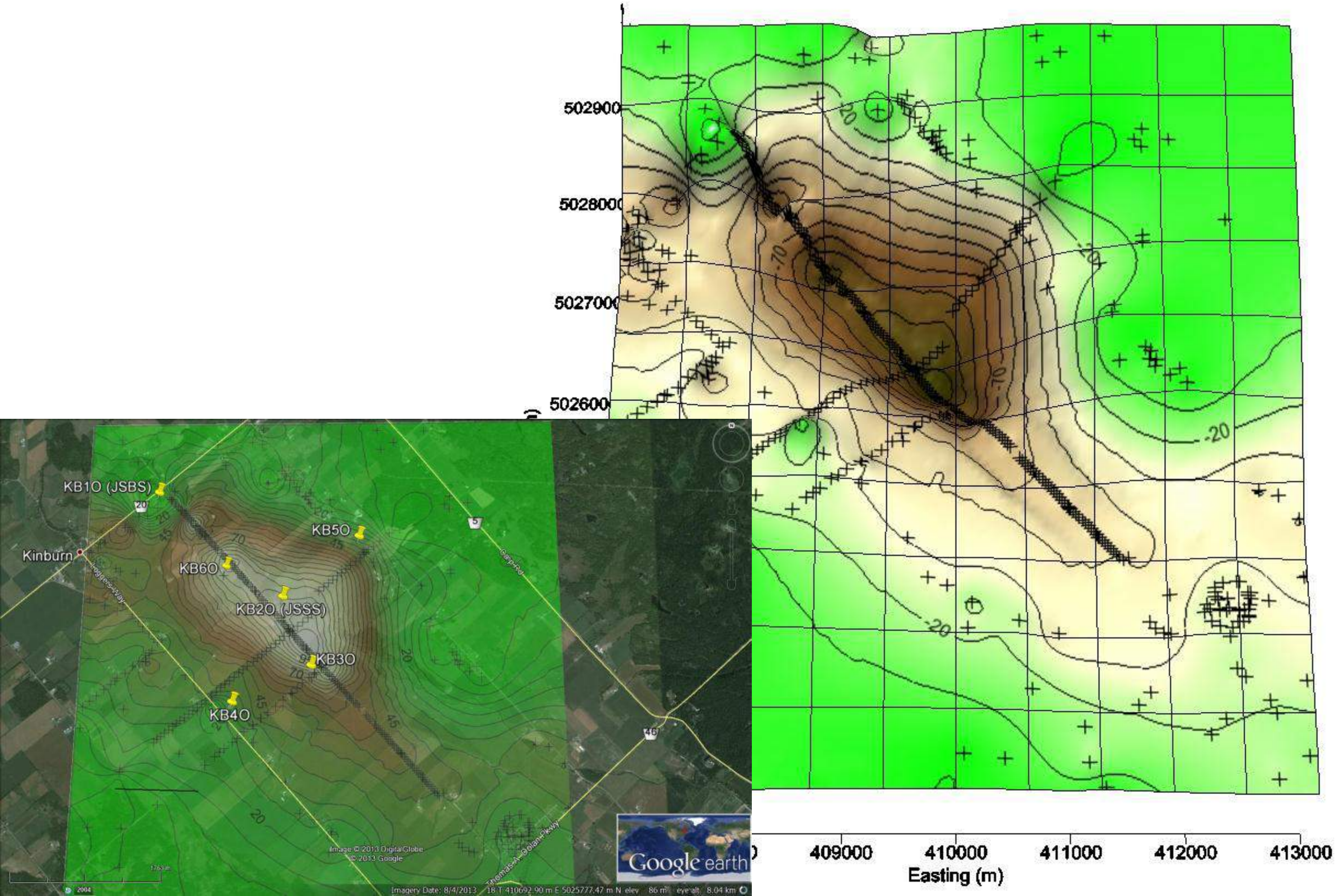




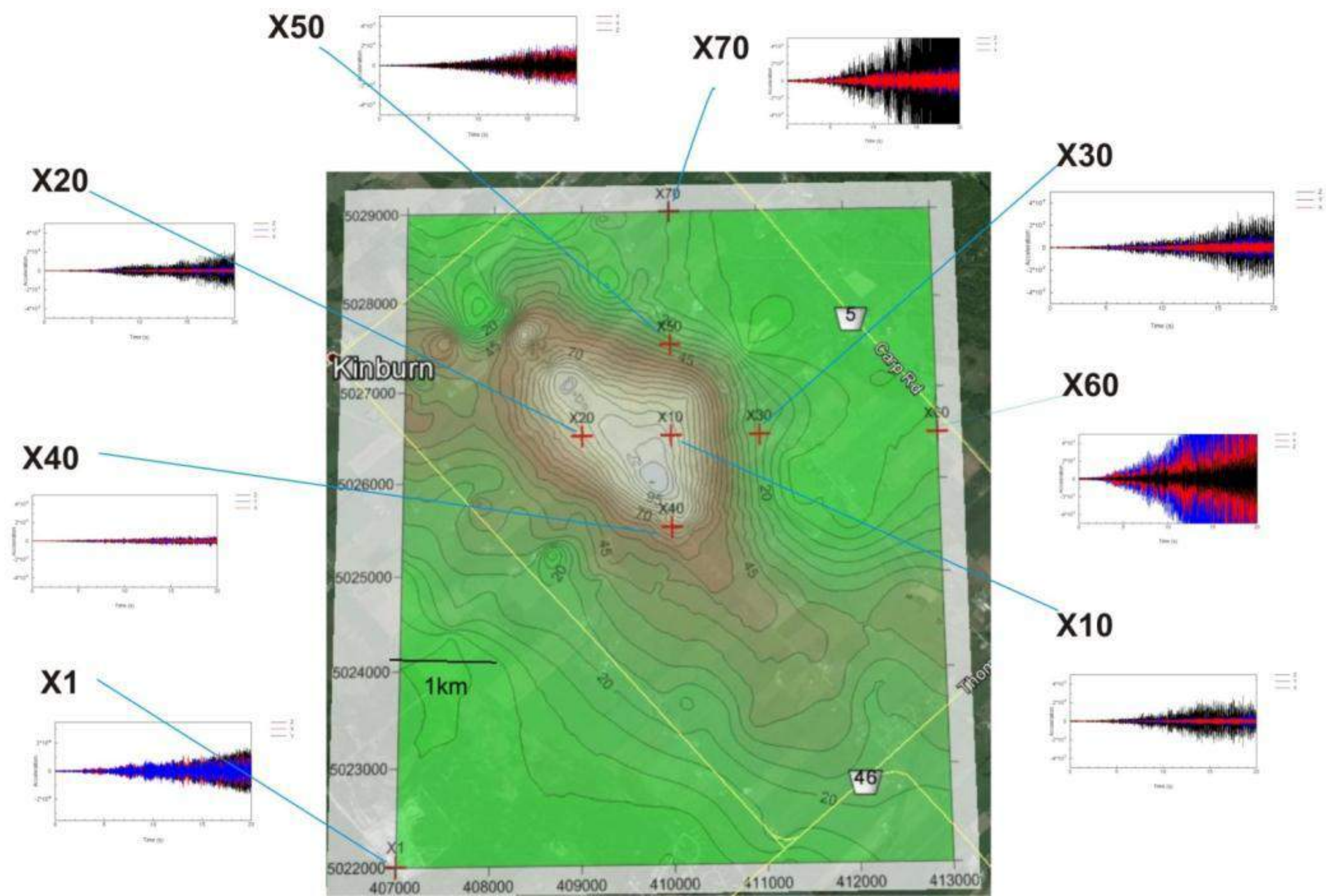
Above: John Shaw Rd. North-West to South-East then Grants Side Rd. North-East to South-West Landstreamer sections

