CSRN
RCRP

Canadian Seismic Research Network
Réseau canadien pour la recherche parasismique

Funded by NSERC / *Subventionné par le CRSNG*

- **Microzonation Studies for The City of Ottawa**
- This research is a part of theme 1; Project 1.2

- A combined research team from Carleton University and GSC have been surveying the Ottawa to obtain site classifications

- Dariush Motazedian (CU), Jim Hunter (GSC), Heather Crow (GSC, CU), Siva Sivathayalan (CU), Kasgin Khaheshi Banab (CU), Andre Pugin (GSC), Susan Pullan (GSC), Greg Brooks (GSC), Greg Oldenborger (GSC), Rob Burns (GSC), Tim Cartwright (GSC), Marten Douma, (GSC), Ron Good (GSC), **a dozen of Carleton Students**

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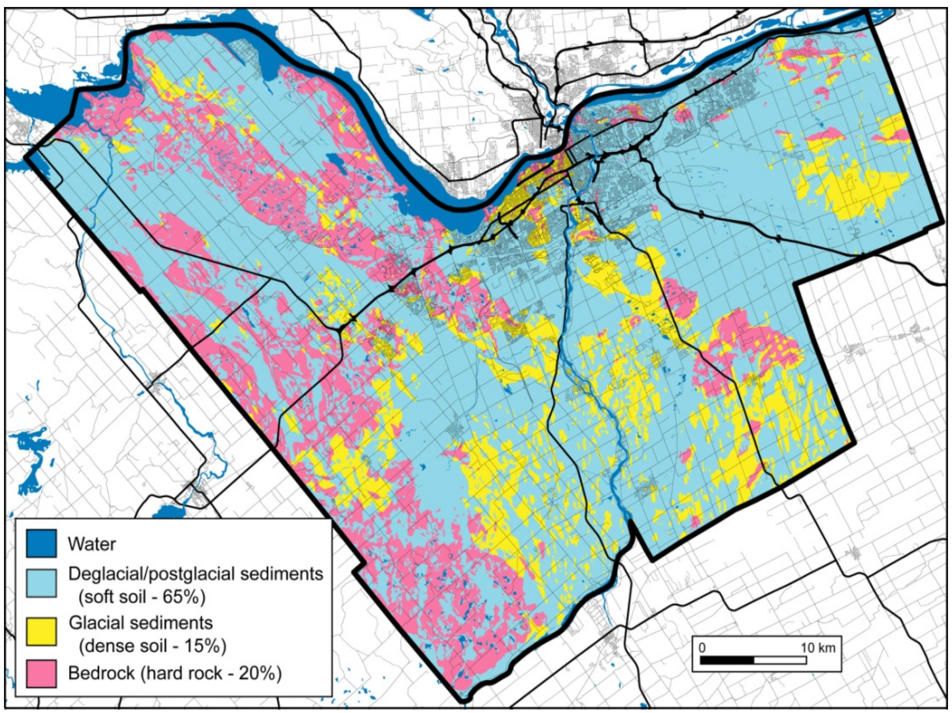
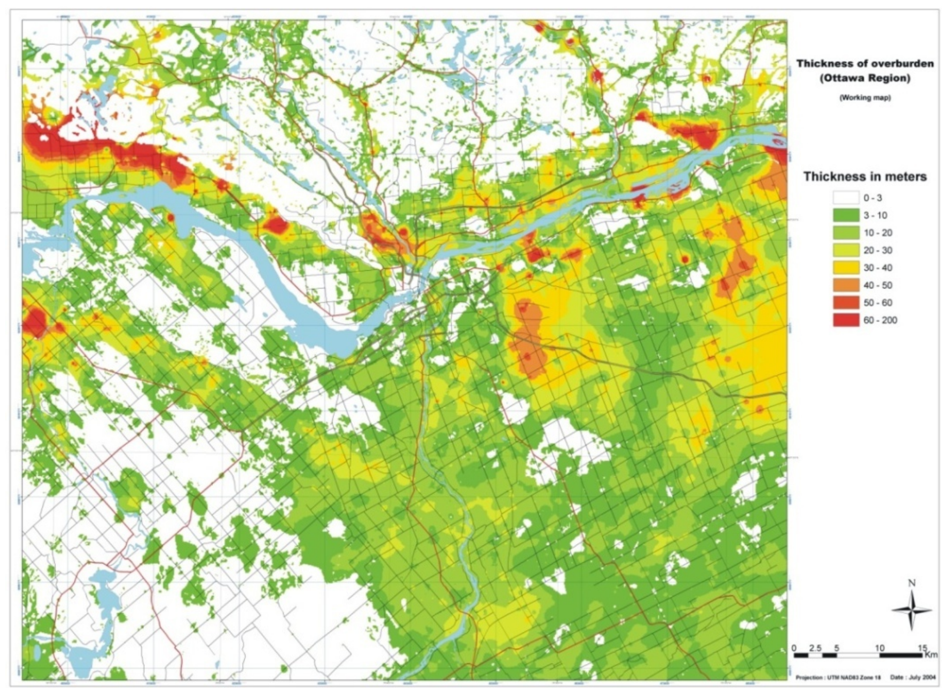
CANADA 1842 GEOLOGICAL SURVEY - COMMISSION GÉOLOGIQUE

- **National Building Code of Canada (NBCC, 2005)**
  - Following the NBCC 2005 Seismic **site classification** and **amplification** has become an important issue for Ottawa.

- **Surficial geology of Ottawa**
  - ➢ 65% is late/post-glacial sediments, Leda Clay(**Vs~150 m/s**)
  - ➢ 20% , bedrock outcrop (**Vs~2700 m/s**)
  - ➢ 15% is glacial sediment (**Vs~580 m/s**)
  - ➢ **Contrast around 20!**
- **Soil thickness**
  - ➢ In addition, there are many areas of Ottawa, with relatively thick soils





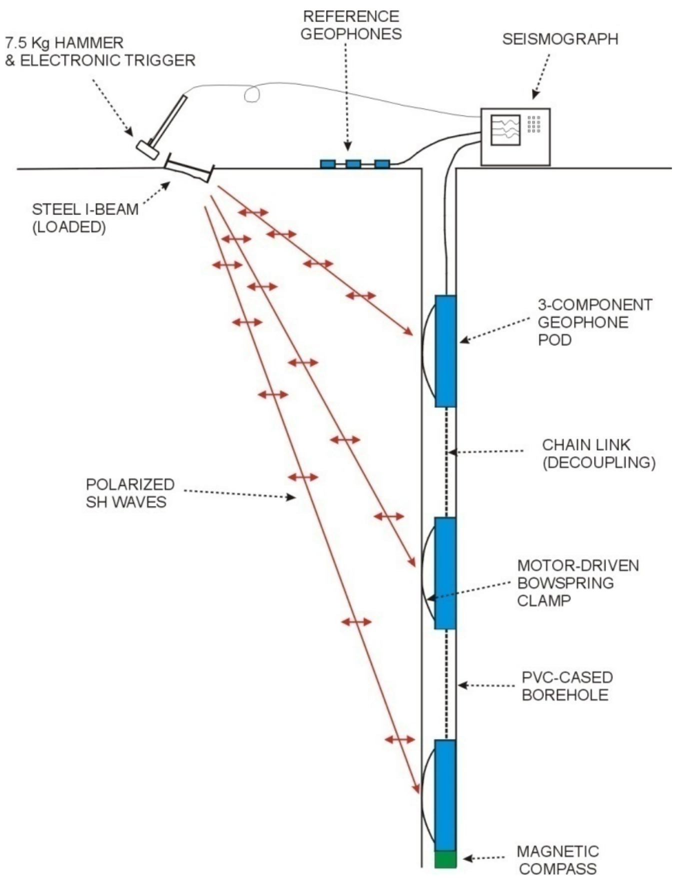
- In NBCC 2005 Seismic site classification is based on shear-wave velocity averaged over the top 30 m (**V_{s30}**)

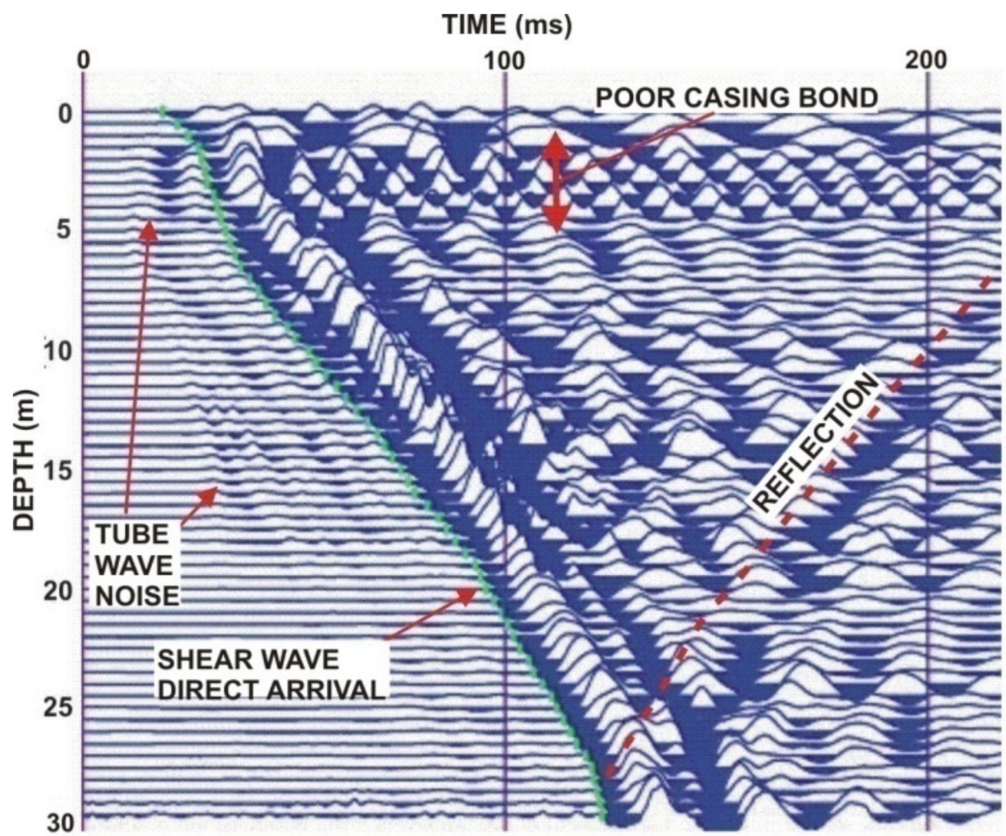
CLASS	Vs_{30} (m/s)	Description
A	> 1500	hard rock
B	760 - 1500	rock
C	360 - 760	soft rock or firm soil
D	180 - 360	soft soil
E	< 180	very soft
F		

