Use of Tracer Dyes to Understand Fractured Bedrock Flow during a Pumping Test

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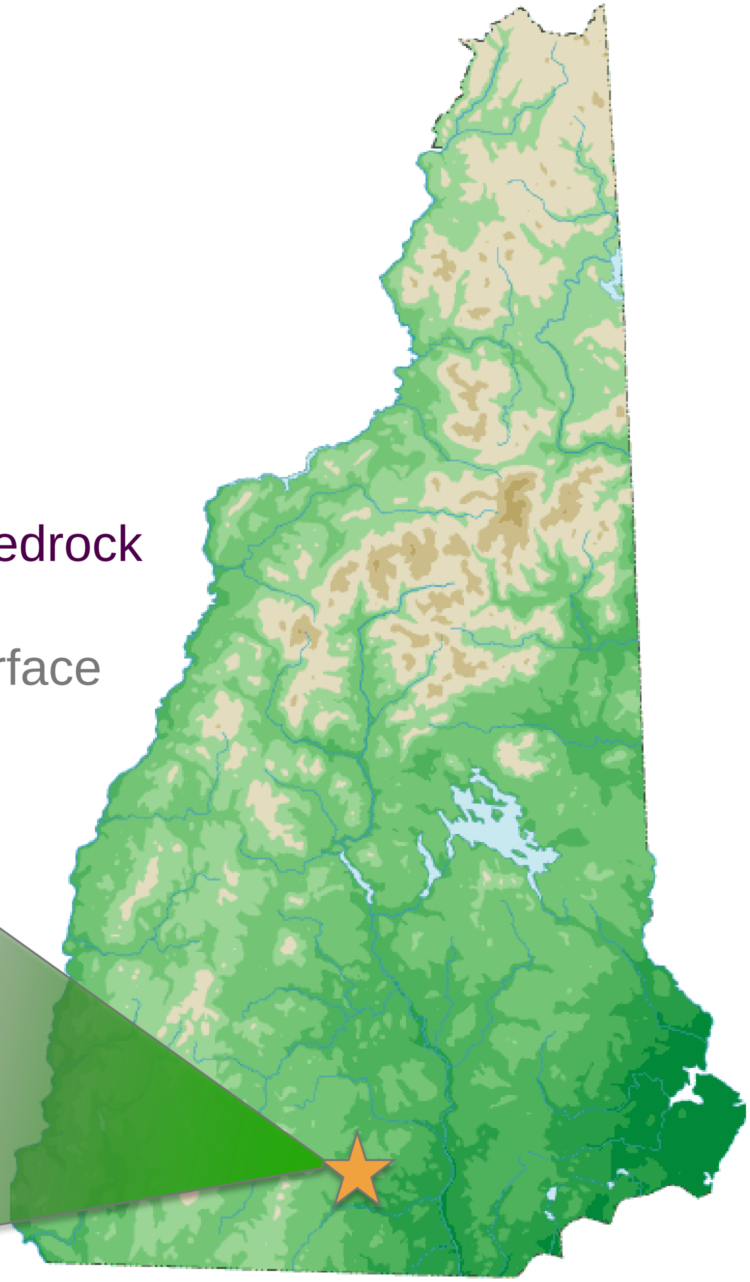
Savage Municipal Water Supply Superfund Site Milford, NH - Background

PCE contamination in overburden aquifer
- DNAPL present in overburden
- 1991 ROD addressed overburden

Previous remedial actions
- Slurry wall
- Pump and treat
- ISCO with $NaMnO_4$

Highest levels of remaining contamination are in bedrock
- Up to 100 ppm PCE in fractures beneath site
- At depths of more than 500 ft below bedrock surface



Purpose of Tracer Dye Use during Pumping Test

Part of a Remedial Investigation (RI) to ***characterize bedrock*** at the site

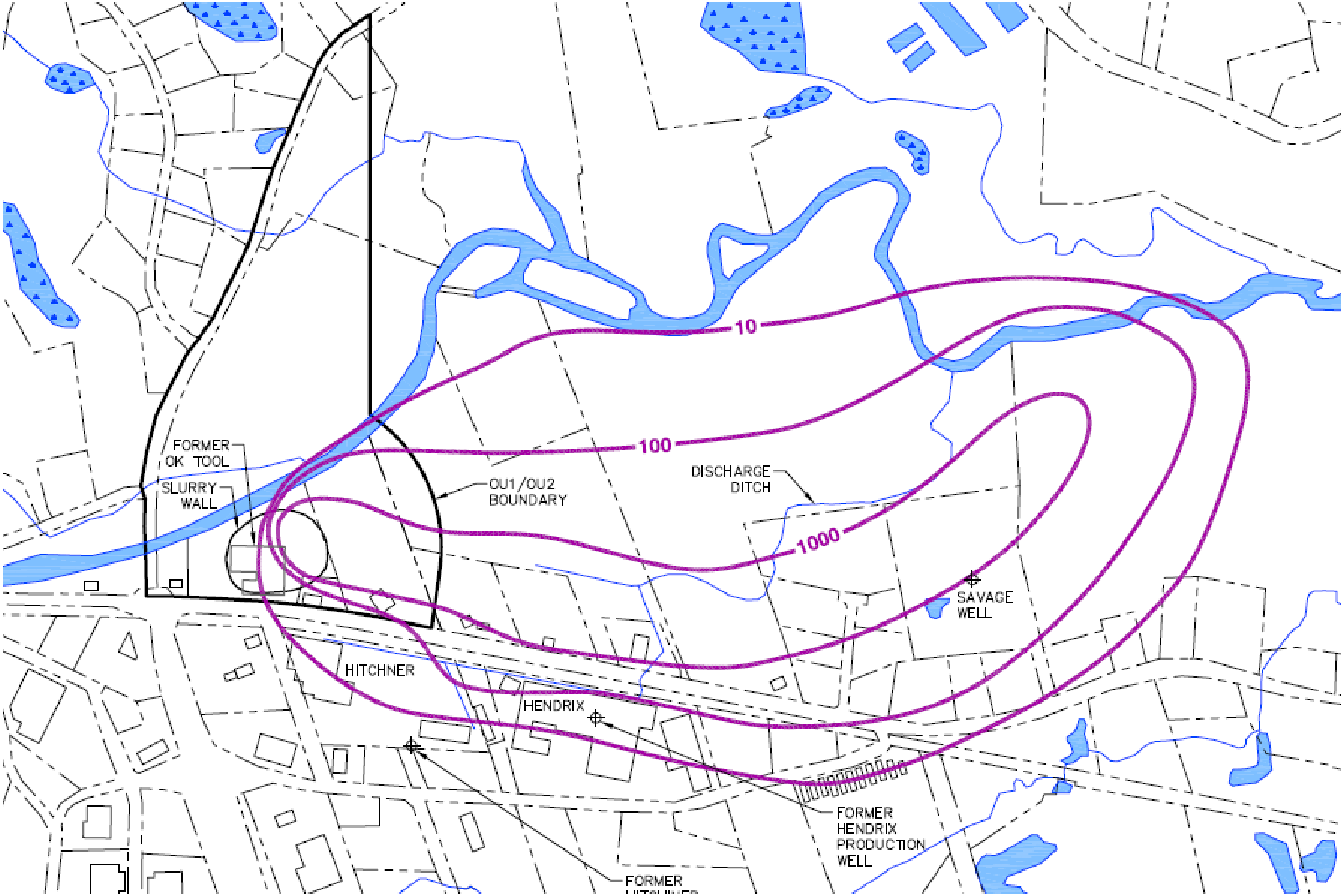
Gain a better understanding of ***migration pathways*** through fractured bedrock

Qualitatively evaluate relative ***flow rates*** through fractured bedrock

Evaluate potential ***risks to residential wells*** located north of the site.

