Ground Water Remedial Investigation Bedrock Characterization

Andrew Michalski
Michalski and Associates, Inc.

WHAT'S INCLUDED IN THE BEDROCK TECHNICAL GUIDANCE?

CONCEPTUAL GW FLOW MODELS FOR BEDROCK SITES ⟷ BEDROCK CHARACTERIZATION TOOLS

- POROUS MEDIUM
- DISCRETE FRACTURE
- HYBRID MODELS

FLOW-SENSITIVE CHARACTERIZATION TOOLS ARE NEEDED.

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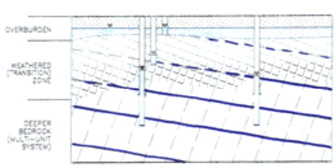
GENERIC CONCEPTUAL MODEL FOR THE NEWARK BASIN & SEDIMENTARY BEDROCK SITES



LMAS MODEL WITH WEATHERED ZONE & SATURATED OVERBURDEN (Michalski, 1990)

- Few dipping bedding fractures with larger apertures act as discrete aquifers (high T, low S) and preferential flow pathways.
- Such aquifer units occur at uneven intervals and tend to lose their aquifer properties updip and downdip of their prime extent areas.

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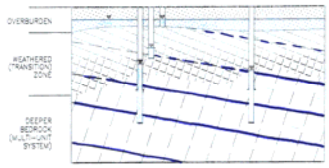
GENERIC CONCEPTUAL MODEL
FOR THE NEWARK BASIN & SEDIMENTARY BEDROCK SITES



- The gw flow is bedding-parallel, with prevailing flow direction along the strike of bedding;
- Sub-vertical joints provide pathways for leakage between the bedding fractures. Note: Thick aquitard units have complex structure and flow;

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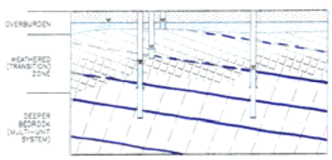

- The weathered bedrock zone typically exhibit higher porosity/storage (S) but reduced permeability (K). Up-dip extensions of the bedding fractures into the weathered zone connect this zone and the overburden (if present) with the multiunit bedrock;

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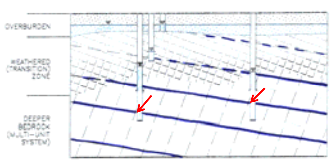

THE TWO DEEPER WELLS, COMPLETED TO THE SAME DEPTH, ARE OPEN TO DIFFERENT DIPPING AQUIFER UNITS. INCORRECT GW FLOW DIRECTION IS OBTAINED FROM WATER LEVELS TAKEN IN SUCH WELLS.

ONLY WELLS COMPLETED INTO THE SAME AQUIFER UNIT SHOULD BE USED TO DETERMINE HORIZONTAL GW FLOW DIRECTION.

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Characterization Needs
FOR A LEAKY, MULTIUNIT BEDROCK

1. **Identify** major transmissive bedding fractures (aquifer units) and the intervening aquitards.
2. For each aquifer unit of interest, **determine**:
   - Hydraulic heads (water levels, vertical and horizontal gradients);
   - Contaminant concentrations (delineation), and
   - Hydraulic parameters T and -if needed - S.
3. **Assess** flow disturbance caused by nearby supply wells and open-hole segments of existing monitoring wells.

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HOW TO IDENTIFY TRANSMISSIVE BEDROCK FRACTURES?

✓ OUT OF HUNDREDS OF FRACTURES OBSERVED IN CORES OR OUTCROPS – VERY FEW ARE HYDRAULICALLY ACTIVE, SO VISUAL METHODS WILL NOT SUFFICE.

✓ INSTALLATION OF TEMPORARY TEST HOLES (TTH) WITH LONG OPEN HOLES CREATES HYDRAULIC SHORT-CIRCUITING OF TRANSMISSIVE FRACTURES. IT REVEALS LOCATIONS OF SUCH FRACTURES AND OFFERS THE MOST RELIABLE MEANS OF THEIR IDENTIFICATION AND CHARACTERIZATION.