Left: Mohrs Rd. To Diamondview Rd. South-West to North-East section

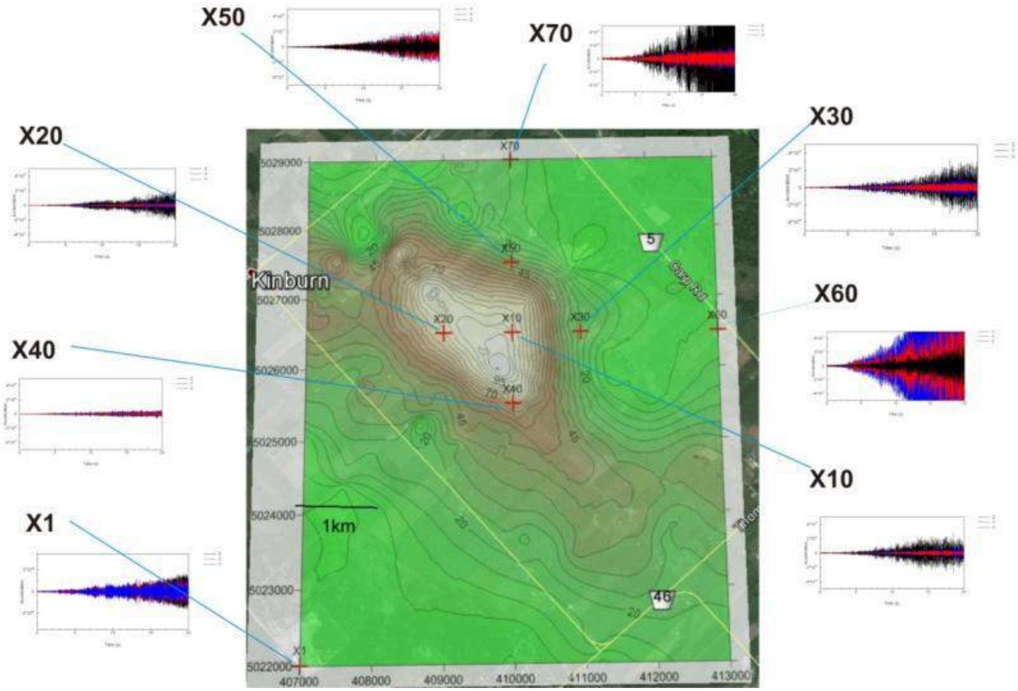
Kinburn Basin Model

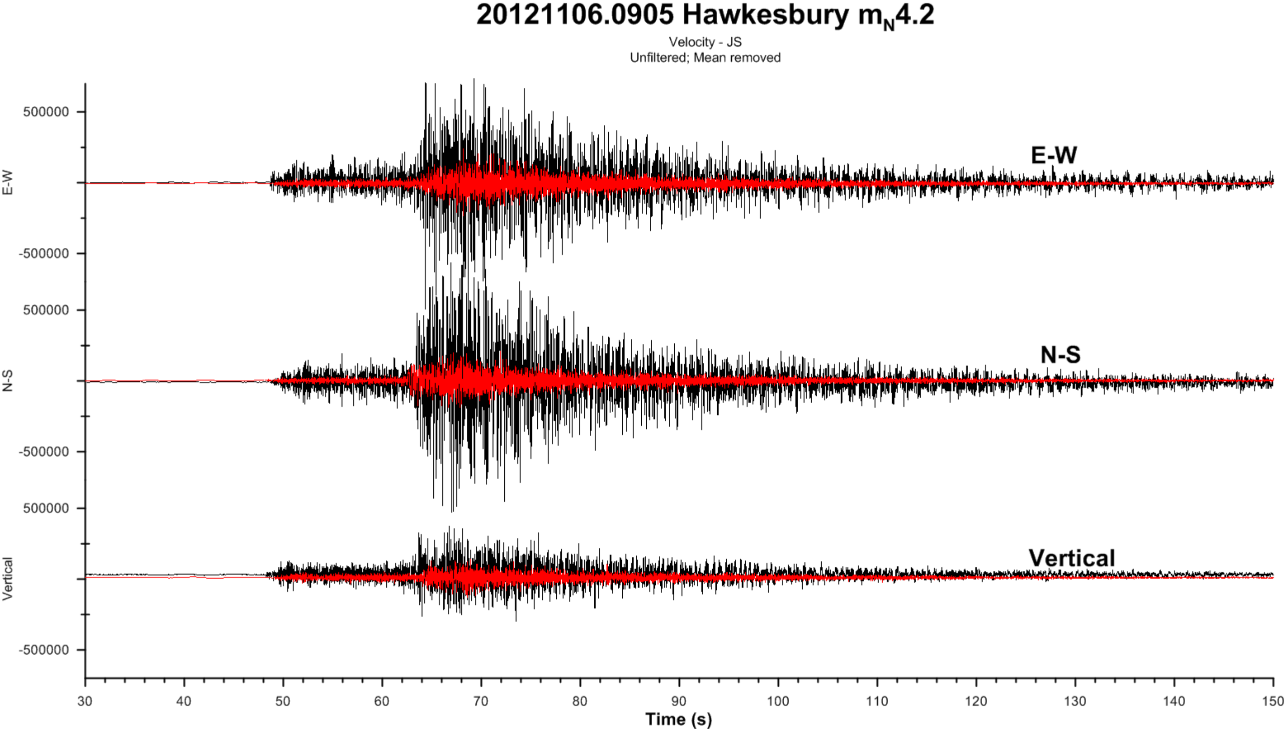


- Numerical Modelling of Seismic Response in a Soft Soil Basin: Kinburn, Ontario.
- Two months on super computers with 1024 cores(Thanks to Compute Canada).
- **Just the beginning !**
- It is an ongoing process