- **NBCC 2005 Site amplification factors**

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				

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





➢18 borehole sites

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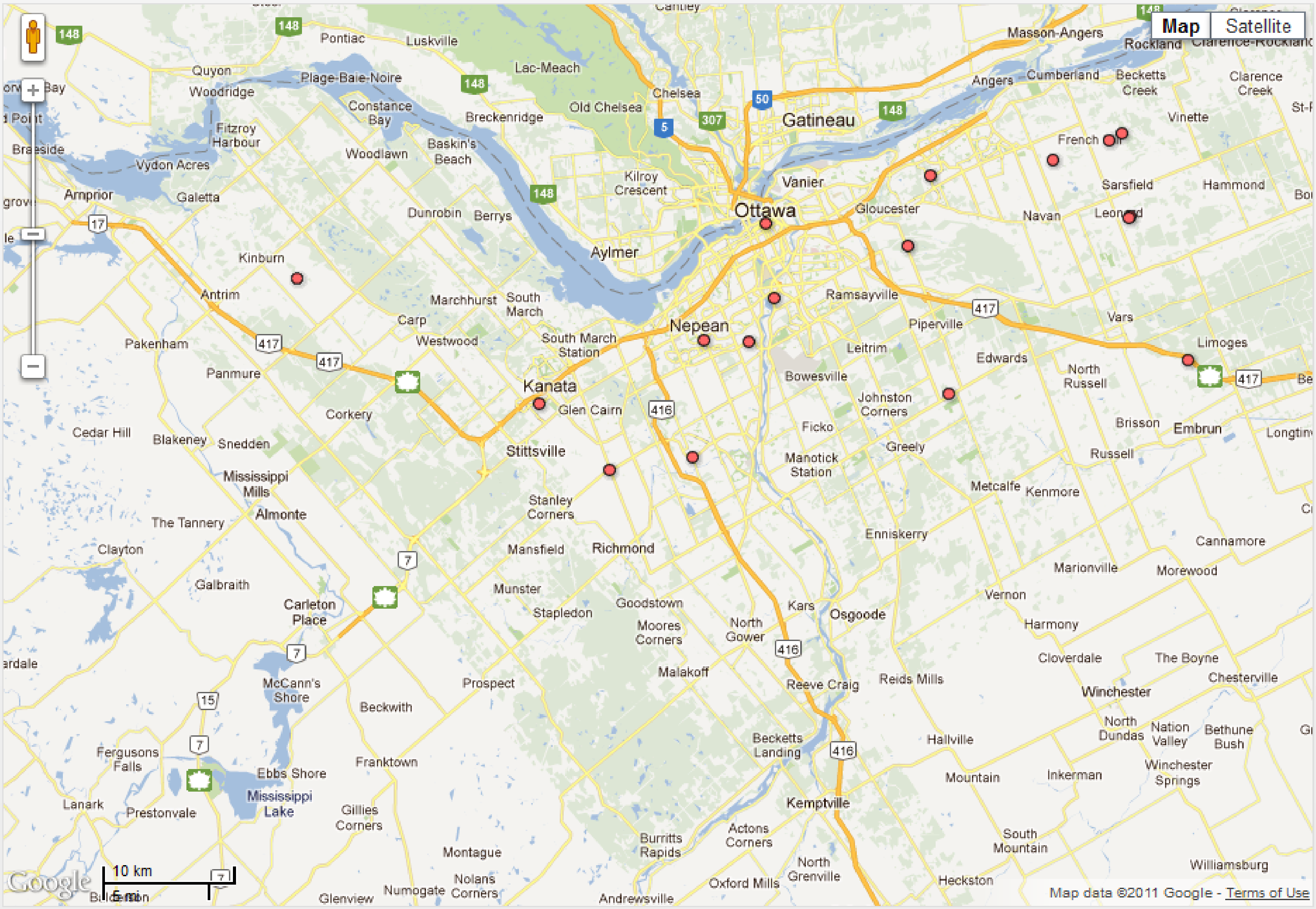
Interactive Vs30 Google Map for the City of Ottawa

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
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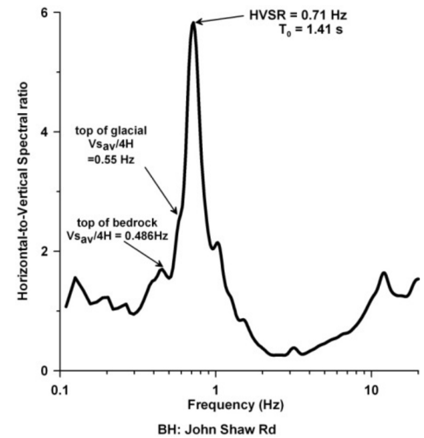
- **T_0 based on HVSR** of background noise analysis
- It is based on Spectral ratio of horizontal component to vertical component of background noise
  - **Spectral peak(s)** correspond approximately with
    - **F0 = Vs/4*H**
    - Vs = the average shear wave velocity of overburden layer
    - H = 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!



➢400 HVSR

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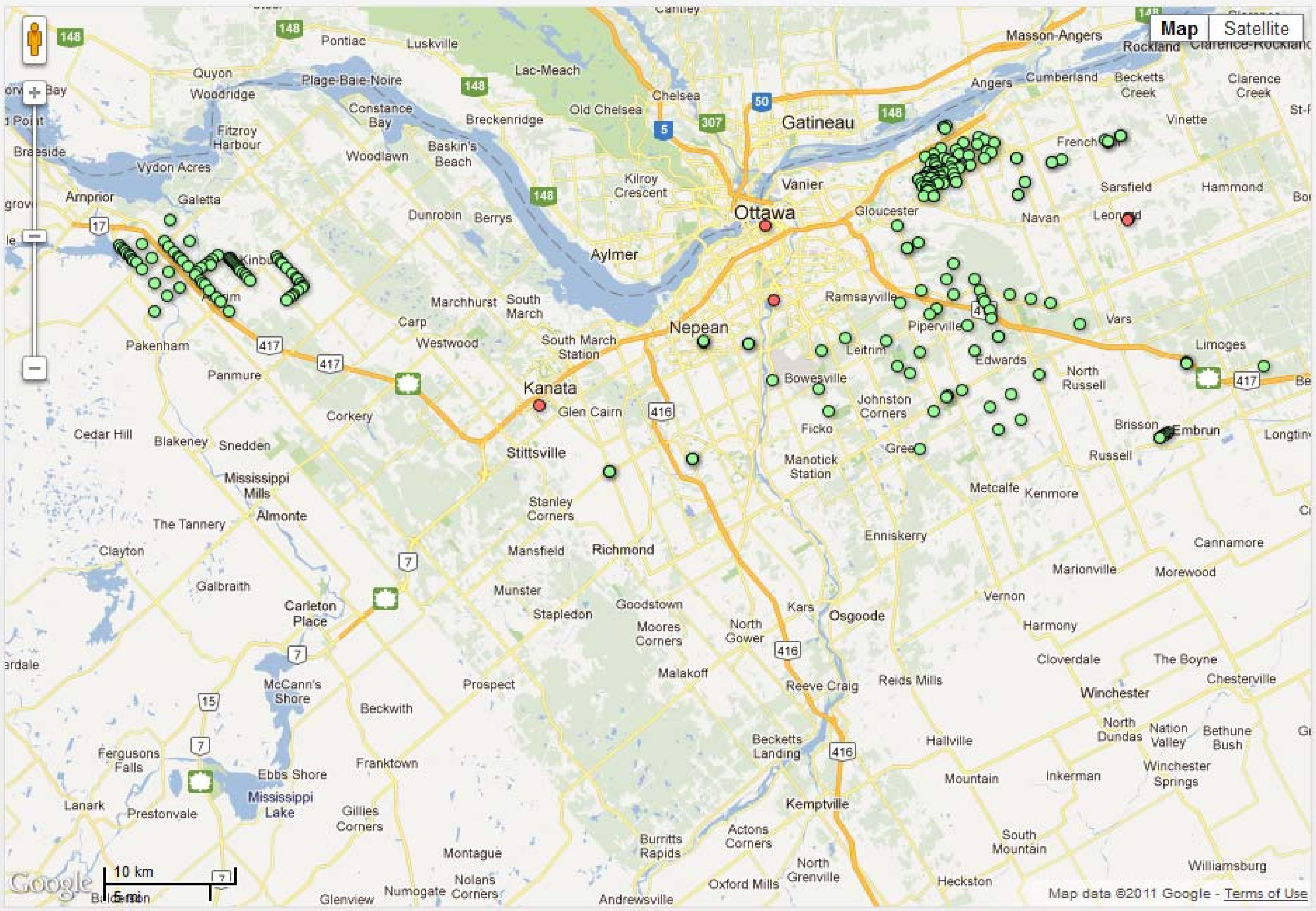