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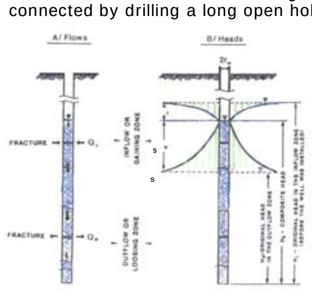
HYDRAULICS OF VERTICAL CROSS-FLOWS WITHIN A LONG OPEN HOLE

Consider two transmissive bedding fractures are cross-connected by drilling a long open hole.



SOURCE: MICHALSKI & KLEPP, 1990

$$Q_{IN} = Q_{OUT}$$

$$s_i = H_i - H_c$$

$$s_o = H_o - H_c$$

$$Q_i = \frac{2\pi T_i s_i}{\ln\left(\frac{R}{r_w}\right)} \qquad Q_o = \frac{2\pi T_o s_o}{\ln\left(\frac{R}{r_w}\right)}$$

$$H_c = \frac{H_i T_i + H_o T_o}{T_i + T_o}$$

$$\frac{s_i}{s_o} = \frac{T_o}{T_i}$$

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TESTING MENU FOR TTHs

- BOREHOLE GEOPHYSICS
- VERTICAL FLOW MEASUREMENTS
- DEPTH-DISCRETE SAMPLING
- PACKER TESTING

Best results in conjunction with air-rotary drilling of TTHs (observation of dust suppression depth, water producing fractures, logging of cuttings, penetration rate, etc.)

Wet drilling methods –use of foreign water - may impact the testing results.

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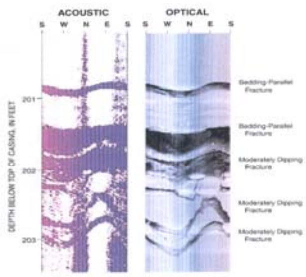
BOREHOLE GEOPHYSICS: BOREHOLE IMAGING



SOURCE: WILLIAMS, 2002; Fig 6

Figure 6. Acoustic- and optical-televiewer images of the flow zone near 201 feet in borehole RD-35B, Rocketdyne Santa Susana Field Laboratory, Ventura County, California.

- SUBSTITUTE FOR CORING
- FRACTURE ORIENTATION
- AID IN CORELATION

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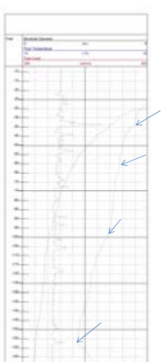
BOREHOLE GEOPHYSICS: FLUID EC, T & CALIPER LOGS



- Indentations on fluid EC and T logs point to possible locations of hydraulically active fractures.
- Enlarged hole diameter on the caliper logs identifies weak or fractured strata. Relevant for flowmeter data and the placement of packers.

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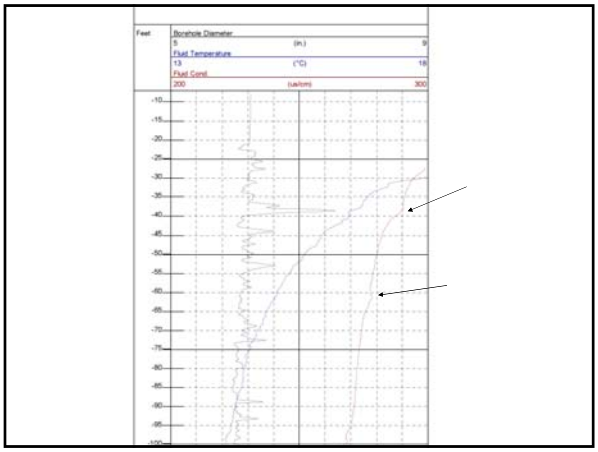
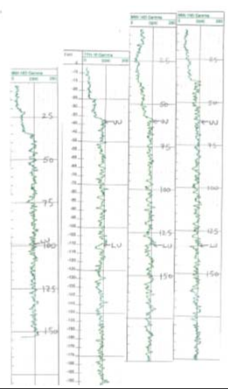


BOREHOLE GEOPHYSICS: GAMMA LOG



USEFUL FOR STRATIGRAPHIC CORRELATIONS BETWEEN TTHs AND STRIKE & DIP DETERMINATION

STANDARD LOGGING SUIT ALSO INCLUDE SP AND RESISTIVITY LOGS.

