ADVANCES IN APPLIED HYDROGEOLOGY OF THE NEWARK BASIN

2024 Conference proceedings for the 40th Annual Meeting of the Geological Association of New Jersey

Evolving Conceptual Site Models, Characterization Techniques & Remediation to Meet 21st-Century Challenges

October 18th & 19th 2024

Edited by James L. Peterson, PG, LSRP
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Field Guides and Proceedings of Prior Annual Meetings

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2015 XXXII Neotectonics of the New York Recess, Gregory Herman and Suzanne Macaoay Ferguson

2014 XXXI Global Environmental Issues and Local Consequences: Earth Processes and Urban Environmental Quality, Nurdan Duzgoren-Aydin

2013 XXX Igneous Processes During the Assembly and Break-up of Pangaea: Northern New Jersey and New York City, Alan Benimoff

2012 XXIX Geology and Public Lands, Jane Alexander

2011 XXIII Environmental Geology of Central New Jersey, Emma Rainforth and Alan Uminski

2010 XXVII Geology of the Greater Trenton Area and Its Impact on the Capital City, Pierre Lacombe

2009 XXVI New Jersey Coastal Plain Stratigraphy and Coastal Processes, Deborah Freile

2008 XXV Environmental and Engineering Geology of Northeastern New Jersey, Matthew Gorring

2007 XXIV Contributions to the Paleontology of New Jersey 2, Emma Rainforth

2006 XXIII Environmental Geology of the Highlands, Suzanne Macaoay and William Montgomery

2005 XXII Newark Basin - View from the 21st Century, Alexander Gates

2004 XXI Proterozoic, Paleozoic, and Mesozoic Mafic Intrusions of Northern New Jersey and Southeastern New York, John Puffer and Richard Volkert

2003 XX Periglacial Features of Southern New Jersey and Adjacent Areas, Michael Hozik and Mark Mihalsky

2002 XIX Geology of the Delaware Water Gap Area, Dana D'Amato

2001 XVIII Geology in the Service of Public Health, Pierre Lacombe and Gregory Herman

2000 XVII Glacial Geology of New Jersey, David Harper and Fred Goldstein

1999 XVI New Jersey Beaches and Coastal Processes from Geologic and Environmental Perspectives, John Puffer

1998 XV The Economic Geology of Central New Jersey, John Puffer

1997 XIV The Economic Geology of Northern New Jersey, Alan Benimoff and John Puffer

1996 XIII Karst Geology of New Jersey and Vicinity, Richard Dalton and James Brown

1995 XII Contributions to the Paleontology of New Jersey 1, John Baker

1994 XI Geology of Staten Island, Alan Benimoff

1993 X Geologic Traverse Across the Precambrian Rocks of the New Jersey Highlands, John Puffer

1992 IX Environmental Geology of the Raritan River Basin, Gail Ashley and Susan Halsey

1991 VIII Evolution and Assembly of the Pennsylvania-Delaware Piedmont, Maria and William Crawford

1990 VII Aspects of Groundwater in New Jersey, James Brown and Richard Kroll

1989 VI Paleozoic Geology of the Kittatinny Valley and Southwest Highlands Area, New Jersey, Irvin Grossman

1988 V Geology of the Central Newark Basin, Jonathan Husch and Michael Hozik

1987 IV Paleontology and Stratigraphy of Lower Paleozoic Deposits of the Delaware Water Gap, William Gallagher

1986 III Geology of the New Jersey Highlands and Radon in New Jersey, Jonathan Husch and Fred Goldstein

1985 II Geological Investigation of the Coastal Plain of Southern New Jersey, Ray Talkington and Claude Epstein

1984 I Igneous Rocks of the Newark Basin: Petrology, Mineralogy, and Ore Deposits, John Puffer

In Memory of Howard (Howie) Parish

James O. Brown

Howard (Howie) Parish, former president of GANJ, passed away in January 2024 in Florida. Howie's technical background in geology focused on Geomorphology, notably Coastal Geology, which served him well as a Trustee of the NJ Sea Grant Consortium. In general, Howie's significant contributions to New Jersey geology were mainly achieved via his skill as an administrator working with academic and professional organizations.

Howie's ability as an administrator was especially important in what might be termed the second phase of GANJ, where the organization's founders began to transfer leadership to others in the early 1990's. As president of GANJ, he coordinated the first out-of-state GANJ meeting, led by Maria and William Crawford (1991). While the technical aspects of the field trip were done by the Crawfords, Howie directly or indirectly coordinated the meeting's logistics of hotel, buses, food, guidebook, and registration. As the new Treasurer of GANJ involved with both regular finances and getting federal non-profit status, I greatly appreciated Howie's insights and help.

Besides "logistics", Howie had a gift for "pushing" people in a positive way. As the long-time chair of the now defunct geology department at Jersey City State College (now New Jersey City University), it seemed for a decade that a third of one of GANJ's annual field trip buses was filled with NJSC students and faculty whether or not Howie was in attendance.

As a personal example I would not have a Ph.D. today if not for his mentorship. He "pushed" me by giving carte blanche access to the NJSC geology department's facilities where I could do my lab research. He introduced me to the late Barry Perlmutter of his faculty who would serve on my doctoral committee, although I was in the Graduate Program at City University of New York. (This was a subtle way for Howie to also "push" Barry into more research.)

In retirement, Howie was a snow-bird between Florida and New Jersey. He was still quite active with a number of geologic and non-geologic organizations: the NJ Sea Grant Consortium and Rotary Club in Jersey City being examples of each. Over the last few years, he and I would get together for lunch, and I still received wonderful insights from him. I'm happy to say we met in the Fall of 2023 just before his final trip to Florida.

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COASTodian. Winter 2024. New Jersey Sea Grant Consortium Mourns the Loss of Two Pivotal Members, p. 7.

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Orland, Max. 2024. Obituaries: Howard Parish, Orland's Ewing Memorial Chapel, https://orlandsmemorialchapel.com/howard-parish.

Jim Brown, Ph.D. CUNY 2001, is a past Treasurer and two-time former president of GANJ.

Table of Contents

Acronyms

ATV- Acoustic Televiewer

DCE- Dichloroethylene

DFN- Discrete Fracture Network

DNAPL-Dense Non-Aqueous Phase Liquid

FT- Feet

HPFM- Heat Pulse Flow Meter

LSRP - Licensed Site Remediation Professional

k- Hydraulic Conductivity

NJDEP – New Jersey Department of Environmental Protection

NJGS- New Jersey Geological & Water Survey

m- Meters

MLS- Multi Level Monitoring System

GW-Groundwater

OTV-Optical Televiewer

PCE- Tetrachloroethene

PFAS- Per- and Polyfluoroalkyl Substances

TCE- Trichloroethylene

USGS- United States Geological Survey

USEPA- United States Environmental Protection Agency

VC- Vinyl Chloride

VOC- Volatile Organic Compounds

XRF- X-ray Fluorescence

Schedule for Day 1 – Platform Presentations

8:00 AM Registration

8:30 AM Opening Remarks James L. Peterson

8:40 AM Session 1 - Keynote Jessica R. Meyer Using Existing DNAPL Contamination as a Tracer to Elucidate Aquitard Characteristics in a Layered Sandstone Aquifer System

9:25 AM Session 2 Andrew Michalski Choice of Conceptual Groundwater Flow Model as a Critical Issue for Characterization and Remediation of Contaminated Bedrock Sites in the Newark Basin

10:10 AM Session 3 Pierre Lacombe Hydrogeologic Framework at a Contamination Site based on Geologic, Offloading, and Weathering Strata Augmented with Water-quality and Water-level Data and Concepts

10:55 AM Break

11:10 AM Session 4 Thomas D. Gillespie Hydrostructural Geology: Examining the Anisotropy Assumption for Solute Distribution in Bedrock Aquifers

11:55 AM Session 5 Gregory C. Herman NJGS Bulletin 77 Summary of Fractured-Bedrock Aquifer Borehole Research in the Eastern Half of the Newark Basin

12:40 PM Lunch

1:40 PM Session 6 Rich Britton Utility of the LMAS Model to Resolve Responsibility for Off-Site Groundwater Contamination in Bedrock

2:25 PM Session 7 Paul Trudell Vertical Delineation of the Weathered Bedrock Geological and Hydrogeological Unit in Central New Jersey

3:10 PM Break

3:25 PM Session 8 Bob Bond Application of Environmental Sequence Stratigraphy to Sedimentary Bedrock Aquifers with Commingled and Co-located VOC and PFAS Plumes

4:10 PM Session 9 Grace Chen & John N. Dougherty Remediating Contaminated Bedrock Aquifer Using In Situ Bioremediation Technology

4:55 PM Closing Thoughts James L. Peterson

5:10 PM Business Meeting James L. Peterson

Schedule for Day 2 – Field Demonstrations

8:00 AM Bus Pickup at USGS

8:30 AM Registration

9:00 AM Field Demonstrations – Concurrent

Breakout Session 1 Timothy J. Hull
Borehole Geophysical Logging Techniques – Standard and Unique Investigative Tools

Breakout Session 2 Lee Slater
Advancing Hydrogeophysical Characterization of the Newark Basin: High Resolution Electrical Tomography Characterization of the Former Naval Air Warfare Center (NAWC) Site

Breakout Session 3 Pierre LaCombe & Alex Fiore
USGS Naval Air Warfare Center Fractured Bedrock Research Findings and Rock Core Review

Breakout Session 4 Valerie Holliday
Review of Core and Geophysical Logs from a Central NJ DNAPL Site

Breakout Session 5 Sean Kinney
Review of ongoing Research by Rutgers / LDOE Geological Core Laboratory Repository Scientists

12:00 PM Lunch

1:30 PM Field Demonstrations - Concurrent

Breakout Session 6 James L. Peterson
Correlation of Geophysical Logs—A Crucial and Underutilized Geological Skill

Breakout Session 7 John N. Dougherty
3-D Visualization of Hydrogeologic Models Using Leapfrog

Breakout Session 8 Gregory C. Herman, Timothy J. Hull, & Andrew Michalski
Single-Packer and Short-Term Pumping Testing to Evaluate Hydrostratigraphy of the Multi-Unit Bedrock Aquifer System at the Watershed Institute Wellfield

4:00 PM Take-Home Messages and Conclusion
Panel Discussion, Q&A

5:15 PM Bus Pickup at the Pond House

Introduction

James L. Peterson

The sedimentary and igneous rocks of the Newark Basin underlie much of the current and former industrial corridor in New Jersey, where many of the most complex and costly remediation projects overseen by LSRPs are located. Efforts to effectively remediate, or even to initially understand or eventually monitor, contaminant plumes in the Newark Basin rocks are sensitive to a number of factors. These include but are not limited to the dipping structure of the rock units; characteristics of transmissive fractures developed within the rocks; locations of natural and artificial recharge and discharge; historical and current presence of deep, open-borehole supply wells cross-connecting aquifer sub-units; and the near-ubiquity of sources of contamination.

In such a setting, the potential for mischaracterization is significant. Mischaracterization of sites can lead to futile remediation efforts; adoption of plumes from offsite sources; outstanding but unknown risks to receptors, financial resources of responsible parties and professional reputations of remediation practitioners; and other outcomes no stakeholder wishes to experience.

Many Newark Basin sites were formerly vacant or underutilized for decades and are now undergoing redevelopment. Along with this revitalization, and in response to other stimuli (e.g., SRRA Remediation Timeframes, need to assess Contaminants of Emerging Concern such as PFAS), efforts (both new and renewed) to remediate groundwater impact within Newark Basin rocks, and related sources, are increasing. As ever, LSRPs, and the experts whose work they may review and rely upon in the development of their independent professional judgment, must ground their work on fundamentally sound Conceptual Site Models (CSMs), investigative practices and interpretations.

Some stakeholders have remarked that the Leaky, Multi-Unit Aquifer System (LMAS) generic CSM and related investigative practices already embraced within NJDEP's groundwater guidance are either misunderstood or ignored, or simply unknown by many practitioners. Others have held that different CSMs and investigative approaches are scientifically supported but less-readily accepted by some practitioners or reviewers.

GANJ 2024 will bring together a special combination of research and consulting industry professionals (including several whose work is integral to the NJDEP groundwater guidance) for a 2-day exploration of current and emerging trends in the applied hydrogeology of the Newark Basin. The event will take place at the Stony Brook-Millstone Watershed Institute, in Pennington, Mercer County, NJ. Day 1 will consist of 9 lectures spanning subject matter ranging from fundamental scientific principles critical to CSM development; evolving CSMs and investigative practices; evaluation of the "weathered bedrock" zone; and remediation case studies, including one dealing with PFAS. Notably, Day 1 will include presentations by former New Jersey Geological Survey Geologist Gregory C. Herman discussing his fractured bedrock research and former USGS Geologist Pierre Lacombe, describing the development of a stratigraphy-based hydrogeologic framework.

Activities on Day 2 will include hydrogeologic field demonstrations at a radial wellfield in the Passaic Formation, installed on the site in the 1960s to support research by USGS to aid understanding of the apparent strike-parallel anisotropy of rocks then referred to as the Brunswick Formation. Day 2 will include demonstration of borehole geophysical logging, well interference testing and other field methods utilized to characterize complex subsurface flow systems in Newark Basin rocks. A presentation of how geophysical logs are correlated, to enable development of site-wide stratigraphic frameworks will be made. Day 2 will also include review of core and other data from the extensively studied USGS Naval Air Warfare Center (NAWC) site and one other well-characterized central NJ remediation site. Scientists from USGS will review findings of the NAWC studies, while researchers from Columbia and Rutgers Universities will present initial data of continuous X-Ray Fluorescence geochemistry from legacy Newark Basin cores and a High-Resolution Electrical Tomography study, respectively. Finally, a panel discussion will be convened for Q&A with presenters.

Attendees of GANJ 2024 will be exposed to a wide range of technical information directly relevant to, and in many cases critical to, the practice of site remediation within Newark Basin settings. There will be ample opportunity throughout both days for interactions with presenters and it is expected that all attendees will gain substantial new or refined understanding which they will apply to the improved protection of public safety, human health and the environment in New Jersey.

Proceedings XL (40) – Platform Presentations

1. Using Existing DNAPL Contamination as a Tracer to Elucidate Aquitard Characteristics in a Layered Sandstone Aquifer System

Jessica R. Meyer, PhD; University of Iowa

Aquitards are not typically the focus of hydrogeologic investigations because they are not water supply units. However, identification and characterization of aquitards is critical because they shape flow path trajectories, exert strong control on groundwater residence times, and protect adjacent aquifers from contamination. Much of the research specifically addressing aquitards and their integrity with respect to a variety of contaminants has focused on shallow clay units (e.g., Jørgensen and Fredericia, 1992; Hinsby et al., 1996; Jørgensen et al., 1998; O'Hara et al., 2000; Rodvang and Simpkins, 2001; Parker et al., 2004). In contrast, shallow sedimentary rock aquitards have received less attention. Identifying and characterizing aquitards in thick sandstone packages can be a challenging task. The difficulty arises, at least in part, because vertical hydraulic conductivity (K) contrasts can be subtle and are controlled by fracture network characteristics that are difficult to quantify. Several studies, including the one presented here, have identified aquitards in sedimentary rock sequences that are highly anisotropic with large K parallel to bedding and moderate to low K perpendicular to bedding (e.g., Eaton and Bradbury, 2003; Runkel et al., 2018). This has led to the descriptive term 'aquitardifer' (Anderson et al., 2011). This type of anisotropy may also be important to consider for the Mesozoic sedimentary rocks of the Newark Basin because of their strong layering and well documented presence of highly transmissive bedding plane fractures (e.g., Lacombe and Burton, 2010). Standard characterization techniques often applied in open boreholes tend to highlight the high lateral transmissivity of these units and obscure their role as important aquitards in the system. This presentation will describe a how a combination of novel, high-resolution field data sets and modeling were used to identify and characterize aquitards in a thick package of sandstones and provide new insights into the properties of shallow, fractured sedimentary rock aquitards. For those interested, the manuscript (Meyer et al., 2023) describing the study is open access and available for download by following this link: https://doi.org/10.1016/j.jhydrol.2023.130347 .

Dense non-aqueous phase liquid (DNAPL) contaminants in fractured bedrock aquifers are complex hydrogeological systems to characterize, particularly after several decades of evolution due to dissolution, diffusion, and degradation (Parker et al., 2012). At a site in southern Wisconsin, a multicomponent DNAPL migrated through glacial sediments and sedimentary bedrock ultimately accumulating between 45 and 55 m below ground surface (bgs) in a fractured sandstone. Previous investigations noted there was not an obvious aquitard beneath the accumulated DNAPL leaving an important gap in the conceptual site model (CSM). The objective of this study (Meyer et al., 2023) was to improve the delineation and characterization of aquitard units at the field site to answer two key questions: (1) what aquitard characteristics contributed to stopping downward DNAPL migration and (2) do these same aquitard characteristics occur at other positions between the DNAPL and the underlying regional aquifer. Aquitards were identified and characterized using a diverse set of high-resolution data sets. Here, an aquitard was defined as an interval of rock that produces a distinct increase in the vertical component of hydraulic gradient in a high-resolution (3 zones/10 m) head profile (Meyer et al., 2014). The aquitards were then described within a sequence stratigraphic framework based on detailed sedimentological logs from core and natural gamma logs collected in the boreholes (Meyer et al., 2016). Fracture network characteristics and connectivity were assessed using cores, borehole image logs, and outcrop observations. Estimates of bulk vertical hydraulic conductivity (K) were provided by a 3-D numerical groundwater flow model constructed and calibrated with emphasis on matching the observed high-resolution head profiles. The distribution of contaminants with depth was quantified based on results from detailed (≥1 sample/30 cm) sampling of continuous cores. The results indicated the DNAPL accumulated in HGU8, a 6 m thick maximum flooding interval with the lowest bulk vertical K at the site. Although defined as an aquitard, HGU8 also has one of the highest average bulk horizontal K values of the bedrock units due to laterally extensive bedding parallel fractures. Rock core contaminant profiles from the source zone showed high contaminant concentrations all the way to the bottom of HGU8 followed by a dramatic decline to non-detect concentrations. Consequently, lateral spreading in the HGU8 bedding parallel fractures likely contributed to cessation of downward DNAPL migration but was not sufficient to stop it completely. Fracture network data indicated poor vertical connectivity between the fracture networks in HGU8 and the underlying aquifer unit, that likely impeded further downward DNAPL migration. The complementary high-resolution data sets also identified two additional aquitards with similar properties to HGU8 and at least one additional horizon with poor fracture network connectivity between the contaminated interval and the regional water supply aquifer. This study highlights the importance of multiple, high-resolution data sets for aquitard characterization and demonstrates the potential for poor fracture connectivity across a contact to function as an aquitard, influencing groundwater pathways and impeding downward contaminant migration.