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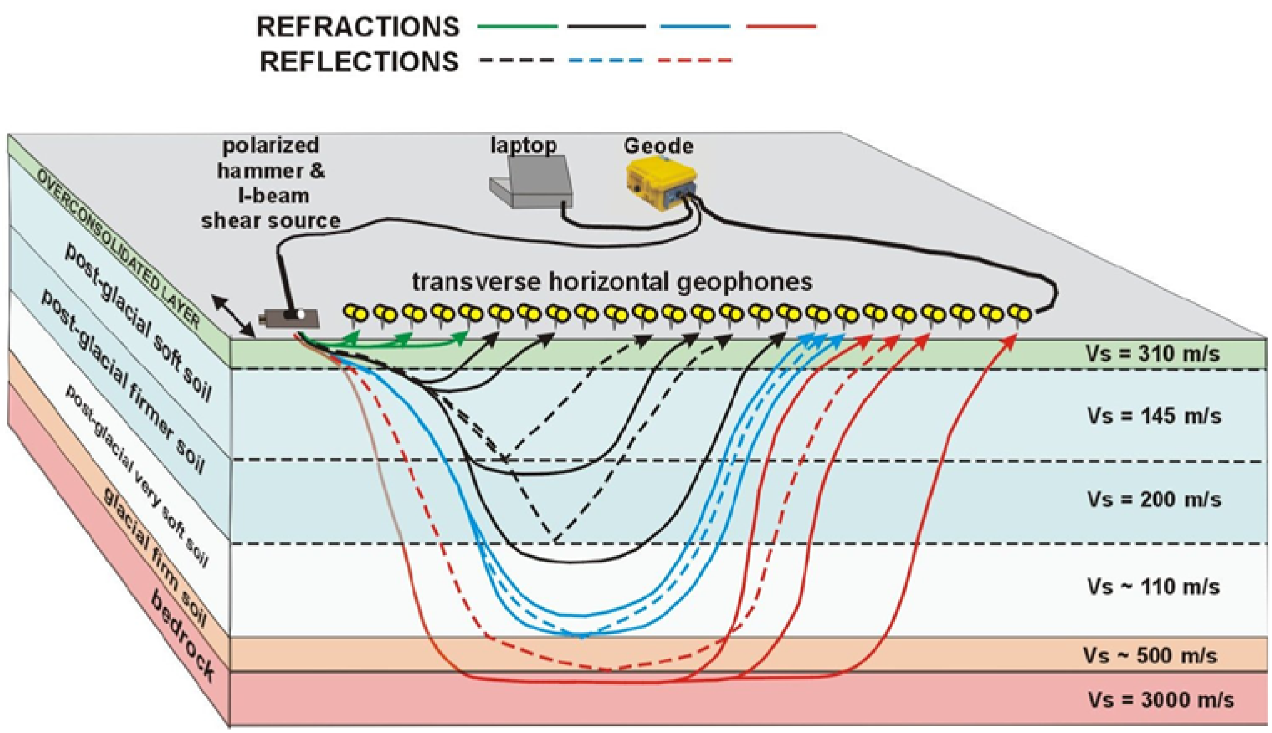
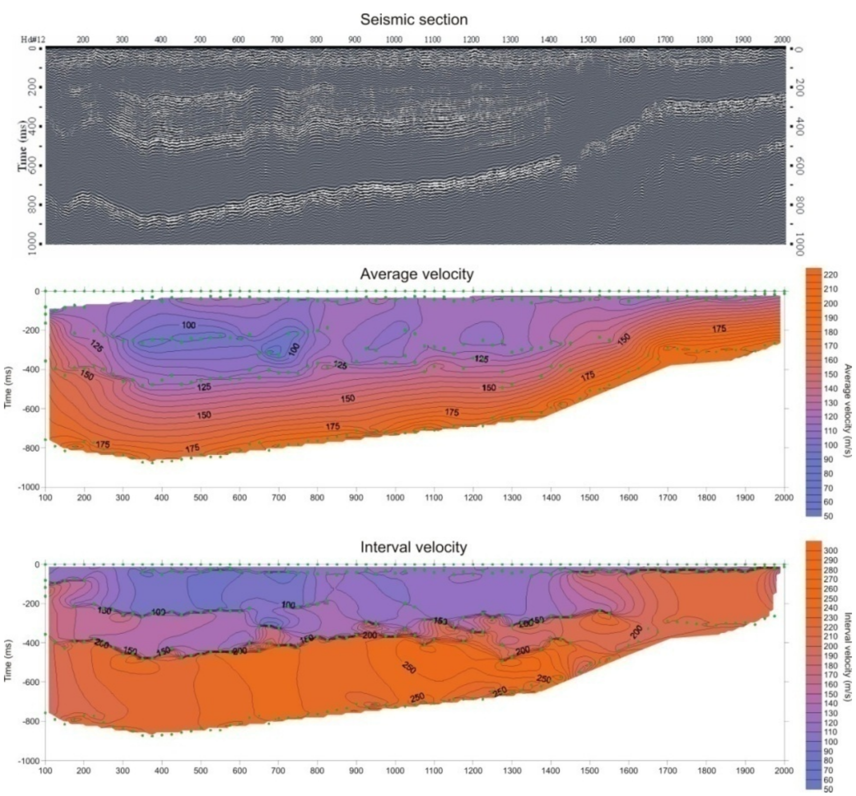
- **Seismic reflection/refraction sites suitable for Ottawa**
  - Because of the very **high shear wave velocity contrast** between soil (**150 m/s**) and very hard bedrock (**2700 m/s**)
  - ➢ **Practical** and **fast** method for Ottawa (**3 sites a day**).

- 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
- **25 line-km landstreamer profiling in Ottawa**



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

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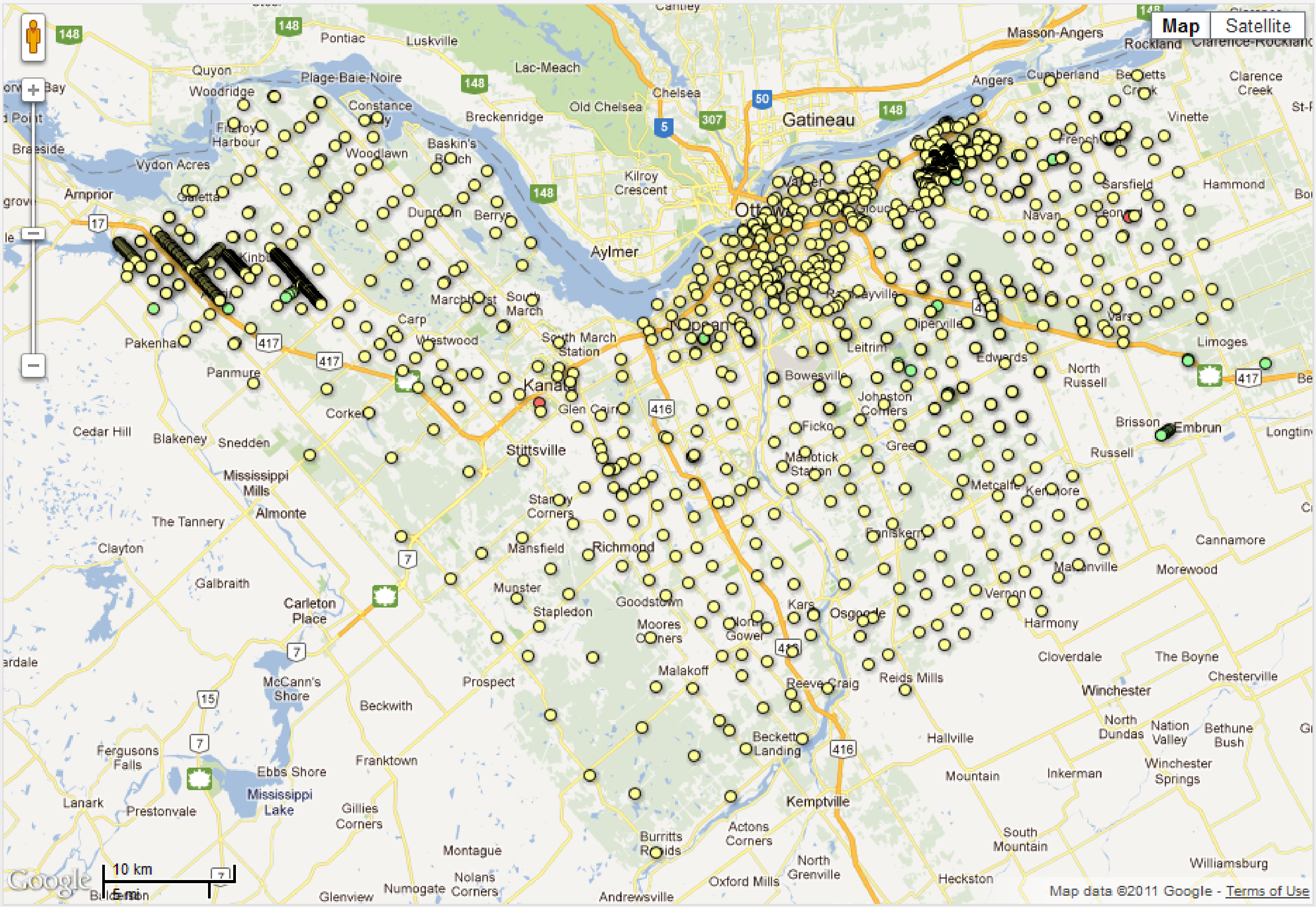
Interactive Vs30 Google Map for the City of Ottawa

GSC



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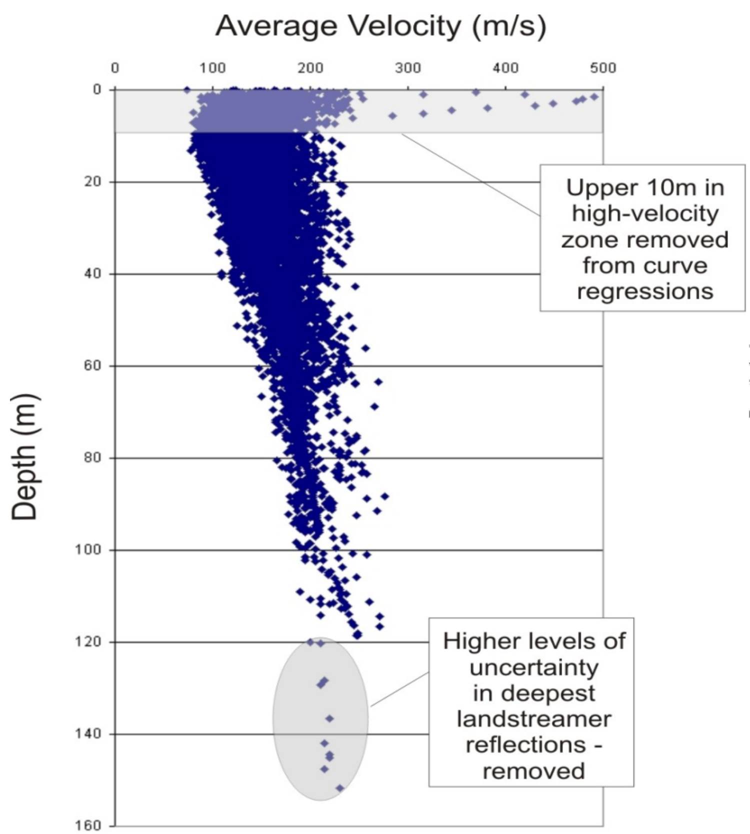
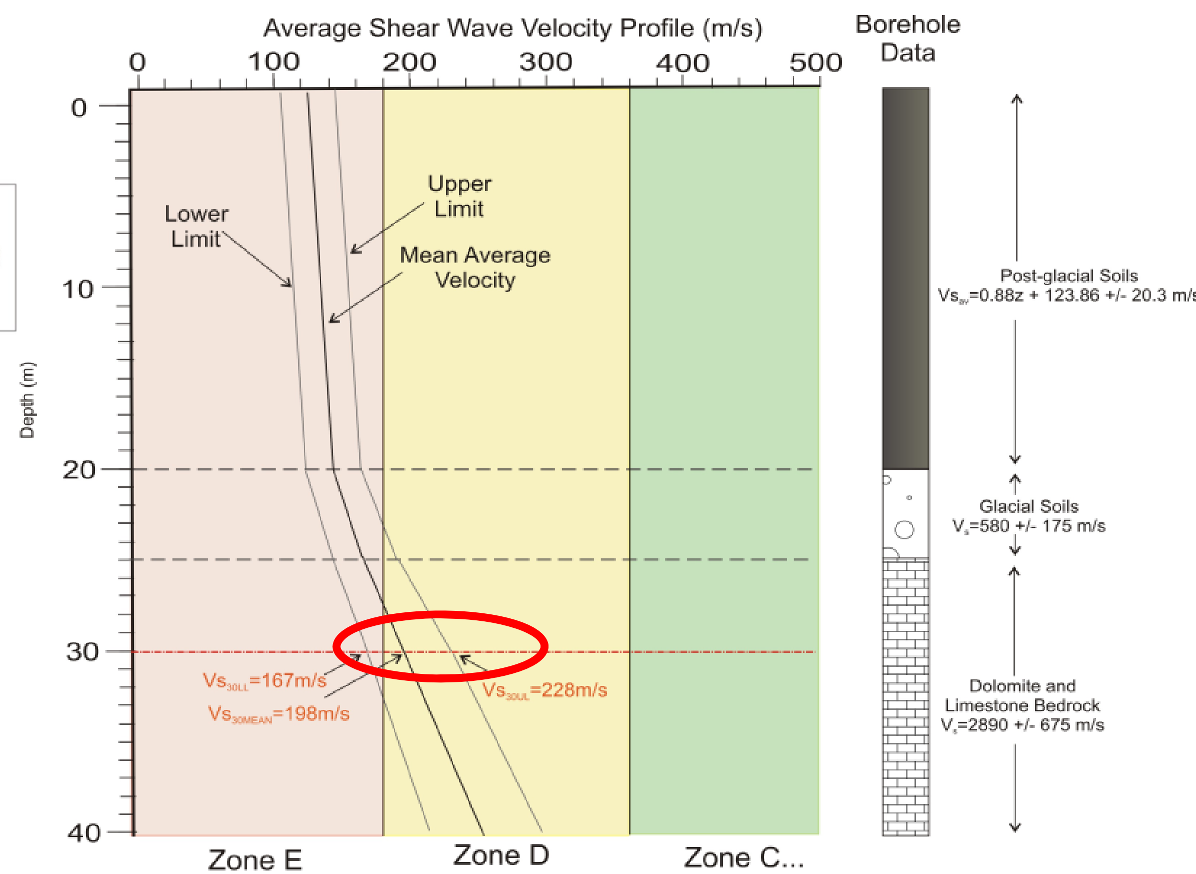
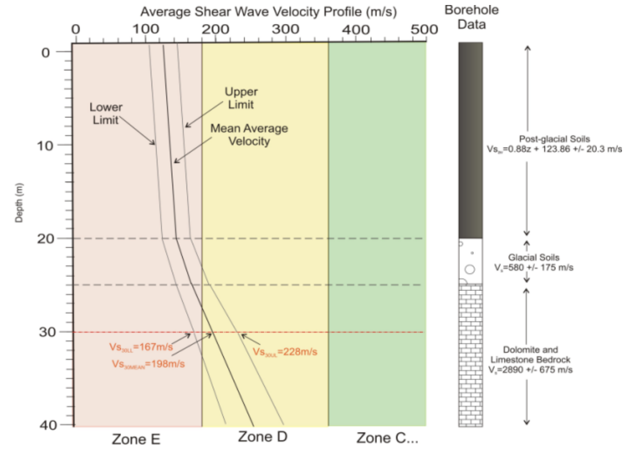
- **Velocity-depth database** for **Champlain Sea sediments** was compiled
- Typical average shear wave velocity profile for the Ottawa region.
- Error associated with the mean velocity