Recorded Seismic Response

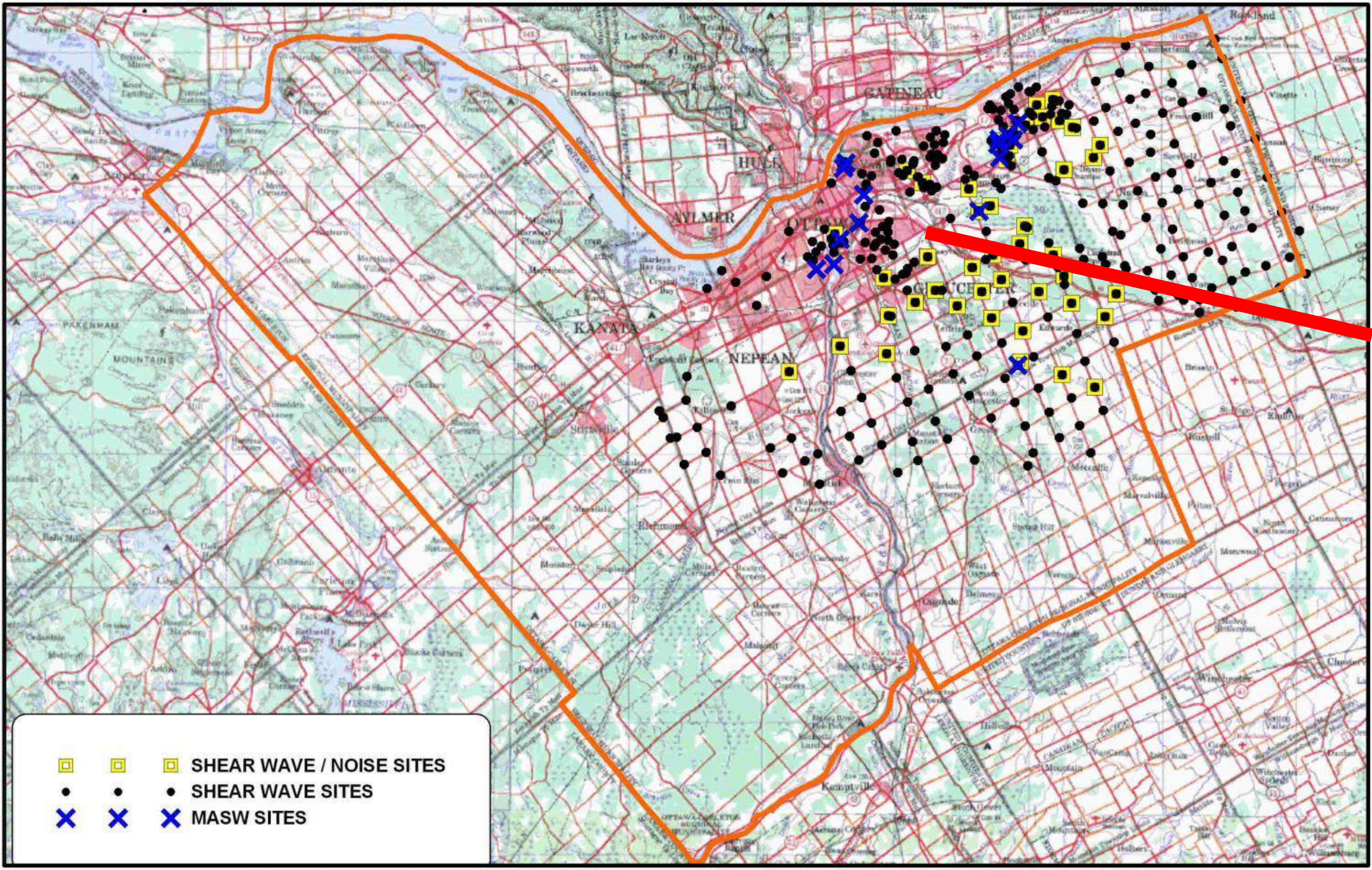




- Desperate for strong motion data!
  - **We do not have enough strong earthquake recordings to observe the seismic soil behaviour!**
  - We tried the following method.
  - **Train Monitoring!**

- **The results are different from VAL-DES-BOIS June 23rd 2010 GSC strong motion earthquake recordings!**

