TEMPORARY DEPLOYMENT OF SENSORS: A COST-EFFECTIVE APPROACH FOR HIGH RESOLUTION SPATIAL AND TEMPORAL ASSESSMENT OF HYDRAULIC CONDITIONS IN A FRACTURED BEDROCK BOREHOLES

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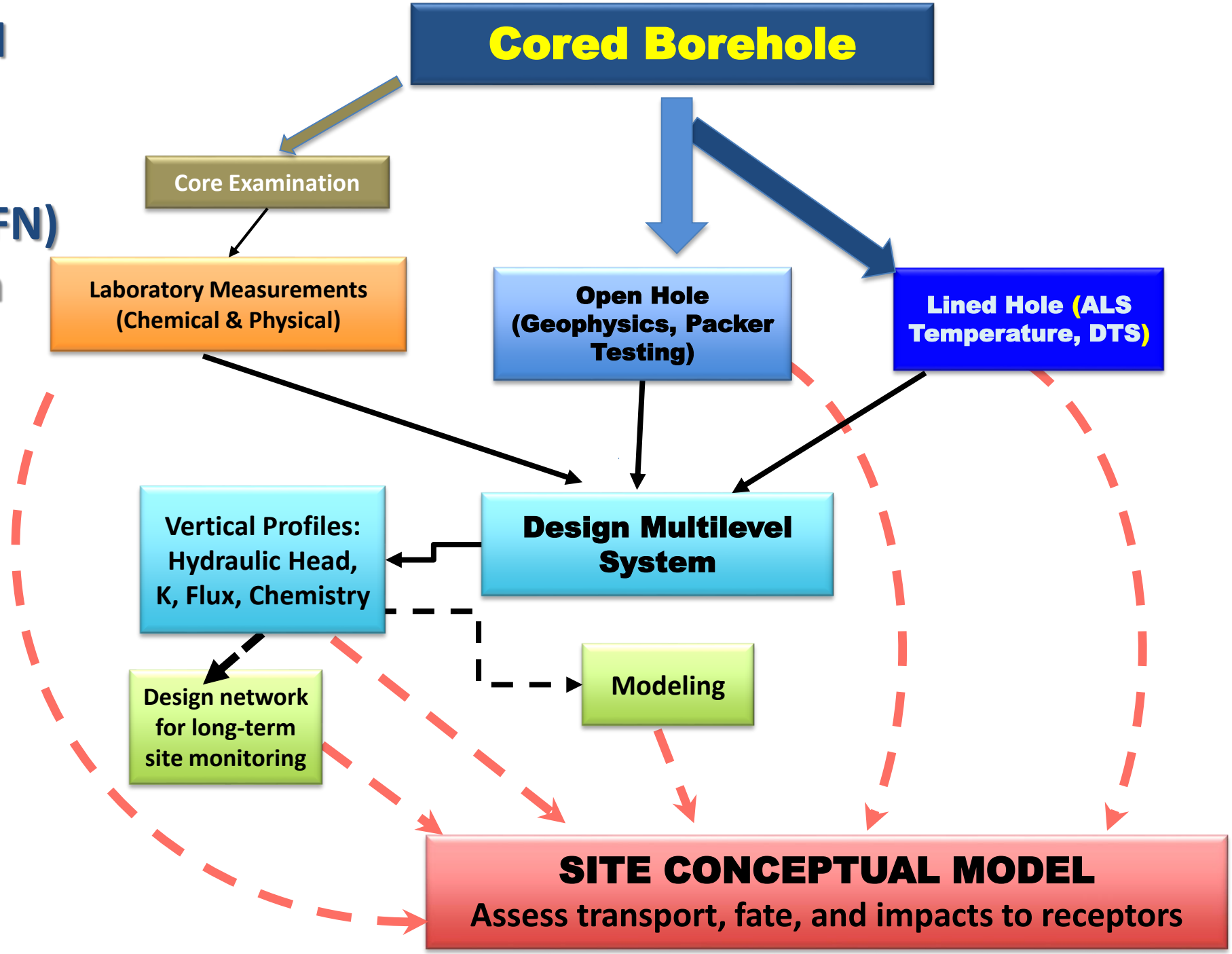
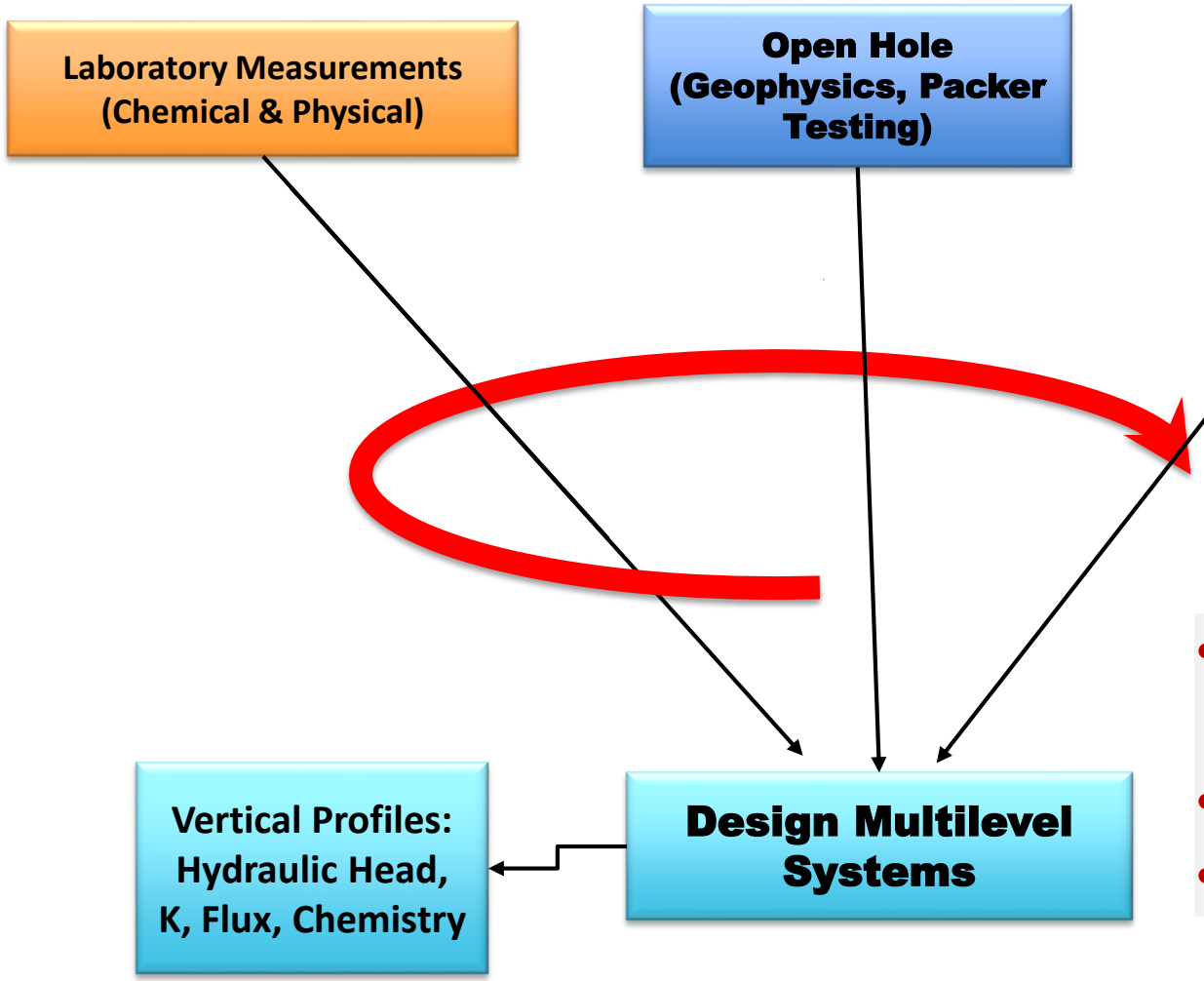
11/09/19

Simplified Discrete Fracture Network (DFN) Approach



Simplified Discrete Fracture Network (DFN) Approach



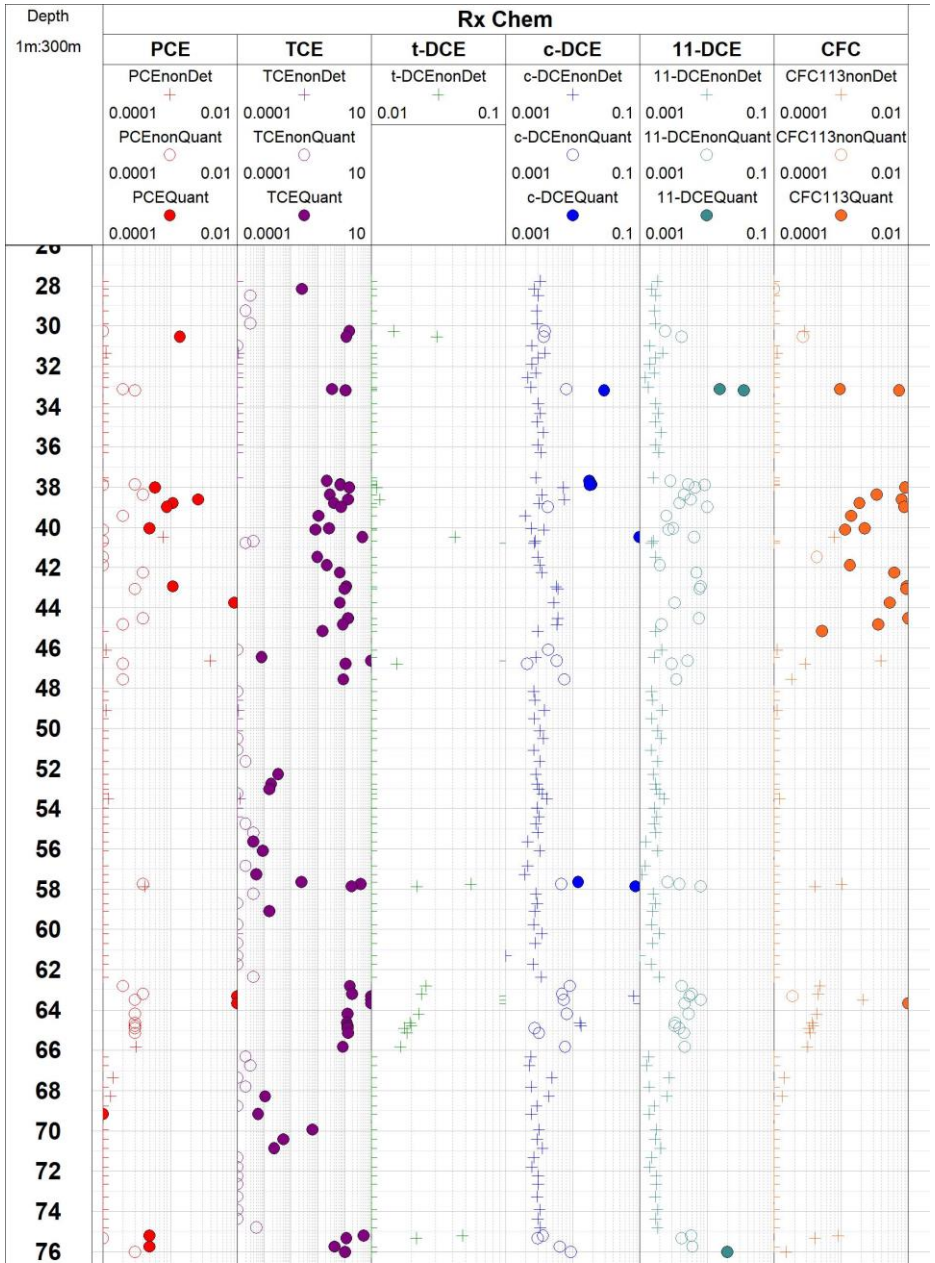
- **LOTS of Measurements**
- **Continuous along the borehole**
- **Highly Detailed**
- **Flexibility**

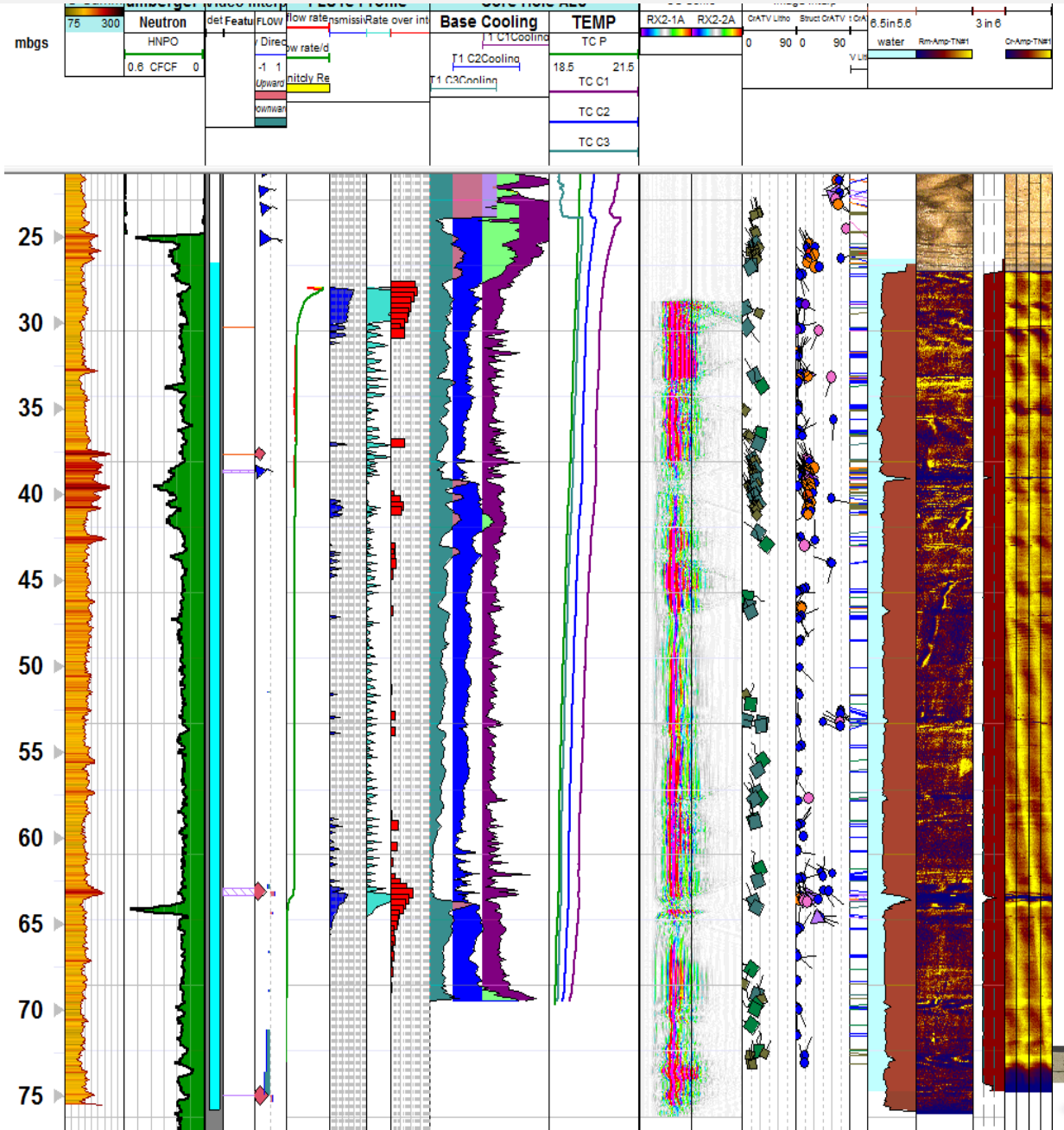
- **Handful Sampling Intervals (3, 6, 10-12, ???)**
- **Discrete,** Detailed vs Long Blended
- **Permanent**

SITE CONCEPTUAL MODEL

Assess transport, fate, and impacts to receptors

Rock Core Chem …… Data Montage (open & lined hole)