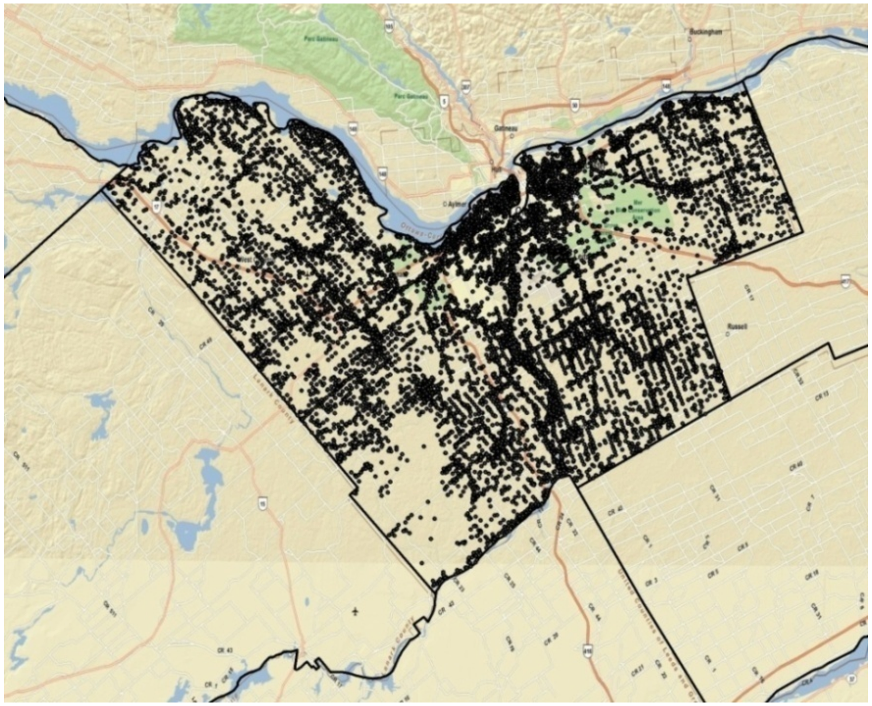
- Post glacial sediments : $\mathbf{Vs_{av} = 124 + 0.88z \pm 20}$ **m/s for 10m ≤ Z ≤ 100m**
- Glacial soils : **580 ± 175 m/s**
- Typical bedrock : **2700 ± 675 m/s**

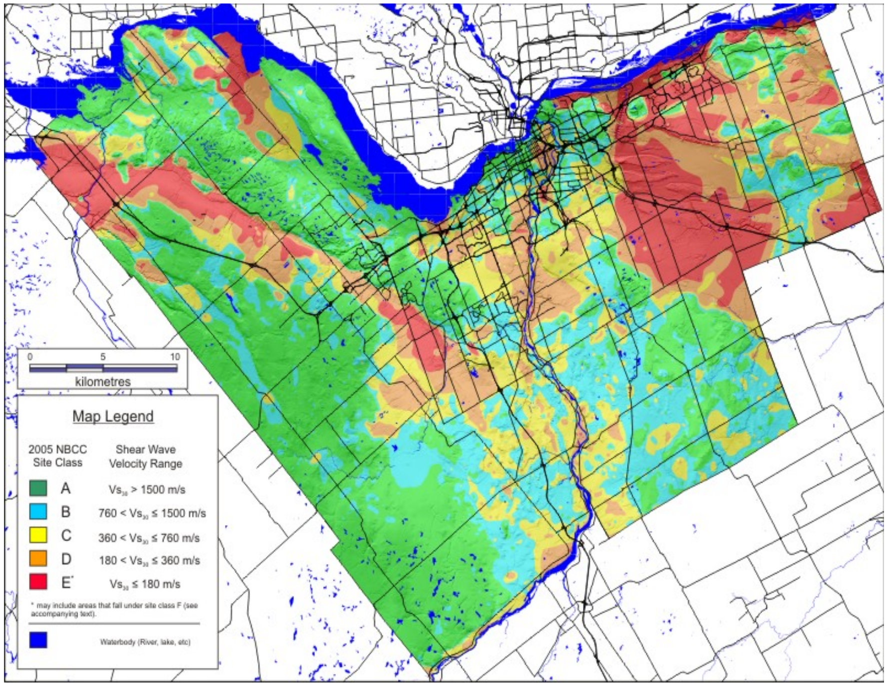




- **The velocity-depth function**
- **~21,000** GSC borehole database
- Then, the velocity-depth functions were applied to all boreholes !
- **V_{s30} map (2005 NBCC)**
- Eastern part of Ottawa is mainly site **class E or F** (very loose soft soil)
- In just a few hundred meters you can see **dramatic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







- Example : Seismic Hazard map of OttawaSeismic Hazard map for **5 Hz**, **site class C** (**2%/50yr return**) 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				
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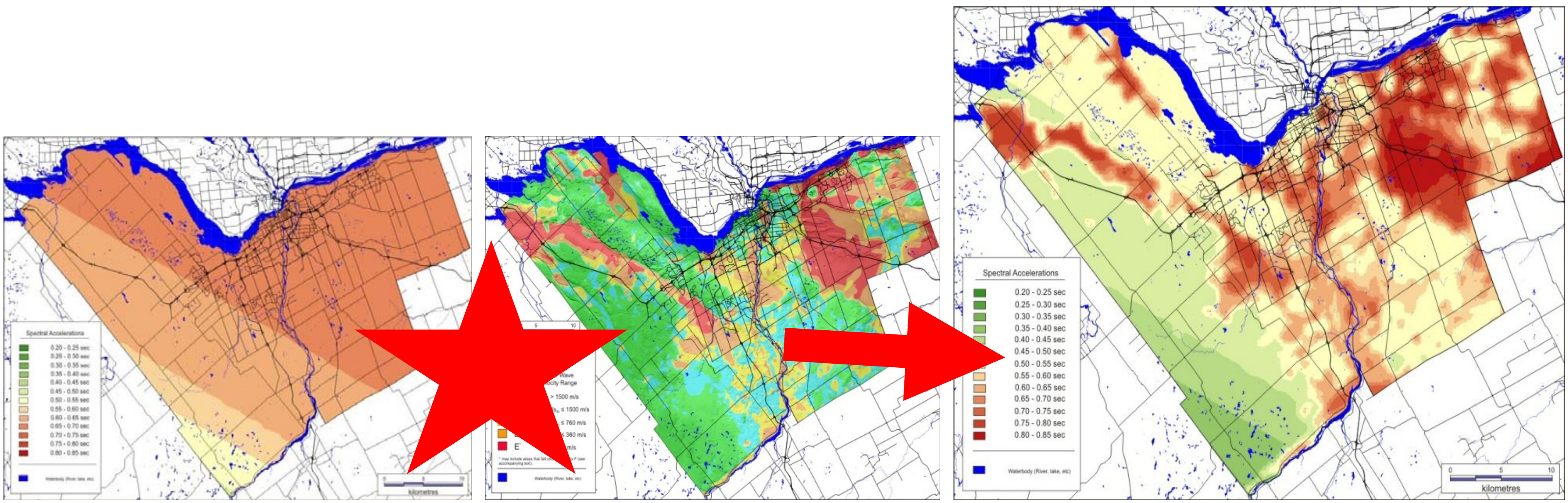

- More information
  - **GSC Open File Report 6273 (2010)**
  - **Canadian Geotechnical Journal paper (2011).**
  - **Interactive Google map http://http-server.carleton.ca/~dariush/Microzonation/main.html/**

