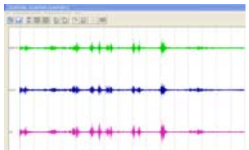
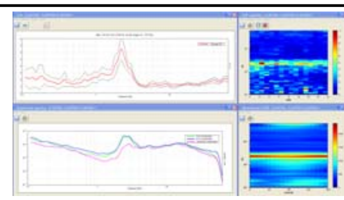
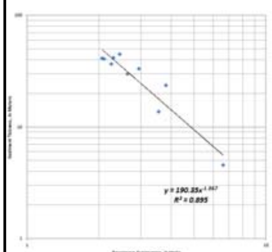




Evaluation of the Horizontal-to-Vertical Spectral Ratio (HVSR) Passive Seismic Method for Bedrock Depth Determination in Michigan

John Esch, Senior Geologist
Michigan DEQ
Office of Oil, Gas, & Minerals
Permitting & Technical Services Section
Petroleum and Mining Geology Unit



Geological Society of America
North-Central Section Meeting
Madison, Wisconsin
May 20, 2015

GEOLOGICAL SOCIETY OF AMERICA®

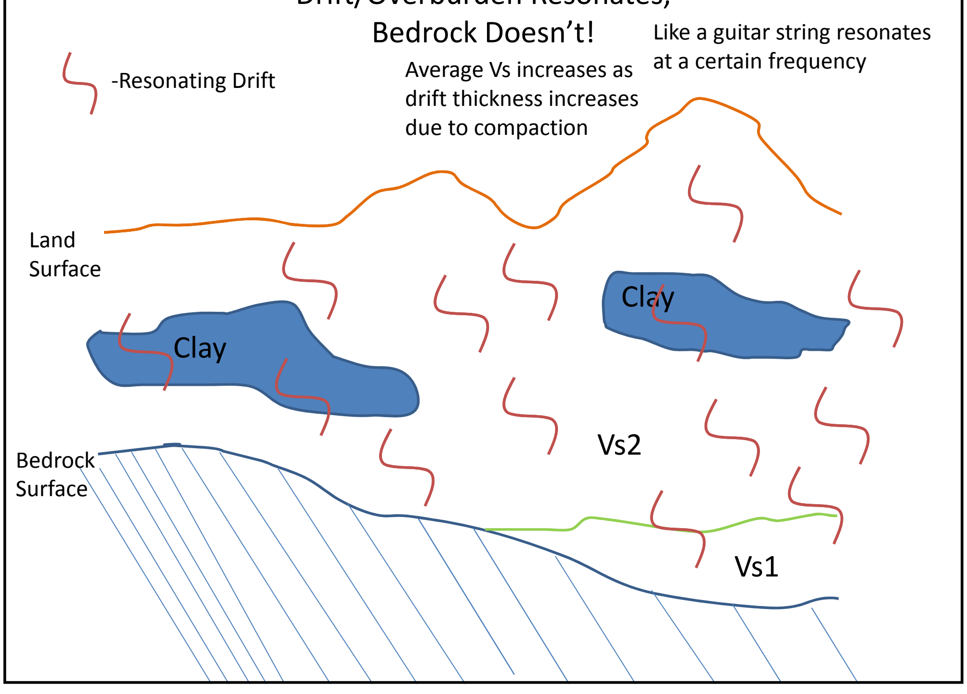
Special Thanks

- Val Chandler Minnesota Geological Survey
- John Lane USGS
- Dr. Al Kehew
- Dr. William Sauck

Bedrock Surface/Drift Thickness-Who Cares!

- Bedrock Surface: the ultimate unconformity!
- Can learn much about the geological history of an area by understanding the bedrock surface.
  - bedrock resistance
  - regional structures
  - inferences to subsurface structures
- Invaluable for geologists of many disciplines: hydrogeologists, mining geologists etc.,
- Fundamental surface for quaternary geologists

Drift/Overburden Resonates, Bedrock Doesn't!



Take home points

- HVSR- **Horizontal-to-Vertical Spectral Ratio Method**
- Passive/Ambient Seismic Technique
  - Uses natural and anthropogenic noise
- Used to Determine/Estimate Depth to bedrock (drift thickness)
- Single station measurements
- Looking for a single very sharp high amplitude peak – site resonance frequency
- $Z = Vs/4fo$
- Resonance Frequency related to bedrock depth
  - Low Frequency deeper bedrock depth
  - High Frequency shallow bedrock depth
- Calibration Points/Curve generally needed

Take home points

- How large or what defines a calibration area?
- Not a silver bullet (may not work everywhere, may give good resonance frequency but it may be due to some contact other than the top of bedrock
- Concepts proposed 1950s
- **'Nakamura' Method-**Seismic Hazards Delineation Method
- Widely adopted in 1990s (Japan and Europe)
- Introduced to USA by USGS, slow to take off
- Same instrument used for seismic hazard studies
- Drift/Overburden resonates due to noise - Bedrock doesn't!

Use in Seismic Hazard Studies

- Amplifaction___

Noise-Microtremors

This is data (noise) that seismologist filter out

- Natural
  - Wind
  - Waves
  - Distant Weather
  - Tectonic
- Anthropogenic
  - Traffic
  - Industry
  - Utilities
  - Pedestrians/Geologists
  - Airplanes (sometimes)
  - GeoProbe???
  - Ducks

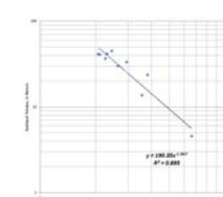
- Not Microseismic
- Not traditional seismic reflection or refraction!
- HVSR records Ambient Seismic Noise (3 components)

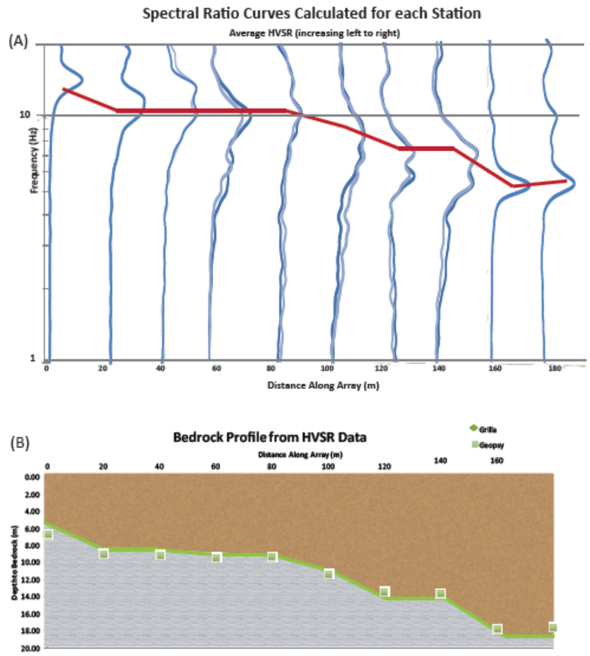
What You Can Do With the Data?

1. Collect HVSR Calibration Points at wells/borings of known bedrock depth to develop local/regional HVSR curve and HVSR Equation. Pick f_o, plot in Excel: log rock depth vs log f_o. Use local HVSR curve equation ex> $y = 328.33x^{-1.682}$ and then solve for y (depth to bedrock).
2. If Vs is Known (from some other source), gather HVSR data, pick f_o, $Z=Vs/4f_o$ solve for Z (depth to bedrock)
3. If small site w/a few bedrock depth calibration points, gather HVSR data, pick f_o, $Vs=f_o*4Z$. Solve for Vs. Calculate Vs average, then solve for h (depth to bedrock)
4. Quick and Dirty-don't need actual bedrock depths, just relative depths, plot the f_o in cross-section, contour or chart $1/f_o$, or plot the HVSR curves in cross-section
5. Make relative comparison of f0 from a reading at a known bedrock depth to single an field reading at unknown bedrock depth

Two Steps

1. Develop (local/regional) HVSR Calibration Curve
   - Take HVSR "Calibration Readings" at wells/borings with good depth to bedrock picks (water wells, oil & gas wells, environmental borings, etc.,)
   - Download/process the data & pick resonance frequency
   - Develop (local/regional) Calibration Curve of depth to rock vs resonance frequency and resulting curve equation
2. Take "Exploration Readings" at places on unknown depth to rock
   - Download/process the data & pick resonance frequency
   - Plug resonance frequency into Calibration Curve Equation in Step 1 above and solve for depth to rock

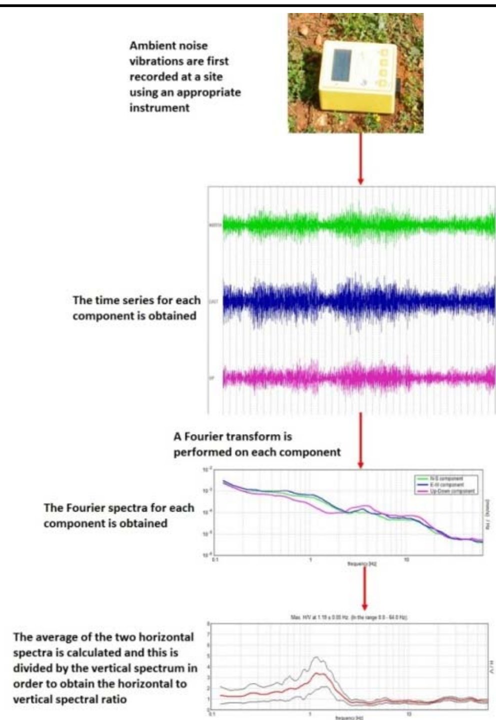




Qualitative Interpretation of Bedrock Depth Without Calibration Curve

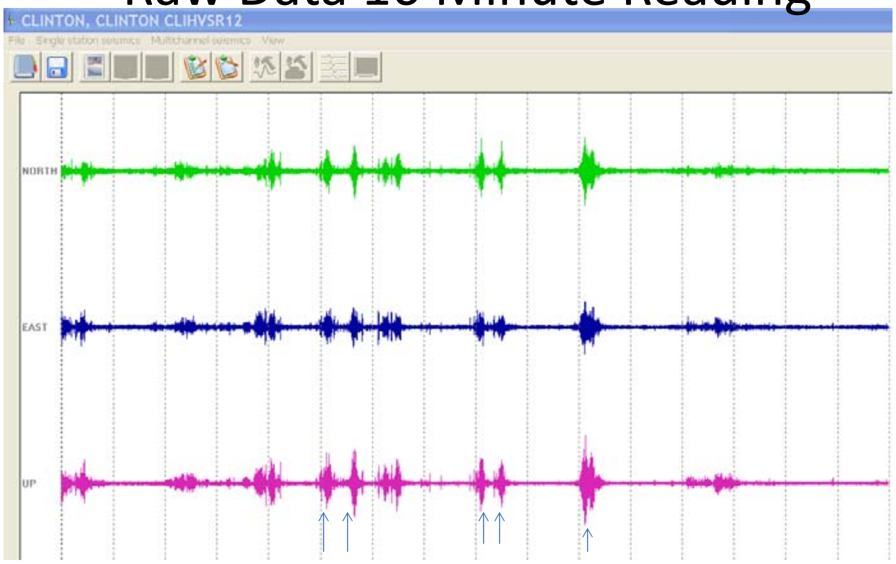
Still provides useful information

Sarah L.C. Morton, Lanbo Liu, John W. Lane Jr., Emily B. Voytek, 2012, NEAR-SURFACE SITE CHARACTERIZATION OF THE FENTON RIVER WELLFIELD IN EAST CENTRAL CONNECTICUT USING MULTIPLE GEOPHYSICAL TECHNIQUES, Northeastern Section - 47th Annual Meeting (18–20 March 2012), Geological Society of America Abstracts with Programs, Vol. 44, No. 2, p. 47



http://www.um.edu.mt/science/physics/smru/generalinformation/hvsrmethod

Raw Data 16 Minute Reading



Cars driving by

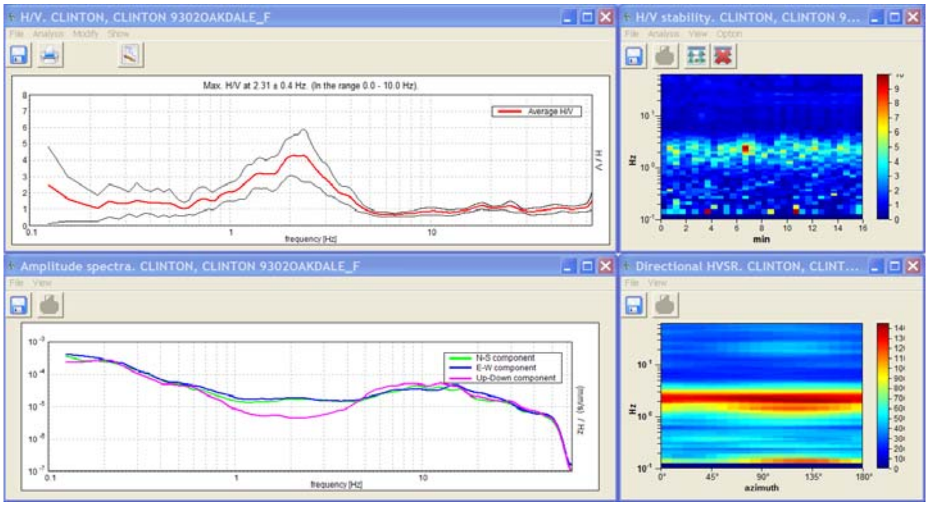
Looking For:

- Single high amplitude sharp peak
- With "eye" anomaly directly below peak.
  Horizontal: EW & NS curves track together
  Vertical curve under peak less
- Left side lower frequency-deeper to rock
- Right side higher frequency-shallower to rock

Example of a good peak

HORIZONTAL TO VERTICAL SPECTRAL RATIO

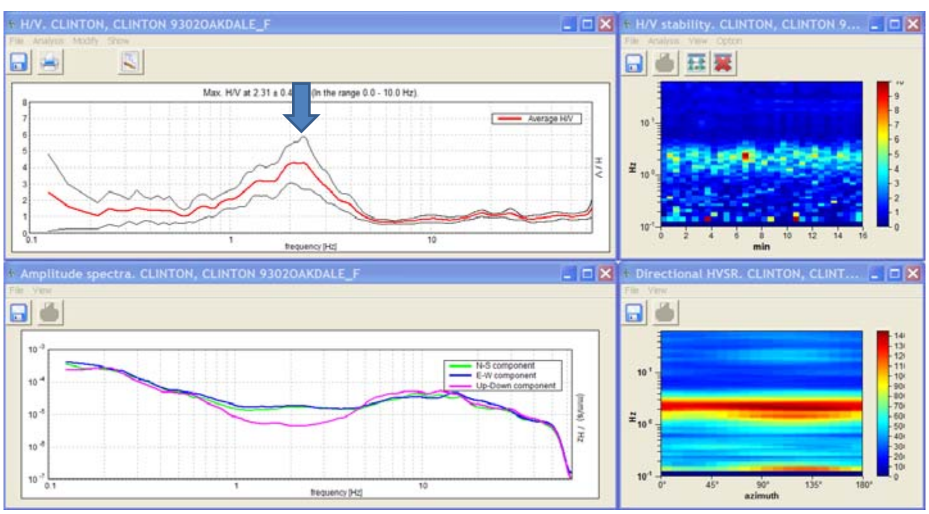
H/V TIME HISTORY



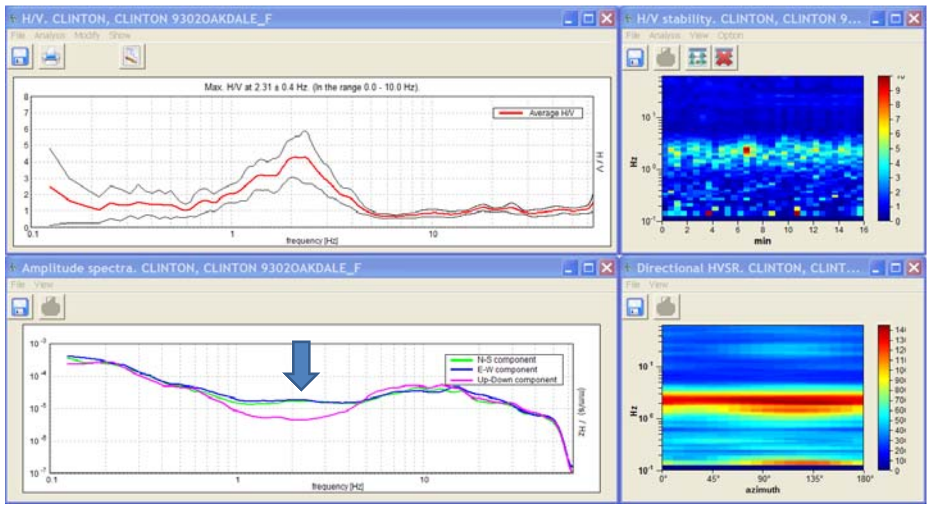
SINGLE COMPONENT SPECTRA

DIRECTIONAL H/V

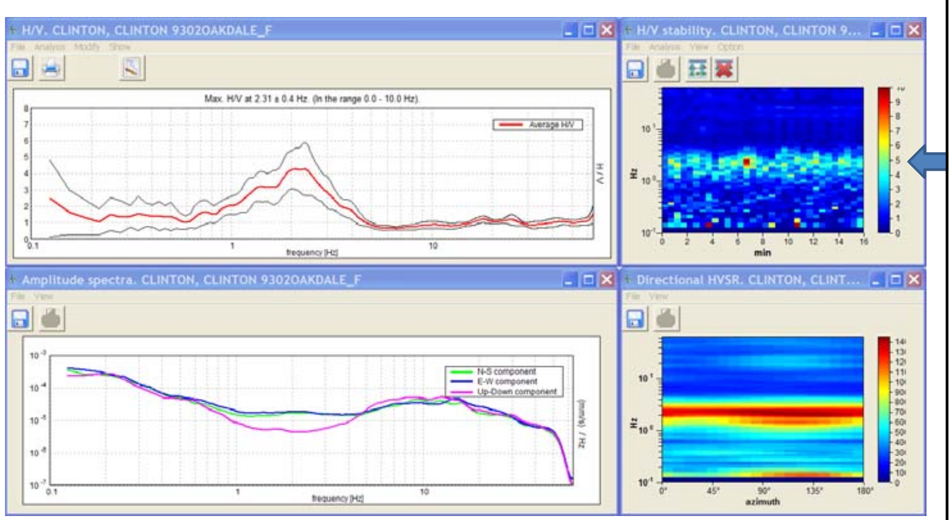
Example of a good peak



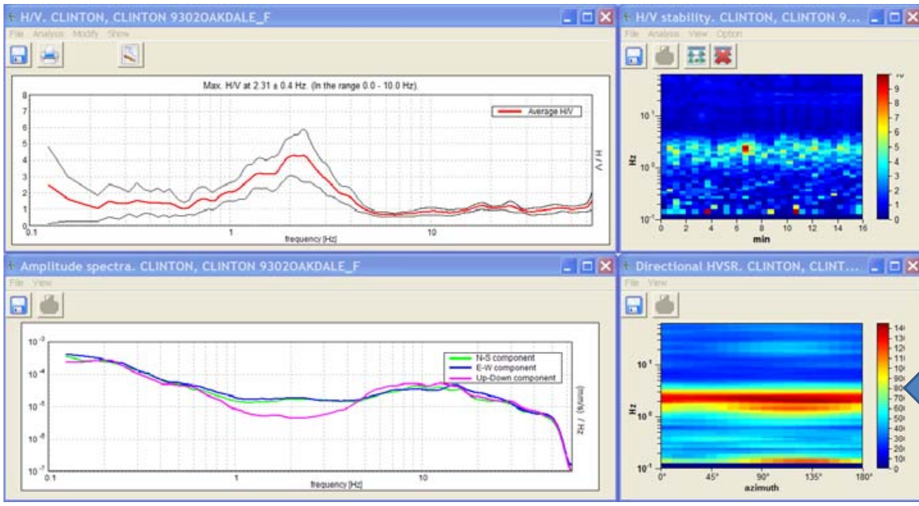
Example of a good peak



Example of a good peak

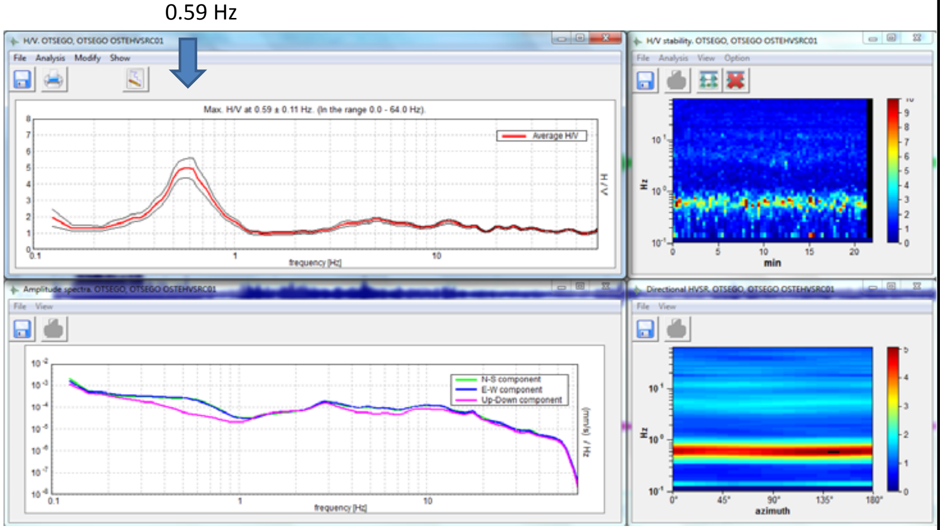


Example of a good peak

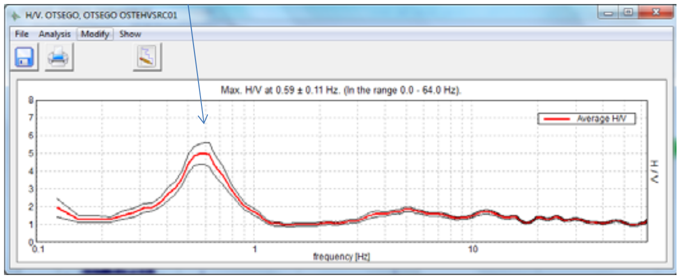


Otsego County-Waters Area, PN 42886
Thick Drift Area: 778’ still getting good results