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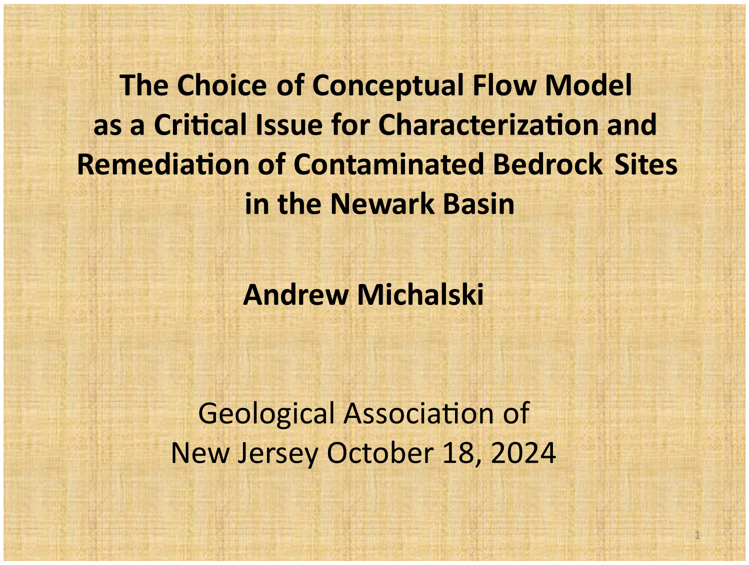
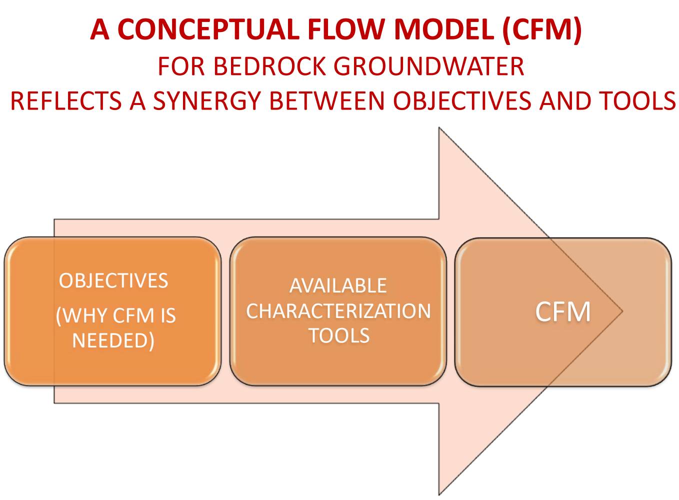
2. Choice of Conceptual Groundwater Flow Model as a Critical Issue for Characterization and Remediation of Contaminated Bedrock Sites in the Newark Basin

Andrew Michalski, PhD, CGWP, PG





EVOLUTION OF CFMs
Has Been Driven by Changing Objectives and Tools

PRIOR TO ~1980s
BEDROCK TREATED AS EQUIVALENT POROUS MEDIUM (EPM)

OBJECTIVES

Water Supply Issues Dominant:

- Well Yield/Specific Capacity
- Wellfield Configuration
- Saltwater Intrusion
- Aquifer Safe Yield

CHARACTERIZATION TOOLS:

- Drilling
- Water Level Measurements
- Pumping Tests
- Theis Method
- Lab Tests for Inorganics

EVOLUTION OF CFMs
Has Been Driven by Changing Objectives and Tools

FROM MID-1980s TO 2012
WHAT HAPPENED THEN?

OBJECTIVES:

Shift from water supply to contaminant hydrogeology issues. The focus switches from bulk hydraulic properties to migration pathways.

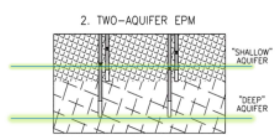
NEW CHARACTERIZATION TOOLS:

- Borehole Geophysics
- Flowmeters
- Pressure Transducers
- Packer & Slug Testing
- Tracer Tests (Environ., CSI)
- Lab Testing for Organics
- Modeling

EVOLUTION OF CFMs
Has Been Driven by Changing Objectives and Tools

HOW DID CONSULTANTS RESPOND TO THESE BIG CHANGES DURING MID-1980s TO 2012 PERIOD?

THEY RELIED ON THE EPM CONCEPT
(SHALLOW, INTERMEDIATE, DEEP AQUIFER)



IGNORING THE <u>STRUCTURAL DIP</u> AND <u>DISCRETE NATURE</u> OF BEDROCK GW FLOW.
LONG OPEN HOLES COMMONLY USED AS MONITORING WELLS.

EVOLUTION OF CFMs
Has Been Driven by Changing Objectives and Tools

POST-2012

The 2012 Technical Guidance makes the **Leaky Multi-unit Aquifer System (LMAS;** **Michalski 1990) a default conceptual model** for conducting groundwater RI at contaminated bedrock sites in the Passaic Formation.

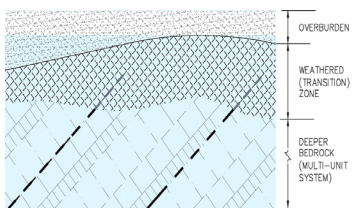
But the old EPM model of shallow, intermediate and deep units, sliced horizontally, is still used at many contaminated bedrock sites.

New Jersey Department of Environmental Protection

Site Remediation Program

Ground Water Technical Guidance:
Site Investigation
Remedial Investigation
Remedial Action Performance Monitoring

LMAS Description



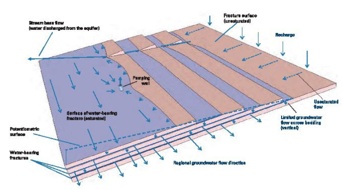
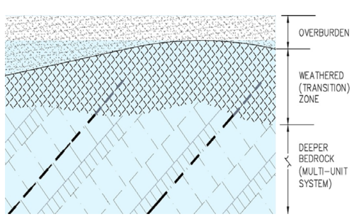


Fig 21 of Heisig, 2010 (SIR 2010 -5245)

- BEDDING-PARALLEL GW FLOW PREVAILS WITHIN THE DIPPING BEDROCK;
- THE BULK OF THIS FLOW IS CARRIED OUT THROUGH A VERY FEW MOST TRANSMISSIVE BEDDING FRACTURES – A VERY SMALL SUBSET OF ALL FRACTURES;
- THEY ACT AS MAJOR AQUIFER UNITS (*AUs*) OF A SPECIAL TYPE: HIGH ***T*** BUT VERY LOW ***S*** (~10-6), AND PROVIDE PREFERENTIAL MIGRATION PATHWAYS SEPARATED BY THICK CONFINING UNITS (AQUITARDS).

7

LMAS Description



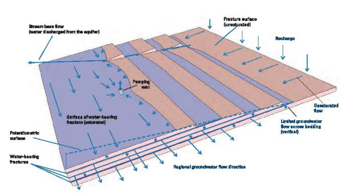
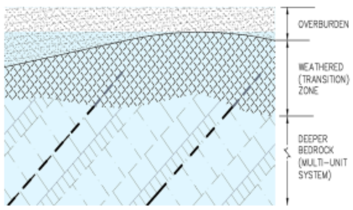


Fig 21 of Heisig, 2010 (SIR 2010 -5245)

- THE WEATHERED ZONE (AND SATURATED OVERBURDEN WHERE PRESENT) ACTS AS GW RESERVOIR THAT RECHARGES THE *AUs*. THIS ZONE GENERALLY EXHIBITS HIGHER FRACTURE DENSITY AND POROSITY BUT MUCH LOWER PERMEABILITY THAN THE *AUs* IN THE DEEPER BEDROCK.
- UP-DIP EXTENSIONS OF *AUs* INTO WEATHERD BEDROCK FEED THE *AUs*.

8

LMAS Description



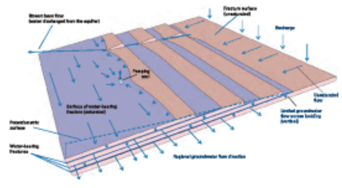
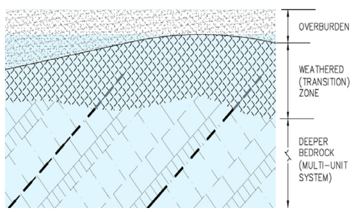


Fig 21 of Heisig, 2010 (SIR 2010-5245)

- THE *AUs* EXTEND FOR A LIMITED DISTANCE IN DOWN-DIP DIRECTION BUT FAR IN ALONG-STRIKE DIRECTION. THEY APPEAR AS STRIP-, OR BAND-LIKE FEATURES THAT MAKE THE GOLDILOCKS TRANSMISSIVITY BELTS ;
- THE BEDDING *AUs* ACT AS LOW-HEAD CENTERS ATTRACTING FLOWS FROM ADJACENT AQUITARDS;
- THE REGIONAL FLOW IN THE *AUs* IS STRIKE-PARALLEL (Picture on the upper right).

9

LMAS Description



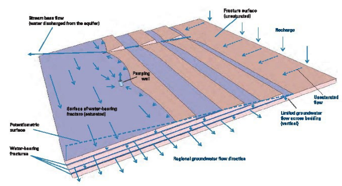
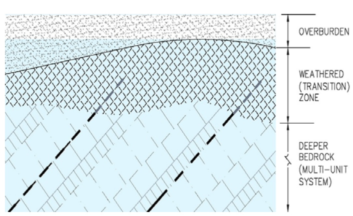


Fig 21 of Heisig, 2010 (SIR 2010 -5245)

- SUBVERTICAL JOINTS PROVIDE FOR LEAKAGE BETWEEN*AUs*. THIS LEAKAGE CAN VARY FROM NEGLIGIBLE TO SIGNIFICANT. JOINTS GENERALY DO NOT CROSS BED BOUNDARIES, WHICH LIMITS THE LEAKAGE.
- SOME CONTAMINATED SITES ARE LOCATED ENTIRELY WITHIN SUBCROPS OF THICK AQUITARDS UNITS THAT ONLY CONTAIN <u>MINOR *AUs*</u>. THE LATTER CONTROL CONTAMINANT MIGRATION AND SHOULD BECOME TARGETS. NOTE THAT BEDDING-PARALLEL FLOW IS STILL PREVALENT WITHIN SUCH MINOR *AUs* PRESENT WITHIN THCK AQUITARDS.

10

LMAS Description



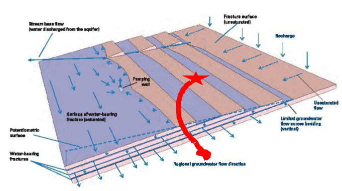


Fig 21 of Heisig, 2010 (SIR 2010 -5245)

- CONTAMINANTS FOLLOW A <u>CRESCENT-LIKE FLOWPATH</u> FROM THEIR SOURCE AREA. IT INCLUDES 1) DOWNDIP SEGMENT ACROSS THE WEATHERED ZONE, 2) ALONG-STRIKE SEGMENT UPON JOING THE REGIONAL FLOW, AND 3) UP-DIP SEGMENT IN THE DISCHARGE AREA (not shown here).

11

PRACTICAL TIPS

THE REMINDER OF THIS TALK PRESENTS SOME <u>14 PRACTICAL CLUES DERIVED FROM THE GENERIC LMAS CONCEPT</u>.

THESE CLUES HELP IN PLANNING AND EXECUSION OF AN EFFIECIENT AND EFFECTIVE REMEDIAL GW INVESTIGATION .

12

PRACTICAL TIPS

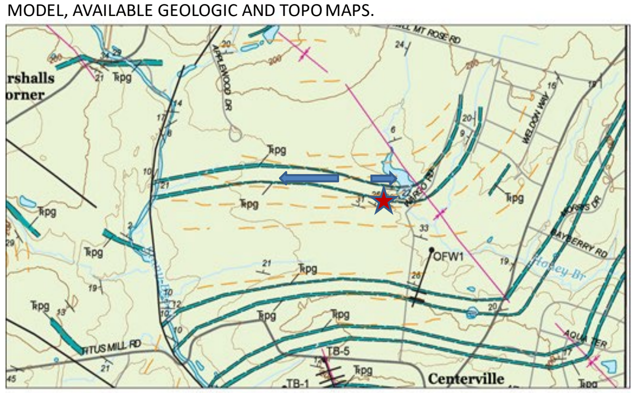
THE REMINDER OF THIS TALK PRESENTS SOME <u>14 PRACTICAL CLUES DERIVED FROM THE GENERIC LMAS CONCEPT</u>.

THESE CLUES HELP IN PLANNING AND EXECUSION OF AN EFFIECIENT AND EFFECTIVE REMEDIAL GW INVESTIGATION .

12

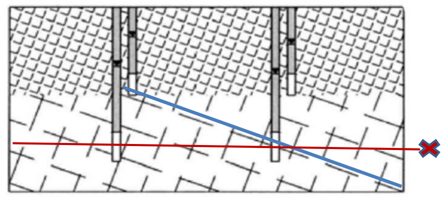
PRACTICAL CLUES FROM THE GENERIC LMAS MODEL

1. WE CAN **PREDICT THE DIRECTION OF GW FLOW AND BEDROCK PLUME MIGRATION, PLUME DISCHARGE LOCATION(S) AND IMPACTS TO RECEPTORS - <u>PRIOR TO ANY DRILLING INTO BEDROCK,</u>** BASED ON THE GENERIC LMAS MODEL, AVAILABLE GEOLOGIC AND TOPO MAPS.



PRACTICAL CLUES FROM THE GENERIC LMAS MODEL

2. IN A MULTI-UNIT FLOW SYSTEM, A **TRUE GW FLOW DIRECTION** IS DETERMINED ONLY FROM WATER LEVELS IN WELLS COMPLETED INTO THE SAME DIPPING *AU; As shown by the blue line below.*



2A. If two or more bedding *AUs* are penetrated by an open hole vertical cross-flow develop in the hole.

- The **water level** in such a hole represents a **composite**, *with transmissivity of individual AUs serving as the weighing factor*.
- Long open holes/wells are **self-purging**.

14

PRACTICAL CLUES FROM THE GENERIC LMAS MODEL

3. THE BEST STRATEGY FOR BEDROCK PLUME DELINEATION IS TO FOLLOW THE BEDDING AND CHASE PLUMES WITHIN THE MOST TRANSMISSIVE CONTAMINATED *AU*, BECASUE THE LATTER PROVIDES THE FARTHEST POTENTIAL MIGRATION PATHWAY TO RECEPTORS.

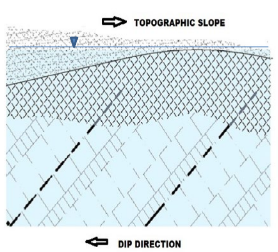
THIS STRATEGY REDUCES THE NUMBER OF BEDROCK WELLS NEEDED FOR PLUMES DELINEATION BY ONLY TARGETTING THE MOST TRANSMISSIVE CONTAMINATED BEDDING *AU* IDENTIFIED BENEATH SOURCE AREA(S) .

THE MOST CONTAMINATED BUT LESS TRANSMISSIVE FRACTURE CAN ALSO BE TARGETED TO MONITOR THE STRENGTH OF SOURCE AREA OVER TIME.

15

PRACTICAL CLUES FROM THE GENERIC LMAS MODEL

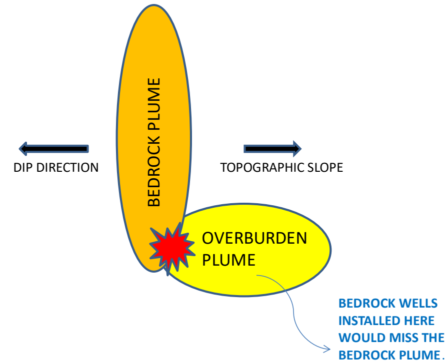
4. CONTRARY TO A PREVALING VIEW, ***GW FLOW IN BEDROCK MAY NOT FOLLOW LOCAL TOPOGRAPY*** .



A CASE OF TOPOGRAPHIC SLOPE OPPOSING STRUCTURAL DIP: GW FLOW IS DOWN-DIP THEN ALONG-STRIKE; See the next slide.