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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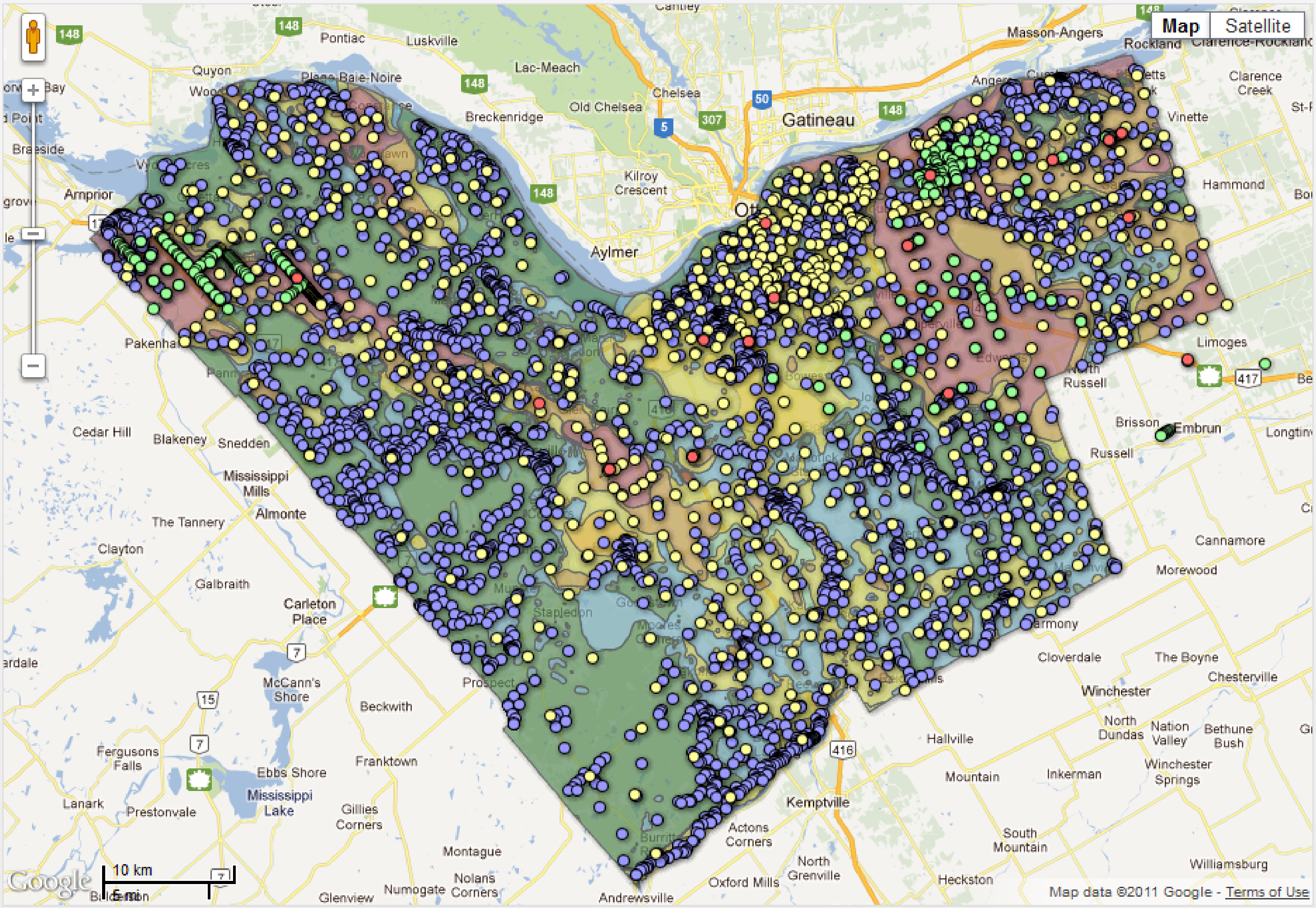
Interactive Vs30 Google Map for the City of Ottawa

GSC



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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

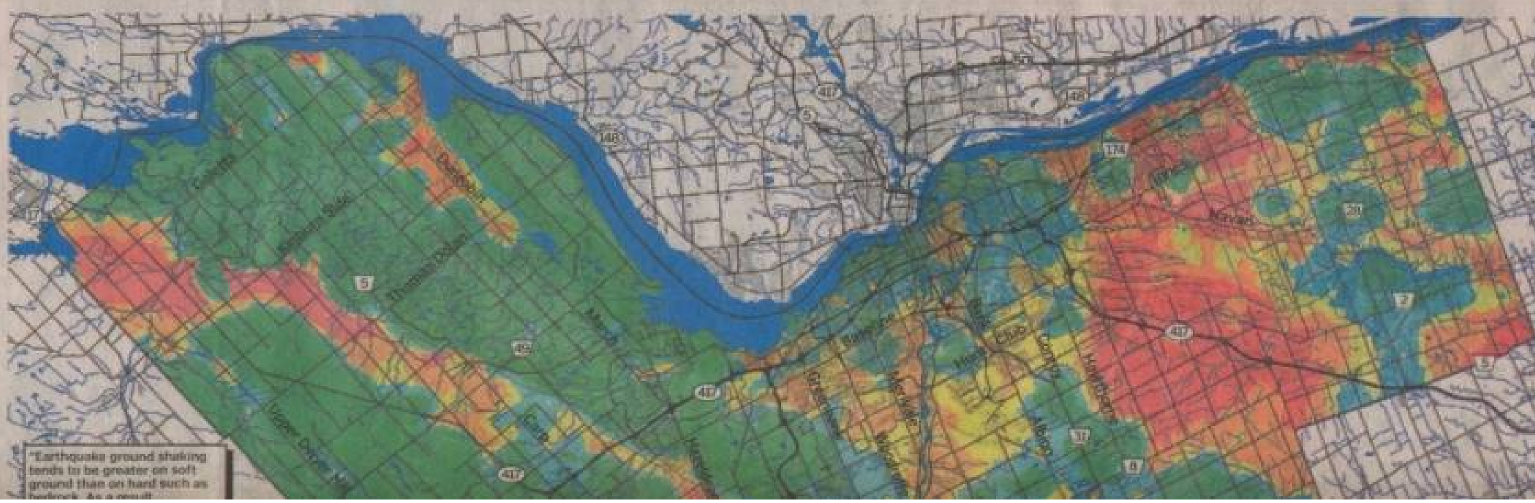
Scientists map Ottawa quake risk

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



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

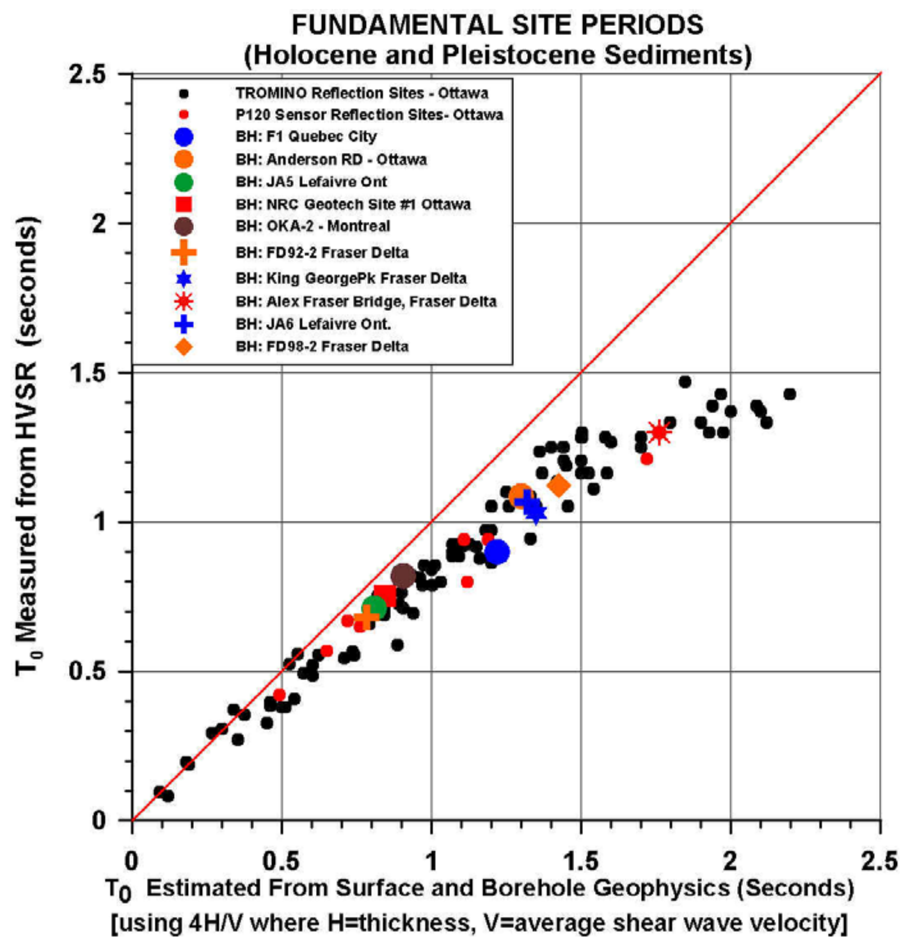
- Thus, we added the evaluation of Fundamental Site Period (T_0)

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.

• However a calibration is needed!

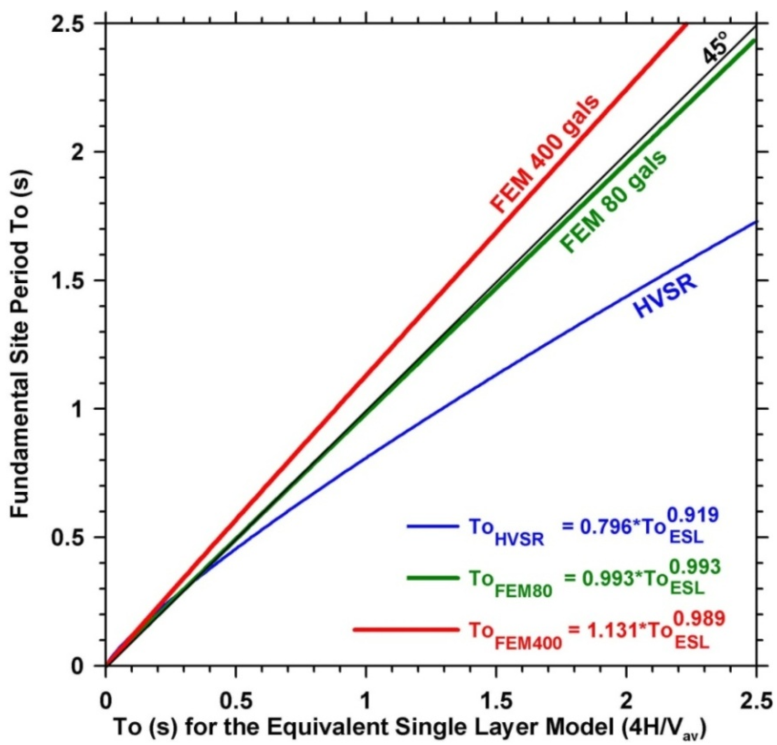
- Comparison between
  - T_0 based on HVSR and
  - T_0 based on NBCC 2005 (4H/Vsav)
  - Boreholes **(very accurate Vs)** locations from:
    - Ottawa
    - Quebec City
    - Eastern Ontario
    - NW Montreal
    - and Richmond BC



