Applied Geology for Investigation, Design and Mitigation of a Landslide in Newport, Vermont

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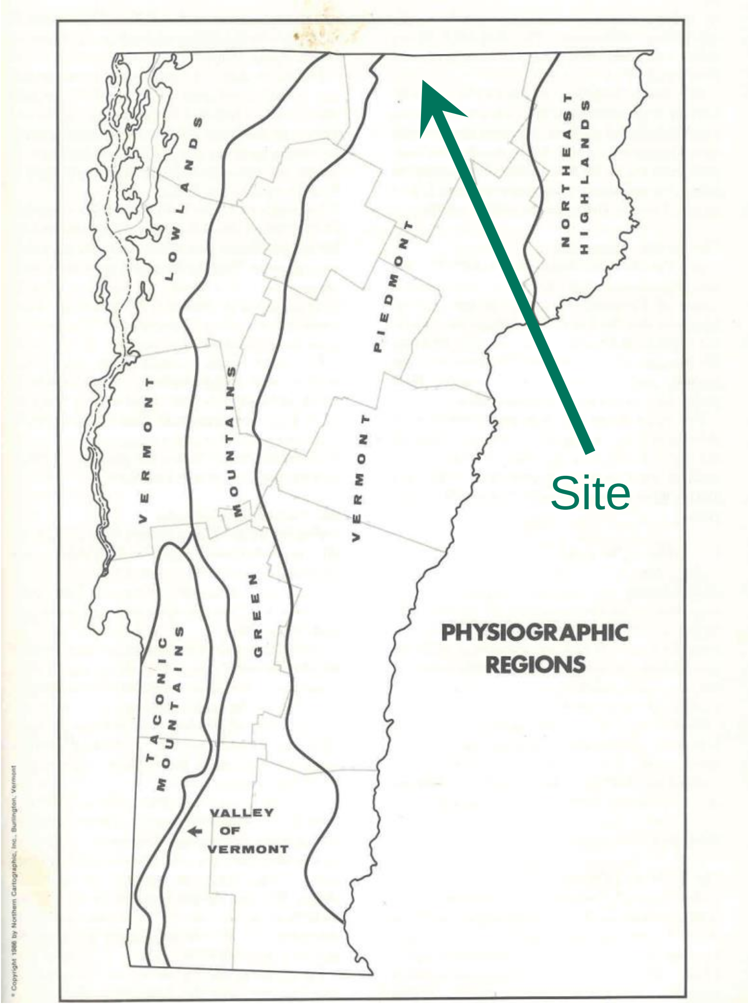
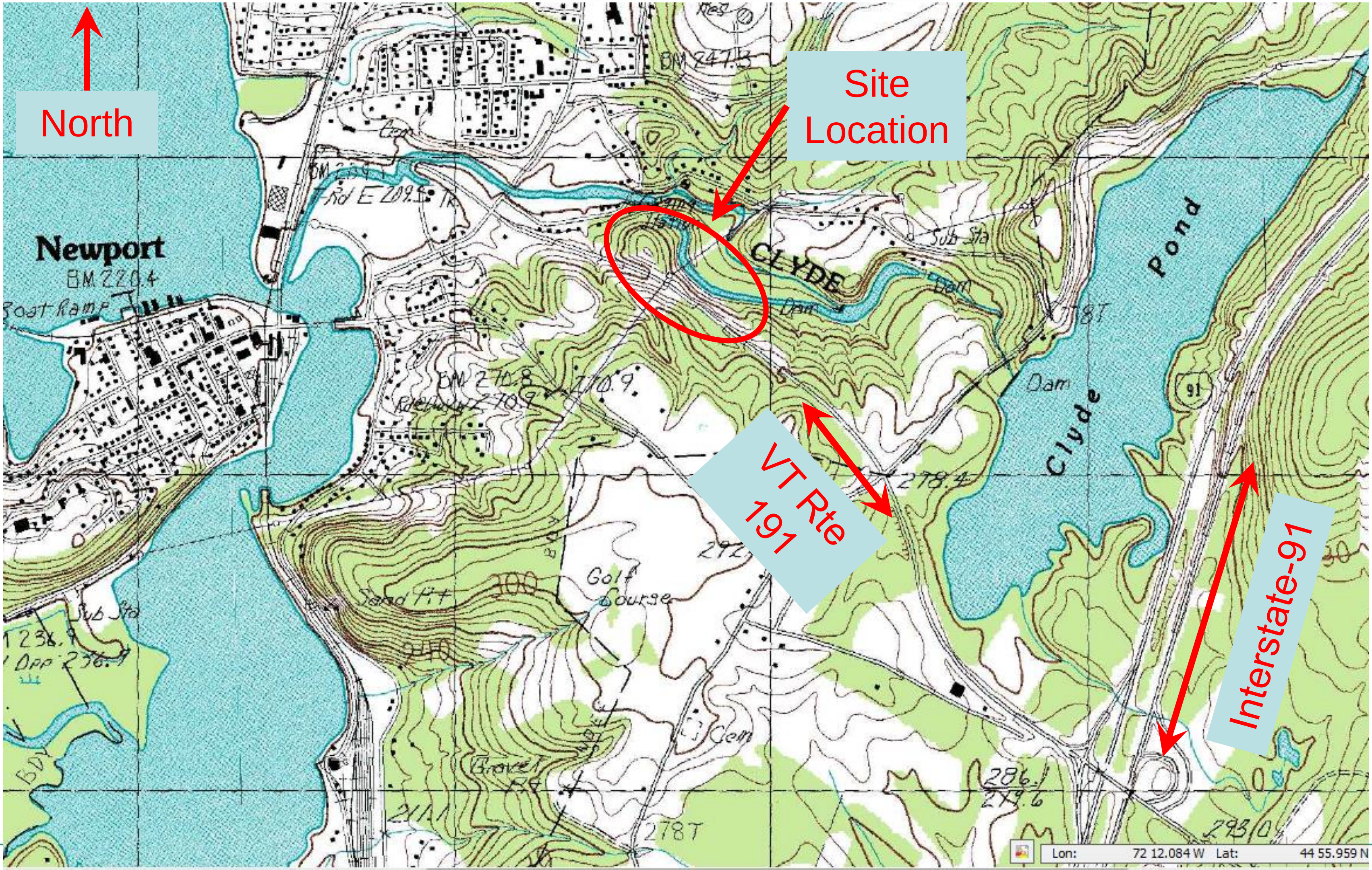
Regional Location

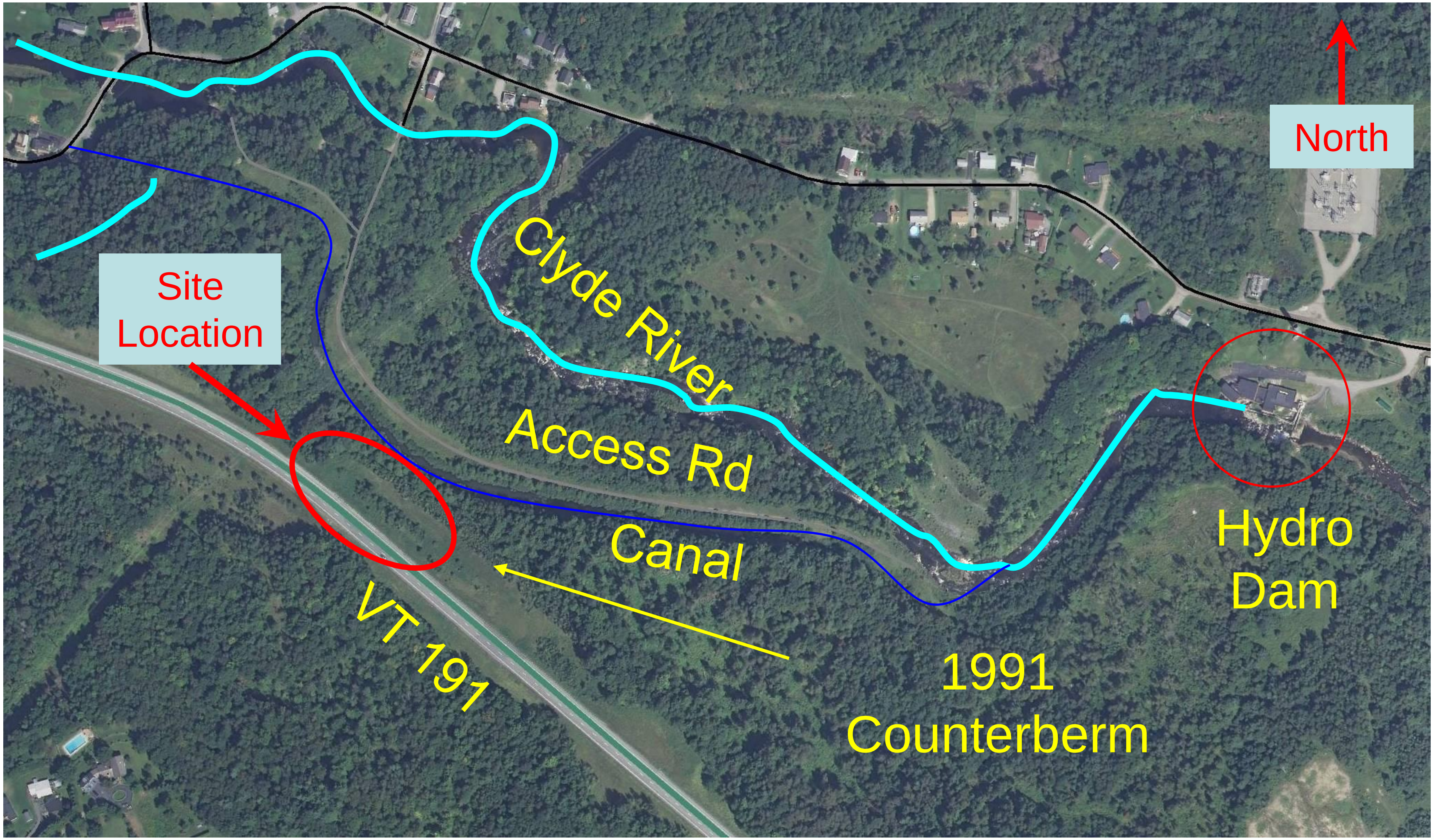
- State Route 191 in Newport, VT
- ~ 5 miles from Quebec border
- Piedmont Physiographic Province
- Relatively rural location, last major town off of I-91 before border
- Skiing, boating, outdoor recreation, logging