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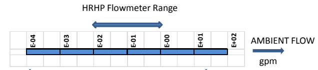
VERTICAL FLOW MEASUREMENTS
Critical Characterization Aspect

FLOWMETERS
Need to use a high-resolution heat-pulse(HRHP) flowmeter with a flow diverter (shroud) to achieve the claimed lower measurement range of 0.02 gpm. Some commercial flowmeters measure flows >0.4 gpm, and would not detect vertical flows in the majority of open holes.

SALT TRACING
Described in APPENDIX B



FLOWMETERS MEASURE INSTANT FLOW AT DISCRETE LOCATIONS WITHIN AN OPEN HOLE WHILE SALT TRACING PROVIDES CONTINUOS FLOW MEASUREMENTS OVER LONGER TIMES.

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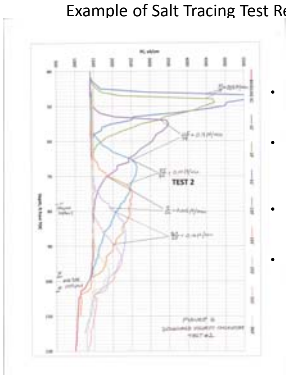
VERTICAL FLOW MEASUREMENT VIA SALT TRACING

Example of Salt Tracing Test Record and Interpretation



- Salt tracer solution was injected at 47 ft, and its first image was obtained with a downhole EC probe 10 min later (dark blue shape).
- A series of subsequent tracer images at various elapsed times shown reveals a downward tracer migration, and two major fracture inflows ~ 100 ft.
- Plotting the series of tracer images on one graph helps in tracer velocity calculations (shown in pencil).
- Flow = Velocity x Unit cross-sectional storage

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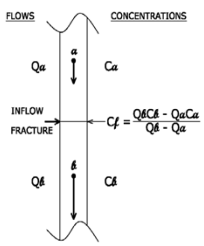
DEPTH-DISCRETE SAMPLING



1. COLLECT GRAB GW SAMPLES IN THE TTH ABOVE AND BELOW EACH INFLOW FRACTURE – NOT AT THE FRACTURE (MIXING ZONE);
2. CALCULATE CONTAMINANT CONCENTRATION IN EACH FRACTURE, BASED ON MEASURED FLOWS AND CONCENTRATIONS IN THE GRAB SAMPLES ABOVE AND BELOW.

Discussed in APPENDIX C

POWERFULL SCREENING TOOL TO QUICKLY ASSES VERTICAL CONTAMINANT DISTRIBUTION, IDENTIFY THE MOST CONTAMINATED FRACTURE AND CROSS-FLOW IMPACTS ON EXIT FRACTURE(S).

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EXAMPLE OF MEASURED AMBIENT FLOWS AND DEPTH-DISCRETE SAMPLING RESULTS.