Google Earth Air Photo of Site and Vicinity

Historical 1990 PCE Overburden Plume



Site Geology

Overburden

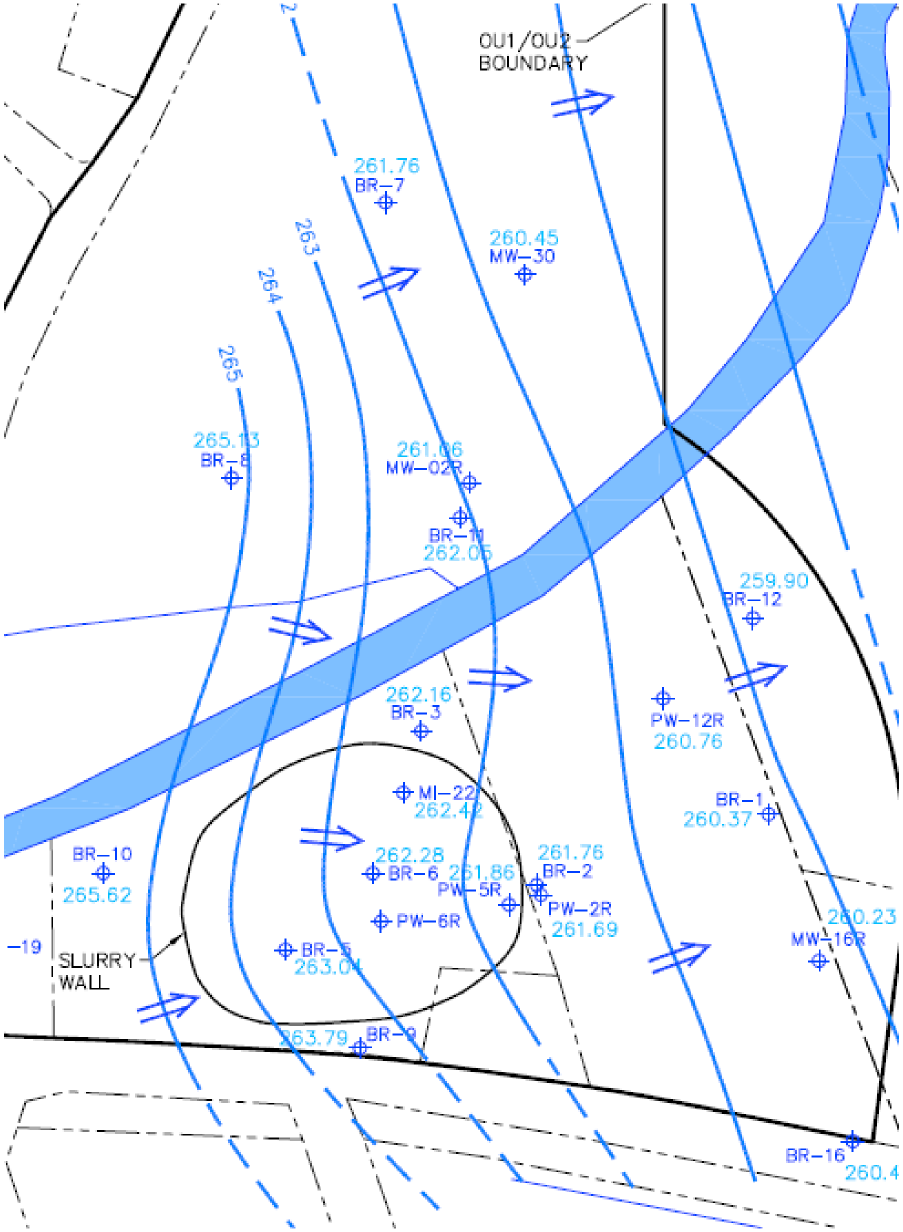
- Milford Souhegan glacial drift
- Highly transmissive
- 60 to 110 ft thick
- Water table at 5 to 15 ft bgs
- Hydraulic gradients toward the east

Bedrock

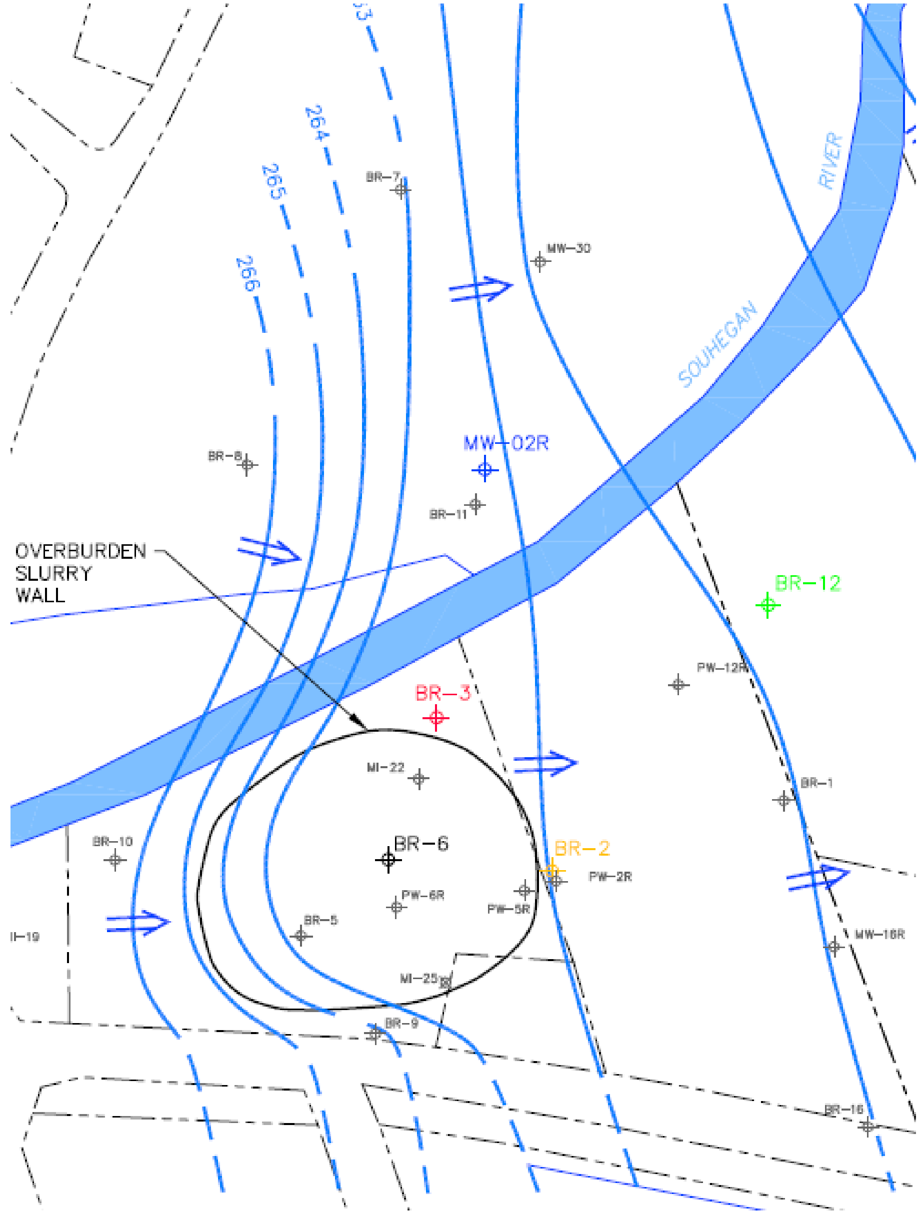
- Granite & Gneiss
- Steeply dipping fractures
- Predominant north-northeast strike orientation
- Hydraulic gradients toward the east.

Bedrock Hydrogeology

Gradients w/o Pump & Treat



25 gpm Pump & Treat Operating
(baseline condition for pumping test)



Bedrock Fracture Strikes and Dips

Borehole geophysics courtesy of Northeast Geophysical

Rose diagram

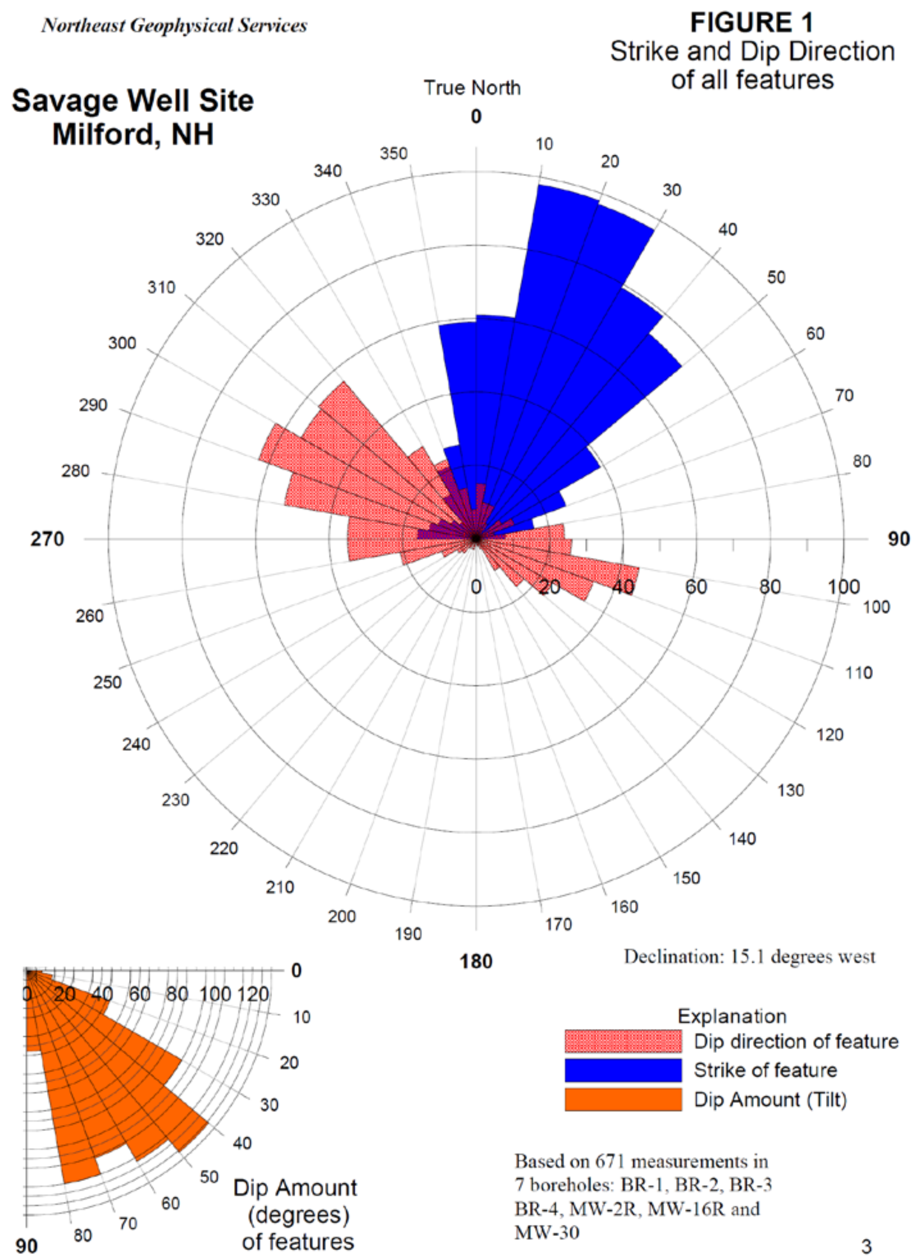
- Based on 671 measurements in 7 boreholes