Site Location – USGS Topographic Map

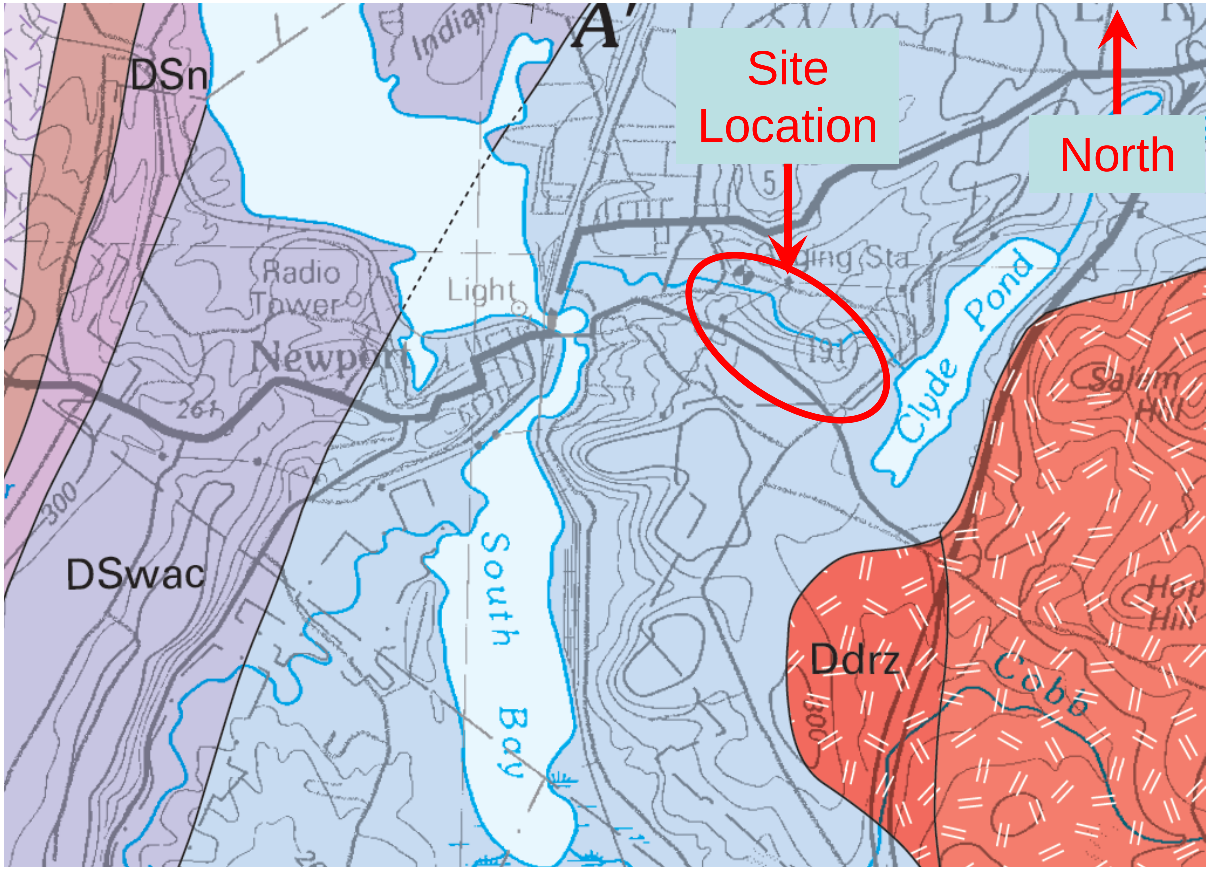


Site Location



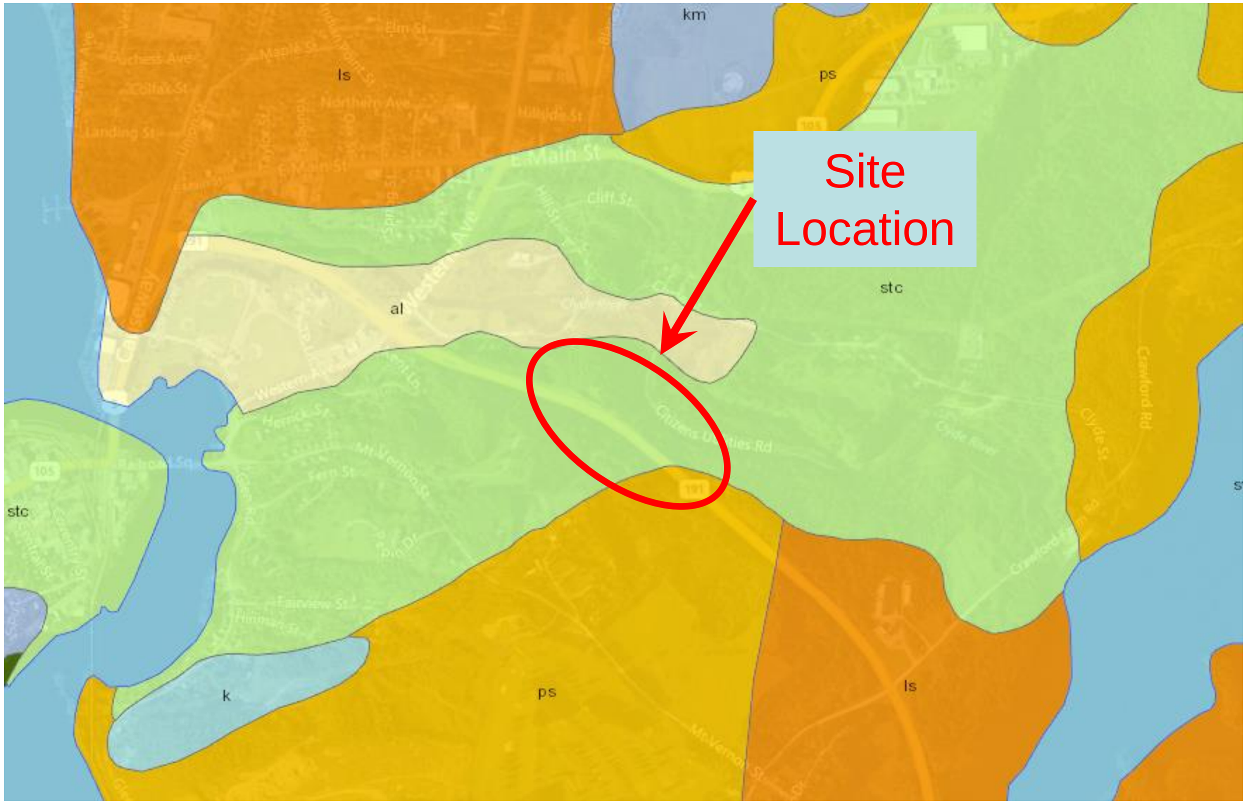
Site Geology - Bedrock

- Western Margin of Connecticut Valley Trough
- Lower Devonian/ Upper Silurian Waits River Formation – carbonaceous phyllite and limestone member



From Ratcliffe et al., 2011, Bedrock Geologic Map of Vermont. USGS SIM 3184.

Site Geology - Surficial



From VTANR

- Pleistocene-aged glacial lake dammed by ice contact deposits (Glacial Lake Memphremagog)
- Clays, silts & fine sands deposited in glaciolacustrine environment
- Dropstones common

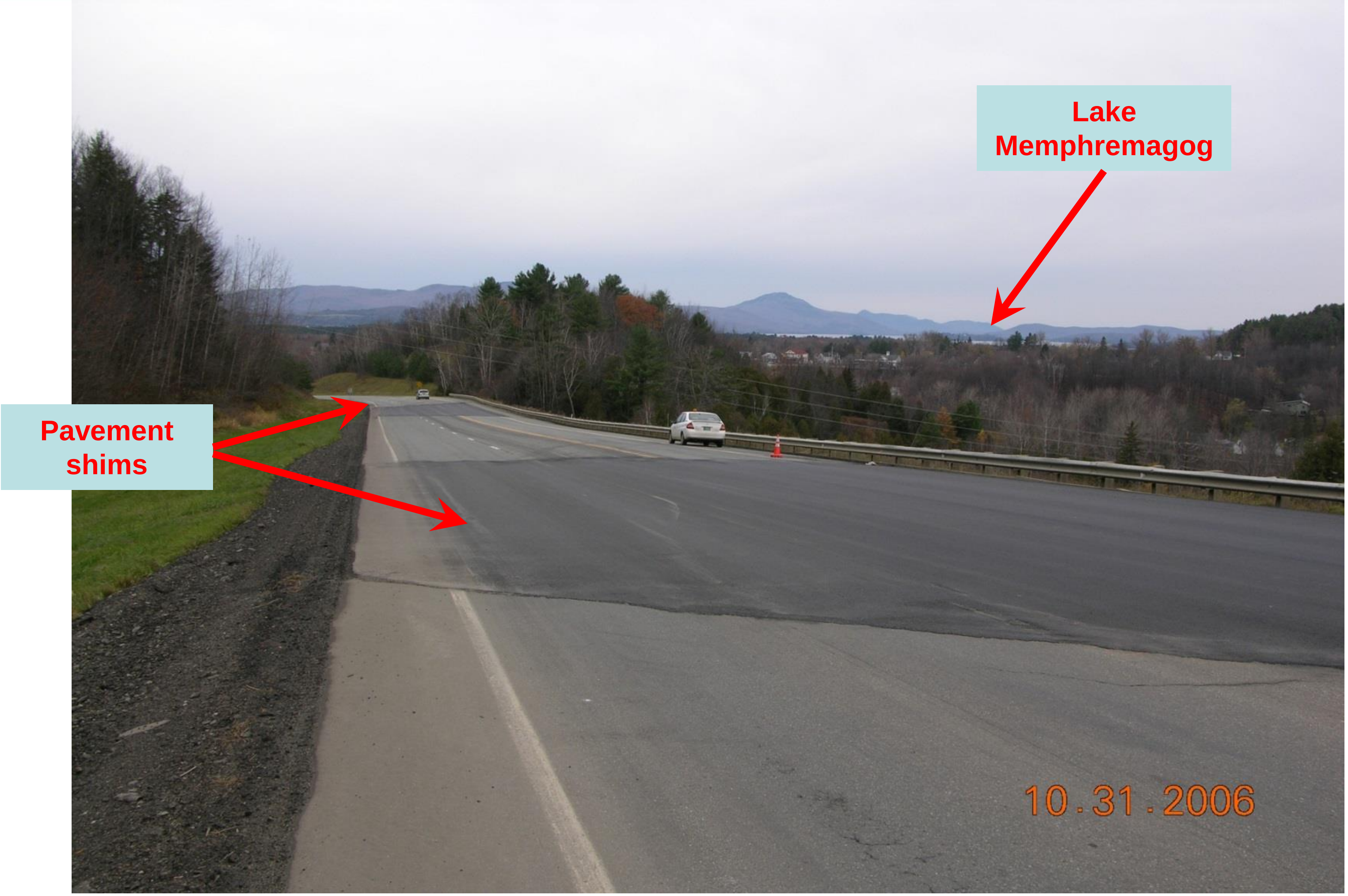
Site History

Date	Event Description
1969-1971	Original embankment construction.
1971	April: first sign of slope movement; 5 in. of separation at 30-in culvert beneath roadway within embankment fill. June: installed underdrain system at toe of upslope embankment slope.
1973	Installed 17 horizontal drains.
1974	1.5 ft of settlement measured since 1971 (average of 6 in/yr).
1971-1976	Roadway pavement settlements average 4 in/yr.
1986	Removed 4 ft of pavement (avg = 3.2 in/yr 1971-1986).
1989	Subsurface investigation. Failure surface identified 10 to 25 ft below original ground surface beneath embankment.
1991	Counterberm and more horizontal drains.