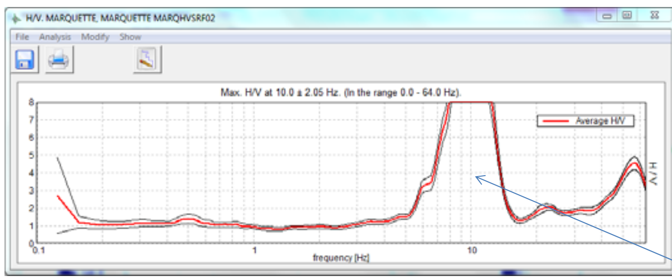
0.59 Hz



LOWER FREQUENCY PEAK
DEEPER TO BEDROCK



Otsego Co.
Waters area
Rock @778’

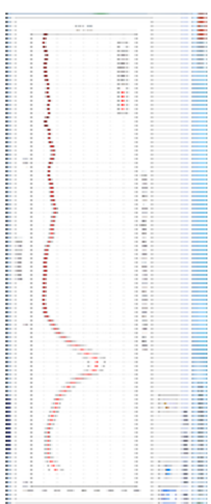


Marquette Co.
Sands Area
Rock @10’

HIGHER FREQUENCY PEAK
SHALLOWER TO BEDROCK

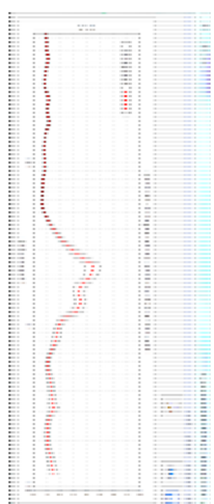
LOWER FREQUENCY PEAK
DEEPER TO BEDROCK

Otsego Co.
Waters area
Rock @778’

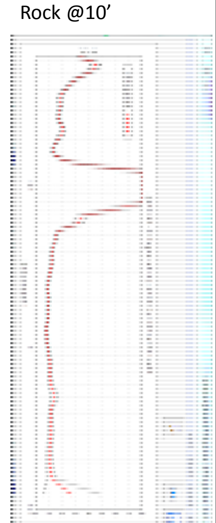


Roscommon Co,
Higgins Lake area
Rock @400’

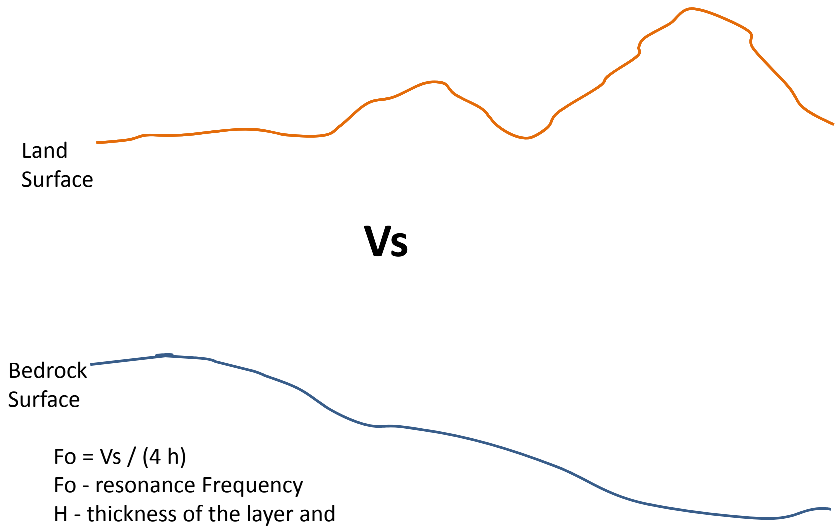
Clinton Co.
Laingsburg area
Rock @120’



Marquette Co.
Sands Area
Rock @10’



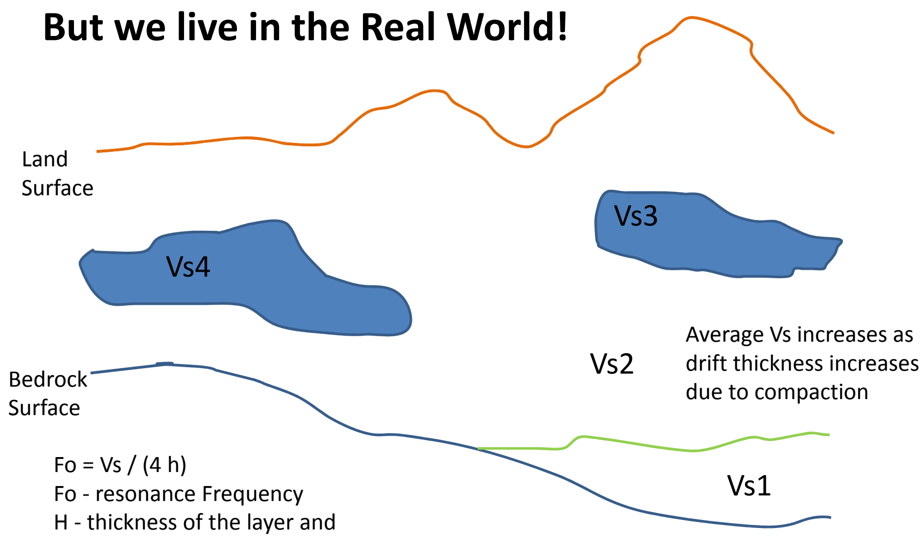
Equation Assumes a Simple 1 Layer over Bedrock ½ Space and a Single Shear Wave Velocity (Vs) for this layer



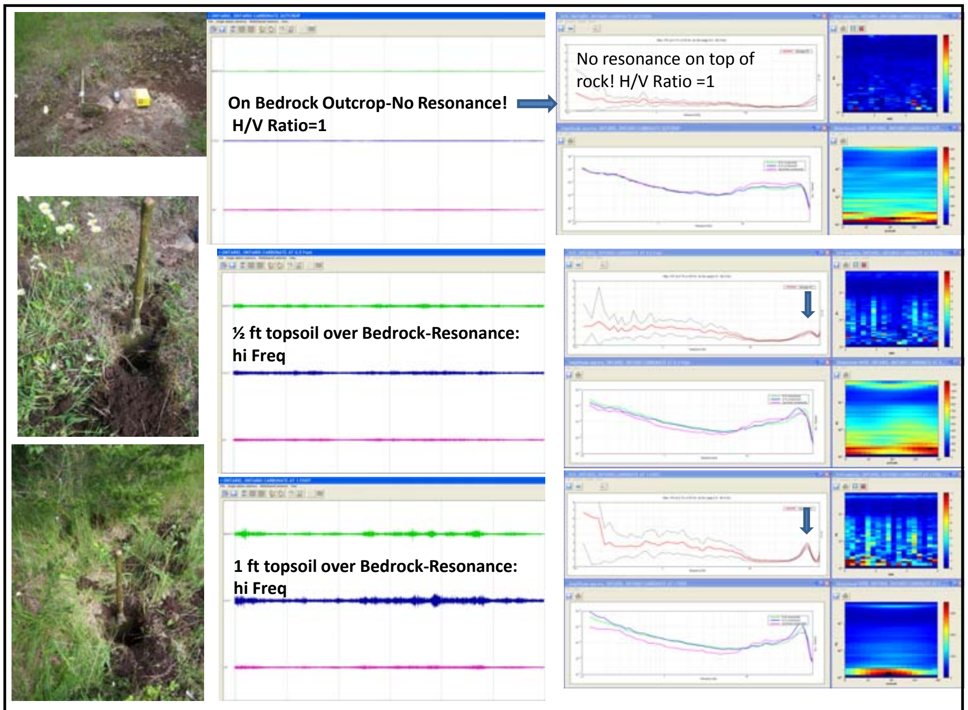
Fo = Vs / (4 h)
Fo - resonance Frequency
H - thickness of the layer and
Vs - shear wave velocity

Equation Assumes a Simple 1 Layer over Bedrock ½ Space and a Single Shear Wave Velocity (Vs) for this layer

But we live in the Real World!



Fo = Vs / (4 h)
Fo - resonance Frequency
H - thickness of the layer and
Vs - shear wave velocity



Deeper bedrock depth or overly noisy area Sample longer

- 0-50 feet (0-15 m) 6 min
- 50-130 feet (15-40 m) 8 min
- 130-300 feet (40-90 m) 12-14 min
- 300-500 feet (90-150 m 14-16 min
- 500-800 feet (150-240 m) 16-20 min
- 800-1300 feet (240-390 m) 20 min
  - Longer sample-better, can remove too noisy periods,
  - Shorter sample-length can collect more samples
  - USGS samples for 30 minutes
  - Minnesota Geological Survey samples for 20 minutes

Acoustic Impedance Contrast

- Need Strong Acoustic Impedance Contrast between drift/bedrock or regolith/bedrock
- Assumed to need 2.5 x higher bedrock than drift
- Acoustic Impedance Contrast
  - Velocity
  - Density
- So in theory a lacustrine clay or till over a weathered shale likely doesn't have as good an impedance contrast as a sand over unweathered granite.

HVSR Equation

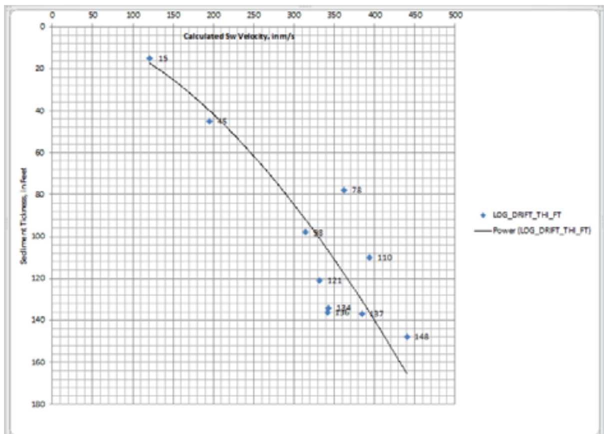
- $V_s = f_o * 4Z$

  $f_o = V_s / (4\ Z)$
- $Z = V_s / 4f_o$

- f_o Resonance Frequency
- Z Thickness of the layer (depth to rock)
- Vs (the shear wave velocity in the same layer)

Vs - Shear Wave Velocity

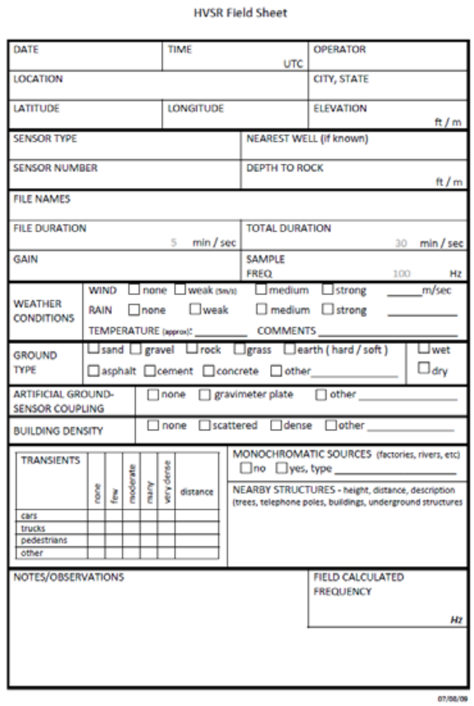
- clay has Vs typically 100-180 m/s,
- sand has Vs typically 180-250 m/s,
- gravel has Vs typically 250-500 m/s



- Drift thickness Dependent
- Thus: Compaction
- Michigan Vs Ranges
  - 50 m/s
  - 700 m/s

Taking a Reading in the Field

- Select site
- Remove topsoil and loose dirt if necessary
- Set instrument on ground, orient instrument north
- Level seismometer bubble level, good coupling is critical
- Turn on instrument and set sample length, sensitivity (gain) and frequency
- Record current partition on log sheet
- Set timer on your watch to match the sample length
- Setup anemometer to measure wind speed during reading (max and ave) if wind is >14 mph, may be too windy (too much noise). If no wind don't need to measure wind speed.
- Start reading and start timer on watch ~ same time
- Walk a safe distance away and try to remain stationary as possible during reading (see note on dancing).
- Fill out HVSR log sheet: Station ID, location info, noise sources and distances, calibration/field reading, specific transient noise events: "car 250' south @ 4:30, 4:35, 6:10…"
- When reading is finished (watch timer beeps) turn off instrument, pack up and put in case.
- Collect GPS location of site, record wind speed (max and ave) on log sheet


HVSR Field Sheet

DATE | TIME UTC | OPERATOR

LOCATION | CITY, STATE

LATITUDE | LONGITUDE | ELEVATION ft / m

SENSOR TYPE | NEAREST WELL (if known)

SENSOR NUMBER | DEPTH TO ROCK ft / m

FILE NAMES

FILE DURATION 5 min / sec | TOTAL DURATION 30 min / sec

GAIN | SAMPLE FREQ 100 Hz

WEATHER CONDITIONS
WIND ☐ none ☐ weak (5m/s) ☐ medium ☐ strong ____m/sec
RAIN ☐ none ☐ weak ☐ medium ☐ strong ________
TEMPERATURE (approx): ________ COMMENTS ________

GROUND TYPE
☐ sand ☐ gravel ☐ rock ☐ grass ☐ earth (hard / soft) ☐ wet
☐ asphalt ☐ cement ☐ concrete ☐ other________ ☐ dry

ARTIFICIAL GROUND-SENSOR COUPLING ☐ none ☐ gravimeter plate ☐ other ________

BUILDING DENSITY ☐ none ☐ scattered ☐ dense ☐ other ________

TRANSIENTS	none	few	moderate	many	very dense	distance
cars						
trucks						
pedestrians						
other						

MONOCHROMATIC SOURCES (factories, rivers, etc)
☐ no ☐ yes, type ________

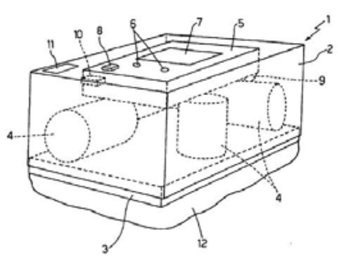
NEARBY STRUCTURES - height, distance, description (trees, telephone poles, buildings, underground structures

NOTES/OBSERVATIONS | FIELD CALCULATED FREQUENCY Hz

07/08/09

Tromino

- Small
- Simple
- AA batteries
- Inexpensive
- 3 Component Geophone NS, SW, V



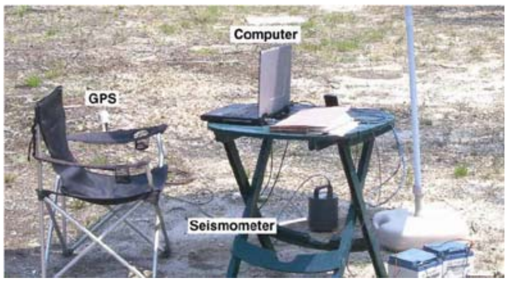
Horizontal-to-Vertical (H/V) ambient-noise seismic method for estimation of bedrock depth

Three-component seismometer connected to field laptop for H/V seismic surveys

This is my kind of field work!

Lane, J.W., Jr., White, E.A., Steele, G.V., and Cannia, J.C., 2008, Estimation of bedrock depth using the horizontal-to-vertical (H/V) ambient-noise seismic method, *in* Symposium on the Application of Geophysics to Engineering and Environmental Problems, April 6-10, 2008, Philadelphia, Pennsylvania, Proceedings: Denver, Colorado, Environmental and Engineering Geophysical Society, 13 p.

Which would you prefer?



or

No Rock & Roll and Especially no Dancing!

"Concerning the recording team,...not good to forget to turn the car engine off, and that while it is not a problem to listen to music while waiting for the data to be recorded, as long as it is not too loud, **it is recommended not to dance around the sensor, even though the music is great**."

Chatelain J-L, etal, 2008, Evaluation of the influence of experimental conditions on H/V results from ambient noise recordings, Bulletin of Earthquake Engineering February 2008, Volume 6, Issue 1, pp 33-74

Should have had a beer while waiting for the reading to finish

Not All Readings Have a Single High Amplitude Peak

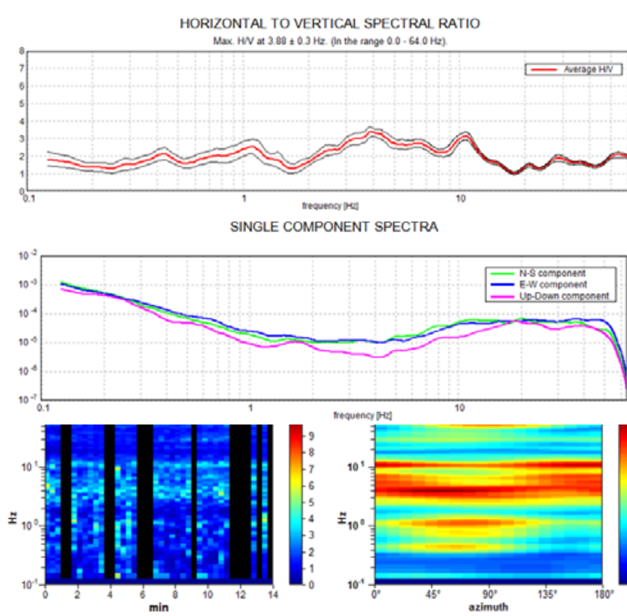
- Bart Simpson Peaks
- Multiple Smaller Peaks on a Broad Low Amplitude Peak
- Multiple Peaks-Indicating Different Units
  - Generally Pick the Lowest Amplitude Peak (but not always)
  - Can often use 1^{st} Trough/2 to help in selecting correct one
  - Simple back of envelope calculation
    - Fo ~ 40 hz ~ 2’
    - Fo ~ 20 hz ~10’
    - Fo ~ 10 hz ~ 25’
    - Fo ~ 2 hz ~ 120’
    - Fo ~ 1 hz ~ 300’
    - Fo ~ 0.5 hz ~ 900’

Qualitative

- Very Good
- Good
- Fair
- Poor
- No Peak

- Single Peak
- Compound Peak on Hump
- Multiple Peaks (Bart Simpson hair)
- Low Amplitude Peak (usually broad)

Multiple Peaks (Bart Simpson hair)

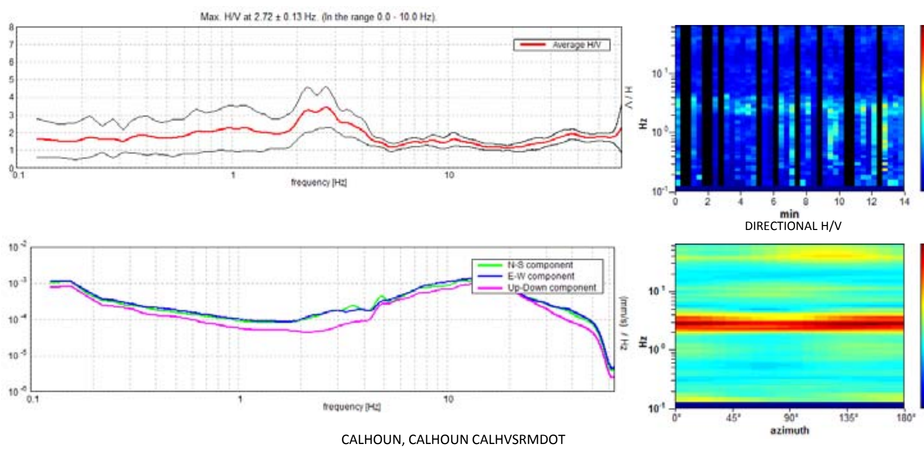


Calhoun County

Not all data is great

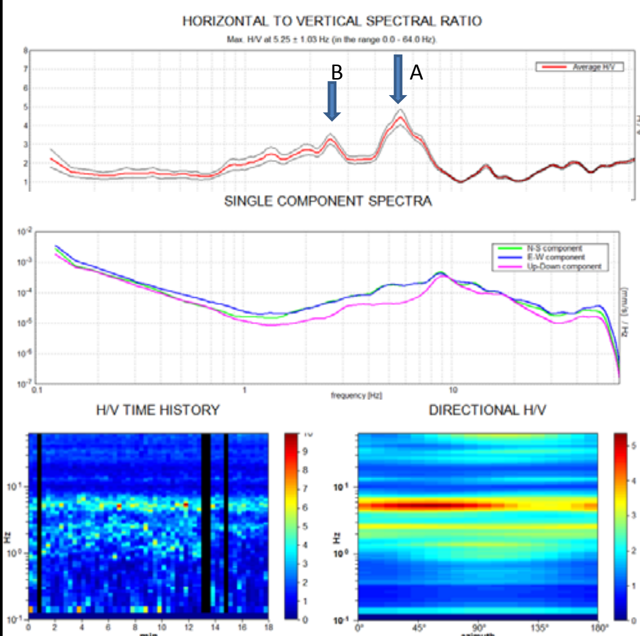
HORIZONTAL TO VERTICAL SPECTRAL RATIO

H/V TIME HISTORY



CALHOUN, CALHOUN CALHVSRMDOT

The Highest Amplitude isn't Always the Top of Bedrock



Calibration well
rock at 157'

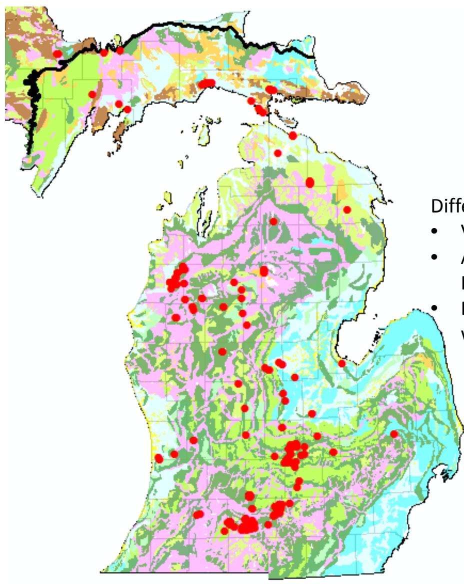
A bigger peak 5.25 hz
Results in rock at 76.3'

B subtle peak 2.47 hz
Results in rock at 165'

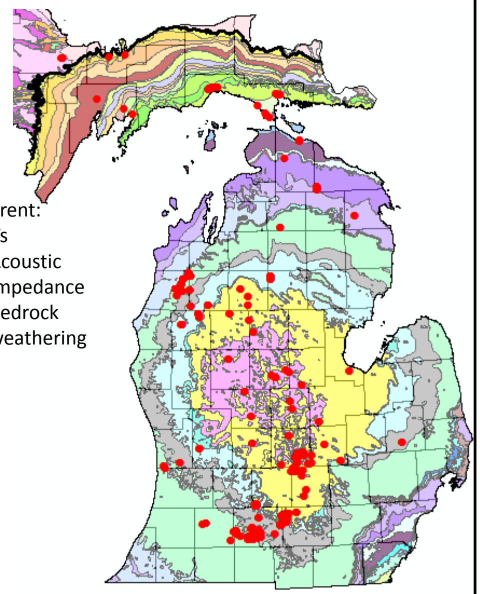
WASAS28C

Different

Glacial Deposits Bedrock



Different:
- Vs
- Acoustic Impedance
- Bedrock weathering



Why HVSR?