Predominant fracture strike

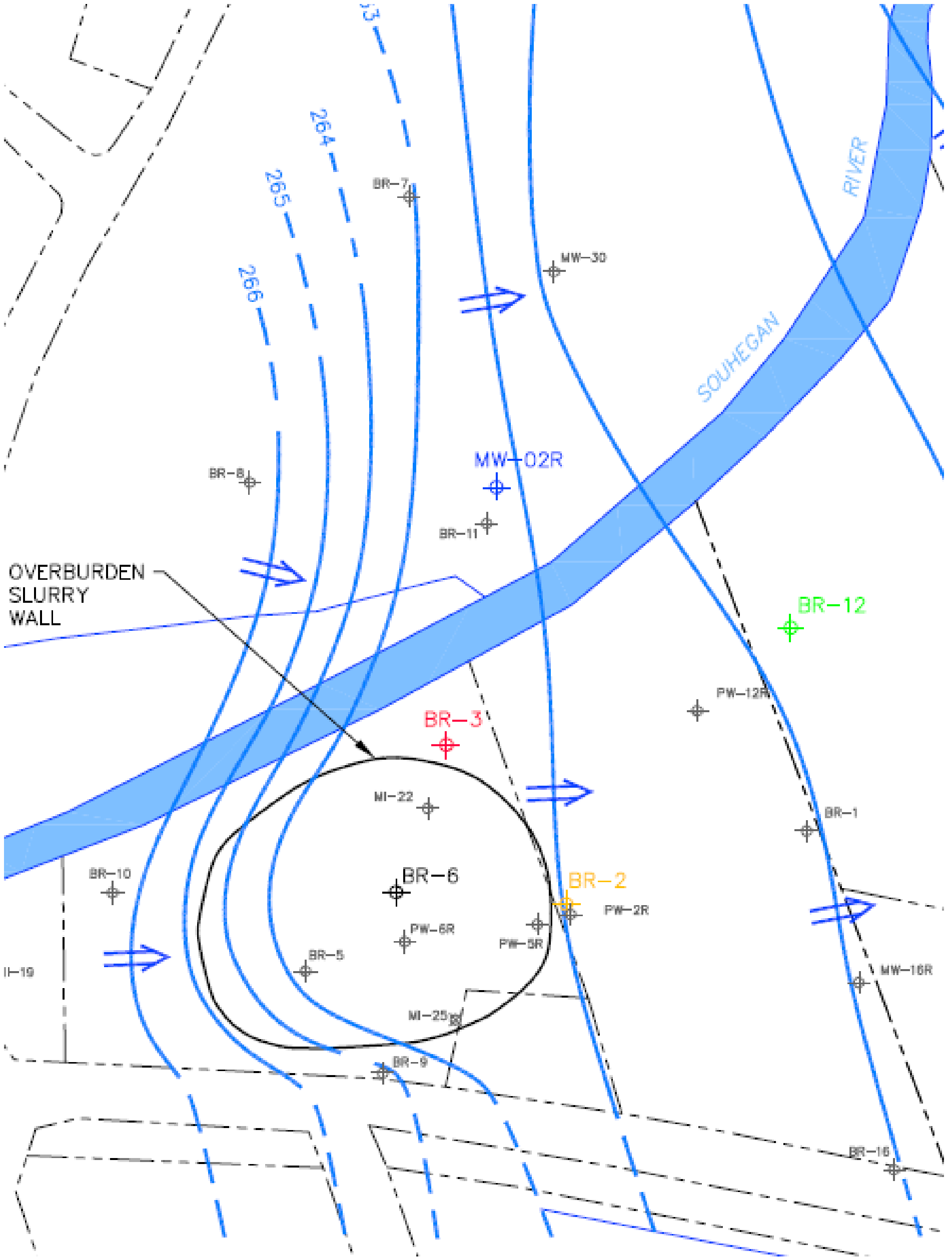
- North/northeast

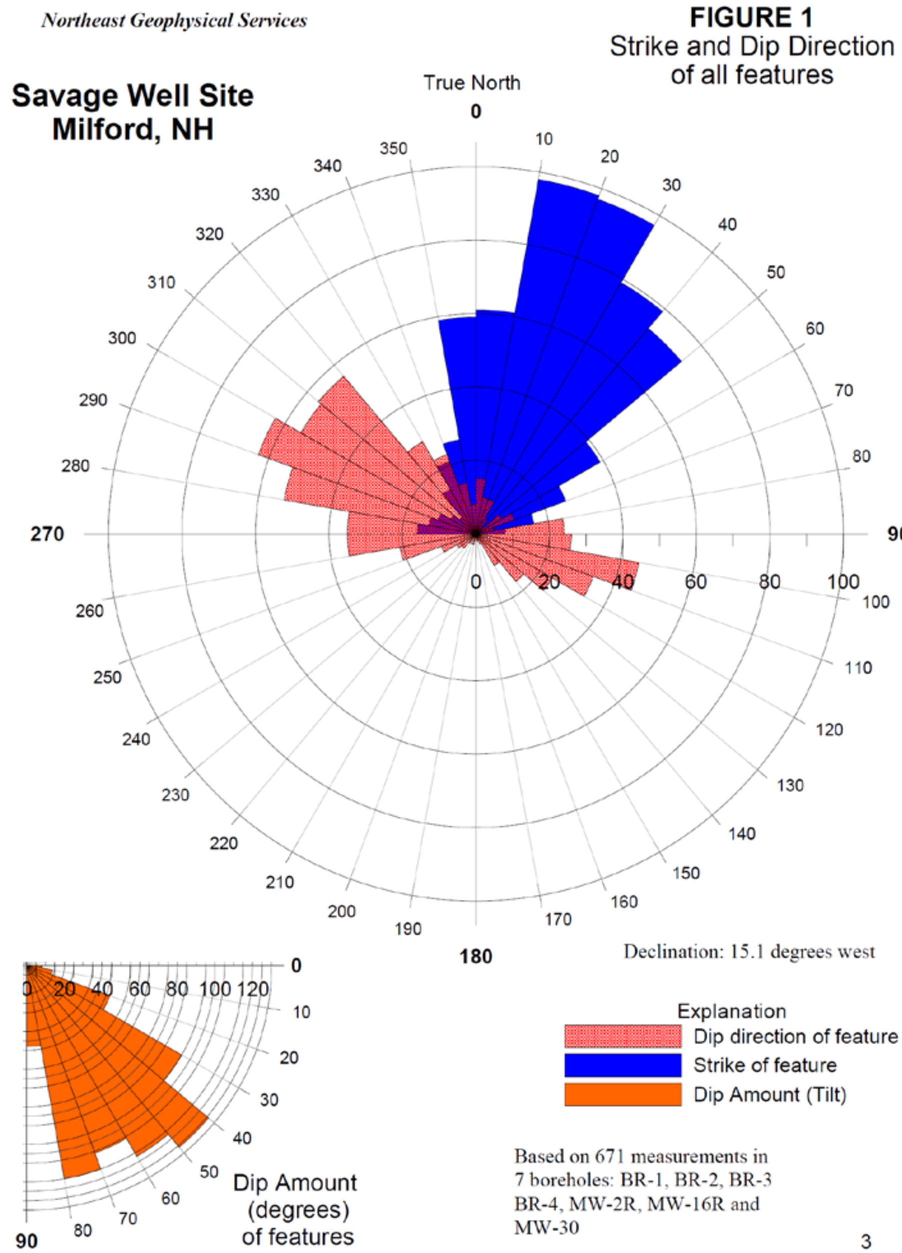
Predominant fracture dip angle

- 40 to 80 degrees from horizontal



Gradients vs. Predominant Fracture Orientation





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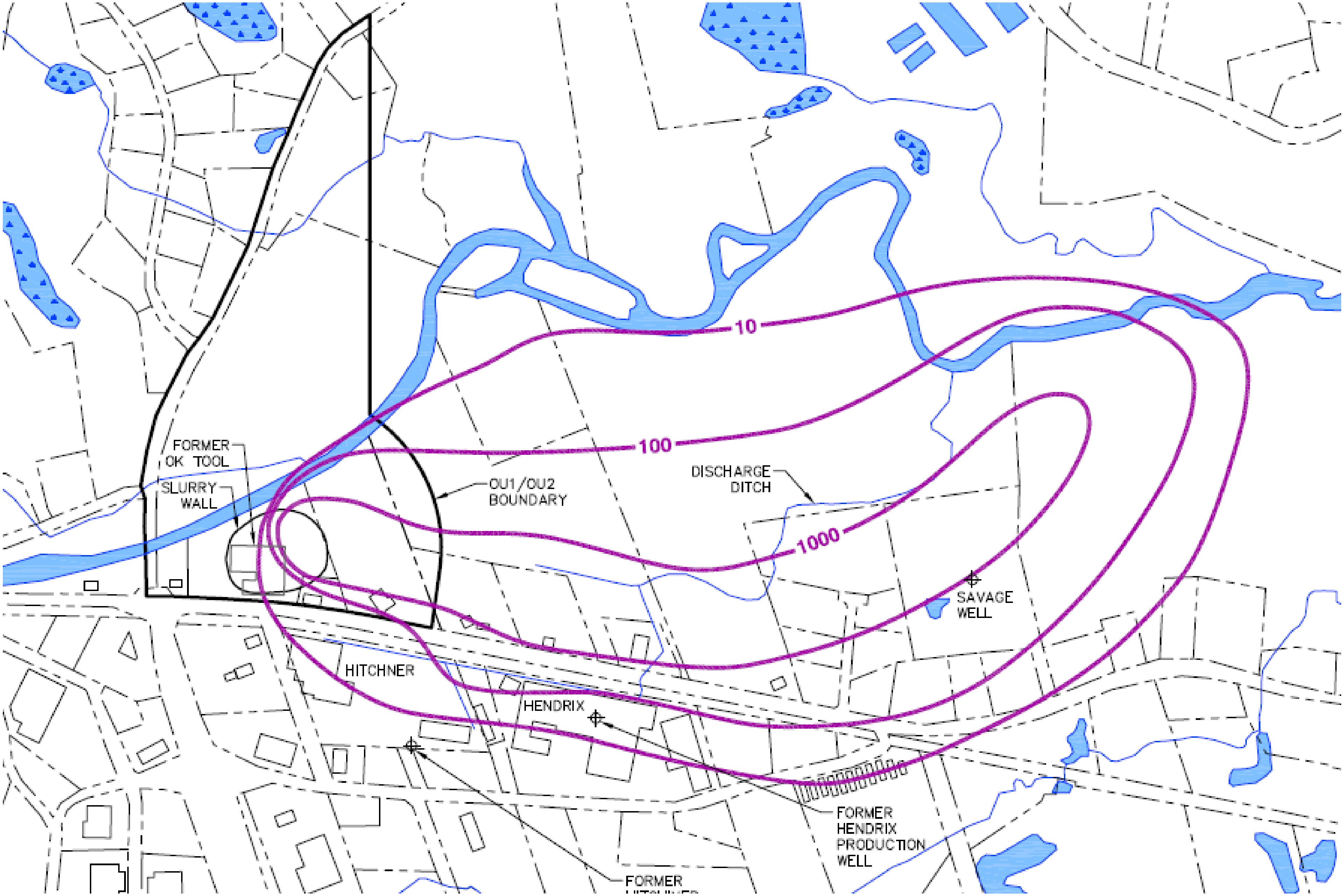
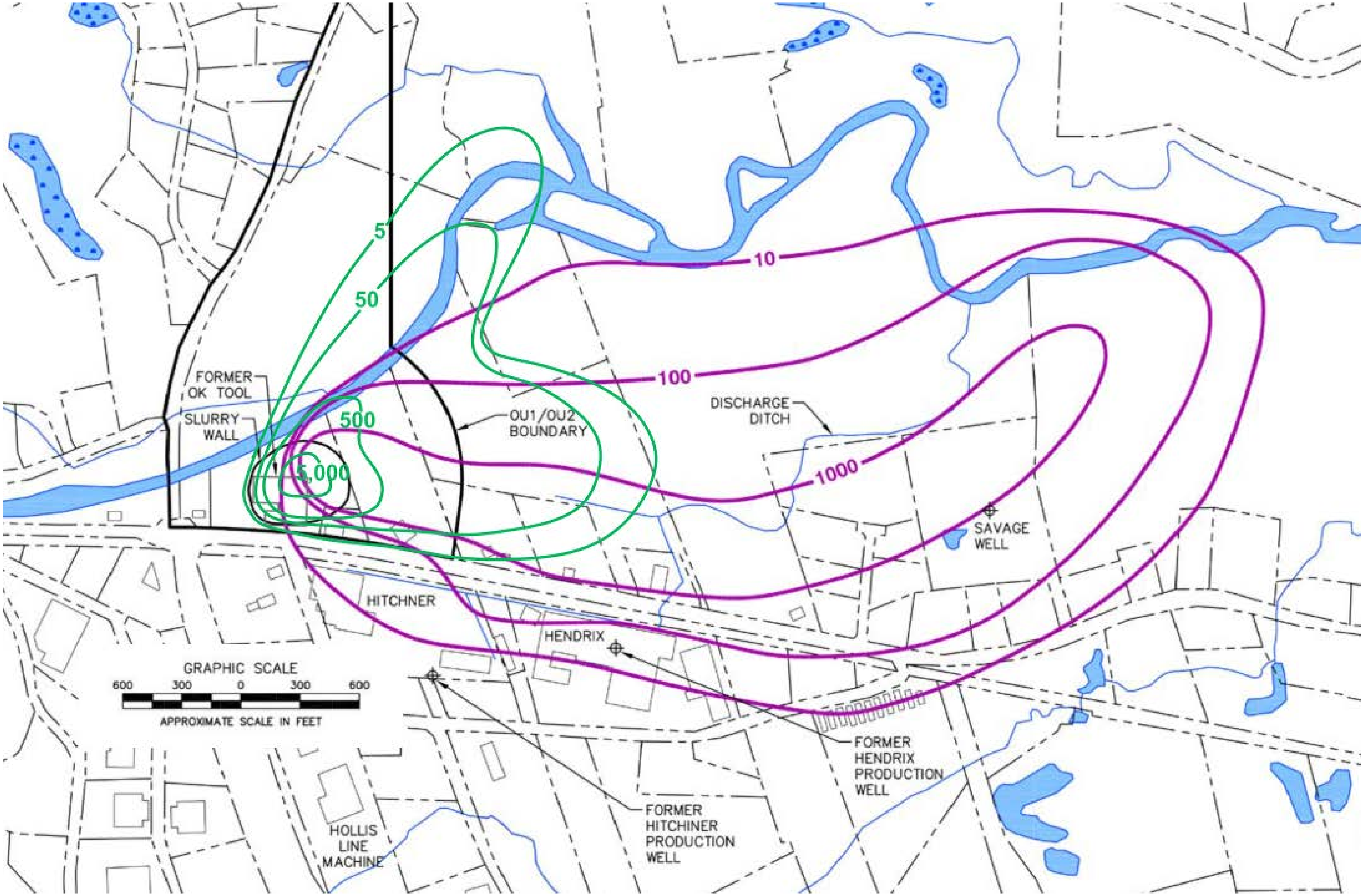