Site History

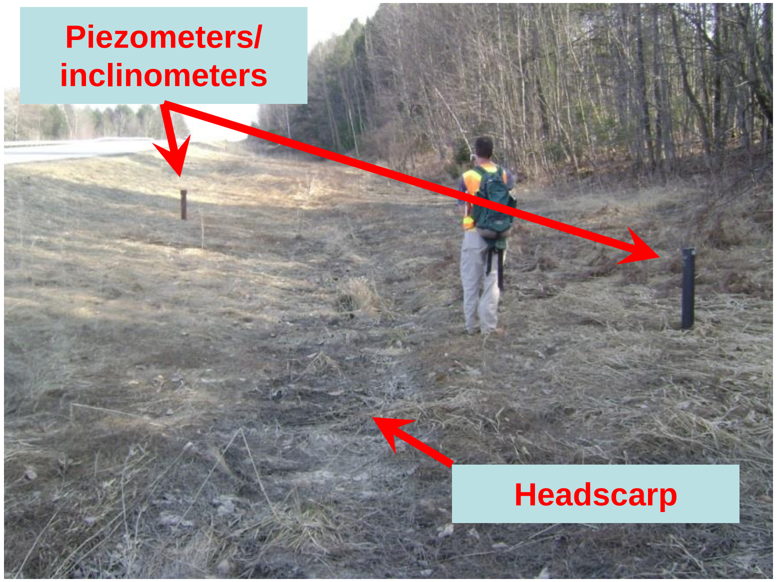
Date	Event Description
1996	Sinkhole developed at 30-in culvert due to 8 ft of vertical separation. Culvert replaced.
1996-2011	Numerous pavement leveling operations. Culvert still experiencing significant deformation.
2006-2009	Additional subsurface investigations including borings, instrumentation, testing and culvert inspection. Culvert deformation 8 in.
2006-2011	Inclinometer data indicates base of slide mass located up to 120 ft bgs at counterberm and extends to base of slope near Clyde River
2011	Stability evaluations/mitigation alternatives presented ASCE conference. Groundwater lowering identified as preferred mitigation alternative.
2012	Inspection of 30-in. diameter culvert indicates additional deformation.
2013	Focused geologic, hydrogeologic and geotechnical subsurface investigation and remote instrumentation installation.
2014-2015	Mitigation alternatives evaluation and final design

2006 Conditions

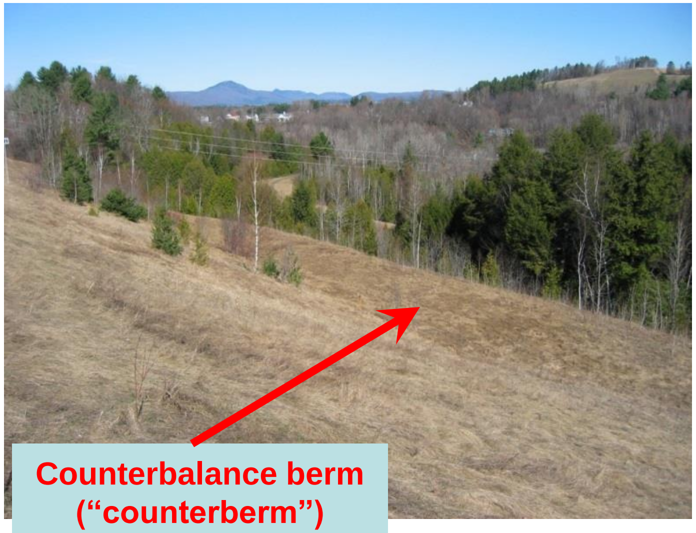


View looking downgrade (northwest) along VT 191 (October 2006)

2012 Conditions

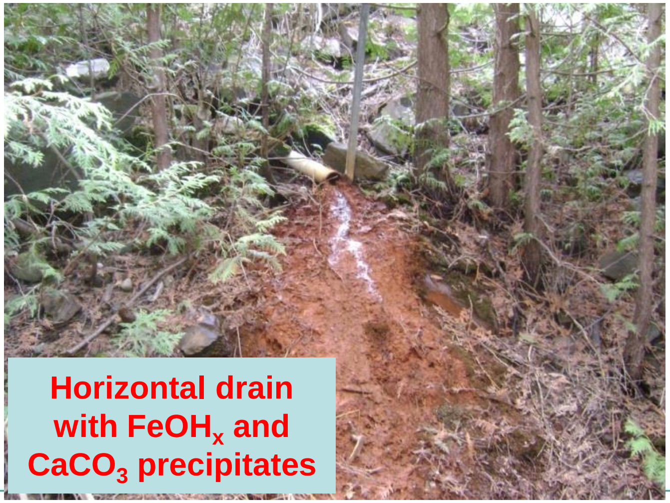


2012 Conditions



Counterbalance berm
(“counterberm”)

Inclinometer near toe with artesian groundwater flow (~800 mL/min)



Horizontal drain with $FeOH_x$ and $CaCO_3$ precipitates

Damaged culvert beneath roadway

Phase 1 - Desktop Study

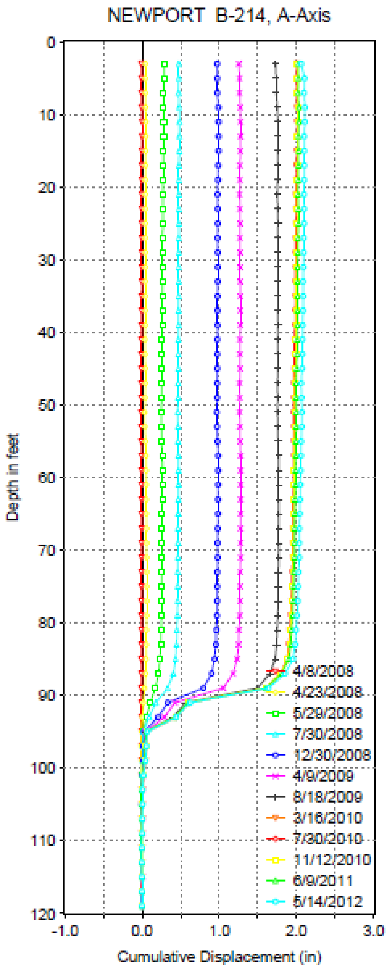
Records Review

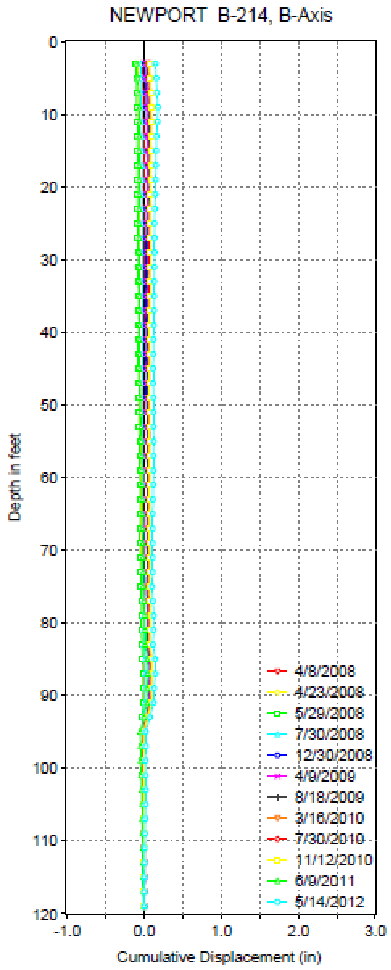
- Site logically investigated, mitigation approaches reasonable given understanding of subsurface conditions
- Existing instrumentation condition poor (some damaged beyond usefulness)
- Slide extent not fully characterized
- Slope movement mechanisms likely a complex combination of stratigraphy, groundwater conditions, continuous creep, and soil strength characteristics (common to slow moving landslides)
- Model complicated by no evidence of slide toe at surface (under Clyde River?)

Monitoring, Additional Investigation & Risk Management

- Confirm validity of preliminary analytical models
- Install monitoring equipment
- Refine geologic/hydrogeologic/geotechnical model
- Allow development of mitigation option evaluation/costs