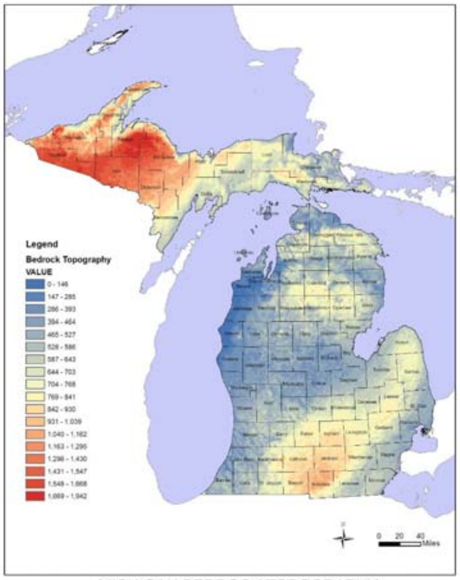
- To add additional control for bedrock topography and drift thickness mapping
- Poor bedrock depth control over large areas
  - Northern Schoolcraft County, Leelanau & Monroe Counties
- Anomalous bedrock highs or lows
- Better define bedrock valleys
- Cheaper then other drilling and geophysical techniques (seismic refraction)
- Poor quality of bedrock depth control in certain areas
  - Central basin area
  - Calhoun County oil and gas well data..

Why HVSR 2?

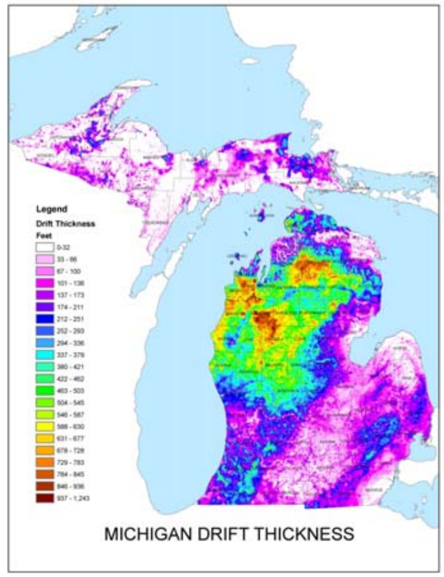
- Geological mapping
  - Quaternary
  - Bedrock Geology mapping – in mostly drift covered areas like Michigan- how much more effective will the mapping be if it is done in the context of mapping the bedrock topography at the same time
- Oil and gas exploration
- Minerals exploration
- Groundwater exploration
- Groundwater contaminant investigations
- Site characterization
- Geotechnical/engineering… (pipeline planning Western U.P. …)

Bedrock Valleys/Bedrock Surface

- Oil an Gas Well Drilling Casing/cementing 1st line of defense
- Blowout-Marshall 1968
- Contamination sinker-brine bedrock valleys
- Drift Gas in areas down dip from Antrim subcrop can come from bedrock valleys
- Water Withdrawal Tool doesn't handle shallow bedrock or bedrock valleys
- Industry wants this data for seismic static correction
- Mining industry wants this data

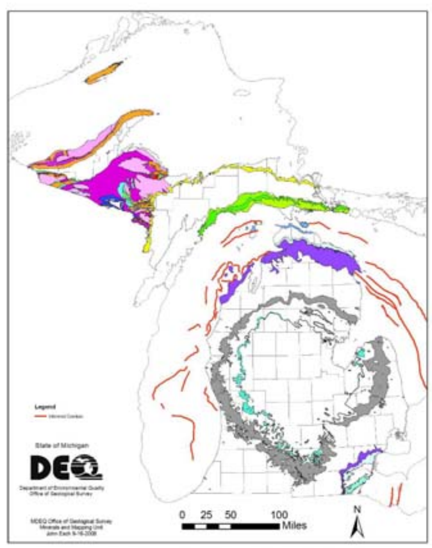


MICHIGAN BEDROCK TOPOGRAPHY



MICHIGAN DRIFT THICKNESS

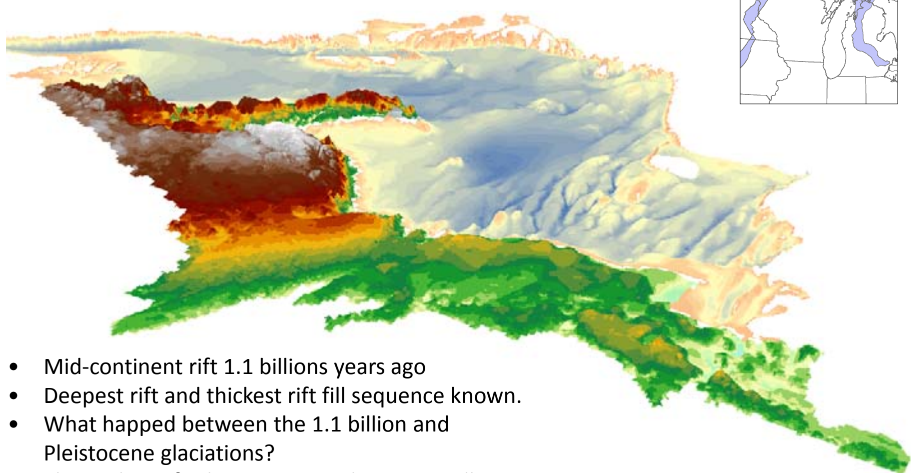

MICHIGAN BEDROCK VALLEYS

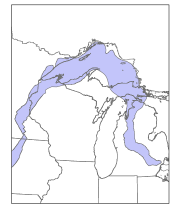


MICHIGAN CUESTA AND RIDGE FORMING FORMATIONS

Upper Peninsula Bedrock Topography and Lake Superior Bathymetry

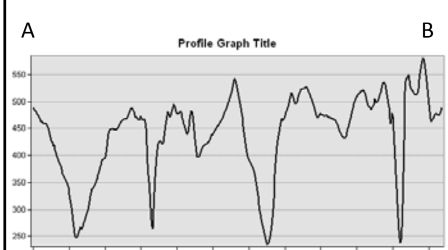
What the hell is going on under Lake Superior?



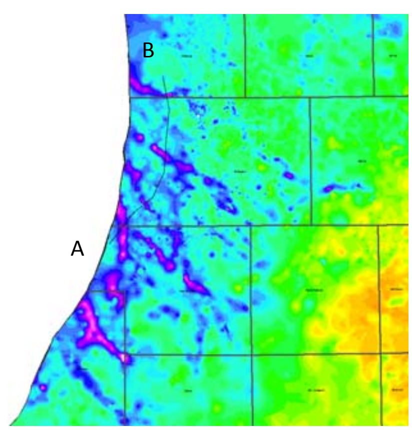


- Mid-continent rift 1.1 billions years ago
- Deepest rift and thickest rift fill sequence known.
- What happed between the 1.1 billion and Pleistocene glaciations?
- The outline of Lake Superior today essentially demarcates a portion of the rift.

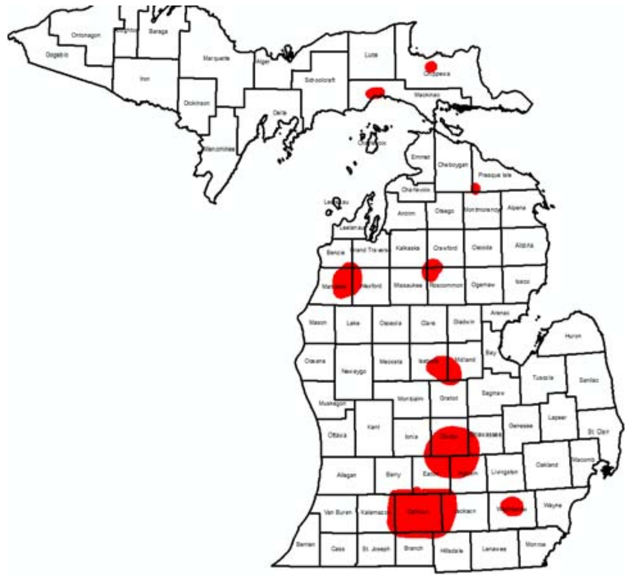
Bedrock Topography SW MI



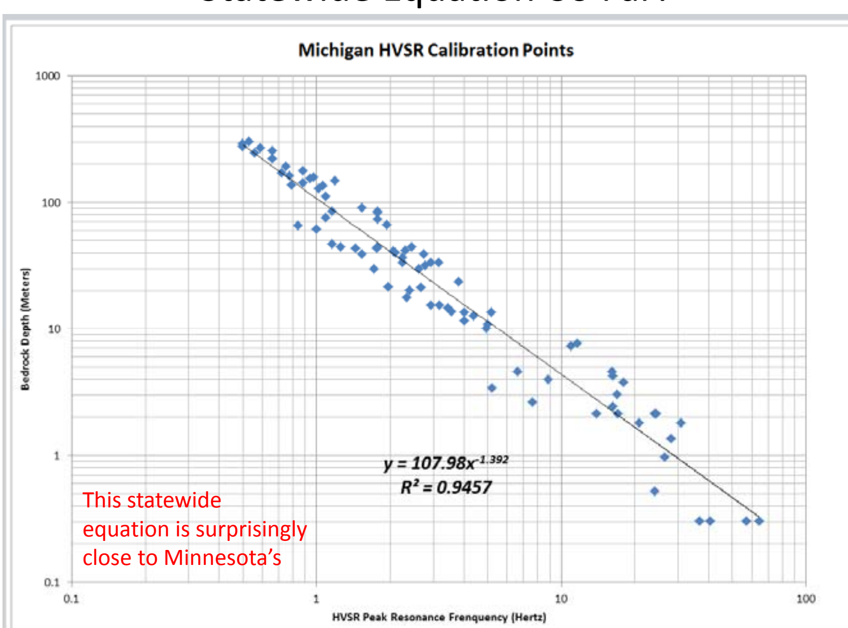
Do these look similar to the deep valleys in Lake Superior?

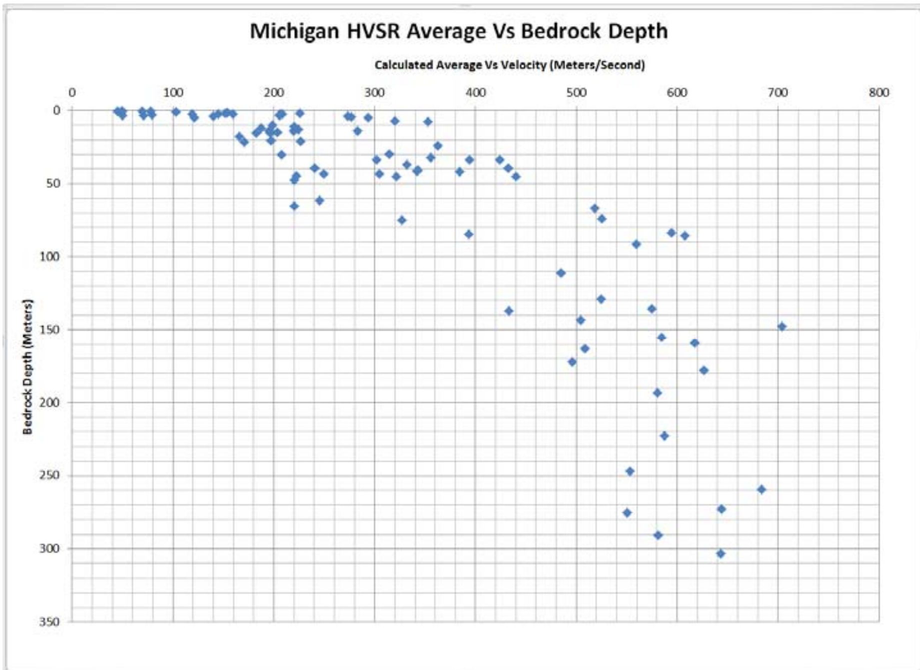


HVSR Example Areas



Statewide Equation-So Far!

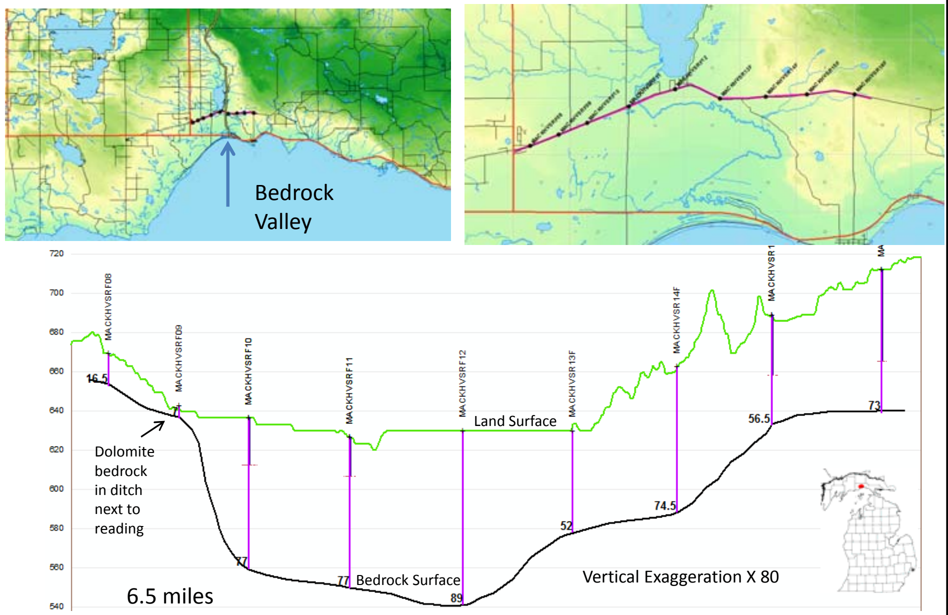




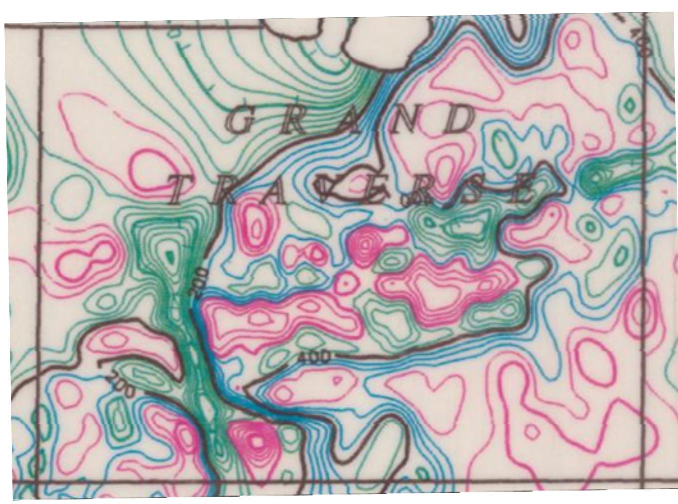
Examples

- Hiawatha Trail bedrock valley U.P.
- 500 feet deep bedrock valley and thickest drift in North America-Grand Traverse County
- Bellevue, Eaton County-pseudo sinkhole
- Former Raco Airbase, Chippewa County
- Presque Isle County-Sinkholes Pathway
- Used to constrain geophysics data
- Western Ann Arbor
- Kalamazoo Moraine transects (Dr. Sauck, WMU)
- South Manitou Island

Hiawatha Trail HVSR Bedrock Elevation Profile, W. of Engadine

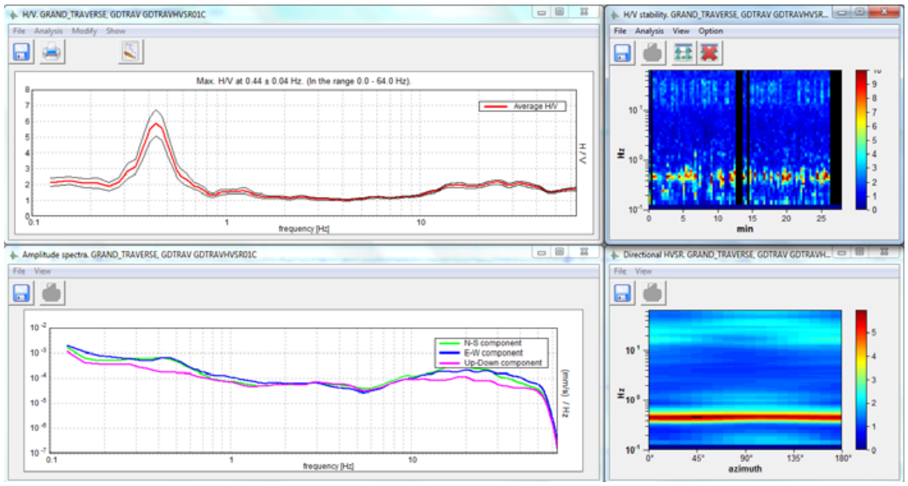


Grand Traverse County Bedrock Topography



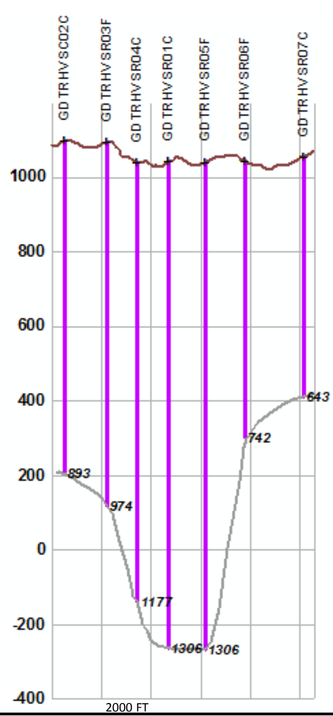
- 550 feet deep bedrock valley
- 1300’ thickest drift on land in North America
- Crossing bedrock valleys indicating two generations of erosion
- Other bedrock valleys at much higher elevation
- Bedrock valley underlie the Boardman River (rare in thick drift areas)

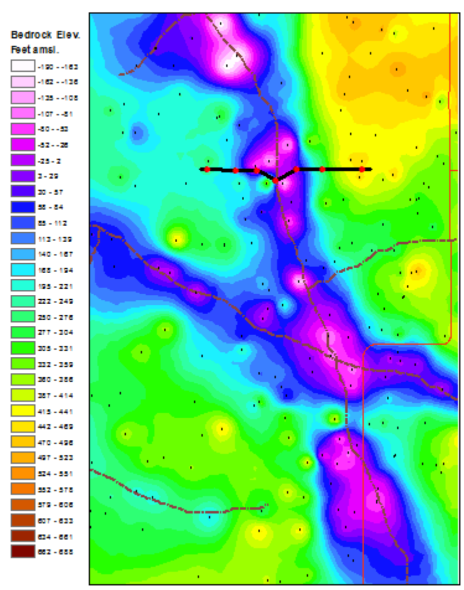
Thickest Drift on Land in North America >1320 ft (400 m)
Still getting good data!