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

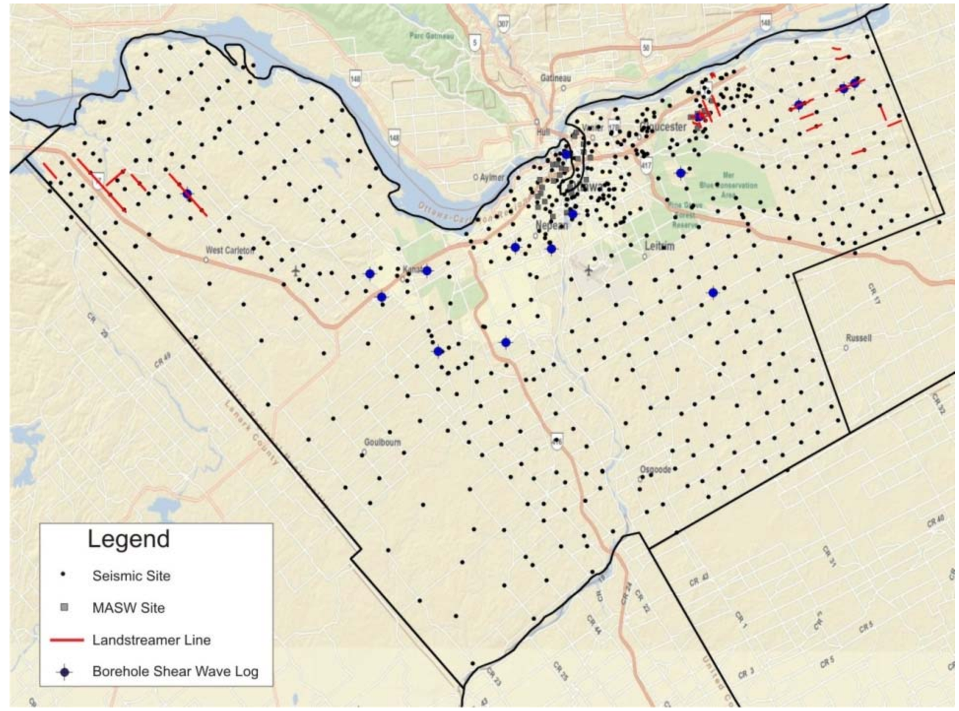
- **We applied many methods to obtain T_0**
  - NBBC 2005
  - HVSR using background noise analysis
  - Finite element modeling for **80 gal**
  - Finite element modeling for **400 gal** (**design earthquake for Ottawa**)
  - **They do not match!**
  - The relationships between all are obtained.

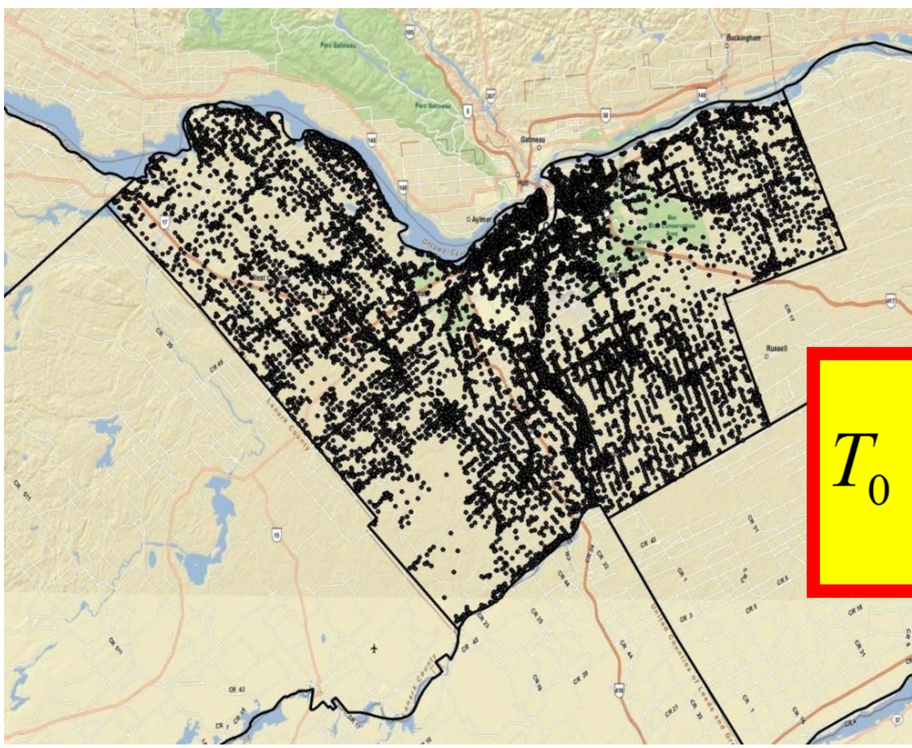
- **HVSR is fast and its T0 can be used to obtain T0 for the design EQ!**



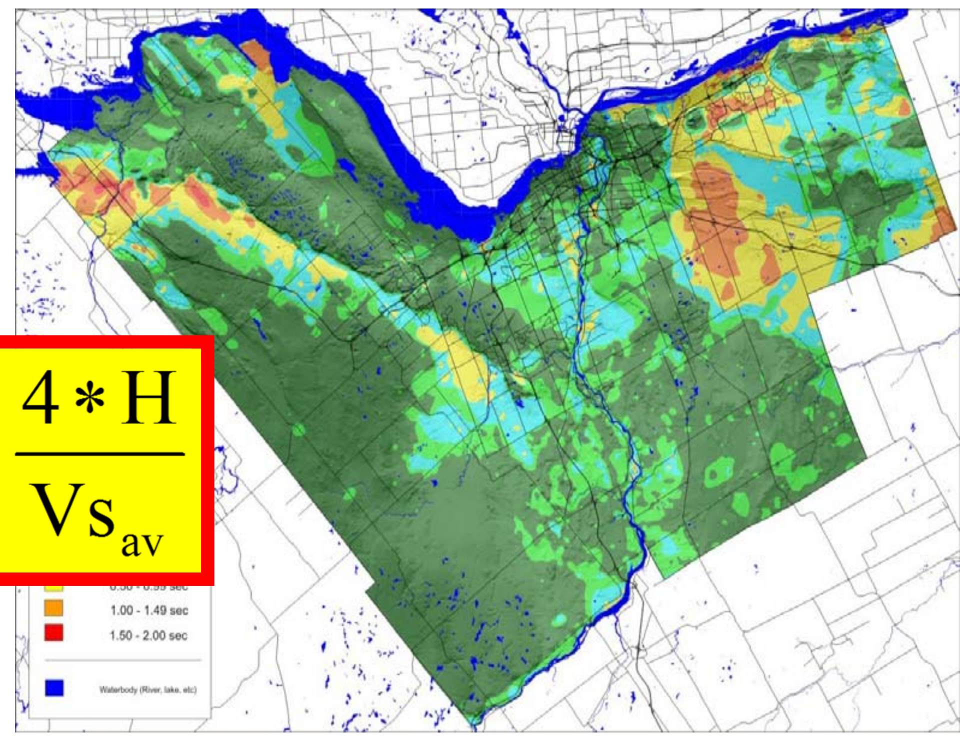
- # T_0 map
- Based on NBCC 2005 guidelines