ALSO SHOWN IS COMPARISON OF THE CALCULATED CONCENTRATIONS WITH SUBSEQUENT PACKER SAMPLING ANALYTICAL RESULTS

AMBIENT FLOW gpm		SAMPLE NO. and Depth	CT	CF	PCE	TCE	1,1DCE	
			CONTAMINANT CONCENTRTIONS					
	BOC @ 22.4							
	40' fracture							
	47' fracture							
0.20								
	62' fracture	PACKER 57'-67'	25	2.3	0.38J	3.4	0.35J	
0.18		GW-04 70'	160	14	ND(10)	14	ND(10)	
	94' fracture	PACKER 90'-100'	163	15.9	1.2J	8.9	1.3J	UNIT B
		Calculated Conc.	*182*	*16*		*15*		
0.027		GW-03 110'	38	3.2	1.3	11	1.1	
	120' fracture	PACKER 115'-125'	19	2	2	17	1.4	UNIT C
		Calculated Conc.	*55*	*4*	*2*	*13*		
0.01		GW-02 140'	9.8	1.1	0.55J	6.9	ND(1)	
	158' Fracture	PACKER 153'-163'	*NS*	*NS*	*NS*	*NS*	*NS*	
		GW-01 165'	10	1.2	0.39J	6.2	ND(1)	

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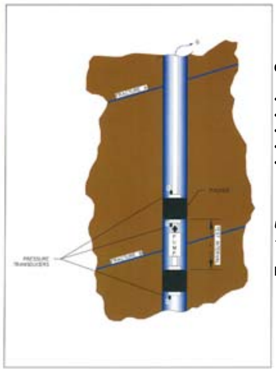
PACKER TESTING



CAPABILITIES:

- PACKER SAMPLING
- VERTICAL HEAD PROFILING
- TRANSMISSIVITY DETERMINATION
- LEAKAGE ASSESSMENT
- PUMPING TESTS WITH EXISTING WELLS USED AS OBSERVATION WELLS

UTILIZE ALL CHARACTERIZATION CAPABILITIES - NOT ONLY ROUTINE PACKER SAMPLING.

Packer tests discussed in APPENDIX D.

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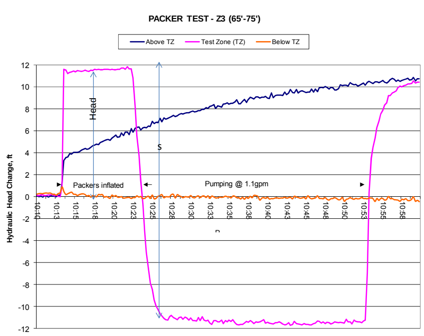
PACKER TESTING RECORD EXAMPLE FOR A TEST ZONE STRADDLING A MINOR BEDDING FRACTURE



$$T = \frac{Q\ln(L/r)}{2\pi s}$$

T – Transmissivity
Q – Pumping Rate
s - Drawdown
L – Test Interval Length
r – Hole Radius

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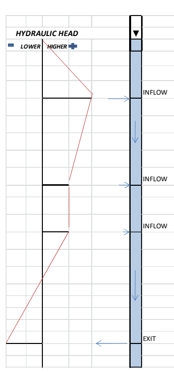
PACKER TESTING

VERTICAL HEAD PROFILE
FROM PACKER TESTS CONDUCTED IN A TTH



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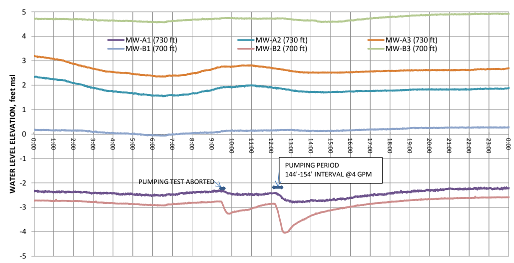
USE OF PACKER TESTING FOR INTERWELL PUMPING TESTS
RESPONSE OF OBSERVATION WELLS IN CLUSTERS "A" (730 ft away) & "B" (700 ft away) DURING A 24-HOUR PERIOD THAT INCLUDED PUMPING OF PACKER-ISOLATED BEDDING FRACTURE @ 149 ft IN A TTH