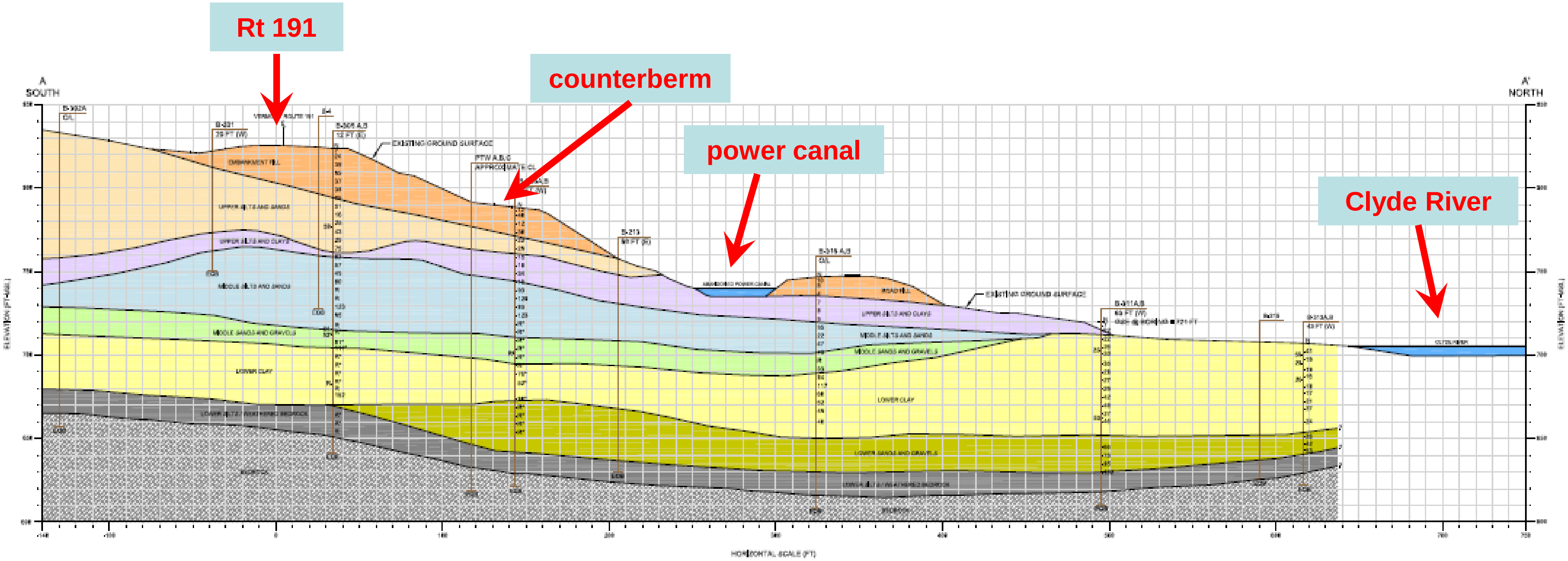
Phase 1 – Inclinometer Data





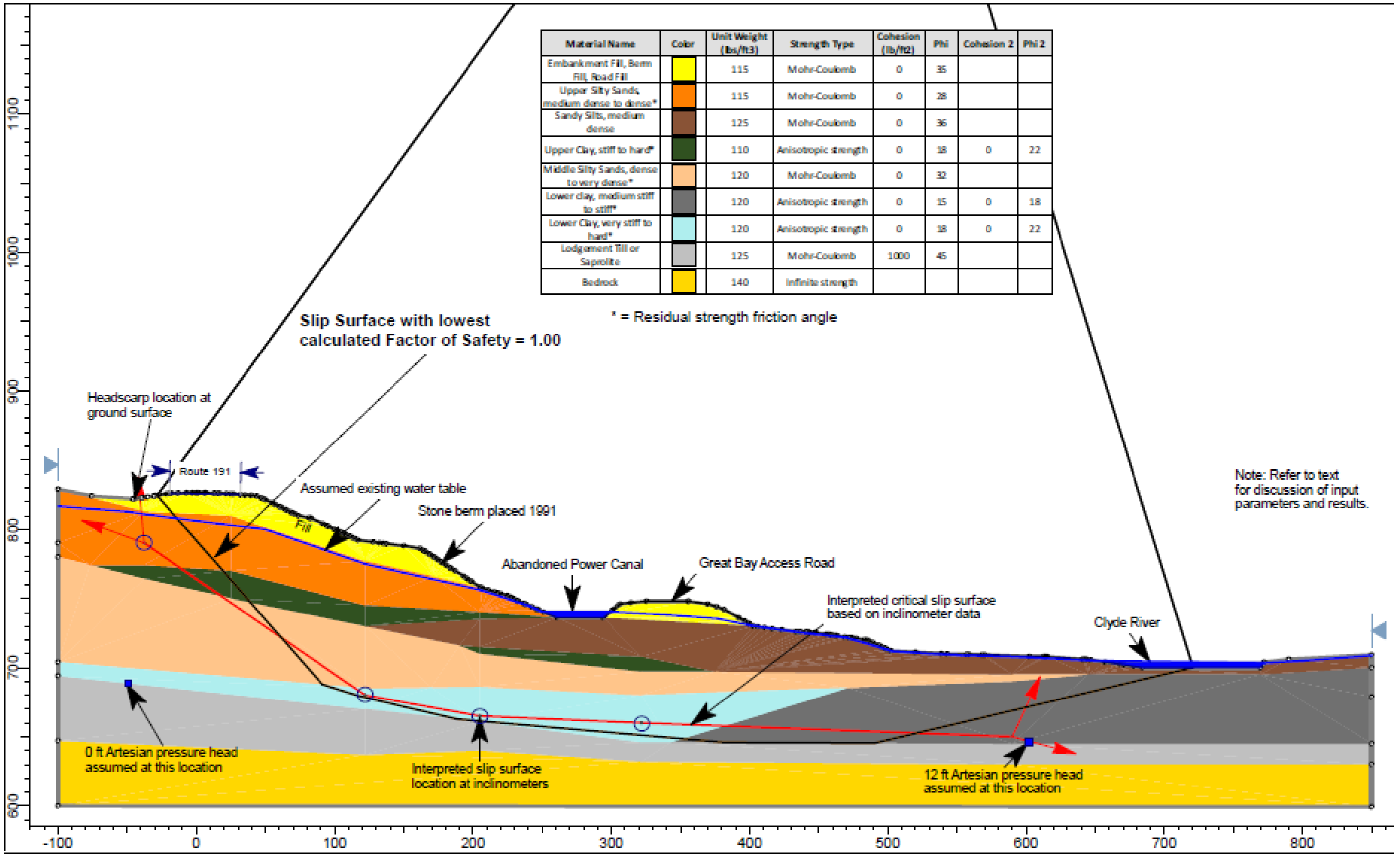
- Inclinometers indicate deep failure surface(s) exist
- Movement slowed after installation of deep inclinometers near toe of slide 2007-2008
- Difficult installation conditions due to artesian pressures (relief tubes needed to grout casings)

Phase 1 - Profile



Geology consist of fill materials, alternating fine to coarse sands and gravels, sandy silts and clayey silts, underlain by phyllitic bedrock.

Phase 1 - Back Failure Analysis (FS=1.0)



Material Name	Color	Unit Weight (lbs/ft3)	Strength Type	Cohesion (lb/ft2)	Phi	Cohesion 2	Phi 2
Embankment Fill, Berm Fill, Road Fill		115	Mohr-Coulomb	0	35		
Upper Silty Sands, medium dense to dense*		115	Mohr-Coulomb	0	28		
Sandy Silts, medium dense		125	Mohr-Coulomb	0	36		
Upper Clay, stiff to hard*		110	Anisotropic strength	0	18	0	22
Middle Silty Sands, dense to very dense*		120	Mohr-Coulomb	0	32		
Lower clay, medium stiff to stiff*		120	Anisotropic strength	0	15	0	18
Lower Clay, very stiff to hard*		120	Anisotropic strength	0	18	0	22
Lodgement Till or Saprolite		125	Mohr-Coulomb	1000	45		
Bedrock		140	Infinite strength				

* = Residual strength friction angle

Golder Associates	Project	VTRANS Rt 191 Slide Review, Newport, Vermont		
	Analysis Description	Cross-Section A-A': Results of Stability Analysis - Existing Conditions Assuming Artesian Pressures		
	Design By:	Checked by:	Reviewed by:	Scale 1:1150
SLIDEINTERPRET 6.012	Date 10/22/2012	File: Figure 4h.slim		FIGURE 4

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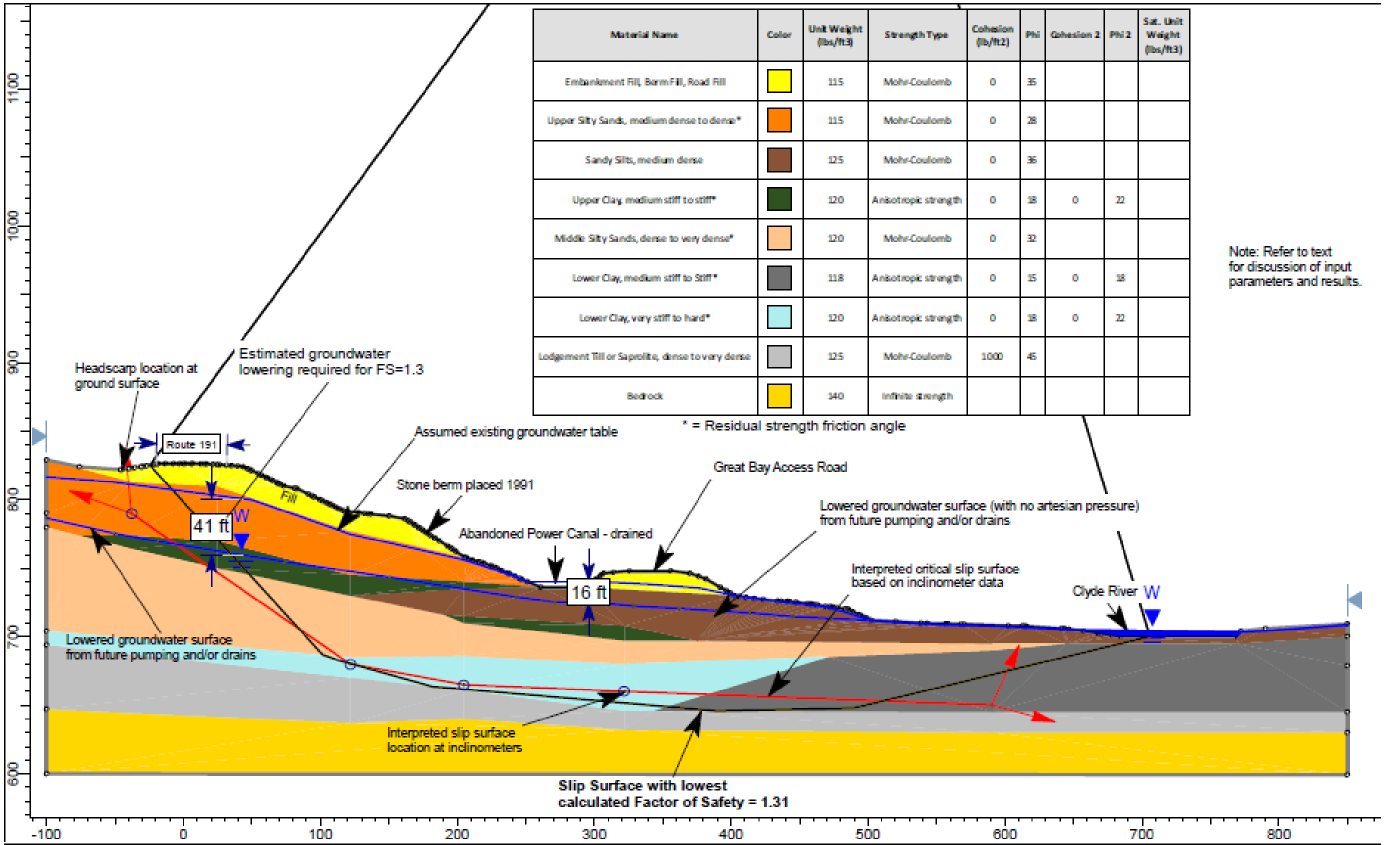
Phase 1 - Lower Groundwater (FS=1.3)



Material Name	Color	Unit Weight (lbs/ft3)	Strength Type	Cohesion (lb/ft2)	Phi	Cohesion 2	Phi 2	Sat. Unit Weight (lbs/ft3)
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Middle Silty Sands, dense to very dense*		120	Mohr-Coulomb	0	32			
Lower Clay, medium stiff to Stiff*		118	Anisotropic strength	0	15	0	18	
Lower Clay, very stiff to hard*		120	Anisotropic strength	0	18	0	22	
Lodgement Till or Saprolite, dense to very dense		125	Mohr-Coulomb	1000	45			
Bedrock		140	Infinite strength					

* = Residual strength friction angle

SLIDEINTERPRET 6.012

Project
VTRANS Rt 191 Slide Review, Newport, Vermont

Analysis Description
Cross-Section A-A': Results of Stability Analysis - No Artesian and Lowered Groundwater Surface

Design By:	*Checked by:*	*Reviewed by:*	*Scale* 1:1150	**FIGURE 5**
Date 10/22/2012		File: Figure 5.slim		

Phase 2 - Detailed Site Investigation 2013

- Sonic & conventional geotechnical drilling
- Soil/rock sample collection
- Groundwater levels
- Laboratory testing:
  - Grain size analyses (VTrans)
  - Preconsolidation stress (UMass Amherst)
  - Vertical over consolidation ratio [OCR_v]
  - Permeability
  - Direct shear