16

PRACTICAL CLUES FROM THE GENERIC LMAS MODEL

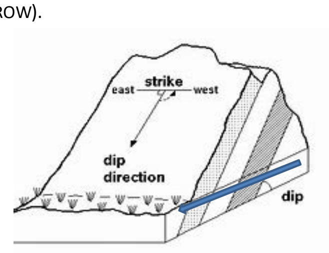


CONSEQUENCES OF THE LATTER CASE: ***DIFFERENT FLOW DIRECTIONS OF THE OVERBURDEN AND BEDROCK PLUMES***.

PRACTICAL CLUES FROM THE GENERIC LMAS MODEL

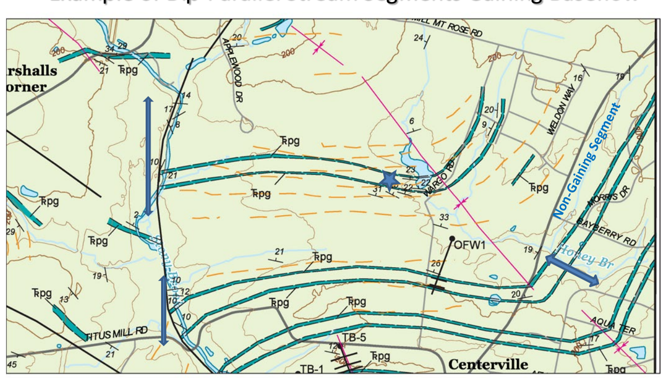
5. THE LMAS MODEL HELPS TO PINPOINT**LOCATIONS OF DISCRETE GW DISCHARGES TO STREAMS**, BASED ON A SIMPLE GEOMETRIC EVALUATION OF INTERSECTIONS OF *AUs* WITH STREAMBEDS.

THE BULK OF THE GW DISCHARGES FROM THE BEDROCK OCCURS INTO STREAM SEGMENTS THAT ARE DIP-PARALLEL (WHERE MOST OF THE *AUs* IS INTERSECTED BY THE STREAM - SEE BLUE ARROW).



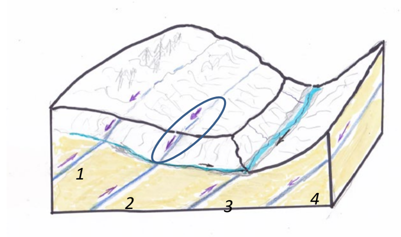
PRACTICAL CLUES FROM THE GENERIC LMAS MODEL

Example of Dip-Parallel Stream Segments Gaining Baseflow



PRACTICAL CLUES FROM THE GENERIC LMAS MODEL

6. **<u>DIFFERENT GW FLOW DIRECTIONS *(AND PLUMES)* CAN BE PRESENT IN DIFFERENT AUs</u>**, AS CONTROLLED BY *THE INTERPLAY BETWEEN STRUCTURAL DIP, TOPOGRAPHY, AND DISCHARGE BOUNDARIES* .

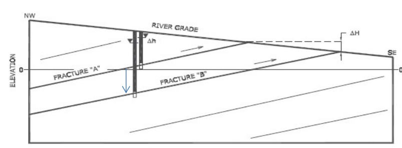


A CASE OF STRIKE–PARALLEL MAIN RIVER SEGMENT WITH A DIP-PARALLEL TRIBUTARY
In uplands segments of *AUs 1* and *2*, GW flow direction is down-dip (away from the river) and toward the tributary. But *AU 3* discharges to is the main river. *AU 4 would* discharge to the river farther downstream.

PRACTICAL CLUES FROM THE GENERIC LMAS MODEL

7A. THE LMAS CONCEPT EXPLAINS THE OCCURENCE OF **<u>DOWNWARD FLOW (DOWNWARD HYDRAULIC GRADIENT) ALONG LONG OPEN HOLES INSTALLED IN GW DISCHARGE AREAS</u>**.

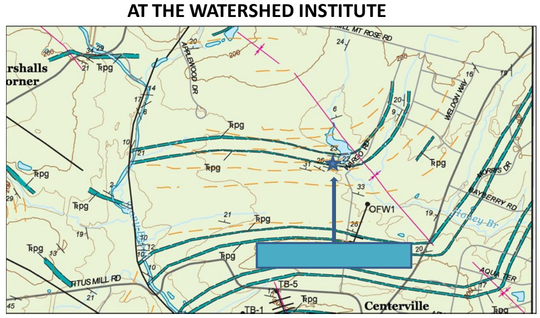
THIS APPARENT ODDITY IS COMMON IN PARTS OF THE NJ NEWARK B. WHERE MAJOR RIVERS GENERALLY FLOW TO THE *SE* WHILE BEDROCK DIPS TO THE *NW*.



THE DISCHARGE OCCURS VIA UP-DIP FLOW WITHIN THE BEDDING *AU*s (LABELLED BELOW AS FRACTURE *A* AND *B)*.

PRACTICAL CLUES FROM THE GENERIC LMAS MODEL

7B. THE LMAS CONCEPT EXPLAINS THE OCCURENCE OF **<u>UPWARD FLOW</u>**
OBSERVED IN THE SOUTHERN BEDROCK WELLS
AT THE WATERSHED INSTITUTE



UPWARD FLOW RESULTS FROM THE DEEPER BEDDING *AUs* IN THESE WELLS CROPPING OUT AT A HIGHER ELEVATION RECHARGE AREA UPDIP (SOUTH) OF THE WELLS – A U-YUBE EFFECT.

PRACTICAL CLUES FROM THE GENERIC LMAS MODEL

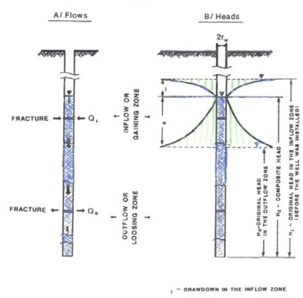
8. POTENTIAL **VAPOR INTRUSION** ISSUES IN THE DIPPING BEDROCK ARE LIMITED TO THE ***SOURCE AREA AND THE DISCHARGE AREA.***

IT IS THE RESULT OF A GW PLUME DIPPING/DIVING ALONG BEDDING *AUs*.

PRACTICAL CLUES FROM THE GENERIC LMAS MODEL

9. LONG OPEN HOLES OF BEDROCK PRODUCTION WELLS
PLAY A MAJOR ROLE IN THE **SPREAD OF DNAPLs AND DISSOLVED PLUMES**.

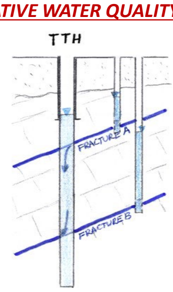
A *RI* SHOULD START WITH INVESTIGATING OF EXISTING AND FORMER PRODUCTION WELLS AS ***CRITICAL SINGULAR POINTS***.



PRACTICAL CLUES FROM THE GENERIC LMAS MODEL

10. WHEN COLLECTING **GRAB OR PACKER GW SAMPLES IN OPEN HOLES**, ONE SHOULD KNOW IF A GIVEN SAMPLE IS COLLECTED FROM AN INFLOW OR OUTFLOW FRACTURES.

SAMPLES FROM OUTFLOW FRACTURES ARE NOT LIKELY TO YIELD TRUE NATIVE WATER QUALITY *AND SHOULD BE FLAGGED AS SUCH .*



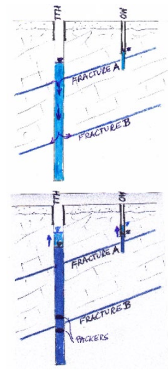
WHEN OUTFLOW FRACTURE ***B*** IS ISOLATED DURING PACKER TESTING, A SAMPLE COLLECTED FROM IT IS IMPACTED BY THE WATER DERIVED FROM FRACTURE ***A*** DURING PRECEEDING OPEN HOLE CROSS-FLOW PERIOD.

EVEN AFTER INSTALLATION OF A PERMANENT WELL STRADDLING FRACTURE ***B,*** PRIOR CROSS-CONTAMINATION RESIDUE REMAINS FOR SOME TIME. CONSEQUENTLY, EARLYWELL SAMPLING RESULTS MAY NOT BE REPRESENTATIVE OF NATIVE WATER QUALITY.

PRACTICAL CLUES FROM THE GENERIC LMAS MODEL

11. ONLY LMAS EXPLAINS **ODD OCCURRENCE OF RISING OF WATER LEVEL IN SOME DISTANT OBSERVATION WELLS DURING PACKER TESTING.**

THE RISE IS CAUSED BY ***PACKER INFLATION* THAT TERMINATES PRE-EXISTING DOWNWARD FLOW IN THE OPEN HOLE** . THIS RESULTES IN A HEAD BUILDUP ABOVE THE PACKER. THE BUILDUP PROPAGES FAST ALONG TRANSMISSIVE BEDDING FRACTURE (*AU)* TO A DISTANT OBSERVATION WELL.



Open hole before inflating

After Inflating the packers to isolate *Fracture B*

26

PRACTICAL CLUES FROM THE GENERIC LMAS MODEL

12. THE LMAS MODEL IMPLIES A **SIGNIFICANT DILUTION AND HYDRODYNAMIC DISPERSION** EFFECTS UPON PLUME JOINING THE REGIONAL FLOW.

BUT IT ALSO IMPLIES A **LIMITED ROLE OF MATRIX DIFFUSION ADJACENT TO TRANSMISSIVE BEDDING *AUs***

It's because transverse flow from adjoining aquitards into the low - head bedding *AU* would *counter* matrix diffusion effects. (*This applies to bedding AUs away from source and discharge areas*.)

THIS CLUE IS CONTRARY TO A PREVAILING PARADIGM THAT MATRIX DIFUSION PLAYS A VERY IMPORTANT ROLE IN CONTAMINATING THE BEDROCK.

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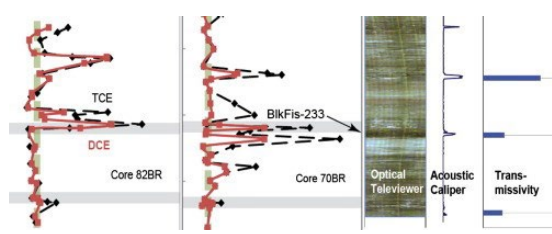
PRACTICAL CLUES FROM THE GENERIC LMAS MODEL

Data from the NWS West Trenton site is consistent with the LMAS prediction on the limited role of matric diffusion from *AUs*.



Actual **core concentration data** from the NWS Site West Trenton, NJ (Goode et al, 2014)

- *Findings of the referenced paper:*
- ***Diffusion halo for TCE into matrix from a transmissive bedding fracture was less than 1 inch after ~ 50 years of contaminant migration. Not even clear if diffusion or sorption caused this small penetration into the matrix.***

22

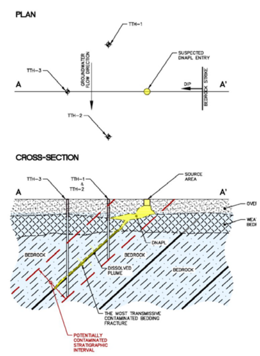
PRACTICAL CLUES FROM THE GENERIC LMAS MODEL

13. LMAS HELPS IN **DEALING WITH BEDROCK DNAP SITES**.

TRANSMISSIVE BEDDING FRACTURES (*AUs*) TEND TO ATTRACT DNAPLs, BECOUSE LOWER DNAPL ENTRY PRESSURE IS NEEDED TO INVADE LARGER APERTURE FRACTURES.

THUS DNAPL TENDS TO MIGRATE DOWN-DIP THE *AU* WHILE GW FLOW IS IN ALONG -STRIKE DIRECTION.

FOR INITIAL PLACEMENT OF TEST HOLES/M. WELLS AT **DNAPL SITES**, FIRST ESTIMATE THE ***POTENTIALLY DNAPL-CONTAMINATED STRATIGRAPHIC INTERVAL (PDCSI) EXPECTED TO STRADDLE DNAPL CONTAMINATION*.**



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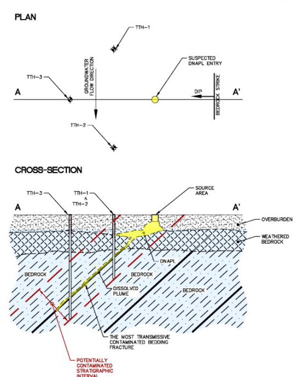
PRACTICAL CLUES FROM THE GENERIC LMAS MODEL

PLACEMENT OF TTHs AT SUSPECTED BEDROCK DNAPL SITES:

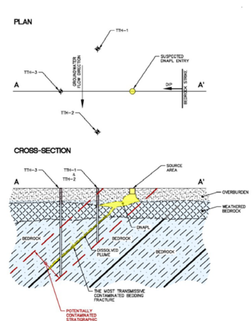
- Use outside-in sequence, i.e. postpone drilling through suspected DNAPL source area until it is remotely characterized by TTHs.
- At a new potential DNAPL bedrock site, start with installation of 3 TTHs that penetrate the ***PDCSI***.
- Start with installing an upgradient test hole (here TTH-1).
- Next install a TTH downgradient of the source area, TTH-2, to get data on site hydrostratigraphy, fracture continuity beneath the source, and its impacts on gw quality.



PRACTICAL CLUES FROM THE GENERIC LMAS MODEL

PLACEMENT OF TTHs AT SUSPECTED BEDROCK DNAPL SITES:

- Then install a down-dip test hole (TTH-3) and look for evidence of DNAPL phase (usually high dissolved conc.), *particularly within the hole segment intersecting a major bedding fracture subcropping beneath the source area.*
- Convert TTHs to MWs upon completion of a testing program (Section 4).



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PRACTICAL CLUES FROM THE GENERIC LMAS MODEL

14. THE LMAS MODEL OFFERS HINTS FOR **CLASSIFICATION EXCEPTION AREA (CEA)** DETERMINATION AT CONTAMINATED BEDROCK SITES:

First, ***identify the most transmissive contaminated bedding fracture (AU)*** that is connected to the source area. This is a preferential flow route for the farthest (as well as fastest) migration pathway. It should be the target for delineation of the maximum extent of the CEA.

(If contaminated overburden is also present a separate overburden CEA should be defined.)

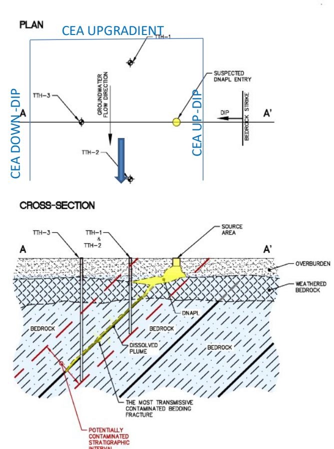
32

PRACTICAL CLUES FROM THE GENERIC LMAS MODEL

*BASED ON LMAS MODEL**, CEA BOUNDARIES** CAN BE EASILY DEFINED FROM THESE THREE SIDES:*

- UP-DIP, AS DEFINED BY THE SUBCROP OF THE CONTAMINATED INTERVAL;
- UPGRADIENT, AS DEFINED BY NO OR BACKGROUND CONTAMINATION;
- DOWN-DIP, AS DEFINED BY CONCENTRATIONS BELOW A REMEDIATION STANDARD OR A DEPTH BEYOND THE REACH OF SUPPLY WELLS.

SO, THE INVESTIGATOR IS LEFT WITH DETERMINING A CEA EXTENT IN THE DOWNGRADIENT (ALONG-STRIKE) DIRECTION.
ACTIONS AT THIS THIS STEP DEPEND ON THE STATUS OF THE PLUME, WHETHER IT IS SHRINKING, STABLE OR EXPANDING.