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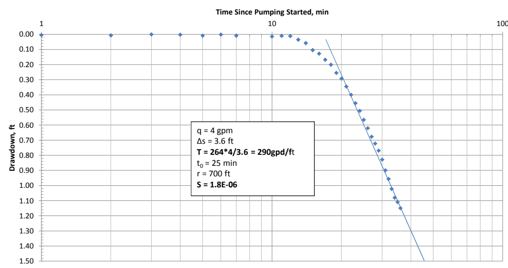
PACKER TESTING – INTERWELL PUMPING TESTS
RESPONSE OF OBS. WELL MW-B2 TO PACKER TEST PUMPING ANALYZED ON DRAWDOWN v.LOG OF TIME GRAPH



THIS VERIFIES THE CONTINUITY OF THE 149 FT FRACTURE AND THE OBS WELL AND ALLOWS FOR CALCULATION OF AQUIFER PARAMETERS FOR THIS FRACTURE (AQUIFER UNIT).

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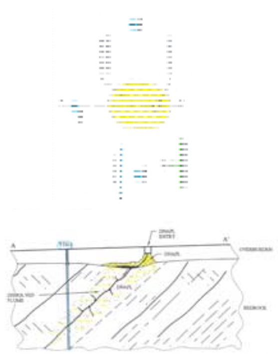
PLACEMENT OF TTHs
RELATIVE TO BEDROCK STRUCTURE AND SOURCE AREA AT NEW CONTAMINATED SITES



MINIUM OF THREE TEST HOLES NEEDED FOR AN INITIAL INVESTIGATION CONDUCTED IN OUTSIDE-IN FASHION:

1ST TTH IS PLACED UPGRADIENT OF THE SOURCE

2ND TTH IS DOWNGRADIENT AND ALONG STRIKE

3RD TTH, DOWN-DIP OF THE SOURCE, IS DRILLED TO A GREATER DEPTH THAN TTH-1 AND 2; SEE THE CROSS-SECTION.

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CONVERTING TTHs TO SHORT-SCREEN MWs

At the completion of the testing program, convert TTHs to MWs. Monitoring targets may include:

- Exit units/fractures
- Most contaminated
- Most transmissive

Once the bedrock hydrogeology is adequately characterized, installation of additional wells can be based on projections of monitoring targets. The projections require reliable determination of site-specific dip and strike.

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RE-EVALUATION OF CONTAMINATED SITES WITH EXISTING MONITORING WELLS

Needed for sites with excessive open-hole segments and sites with generic flow models that *de facto* ignore bedrock structure, including sites with horizontal slicing of dipping bedrock into the “shallow”, “intermediate”, and “deep” aquifers. Steps to re-evaluate such sites:

- Conduct supplemental testing in existing wells (borehole geophysics, or at least EC-T logging, salt tracing and depth-discrete sampling, if appropriate). Determine dip and strike of bedding.
- Prepare a cross-section projecting onto it open/screened well intervals and locations of identified conductive fractures (initial site hydrogeologic model).
- Identify data gaps, needs for additional wells and correcting well construction in problem wells.
- When adding new wells, consider at least one TTH with a comprehensive testing program.
- Demonstrate the continuity of aquifer units and the validity of the site model by observed responses to short-term pumping/hydraulic stresses.

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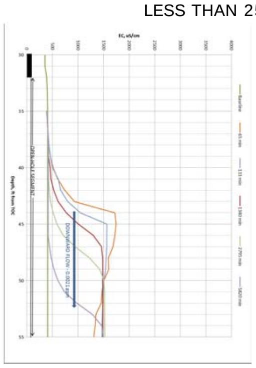
PREFERENCE FOR SHORT OPEN-HOLE SEGMENTS/WELL SCREENS LESS THAN 25 FT ALLOWED



- ✓ A short (10-15 ft) open-hole or screen should only straddle aquifer units. Avoid screen placement in vertical gradient zones, as exemplified by a MW on the left.
- ✓ V. slow downward flow was measured via salt tracing in this 23-ft long open hole in weathered bedrock: 0.0021gpm=3gpd=90gal/quarter

GW quality in this well was controlled by clean inflow (ND) from the upper well portion. Low-flow sampling was unable to detect contamination present in the receiving zone at the bottom.

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