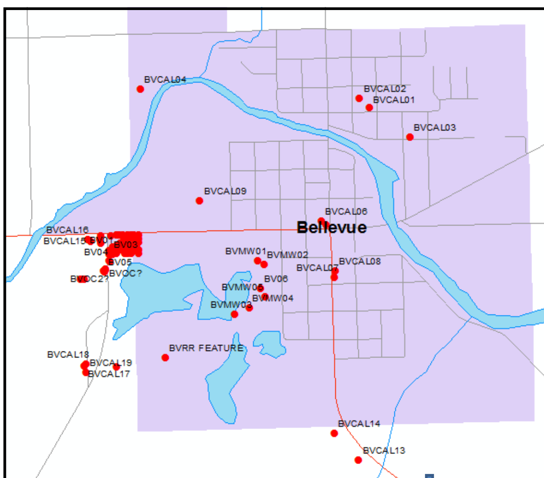
Likely the thickest test of this technique in North America

Thickest Drift on Land in North America >1320 ft (400 m)
2 Crossing Bedrock Valleys
400-550 feet deep bedrock valley

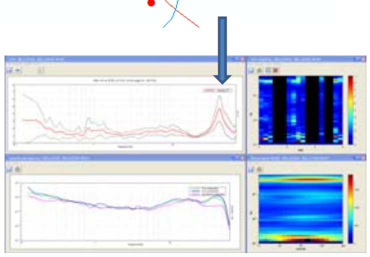




Bellevue "Sinkhole"? SW Eaton County



BV47 Resonance Frequency 39.6 hz



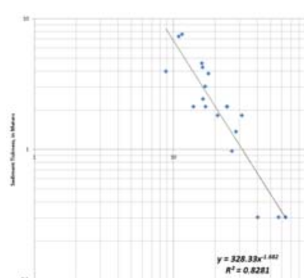
Bellevue Area HVSR Calibration Curve
$y = 328.33x^{-1.682}$

Insert 39.6 into equation for X and solve for Y (meters)