CONCLUDING NOTES

- THE 14 PRACTICAL CLUES JUST PRESENTED DEMONSTRATE **PREDICTIVE CAPABILITIES OF THE LMAS CONCEPT.** THEY AID IN DESIGNING EFFECTIVE AND EFFICIENT REMEDIAL INVESTIGATIONS OF DIPPING SEDIMENTARY BEDROCK SITES.
- SOME OF THESE CLUES ALSO PROVIDE **VERIFICATION OF THE VALIDITY OF THE LMAS CONCEPTUAL MODEL,** *AS OTHER MODELS CANNOT EXPLAIN ODD AQUIFER RESPONSES DISCUSSED EARIER (e.g., Downward flow in open holes in discharge areas; Rise of water level in distant wells during packer tests; etc.)*

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3. Hydrogeologic Framework at a Contamination Site based on Geologic, Offloading, and Weathering Strata Augmented with Water-quality and Water-level Data and Concepts

Pierre Lacombe; USGS, retired

Development of
Hydrogeologic Framework at
Contaminating Site in
Fractured Bedrock of Newark Basin

Pierre Lacombe
U.S. Geological Survey (retired)
Geological Association of New Jersey
In cooperation with the
NJ Licensed Site Remediation Professional Association
October 18-19, 2024
at
Stoney Brook Millstone
Watershed Institute

Purpose of USGS

USGS provides geologist and hydrogeologist for the other government agencies:

- US EPA
- Department of Defense: Army, Navy, Air Force, etc
- NJ DEP
- NJ County and Local Government

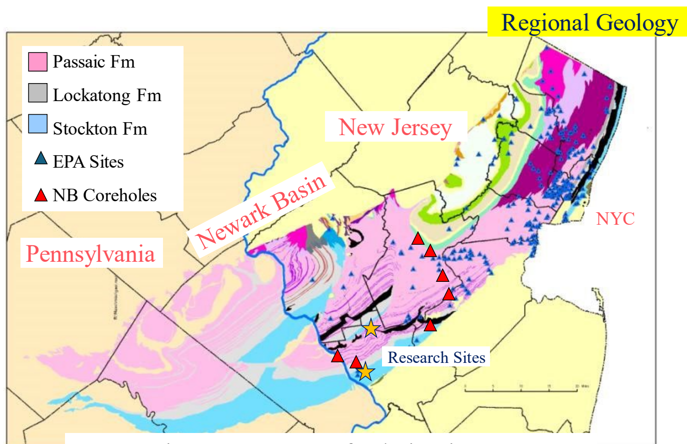
USGS asked to assist on large, multifaceted, groundwater contamination issues:

- Review existing data: Framework, QW, Water levels
- Review existing reports: Environmental Consulting Firms
- Discuss issues with EPA, DEP, and Firms

USGS may then investigate contamination site

Purpose of GANJ presentation

- Explain multi-faceted approach to:
- Build a hydrogeologic framework of a contamination site based on:
  - field data
  - hydrogeologic concepts



~165 Active US EPA Superfund Sites in NJ

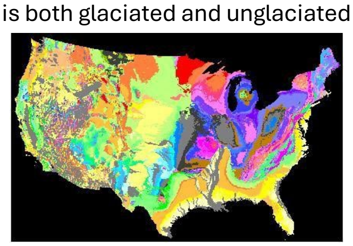
>800 Active NJ DEP Contamination Sites

>200 EPA and PA DEP Contamination Sites (PA)

Newark Basin and US Geology

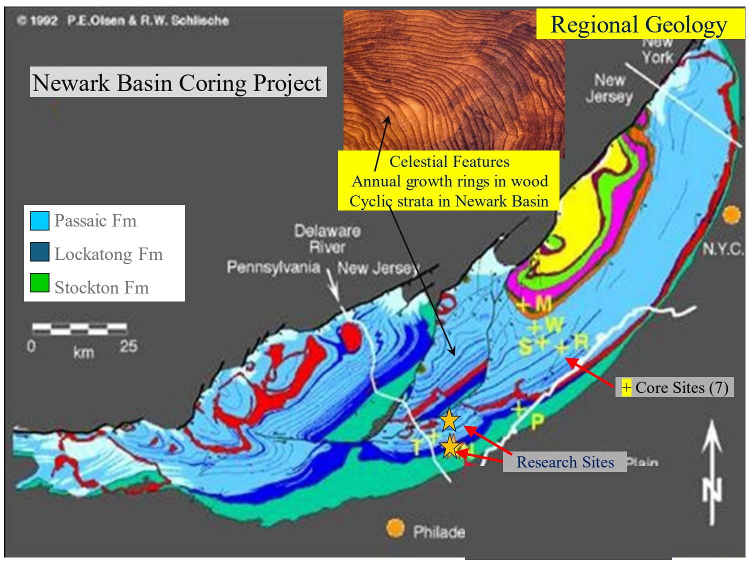
- Why research in Newark Basin for US contamination issues

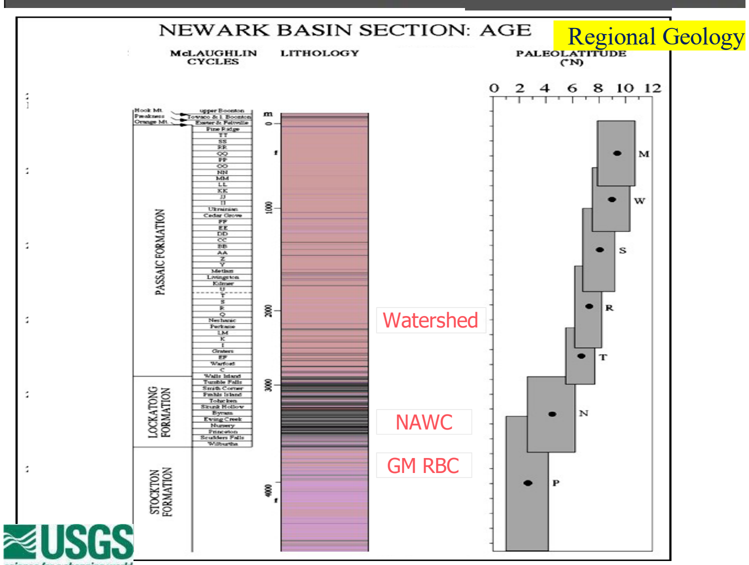
- Newark Basin: mostly sedimentary rock
  - 2/3's of USA outcrops are sedimentary rocks
- Newark Basin: mostly Mudstone
  - 2/3's of all sedimentary rocks are mudstones
- 1000's of industrial contamination in northeast US
- Newark Basin is both glaciated and unglaciated



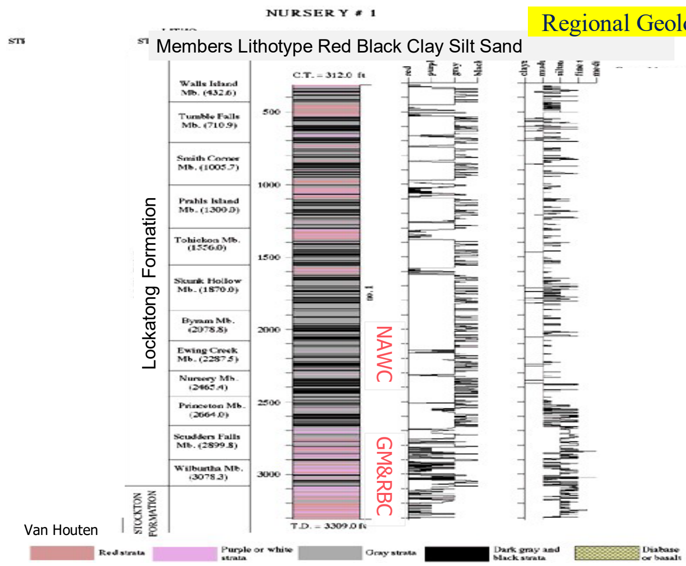
Geologic Framework

- Regional Geology
- Local Geology
  - Outcrops
  - Rock Core
  - Drill Cuttings
  - Geophysics
- Hydrogeology
- Concepts



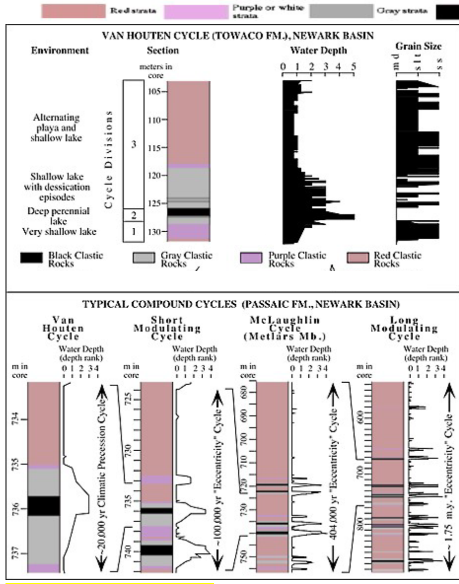


Regional Geology



Regional Geology

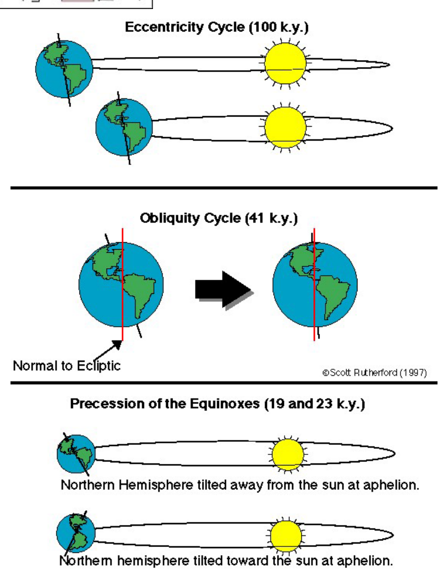
1. Van Houten



1. Van Houten
2. Short Modulating
3. McLaughlin
   Venus Jupiter
4. Long Modulating

Regional Geology

Milankovitch Orbital Cycles



Climate Change

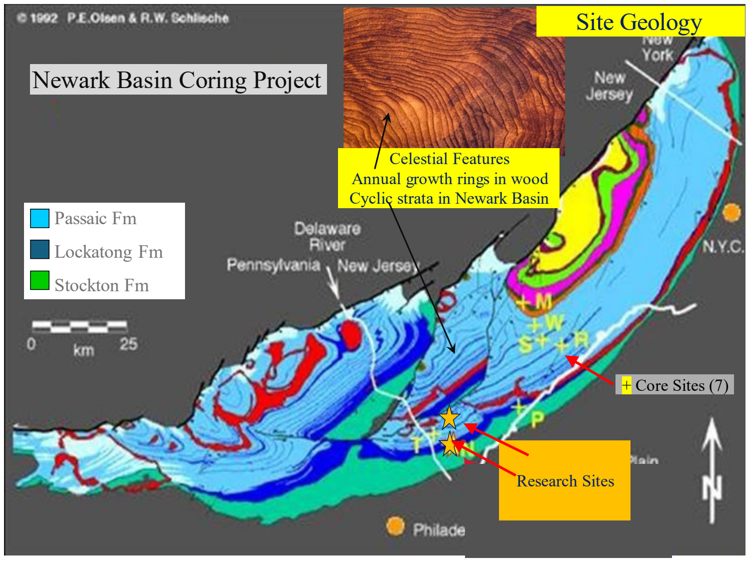
Glacial-Interglacial Cycles

Sedimentary cycles

Van Houten Cycles

Coal Cyclothems

Limestone-Marl Cycles



Site Geology

Hydrogeologic Framework--Conceptual Site Model

<u>What should a client receive from a consultant?</u>

Cost: $100,000 to $500,000 and 2 to 4 months

Work: Drill 10 wells

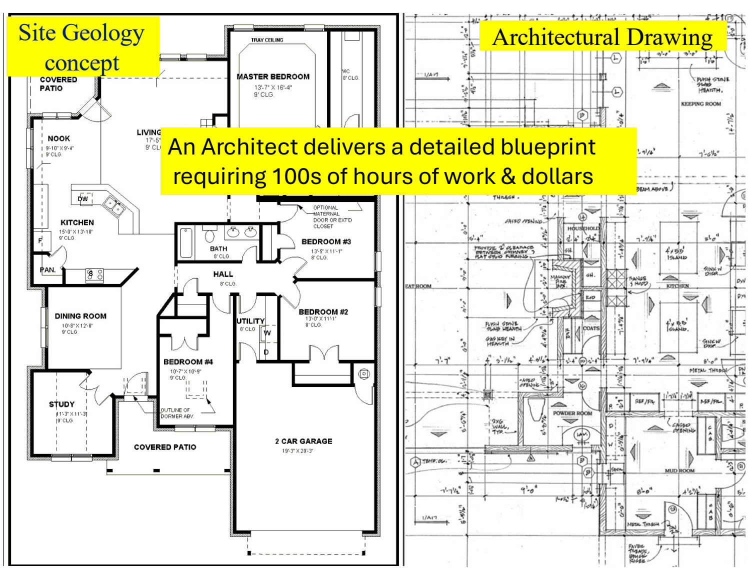
contract, permits, Driller, well rig,

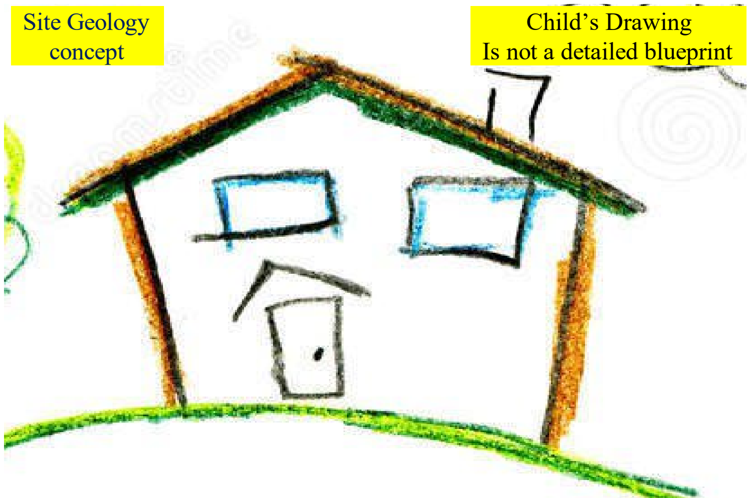
Geologist to log the wells

Geophysical log of the wells

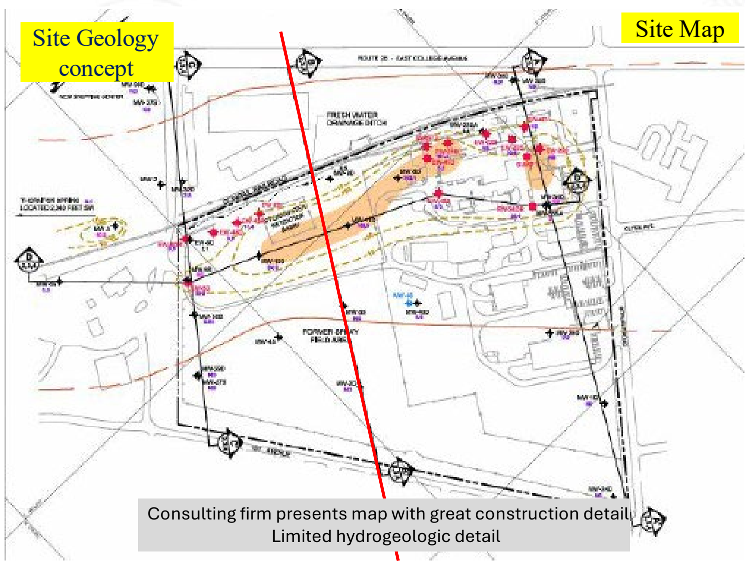
Compilation of the data

Results: Maps, Sections, Report

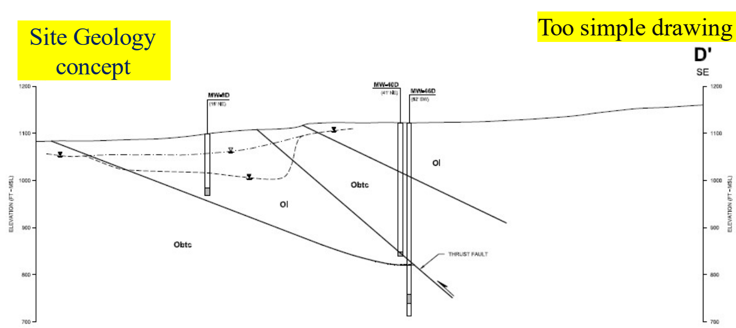




An architect or designer will not give you this and expect to be paid



Consulting firm presents map with great construction detail
Limited hydrogeologic detail



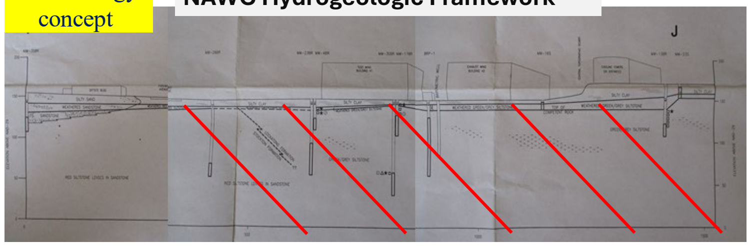
Frameworks evolve and improve with time

- Land surface
- Water table
- Bedrock (2 units)
- Fault plane
- Well location & depth (400 ft)

Consulting firm may draw cross section with little hydrogeologic detail

Site Geology concept

NAWC Hydrogeologic Framework

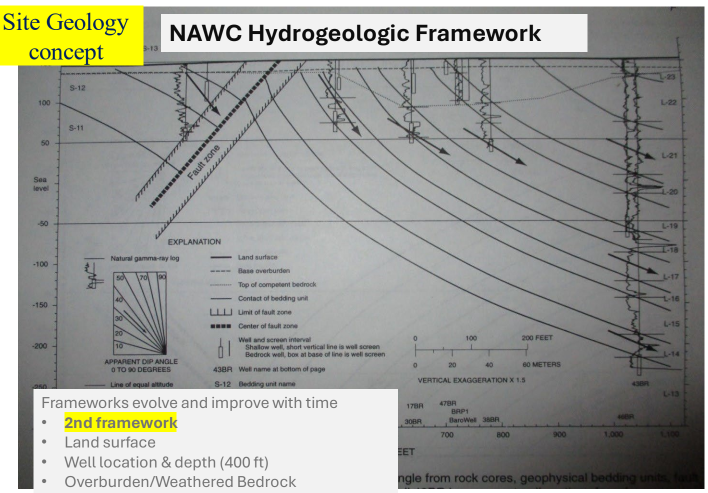


Frameworks evolve and improve with time
- **1st framework**
- Building locations
- Land surface
- Overburden
- Weathered Bedrock
- Bedrock
- Fault Plane
- Well location & depth
- Little detail, so I added bedrock dip

NAWC circa 1992

Site Geology concept

NAWC Hydrogeologic Framework

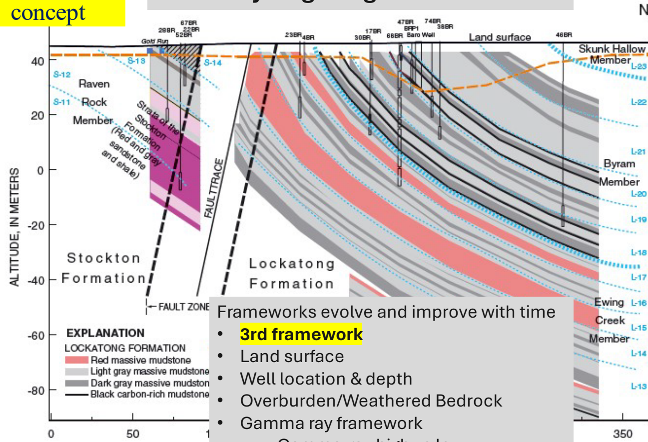


Frameworks evolve and improve with time
- **2nd framework**
- Land surface
- Well location & depth (400 ft)
- Overburden/Weathered Bedrock
- Bedrock, dip angle
- Gamma ray framework
  - Gamma-ray high vs low