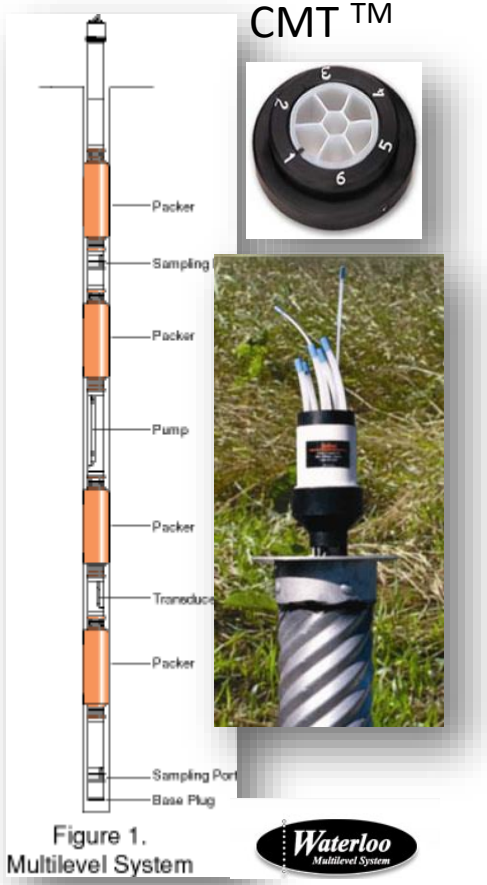




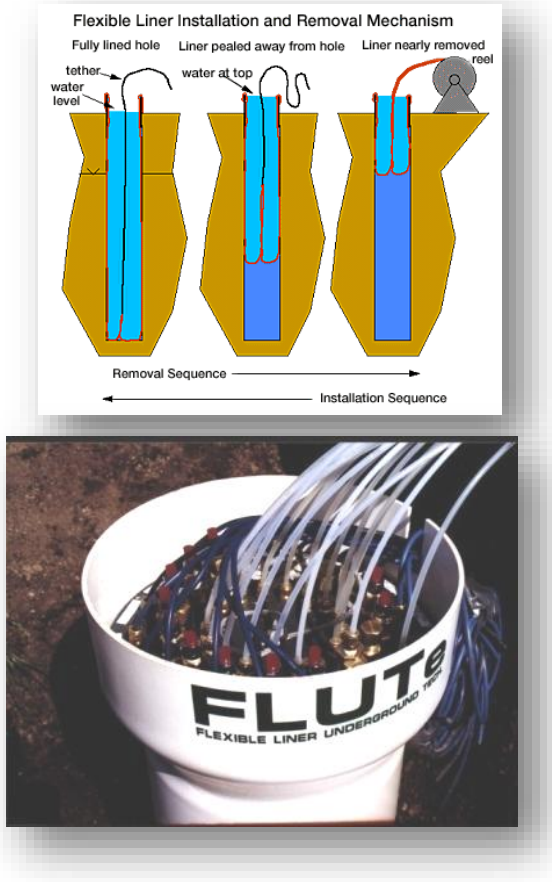
COMMERCIALLY AVAILABLE MULTILEVELS

Solinst

CMT ™

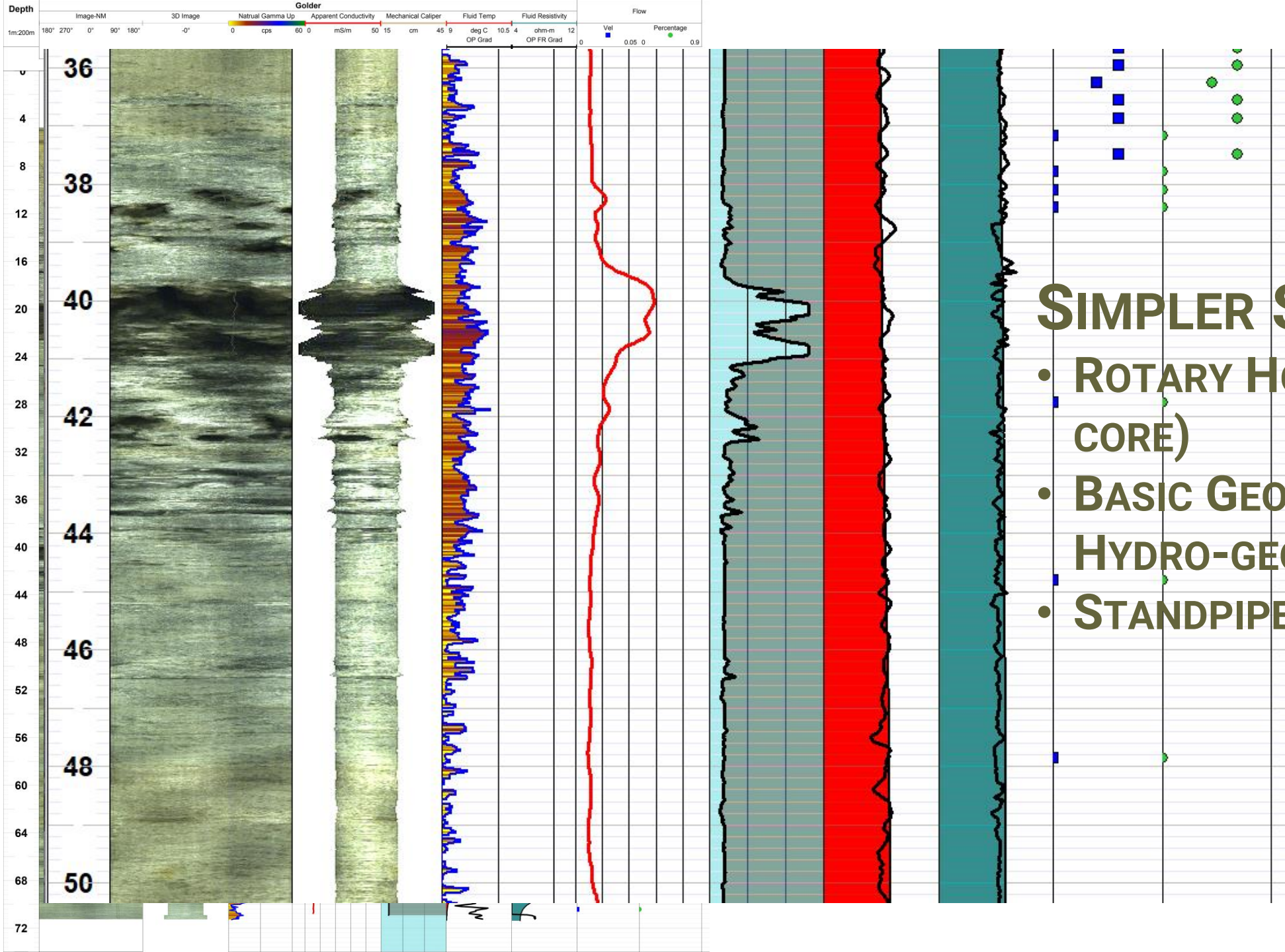


FLUTe



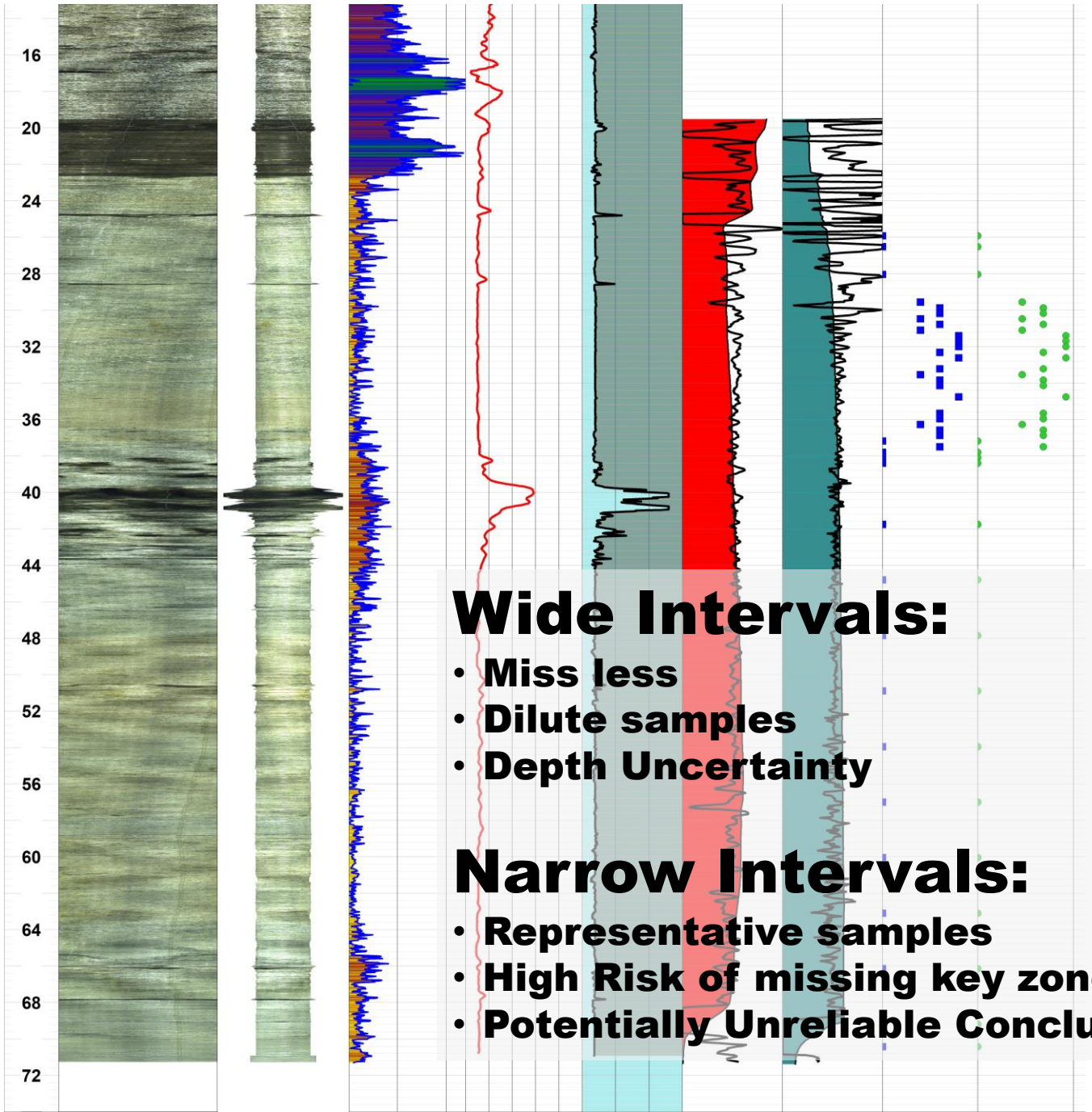
Westbay

From J. Meyer



Simpler Scenario

- Rotary Hole (no core)
- Basic Geophysics / Hydro-geophysics
- Standpipe Monitors

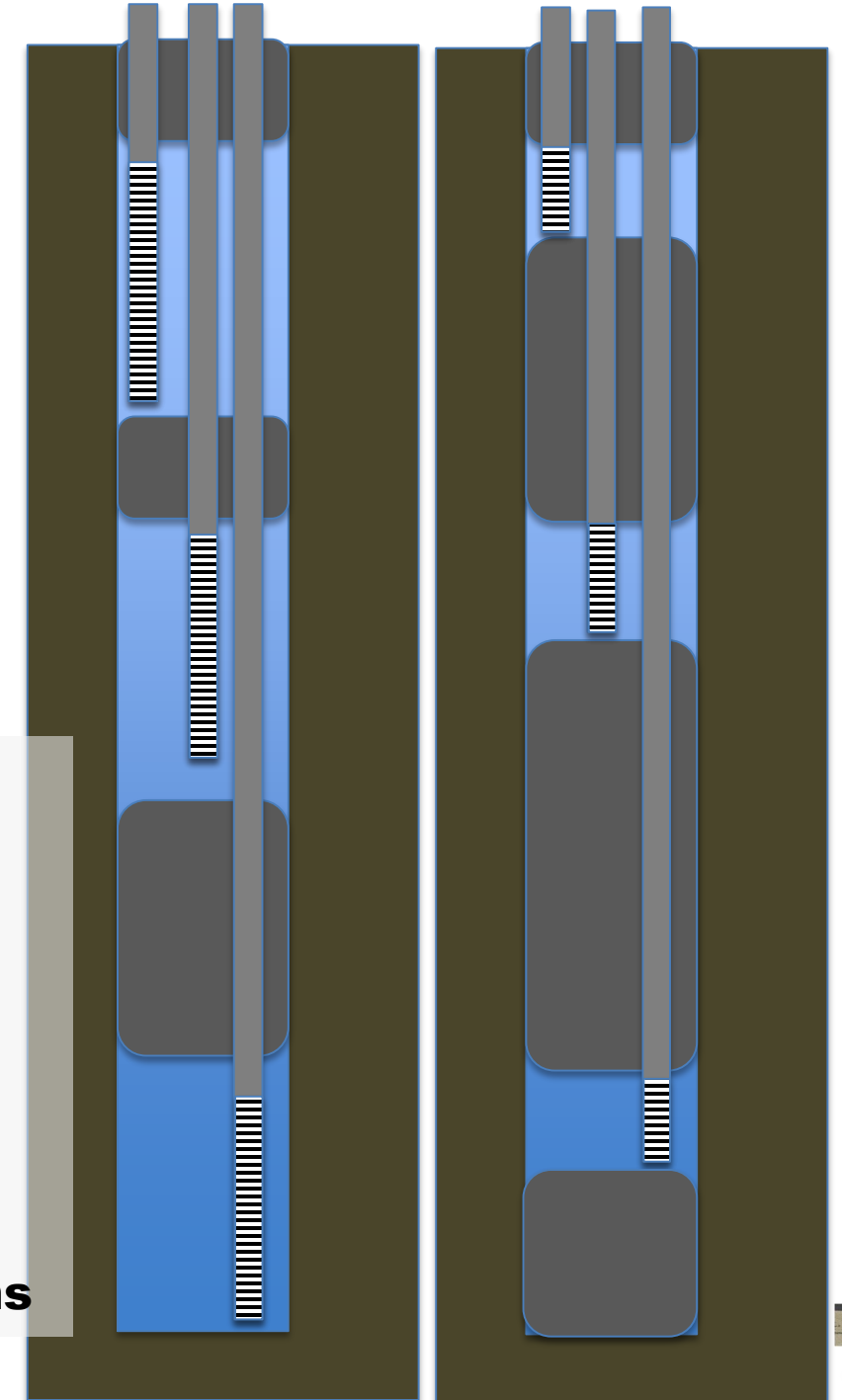


Wide Intervals:

- Miss less
- Dilute samples
- Depth Uncertainty

Narrow Intervals:

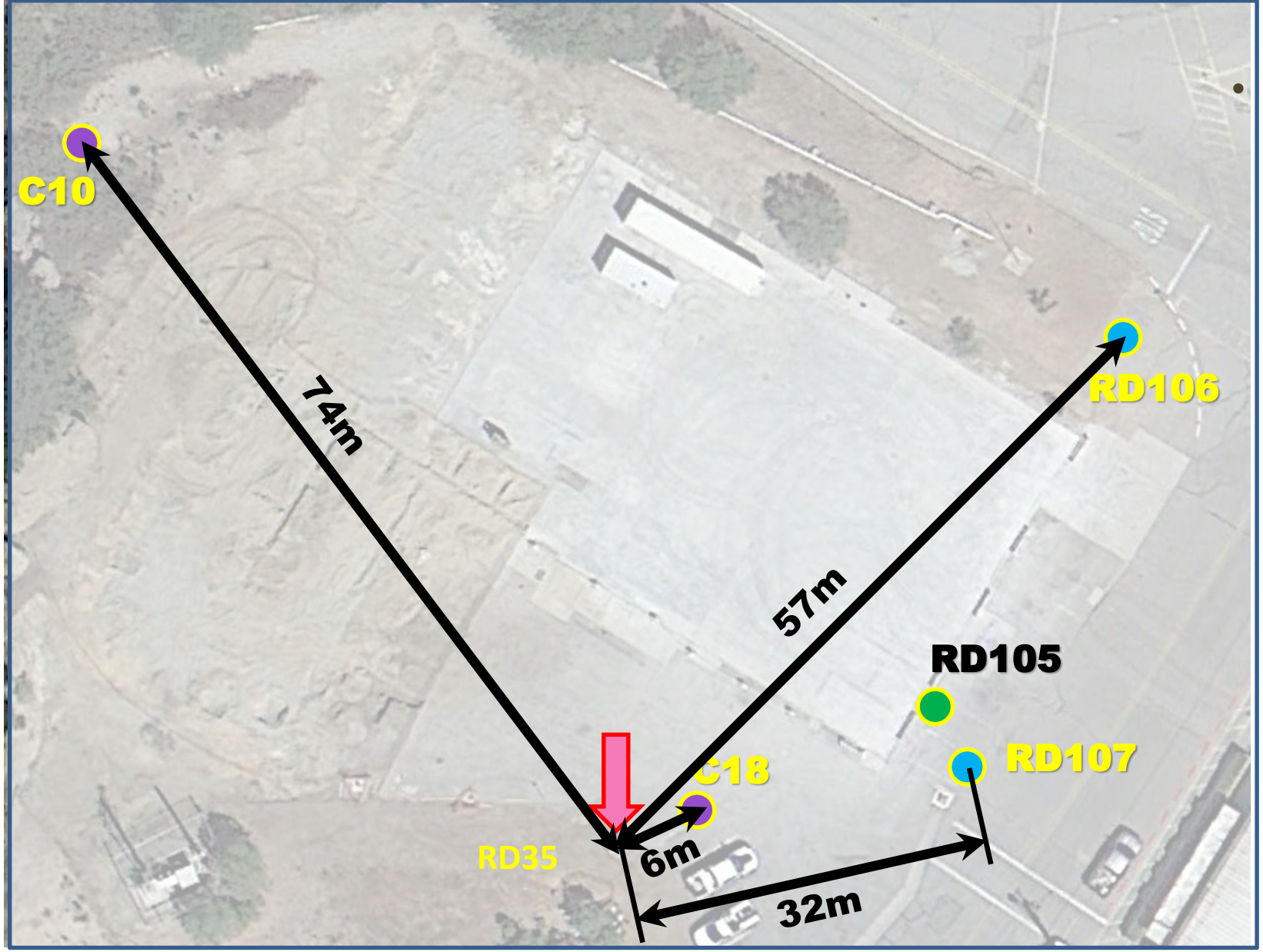
- Representative samples
- High Risk of missing key zones
- Potentially Unreliable Conclusions




Field Research Sites
Simi Valley
Los Angeles
Santa Barbara
Ventura
Oxnard
Port Hueneme
Malibu
Santa Clarita
Pasadena
Anaheim
Long Beach
Torrance
Santa Ana
Irvine
Huntington Beach
Riverside
San Bernardino
Ontario
Redlands
Palm Springs
Palm Desert
Indio
Coachella
Temecula
Murrieta
Lake Elsinore
Perris
Hemet
Escondido
Carlsbad
Vista
San Diego
Chula Vista
El Cajon
Mt Laguna
Julian
Ramona
Borrego Springs
Anza-Borrego Desert State Park
Palomar Mountain
Big Bear Lake
San Gorgonio Mountain
Yucca Valley
Joshua National
Lancaster
Palmdale
Victorville
Hesperia
Adelanto
Lake Los Angeles
Lake Hughes
Acton
Castaic
Ojai
Fillmore
Angeles National Forest
Mt San Antonio
Channel Islands National Park
Santa Rosa Island
San Clemente Island
Catalina Island Essential Fish Habitat...
Two Harbors
Dana Point
San Clemente
Cleveland National Forest
San Bernardino National Forest
Los Padres National Forest
Vandenberg Village
Lompoc
Los Olivos
Solvang
Gaviota
Gorman
Lebec
Ventucopa
Club
Hi Vista
Helendale
Lavic
Ludlow
Ragtown
Siberia
Lucerne Valley
Johnson Valley
Phelan
Landers
Desert Heights
Twentynine Palms
Pioneertown
Desert Hot Springs
Beaumont
Cabazon
Anza
Desert Shores
Salton City
Alpine
Pine Valley
Ocotillo
Jacumba Hot Springs
Campo
Tecate

Heat tracer test in fractured sandstone at an ISCO pilot test site

Test Boreholes



KEY COMPONENT OF TRACER TEST DESIGN

- Characterization of Boreholes with DFN Technique
- **As continuous (temporal & spatial) thermal monitoring as possible**
- Comparison of pressure and temperature effects of Injection
- **DESIGN MULTILEVEL SYSTEM TO INTERCEPT PERMANGANATE INJECTION**