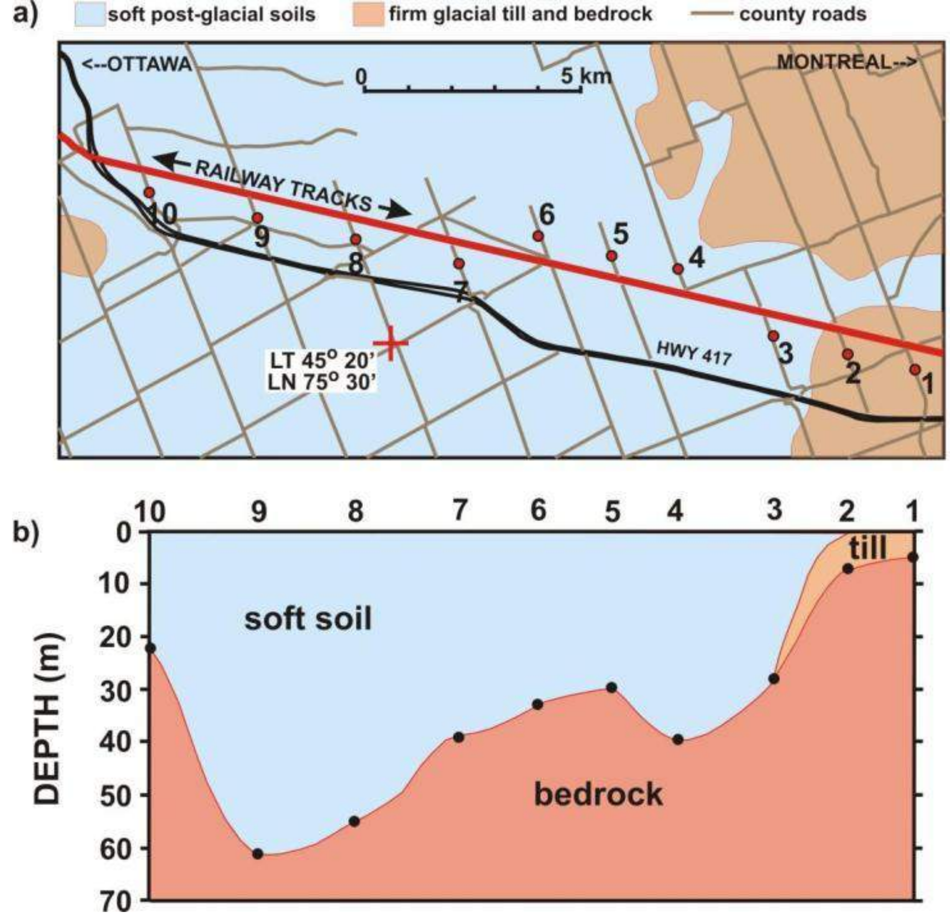
Train Monitoring: A straight line railroad. Ottawa-Montréal main line



CARLETON UNIVERSITY - GEOLOGICAL SURVEY OF CANADA
TEST SITES, OTTAWA REGION

- **Train Monitoring**
- **10 sites**, **500m away** from railway
- All 10 sites were investigated by refraction/reflection methods to find the
  - **Overburden thickness**
  - **Fundamental site frequency**

- Identical broadband seismometers



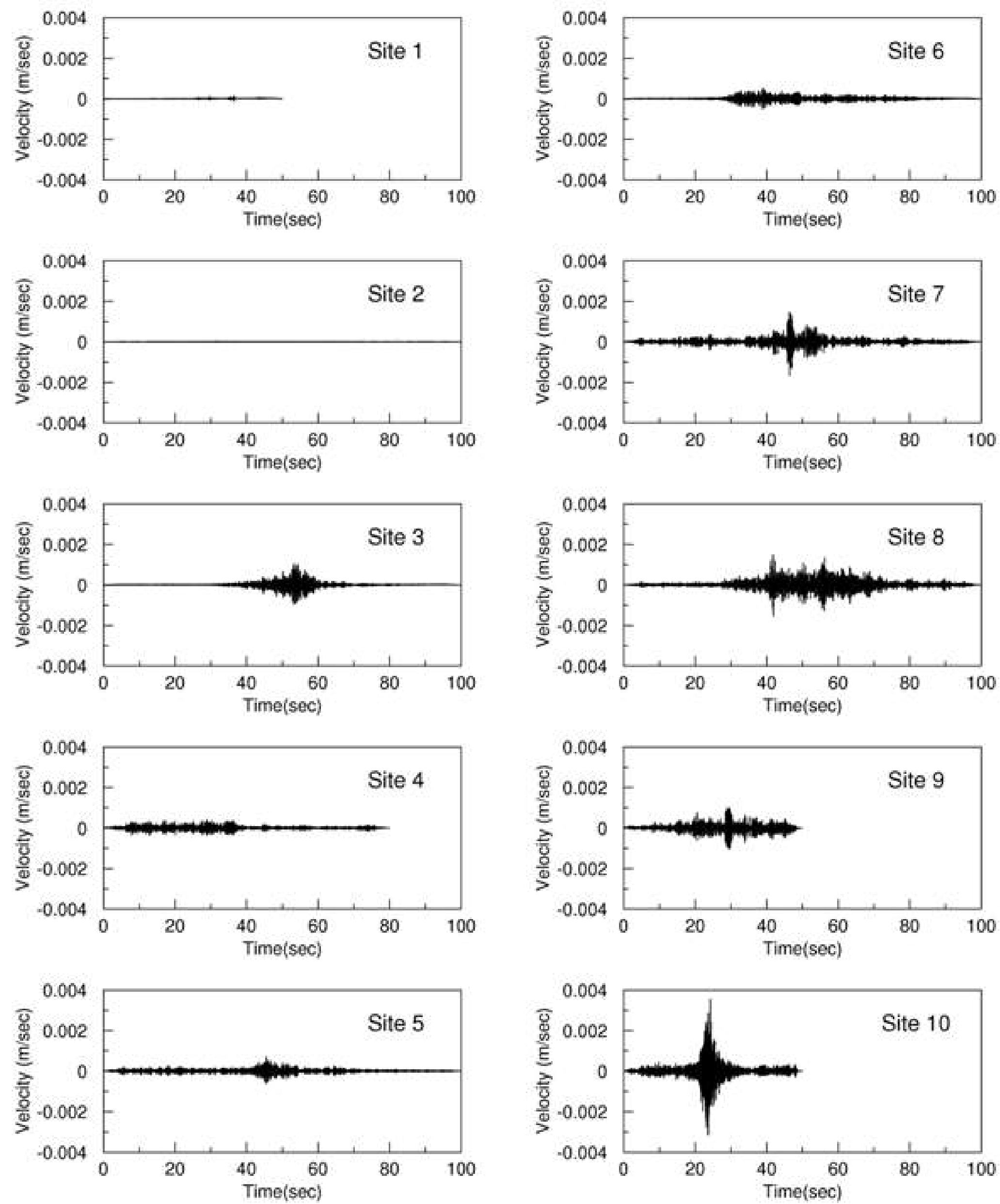
Site #	Depth (m)	2-way TT (ms)	Site frequency (Hz)
1	5	50	10.0
2	7.5	75	6.7
3	28	280	1.8
4	40	400	1.3
5	30	300	1.7
6	33	330	1.5
7	38.5	385	1.4
8	55	550	0.9
9	61	610	0.8
10	22	220	2.3