NAWC circa 1998

Site Geology concept

NAWC Hydrogeologic Framework

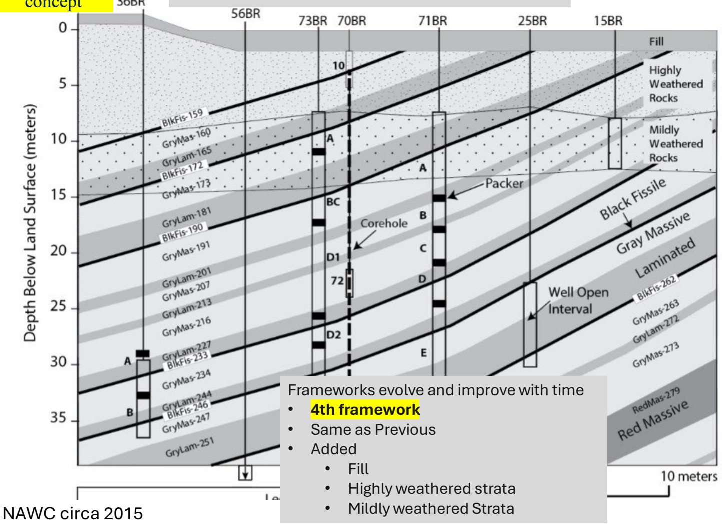


Frameworks evolve and improve with time
- **3rd framework**
- Land surface
- Well location & depth
- Overburden/Weathered Bedrock
- Gamma ray framework
  - Gamma-ray high vs low
- Bedrock, rock type (4) dip angle,
- Fault Zone
- Newark Basin Drilling Program Strata

WC circa 2000

Site Geology concept

NAWC Hydrogeologic Framework



Frameworks evolve and improve with time
- **4th framework**
- Same as Previous
- Added
  - Fill
  - Highly weathered strata
  - Mildly weathered Strata

NAWC circa 2015

Purpose of a framework

Hydrogeologic Framework
Conceptual Site Model

Framework useable for
USEPA
NJDEP
Landowner
Site Manager
Geologist
Hydrogeologist
Chemist
Engineer
Community
Modeler
Microbiologist
Remediation experts
A lot of people

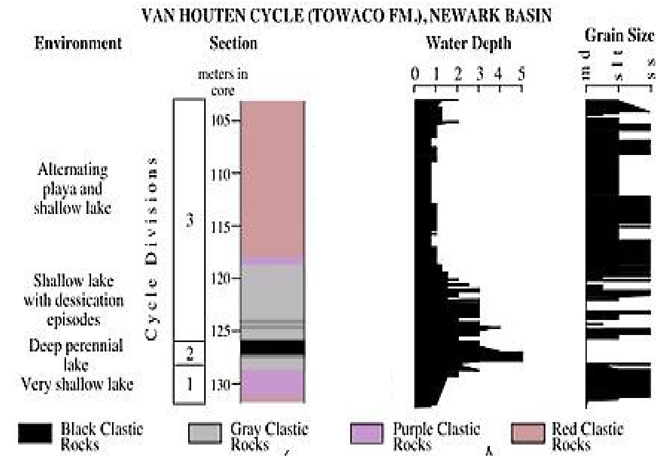
Geology at outcrops

Lithologic Framework Based on Van Houten Sedimentary Cycles of Newark Basin

Permanent Outcrop
Indurated Strata

Ephemeral Outcrop
Fissile Strata

Geology at outcrops, concepts



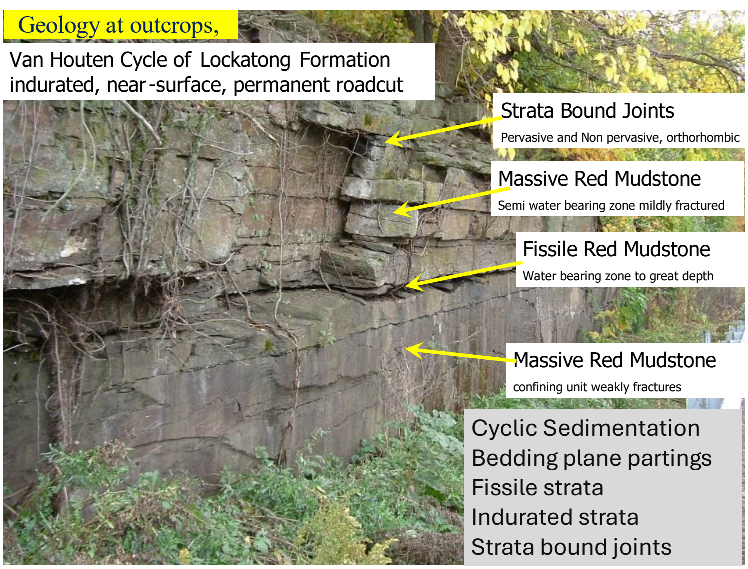
Van Houten

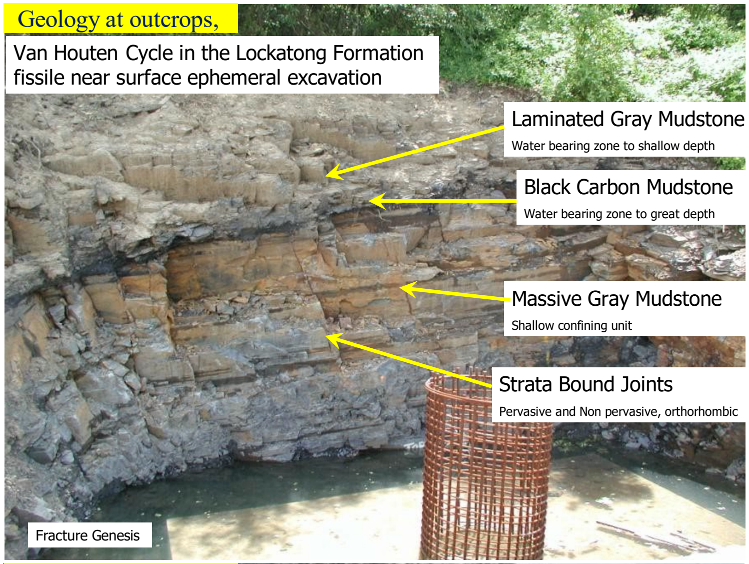
Geology at outcrops, concepts

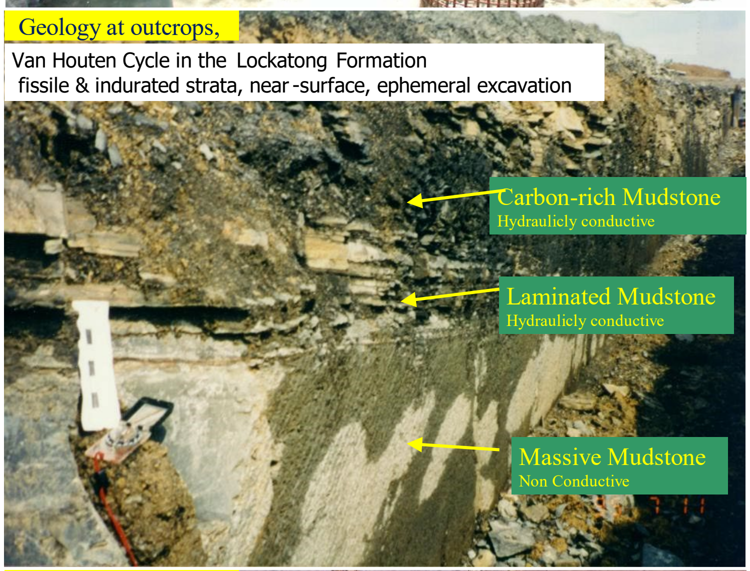
Outcrops and hydrogeology

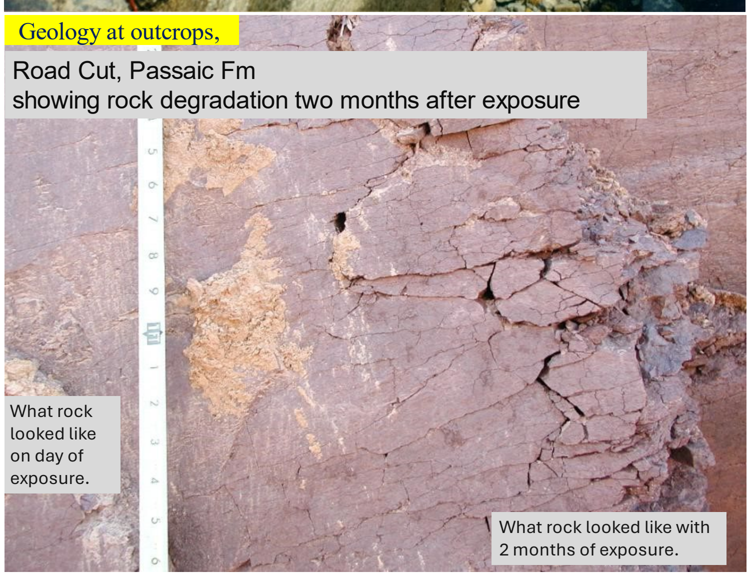
- Highland Natural outcrops are indurated strata
  - Likely are semi-confining units
  - Fractures are near surface features
- Excavations show ambient strata
  - highly weathered, shallow,
  - fissile, and indurated units
- Stream Channel Outcrops
  - indurated strata in fissile setting
- Rock Cores show ambient strata
  - Variable weathering/fracture patterns with depth
- Geophysical logs shows variable geo features
- Cuttings show gross features

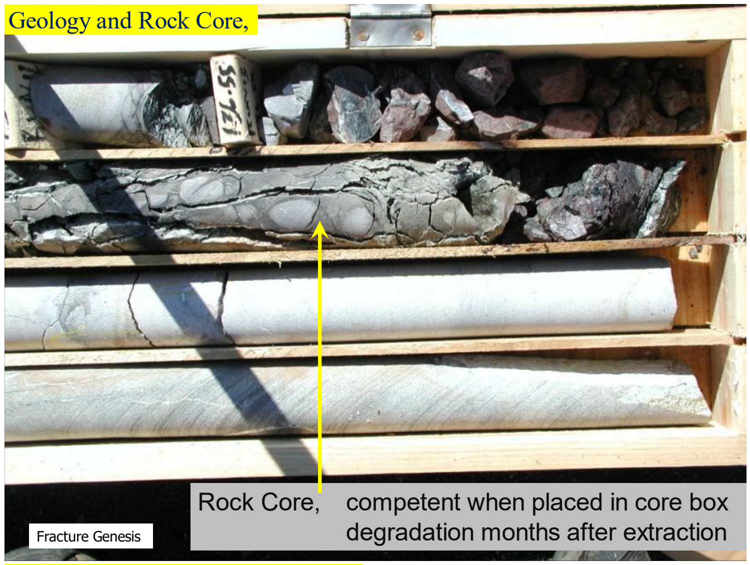
Fracture Genesis




Geology at outcrops,
Van Houten Cycle in the Lockatong Formation
fissile near surface ephemeral excavation
Laminated Gray Mudstone
Water bearing zone to shallow depth
Black Carbon Mudstone
Water bearing zone to great depth
Massive Gray Mudstone
Shallow confining unit
Strata Bound Joints
Pervasive and Non pervasive, orthorhombic
Fracture Genesis


Geology at outcrops,
Van Houten Cycle in the Lockatong Formation
fissile & indurated strata, near-surface, ephemeral excavation
Carbon-rich Mudstone
Hydraulicly conductive
Laminated Mudstone
Hydraulicly conductive
Massive Mudstone
Non Conductive

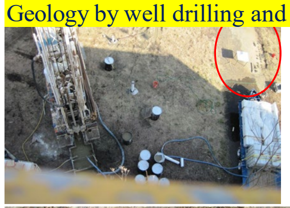

Geology at outcrops,
Road Cut, Passaic Fm
showing rock degradation two months after exposure
What rock looked like on day of exposure.
What rock looked like with 2 months of exposure.



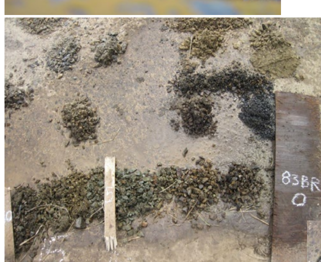
Geology by well drilling and coring

- Grab samples collected during drilling
  - Provides initial lithotype/color framework
  - Indurated units mostly collected in sample
  - Indurated nature will change with time
  - Need to be correlated to Geophysical logs
  - Need to be correlated to hydrogeologic framework

Geology by well drilling and coring



Collect the cuttings
Stock pile
Do not collect, describe, and bag
Study daily in: different lights,
different moisture levels
Compare different wells cutting
See what weathers easily, big chips, small chip,
Compare with Geophysical Logs
Compare with water-bearing zones.
Let others observe and comment (driller will help)
Describe wet and dry, Munsell color chart (wet/dry)
You will generate a much better well cuttings log



You will generate a much better Conceptual Site Model

Geology by well drilling and coring

- Rock core collected during coring
  - Provides high resolution hydrogeologic logs
  - Indurated units preferentially collected
  - Indurated nature will change with time
  - Need to be correlated to Geophysical logs
  - Need to be correlated to hydrogeologic framework
  - Need to be corrected to deviation problems

Geology by well drilling and coring

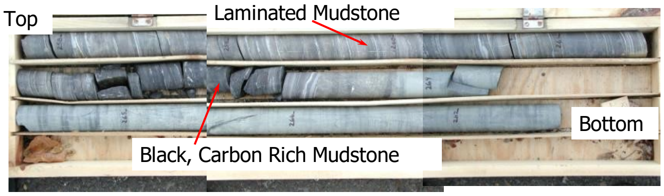
Shallow Mudstone
Highly & Variably Weathered, indurated & fissile rock, much lost fissile core
Pervasive joints and breakage, hard to describe rock type
8 to 17 ft BLS 27 to 37 ft BLS

Geology by well drilling and coring

Intermediate Depth Mudstone
Highly fractured, Unweathered, Mostly indurated rare fissile strata,
joints and breakage common, easy to describe rock type
80 to100 ft BLS

Geology by well drilling and coring

Deep Mudstone
indurated, unweathered, easy to differential stata types,
rare joints and breakage, easy to describe rock type
250 ft BLS

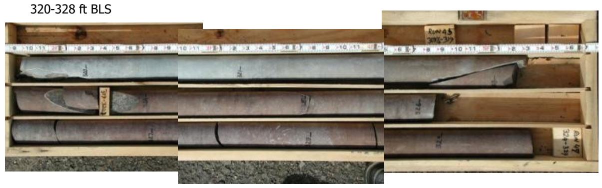


Fracture Genesis

Geology by well drilling and coring

Deep Mudstone
indurated, unweathered, indurated rare joints,
easy to describe rock type
320 to 340 ft BLS

320-328 ft BLS



329-339 ft BLS

ne

Fracture Genesis

Geology by Geophysical logs

GP Logs

- Electric logs in fresh holes show
  - low resistivity and high resistivity
  - You interpret
    - rock type
    - water chemistry
    - fracture nature
    - Weathering
- Electric logs in old holes show
  - Same as above +
  - Impact of weathering
- Caliper logs in fresh hole vs old holes show
  - smooth walls will erode--- in some places
  - Fractures will expand

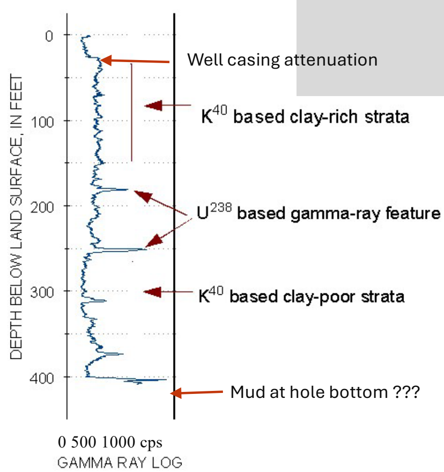
Geology by Geophysical logs

- Gamma logs show
  - low high and very high gamma counts
    - Potasium 40 (K^{40}), uranium, thorium content
  - You interpret
    - Rock type
    - Weathering
- Flow meter logs
    - Flow up hole, down hole, and rate
- Borehole image logs
    - ABI Hardness of wall, wall distance
    - Rock color
    - Bed and fracture strike and dip (with manipulation)