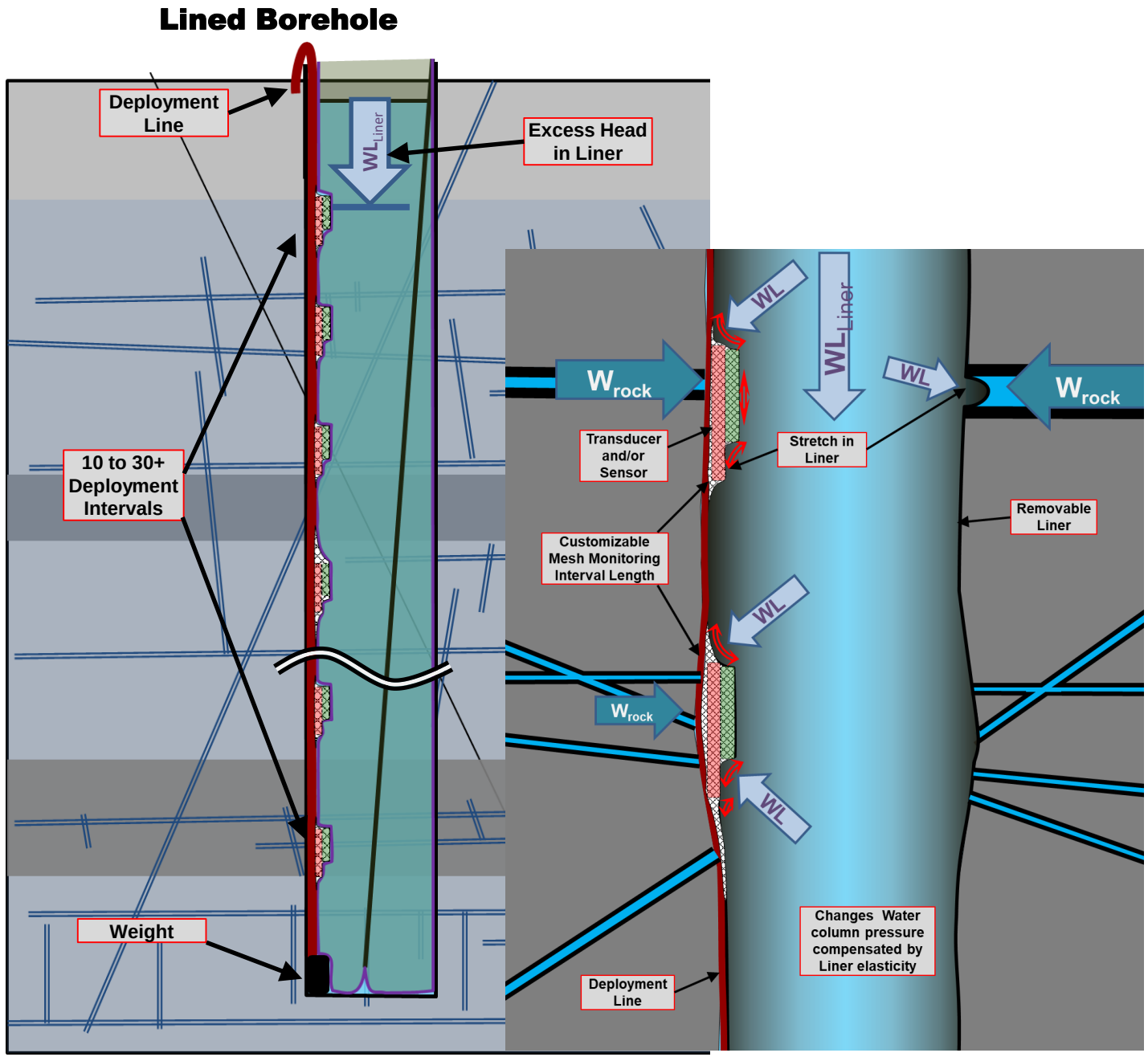
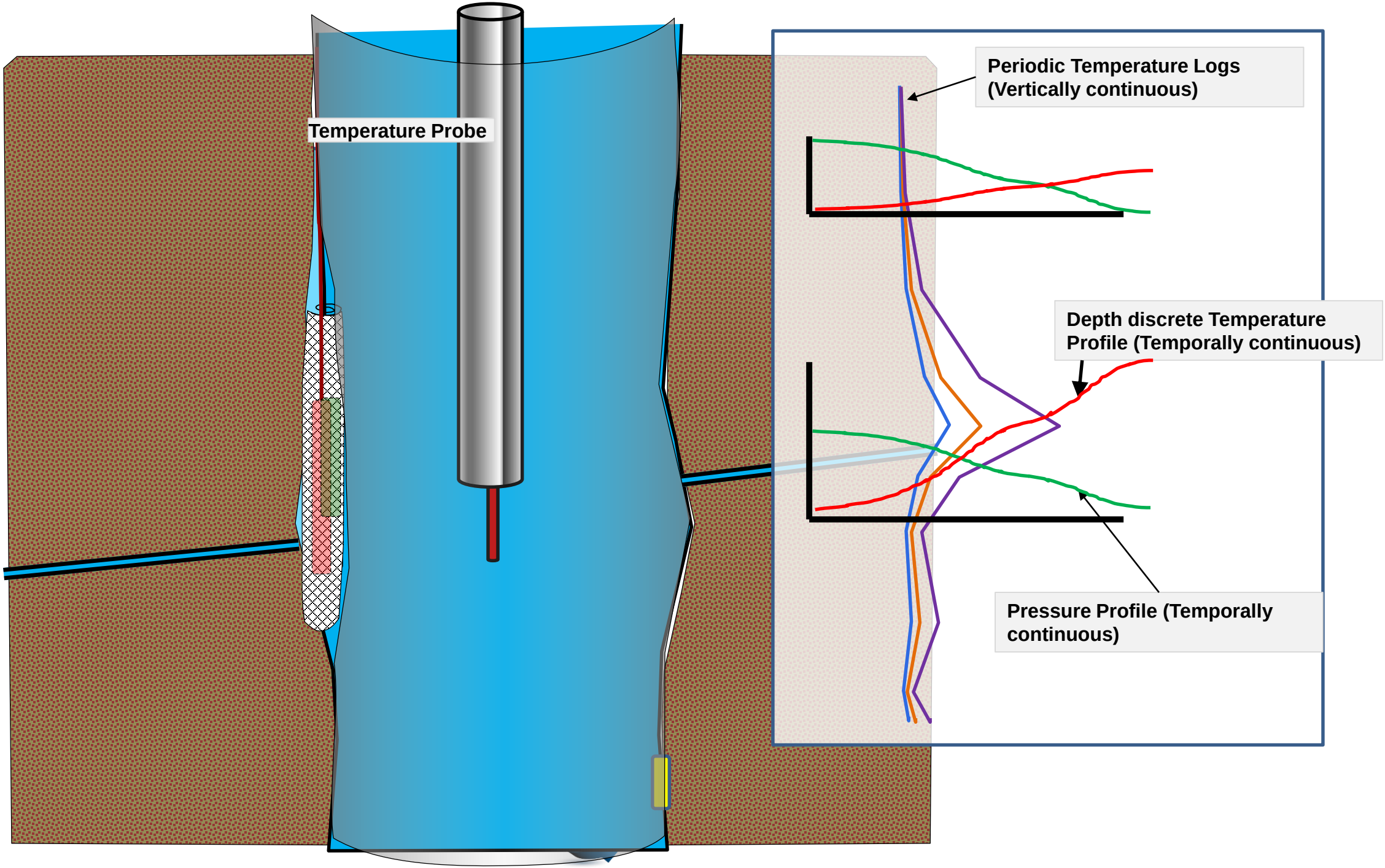
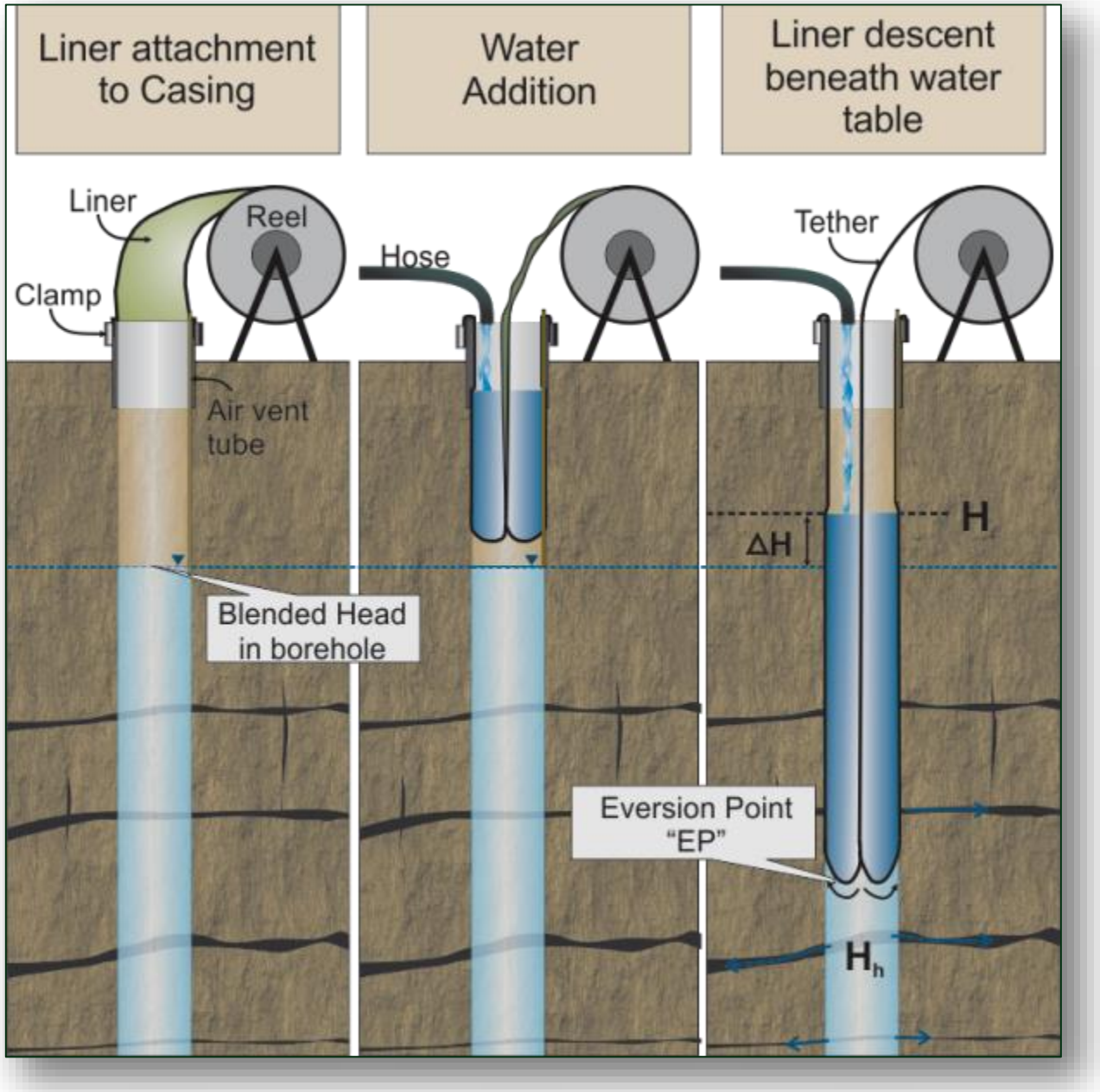
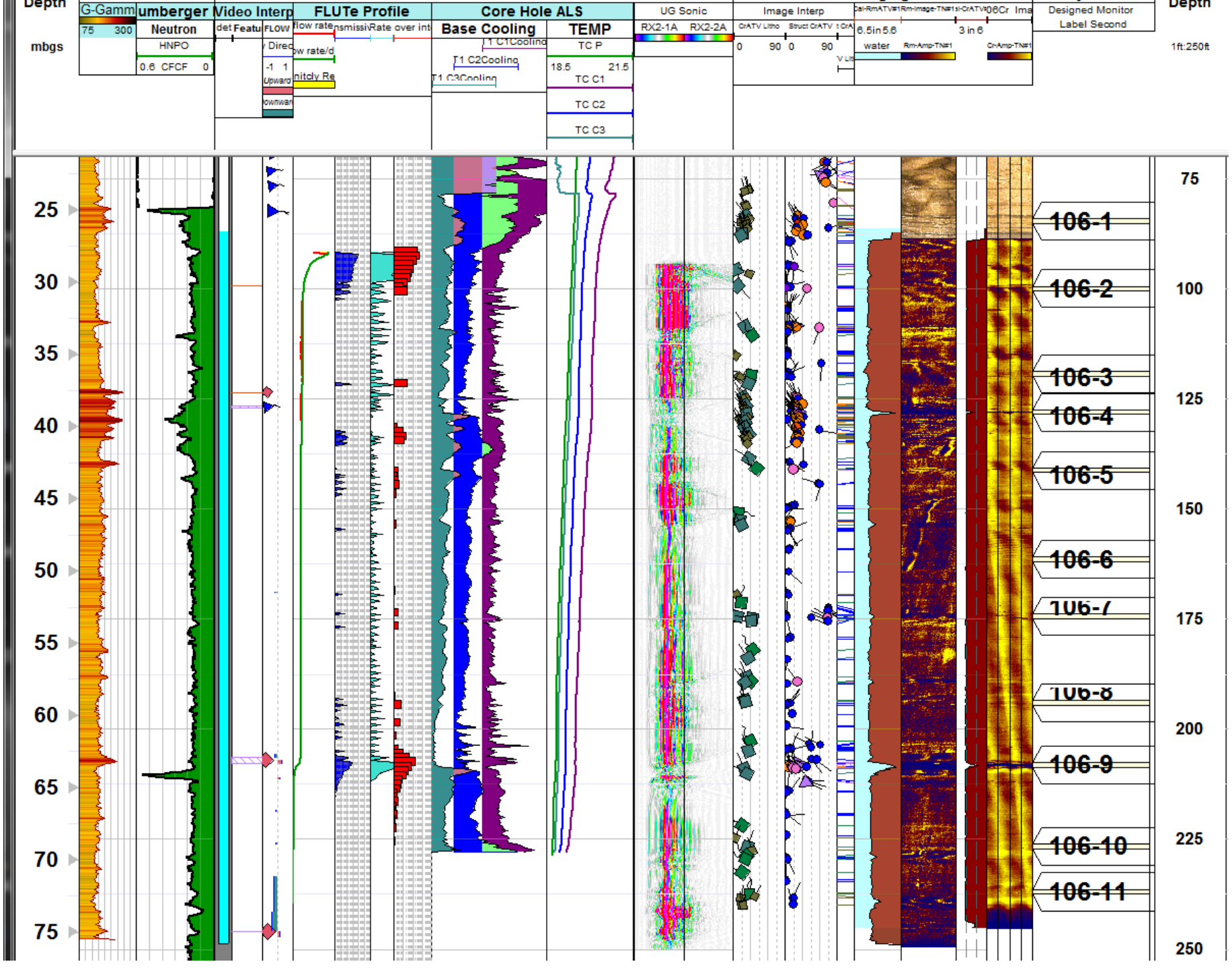

Lined Borehole
Deployment Line
Excess Head in Liner
WL_{Liner}
10 to 30+ Deployment Intervals
Weight
WL
W_{rock}
Transducer and/or Sensor
Stretch in Liner
Removable Liner
Customizable Mesh Monitoring Interval Length
Changes Water column pressure compensated by Liner elasticity
Deployment Line

Figure 1


Temperature Probe
Periodic Temperature Logs (Vertically continuous)
Depth discrete Temperature Profile (Temporally continuous)
Pressure Profile (Temporally continuous)

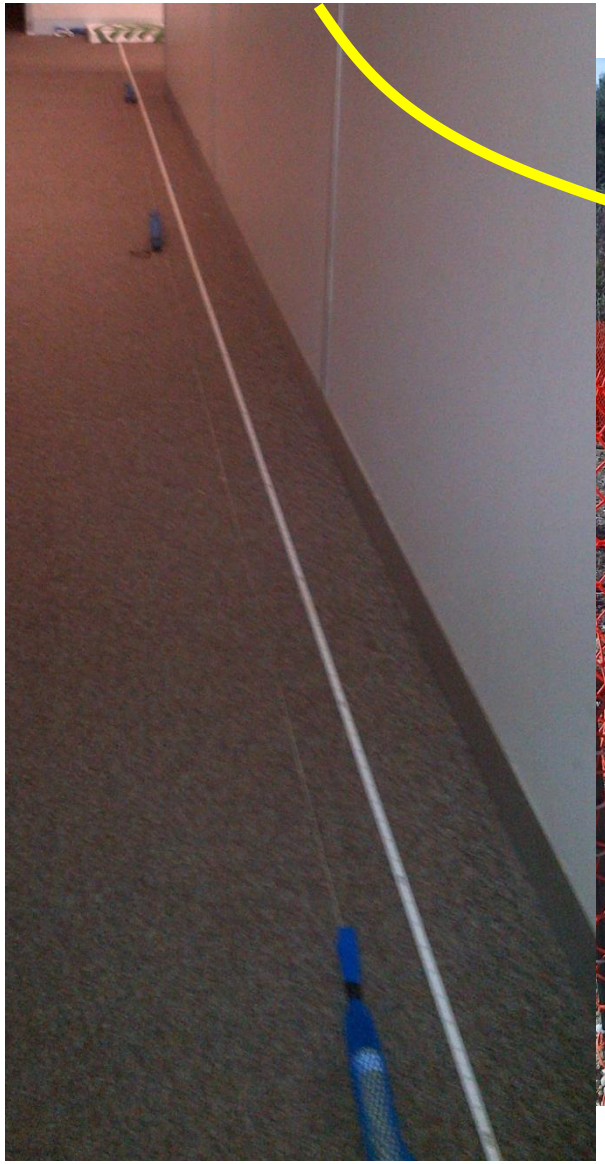
WATER FLUTE INSTALLATION



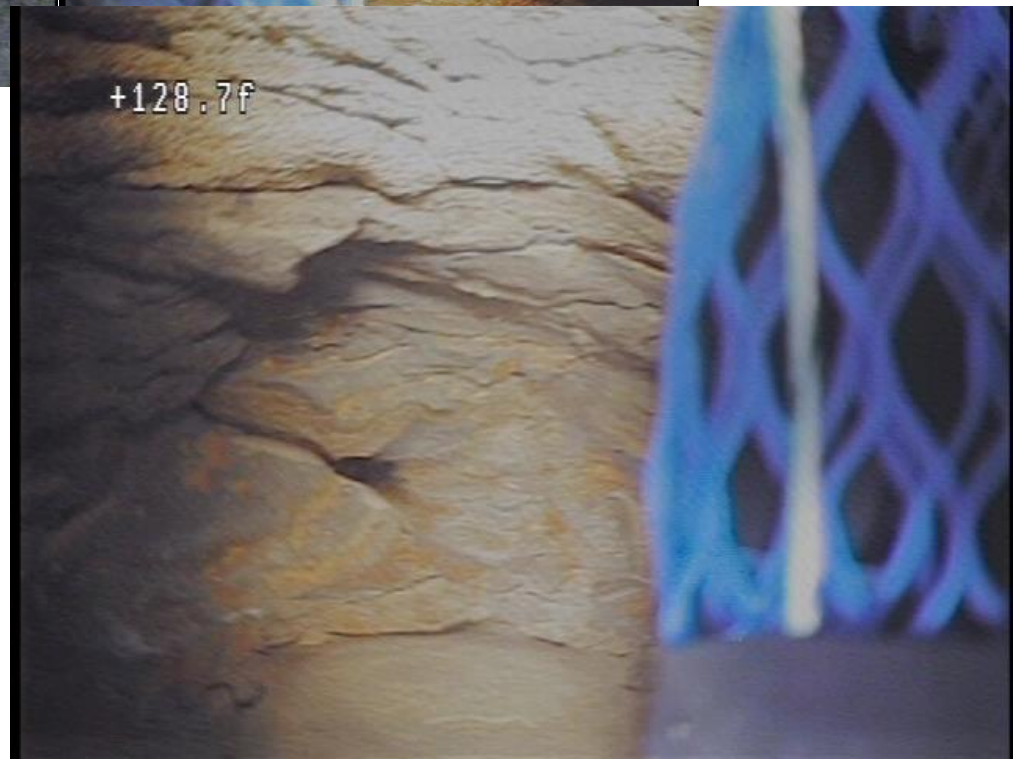


Sensor Array Test Intervals Based DFN Suite of Techniques

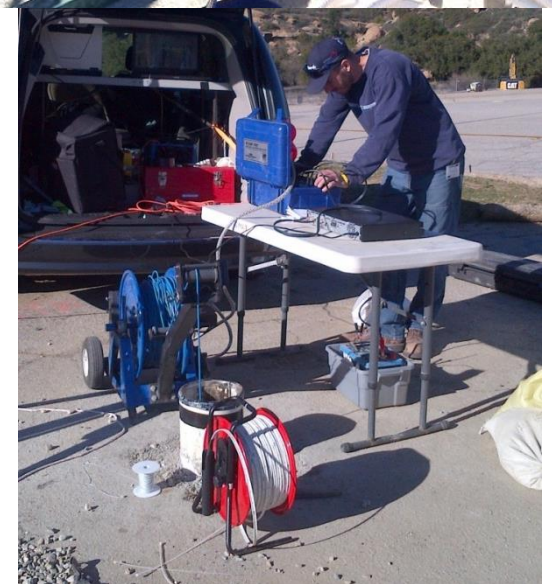
Monitoring Intervals Paired SWS Diver & RBR T-Probe