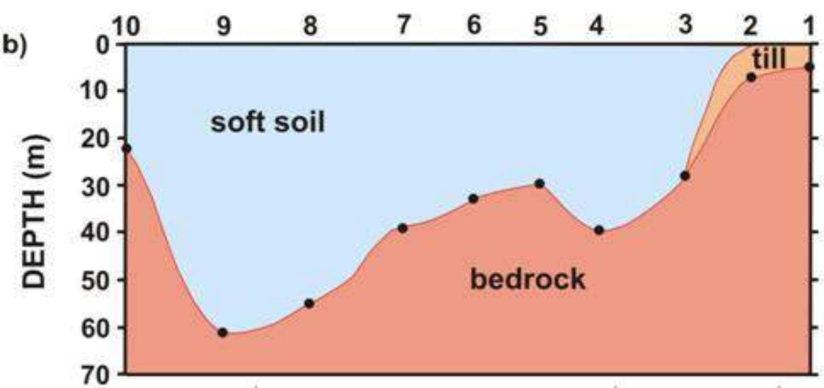
- **Amplification in the time domain**

- S1
- S2
- S3
- S7

- **Increased PGA**

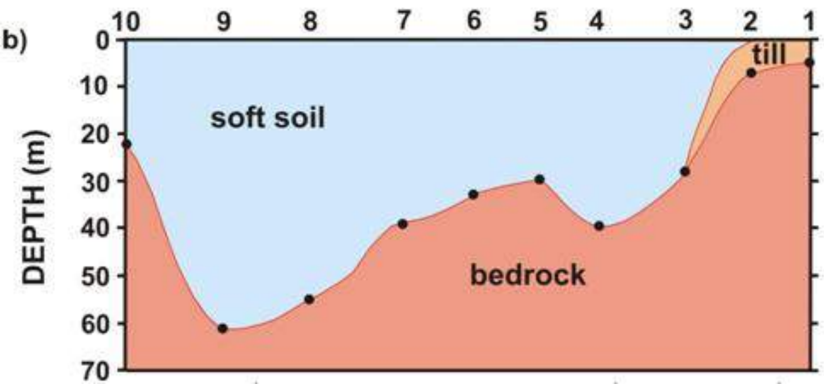
- **Increased duration**

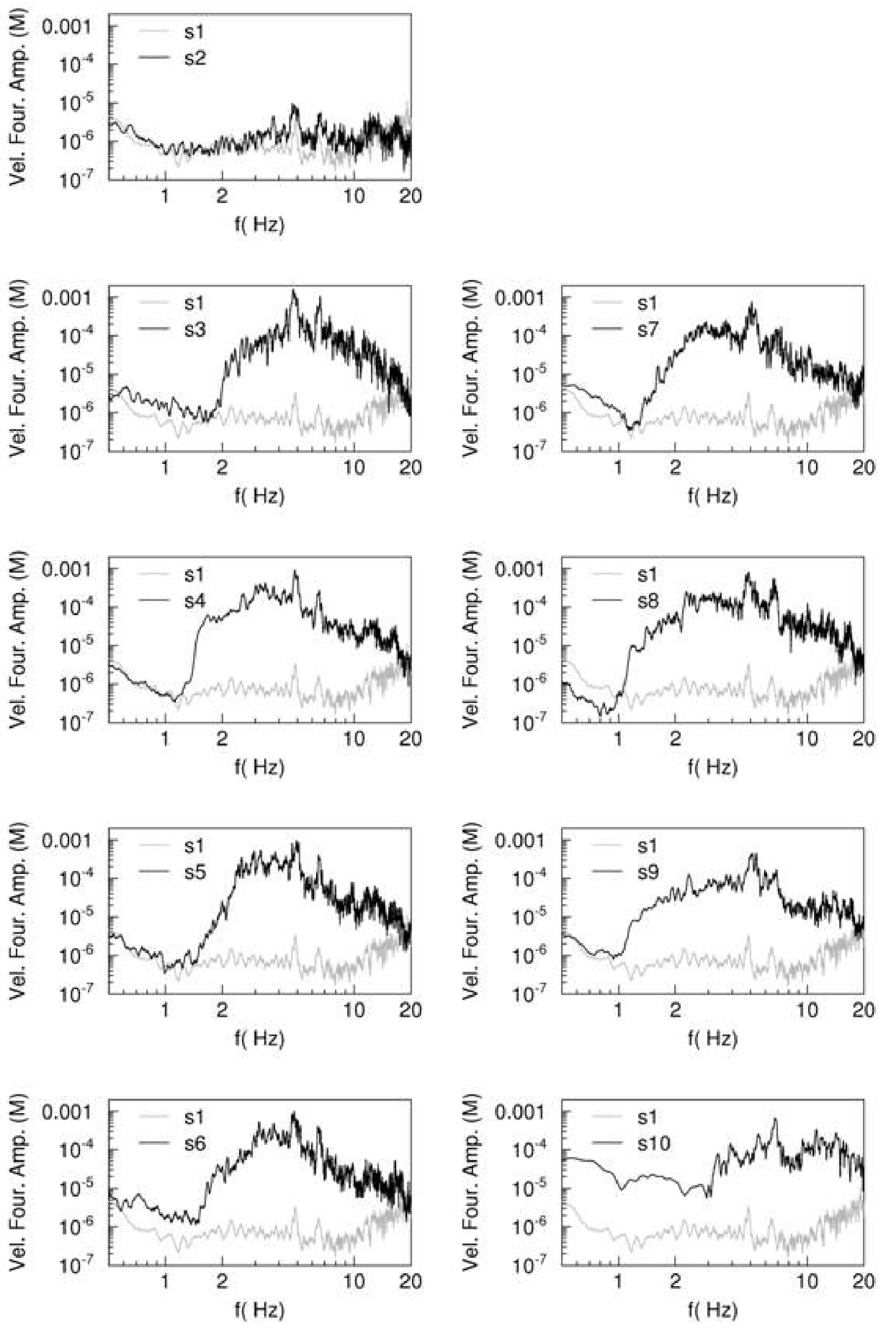




- **Amplification in the frequency domain**
- S1
- S2
- S3
- S7
- …

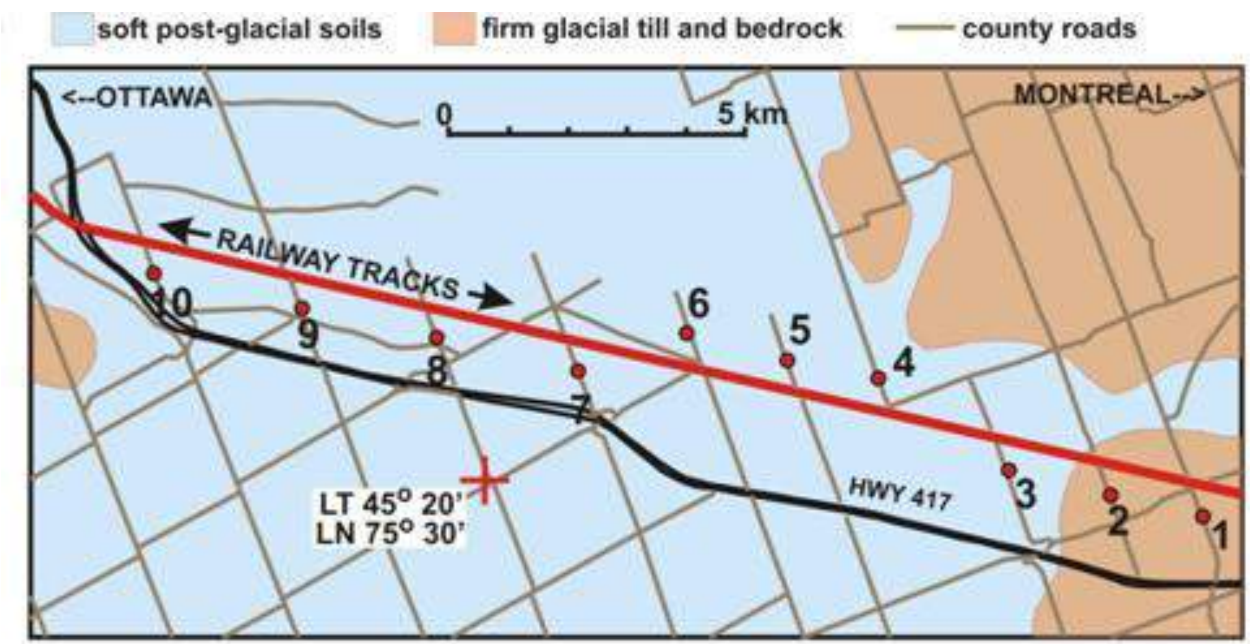