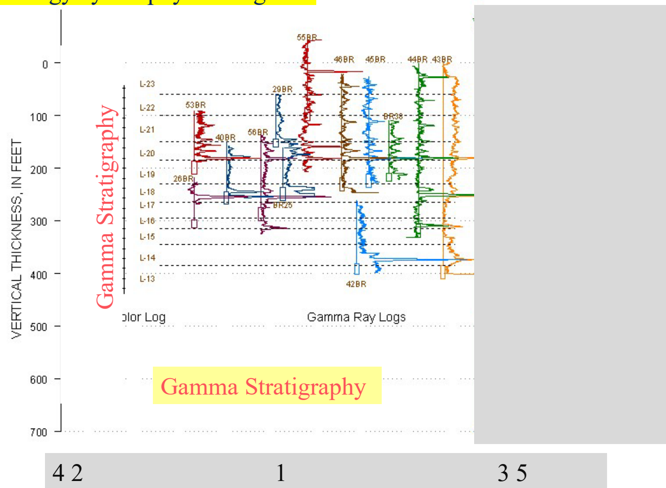
- Must consider
- well casing
  - steel
  - PVC
  - Double-cased; triple-cased
  - screen interval
- Must add
  - Drillers logs,
  - Geologist logs,
  - Construction logs
  - Local hydrologic information
  - Water level data
  - Water quality data
- Must
  - marry multiple logs to create sections to start CSM

Geology by Geophysical logs

Natural Gamma-ray log
Well 43-BR
Naval Air Warfare Center



Geology by Geophysical logs



Geology by Geophysical logs

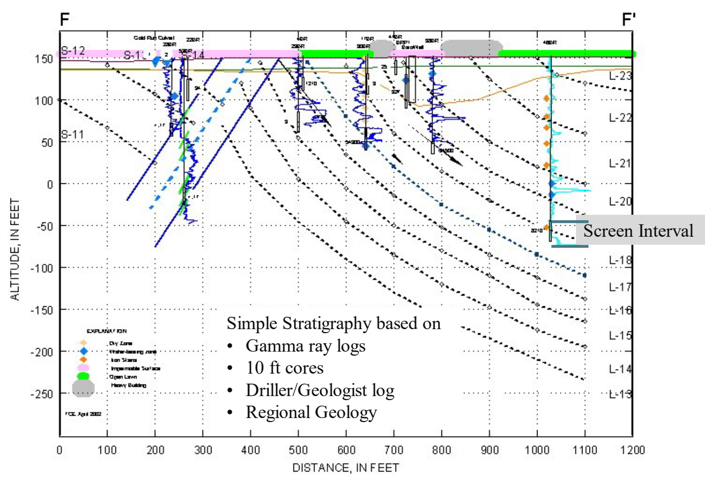
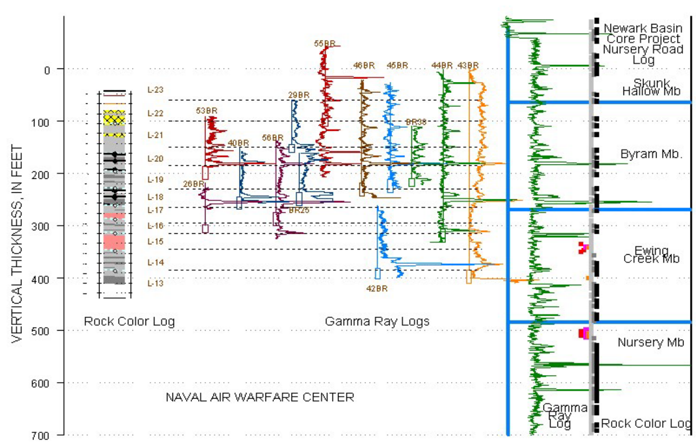


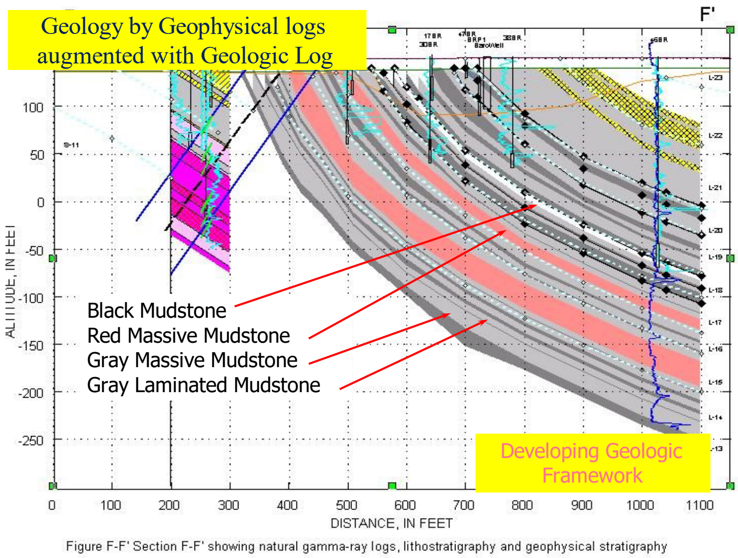
Figure F-F' Section F-F' showing natural gamma-ray logs, lithostratigraphy and geophysical stratigraphy

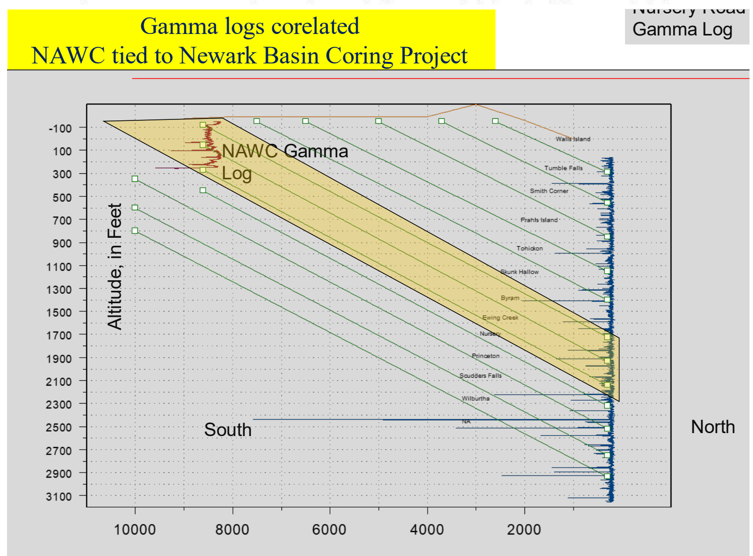
Geophysical logs augmented with

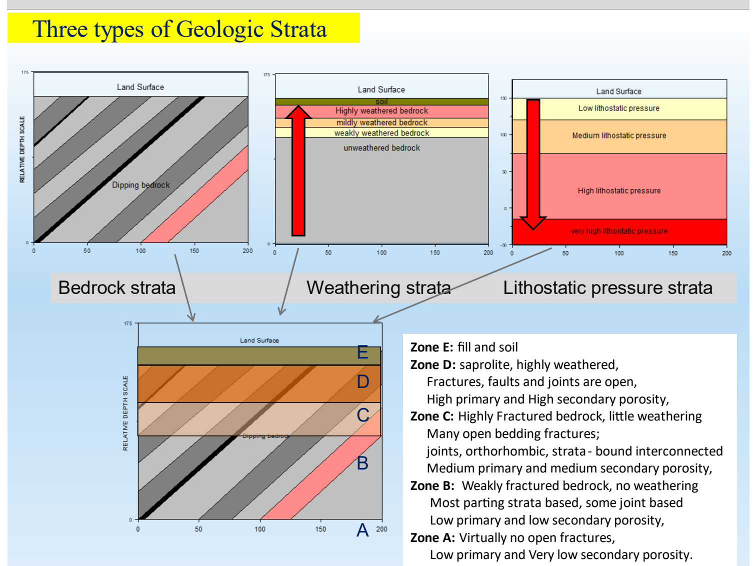
Local Geology

Newark Basin Coring Project Geology & Geophysics




Geology by Geophysical logs
augmented with Geologic Log
F'
100
50
0
-50
-100
-150
-200
-250
ALTITUDE, IN FEET
Black Mudstone
Red Massive Mudstone
Gray Massive Mudstone
Gray Laminated Mudstone
Developing Geologic
Framework
0
100
200
300
400
500
600
700
800
900
1000
1100
DISTANCE, IN FEET
Figure F-F' Section F-F' showing natural gamma-ray logs, lithostratigraphy and geophysical stratigraphy


Gamma logs corelated
NAWC tied to Newark Basin Coring Project
Gamma Log
NAWC Gamma
Log
Altitude, in Feet
-100
100
300
500
700
900
1100
1300
1500
1700
1900
2100
2300
2500
2700
2900
3100
South
North
10000
8000
6000
4000
2000


Three types of Geologic Strata
Land Surface
Dipping bedrock
Land Surface
soil
Highly weathered bedrock
mildly weathered bedrock
weakly weathered bedrock
unweathered bedrock
Land Surface
Low lithostatic pressure
Medium lithostatic pressure
High lithostatic pressure
very high lithostatic pressure
Bedrock strata
Weathering strata
Lithostatic pressure strata
Land Surface
E
D
C
B
A
Zone E: fill and soil
Zone D: saprolite, highly weathered,
Fractures, faults and joints are open,
High primary and High secondary porosity,
Zone C: Highly Fractured bedrock, little weathering
Many open bedding fractures;
joints, orthorhombic, strata - bound interconnected
Medium primary and medium secondary porosity,
Zone B: Weakly fractured bedrock, no weathering
Most parting strata based, some joint based
Low primary and low secondary porosity,
Zone A: Virtually no open fractures,
Low primary and Very low secondary porosity.

Three types of Geologic Strata

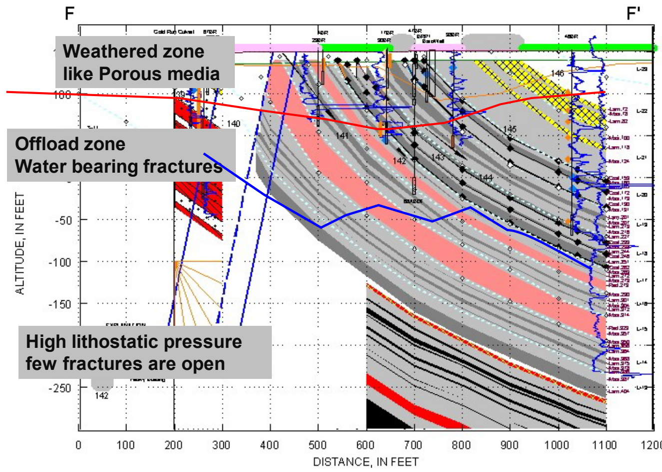


Figure F-F' Section F-F' showing natural gamma-ray logs, lithostratigraphy and geophysical stratigraphy

Contamination, Water levels & Geologic Strata

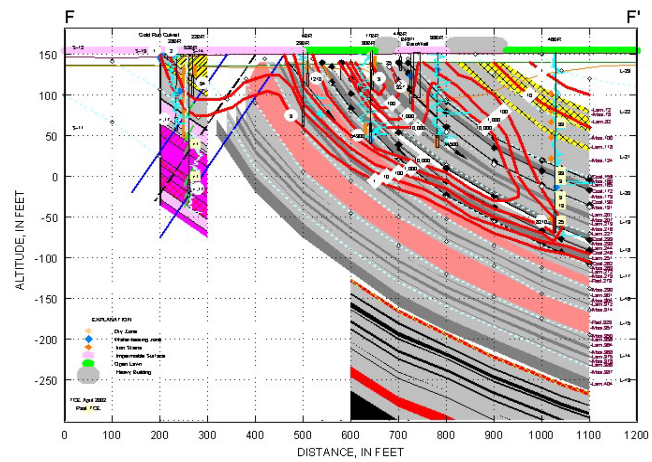
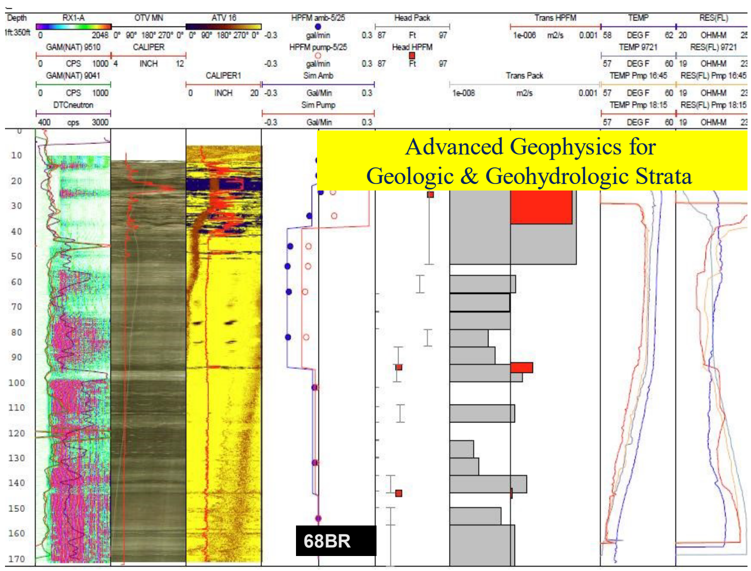


Figure F-F' Section F-F' showing natural gamma-ray logs, lithostratigraphy and geophysical stratigraphy

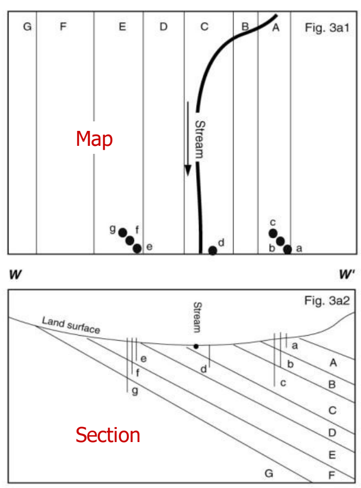


Potentiometric Surface & Geohydrologic Strata

Potentiometric Surface, Frameworks

In fractured sedimentary dipping bedrock

- Water Level Data
- Water Quality Data

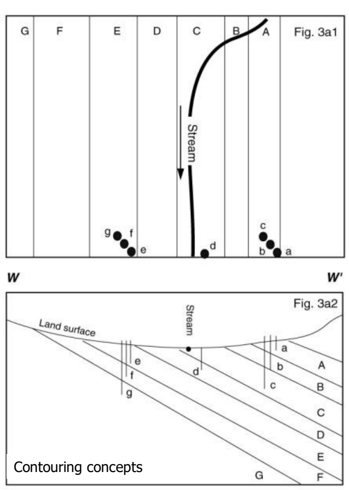


Figures 3a. Map and section *W-W'* showing a hypothetical small valley, strike and dip of bedrock, stream, and wells.

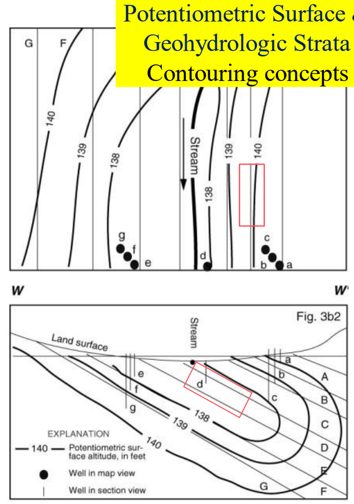
Potentiometric Surface & Geohydrologic Strata
Contouring concepts

potentiometric surface.

Potentiometric Surface & Geohydrologic Strata
Contouring concepts



Figures 3a. Map and section *W-W'* showing a hypothetical small valley, strike and dip of bedrock, stream, and wells.



Figures 3b. Map and section *W-W'* showing static potentiometric surface.

Potentiometric Surface & Geohydrologic Strata Contouring concepts

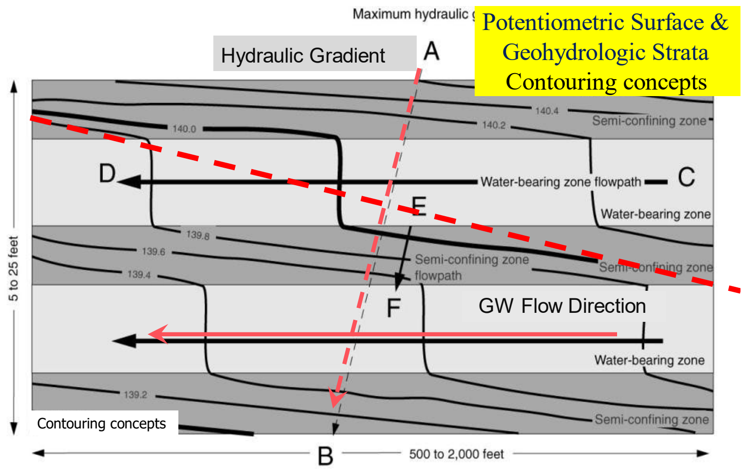
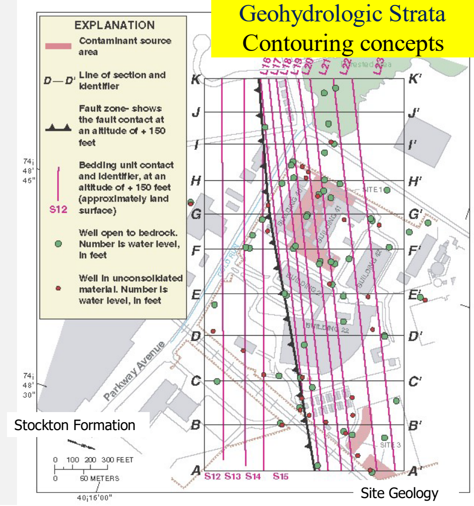


Figure 4. Bedding unit in a hypothetical bedrock aquifer that shows fine-scale water-bearing zones and semi-confining zones. [Potentiometric surface contours are constructed to reflect hydraulic conductivity of the zones. Thin dashed arrow indicates maximum hydraulic gradient (A-B). Thick arrows indicate maximum flow in water-bearing zone (C-D) and limited flow through semi-confining zone (E-F).]