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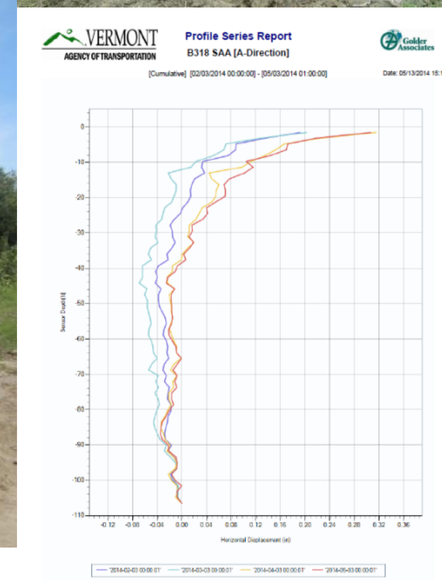
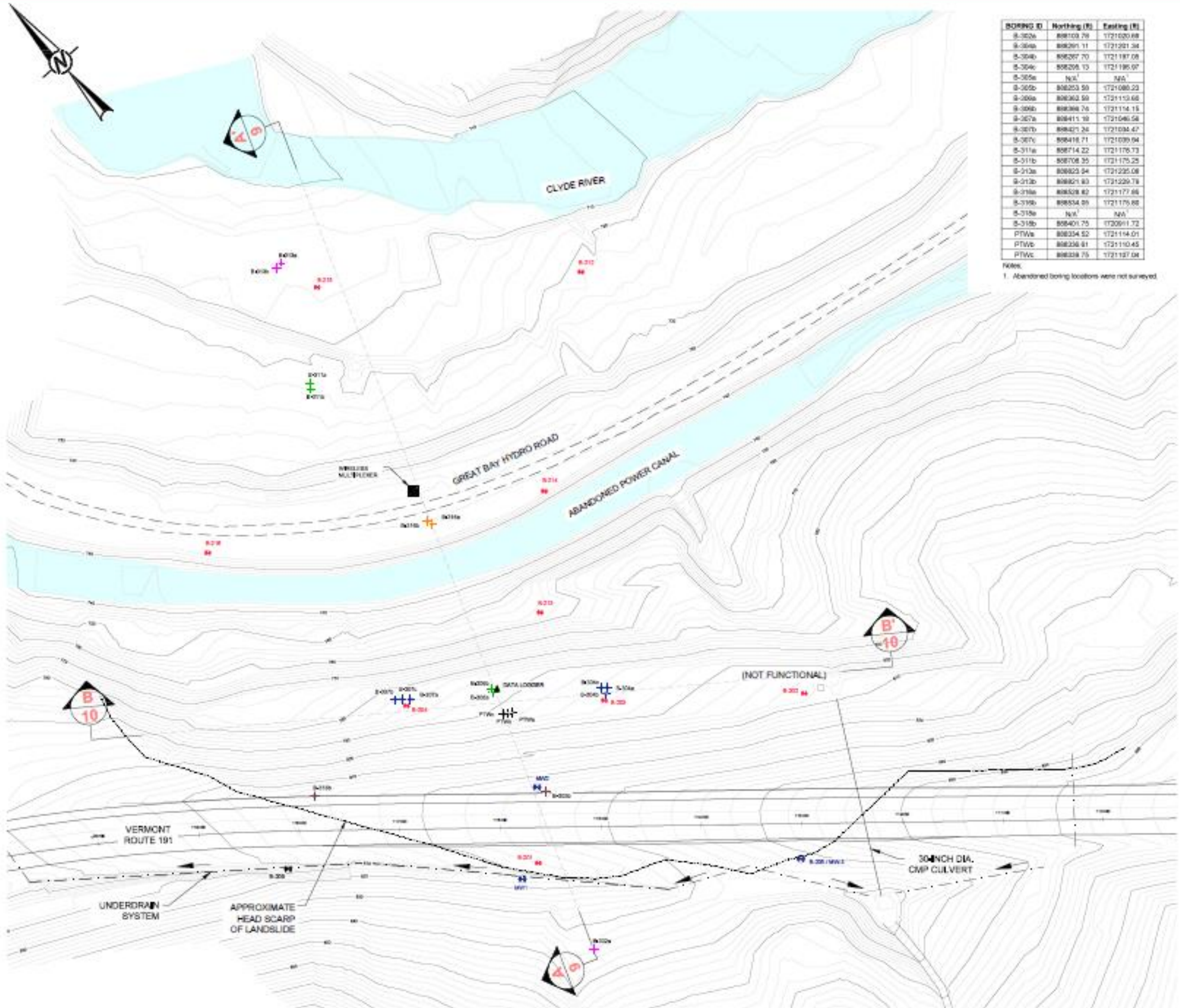
Phase 2 – Instrumentation 2013

- In-Place Inclinometers (IPIs) and ShapeAccelArray (SAA) inclinometers
- Piezometers (manual/automated)
- Pumping/monitoring wells
- Weather station
- Remote monitoring system with real time download capability (via cellular network)



Phase 2 – Investigation Locations



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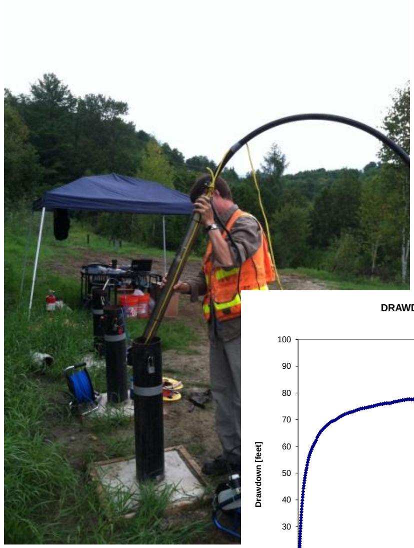
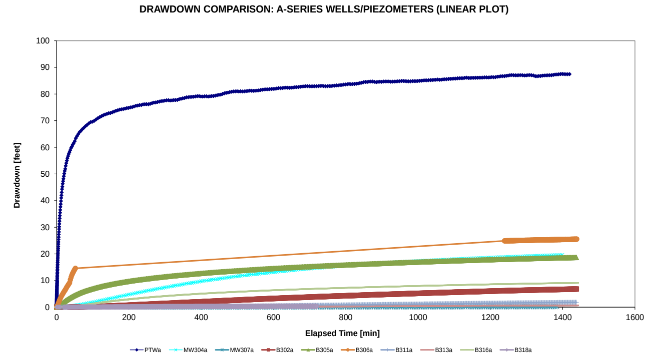
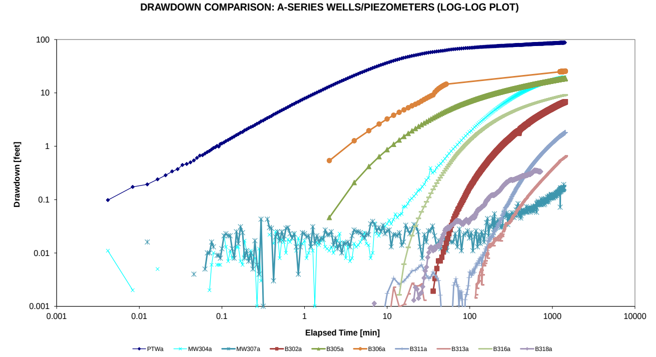
Phase 2 – Hydrogeologic Testing 2013

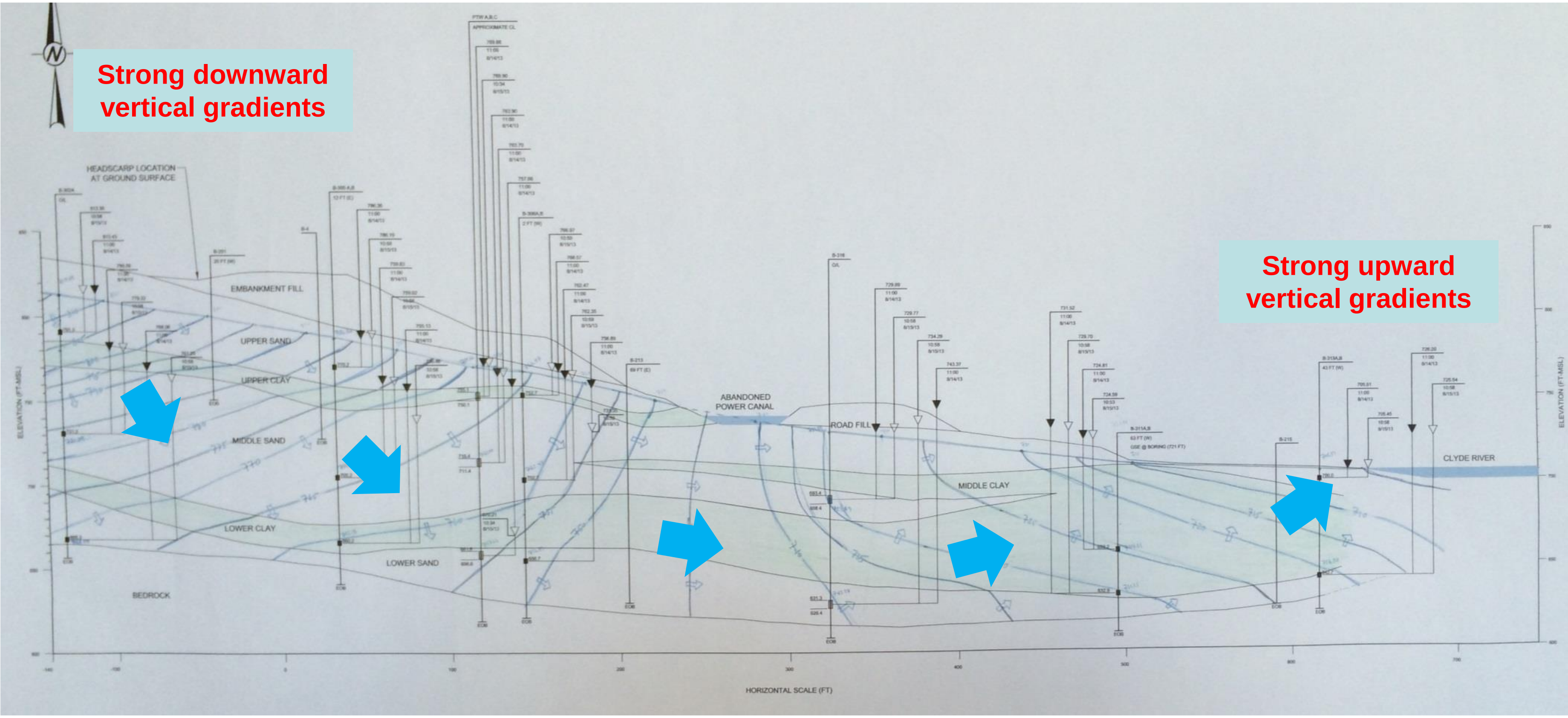
- Groundwater level monitoring
- Slug tests
- 24-hour pumping test (Lower Sand and Gravel)
- Hydraulic conductivity:
  - Lower Sand and Gravel: 5E-03 to 5E-05 cm/s (avg 5E-04 cm/s)
  - Lower Clayey Silt: 2E-05 to 3E-09 cm/s
  - Middle Sand: 2E-04 to 4E-06 cm/s (avg 8E-05 cm/s)