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



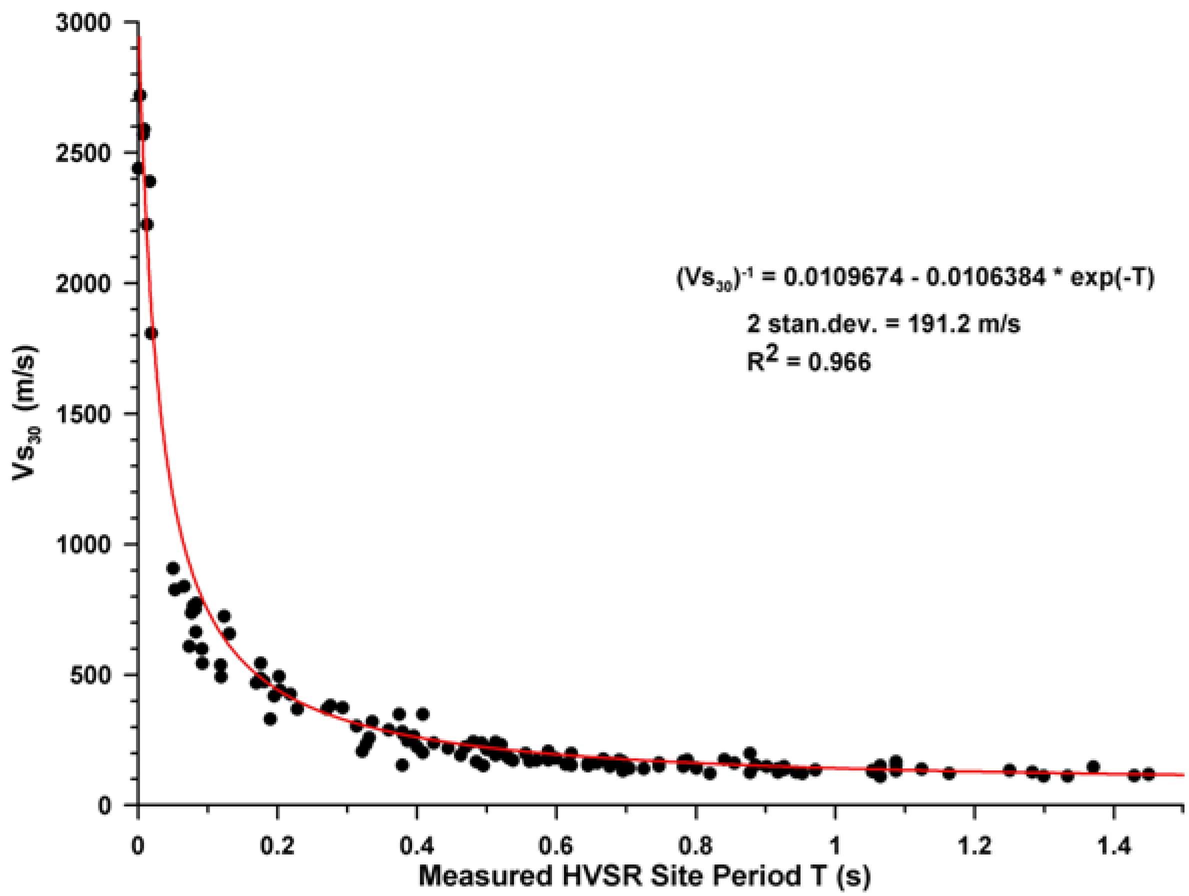


$$T_0 = \frac{4 * H}{Vs_{av}}$$



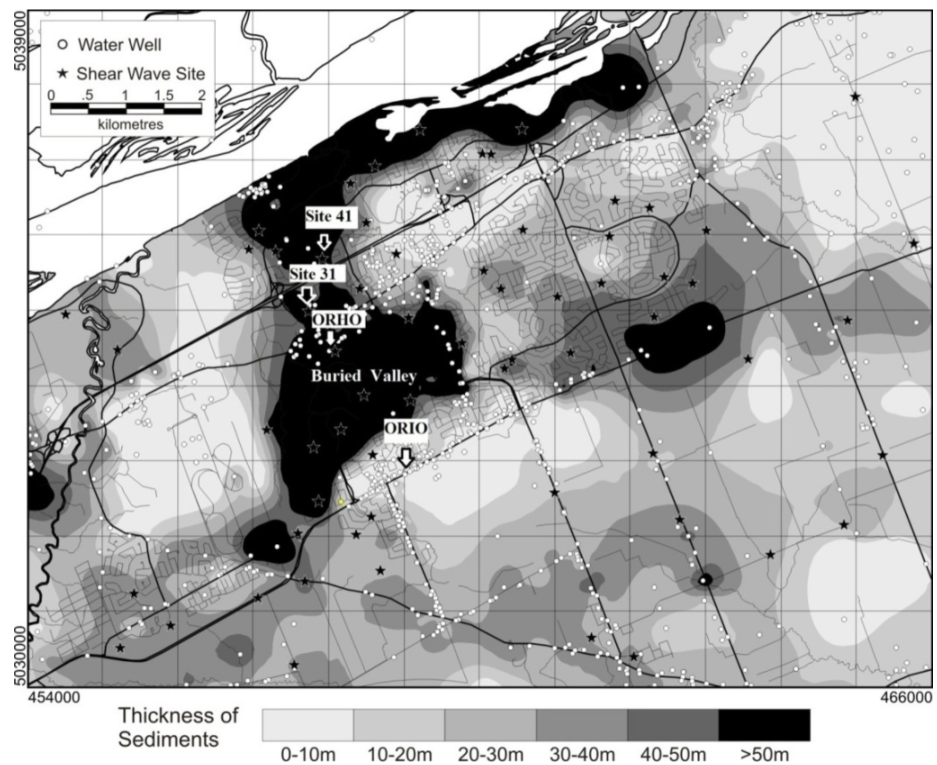
- **Using HVSR to get Vs30!**
  - HVSR is fast (quite a few sites per day)
  - Can be used as a **screening tool to estimate Vs30!**

- Vs30 versus T0 for Ottawa area

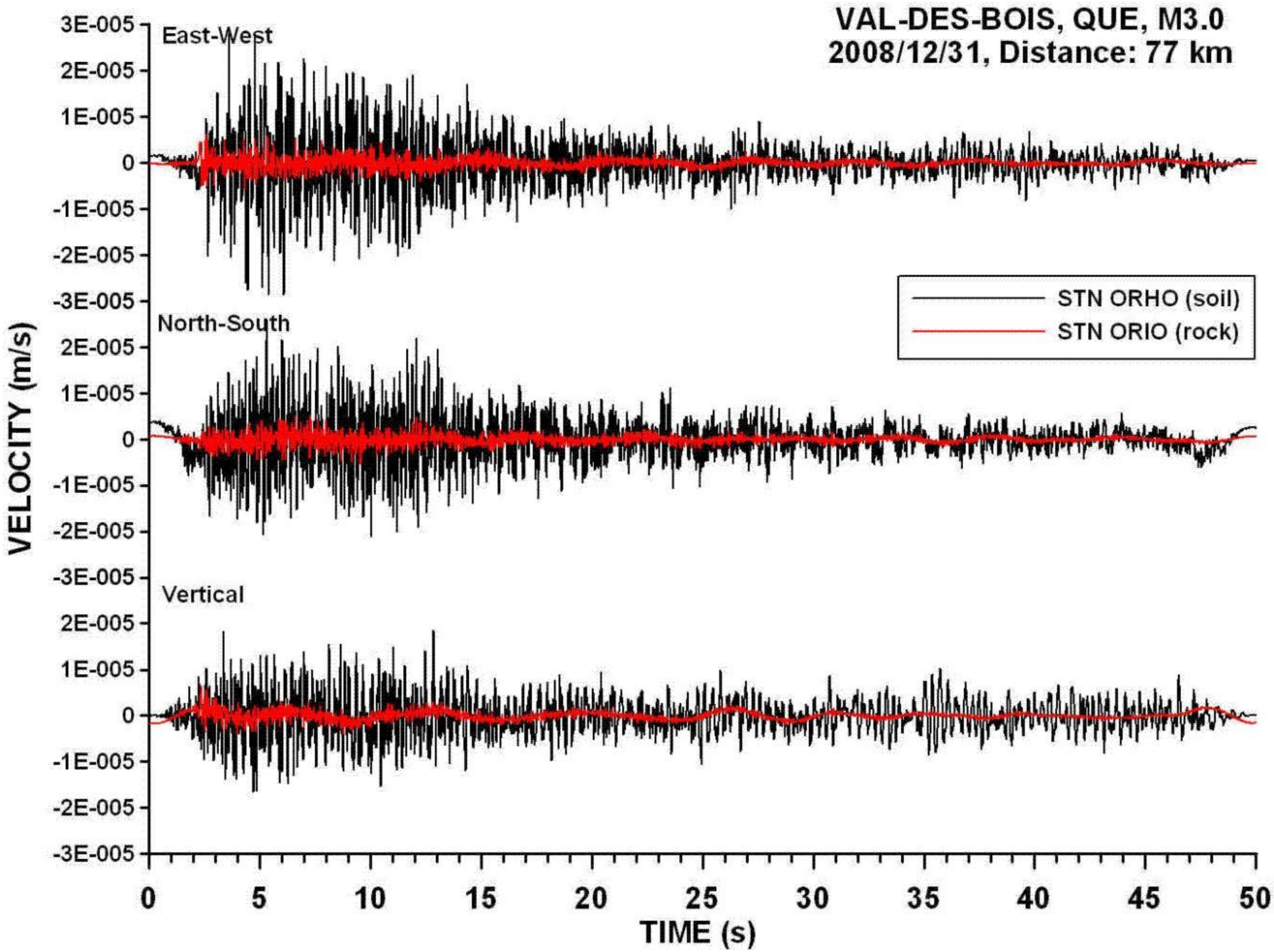


- **Let's look at the earthquake recordings**

- Carleton University and GSC have recorded many local and regional earthquakes
  - ➢ by **two nearby broadband stations** in Ottawa
  - ➢ One on 90m of soil (ORHO) and
  - ➢ one on bedrock (ORIO)
  - ➢ 1.5 km apart
  - ➢ local site conditions are different



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

- Those are small earthquakes

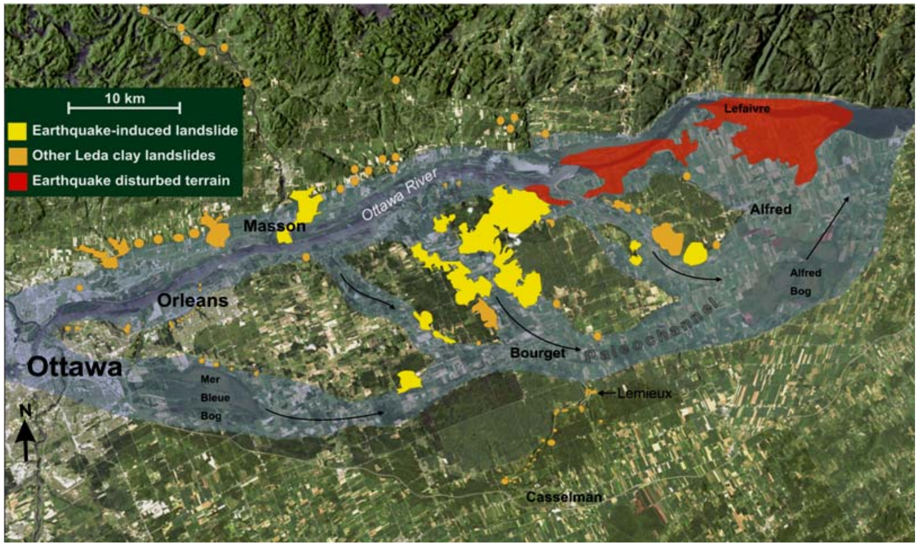
- However, **paleoseismology** of the Ottawa area suggests that **two large earthquakes** occurred in Ottawa region (GSC, Jan Aylsworth)

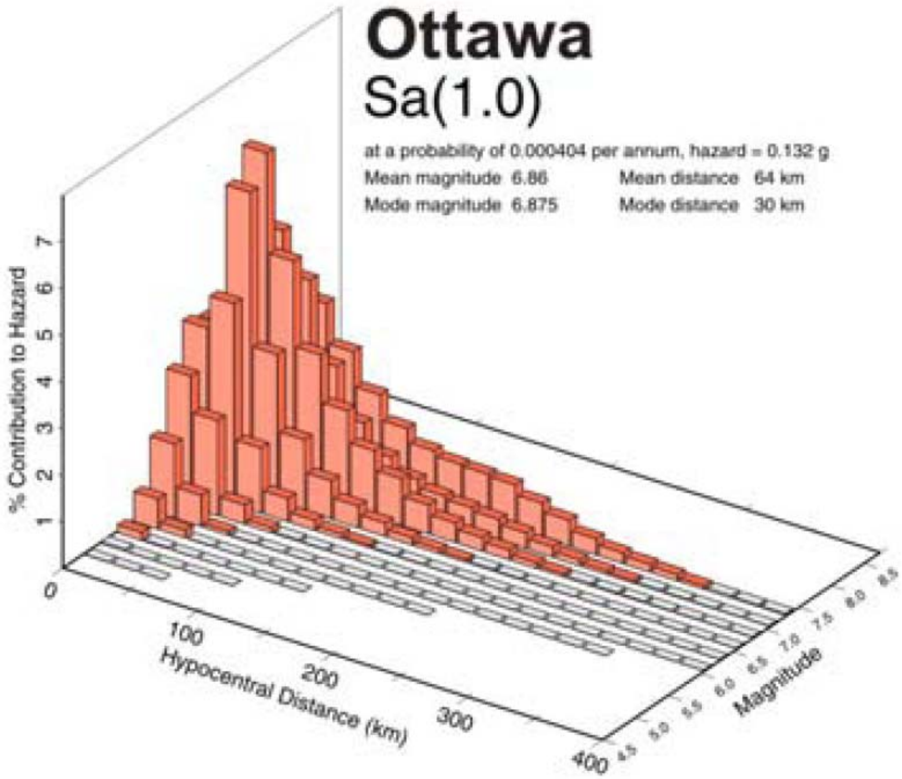
  - **4550 B.P. Event**; Evidence of several very large landslides covering areas much larger than any landslides in recent history

  - **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!**





- **NBCC 2005 Site amplification factors**

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

Site class	Values of F_a				
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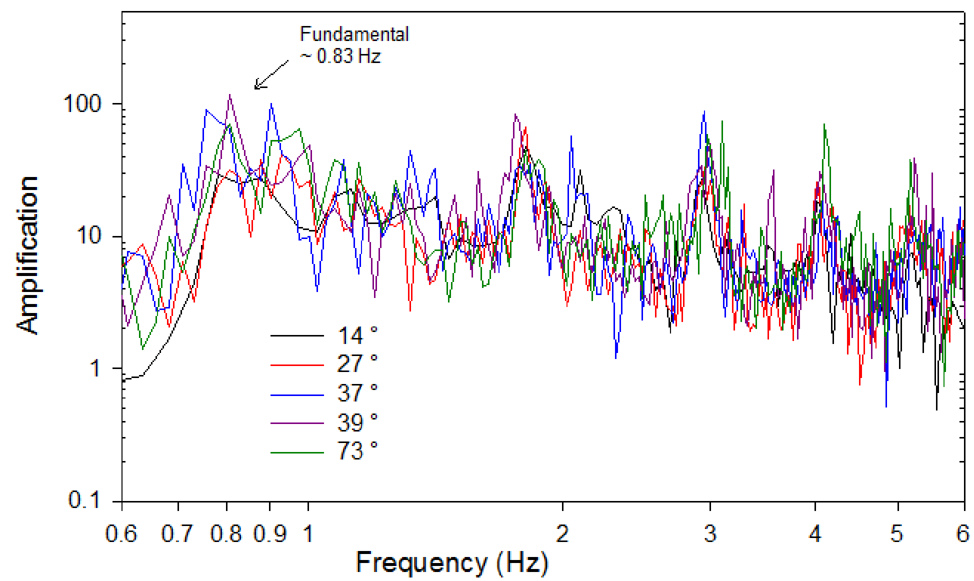
F	Site specific investigation required				

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

- But Strong motion recordings in Ottawa are sparse!