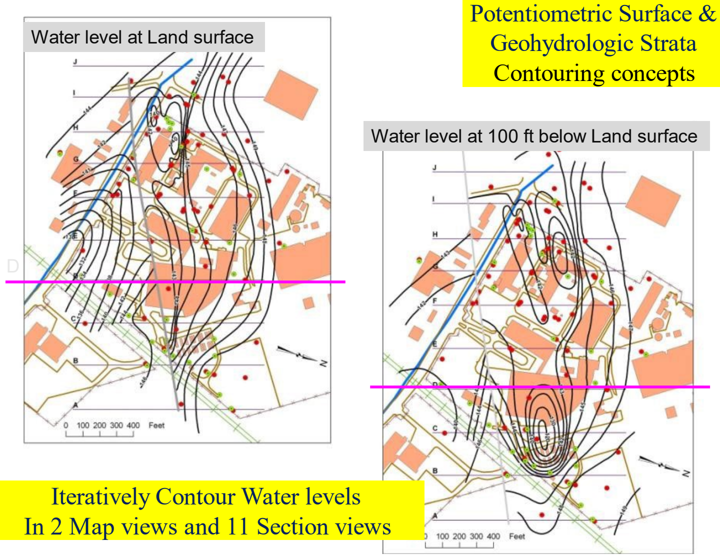
Framework Maps
A) Land Surface
B) 100 ft Below LS
C) show simple framework
D) Sections perpendicular to strike direction
E) Well locations

Framework Sections
A) 11 sections A-A' to K-K'
B) Section // to Dip direction
C) Show well open intervals

Potentiometric Surface & Geohydrologic Strata Contouring concepts



Potentiometric Surface & Geohydrologic Strata Contouring concepts



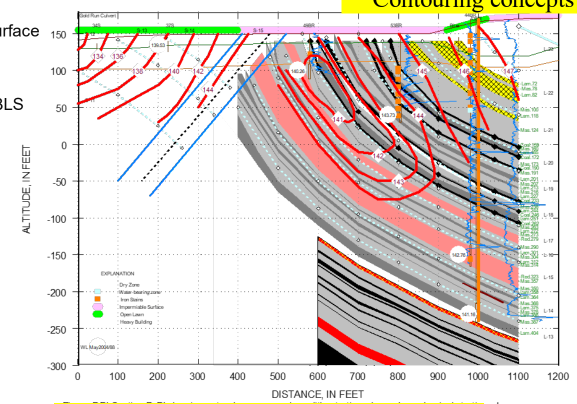
Iteratively Contour Water levels
In 2 Map views and 11 Section views

Potentiometric Surface & Geohydrologic Strata Contouring concepts

Potentiometric Surface

@ Land surface

@ 100 ft BLS



Iteratively Contour Water levels
In 2 Map views and 11 Section views

Potentiometric Surface & Geohydrologic Strata Contouring concepts

Aquifer test –15BR—

Drawdown
100 ft Below Land surface

Pumping well ~15 gpm
Anisotropy about 6 to 1

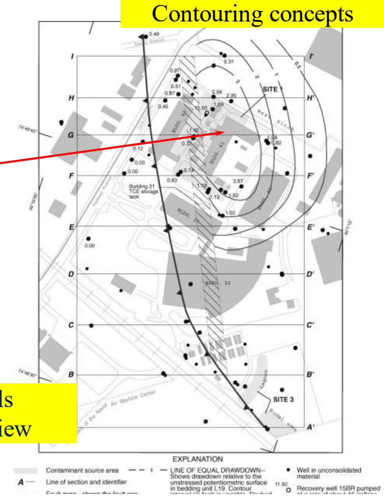
Iteratively Contour Water levels
In 2 Map views and 11 Section views

Contouring concepts

Potentiometric Surface & Geohydrologic Strata Contouring concepts

Aquifer test –15BR—
Drawdown
With in layer L-19

Pumping well ~15 gpm
Anisotropy about 2 to 1



Iteratively Contour Water levels
In Strata layer L-19 and Map view

Contouring concepts

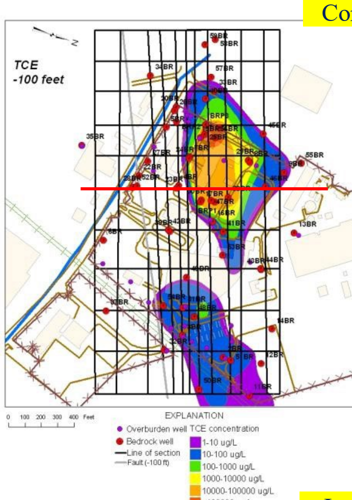
Contamination & Geohydrologic Strata

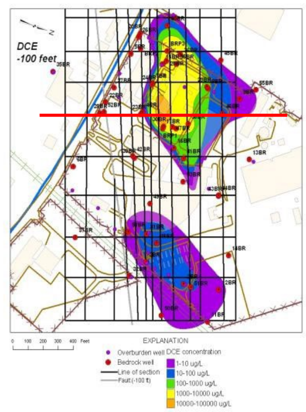
Water Quality Frameworks

In fractured sedimentary dipping bedrock

- Water Level Data
- Water Quality Data

Contamination & Geohydrologic Strata





TCE concentration areas 100 feet below land surface at the Naval Air War
West Trenton, NJ

Iteratively Contour TCE concentration
In 2 Map views and 11 Section views

Contamination & Geohydrologic Strata

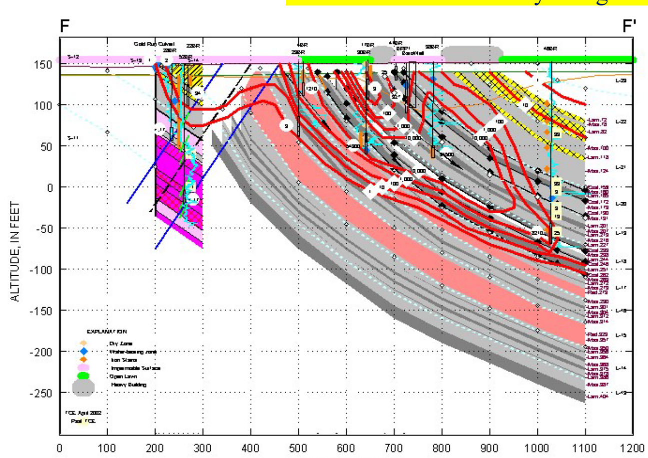


Figure F-F' Section F-F' showing natural ga

Iteratively Contour TCE concentration
In 2 Map views and 11 Section views

Summary

Development of a hydrogeologic framework

a) Should start with an understanding of the regional geologic framework
b) Out crop data is prejudicial only indurated strata exposed
c) Drill cuttings should be collected to bottom of hole & then described
d) Drill cuttings described wet and dry
e) Cores described wet and dry
f) Cores and cuttings described with Geophysical logs
g) Concept, three different strata. 1) Bedding 2) Weathering 3) Offloading STRATA
h) Deep water strata laterally extensive. Shallow water strata punctuated
i) Map both concepts and data.......... not just data
j) Think and draw iteratively.... not serially
k) Hydrogeology of deep indurated strata will change in weathered strata
l) Contour both concepts and data...... not just data
wells are rarely sources of contamination
j) Framework need by many different scientists, agencies, people,
k) Aim for a detailed hydrogeologic map and sections .... not a detailed buildings map and simple sections

4. Hydrostructural Geology: Examining the Anisotropy Assumption for Solute Distribution in Bedrock Aquifers

Thomas D. Gillespie, PG; Gillmore & Associates, Inc.

Abstract

Stratigraphic and structural planar discontinuities which provide for the bulk of groundwater flow through the consolidated rock aquifers of the Newark Rift Basin occur primarily as three-dimensional networks consisting of sets of non-randomly oriented, pervasive, finite, two-dimensional pore spaces. Conceptualizations of groundwater flow through such discontinuity networks range from those in which it is assumed that no planar fabric element exerts a dominating control on flow directions to those in which a single fabric element of several in a network controls flow. The conceptualizations of individual investigators and regulatory agency reviewers is many times applied presumptively, with the investigation being designed and the results interpreted within the constraints of the particular presumptive concept – a practice which has the potential to result in a self-fulfilling prophecy. The position reported herein is that there is no conceptualization of groundwater flow and contaminant transport in bedrock aquifers which can be presumptively applied across all terrains and, more specifically in the case of the structural rift basins inboard of the coastal plain along the length of the Atlantic Continental Margin, no universally applicable conceptualization. That is because both the lithologic and hydraulic properties of the several formations and numerous stratigraphic members within the Basin vary considerably both horizontally and vertically at scales comparable to the study areas of virtually all site investigations, as do the networks of stratigraphic and structural discontinuities through which gravity-driven groundwater flow occurs.

The method described examines flow within individual discontinuities and discontinuity networks at scales of both the Representative Elemental Volume and the hydrogeologic domain and provides for conceptualization of groundwater flow and contaminant transport after site-specific structural and hydrologic data are combined pursuant to the self-evident hydraulic premises that, within the different zones of three-dimensional hydraulic potential fields: all pore spaces are saturated; all particles of groundwater are possessed of a total hydraulic potential; and the local field hydraulic gradient is the controlling factor on groundwater flow direction. The resolution of local field hydraulic gradients into the differently-oriented discontinuity sets of a network determines local groundwater anisotropy characteristics on the scale of the representative elemental volume. The degree to which the anisotropy inherent at the representative elemental volume scale magnifies to the scale of the hydrogeologic domain is a function of: the angular disparity between the field hydraulic gradient and the mean orientation of each discontinuity set considered collectively; the spatial distribution of the discontinuity sets; the connectivity of sets within the network; and the mean surface areas of individual, finite discontinuities in each set. The apparent condition of anisotropy that groundwater is partitioned preferentially into specific stratigraphic zones is herein shown to be a function of lithologic and structural conditions prevalent within those zones; the orientation of the strike of bedding in such zones exerts no more control on flow direction than do the strike directions of other discontinuity sets in the network.

Introduction

Groundwater flow in bedrock aquifers is primarily through three-dimensional discontinuity networks consisting of multiple sets of pervasive, non-randomly oriented structural and/or stratigraphic discontinuities, the strikes of which are typically not co-oriented with the hydraulic gradient. Within each discontinuity set of the sedimentary formations of the Newark Basin, individual discontinuities are finite, two-dimensional pore spaces connected to one or more discontinuities of other sets (Zakharova, et. al., 2016). Formations of the Newark Basin typically contain two types of pervasive discontinuity sets:

- Stratigraphic - consisting of bedding plane partings and member/formation contacts. These tend to be finite, sub-planar partings with generally consistent low dip angles (typically ~10°) toward the northwest, although significant variability is not uncommon;
- Structural - including veins (open and filled; Herman, 2005) and joints, the latter of which are predominantly finite, sub-vertical, planar extensional partings typically consisting of two sets:
    - a systematic joint set, which was the first of the two sets to form. Individual joints within this set are sub-vertical and are continuous over surface areas in the range of approximately 200 m^2 (Twiss & Moores, 2007):
    - a non-systematic joint set, also referred to as cross joints. These joints are sub-vertical, are generally sub-orthogonal to the systematic joints and extend only the distance between two successive systematic joint planes.

Accordingly, it is generally the case that sedimentary rocks of the Newark Basin contain at least three mutually orthogonal discontinuity sets (Harms and Stephens, 1979; Herman, 2001, 2005) including joints, veins, faults and stratigraphic fabric (Figure 1). It is commonly observed that within the scale of any site investigation the rock is segmented by two steeply-dipping brittle failure discontinuities and bedding plane partings (Herman, 2001, 2005). Flow within the igneous rocks of the Basin are not considered herein (Figure 1b).

The several major sedimentary formations of the basin display significant differences in the spacing of bedding plan partings, member contacts and structural discontinuity spacing. Accordingly, the research presented herein is applicable to all of the formations, but is specific to none.

Figure 1a. Photograph of the Stockton Formation depicting bedding plane partings and two sub-orthogonal joint sets (photo from NJDEP)

Figure 1b. Photograph of diabase sill, Plainsboro depicting non-randomly oriented extension joints (photo by the author)

Similar to porous medium aquifers, bulk aquifer flow is down a field hydraulic gradient (Bear, 1983) within the constraints of local/regional three-dimensional hydraulic potential fields and occurs at a velocity consistent with the formation's bulk hydraulic conductivity (Smith and Schwartz, 1993). Except for hydraulic conditions within zones of influence of permanent water supply wells, the distribution of solutes into a plume (Poehls & Smith, 2009) occurs under the hydraulic influence of the natural prevailing field hydraulic gradient. In a bedrock aquifer consisting of multiple, non-randomly oriented, planar discontinuity sets, distributional anisotropy of solutes with respect to the natural field hydraulic gradient can result from unequal rates of flow into and through the differently-oriented discontinuity sets with respect to the field hydraulic gradient (Figure 2) on the scale of the representative elemental volume (REV, Bear, 1983).

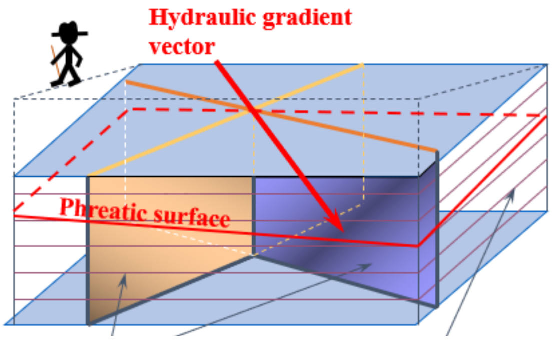


Figure2a. Block diagram schematic of a saturated rock mass with three sub-orthogonal discontinuity sets in which the hydraulic gradient vector is not sub-parallel to any of the sets.

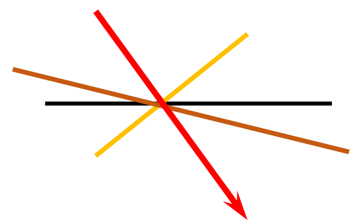


Figure 2b. Strike directions of the three discontinuity sets of Figure 5a, depicting the azimuthal relationships with the field hydraulic gradient vector (red arrow).

The degree to which anisotropy at the scale of the representative elemental volume translates to the domain scale (Surrette and Allen, 2008; Smith and Schwartz, 1993) is a function of: the angular disparity between the field hydraulic gradient and the in-plane gradients of each discontinuity set considered collectively; the spatial distribution of the discontinuity sets; the connectivity of sets within the network; and the mean surface areas of individual, finite discontinuities in each set.

In-Plane Hydraulic Gradients, Flow in Individual Discontinuities and Discontinuity Sets

At the scale of the representative elemental volume, the intersection of the planar phreatic surface and the wall rock of a saturated discontinuity describes an apparent dip (Figure 3). The plunge of the line of intersection (A-B') is at an angle less than the dip of the phreatic surface (Line A – B) with a trend close, but not equal to, the strike of the more steeply dipping discontinuity plane (Ragan, 2009). Because the along-strike decrease of the phreatic surface elevation within the discontinuity is the measure of decreasing total hydraulic potential (Hubbert, 1940), the plunge of the line of intersection of that phreatic surface resolved within the discontinuity describes an in-plane hydraulic gradient vector between Points A and B'. The result is that flow within individual planar discontinuities is in a direction generally, but not exactly parallel to the strike of that structural plane and at some angle, α, to the horizontal which is less than the dip angle of the field hydraulic gradient (A – B, Figure 3).

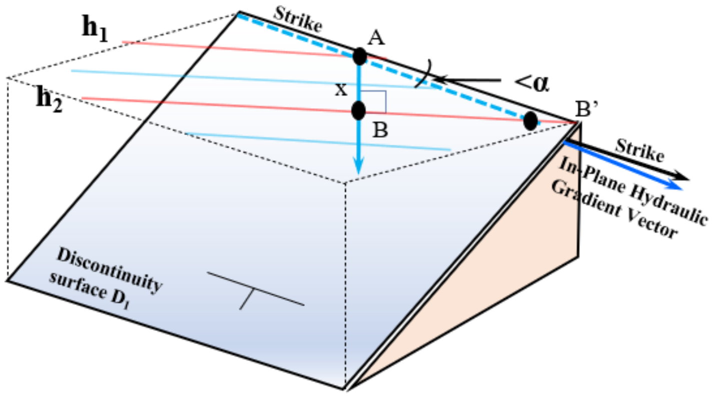


Figure 3. Configuration of the phreatic surface within a planar discontinuity. The line of intersection between the phreatic surface and the discontinuity walls (apparent dip A – B') is at some angle to the strike of the plane.

All pore spaces below the phreatic surface are saturated so every particle of water in the phreatic zone has a hydraulic potential consisting of an elevation head and pressure head consistent with the total hydraulic potential measured as the phreatic surface at any point. Consequently, every particle of groundwater is both affected by and affects that potential field. Therefore, groundwater in three-dimensional hydraulic potential fields flows simultaneously through all discontinuities within the non-randomly-oriented structural and stratigraphic sets. Instantaneous groundwater flow through any unit volume of aquifer, therefore, occurs in several directions, each sub-parallel to the strikes of the containing planar discontinuities (Figures 2 and 3), typically none of which directions are directly down the field hydraulic gradient on the scale of the representative elemental volume (Figure 4).