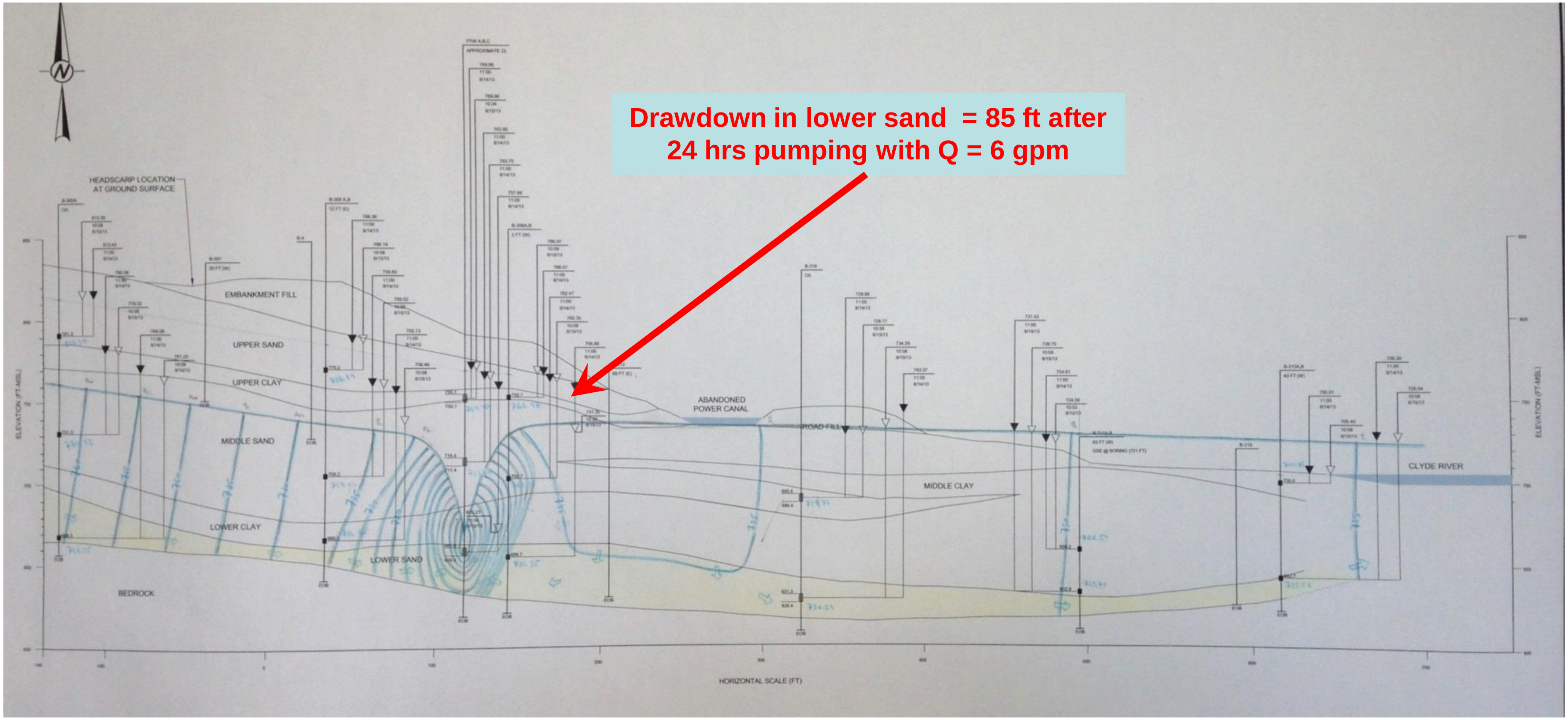




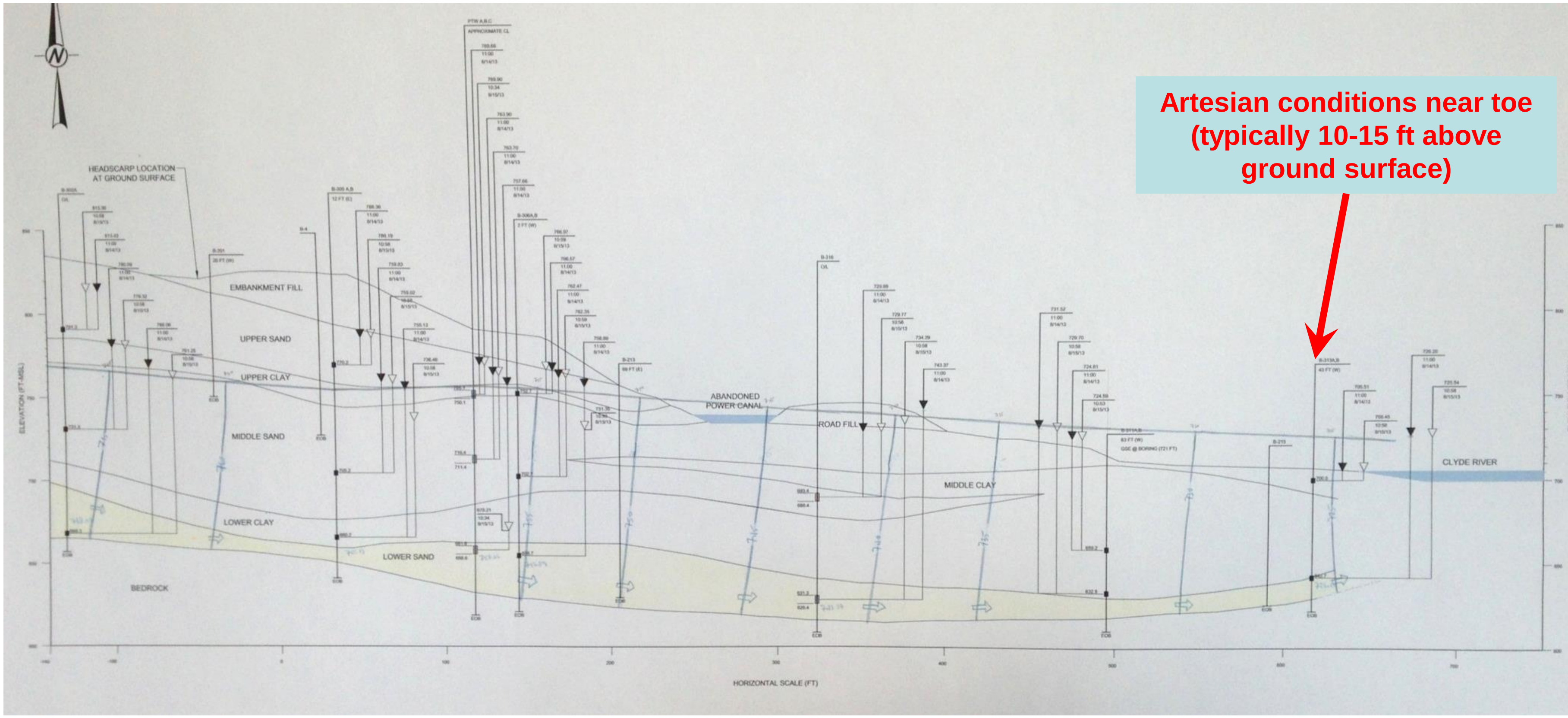
Phase 2 – Flownet



Phase 2 – Lower Sand Piezometric Surface (Pumping Test)



Phase 2 – Lower Sand Piezometric Surface



Artesian conditions near toe (typically 10-15 ft above ground surface)

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Phase 2 – Pre-Pleistocene Deposition?

- Pre-Pleistocene glacial sediments rare in New England, but a few locations suspected in ME, VT, NH, MA & Quebec
- These sediments could be 1.5Ma or older
- Evidence of pre-Pleistocene deposition:
  - Folded varves – intense 3D folding with curved fold axes (glaciotectonic stress)
  - OCR_v 15.7 – 35.4 (very high)
  - N > 100 in Middle and Lower Clayey Silts (similar to lodgement till)
  - Multiple slickensides/shear zones

Folded varves – fold nose "eye" structures from sheath folds (Möller, 2010)

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Phase 2 – Pre-Pleistocene Deposition?

Evidence of pre-Pleistocene deposition:

- Dropstones common in varved silts
- Thin high plasticity clays (smectite/ montmorillonite?) – possible volcanic ash falls?

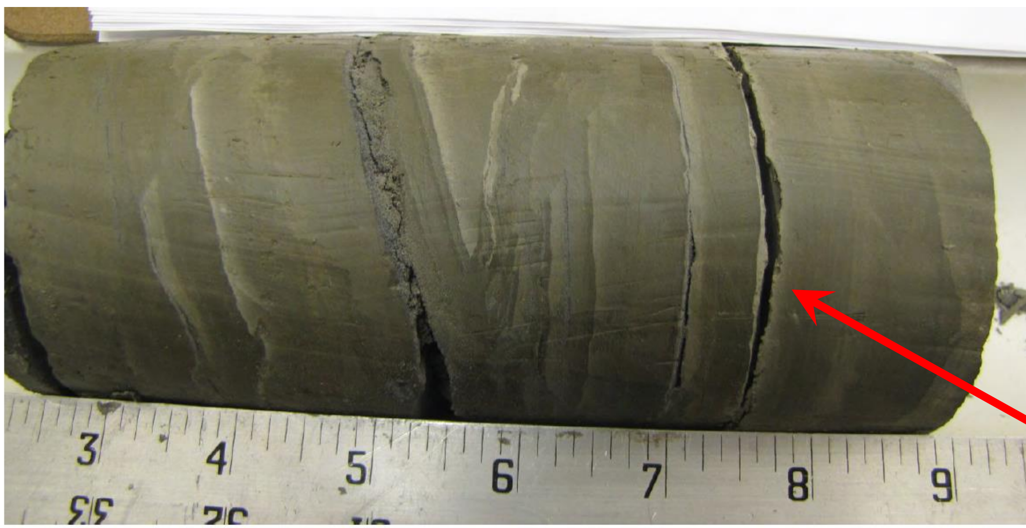

Figure A.2 Sample B-306b U2 110 to 112 ft.: Extruded section of sample located at 2.5 to 9" from bottom of tube (close up of Figure A.1).

This parting is not a fine sand or coarse silt typical of the varves; consists of very plastic fine grained sediment with high LL. When water added, feels greasy – possible smecite/montmorillonite layer

Phase 2 – Folded Varves

- Three folded varve formation mechanisms:
    - Slump/debris flow (Mangili, 2006)
    - Seismic faulting (Gruzska & van Loon, 2007)
    - Ice-margin grounding (Ó Cofaigh & Dowdeswell, 2001)
- Slump study of Pleistocene varved clays in NJ of OCR_v = 9 (Berlingame et al. 2013), much lower than OCR_v range of 15 to 35 at Newport
- Very high n values, commonly > 100 in lower clayey silt (very stiff to hard)
- Ice-margin grounding from advancing Pleistocene ice sheet(s) may have deformed pre-Pleistocene varved sediments
- 1+ km thick Pleistocene ice sheet may have produced high OCRs
- Cosmogenic Be^{10} study of dropstones/cobbles could help determine age of lowermost sediments

Phase 3 – Mitigation Design

- Groundwater extraction will reduce pore pressures, and increase FS (passive/active extraction)
- Compile calibrated 3D numerical groundwater flow model (per WashDOT guidance)
- Use model to simulate groundwater extraction scenarios (artesian wells, pumping wells, horizontal drains)
- Simulate reduced pore pressures in 2D slope stability models, estimate increase in FS for various alternatives
- Choose final design (constrained by site conditions)

Phase 3 - Work Flow

Conceptual Geologic Model (*EVS/MVS*)
Provides framework for groundwater model

↓

Numerical Groundwater Model (*MODFLOW*)
Calibrate to site conditions & simulate groundwater extraction scenarios

↓

Geographic Information System (*ArcGIS*)
Transfer of pore water pressures for input into slope stability analyses