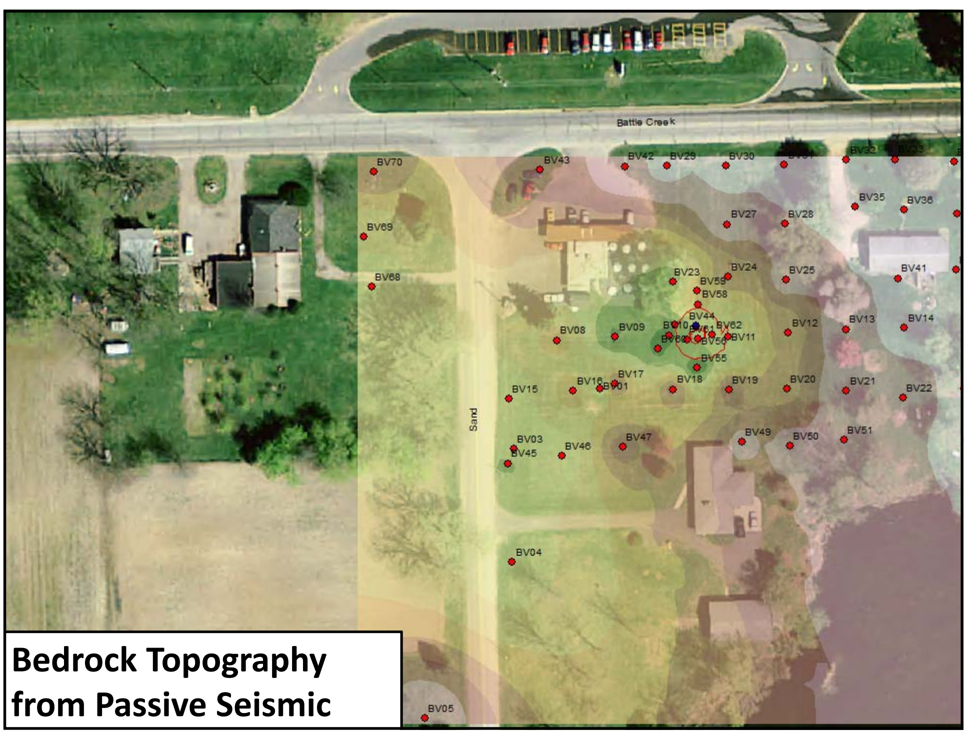
Then convert to feet

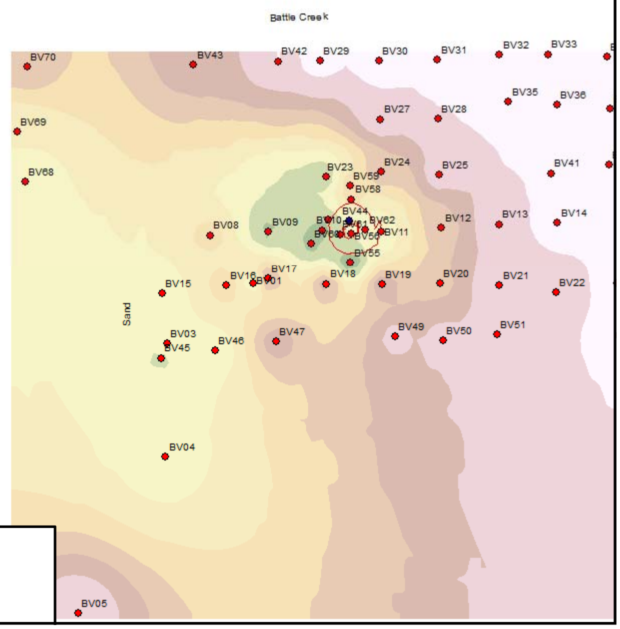
Bedrock depth ~2.2 feet

19 Calibration Points



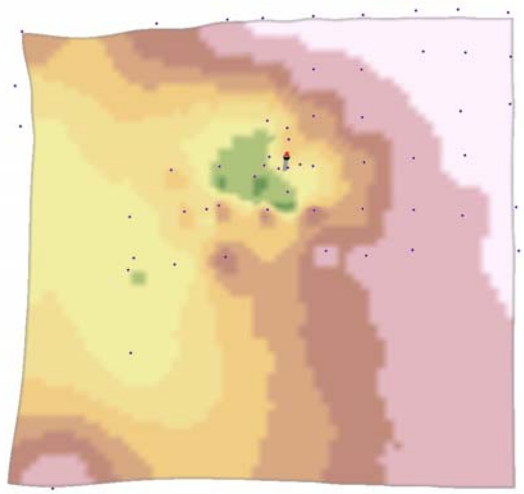

Battle Creek
Sand
Passive Seismic Stations


Battle Creek
Sand
Bedrock Topography from Passive Seismic

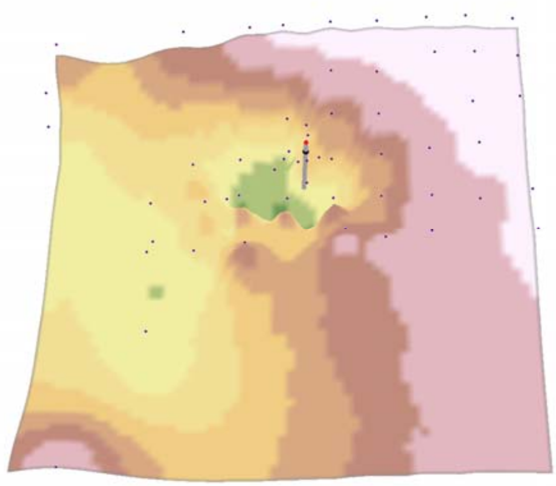


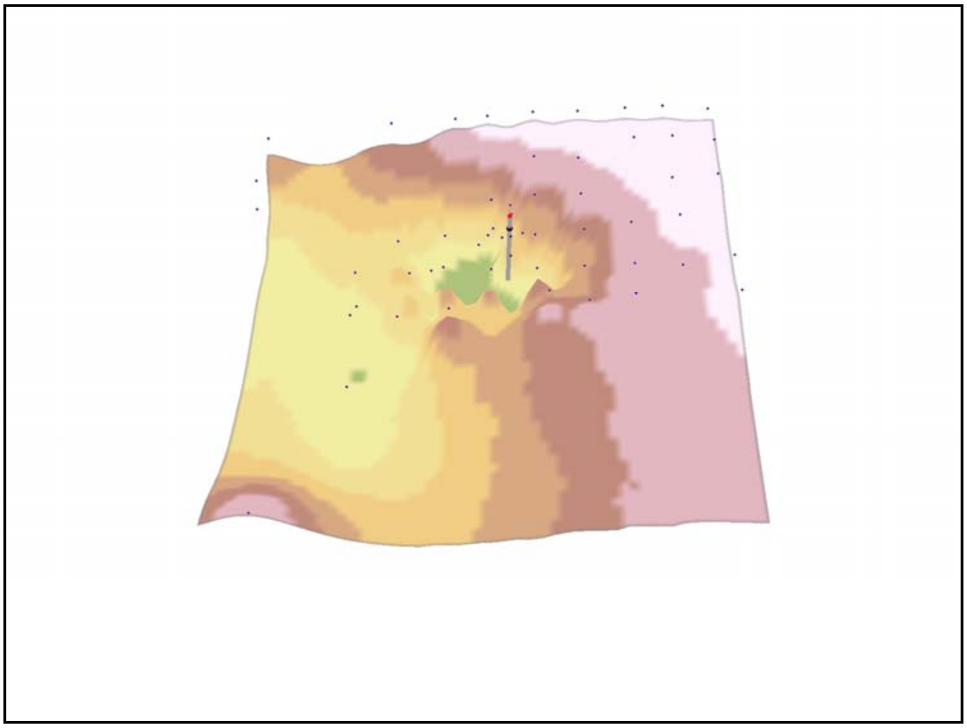
Bedrock Topography from Passive Seismic

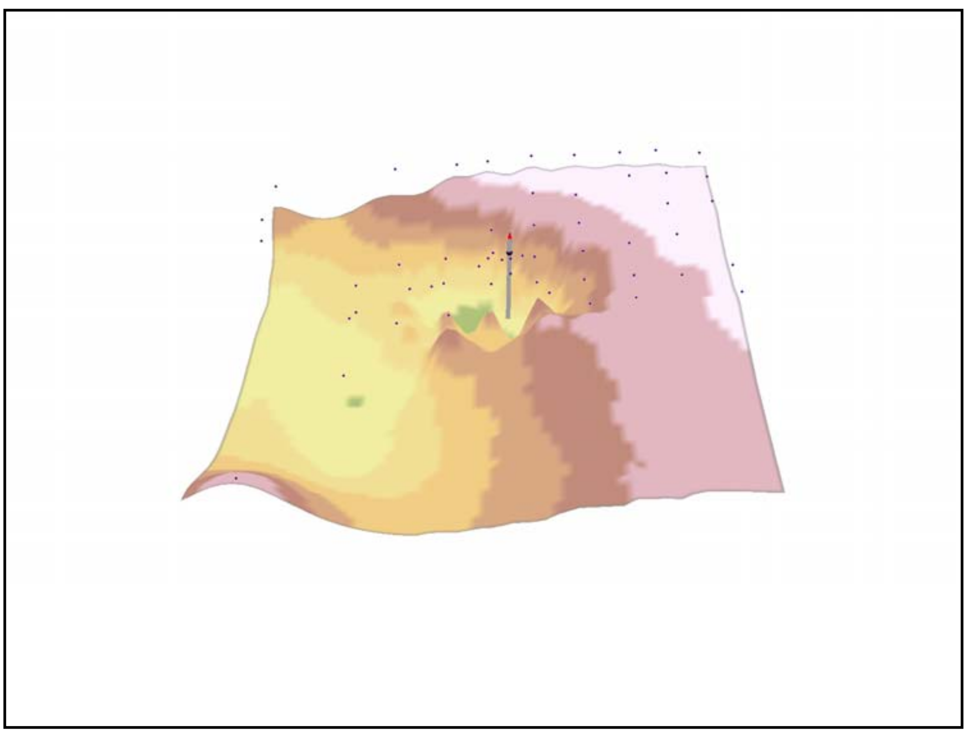
Bellevue Area 3D View

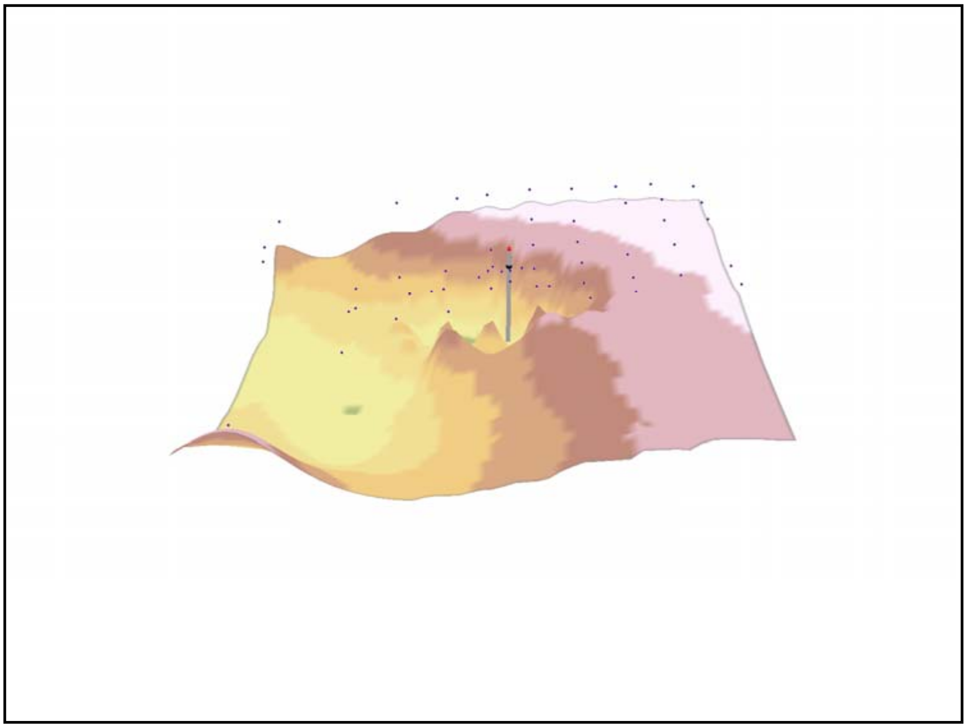


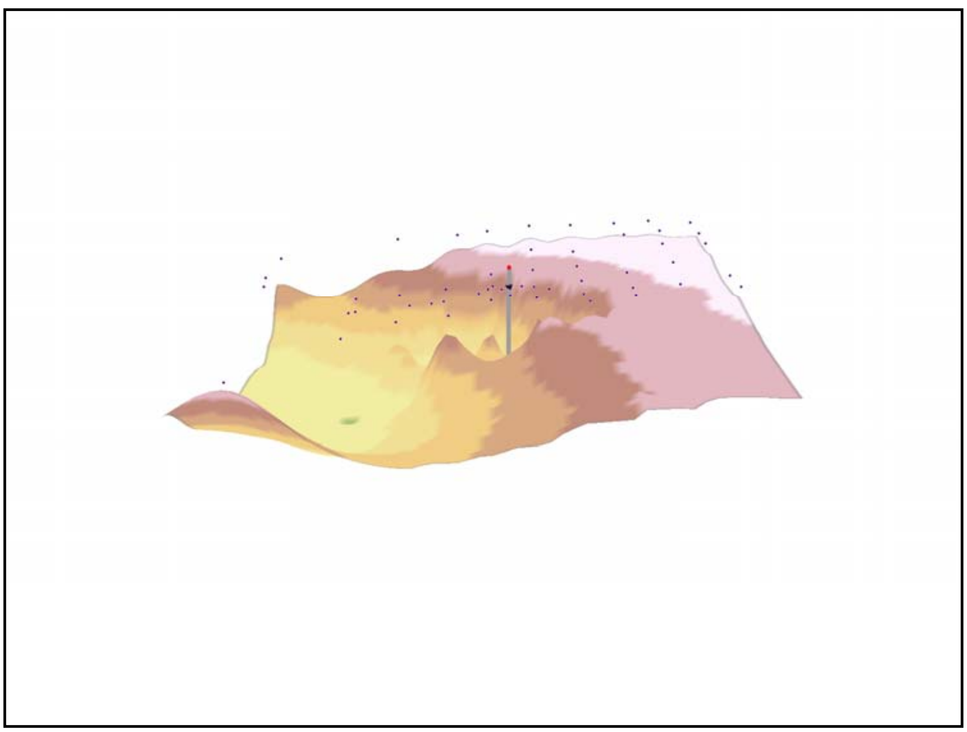
Bedrock Topography
from Passive Seismic

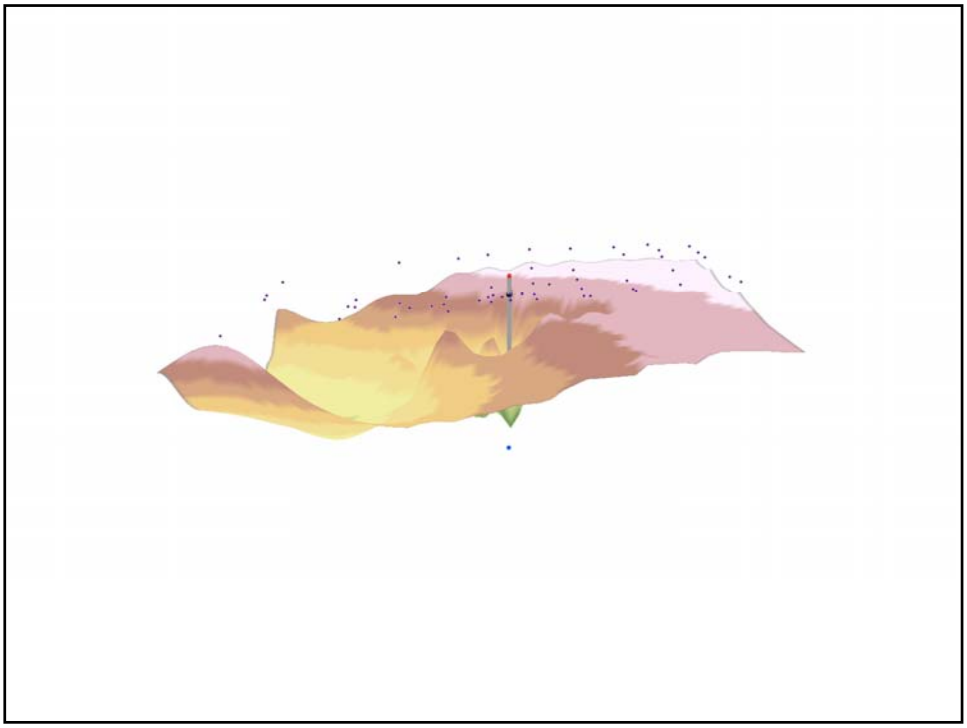


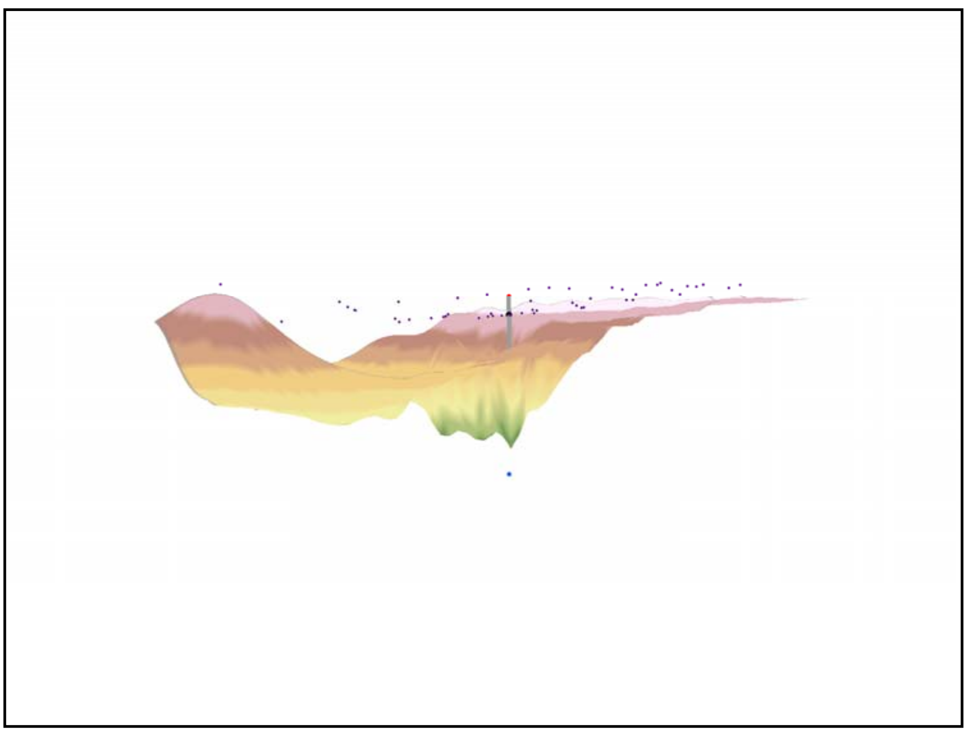




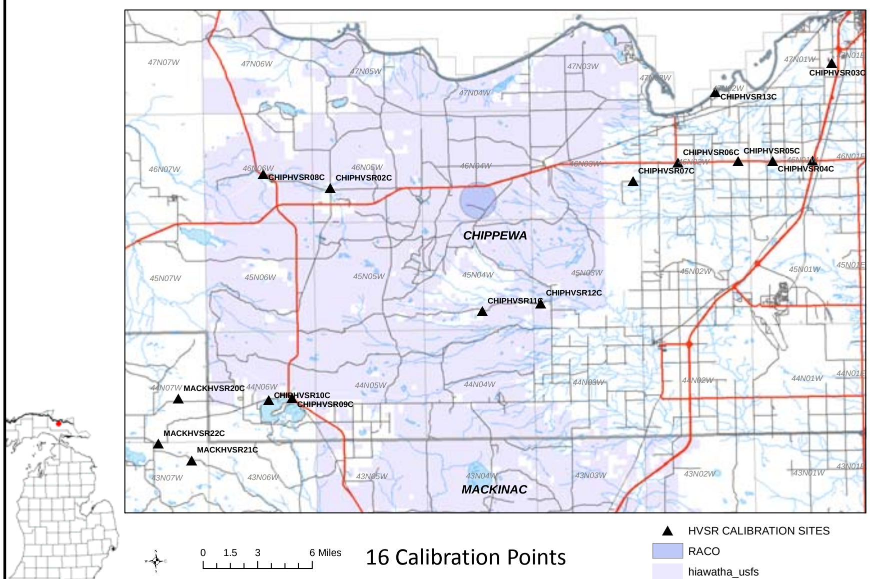




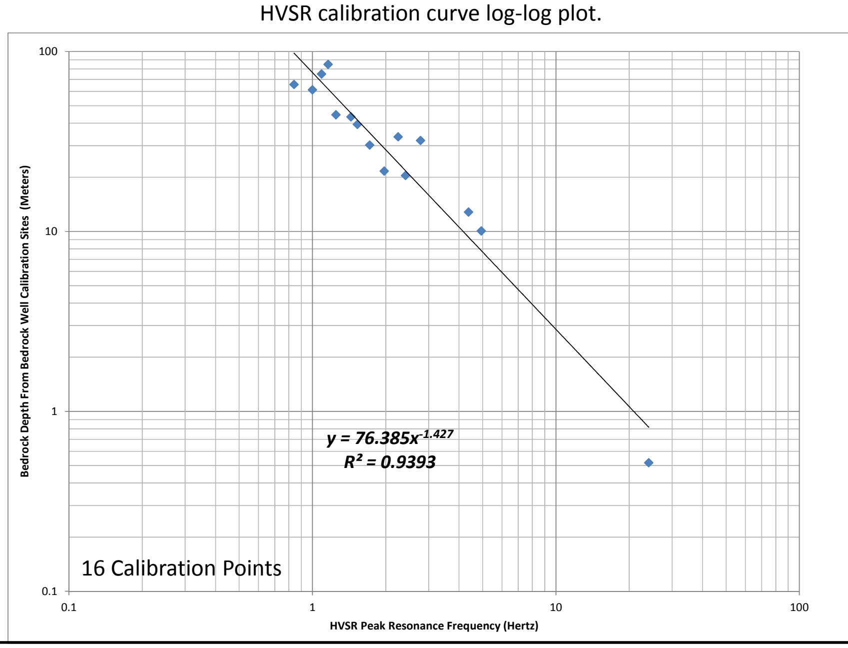




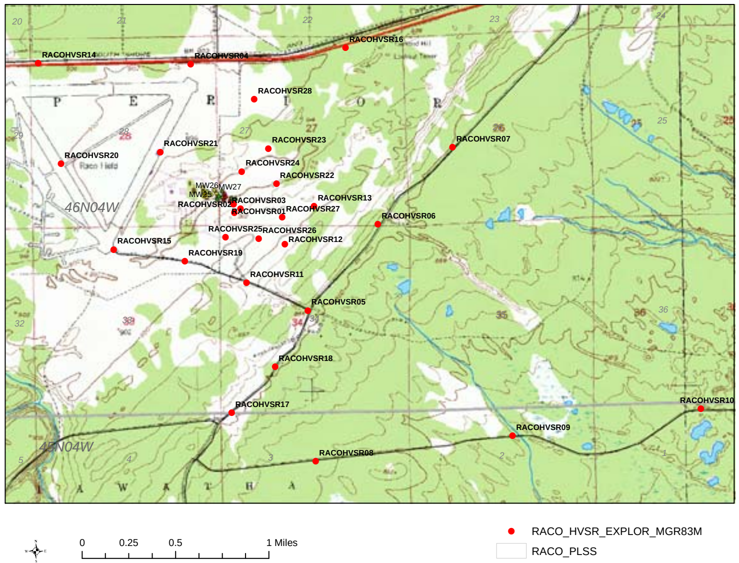
Former Raco Army Airfield and Missile Site, Chippewa County,
HVSR Calibration/Control Sites (borings/wells with known bedrock depth)



Former Raco Army Airfield and Missile Site, Chippewa County,
HVSR calibration curve log-log plot.

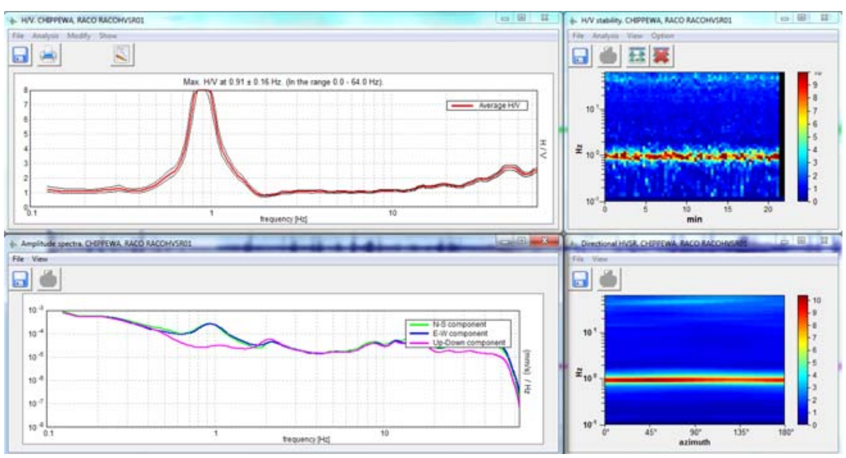


Former Raco Army Airfield and Missile Site, Chippewa County,
HVSR exploration sample points on USGS 7.5 Minute Topographic Quad



28 Exploration Points

RACOHVSR01 processed data.

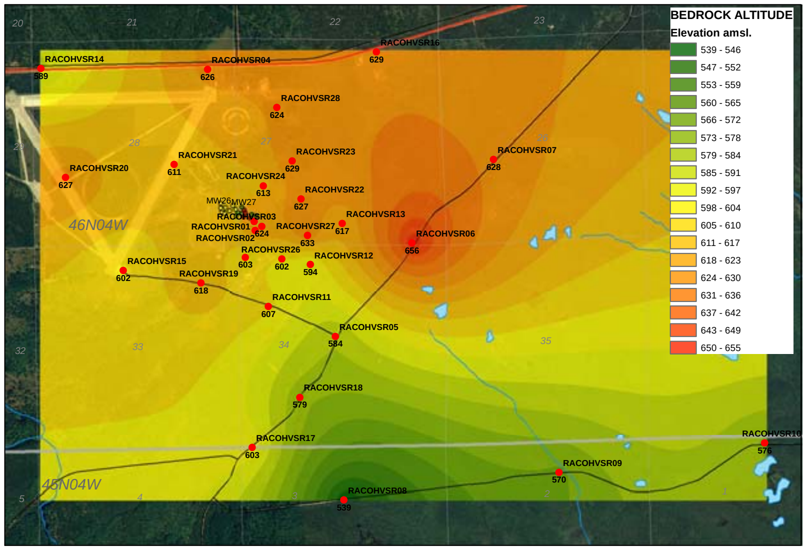


The HVSR peak resonance frequency at 0.91 Hz is easily seen. Note the "eyeball" anomaly in the Amplitude Spectra chart also at 0.91 Hz directly below the peak resonance frequency. This is an example of a very good peak.

Plugging it into "X" in calibration equation: $y = 76.385x^{-1.427}$ and solving for Y results in 87.4 meters. Then multiplying by 3.2808 feet/meter results in a 287 feet bedrock depth estimate at this location

Former Raco Army Airfield and Missile Site, Chippewa County

Bedrock Topography

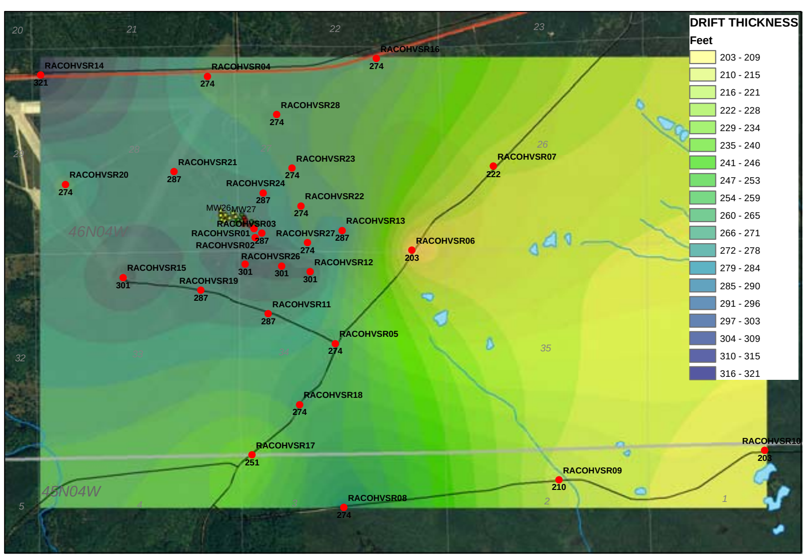


0 0.25 0.5 1 Miles

RACO_HVSR_EXPLOR_MGR83M

Former Raco Army Airfield and Missile Site, Chippewa County

Drift Thickness

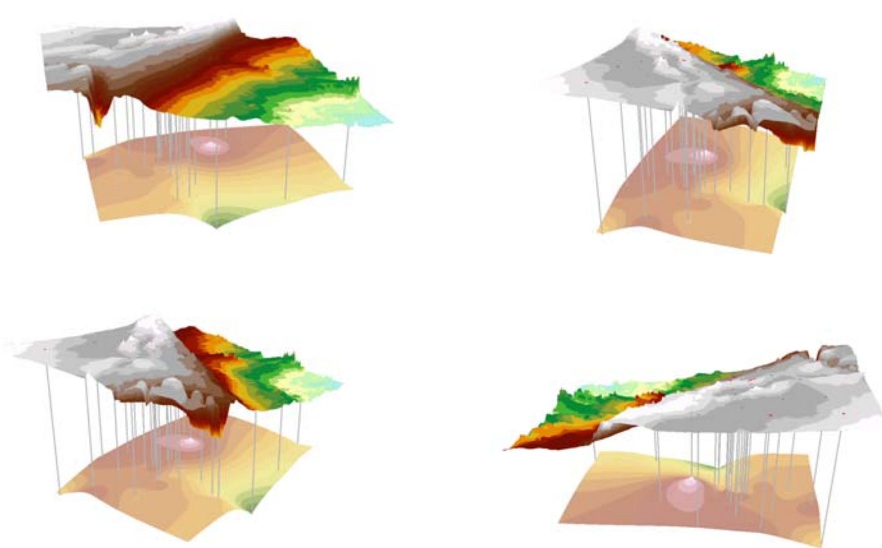


0 0.25 0.5 1 Miles

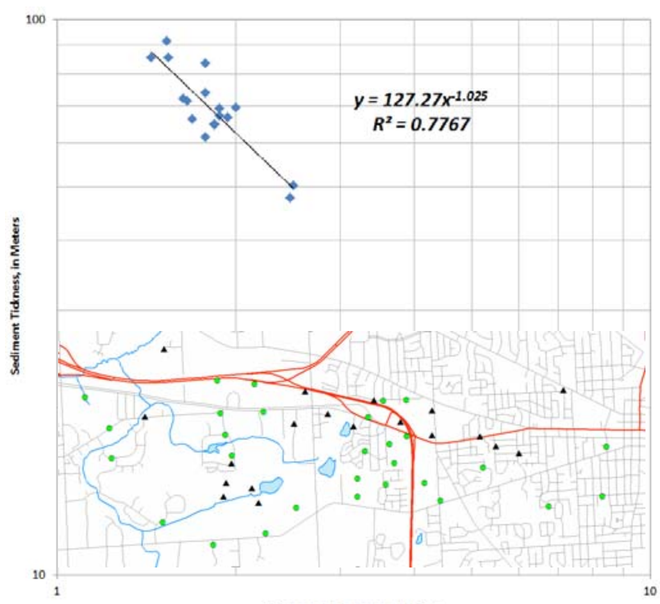
RACO_HVSR_EXPLOR_MGR83M

Former Raco Army Airfield and Missile Site, Chippewa County

3D views of the land surface and bedrock surface (3 times vertical exaggeration). Grey lines - HVSR exploration points extruded down from land surface to bedrock surface.



Western Ann Arbor Area Calibration Curve

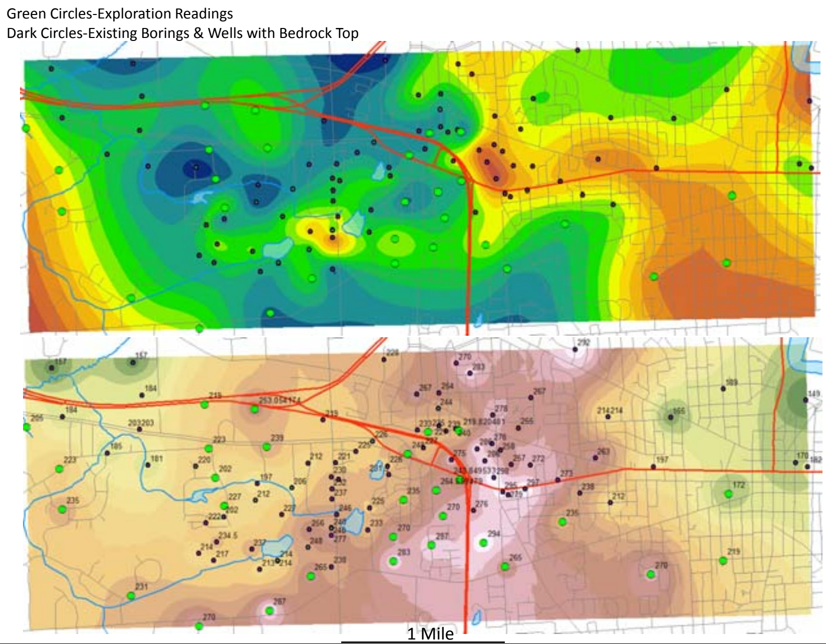


Bedrock depth ranges from 150-300 feet in the area

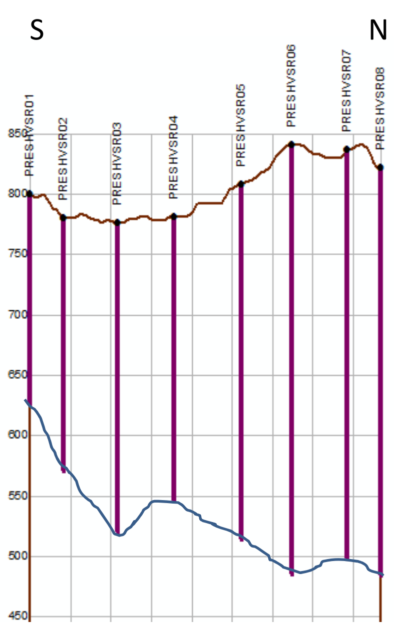
19 calibration readings at borings with known bedrock depth
- Black Triangles

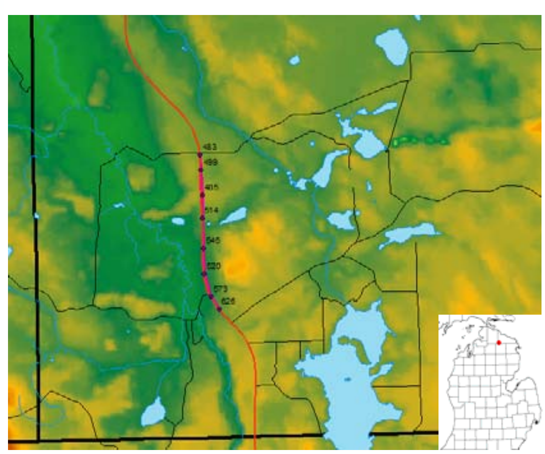
29 exploration readings in areas of unknown bedrock depth
- Green Circle

Western Ann Arbor Area HVSR Results

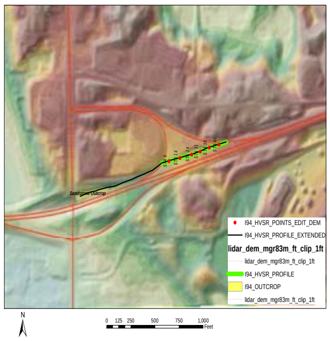


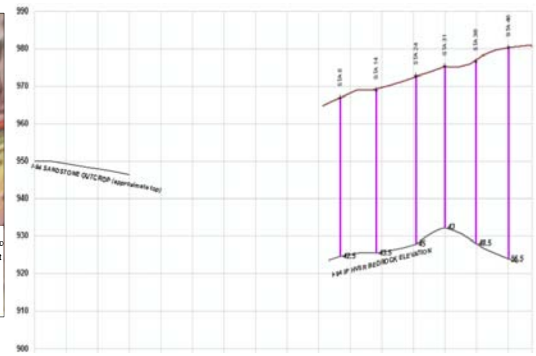
HVSR PROFILE ACROSS SINKHOLE PATHWAY ALONG M-33

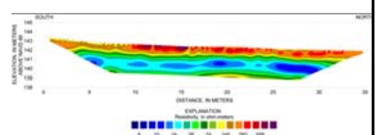




Useful to Help Constrain Other Geophysical Surveys



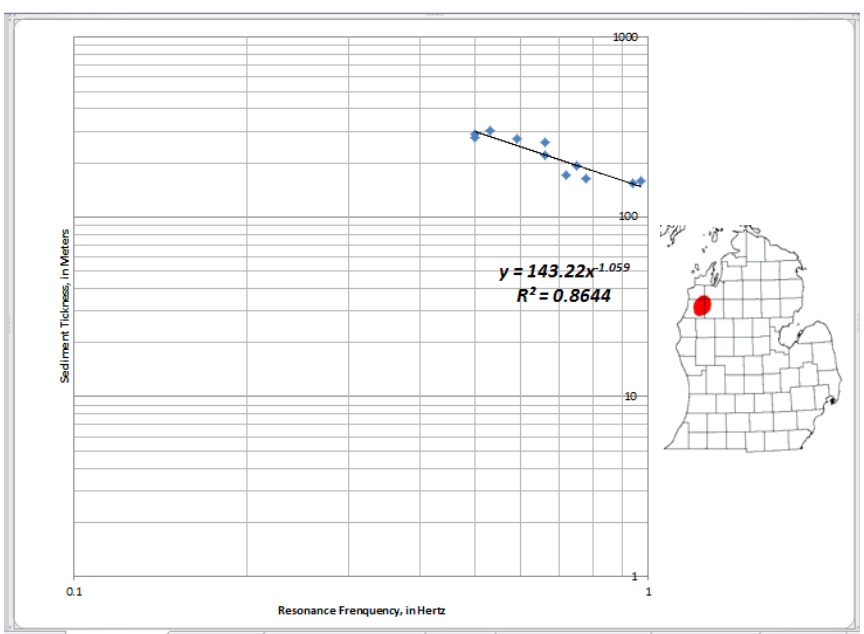




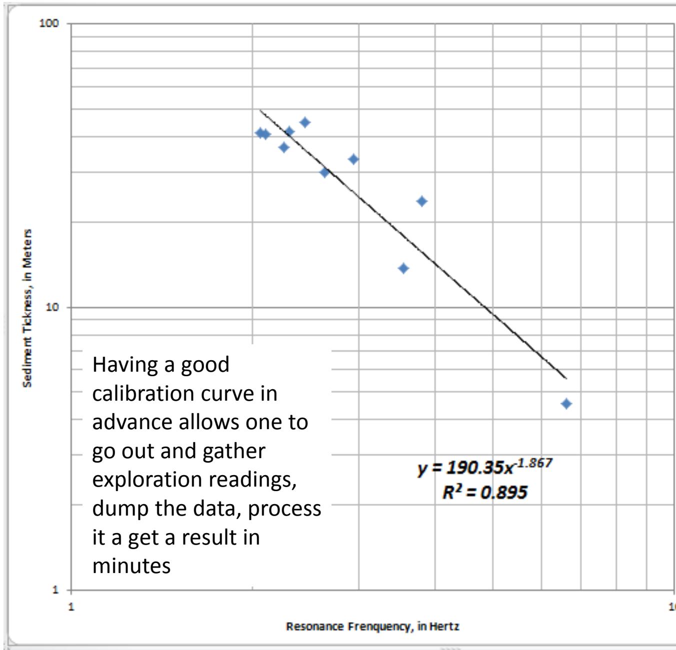
-Induced Polarization profile to determine subsurface geology,
-But no ground truth data along profile
-Collected 6 HVSR readings along same profile readings in 2 hours
-This allows geophysicist to hang specific I.P. bedrock anomaly to specific depths along profile

http://pubs.usgs.gov/sir/2004/5208/

Manistee-Wexford County Area



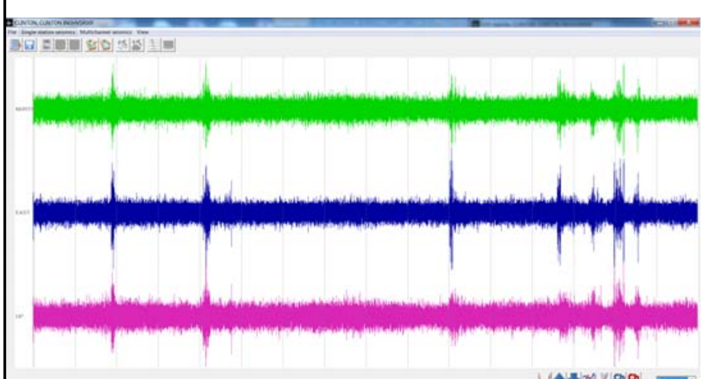
Lansing/Ingham-Eaton & Southern Clinton Counties Calibration Curve



Having a good calibration curve in advance allows one to go out and gather exploration readings, dump the data, process it a get a result in minutes

Some of the best data in the state so far!