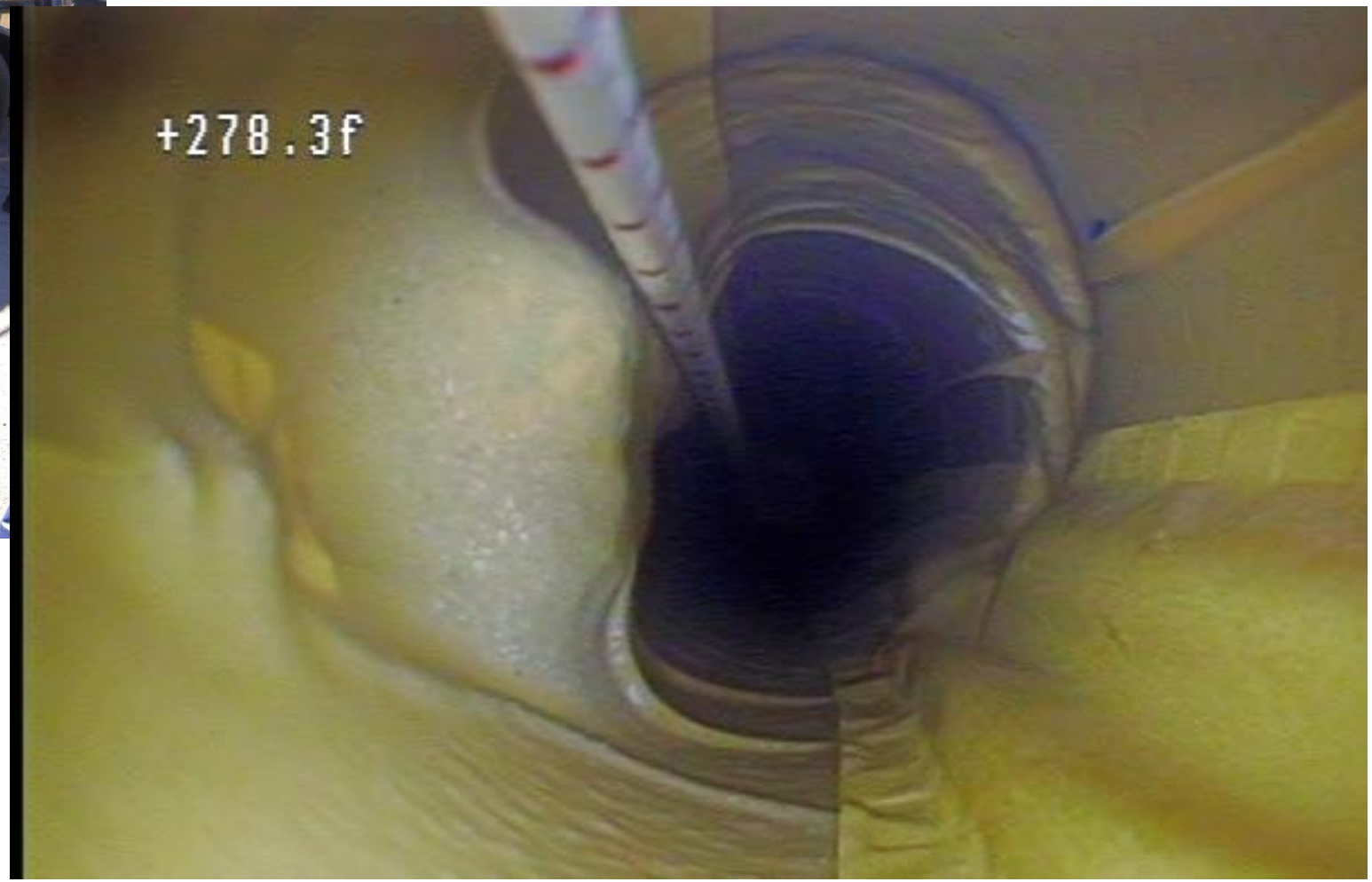


RD106 Open Depth Refinement

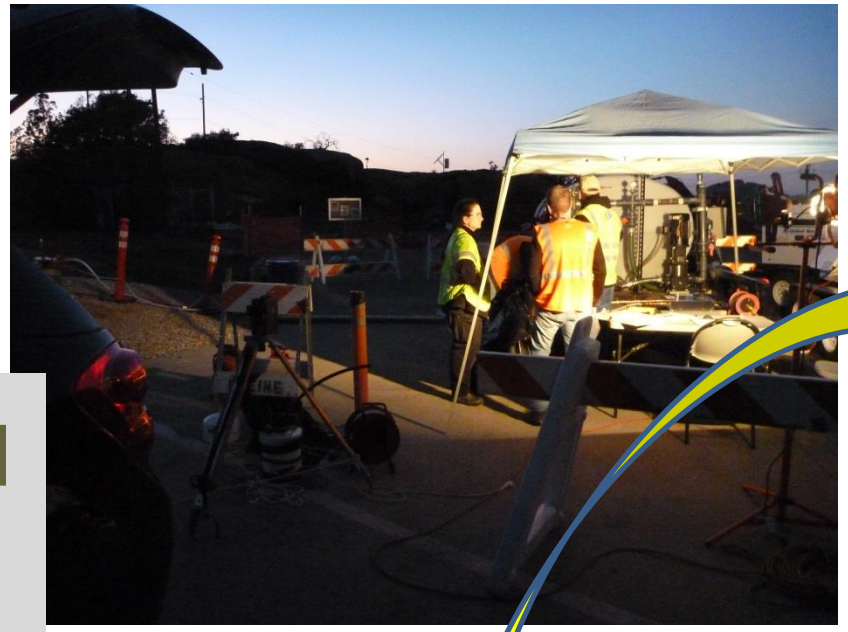


Holes Lined & Sensor Depth Confirmed



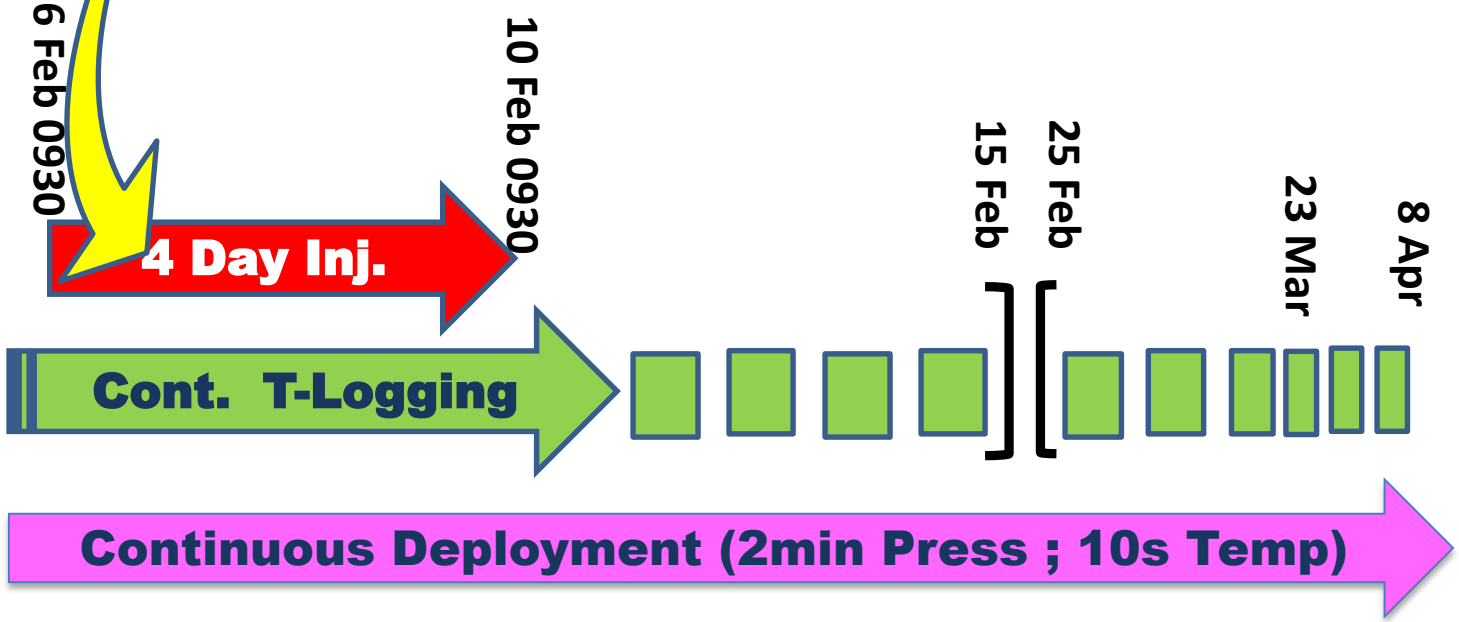


Injection Details

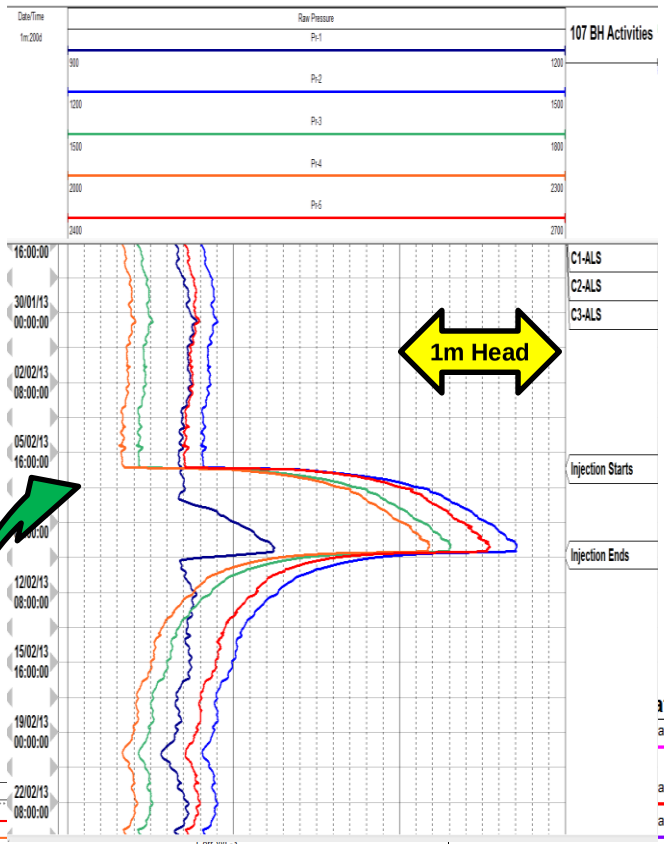


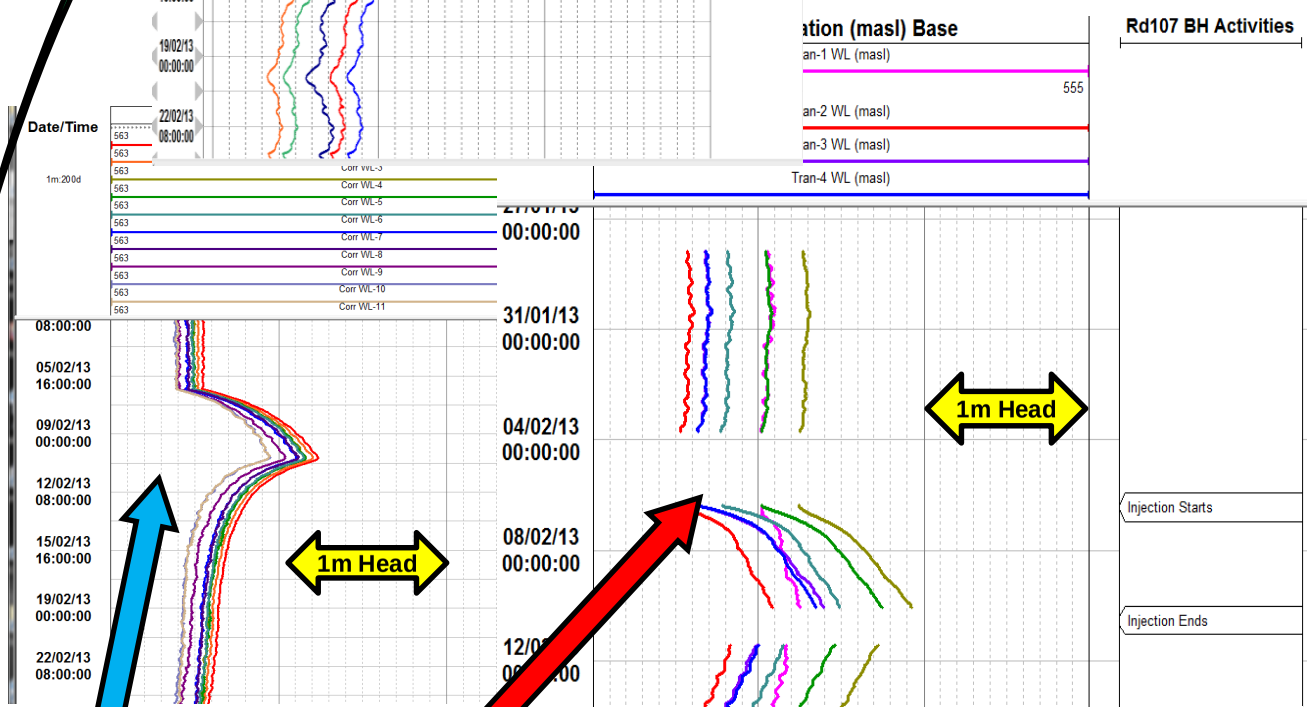
2 gal/min
4 Days (5760 min)
11,520 gal (43.6m^3)
@ **36˚C** (19.6˚C ambient)