Deep Bedrock PCE Plume
(greater than 150ft below bedrock surface – in green)



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Pumping Test

Pumping well (BR-6) 600 ft deep, 500 ft open borehole in rock

9.5 gallons per minute sustained yield

10-day (228-hour) duration

7 frac tanks/~130,000 gallons

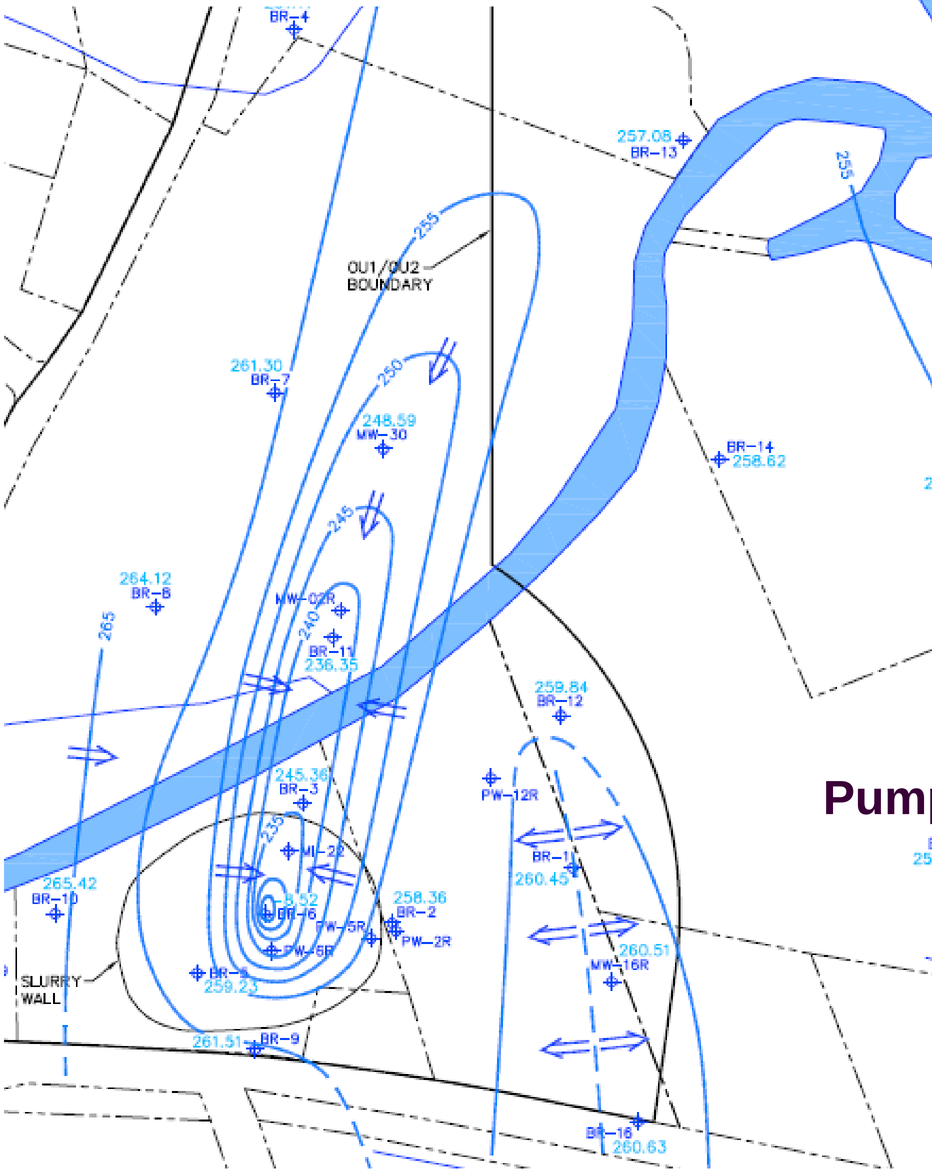
Water level monitoring in 37 bedrock and overburden wells