MSU Natural Science Building, near, NW Corner, relatively noisy- Sunday afternoon (windy) winter break, not a creature was stirring



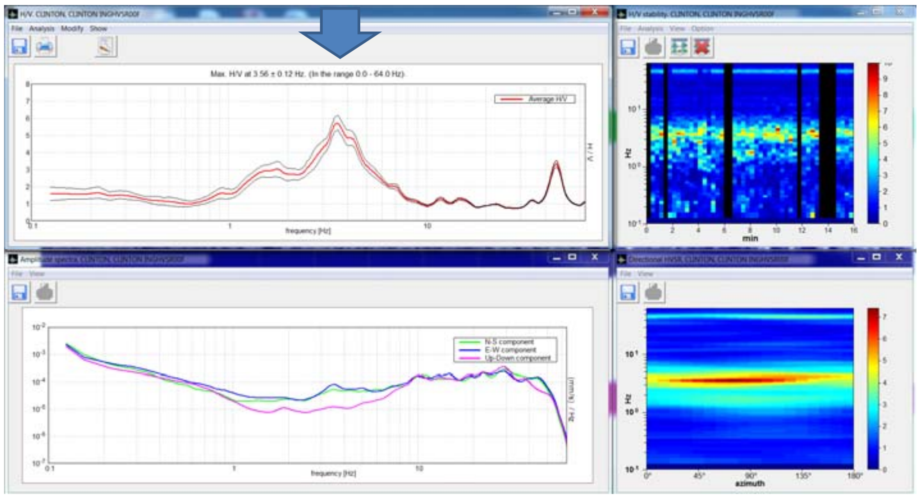
16 minute reading, could have gotten by with a shorter reading

1-3-2016

MSU Natural Science Building, near NW Corner, Processed Data

Using Lansing area equation estimate bedrock depth ~58.3 ft

3.56 hz , High Amplitude Peak



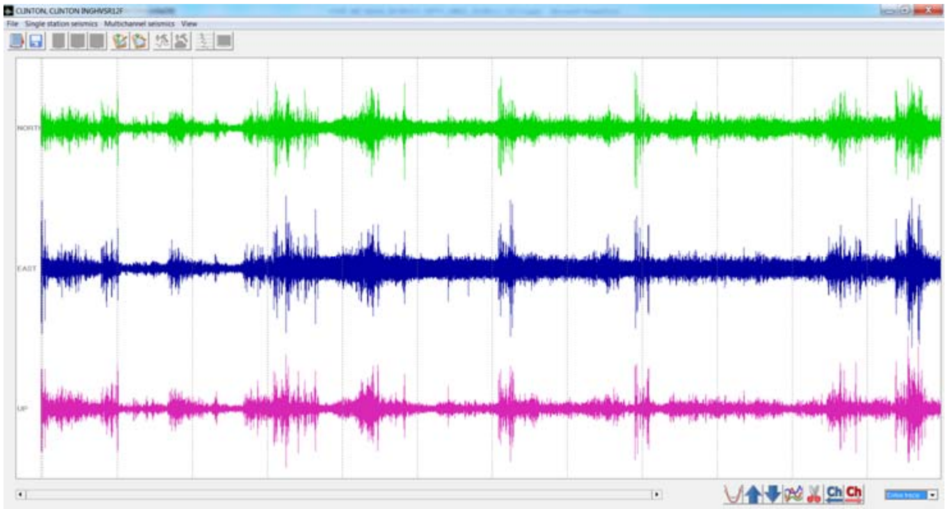
Closest Easily Available Bedrock Control Points

Average depth to bedrock from 5 nearest wells is 57 feet

HVSR bedrock estimate at Natural Science Building 58.3 feet

Superfund Site in Lansing

Shallow soil clean up site, without any borings which tag bedrock. Site geologist wanted to get a better handle how deep it was to bedrock.
Water wells in the mile or so around the site show bedrock depth ranges from ~40 feet to -110 feet (in a bedrock valley).

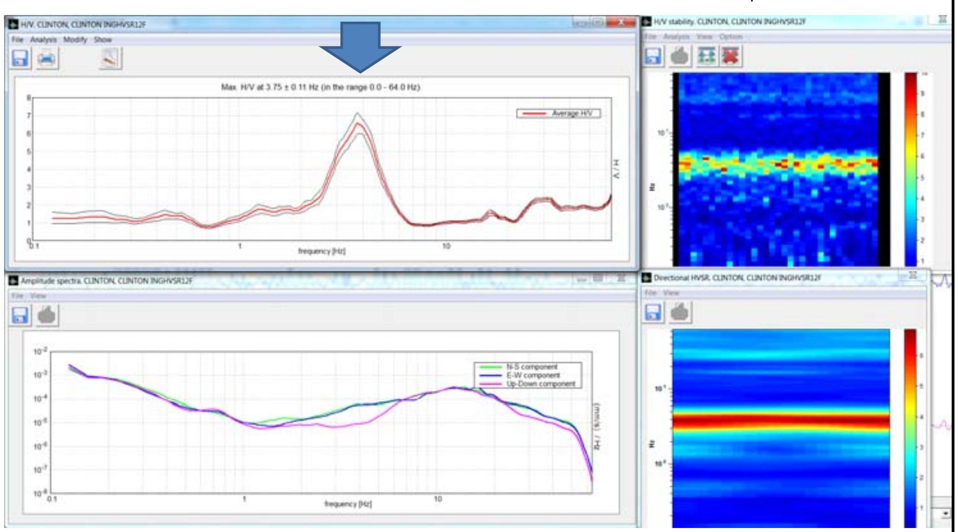


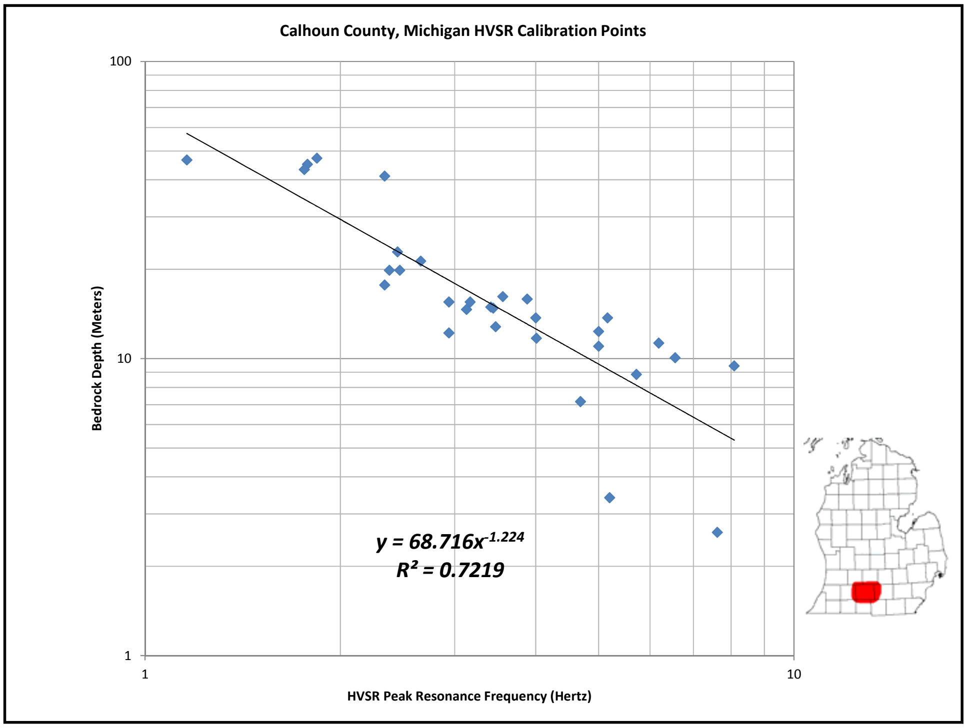
16 minute reading 12-20-2016

Superfund Site in Lansing

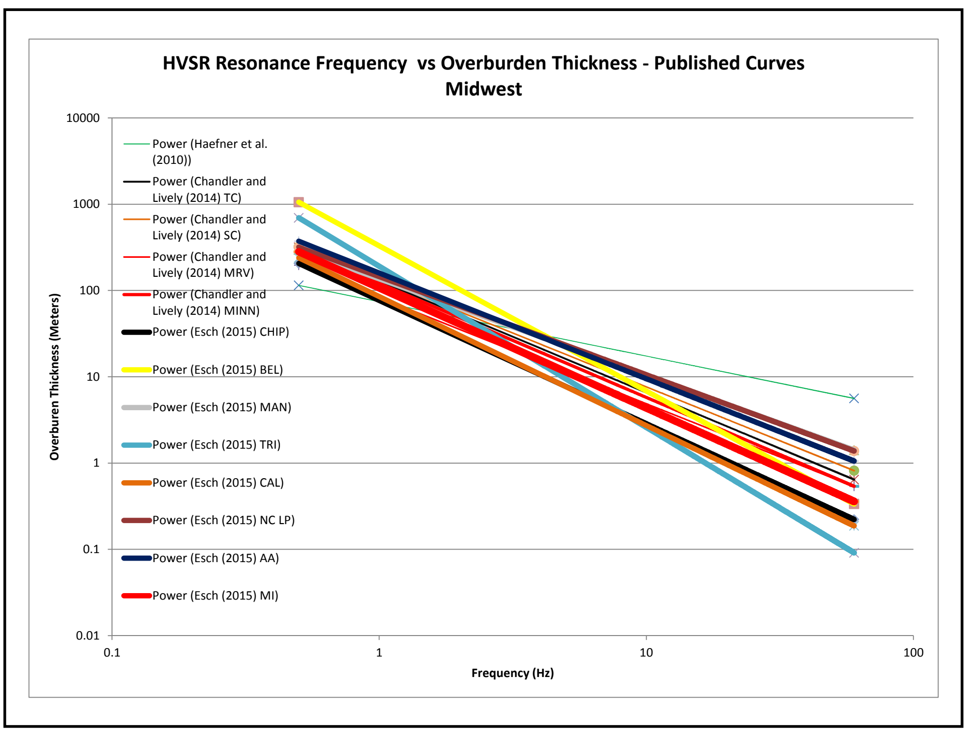
3.75 hz , High Amplitude Peak

Using Lansing area equation estimate bedrock depth ~53 ft





Calhoun County, Michigan HVSR Calibration Points
Bedrock Depth (Meters)
HVSR Peak Resonance Frequency (Hertz)
100
10
1
1
10
y = 68.716x-1.224
R² = 0.7219



HVSR Resonance Frequency vs Overburden Thickness - Published Curves
Midwest
Overburden Thickness (Meters)
Frequency (Hz)
10000
1000
100
10
1
0.1
0.01
0.1
1
10
100
Power (Haefner et al. (2010))
Power (Chandler and Lively (2014) TC)
Power (Chandler and Lively (2014) SC)
Power (Chandler and Lively (2014) MRV)
Power (Chandler and Lively (2014) MINN)
Power (Esch (2015) CHIP)
Power (Esch (2015) BEL)
Power (Esch (2015) MAN)
Power (Esch (2015) TRI)
Power (Esch (2015) CAL)
Power (Esch (2015) NC LP)
Power (Esch (2015) AA)
Power (Esch (2015) MI)

HVSR Advantages

- Quick
- Inexpensive
- One man operation
- Fairly Easy in Field
- Fairly Intuitive Processing
- Non-Invasive
- Can be used in culturally noisy areas
- May be telling us more about the subsurface geology than just depth to bedrock
- Could be used to as independent depth calibration for other geophysical surveys and modeling: resistivity soundings, gravity, seismic, GPR

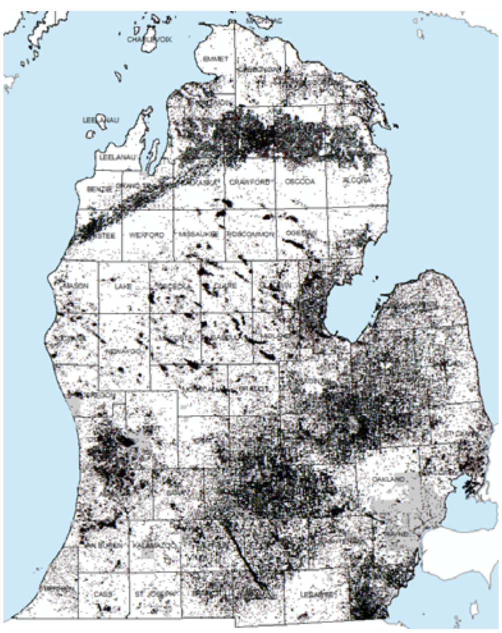
Advantages

- Portable When compared to
  - Drilling
  - Other geophysical techniques
- Potentially large cost savings when comparing to what it would cost for
  - Drilling
  - Other geophysical surveys
  - Area of coverage, speed compared to drilling/other geophysical techniques

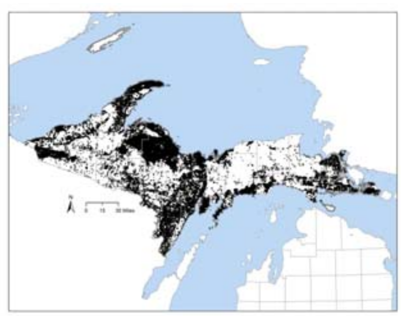
Why Do We Need More/Better Depth to Bedrock Control Points?

- Additional Bedrock Topography/Drift Thickness Control Points: fill in data gaps, check anomalous data points
- Site specific projects: Bellevue
- Groundwater contamination investigations
- Oil and Gas wells data often differs from water wells picks
- Many places have little of no bedrock control

Bedrock Topography and Drift Thickness 300,000 Control Points



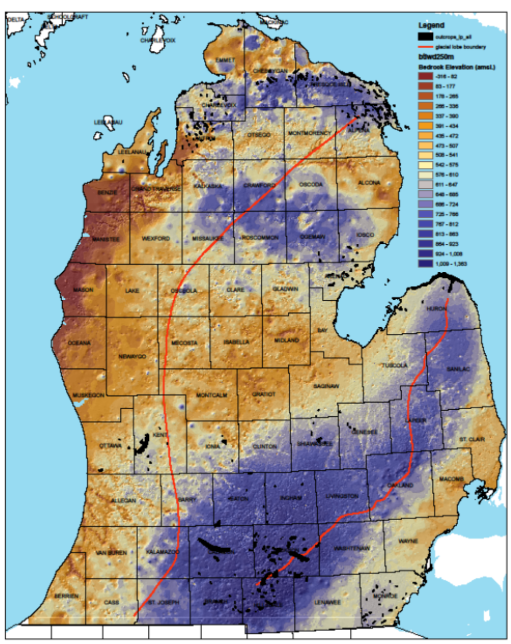
LP 175,000 data points



- **•17,200 Water Wells**
- **•29,300 Outcrop Points (within polygons)**
- **•14,600 Shoreline points ACOE, MNFI**
- **•215, 600 Soils Points (within polygons)**

Filling in Data Gaps With Little Bedrock Top Control

- Lenawee,
- Ionia
- Leelanau
- E Up.
- Manitou Islands (Cuesta under them or not)

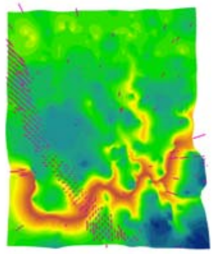


DEQ-Office of Geological Survey
Minerals and Mapping Unit-John Esch

BEDROCK TOPOGRAPHY
LOWER PENINSULA OF MICHIGAN

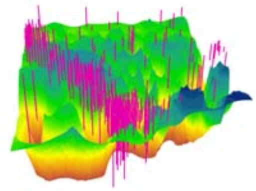
Anomalous Bedrock Topography Elevation

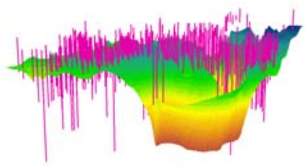
The top of bedrock reported from oil & gas wells is sometimes unreliable

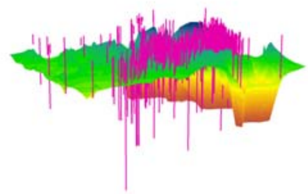


Bedrock Topography SE Albion 7.5 Minute Quad*

Vertical lines are oil and gas wells extruded down to the top of bedrock (base of drift) as reported in well logs. This shows the top of bedrock can be unreliable in places



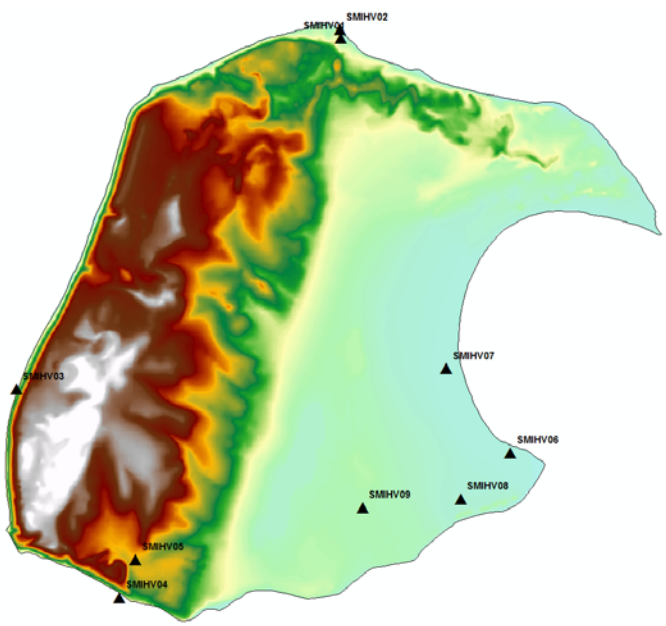




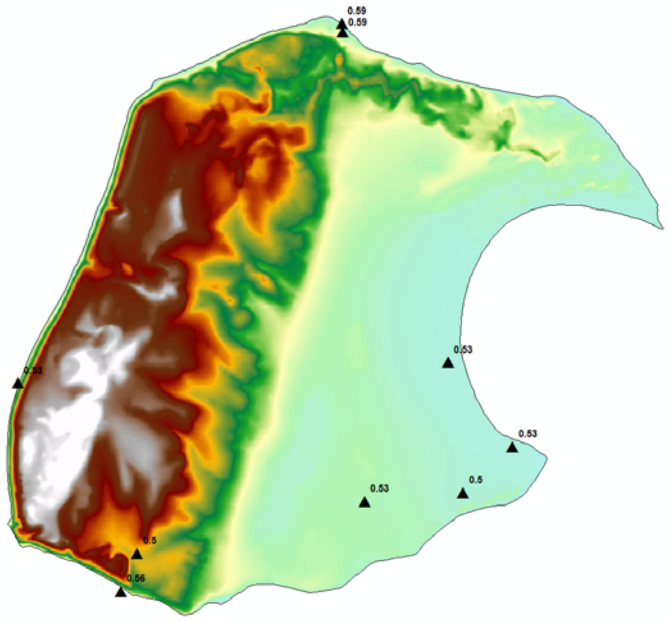
7 X Vertical Exaggeration

* Esch J.M. and Kehew, A.E., 2014. Surficial Geology of the Southeast Albion 7.5 Minute Quadrangle, Calhoun and Jackson Counties, Michigan, Surficial Geologic Map Series SGM-14-05, scale 1:24000.