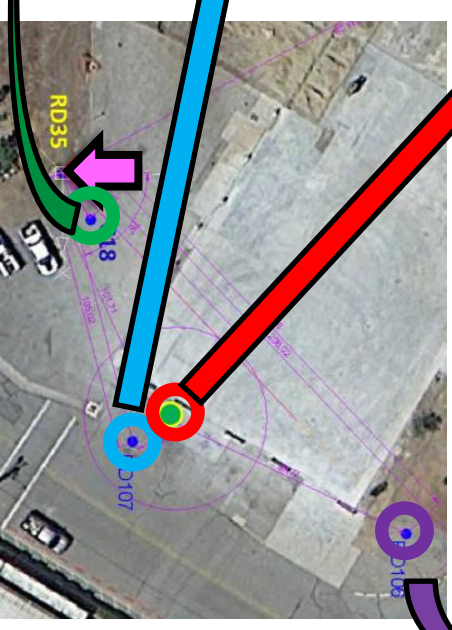
>3mil KJ of Heat Energy

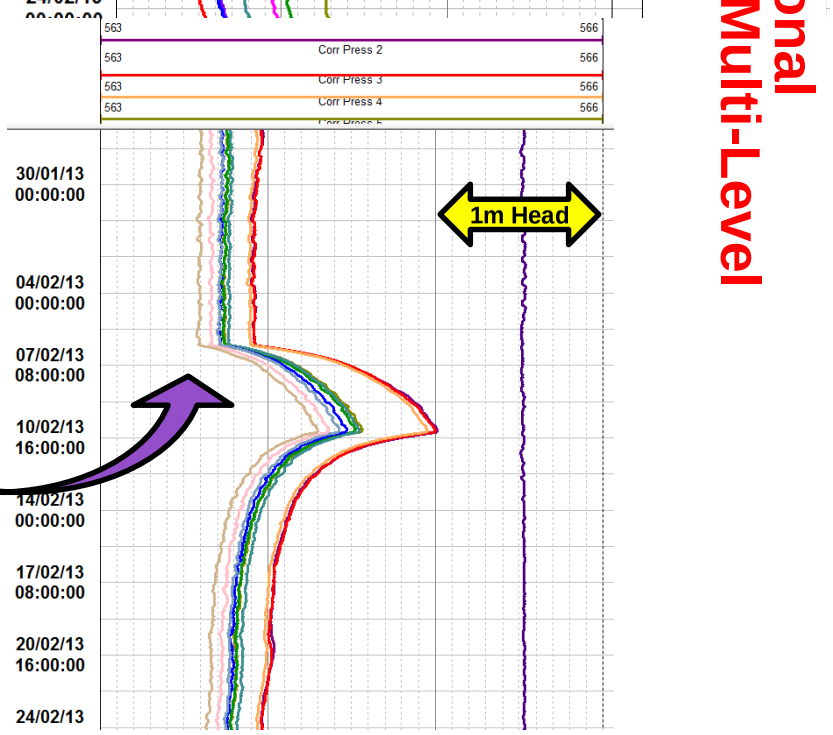


Temporary Deployments





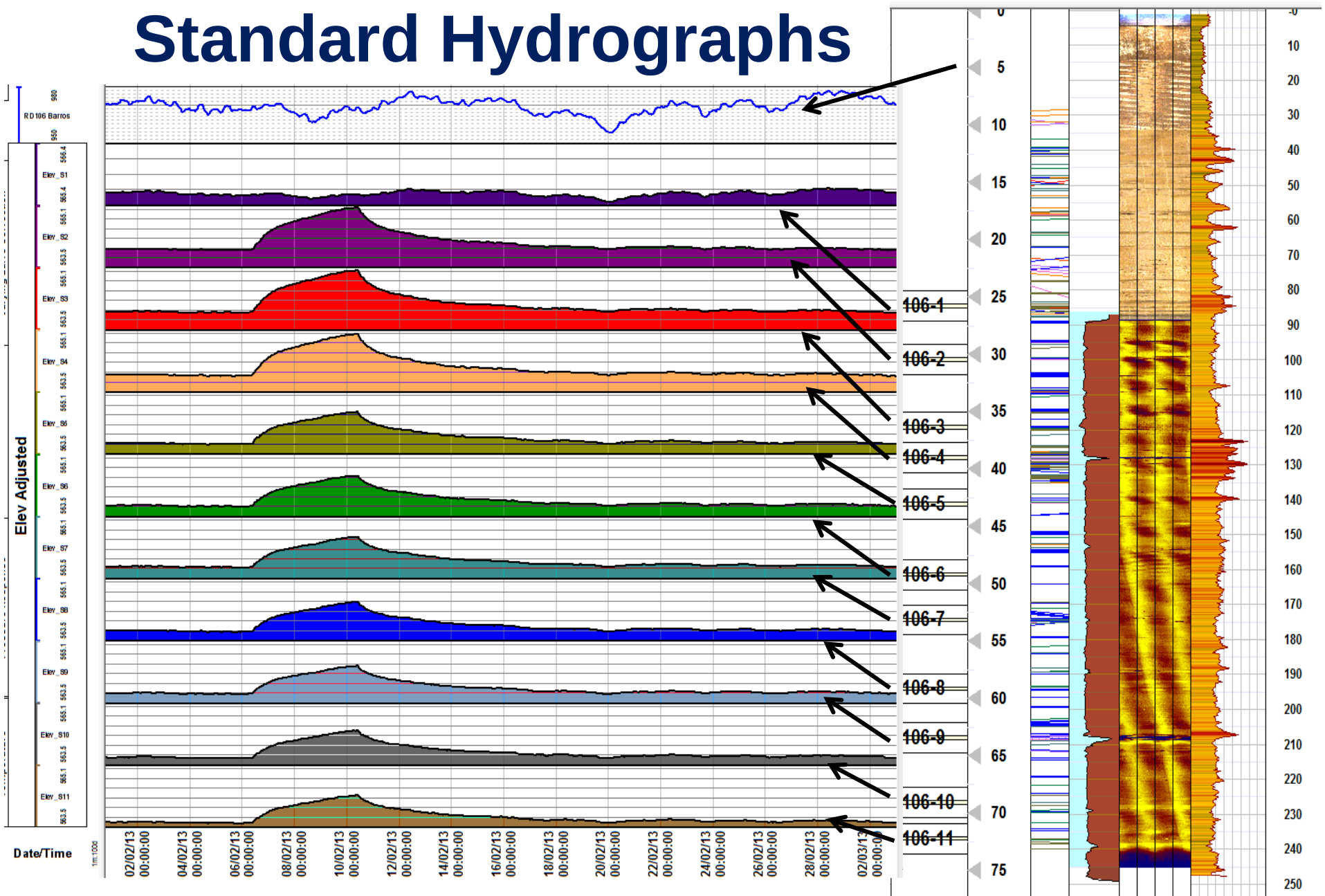




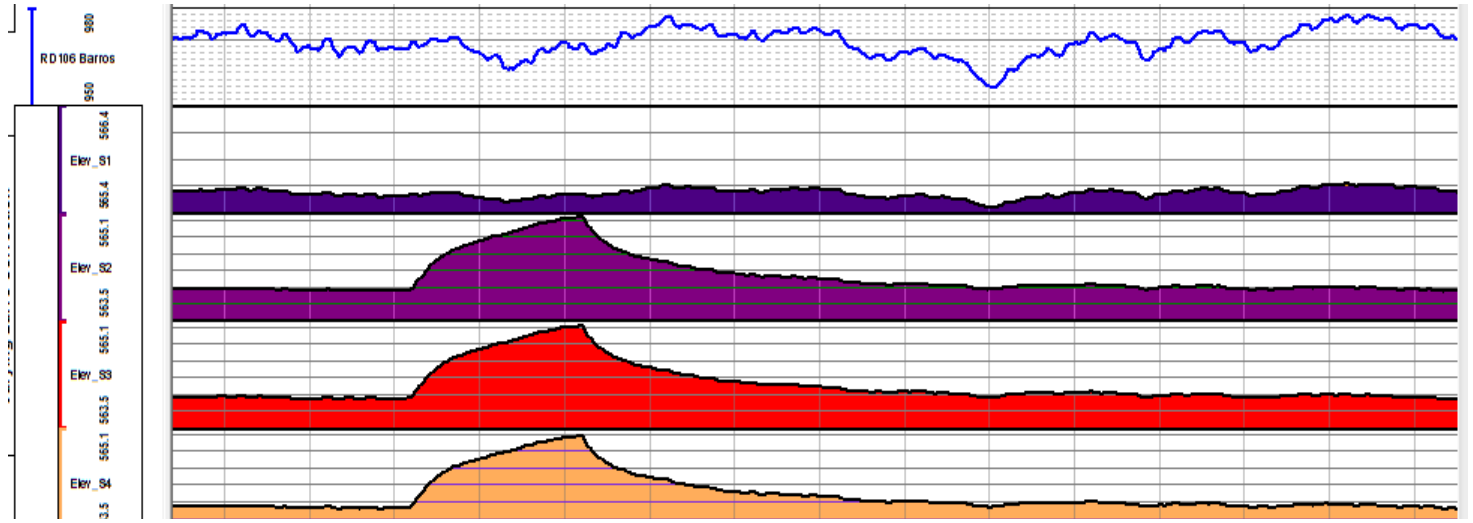
Conventional Waterloo Multi-Level

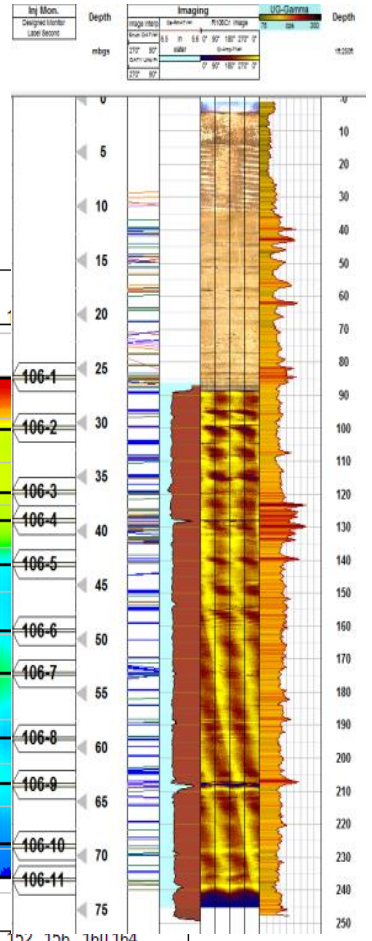
DIVER RESULTS

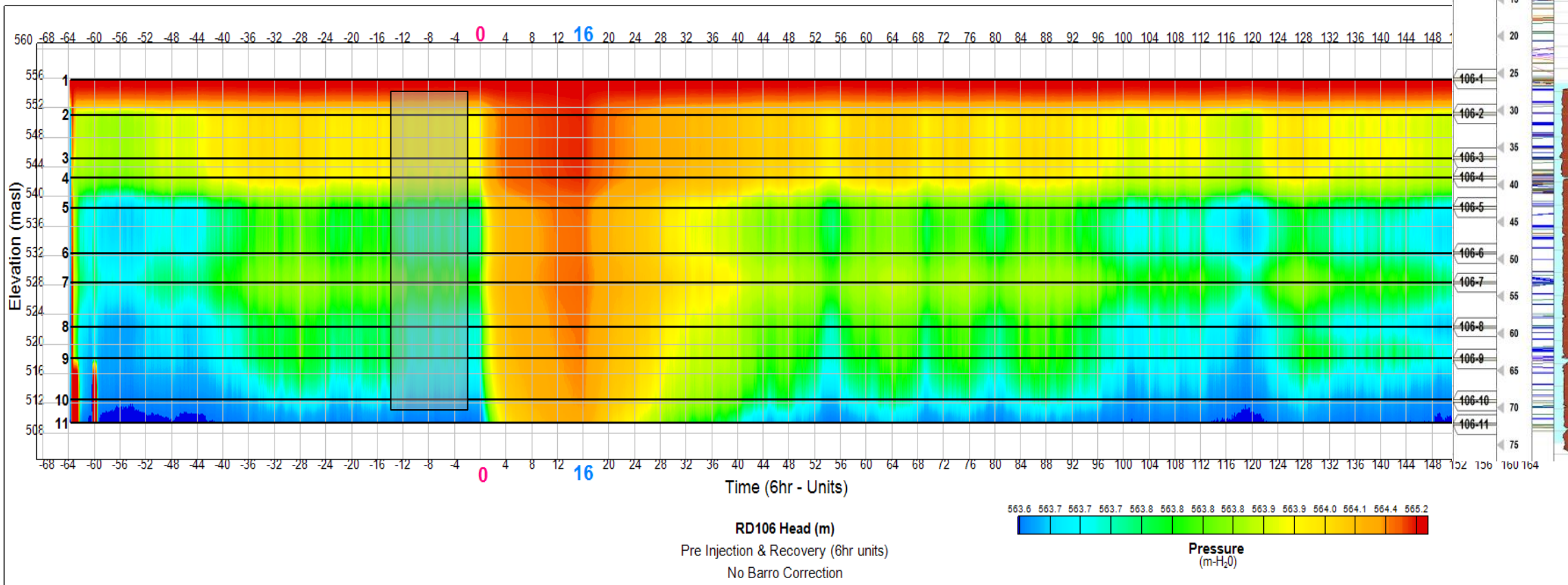
Standard Hydrographs



Time-Elevation-Head (TEH) RD106



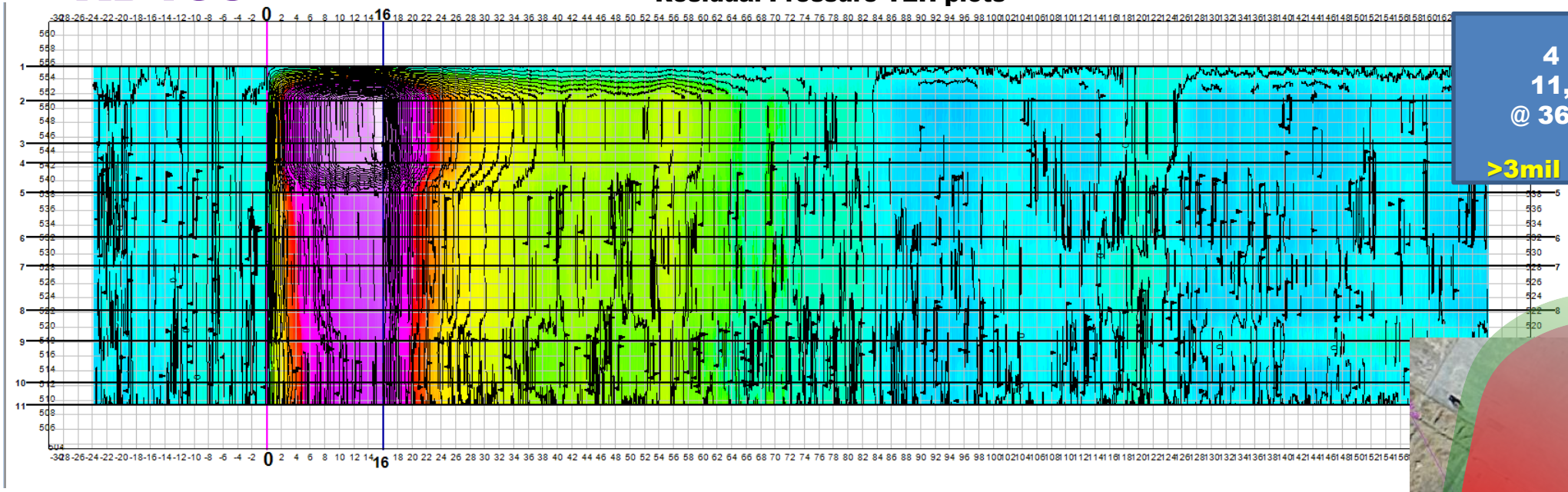




Response to Injection

Residual Pressure TEH plots

RD106



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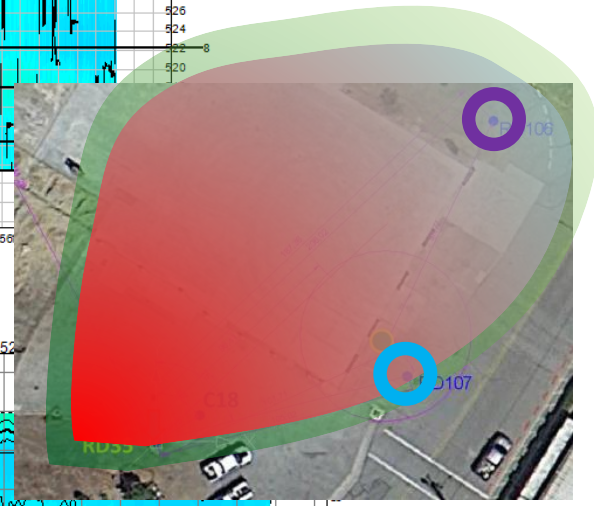
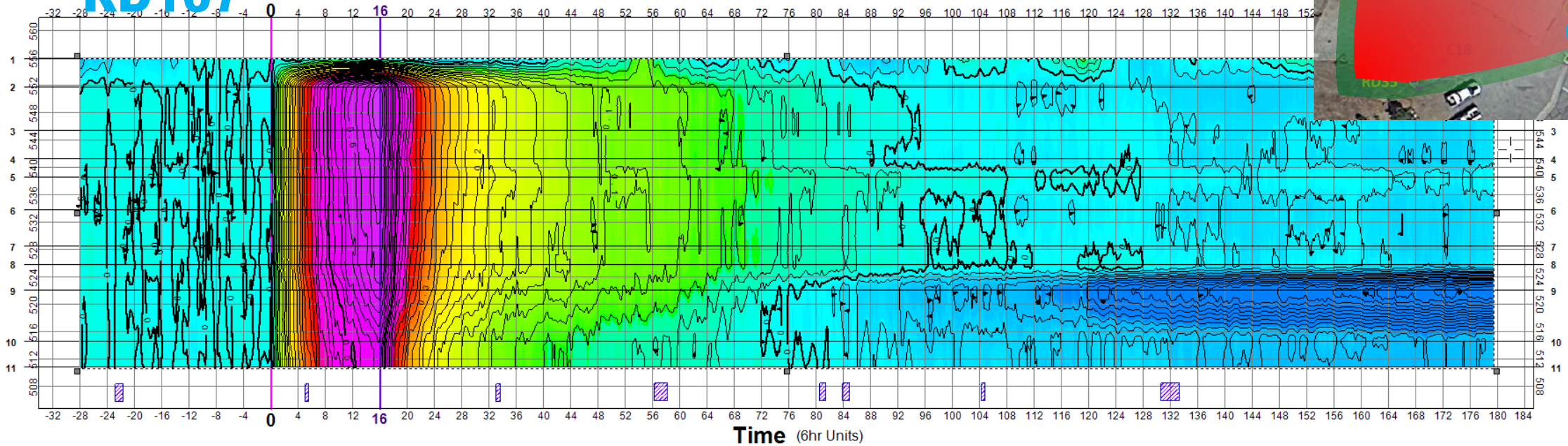
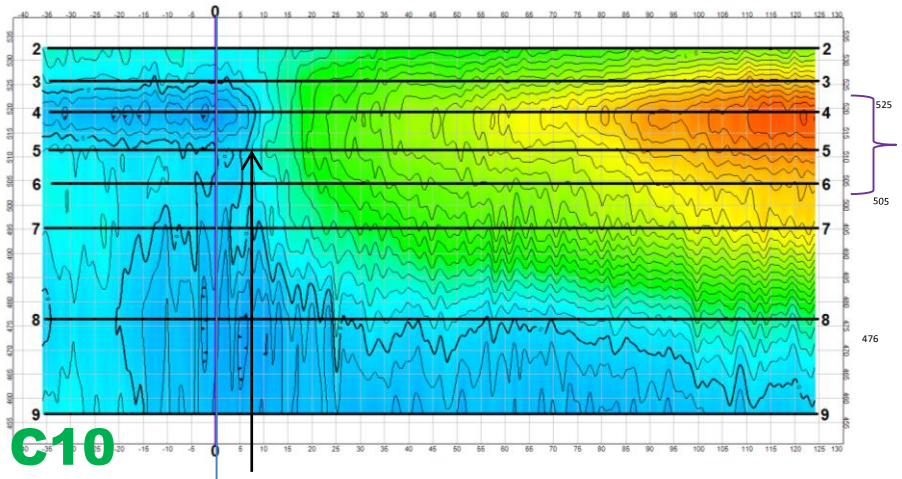
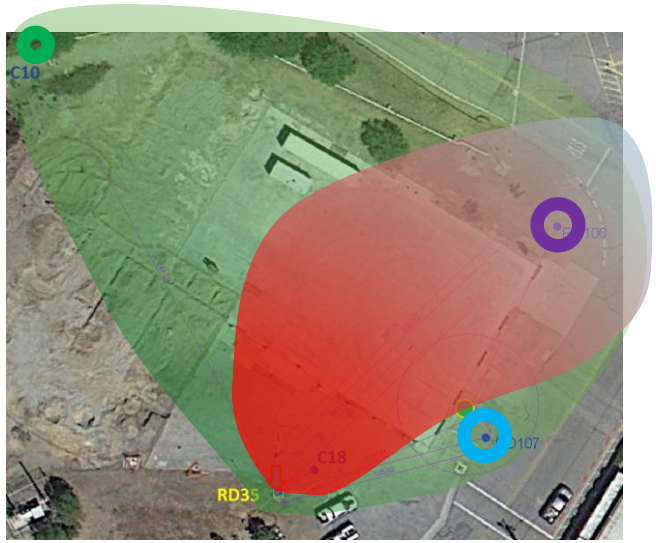
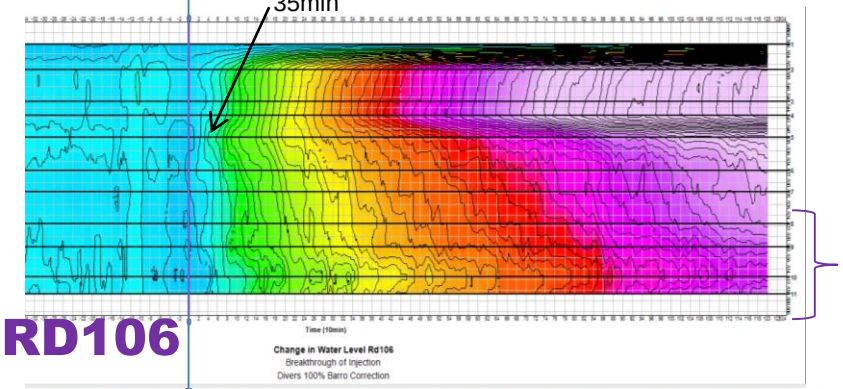


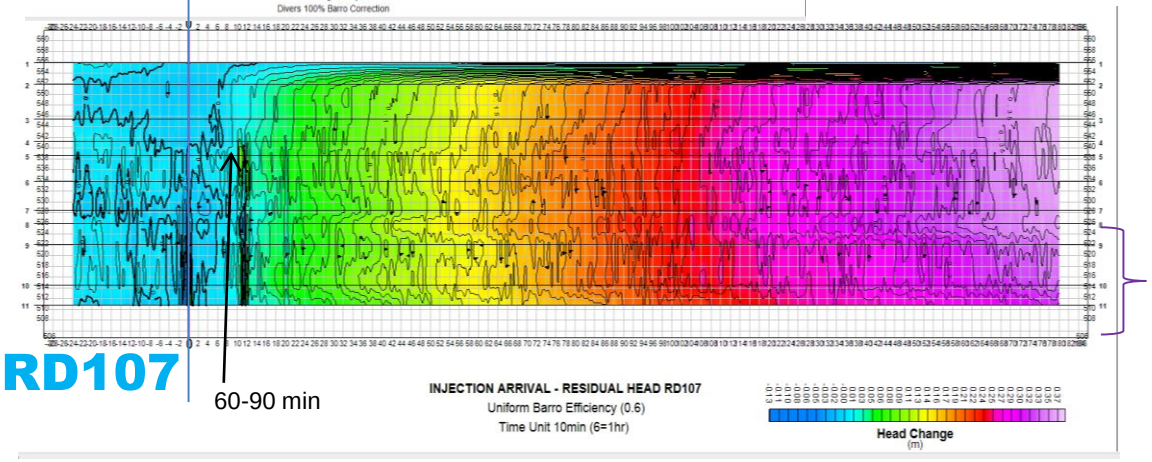
RD107







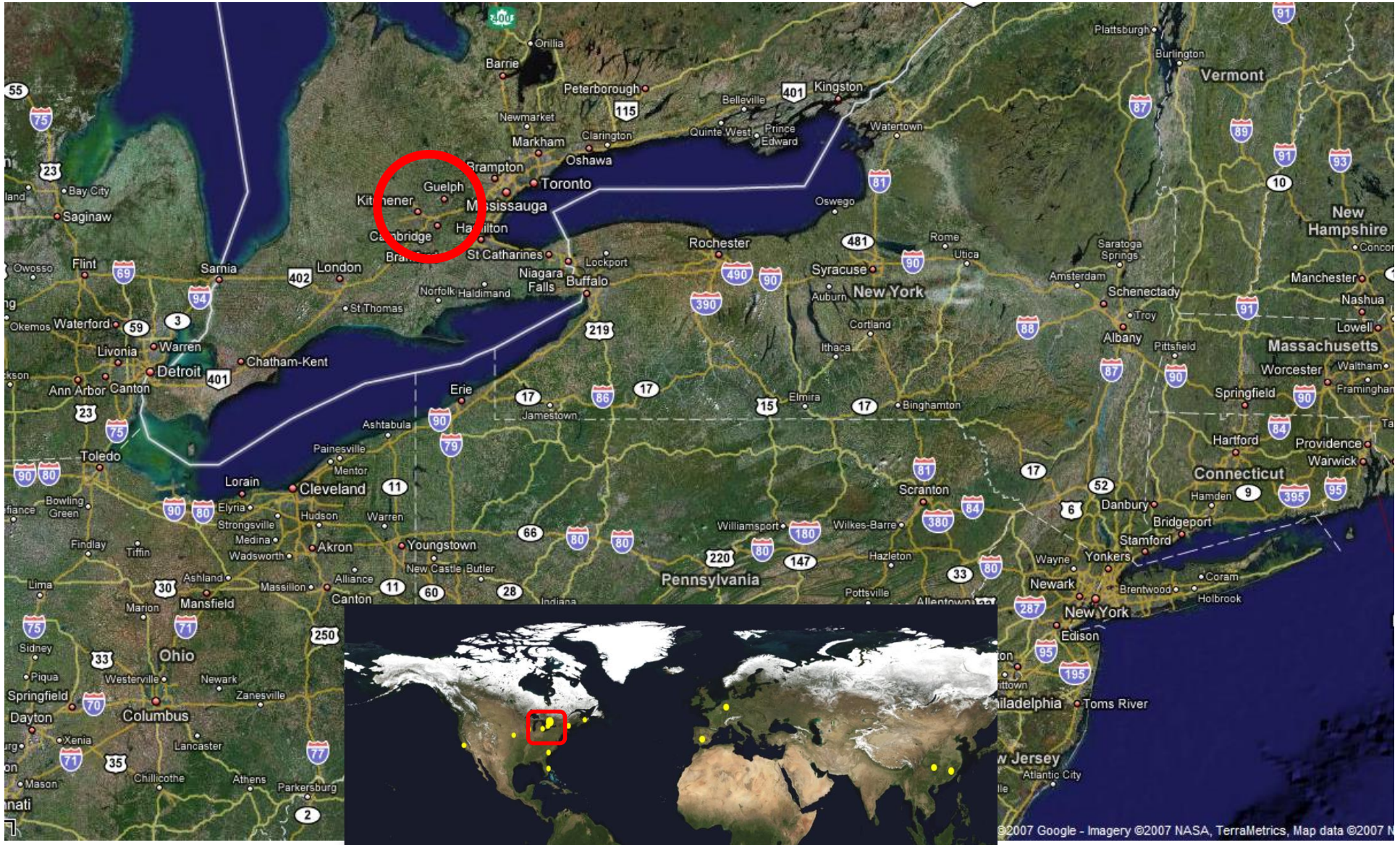




Arrival Residual Pressure TEH plots

Breakthrough of the pressure pulse

- as early as 35min in RD106, and
- as late as 80-90min at RD107.
- C10 is as early as 70min and as late as 250min
- Both C10 and RD106 have some depth variation but RD107 is uniform in time