Heat pulse flow meter (HPFM) monitoring in 11 bedrock wells

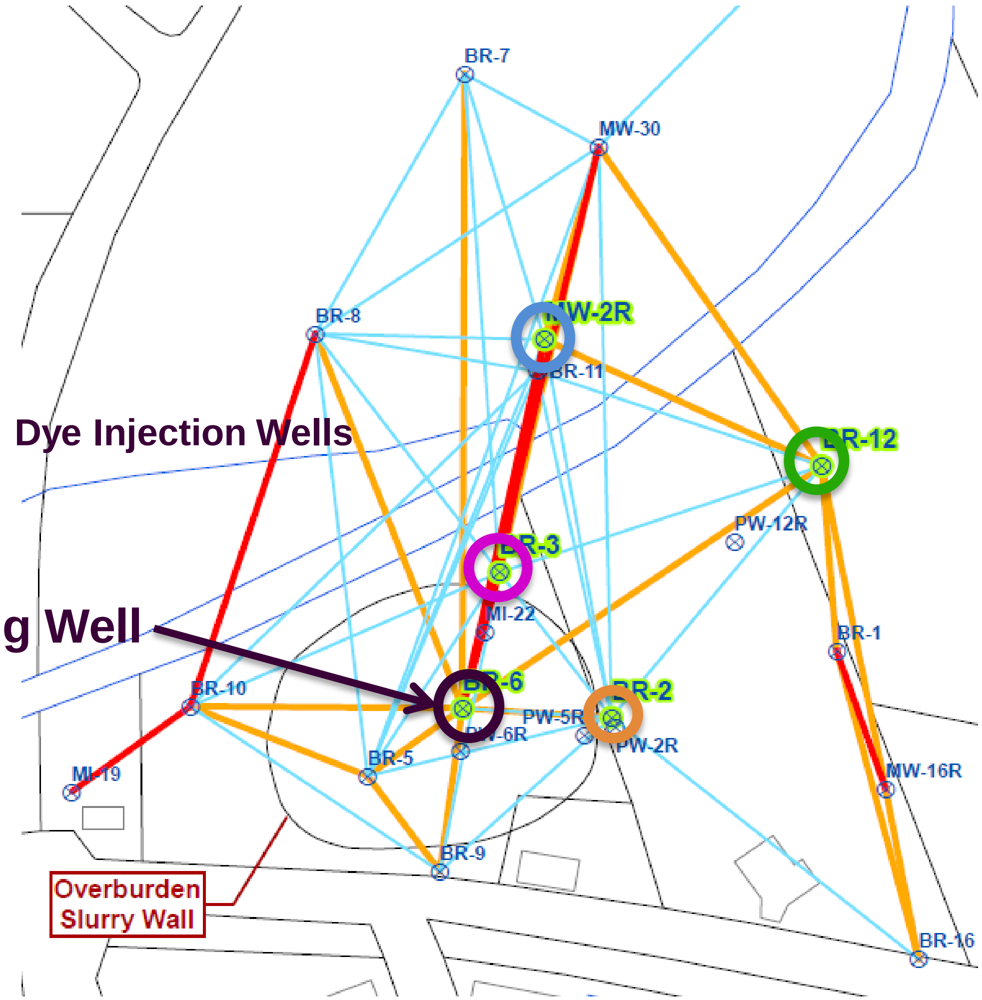
USGS Single Borehole Dilution Testing (SBDT) in 7 wells

Drawdown at end of Pumping Test

Potentiometric surface at hour 228



Interconnections between bedrock wells based on water level responses during drilling, packer sampling, and pumping



Dye Selection

Requirements

- Fluoresce at distinct characteristic wavelengths
- Non-toxic
- Low detection limits
- No interference with USGS SBDT

Dyes Selected:

- Fluorecein – 2 lbs / 2.5 gal
- Eosin – 1 lbs / 2.5 gal
- Rhodamine WT – 128 fl oz
- Tinopal – 1 lbs / 2.5 gal

Suppliers

- Crawford Hydrology
- Cole-Parmer

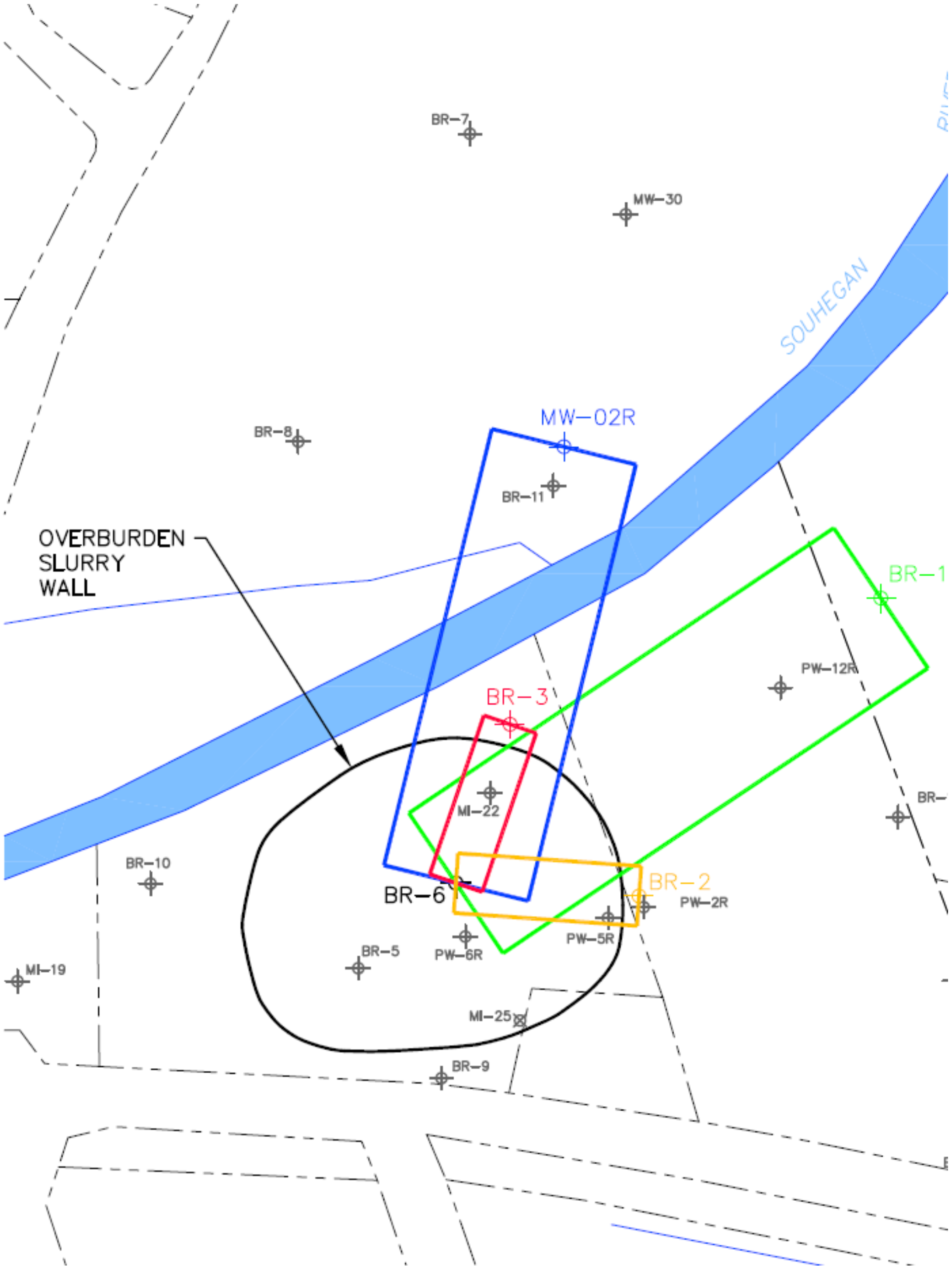
Calculation of Mass of Dye to Inject

Estimated distribution area/volume

- Thickness = length of open boreholes (~400 ft)
- Length = distance between injection well and pumping well
- Width = assumed to be 1/3 of Length

Assumed porosity of bedrock = 0.02 (conservatively high estimate)