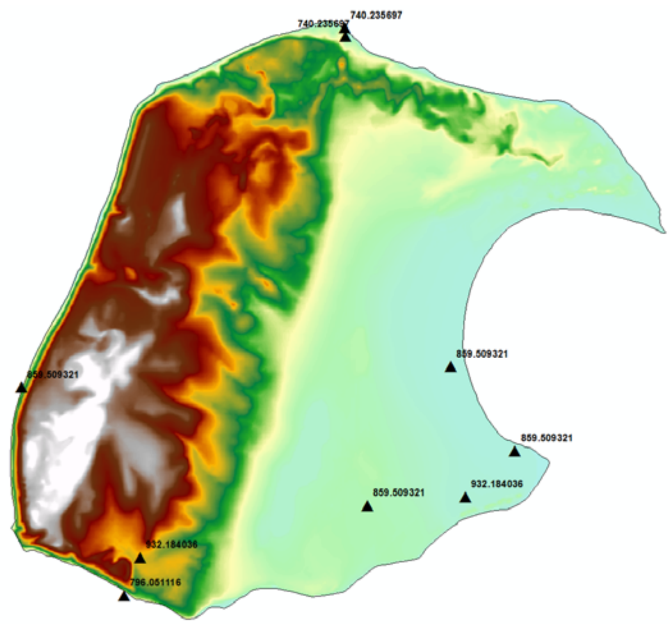
South Manitou Island HVSR Sample Locations



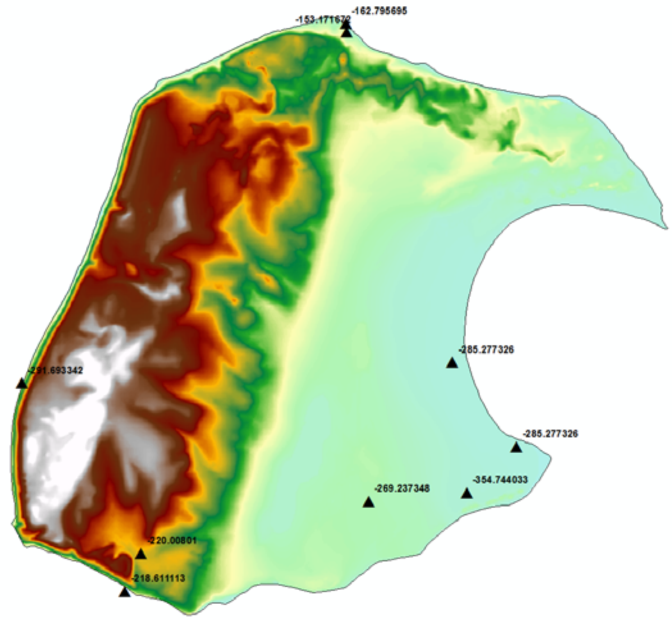
South Manitou Island HVSR Resonance Frequency

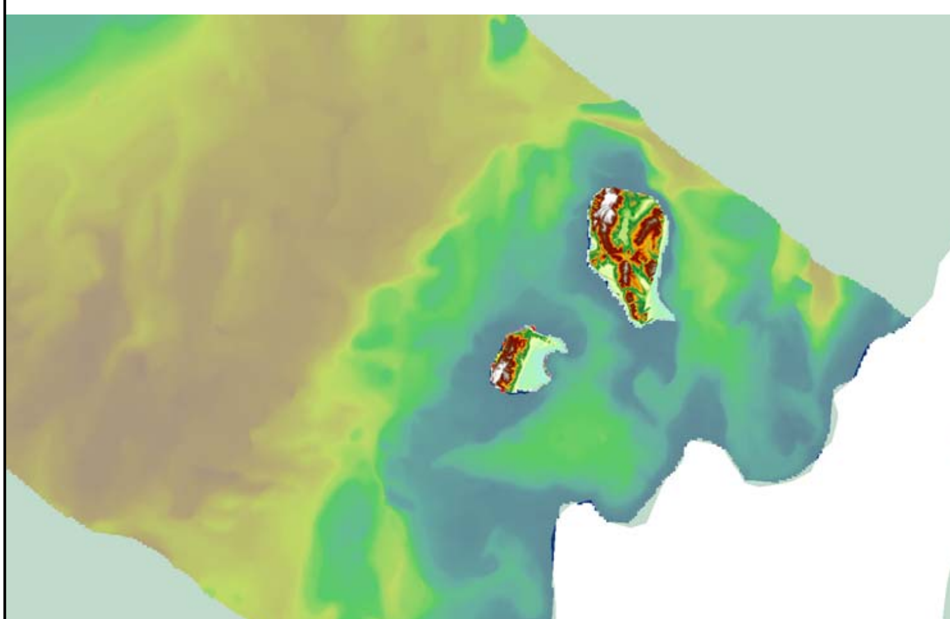


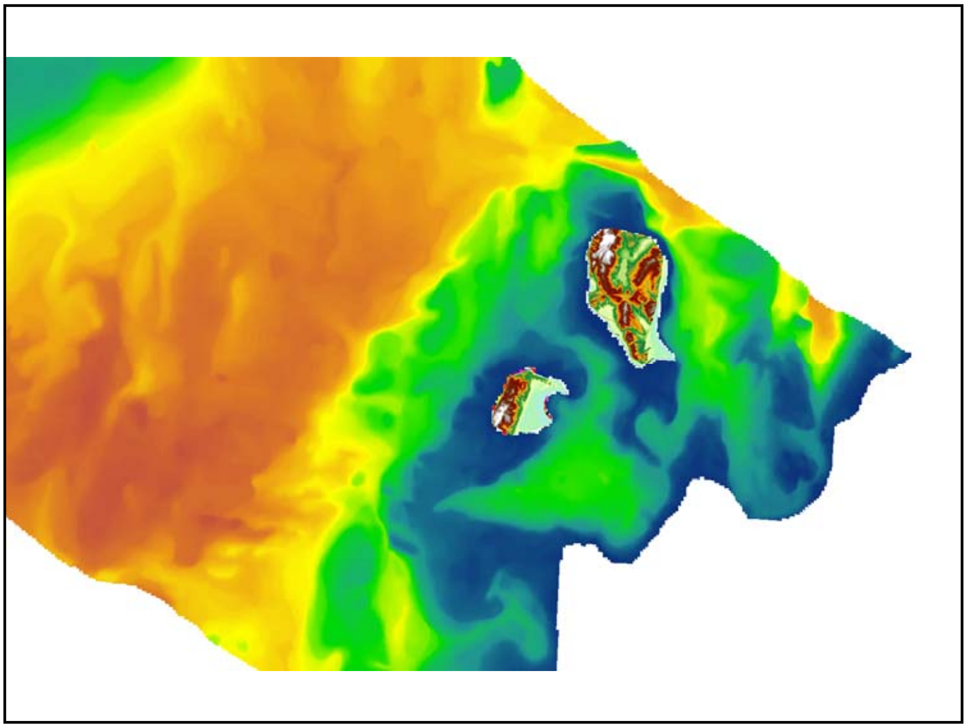
South Manitou Island HVSR Bedrock Depth Estimates

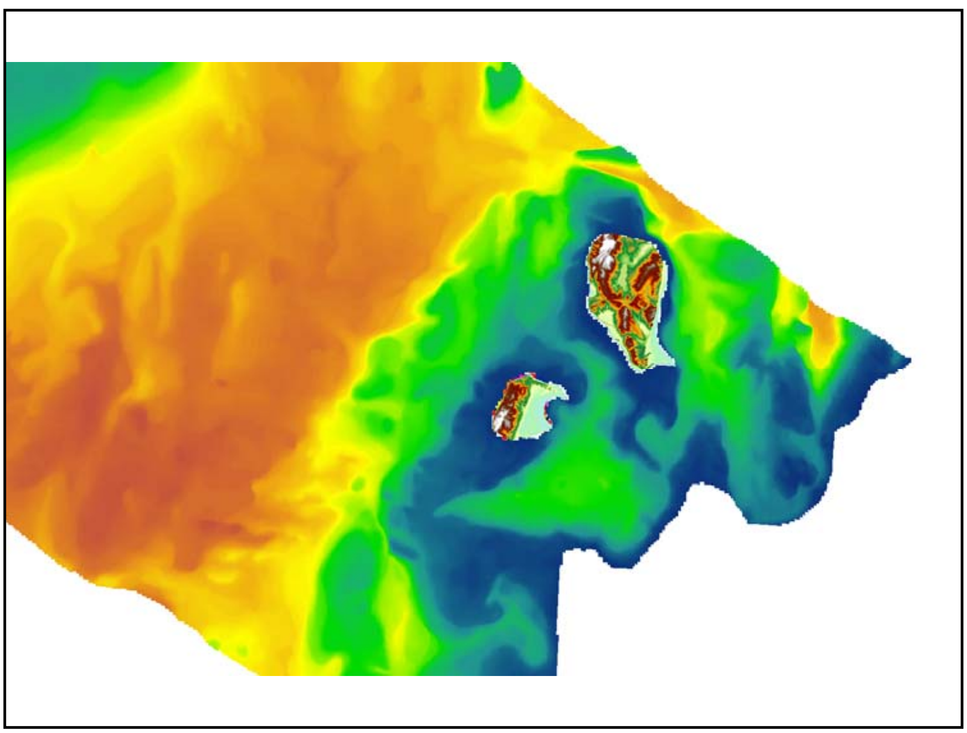


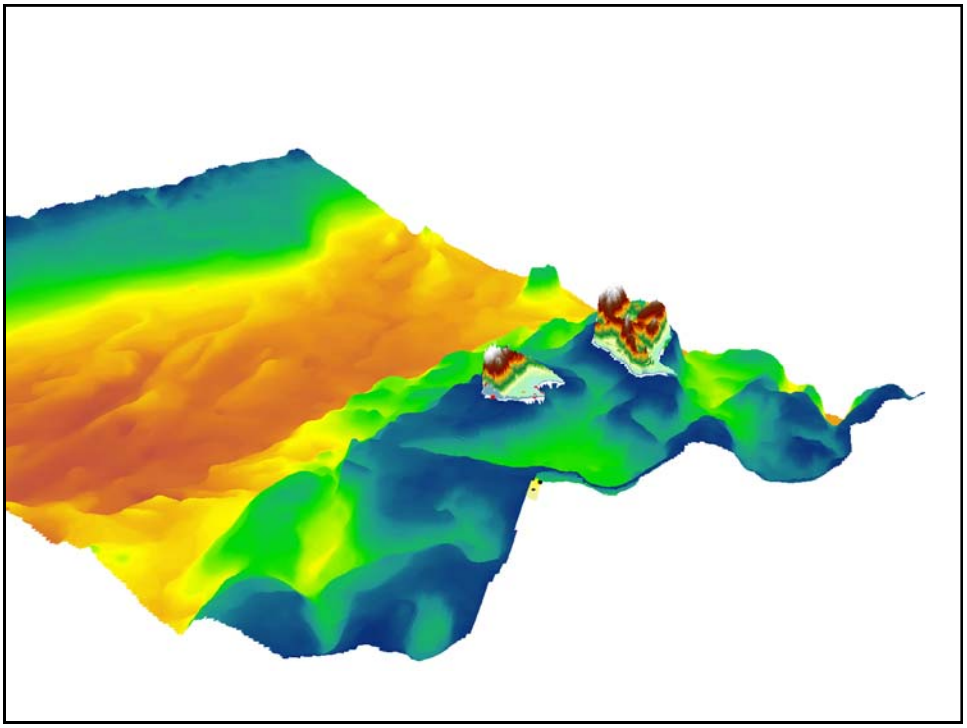
South Manitou Island HVSR Bedrock Elevation Estimates

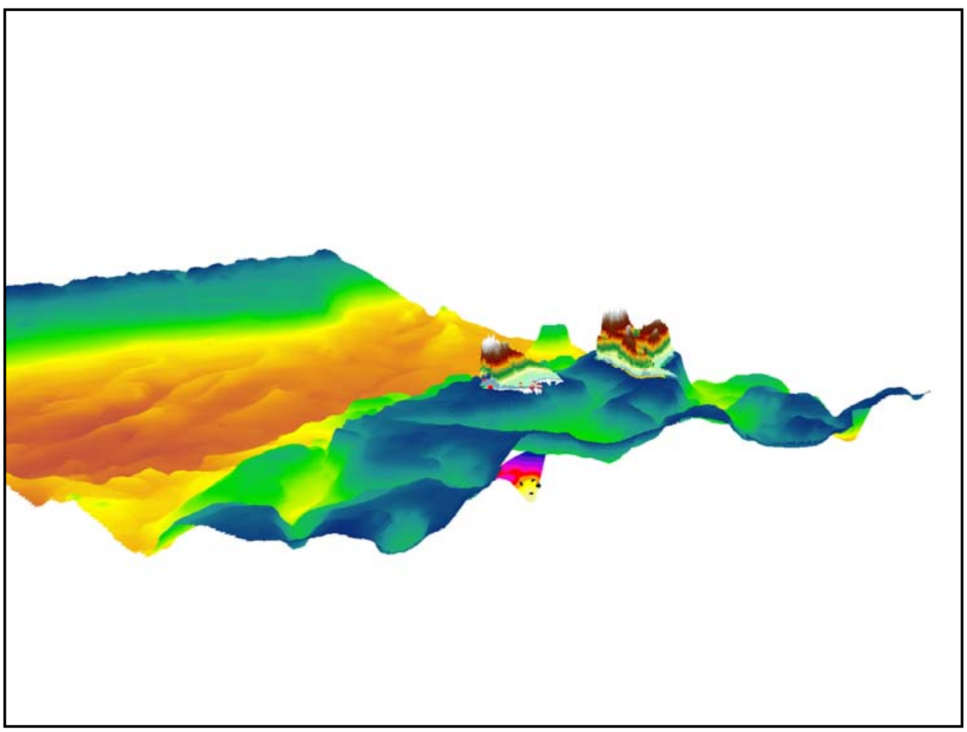


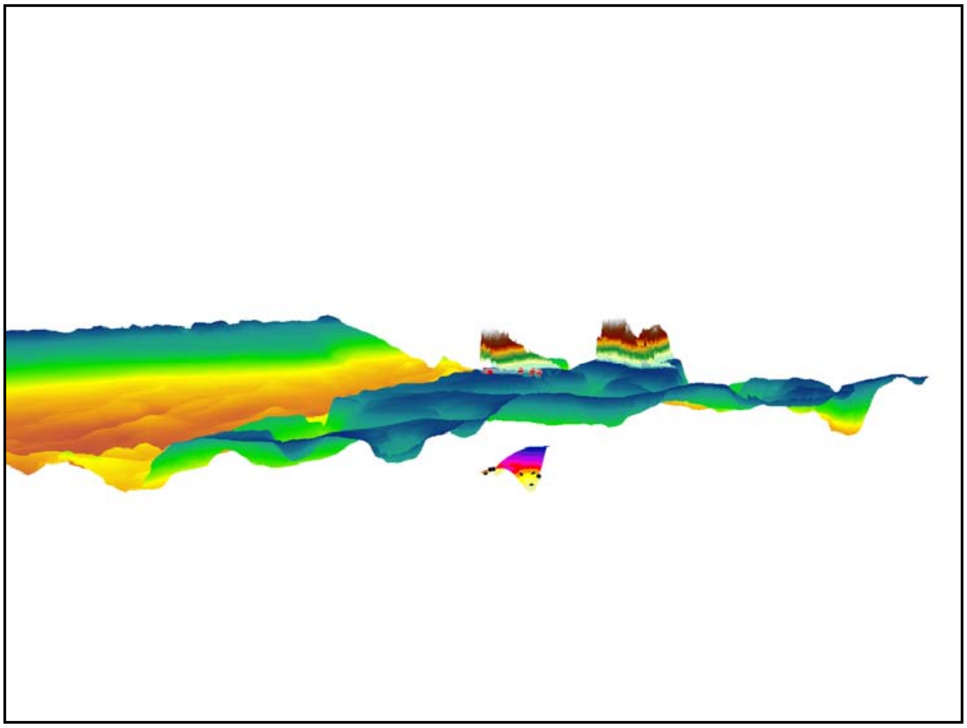


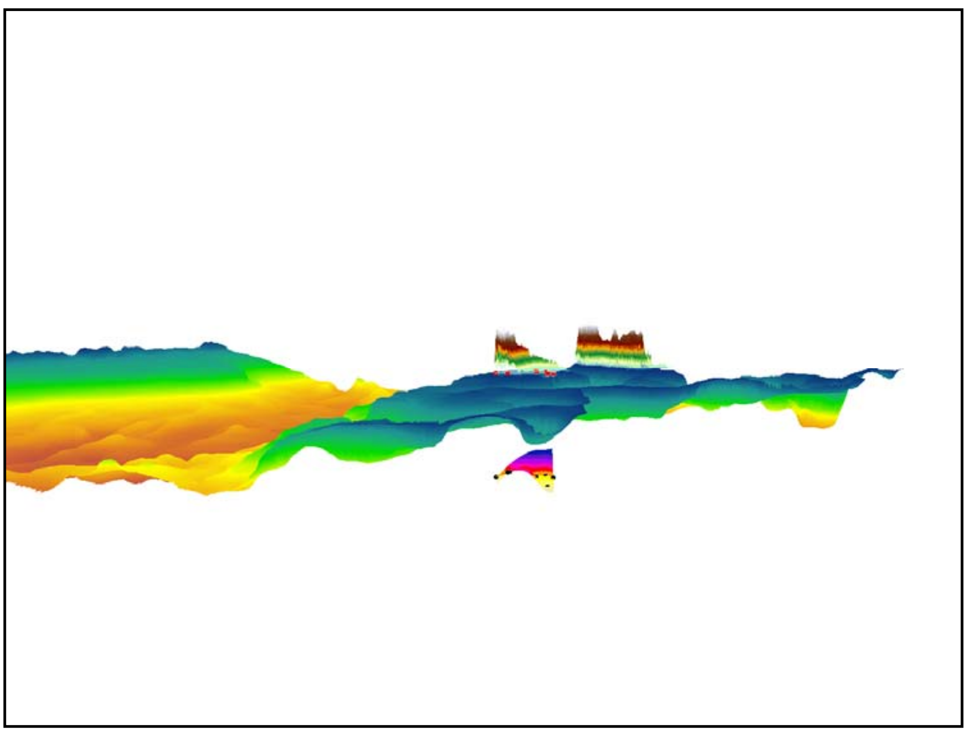


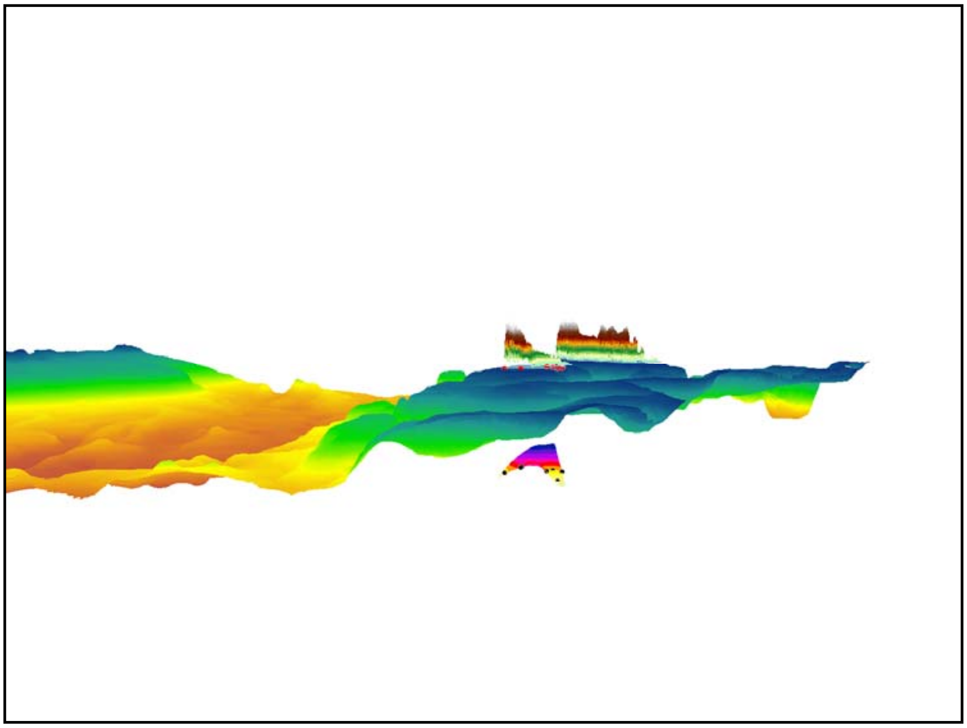


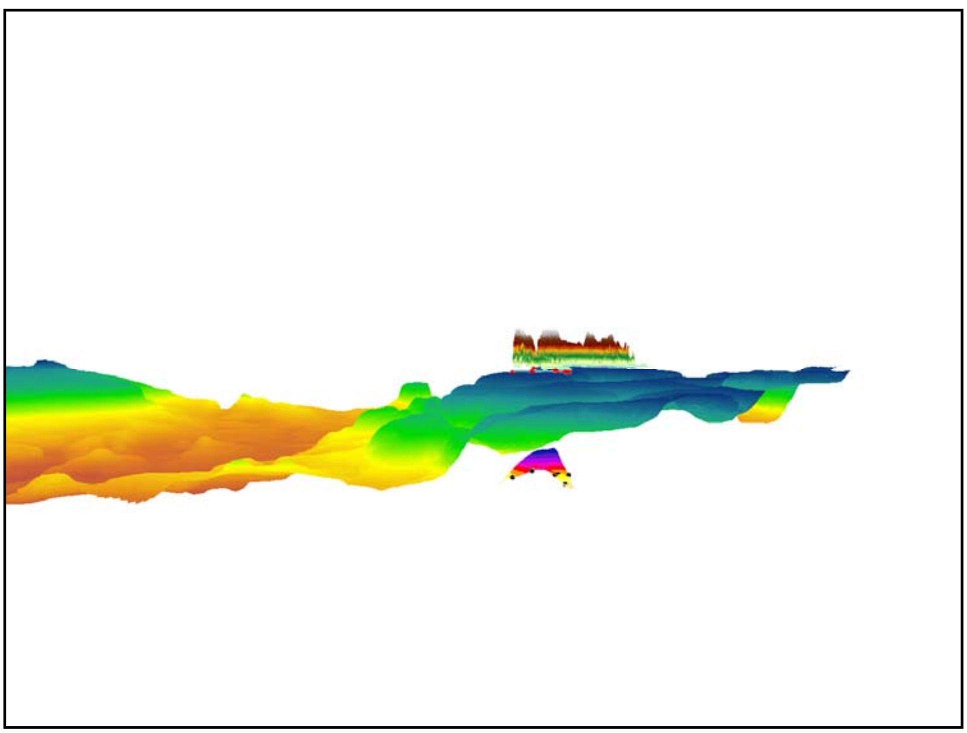




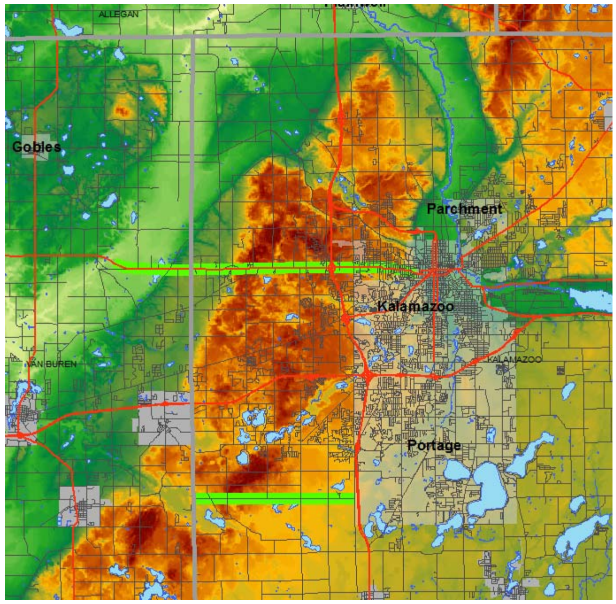






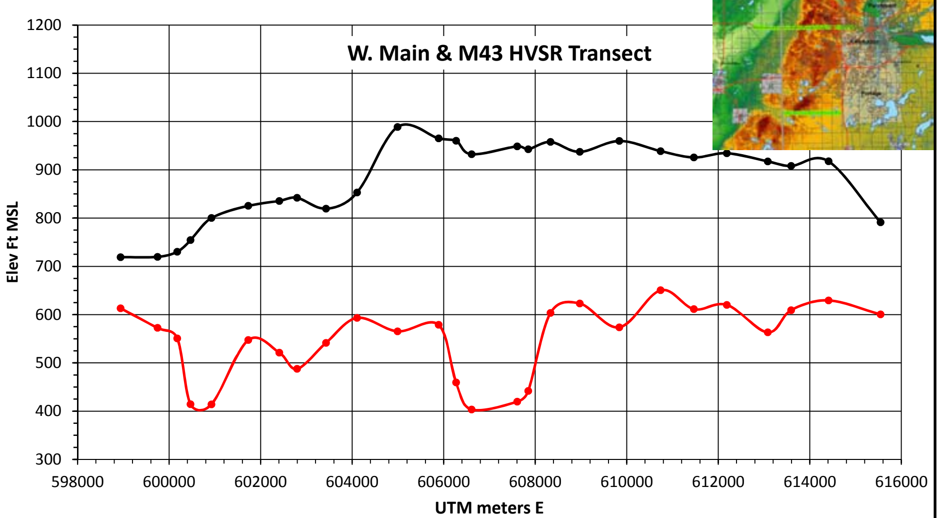


HVSR transects across the Kalamazoo Moraine



Dr. William Sauck, Western Michigan University, MGS

HVSR transect across Kalamazoo Moraine



Transect (17 km) across the Kalamazoo moraine. The Lake Michigan ice lobe was to the left. To the right of the ridge is the outwash fan. This portion of the distal moraine ridge location appears to be controlled by bedrock topography.