- **Amplification above fundamental site frequency is very large.**



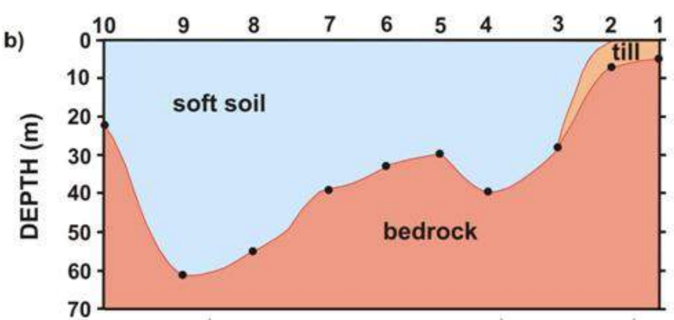


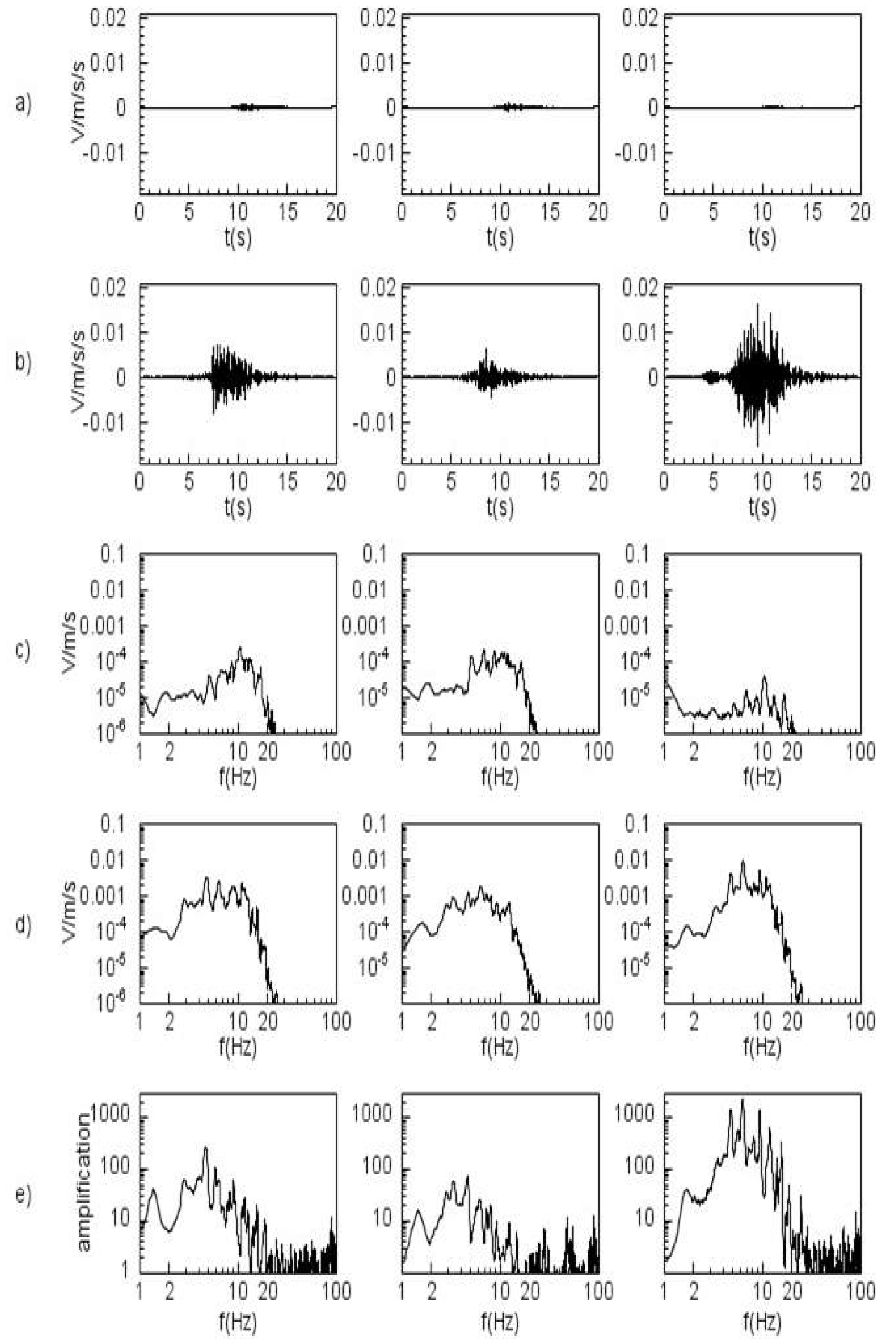
- **Again these are weak motions!!**
- How to observe the train induced ground vibration at a stronger level of shaking for any possible nonlinear behaviour of soil