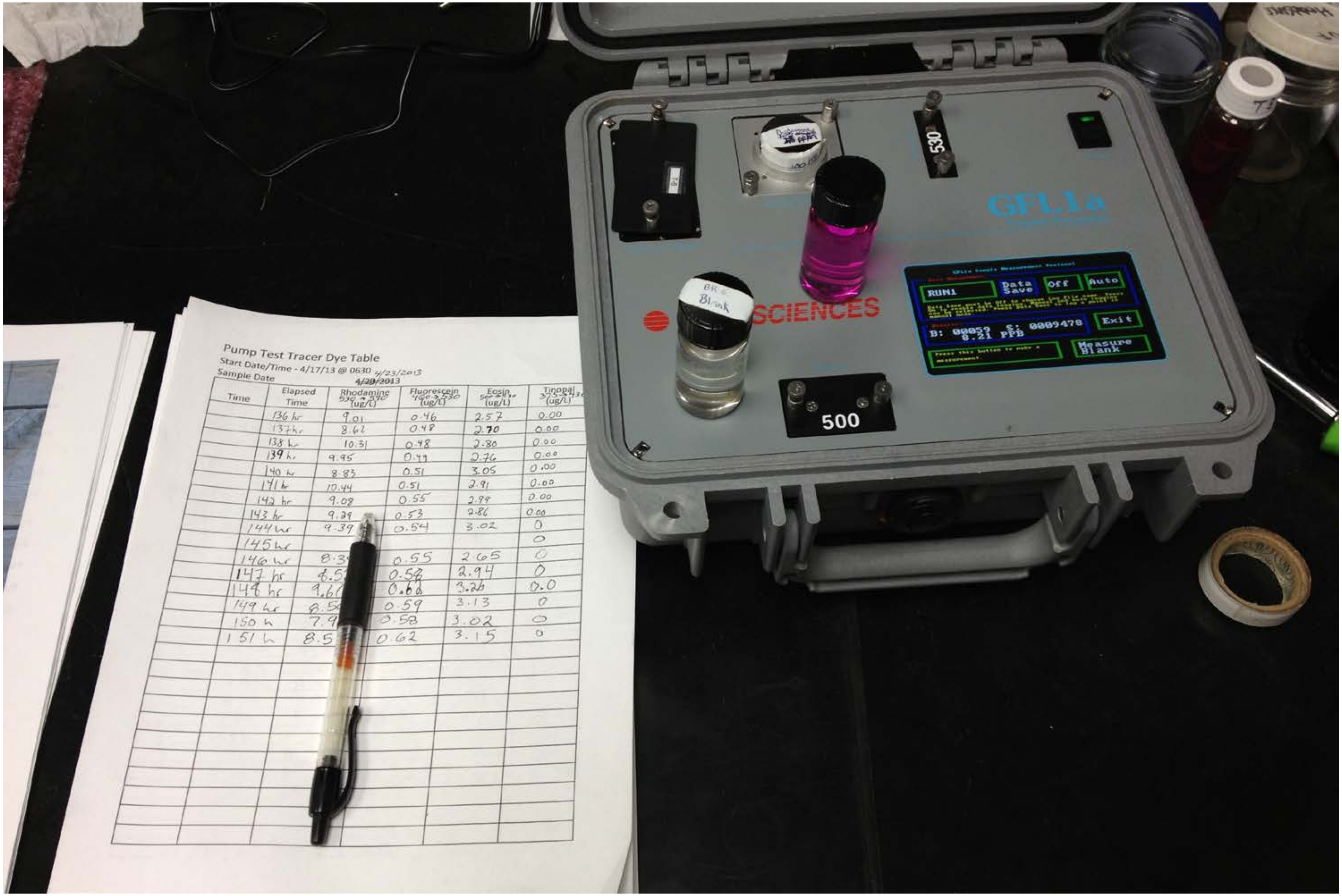
Assumed dyes would be evenly distributed throughout distribution area



Mass of Dye Injected into Each Well

Dye Injection Well	Distance from Pumping Well (ft)	Approximate Open Borehole Length (ft)	Estimated Distribution Area Bedrock Volume (ft^3)	Type of Dye Injected	Mass of Dye Injected (lbs)	Predicted Concentration of Dye at Pumping Well (ug/L)	Detection Limit of Dye (ug/L)
BR-2	270	400	4,860,000	Eosin	1.00	165	0.010
BR-3	230	400	3,526,667	Rhodamine WT	0.21	48	0.006
BR-12	720	400	34,560,000	Fluoroscein	2.00	93	0.002
MW-2R	630	400	26,460,000	Tinopal	1.00	31	0.010

Opti-Sciences GFL-1a Fluorometer



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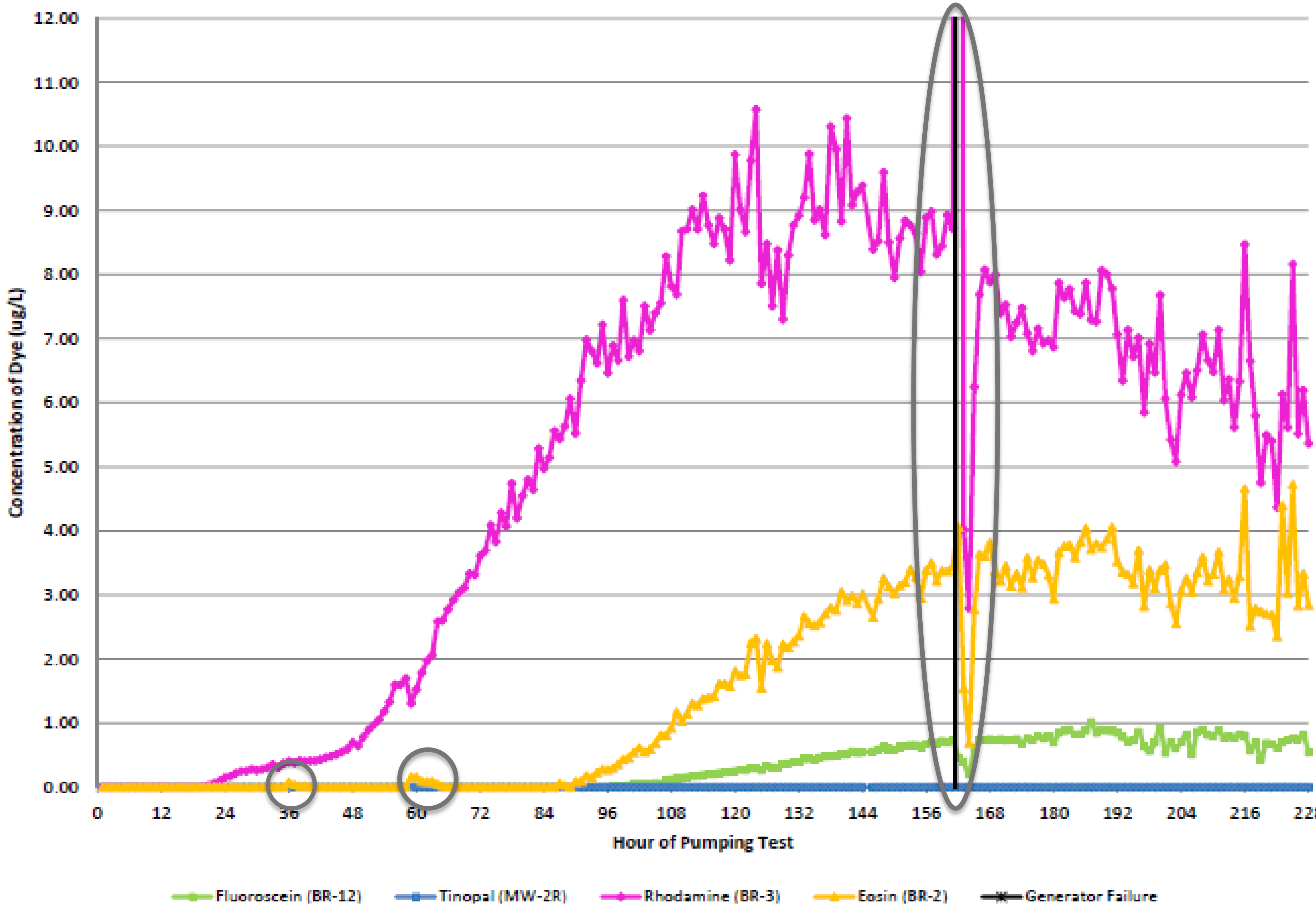
Surprises, Interferences, and Uncertainties

24 hours into the pumping test, $NaMnO_4$ from ISCO in the overburden was drawn into pumping well

- $NaMnO_4$ destroys Tinopal instantaneously
- $NaMnO_4$ reacts with other dyes, slowly decreasing concentrations
- Length of time dyes reacted with permanganate in subsurface was unknown.

Rhodamine WT decayed in samples overnight and a portion fluoresced at Eosine wavelength

Tracer Dye Results



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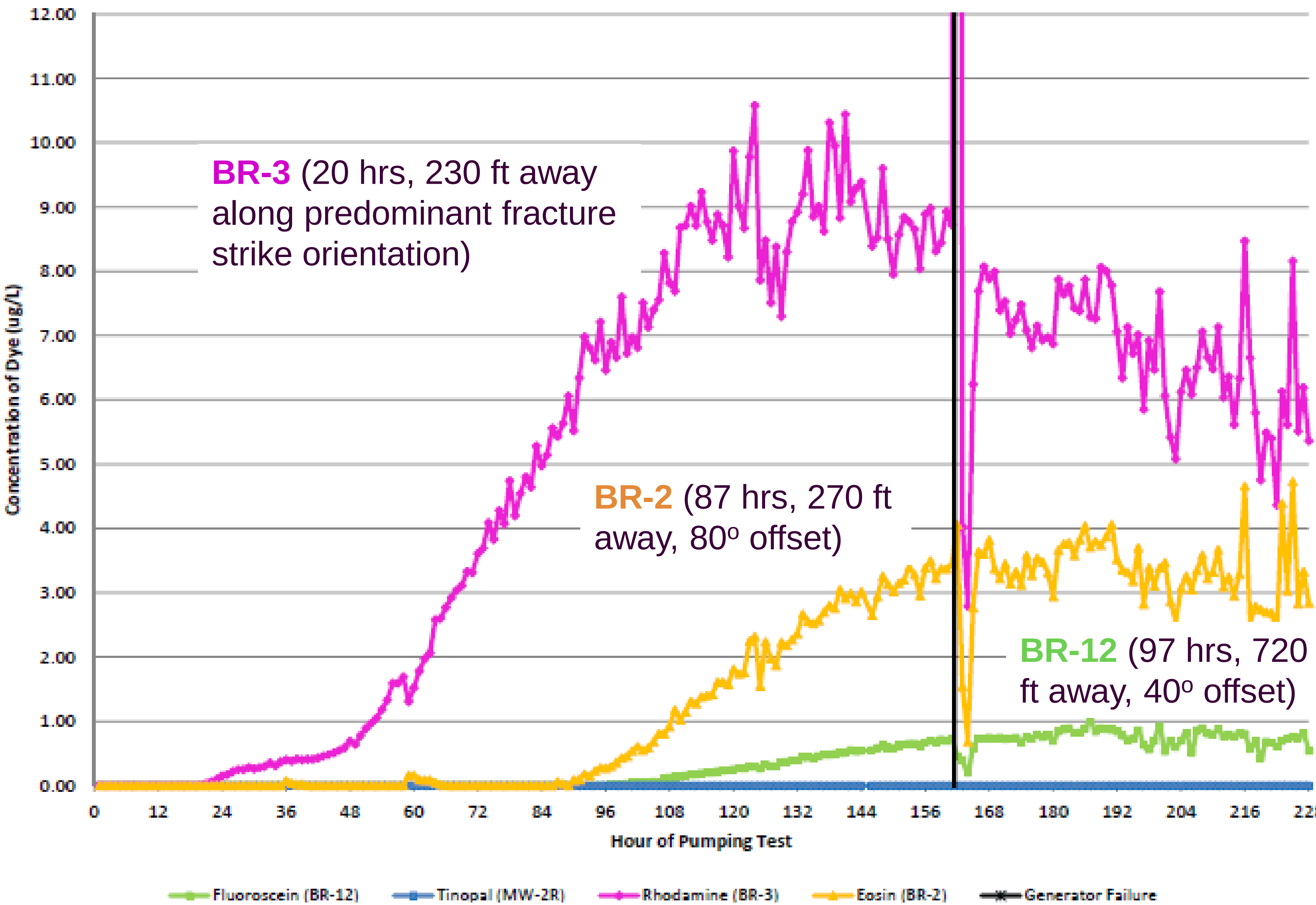
Tracer Dye Results