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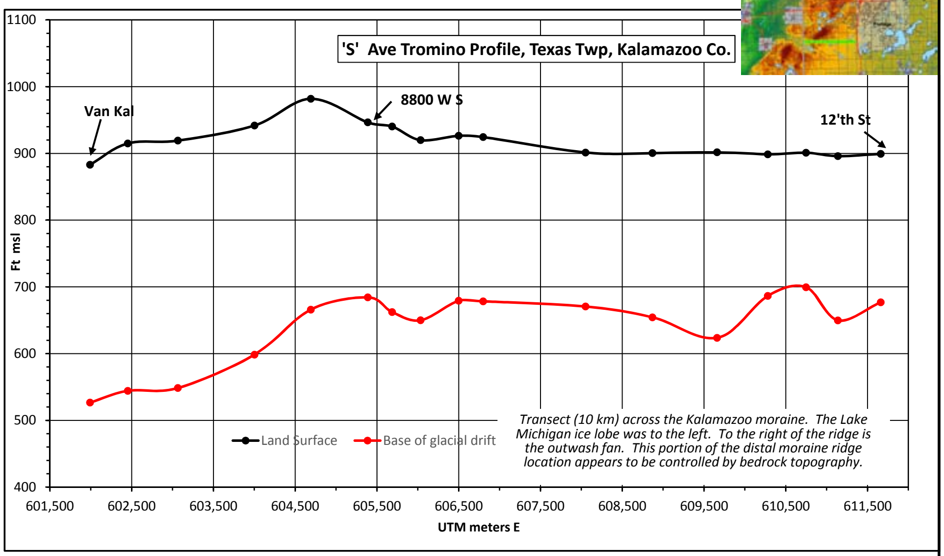
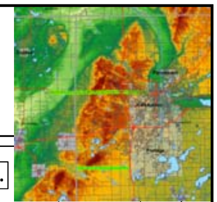
Another transect across Kalamazoo Moraine





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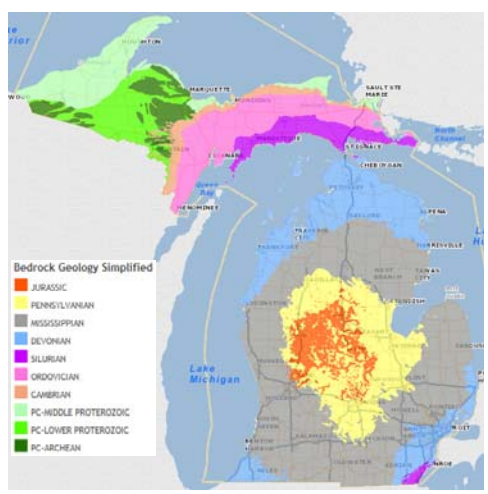
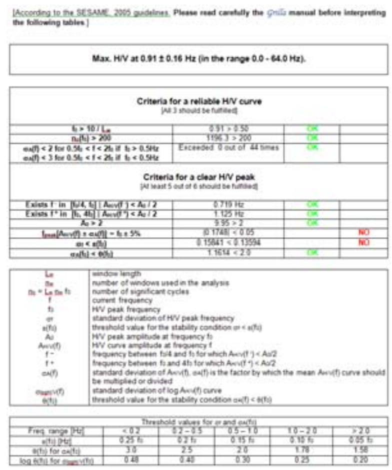
Jurassic Redbeds

- Consolidated-poorly consolidated red-purple sandstone, shale, and gypsum in the middle of the Lower Peninsula
- Youngest bedrock below the drift in the Michigan Basin
- Often spotty occurrence and highly variable thickness
- Sometimes lumped in with the glacial drift on older well logs
- Unclear how well the HVSR technique will work over them
- W & NW Minnesota – similar poorly consolidated Cretaceous aged bedrock below the drift.
- HVSR technique is not working so well. The HVSR technique is seeing the base of the Cretaceous aged material, not the top.



SESAME, 2004, Guidelines

- **SESAME**:
  Site EffectS assessment using AMbient Excitations
- Nine criteria for determining a have a good peak:
  - 3 Criteria for a reliable H/V curve
  - 6 Criteria for clear H/V peak
- Incorporated into Grilla Processing Software
- Even with very good peaks, often only 7/9 nine criteria met
- Practical guidelines recommend procedures for field experiment design, data processing and interpretation of the results



[According to the SESAME, 2005 guidelines. Please read carefully the Grilla manual before interpreting the following tables.]

Max. H/V at 0.91 ± 0.16 Hz (in the range 0.0 - 64.0 Hz).

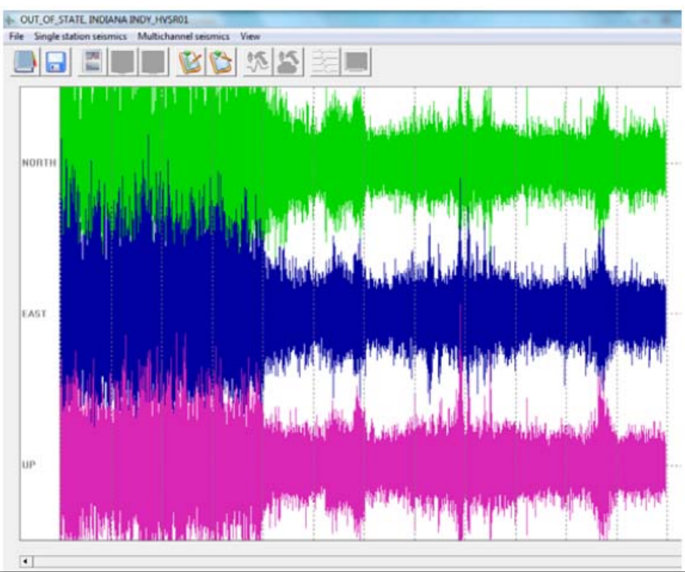
Criteria for a reliable H/V curve [All 3 should be fulfilled]			
$f_0 > 10 / L_w$	0.91 > 0.50	OK	
$n_c(f_0) > 200$	1196.3 > 200	OK	
$\sigma_A(f) < 2$ for $0.5f_0 < f < 2f_0$ if $f_0 > 0.5Hz$ $\sigma_A(f) < 3$ for $0.5f_0 < f < 2f_0$ if $f_0 < 0.5Hz$	Exceeded 0 out of 44 times	OK	
Criteria for a clear H/V peak [At least 5 out of 6 should be fulfilled]			
Exists f^- in $[f_0/4, f_0]$ | $A_{H/V}(f^-) < A_0 / 2$	0.719 Hz	OK	
Exists f^+ in $[f_0, 4f_0]$ | $A_{H/V}(f^+) < A_0 / 2$	1.125 Hz	OK	
$A_0 > 2$	9.95 > 2	OK	
$f_{peak}[A_{H/V}(f) \pm \sigma_A(f)] = f_0 \pm 5\%$	|0.1748| < 0.05		NO
$\sigma_f < \varepsilon(f_0)$	0.15841 < 0.13594		NO
$\sigma_A(f_0) < \theta(f_0)$	1.1614 < 2.0	OK	

L_w	window length
n_w	number of windows used in the analysis
$n_c = L_w n_w f_0$	number of significant cycles
f	current frequency
f_0	H/V peak frequency
σ_f	standard deviation of H/V peak frequency
$\varepsilon(f_0)$	threshold value for the stability condition $\sigma_f < \varepsilon(f_0)$
A_0	H/V peak amplitude at frequency f_0
$A_{H/V}(f)$	H/V curve amplitude at frequency f
f^-	frequency between $f_0/4$ and f_0 for which $A_{H/V}(f^-) < A_0/2$
f^+	frequency between f_0 and $4f_0$ for which $A_{H/V}(f^+) < A_0/2$
$\sigma_A(f)$	standard deviation of $A_{H/V}(f)$, $\sigma_A(f)$ is the factor by which the mean $A_{H/V}(f)$ curve should be multiplied or divided
$\sigma_{logH/V}(f)$	standard deviation of log $A_{H/V}(f)$ curve
$\theta(f_0)$	threshold value for the stability condition $\sigma_A(f) < \theta(f_0)$

Threshold values for σ_f and $\sigma_A(f_0)$					
Freq. range [Hz]	< 0.2	0.2 – 0.5	0.5 – 1.0	1.0 – 2.0	> 2.0
$\varepsilon(f_0)$ [Hz]	0.25 f_0	0.2 f_0	0.15 f_0	0.10 f_0	0.05 f_0
$\theta(f_0)$ for $\sigma_A(f_0)$	3.0	2.5	2.0	1.78	1.58
log $\theta(f_0)$ for $\sigma_{logH/V}(f_0)$	0.48	0.40	0.30	0.25	0.20

SESAME, 2004, Guidelines for the implementation of the H/V spectral ratio technique on ambient vibrations. Measurements, processing and interpretation, WP12 European commission - Research general directorate project no. EVG1-CT-2000-0026 SESAME, report D23.12, 62 pp.

Indianapolis, block from state capitol –looks ugly

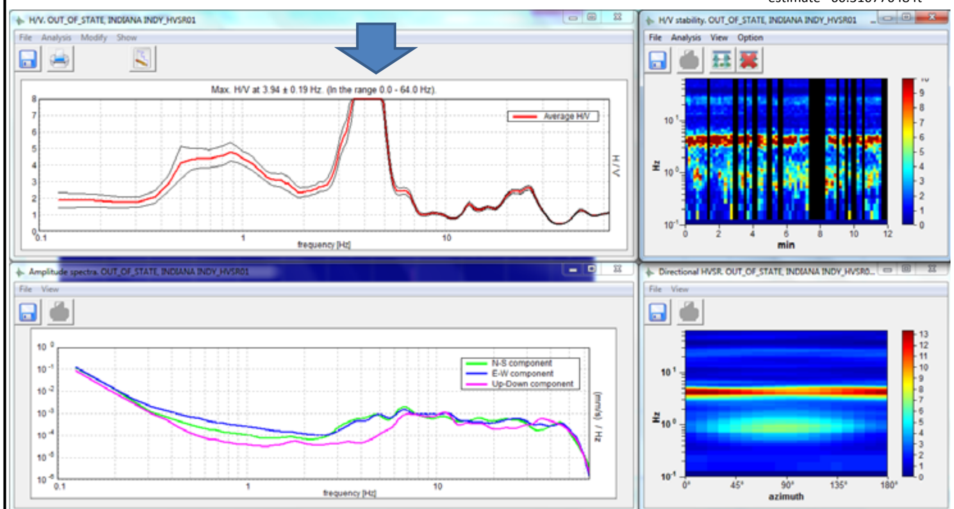


Can be used in culturally noisy areas

Indianapolis, block from state capitol Processed Data

3.94 hz , High Amplitude Peak

Using Michigan Statewide Equation-(Not Valid) estimate ~60.31077648 ft



Can it be used to help in finding more oil & gas?

- Collect HVSR data along seismic reflection line to give independent bedrock elevation profile to assist in reflection static corrections.
- Run along gravity profiles to give independent bedrock elevation profile to assist in gravity filtering and modeling.

Places it has not worked so well

- Calhoun County area
  - Transitional drift to bedrock contact?
  - Tectonized bedrock surface?
  - Buried cemented gravels?
- Northern Clinton County

Vs - Shear Wave Velocity

- What is it?
- How to get it?
- Empirical relationship w/ Split-spoon sampling blow counts n-value
- Seismic Surveys

How large or what defines a calibration area?

Same geological system..County, Twp, Saginaw Lowland, size of your project?

- Drift lithology
- Drift stratigraphy complexity
  - 200' of sand and gravel or
  - 200' of sand & gravel w/thick tills and or lacustrine clay units
  - Overconsolidated tills or cemented gravels
- Drift thickness-thicker drift more compaction higher Vs
- Bedrock lithology Coldwater Shale or Marshall SS
- Weathered or non-weathered bedrock surface
- No clear bedrock surface –(transition from basal till to weathered shale over 30-40 feet)

Or do all these things below our feet change more than we have the data to now these changes are occurring…..

Winter Frozen Ground & Freeze/Thaw

- Poor ground coupling with unit on frozen ground
- Potential velocity inversion at surface due to frozen ground and frost
- Late winter freeze/thaw can get poor results
- Experimenting with different materials to place on frozen ground to help with coupling (fine sand, Play dough, modeling clay, Silly Puddy)
- Geologists get cold!

Questions?

- How big is an area for calibration purposes?
- How accurate are the depths? Depends!
- Use in Winter?
- Some places where it should work but doesn't?
- What if the nice response in area is the top of dense basal till, cemented gravels, not top of bedrock?

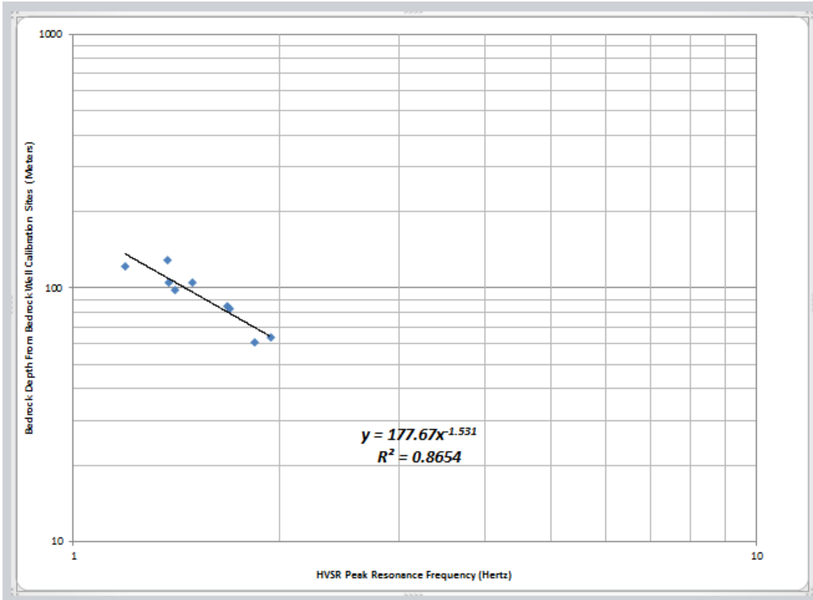
Future Work

- More work over in the Jurassic Redbeds-Will it see the top of them or the bottom of them?
- Are the good results seen so far in Northern Lower Peninsula the true bedrock surface of potentially buried overconsolidated tills above the bedrock surface
- If over a deep steep walled bedrock valley, can it see it?
- Use in winter

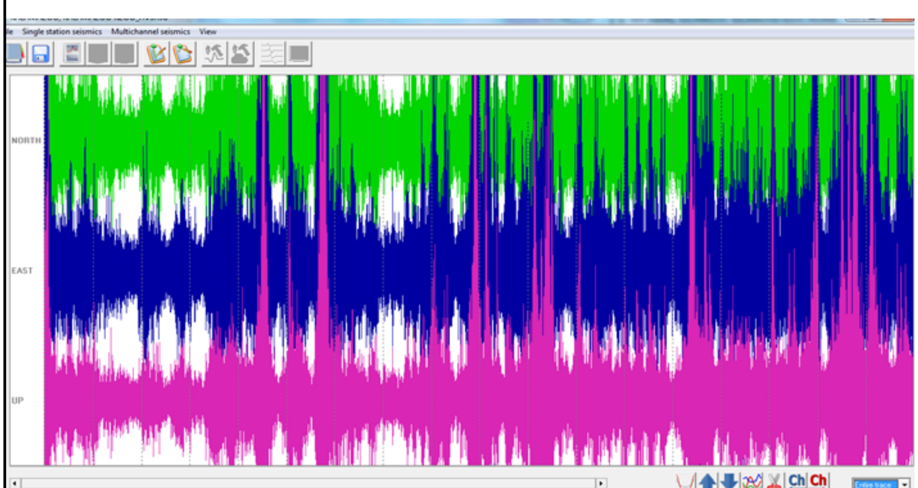
Thanks

- Paul Jankowski
- Adam Wygant
- Steve Wilson
- Beth Carlson
- USGS: John Lane
- Bill Sauck, WMU/MGS
- Alan Kehew WMU/MGS
- Val Chandler
  Minn. Geol. Survey

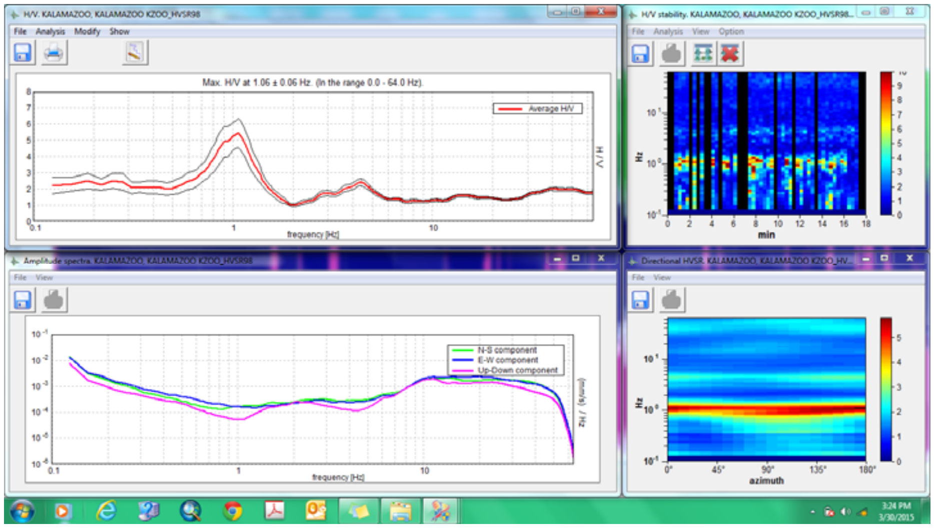
Mt. Pleasant Area



Rood Hall Parking Lot NW Corner Raw, Very Noisy

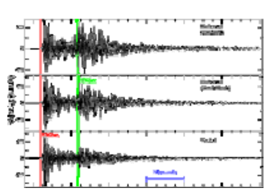


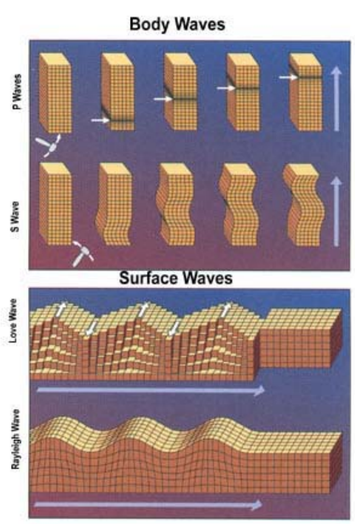
Rood Hall Parking Lot NW Corner, Processed Data   Bedrock Depth Est 232 FT



Seismic Waves Types

- Body Waves
  - P Waves
  - S Waves
- Surface Waves
  - Love Waves
  - Rayleigh Waves





http://en.wikipedia.org/wiki/File:Seismogram.gif http://en.wikipedia.org/wiki/File:Pswaves.jpg