- Second survey
  - **Using strong motion accelerometers**
  - **15 m away from the railway**
  - In anticipation of storing motion!



- **Near railway recordings**
- **Rock site and Soil site**
- The maximum level of shaking was about **60 gal**
- Again, amplification above fundamental site frequency is very large.
- **The results are different from GSC strong motion earthquake recordings.**
- **Why?**





- **The particle motion** at site 3, as an example,
- We noticed the train induced vibration was mainly composed of Rayleigh waves
- Although Love waves and body waves were present in the particle motion plot.

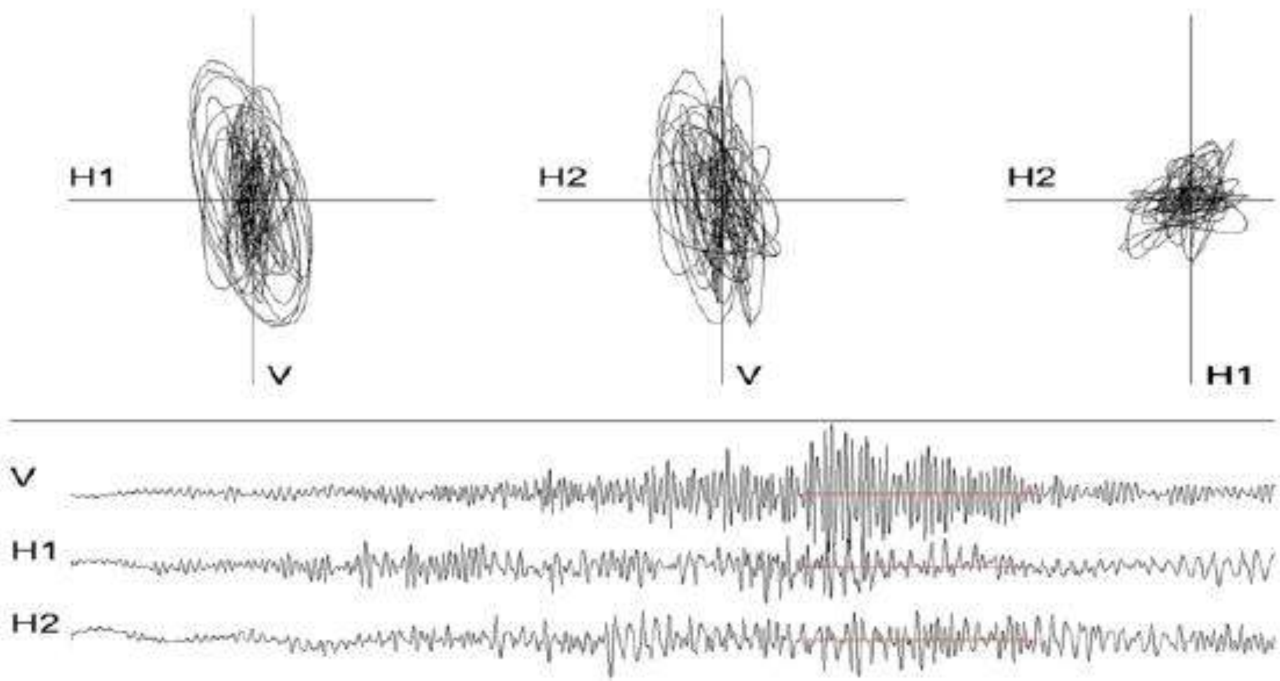


Fig. 3. Particle motion of the train-induced vibration, at the remote site 3, as an example, which is mainly Rayleigh waves with elliptic counter-clockwise motion, although horizontal shear wave energy was also observed in the vertical–transverse plane.

- More info?
- Soil Dynamics and Earthquake Engineering Journal Paper (2011)

- Researcher at the University of Edinburgh in the UK (working in the field of ground vibrations as generated by high speed train) requested our data for their train modeling

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

journal homepage: www.elsevier.com/locate/soildyn

Railway train induced ground vibrations in a low V_S soil layer overlying a high V_S bedrock in eastern Canada

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A B S T R A C T

Railway trains were used as a seismic source to observe the differences in behavior of seismic ground motions at different types of soil and rock sites. Observations indicate that the durations and amplitudes of the train induced seismic waves at the soil sites increased dramatically compared to the reference bedrock site. The very high site effect for railway train induced vibration may be due to the fact that the speed of train was close to the Rayleigh wave velocity of the soil. On the other hand, very large soil amplifications have been observed based on local earthquakes recordings, with a very different source mechanism than train induced seismic waves. Combining these two effects may lead to unusual soil amplification, at least for weak motion, especially when a train is moving at a speed close to the velocity of Rayleigh waves. These findings can be utilized in early warning systems in eastern Canada by mapping the potential railway train induced vibrations and the velocity of Rayleigh waves along railway transportation corridors.