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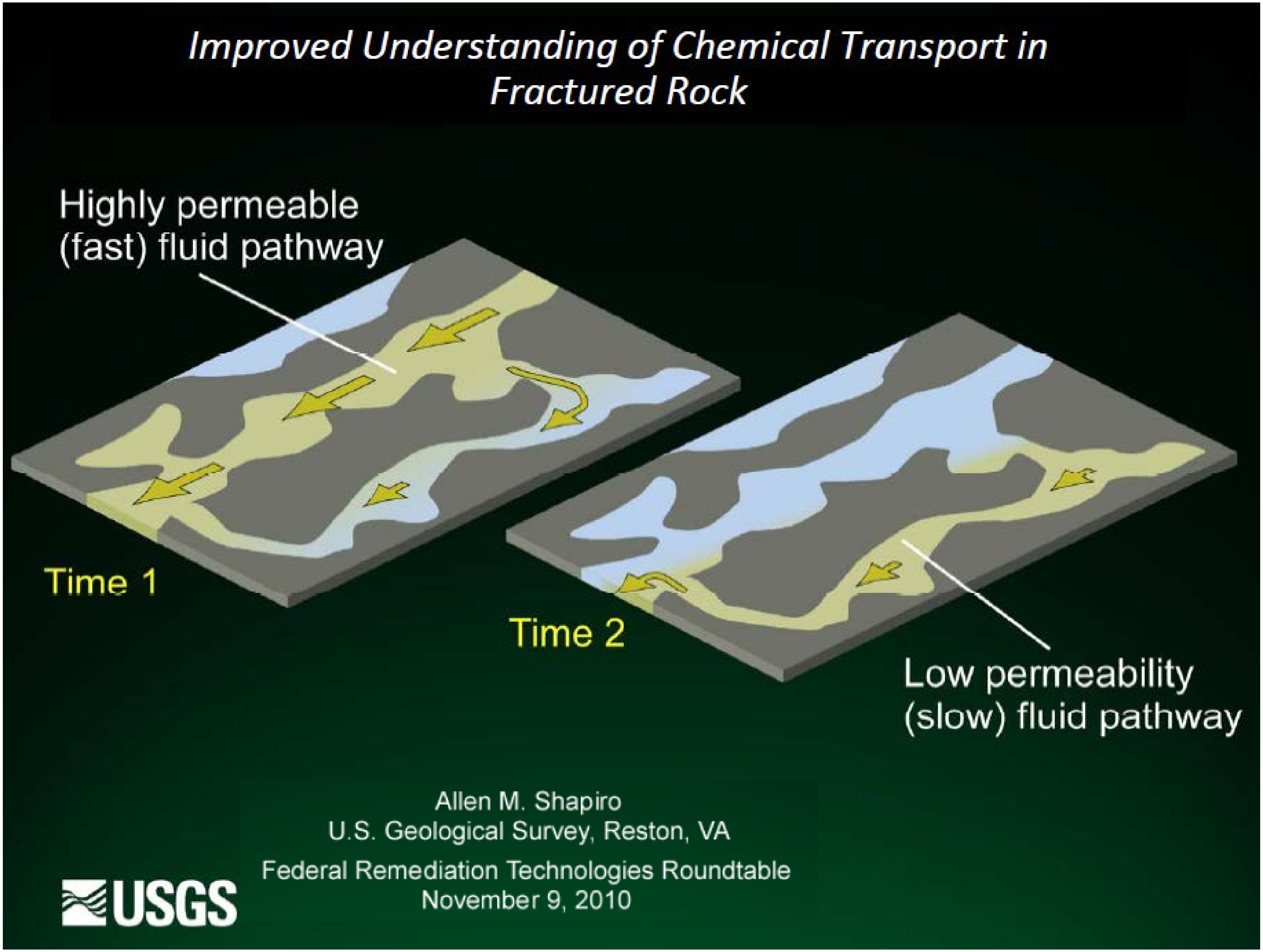
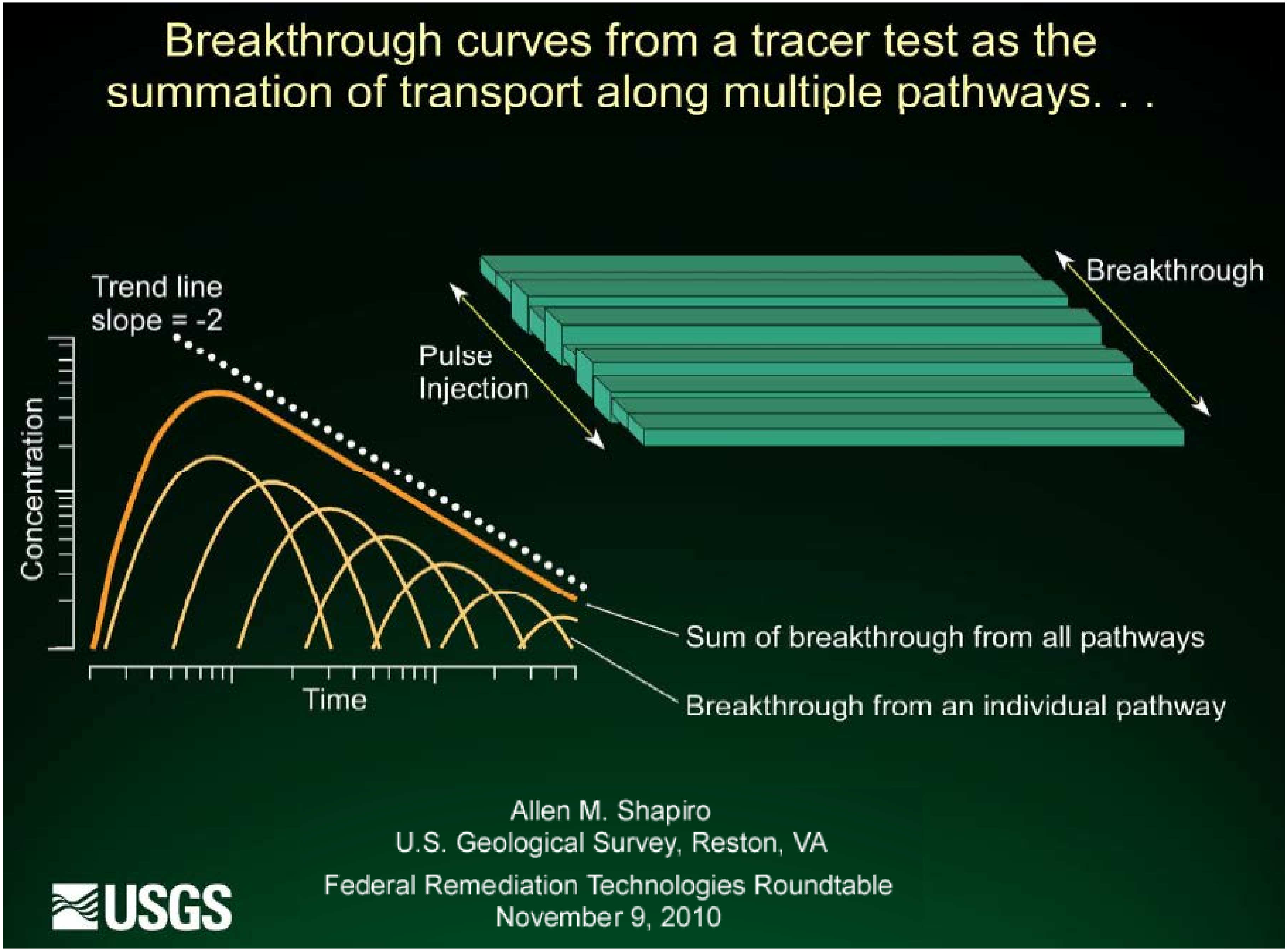
Shapiro Conceptual Model