Barrie
Orillia
Peterborough
Kingston
Belleville
Newmarket
Markham
Clarington
Quinte West
Prince Edward
Watertown
Oshawa
Brampton
Toronto
Guelph
Mississauga
Oswego
Rochester
Rome
Utica
Saratoga Springs
Syracuse
Amsterdam
Schenectady
Auburn
New York
Troy
Albany
Cortland
Ithaca
Lockport
Niagara Falls
Buffalo
St Catharines
London
Sarnia
Flint
Bay City
Saginaw
Owosso
Okemos
Waterford
Livonia
Warren
Detroit
Chatham-Kent
Ann Arbor
Canton
Erie
Jamestown
Elmira
Binghamton
Ashtabula
Painesville
Mentor
Toledo
Lorain
Cleveland
Elyria
Strongsville
Medina
Wadsworth
Akron
Hudson
Warren
Youngstown
New Castle
Butler
Alliance
Massillon
Canton
Ashland
Mansfield
Marion
Findlay
Tiffin
Bowling Green
Lima
Sidney
Piqua
Springfield
Dayton
Xenia
Mason
Westerville
Newark
Zanesville
Columbus
Lancaster
Chillicothe
Athens
Parkersburg
Ohio
Pennsylvania
Williamsport
Wilkes-Barre
Hazleton
Scranton
Pottsville
Allentown
Plattsburgh
Burlington
Vermont
New Hampshire
Concord
Manchester
Nashua
Lowell
Massachusetts
Worcester
Waltham
Framingham
Springfield
Pittsfield
Hartford
Providence
Warwick
Connecticut
Hamden
Danbury
Bridgeport
Stamford
Yonkers
Wayne
Newark
Brentwood
Coram
Holbrook
New York
Edison
Toms River
Atlantic City
Jersey
Field Research Sites
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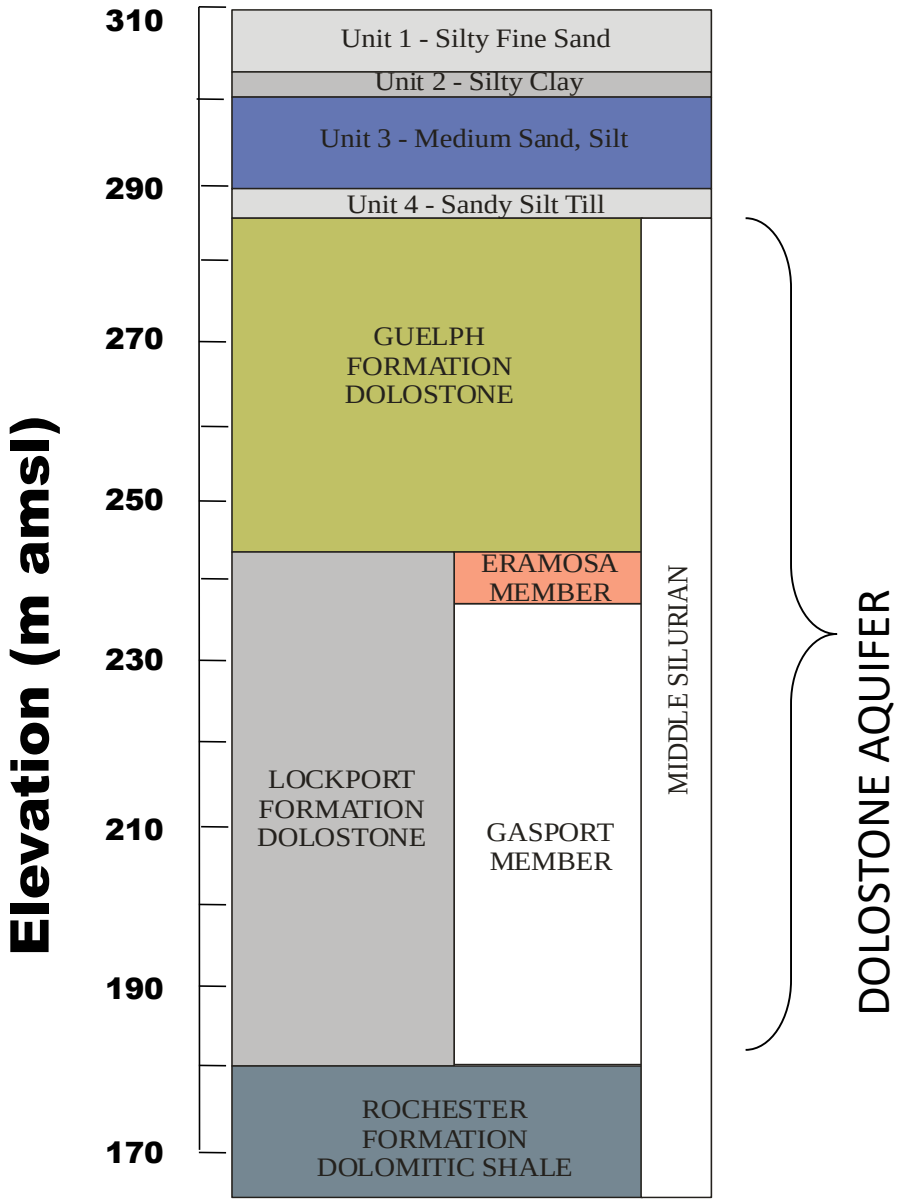
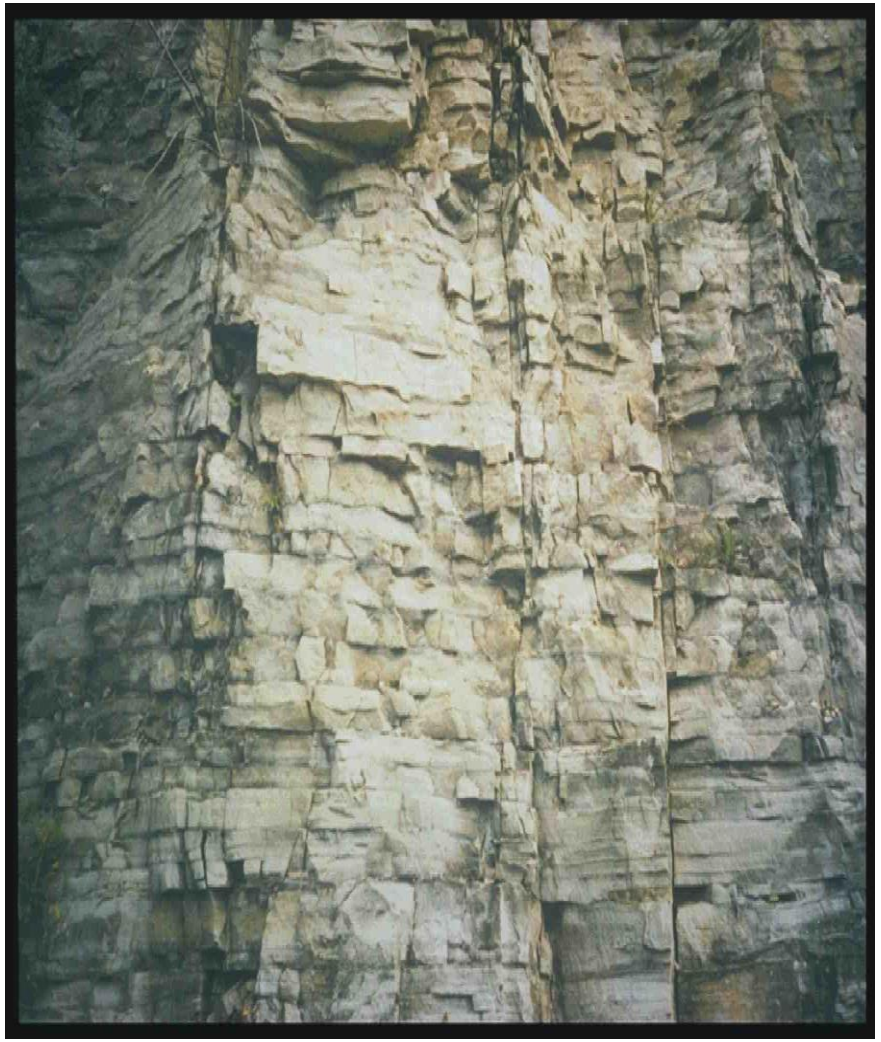
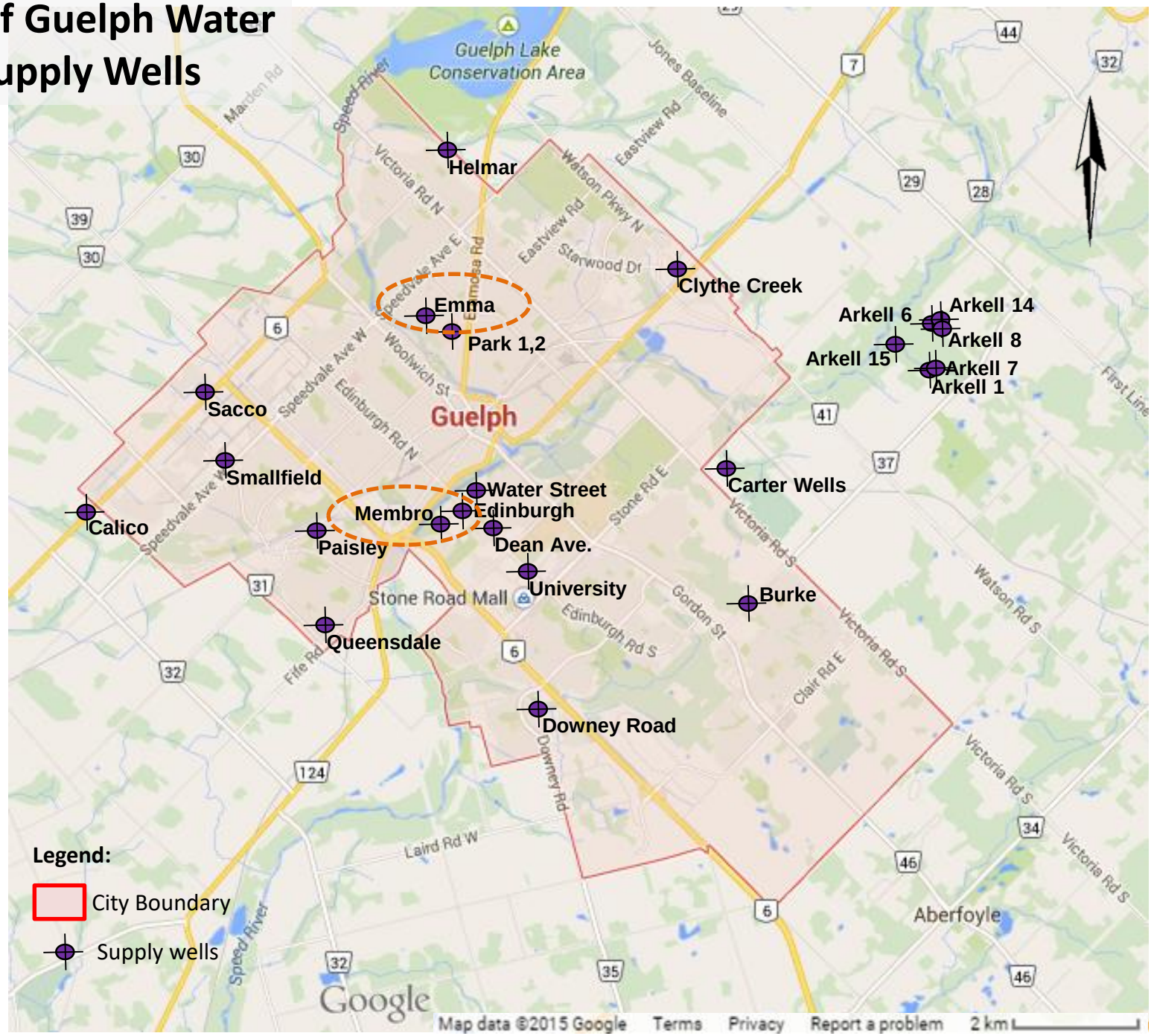
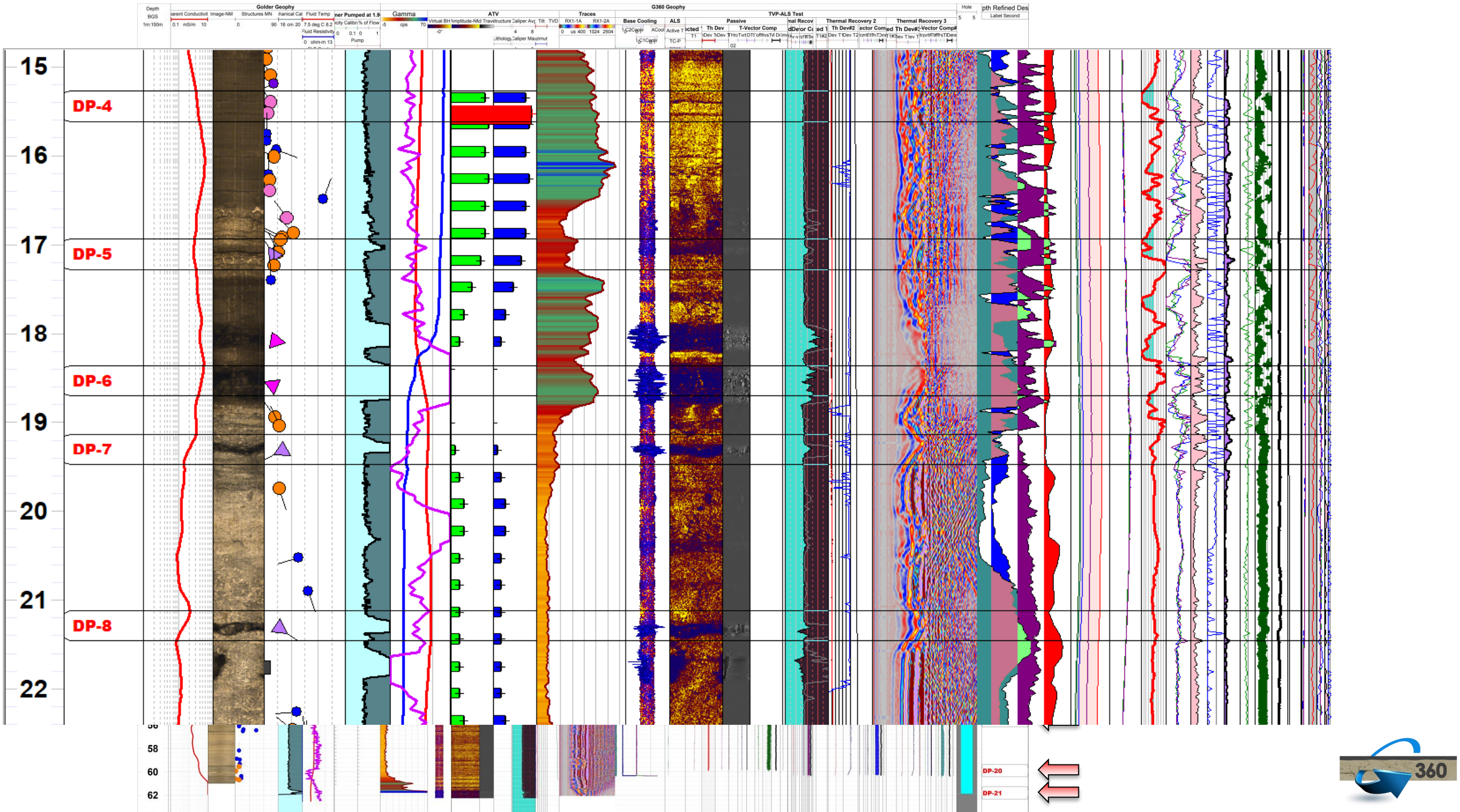
DOLOSTONE AQUIFER BENEATH QUATERNARY DEPOSITS



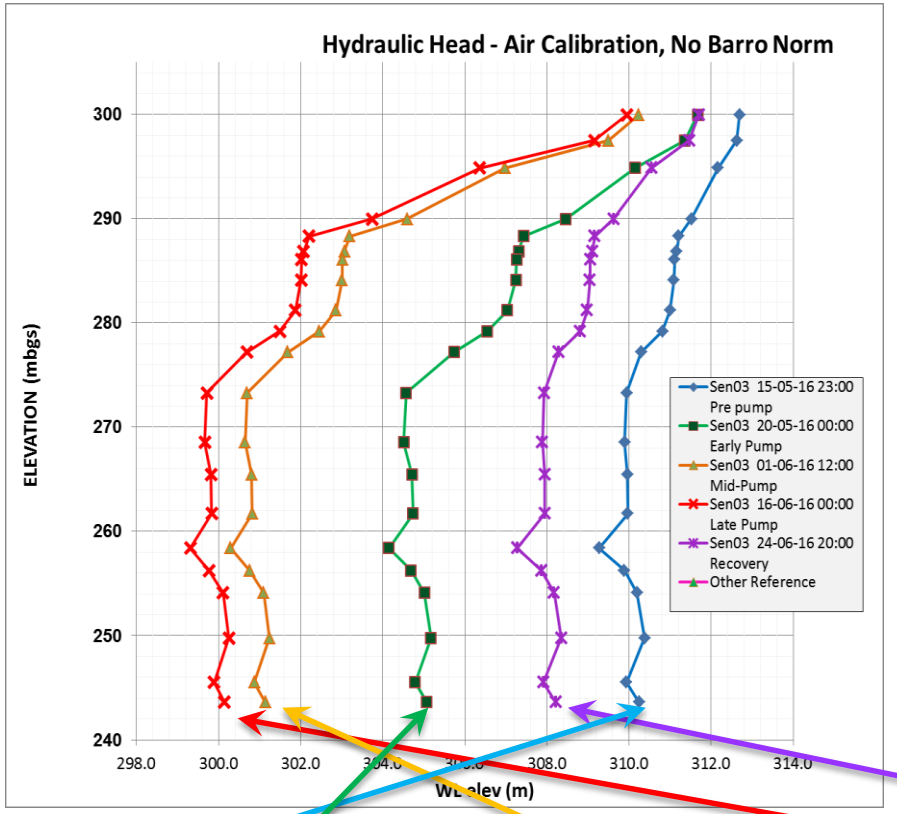


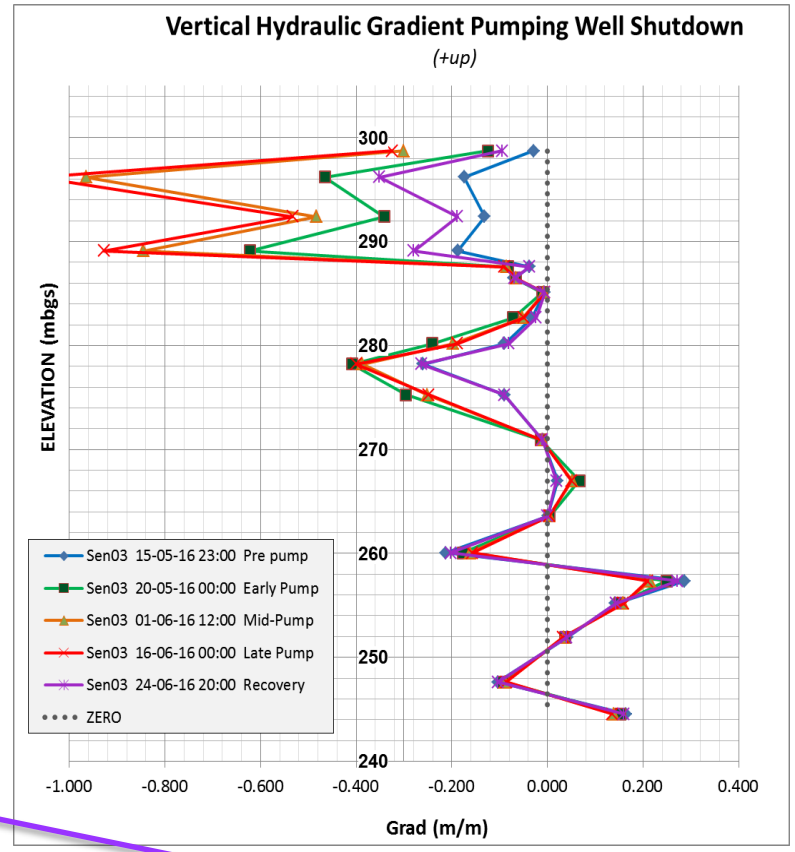
City of Guelph Water Supply Wells

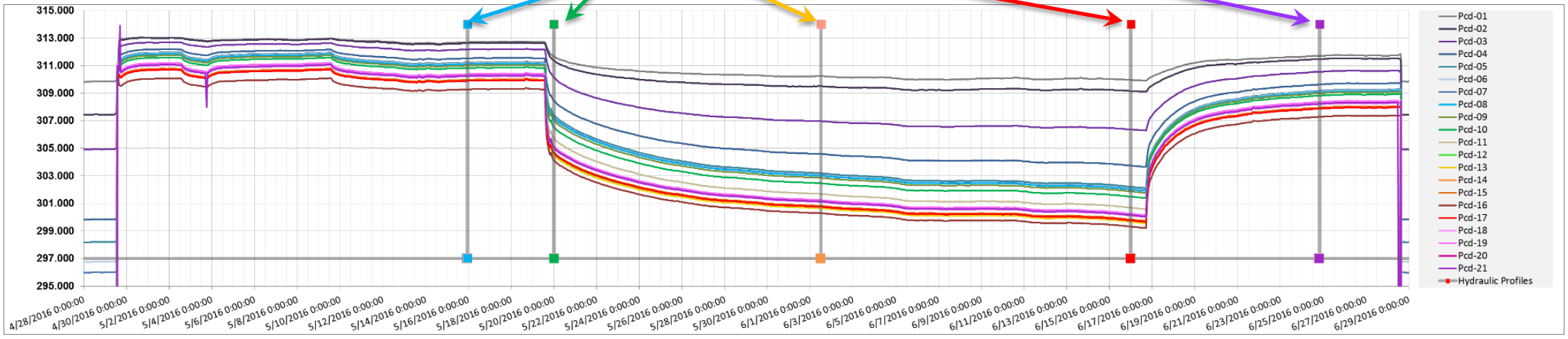



Golder Geophy
G360 Geophy
TVP-ALS Test
Gamma
ATV
Traces
Base Cooling
ALS
Passive
Thermal Recovery 2
Thermal Recovery 3
T-Vector Comp
Th Dev
Fluid Resistivity
Fluid Temp
Pump
Lithology Caliper Maximum
15
16
17
18
19
20
21
22
DP-4
DP-5
DP-6
DP-7
DP-8
56
58
60
62
DP-20
DP-21


~240m


Hydraulic Head - Air Calibration, No Barro Norm
ELEVATION (mbgs)
300
290
280
270
260
250
240
298.0
300.0
302.0
308.0
310.0
312.0
314.0
Sen03 15-05-16 23:00 Pre pump
Sen03 20-05-16 00:00 Early Pump
Sen03 01-06-16 12:00 Mid-Pump
Sen03 16-06-16 00:00 Late Pump
Sen03 24-06-16 20:00 Recovery
Other Reference


Vertical Hydraulic Gradient Pumping Well Shutdown
(+up)
ELEVATION (mbgs)
300
290
280
270
260
250
240
-1.000
-0.800
-0.600
-0.400
-0.200
0.000
0.200
0.400
Grad (m/m)
Sen03 15-05-16 23:00 Pre pump
Sen03 20-05-16 00:00 Early Pump
Sen03 01-06-16 12:00 Mid-Pump
Sen03 16-06-16 00:00 Late Pump
Sen03 24-06-16 20:00 Recovery
ZERO


315.000
313.000
311.000
309.000
307.000
305.000
303.000
301.000
299.000
297.000
295.000
4/28/2016 0:00:00
4/30/2016 0:00:00
5/2/2016 0:00:00
5/4/2016 0:00:00
5/6/2016 0:00:00
5/8/2016 0:00:00
5/10/2016 0:00:00
5/12/2016 0:00:00
5/14/2016 0:00:00
5/16/2016 0:00:00
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Pcd-01
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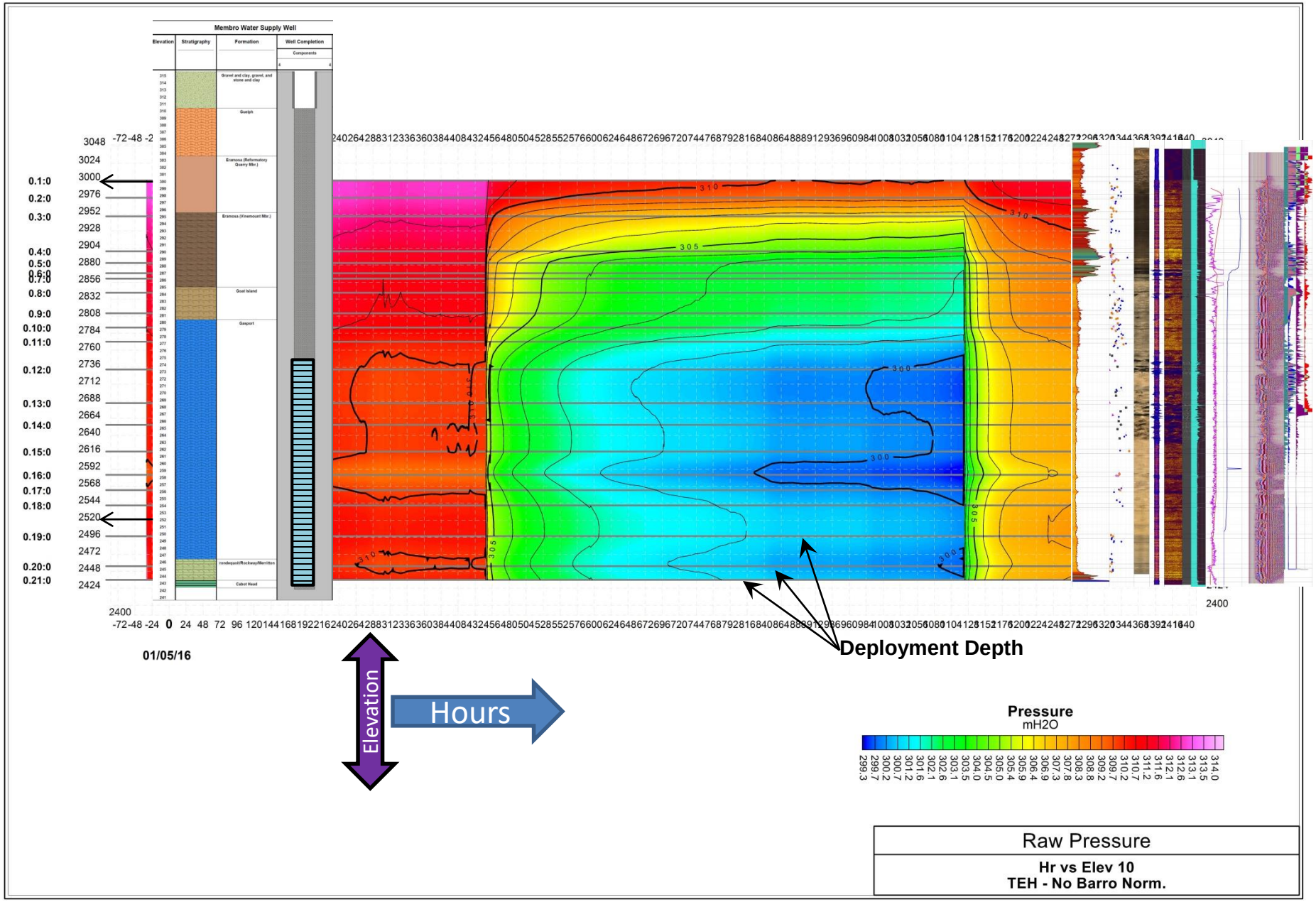
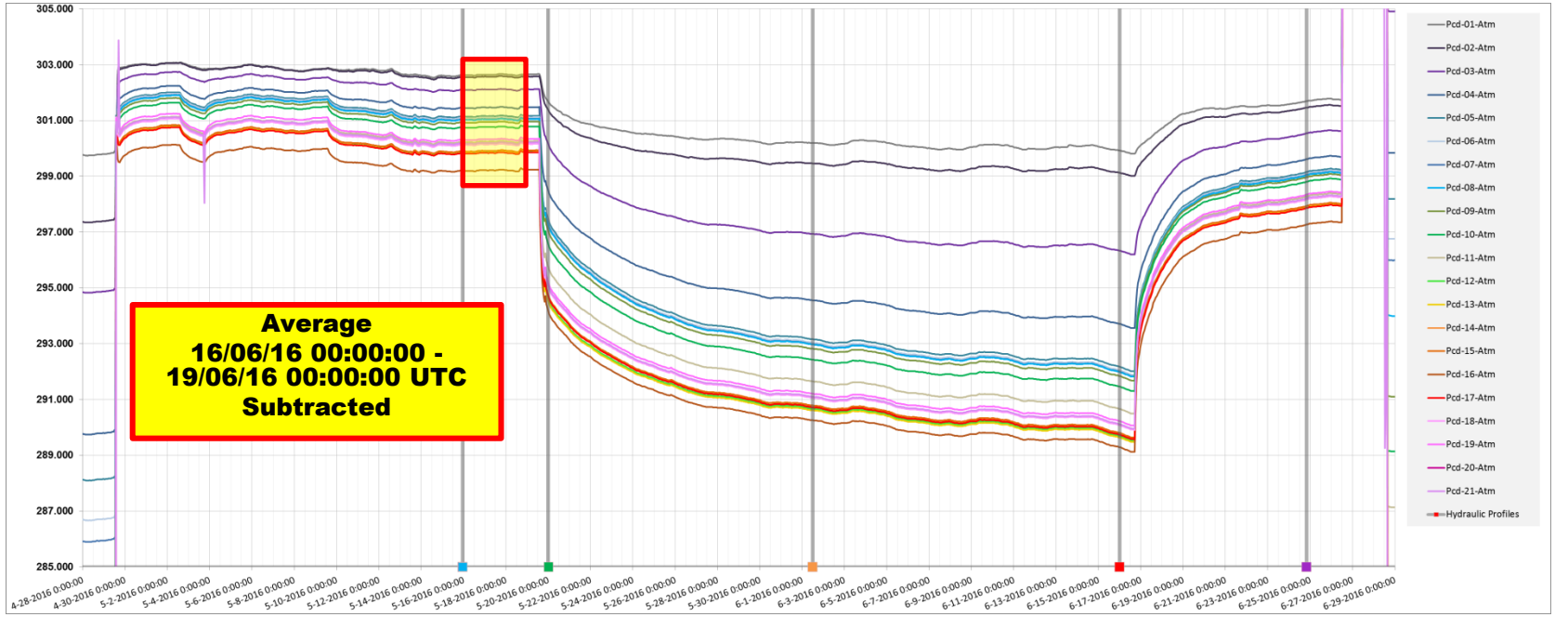
Pcd-21
Hydraulic Profiles