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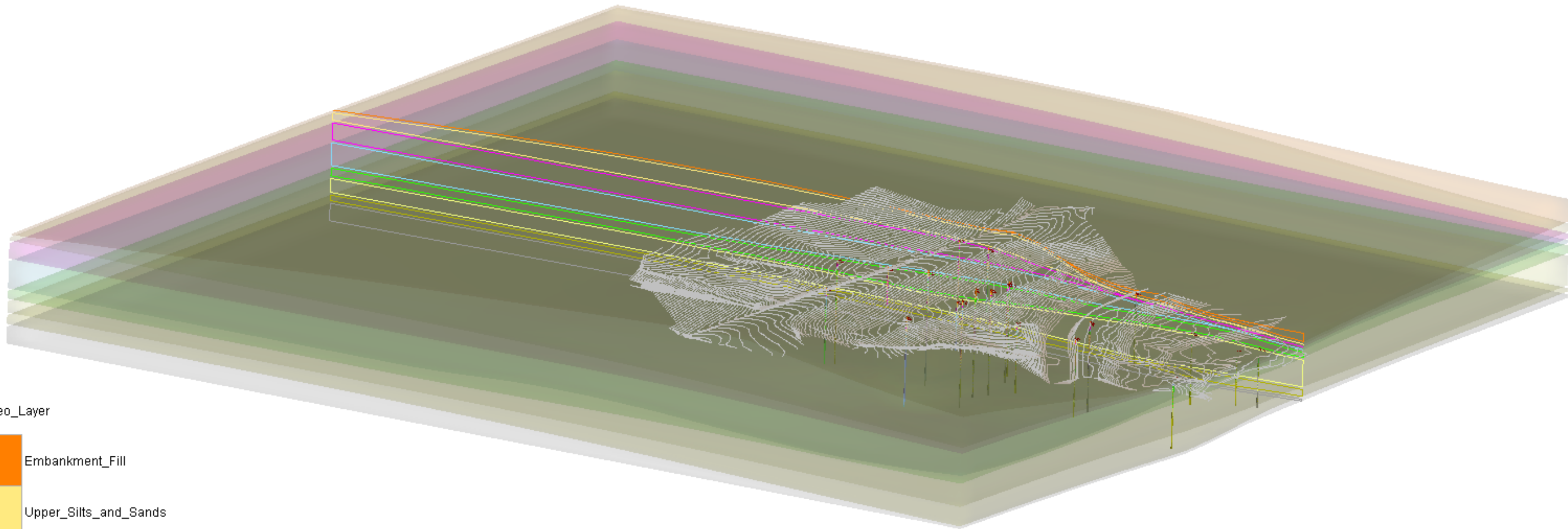
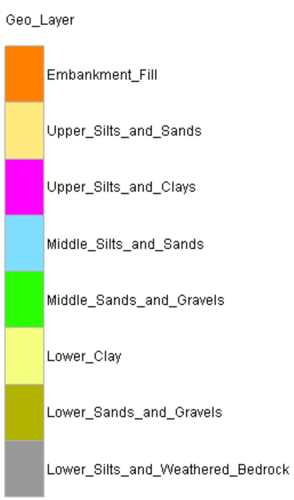
Slope Stability Model (*SLIDE*)
Analyze slope stability and estimate increase in FOS for scenarios

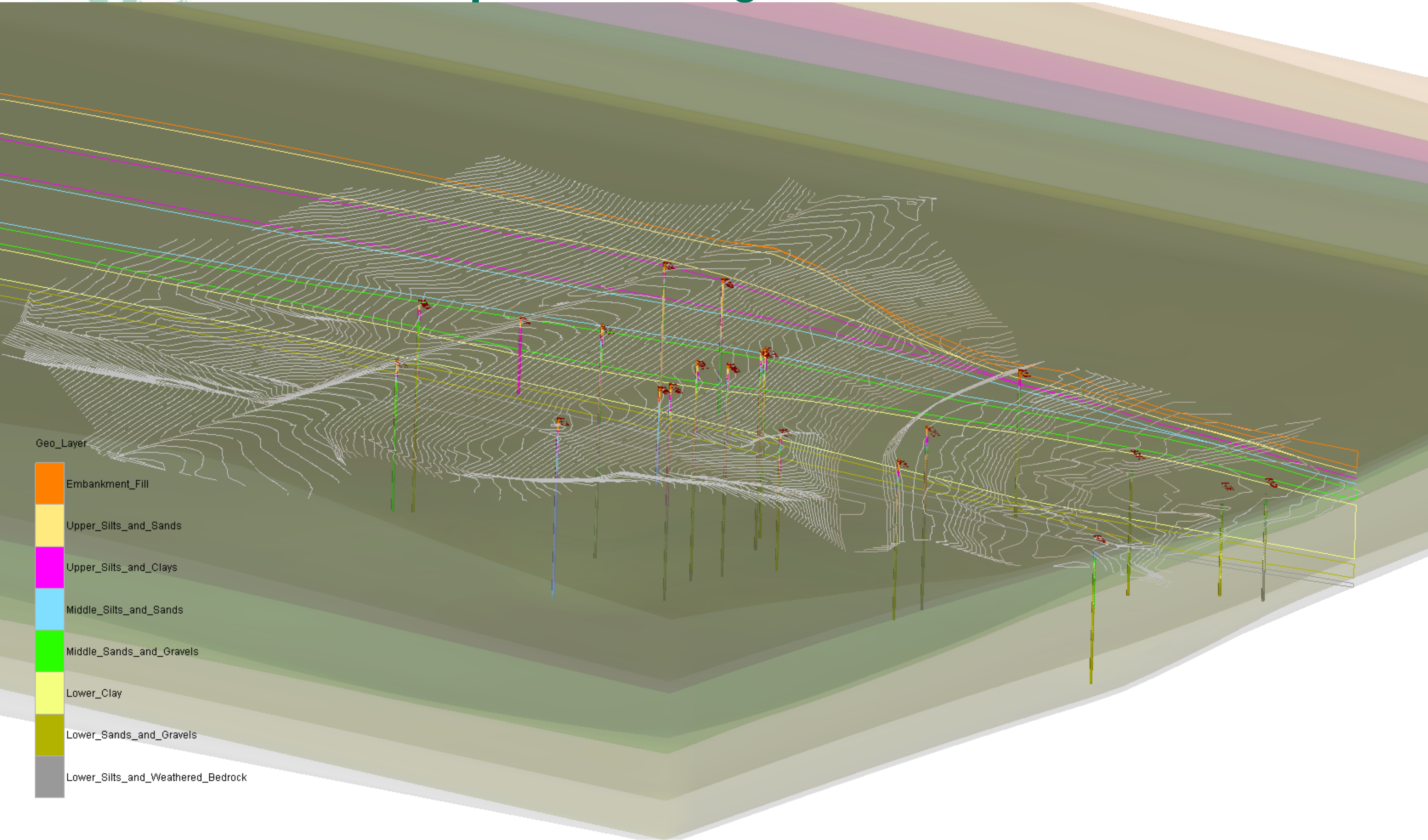
Conceptual Geologic Model





- EVS/MVS 3-D Visualization Software
- Refines conceptual geologic model of site
- Input:
  - Topographic surface
  - Subsurface explorations (VTrans, Golder)
- Provides 3-D geologic framework for numerical groundwater model

Conceptual Geologic Model



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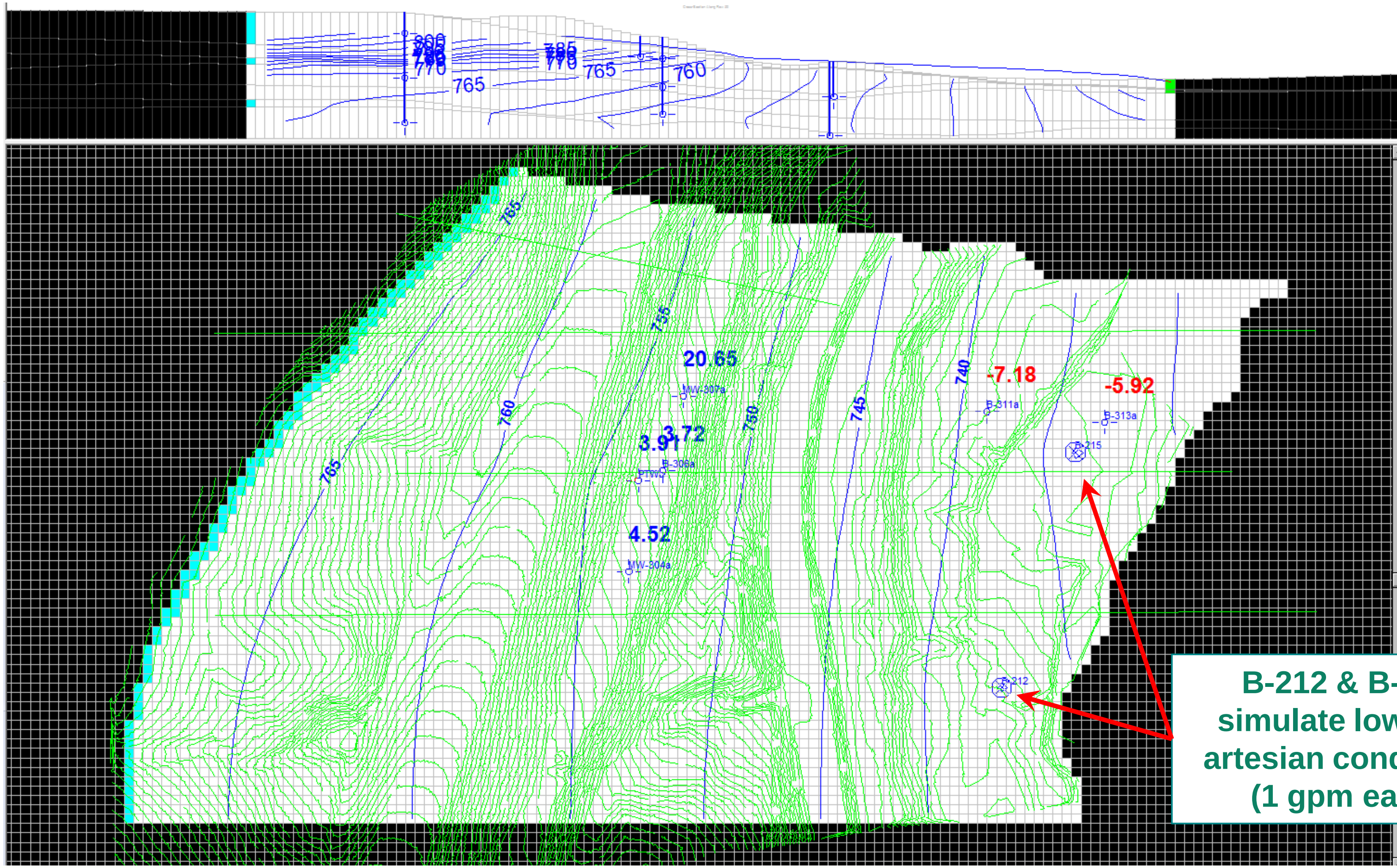
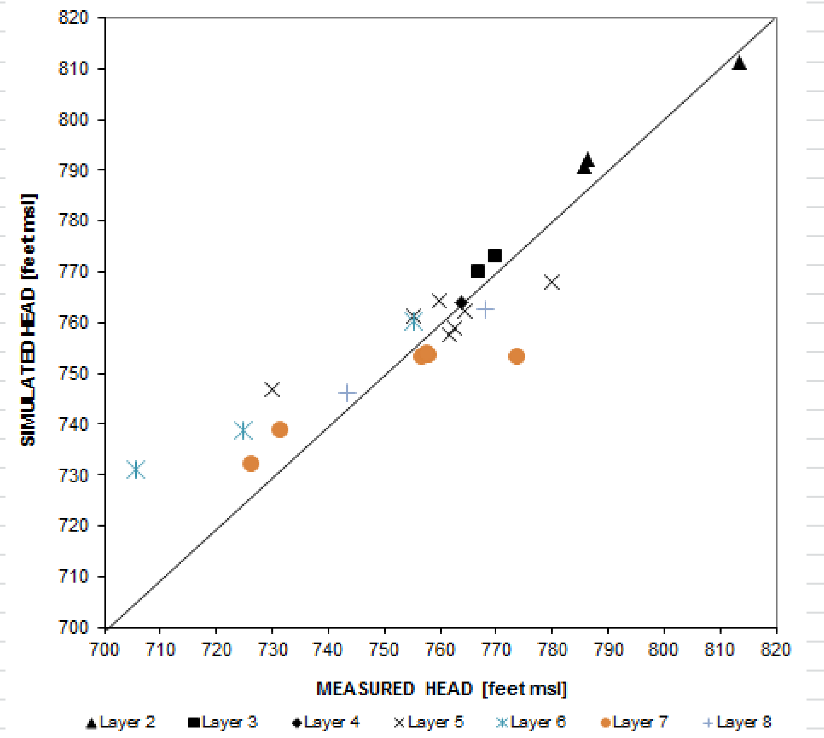
Current Conditions (Layer 7)