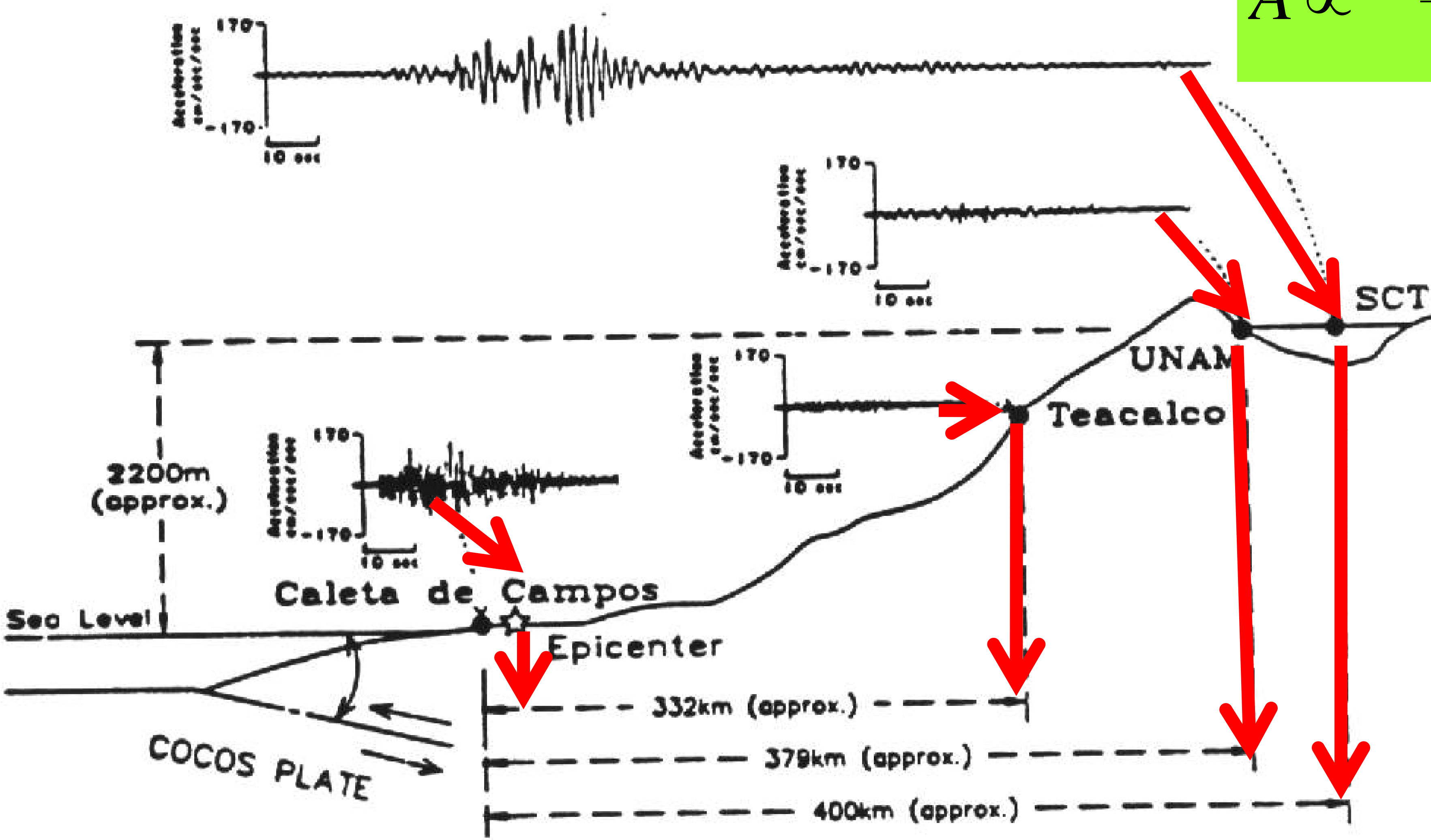
Seismic soil amplification

- Past earthquakes have demonstrated that **local soil conditions** and **topography** dramatically affect the ground motion.
- In most settings, earthquake ground motions are amplified primarily by the **top soil layers**.
- **The most classic example** of the importance of site effects is given by the **1985 M8.3** Mexico earthquake
- **Major subduction event**, M8.3, that occurred about **400 km from Mexico City**
- **Limited damage in coastal areas near the earthquake**
- **Major damage in some parts of Mexico City, where motions should have been minimal due to the large distance**

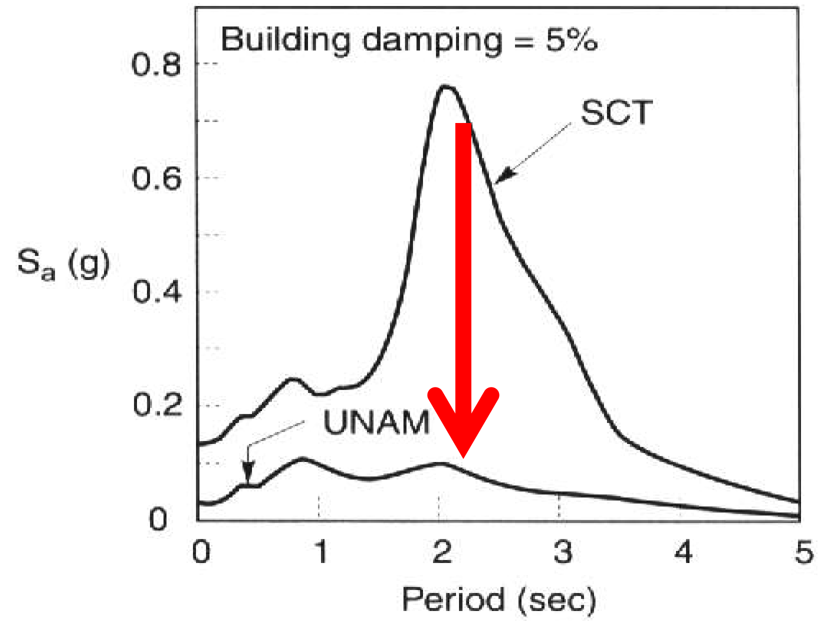
Observations; Mexico City, Mexico

- Very strong motions produced at **400 km** from the fault rupture due to the response of **soft clays**

$$A \propto \frac{A_0}{R}$$



- **Sa:** Compare Rock and Soft Soil Site Spectra in Mexico City
  - UNAM site
  - SCT site
  - **A large site amplification around 2 sec**



- Reminder:
  - For a Reinforced Concrete structure of **N storeys**, the natural period of vibration **T** (seconds) can be estimated from:
  - **T = 0.1 (N)**

- The damage in Mexico City was in a large part due to **COINCIDENCE** between the **dominant period of the ground shaking and the natural period of vibration of these high-rise structures.**

Most severe damage to almost 400 buildings of **between 7 and 18 storeys in height.** (EEFIT, 1986)