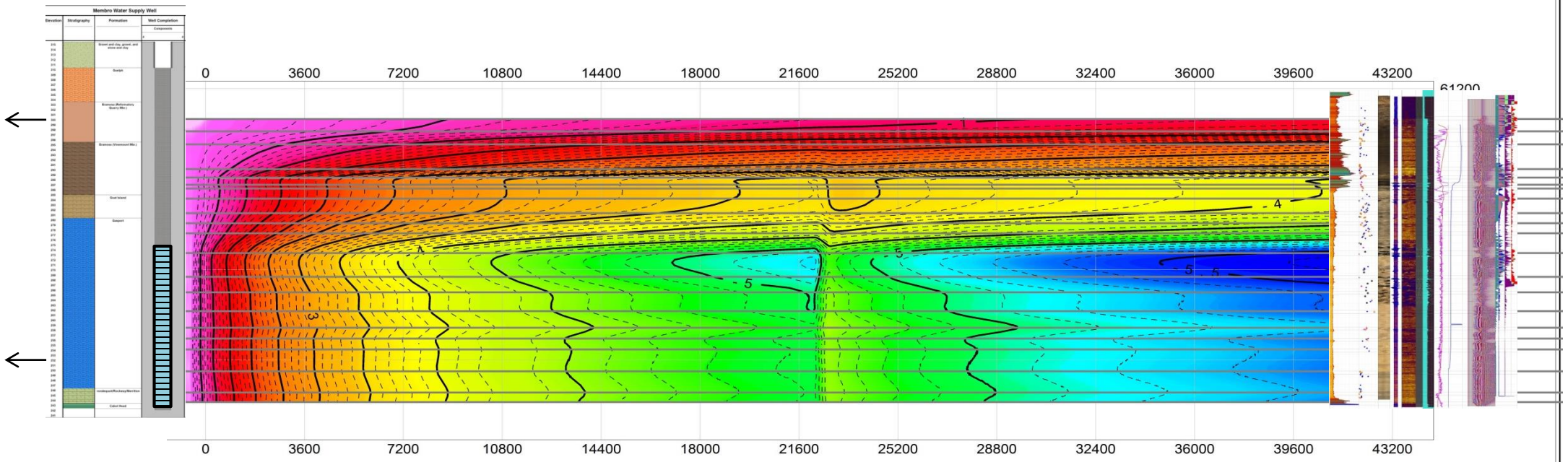


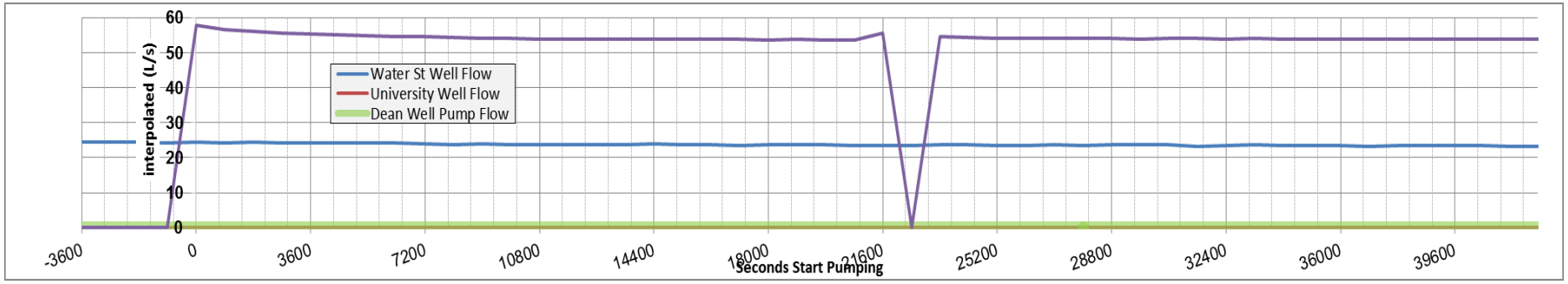
Sentry Well Pump Test as Time-Elevation-Head



Sentry Well 03 City Pump Test

Identifying “Background” for Residual calculations



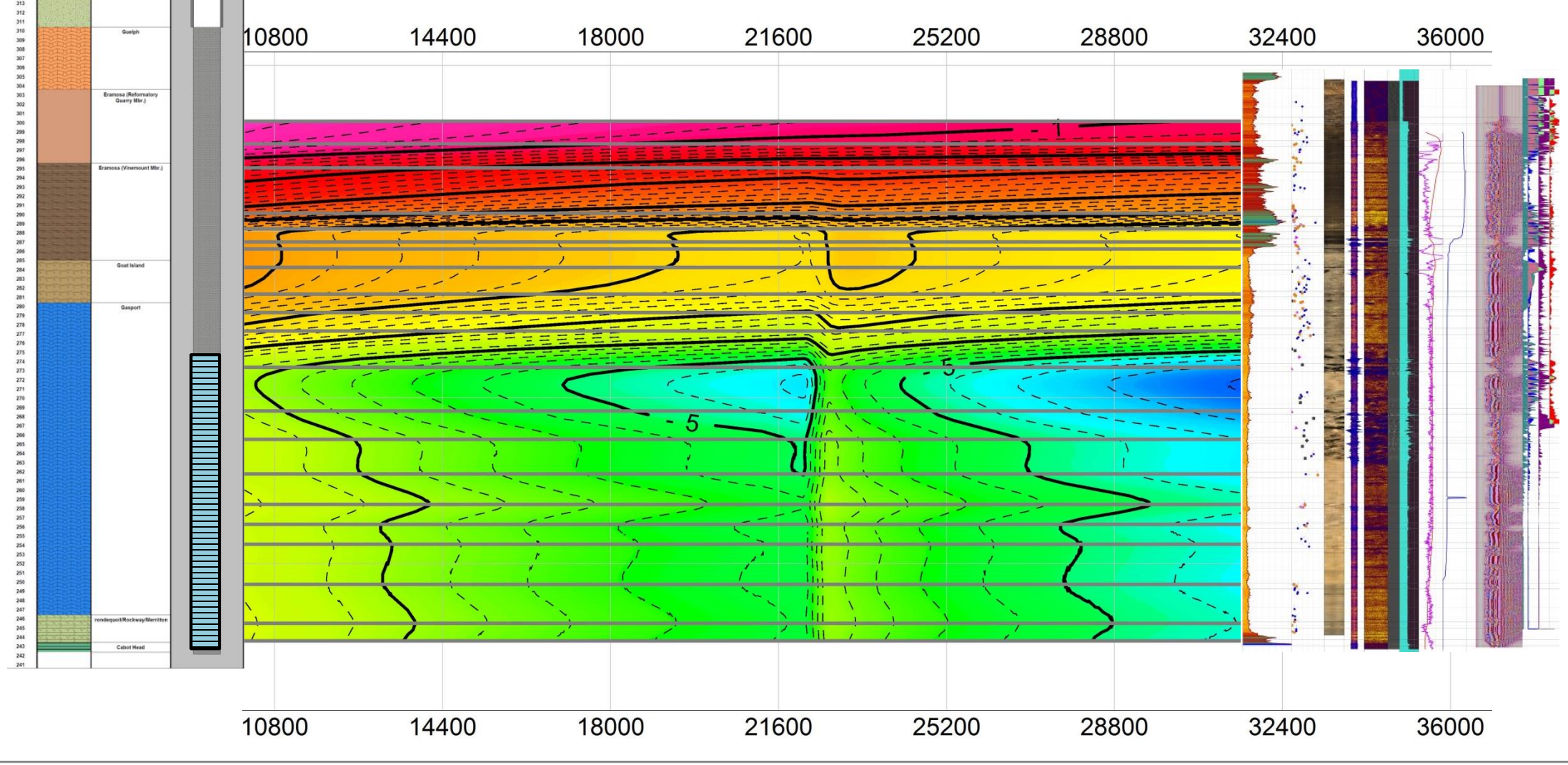


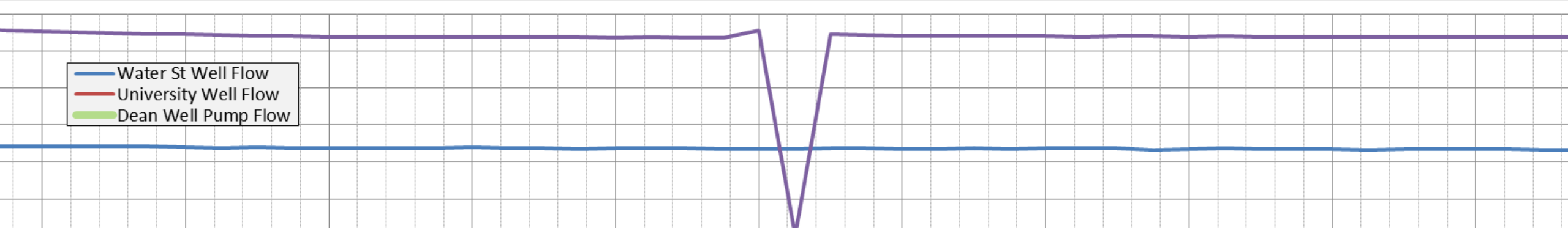
Average
16/06/16 00:00:00 - 19/06/16 00:00:00 UTC
Subtracted

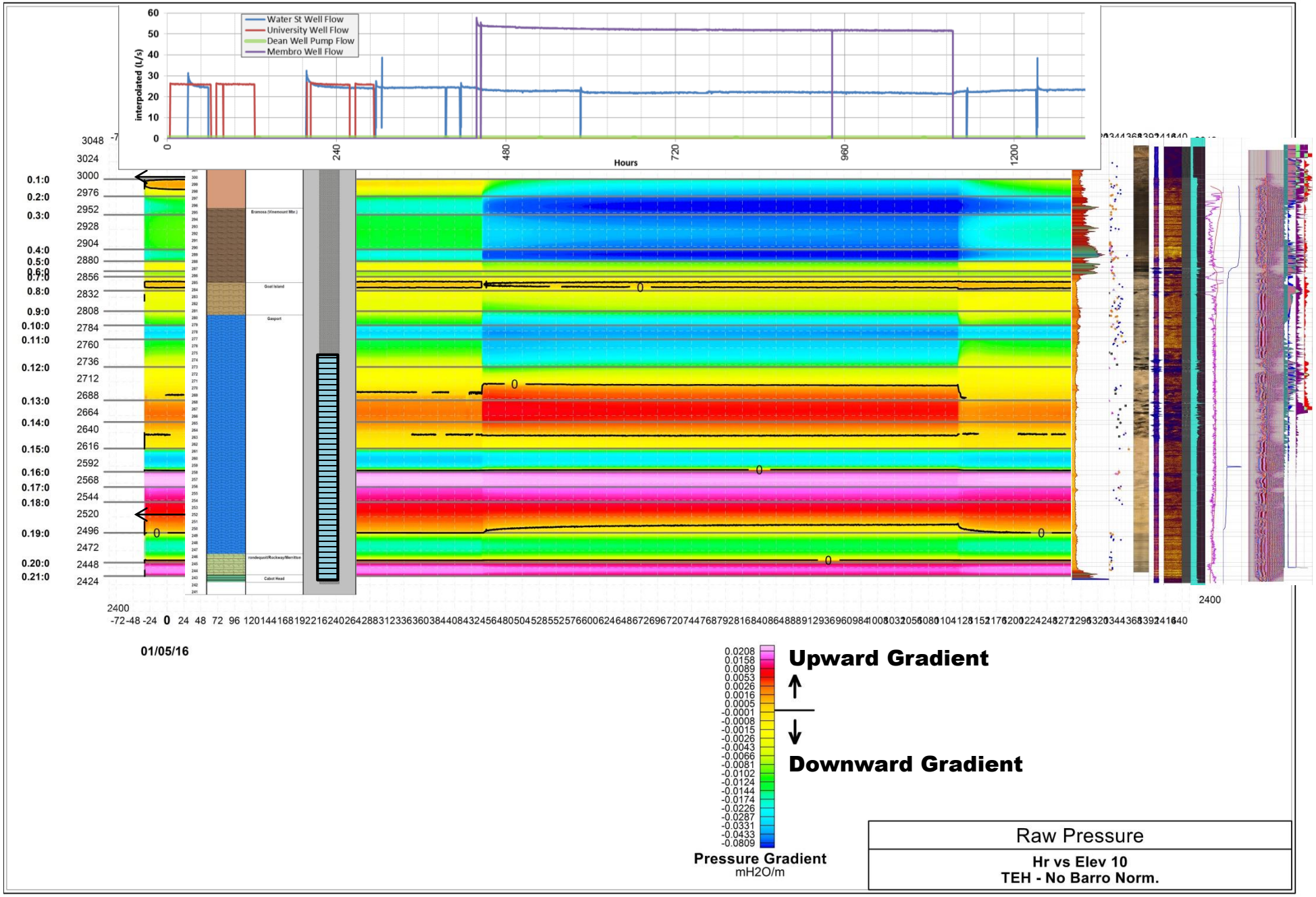
Residual Pressure
mH2O

-5.600 -5.398 -5.333 -5.273 -5.203 -5.125 -5.038 -4.948 -4.876 -4.806 -4.725 -4.628 -4.513 -4.355 -4.176 -4.020 -3.901 -3.758 -3.593 -3.446 -3.221 -2.947 -2.656 -2.372 -2.083 -1.764 -1.414 -1.128 -0.858 -0.376 -0.025 -0.022

Start Pump Test
Residual Pressure sec vs Elev 200 TEH
1 hr grid

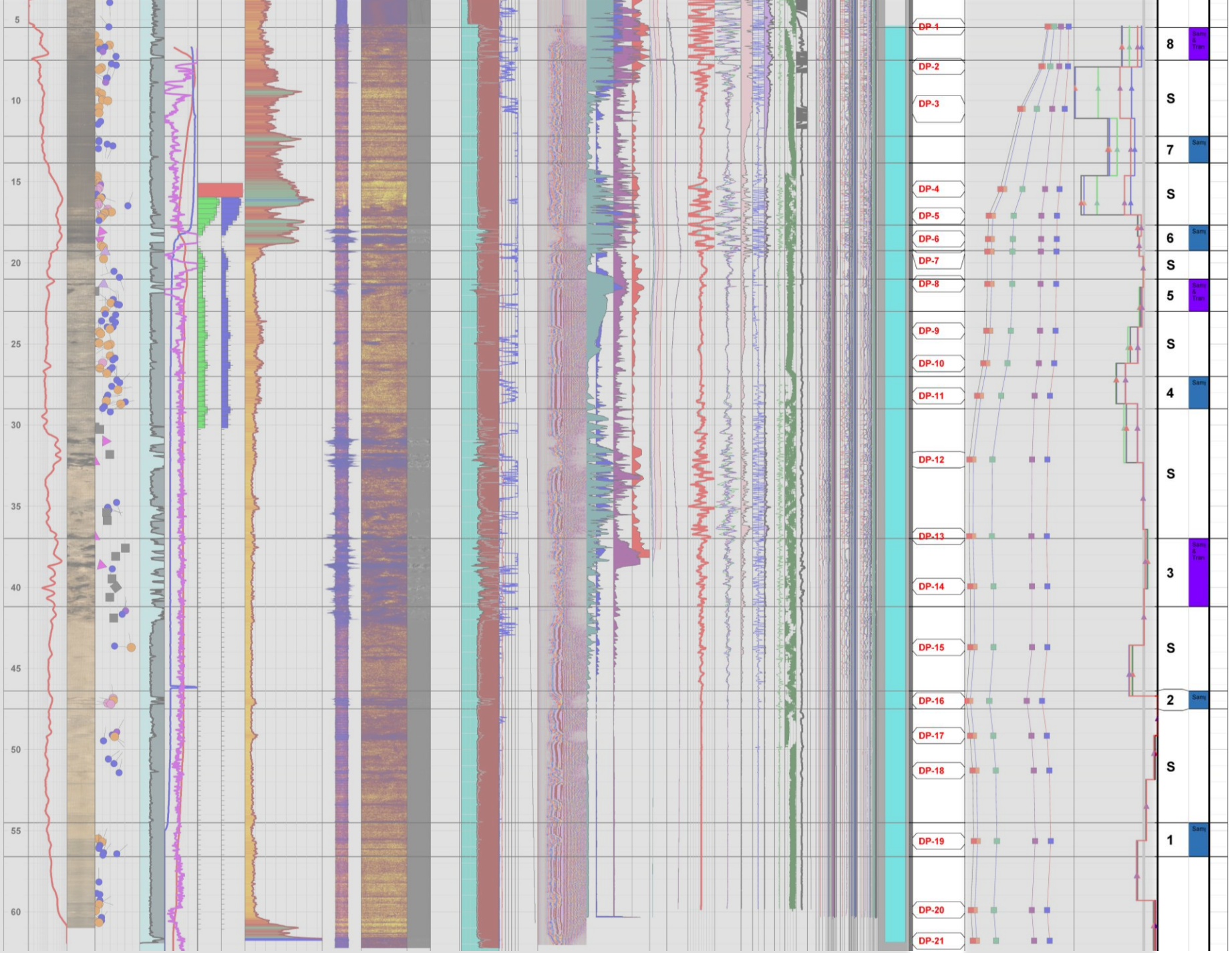

Guelph
Eramosa (Reformatory Quarry Mbr.)
Eramosa (Vinemount Mbr.)
Goat Island
Gasport
Irondequoit/Rockway/Merriton
Cabot Head
10800
14400
18000
21600
25200
28800
32400
36000
-1
-5
-5
10800
14400
18000
21600
25200
28800
32400
36000


Water St Well Flow
University Well Flow
Dean Well Pump Flow



Raw Pressure

Hr vs Elev 10
TEH - No Barro Norm.