- **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

- **Two concerns**
- 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)**
    - At the **higher level of shaking** soil behaviour is **nonlinear (anelastic)**

- **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.
    - $F_a = (1050/ Vs_{30})^{a}$
    - $F_v = (1050/ Vs_{30})^{b}$

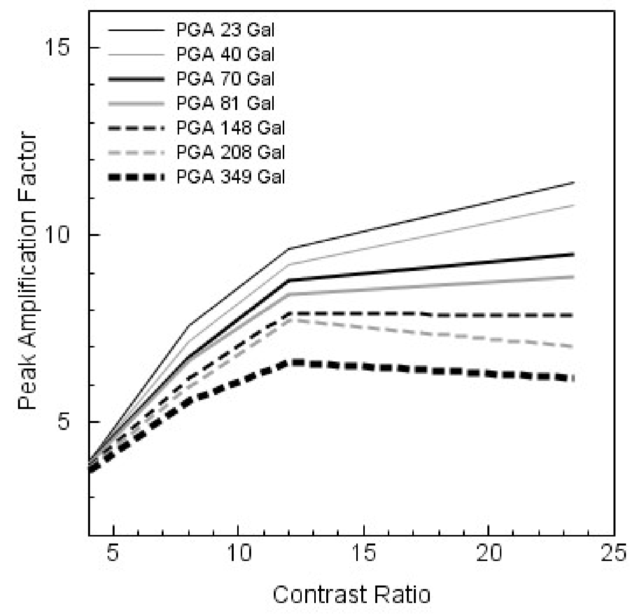
- Note : **1050** (in m/sec) is the average shear wave velocity for bedrock **(Franciscan bedrock in California).**

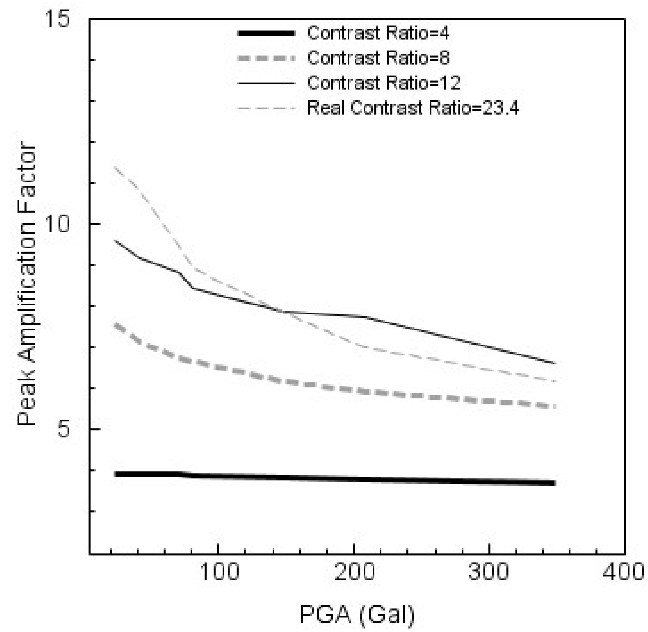
- **Sensitivity of Seismic Amplification to**
  - Contrast Ratio (z_r)
  - Level of Shaking (PGA)

- F_{f0}= (7.812-6.992 **PGA**) Log $_{10}$ z_r

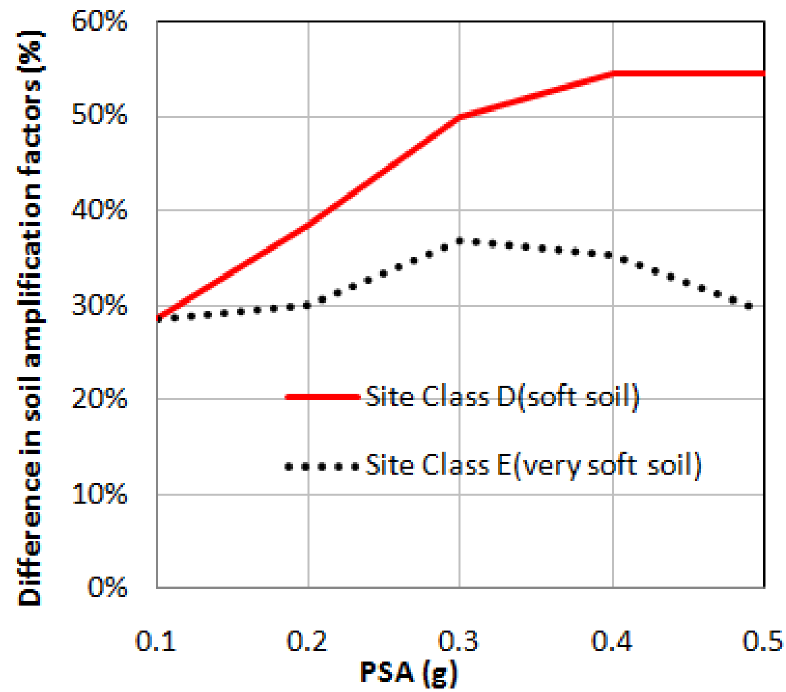
  - where
  - $4 \leq z_r \leq 36$
  - 23 Gal ≤ PGA ≤ 349 Gal.

- (R^2= 0.969)





- **Development of Regional Site Amplification Models for Eastern Canada**
- Our preliminary seismic soil amplification factors exceed the seismic soil amplifications factors given by the NBCC (2005) up to 55%



- The increase in seismic soil amplification factors for site class E (very soft soil) is less than those of site class D (soft soil), emphasizing the importance of damping and nonlinearity of very soft soil.
- This is an important finding that should be studied in detail for a broad range of frequencies and site classes using comprehensive soil modelling techniques.

- Ottawa’s Leda clay is too loose

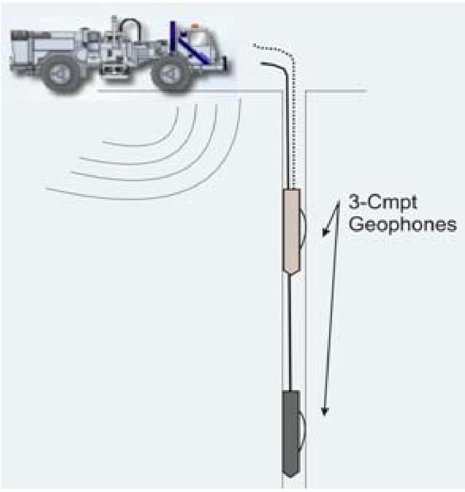
- **Does Q or damping of Leda clay make a difference**

- Is Q (or damping) for Leda clay following the general equation mainly based on a database from west?

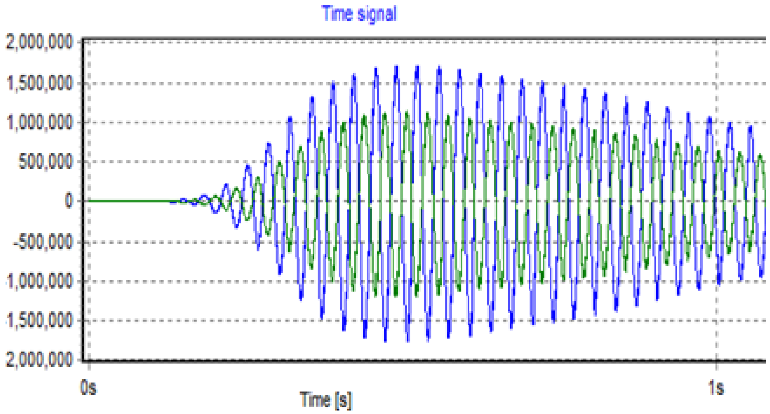
- We need to measure damping or Q which causes the nonlinearity

- **We are working on it!**

- **Measuring Q, or Soil Damping, In Situ**
- **Spectral Ratio Method for Mono-frequency Source Approach:**
  - 10Hz, 15 Hz, 20 Hz...120 Hz

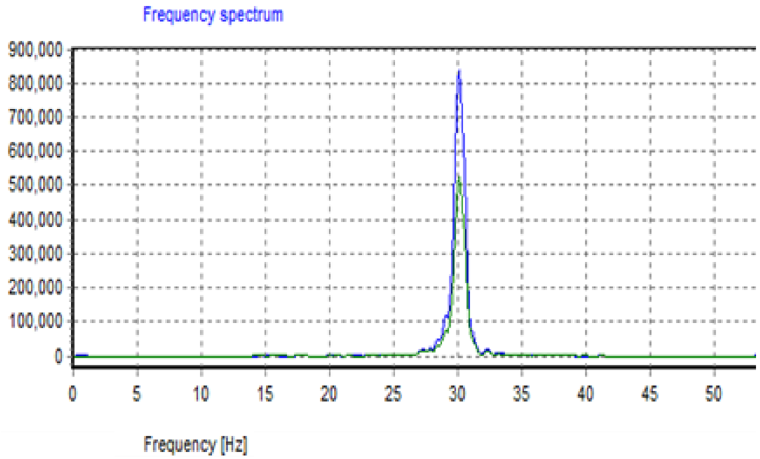


- Example 30 Hz Vibe Input
- It is recorded by **two geophones** at different depths
- Some spectral analysis
  - the peak of spectrum recorded by upper geophone
  - the peak of spectrum recorded by lower geophone
  - The difference leads you to the Quality factor of soil between two geophones



- **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