B-212 & B-215 simulate low flow artesian conditions (1 gpm each)

Model Calibration

Well ID	X	Y	Layer	Measured Head [feet msl]	Simulated Head [feet msl]	Residual [feet]
B-302c	1,721,021	888,104	2	813.43	811.07	2.36
B-305c	1,721,088	888,254	2	786.36	792.14	-5.78
B-318b	1,720,912	888,402	2	785.76	790.92	-5.16
B-306c	1,721,114	888,363	3	766.57	770.26	-3.69
PTWc	1,721,107	888,340	3	769.66	773.19	-3.53
PTWb	1,721,110	888,337	4	763.90	763.93	-0.03
B-302b	1,721,021	888,104	5	780.09	768.01	12.08
B-305b	1,721,088	888,254	5	759.83	764.13	-4.30
B-306b	1,721,114	888,363	5	762.47	759.00	3.47
B-316b	1,721,176	888,534	5	729.87	746.84	-16.97
B-318a	1,720,912	888,402	5	755.20	761.34	-6.14
MW-304b	1,721,197	888,288	5	764.47	762.29	2.18
MW-307b	1,721,034	888,421	5	761.56	757.62	3.94
B-305a	1,721,088	888,254	6	755.13	760.27	-5.14
B-311b	1,721,175	888,708	6	724.81	738.66	-13.85
B-313b	1,721,230	888,822	6	705.51	731.16	-25.65
B-306a	1,721,114	888,363	7	756.89	753.17	3.72
B-311a	1,721,175	888,708	7	731.52	738.70	-7.18
B-313a	1,721,230	888,822	7	726.20	732.12	-5.92
MW-304a	1,721,201	888,291	7	758.14	753.62	4.52
MW-307a	1,721,047	888,411	7	773.87	753.22	20.65
PTWa	1,721,114	888,335	7	757.66	753.75	3.91
B-302a	1,721,021	888,104	8	768.06	762.47	5.59
B-316a	1,721,178	888,529	8	743.37	746.32	-2.95



Statistics			
Residual Mean:	-1.83	Minimum Residual:	-25.65
Residual Standard Deviation:	9.16E+00	Maximum Residual:	20.65
Sum of Squares:	2.09E+03	Head Range:	107.92
Absolute Residual Mean:	7.03E+00	RM/Head Range:	1.69E-02
		ARM/Head Range:	6.51E-02

- Model calibrated to August 2013 conditions, using wells/piezometers as “targets”, and precipitation recharge measured that month
- Calibrated model achieved (RM & ARM <10% of head range)

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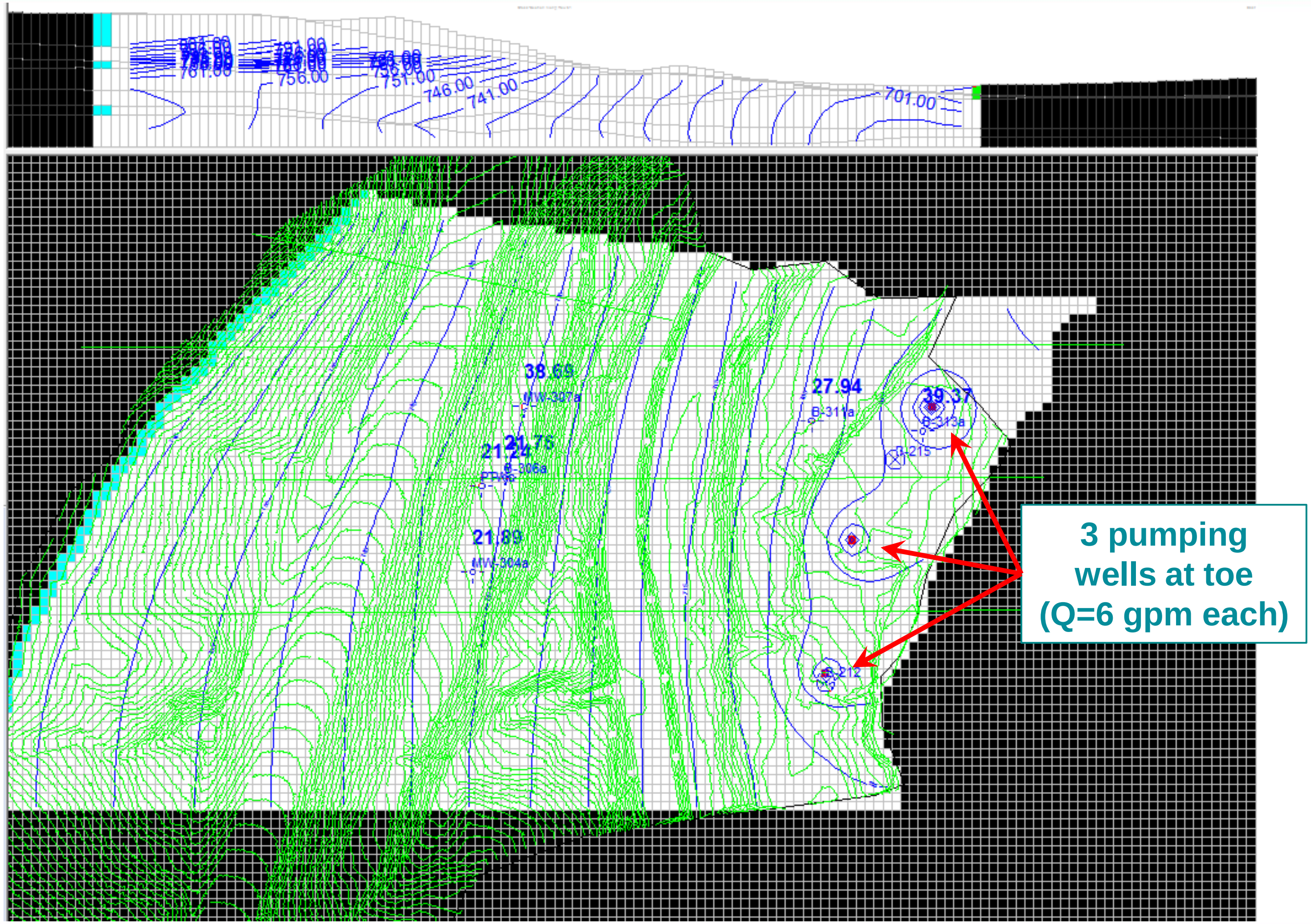
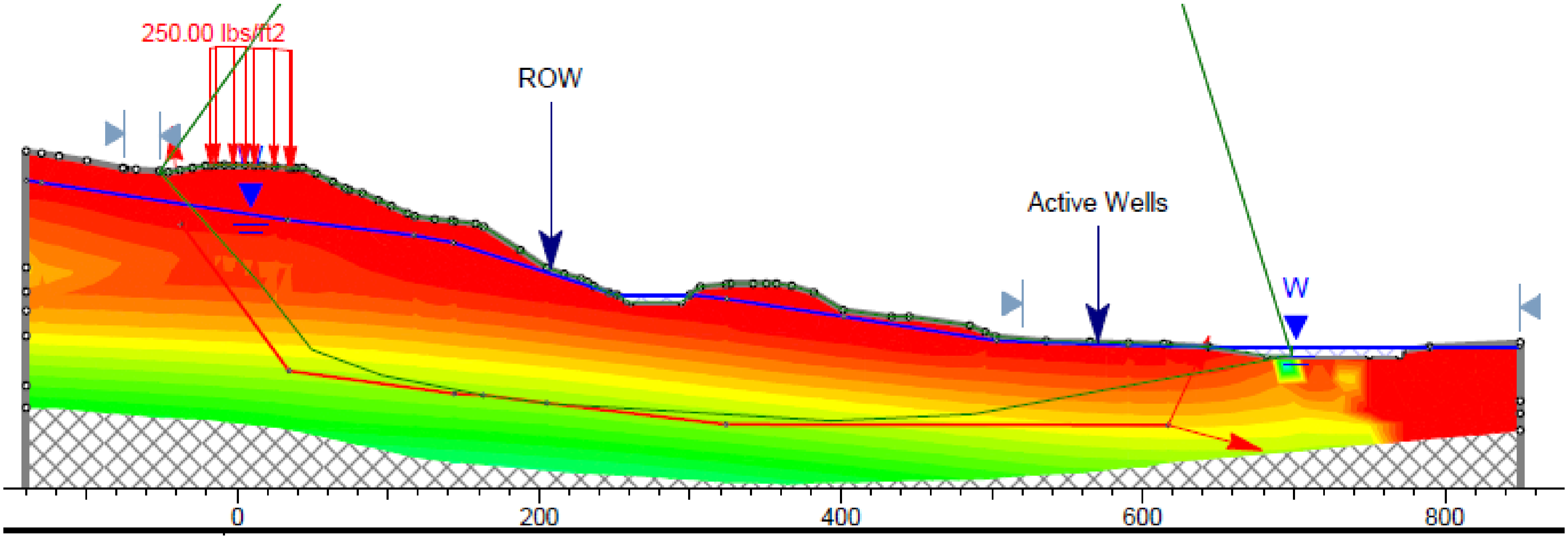
Mitigation Alternative B: 3 Pumping Wells at Toe



Mitigation Alternative B: 3 Pumping Wells at Toe



Section A-A FOS = 1.332

Conclusions

- Applied geology vital to understanding site conditions, landslide mechanism, and evaluation of mitigation alternatives
- Slide complicated by potentially much older glacial sediments
- Current geologic/hydrogeologic/geotechnical models benefited greatly by use of sonic drilling
- Remote monitoring system reduces site visits and allows for real time monitoring - quicker reaction time
- Groundwater control key to slowing/stopping landslide
- Cosmogenic Be^{10} testing of cobbles/dropstones, XRD testing of high plasticity clay layers may assist in geologic interpretation (university research – thesis topics?)