MLS Design

21 Deployments

8 MLS Ports

- **Variable Length**
  - **Rationalized**
    - **Defensible**

Requirements:

- Sensors (1 or 2 to dozens), only restriction is space
- Liner
- Spine Line
- Weight
- Hydraulic Perturbation
  - Natural
  - Induced
- Time (weeks – many months)

KEY BENEFITS

- Superior Understanding of Hydraulic System & Hydodynamics
- Simple
- Flexibility
  - Time
  - Depth
  - Resolution
  - Reconfigure as needed
  - Broad Variety of Applications
- Cost Effective
  - Parts reusable
  - Robust

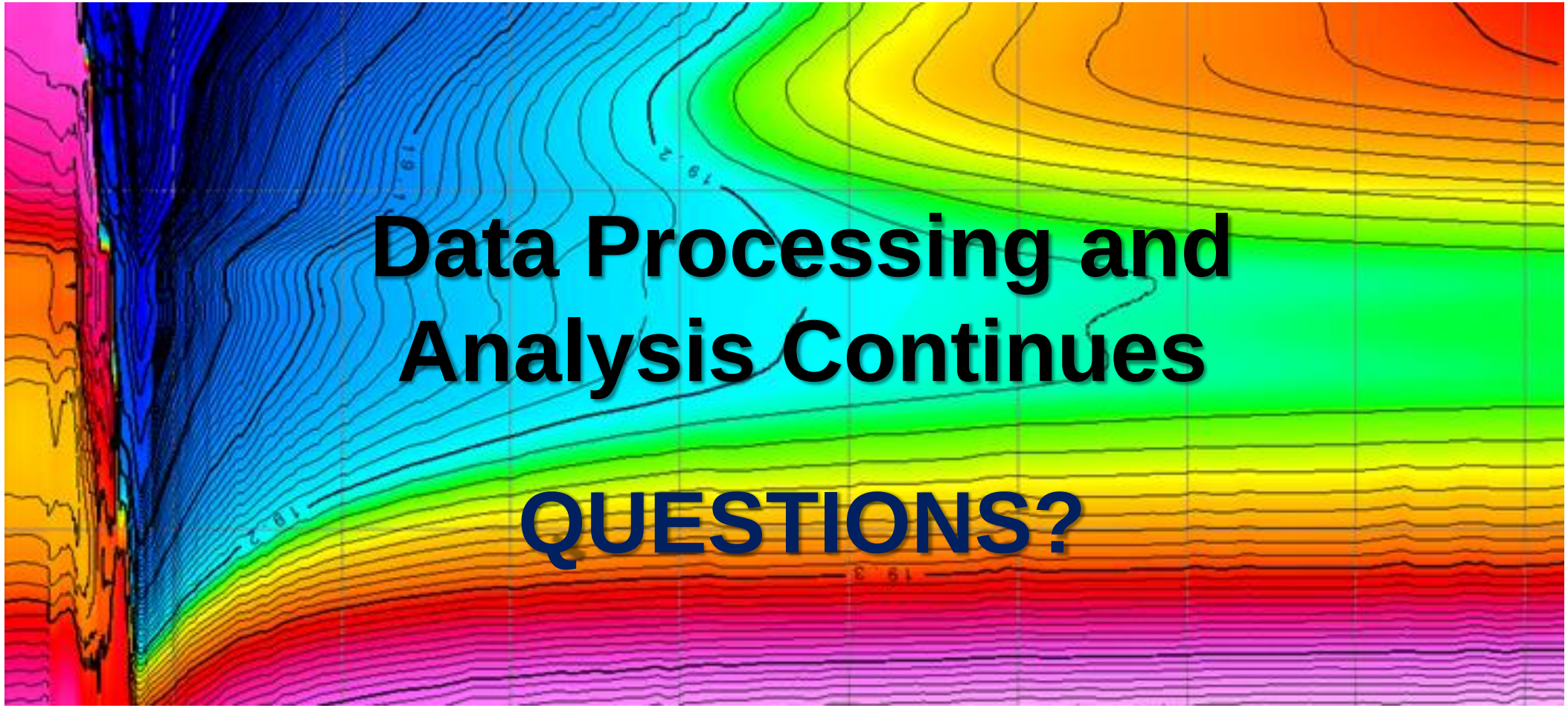
Optimize expensive Multi-Levels

Other Recent, Current & Pending Applications

- **Long Term Monitoring** (Sweden, South Guelph, NWT)
- **Cross Hole Monitoring of Packer Testing**, (SSFL & BAFF)
- **Thermal and Hydraulic Monitoring of Recharge from River** (Scout Camp)
- **Cross Hole Monitoring of Drilling Program** (Hydrite, BC, Sweden)
- **Cross Hole Verification and Testing of Methodologies**
  - Heat Pulse Flow Meter Techniques
  - DTS & ALS / TVP Thermal Tests
  - FLUTe Profiling
  - Etc., etc. ……..

ACKNOWLEDGEMENTS:

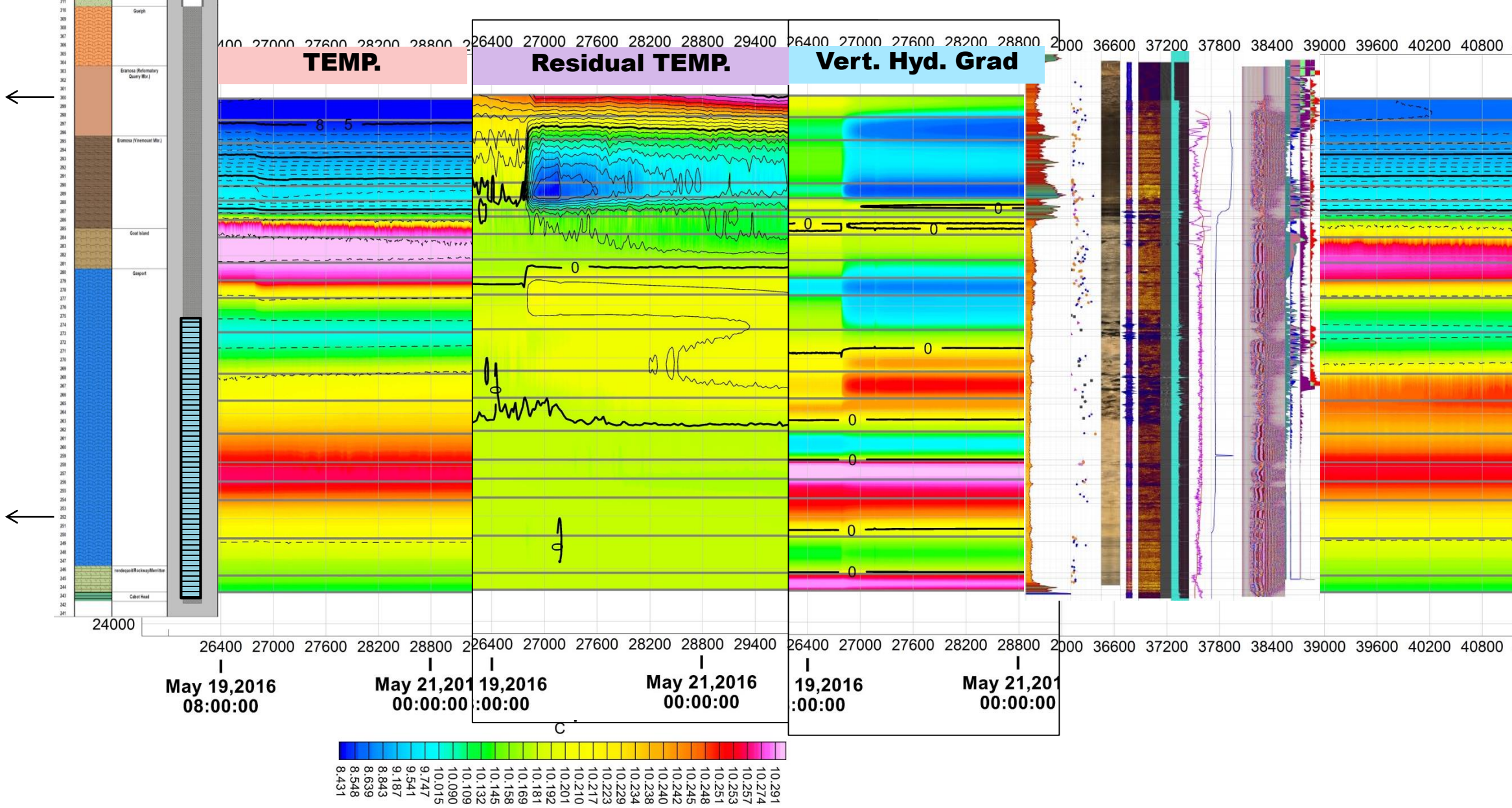
- Parker NSERC IRC Funding,
- Boeing (Mike Bower and others) ; CH2M Hill (Kevin Murdoch & crew)
- City of Guelph (Dave Belanger, Peter Rider and others) ; Golder Assoc. (John Piersol, Greg Padusenko …..)
- FLUTe and Schlumberger for research pricing for liners and transducers,
- University of Guelph G360 staff (especially John Cherry & Ryan Kroeker).


Data Processing and
Analysis Continues
QUESTIONS?

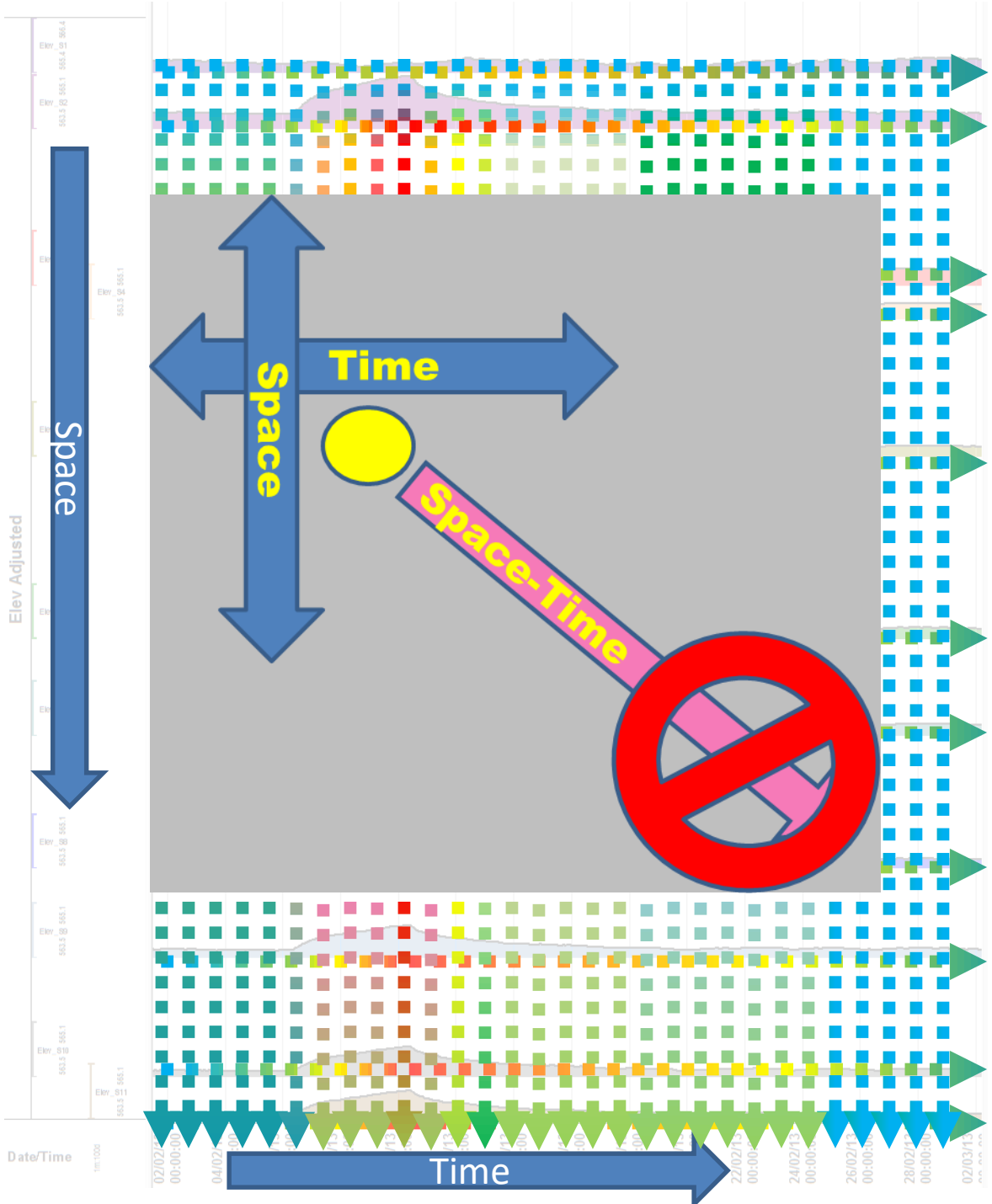
Start at 2019-05-28 9:00

Max Available				Use	Shut Off @
	24000	Mini DIVER		120	2019-06-30 17:00
	48000	Micro Diver/DIVER		100	2019-07-22 22:20
	20000000	RBR Solo		10	2025-09-28 4:34
	30000000	RBR Duet 3		10	2028-11-28 14:20

	Accuracy +/-	Resoloution < than
Temp (C)	0.002	0.00005
Press (dbar)	0.05%	0.001%
20	0.01	0.0002
50	0.025	0.0005
100	0.05	0.001
200	0.1	0.002
500	0.25	0.005
1000	0.5	0.01



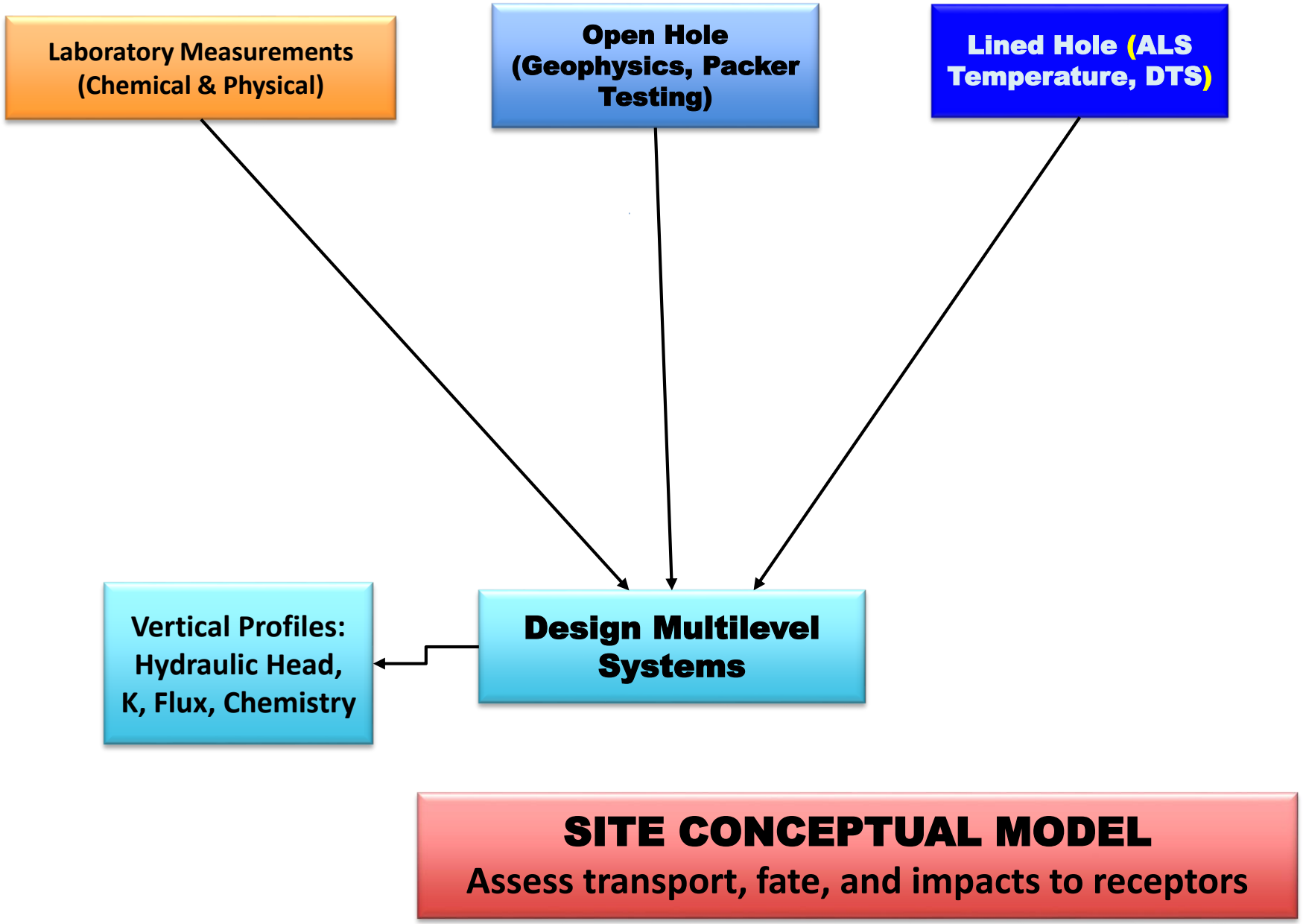
Detailed Comparison Sentry Well Pump Test Start Expanded (min vs Elev x 100)

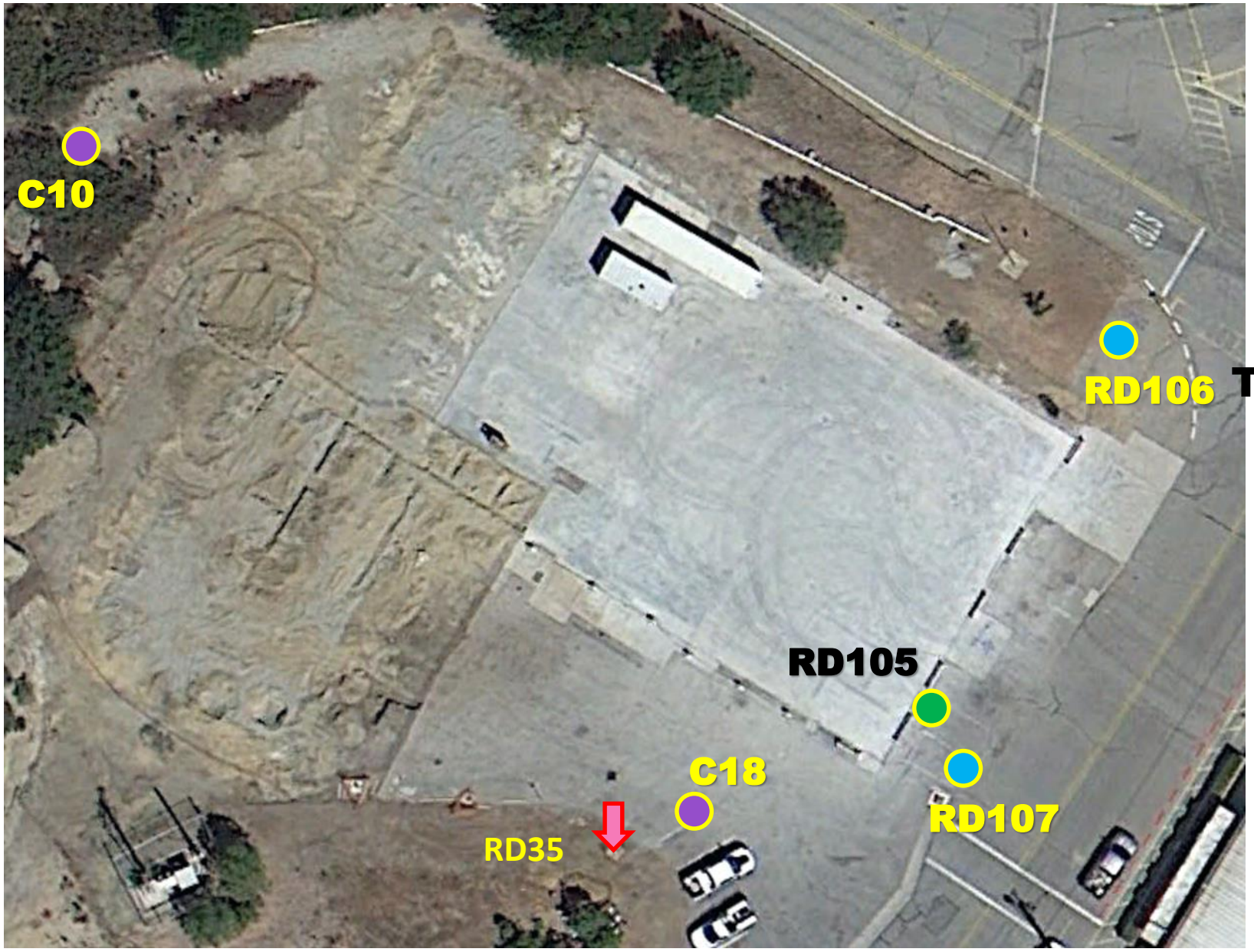


Time-Elevation-Head Plots (TEH)

1. Interpolate in Time
2. Interpolate in Elevation
3. Create a regular (tight) grid of values
4. Filter and contour values

Simplified Discrete Fracture Network (DFN) Approach





Test Boreholes

INJECTION INTO RD35