Shapiro Conceptual Model

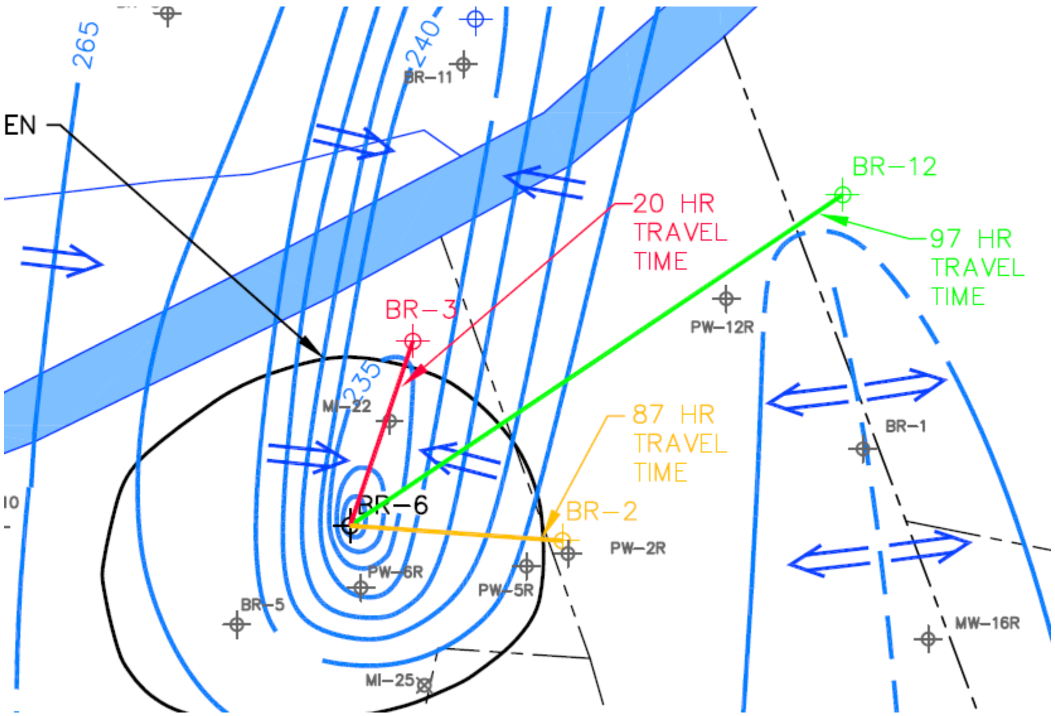


Summary of Results

Dye Injection Well	Dye Injected	Peak Concentration of Dye Detected at Pumping Well (ug/L)	Hours into Pumping Test when Dye First Detected	Observed Rate of Travel during Pumping Test (ft/hr)	Direction of Flow	Notes
BR-2	Eosin	4.73	87	3.10	Approx. 80º Off Predominant Strike Orientation	Detection of Eosin may have been delayed, and detected concentrations decreased, by reaction with permanganate.
BR-3	Rhodamine	10.58	20	11.50	Along Predominant Strike Orientation	Detection of Rhodamine may have been delayed, and detected concentrations decreased, by reaction with permanganate.
BR-12	Fluoroscein	1.01	97	7.42	Approx. 40º Off Predominant Strike Orientation	Detection of Fluoroscein may have been delayed, and detected concentrations decreased, by reaction with permanganate.
MW-2R	Tinopal	0.00	Not Detected	N/A	Along Predominant Strike Orientation	Permanganate drawn down from overburden during pumping test reacted with, and destroyed, Tinopal.

Dye Travel Rates and Borehole Flow Rates

Dye Injection Well	Dye Travel Rate (ft/hr)	HPFM Borehole Flow Rate (gpm)
BR-2	3.10	-0.080
BR-3	11.50	-0.310
BR-12	7.42	NA



Travel rate from **BR-3 to BR-6** was **3.7** times faster than from **BR-2 to BR-6**

Borehole flow in **BR-3** was **3.9** times higher than in **BR-2**

Higher borehole flow rate seems to correlate with faster dye travel rate

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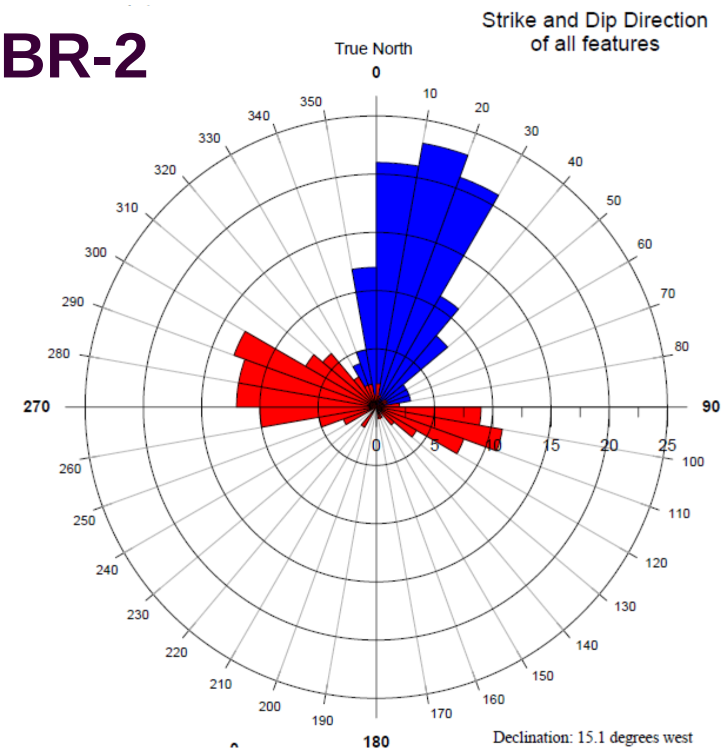
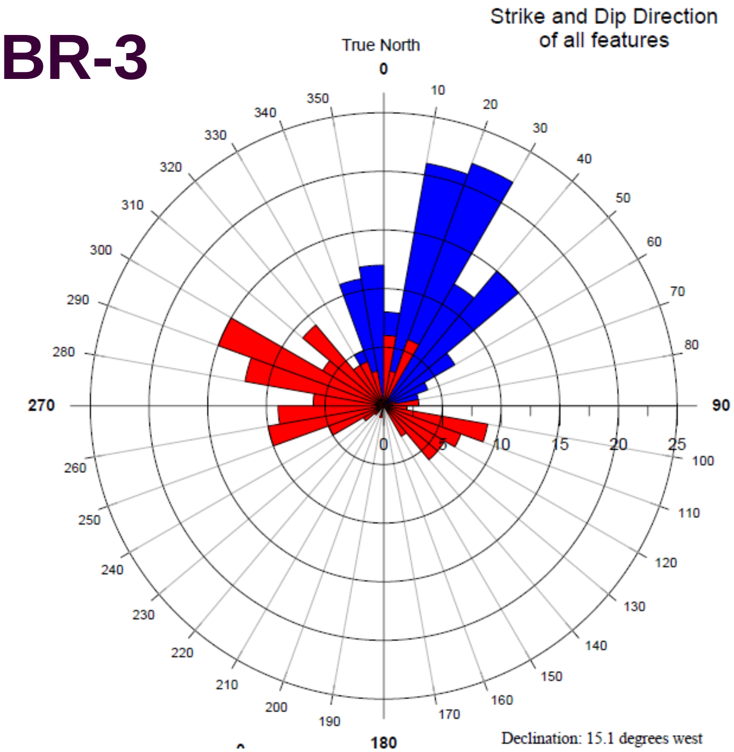
BR-2/BR-3 Fracture Orientations & Transmissivities

BR-2



BR-3



Monitoring Well	Sample Interval (ft btoc)	Dip Direction/Angle	Transmissivity (ft^2/day)
BR-2	158-169 ft	W 50º	0.006
	189-200 ft	SE 75º	0.006
	215-226 ft	SE 80º	0.182
	256-267 ft	SE 55º	3.427
	285-296 ft	ESE 65º	3.795
	339-350 ft	NW 30º	0.012
	387-398 ft	NW 80º	0.314

Monitoring Well	Sample Interval (ft btoc)	Dip Direction/Angle	Transmissivity (ft^2/day)
BR-3	133-144 ft	SE 75º	0.113
	174-185 ft	SSW 39º	0.019
	212-223 ft	NW 75º	0.080
	267-278 ft	WNW 75º	0.033
	330-341 ft	SW 59º	0.040
	348-359 ft	NW 77º/NW 55º/W 47º/SSE 76º/SSE 58º	0.215
	350-361 ft		0.043
	374-385 ft	SE 72º	0.020
	475-486 ft	E 61º/W 88º/SW 45º	0.020

Conclusions

Bedrock groundwater flow direction and dye transport rates were strongly influenced by the fracture fabric of the bedrock.

Bedrock ***anisotropy*** was observed in:

- ***Interconnections*** between monitoring wells
- Elongated ***drawdown*** during pumping test
- Predominant ***fracture strike*** orientation in borehole geophysics.
- Tracer dye ***transport rates***.

Tracer dyes traveled ***fastest along*** predominant fracture ***strike*** alignment. The ***greater the angular off-set, the slower*** the travel rate.

Borehole flow rates correlated with the tracer dye travel rates, i.e. the ***more flow through*** the ***borehole***, the ***faster the dye travel rate*** from the well.

Tracer dye ***breakthrough curves*** generally followed Shapiro's conceptual model for summation of transport along ***multiple pathways*** in fractured rock.

Thank you.

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