In Figure 4, a particle of groundwater at the upgradient end of discontinuity-bounded blocks of rock (Nos. 1 and 2, Point A) enters Discontinuity 1, a single joint plane in a systematic set, the strike of which is oriented θ_1° from the field hydraulic gradient. Within Discontinuity 1, there is a component of cross gradient flow (c) for every unit distance of downgradient flow (a). The actual distance traveled by the particle of water (d) is longer than the distance directly down the field hydraulic gradient by a factor of: $a/\cos\theta_1$ but the difference in elevation (h1 – h2) is the same in plane segment, d, as it is in the direction of the field hydraulic gradient, a. The in-plane hydraulic gradient in plane segment d, therefore, $(h_1 - h_2)/(a/\cos\theta_1)$, is of lesser magnitude than the field hydraulic gradient, $(h_1 - h_2/a)$.

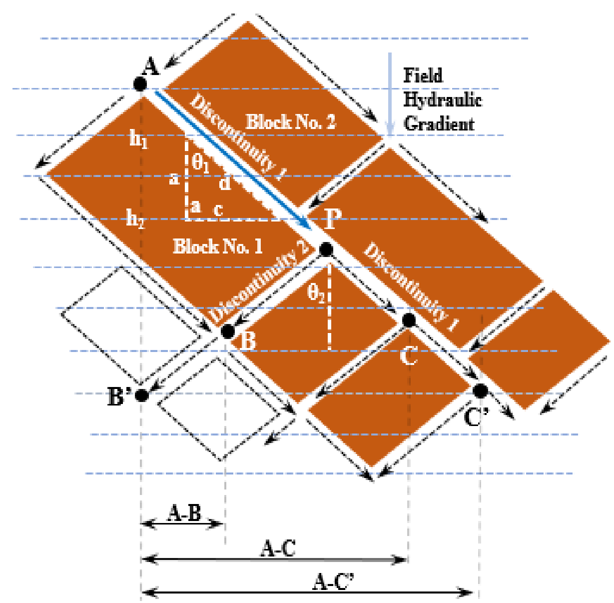


Figure 4. Two-dimensional schematic of flow through multiple, non-randomly-oriented planar discontinuities

The cross-gradient component of flow within Discontinuity 1 (leg c of the right triangle), persists until the particle of groundwater reaches Point P where there is a junction with Discontinuity 2. At Point P the particle of groundwater must either continue along the in-plane gradient in Discontinuity 1 ($(h_1 - h_2)/(a/\cos\theta_1)$) or enter Discontinuity 2 with an in-plane gradient of $(h_1 - h_2)/(a/\cos^{-}\theta_2)$. It is at the infinitesimal inflection points where a particle of water can move from one discontinuity into another that instantaneous flow can be directly down the field hydraulic gradient (Surrette and Allen, 2008; Smith and Schwartz, 1993). Depending on which discontinuity it enters, the particle's flow will be in a direction which will, at the end of traversing the distance of one additional REV, bring it either nearer to (distance A-B) or farther from (distance A-C) a point directly downgradient of Point A where the local diversion from the field hydraulic gradient began. After having traveled the distance of two representative elemental volumes (particle at either Point B' or C'), the potential range of resultant cross-gradient deflections would either bring the particle to a point directly down the field hydraulic gradient from Point A (B'), or to distance A-C' in the cross-gradient direction. Continued deflection(s) into the two discontinuity sets depicted in the two-dimensional schematic of Figure 4 can either normalize or amplify the anisotropy of flow with respect to the direction of the field hydraulic gradient. It is also at the intersections where mixing of solutes occurs and which points are, consequently, the loci of anisotropic transport (Smith and Schwartz, 1993).

Because the loss of hydraulic potential within the confines of a discontinuity is continuous along the plunge of the in-plane gradient vector (Toth, 2009; Hubbert, 1940), the orientation of the in-plane gradient can be determined within the discontinuity (Figure 5) using mapped equipotentials of the field hydraulic gradient.

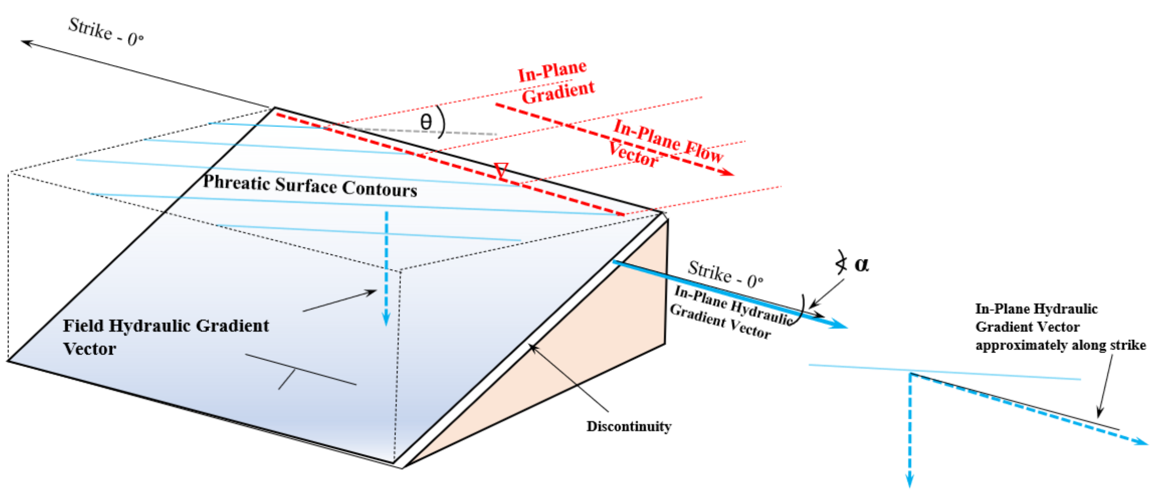


Figure 5. Line of intersection (broken red line) between phreatic surface and planar discontinuity sidewall with a trend direction between the strikes of the two planar surfaces but nearer the strike of the steeper plane and a plunge angle less than the dip angle of the hydraulic gradient (Ragan, 2009).

The degree to which the orientation of the in-plane gradient differs from the field hydraulic gradient can be determined by trigonometrically resolving the field hydraulic gradient contours into the discontinuity. In Figure 6, discontinuity Plane A intersects the field hydraulic gradient at angle Θ, forming a right triangle between the field gradient vector (Line A – C) and the plane. The length of the adjacent leg, AC, which is equivalent to the change in distance (ΔX) over which the phreatic surface elevation of the field gradient decreases from h_1 to h_2, is lesser than the length of the hypotenuse, BC, the measured length of the in-plane hydraulic gradient, ΔX_1, which is given by:

$$\Delta X_1 = \Delta X / \cos \Theta \qquad \text{eq. 1}$$

The change in elevation, $h_1 - h_2$, over both distances ΔX and ΔX_1 remains constant (Figure 6), resulting in an In-Plane Gradient, i_p, lower than the field hydraulic gradient by an amount given by:

$$i_p = (h_1 - h_2)/(\Delta X / \cos \Theta) \qquad \text{eq. 2}$$

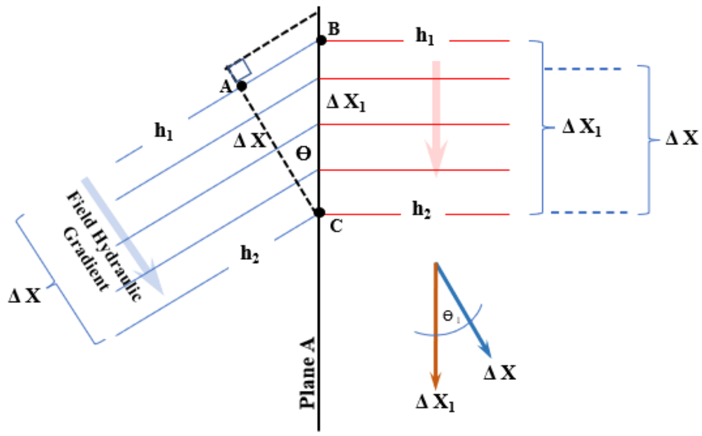


Figure 6. Schematic of groundwater flow within a single discontinuity plane depicting the difference between the FHG and in-plane gradients.

Figure 7 is a schematic of flow within two intersecting discontinuities, the strike of one being parallel to the field hydraulic gradient. The horizontal distances traveled by two particles of groundwater originating simultaneously at the discontinuity intersection, P, and flowing down pathways PB and PC, respectively, are equal (PB = PC = r), but the total hydraulic potential of the particle at Point C is higher than the particle at Point B, having lost only half the energy over the same travel distance. The in-plane hydraulic gradient along pathway PC, therefore, is lower that the gradient along pathway PB. Consequently, the potential velocities of groundwater particles flowing through the two pathways are unequal and can be estimated using the Darcian equation for bulk flow through some domainally-relevant cross-sectional

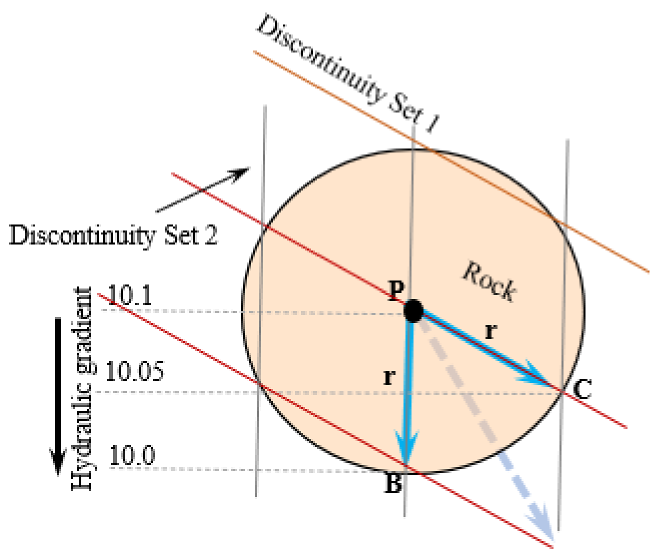


Figure 7. Schematic of differential flow potential and anisotropic distribution of solutes in differently-oriented discontinuities under a single field hydraulic gradient on the scale of the representative elemental volume.

area of the formation (Smith and Schwartz, 1993):

$V_{PB} = k(^{-}0.1/r)/n$ (eq. 3)

$V_{PC} = k(^{-}0.05/r)/n$ (eq. 4)

with the theoretical result that $V_{PC} < V_{PB}$.

Therefore, two particles of water leaving Point P simultaneously but flowing down the two pathways, would not reach Points B and C at the same time. That is intuitive because if they did, the field hydraulic gradient would be at an azimuth mid-way between the strikes of the two discontinuity planes (grey broken arrow in Figure 7) as described by Smith and Schwartz (1993).

Because of the lower gradient of path PC, the travel distance for a particle of water to reach the equivalent hydraulic potential of Point B is illustrated in Figure 8 where distance PC' is given by:

$(r/\cos\Phi) - r$ (eq. 5)

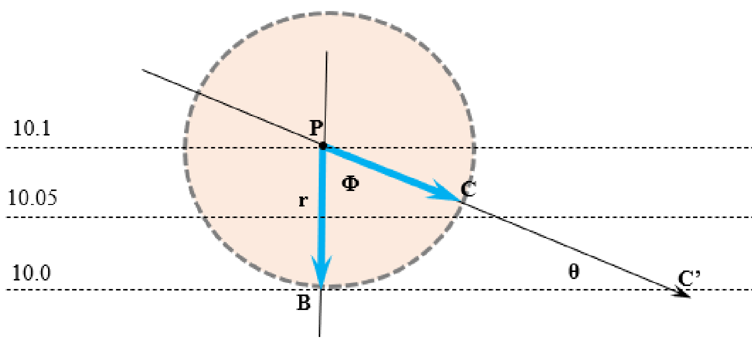


Figure 8. Difference in travel distance for two particles of water beginning at elevation 10.1 at Point P and ending at the same equipotential at elevation 10.0 (Points B and C').

Relative travel times in the two planes are given by:

Discontinuity PB: $t_{PB} = r/(k(^{-}0.1/r)/n)$ (eq. 6)

and

Discontinuity PC' $t_{PC'} = (r/\cos\Phi)/(k(^{-}0.05/r)/n)$ (eq. 7)

Consequently, on the scale of the REV, directional anisotropy in the bulk rate of solute transport down the field hydraulic gradient but partitioned into planar discontinuities at unequal azimuthal angles to the field hydraulic gradient derives from both the difference of in-plane potential velocity (Eqs. 3 and 4) and from extended flow path lengths (eq. 5) with the resulting difference in travel times down the two different pathways (Eqs. 6 and 7). Examining this phenomenon schematically (Figure 9), it is evident that two water particles which begin flowing at time t0 at Points A and B, but flowing down Planes D1 and D2, respectively, will not reach Point C simultaneously. However, because groundwater in the phreatic zone is a continuum, two random particles of water in Discontinuities D1 and D2, respectively, have identical total hydraulic potentials at Points D and D' because they occur within a single flow field and are located on the same equipotential line. But the particles have different potential velocities so the equivalence is instantaneous and transient; i.e., the similar equivalence in hydraulic potential at points E and E' at some later time would not be between the same two particles of water. Consequently, flow through a discontinuity network is not normal to equipotential lines of the field hydraulic gradient at most locations on the scale of the representative elemental volume with the exception of the infinitesimal points of intersection between the several discontinuity sets of the network.

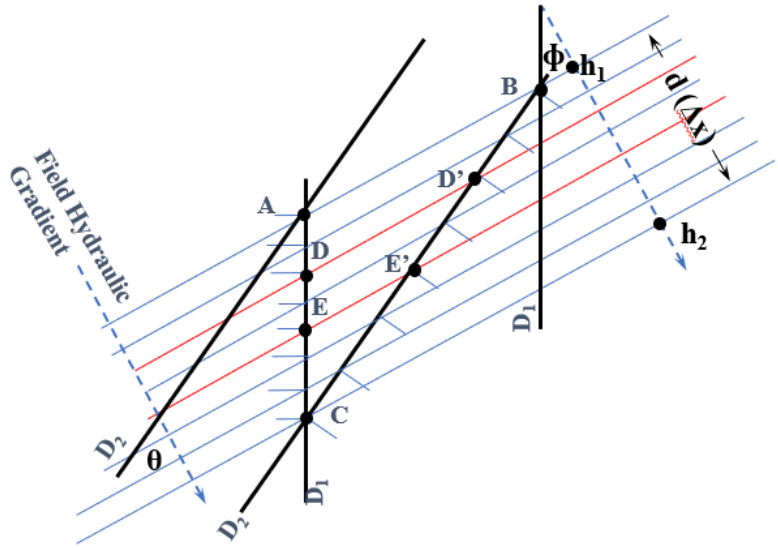


Figure 9. Comparison of in-plane hydraulic gradients in two intersecting discontinuity sets

In Figure 9, the in-plane gradient in Discontinuity Planes D_1 and D_2 are given by:

i_{J1} = (h1-h2)/(d/cosϕ) eq. 8

i_{J2} = (h1-h2)/(d/cosθ) eq. 9

Because bulk formation velocity is $v = ki/n$, and because k, n are equivalent in both planes but i_p in planes D_1 and D_2 are different and unique in that $i(D_1) > i(D_2)$, then the potential velocity $v_p(D_1) > v_p(D_2)$.

Figure 10 depicts the resolution of a field hydraulic gradient into two discontinuities in the manner examined in Figure 6. Representative discontinuities from two sets are superimposed on contours of the field gradient and the in-plane gradients are calculated using Equation 2, with the result that the in-plane gradient in Discontinuity Set D_2 is not just higher than in Discontinuity Set D_1 but is closer in dip angle to the field gradient as evident by the spacing of the red in-plane gradient contours.

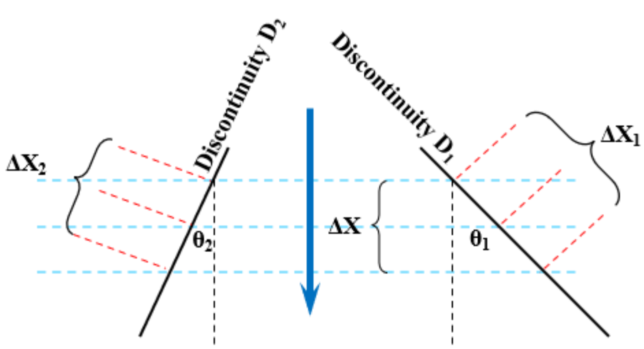


Figure 10. Superposition of two discontinuities onto a field hydraulic gradient, depicting the difference in in-plane gradients

Accordingly, in a condition in which there are no differences between the discontinuities within the two sets other than their orientations, a water particle would have a greater tendency to enter a D_2 plane because it would have a higher gradient than a D_1 plane by a factor of:

$$((h_1-h_2)/(\Delta X_2/\cos \Theta_2))/((h_1-h_2)/(\Delta X_1/\cos \Theta_1)) \qquad \text{eq. 10}$$

and consequently a higher potential velocity. Under such hydraulic conditions, it is many times presumed that the apparent anisotropy of flow would result in a plume deflected from the field hydraulic gradient in the direction of discontinuity D_2. The anisotropy assumption is that the directional anisotropy on the scale of the representative elemental volume translates into directional anisotropy on the domainal scale. That assumption is based on a companion assumption of continuity of the constituent structural or stratigraphic discontinuities across the scale of the domain; i.e., individual discontinuity planes extend over large areas within a hydrogeologic domain.

Individual discontinuities within pervasive sets, whether bedding plane partings or joints, however, are of finite length (Zakharova, et. al., 2016; e.g., Twiss & Moores, 2007; Lacombe and Burton, 2010) and are intersected by other discontinuities (Figure 11). The combination of those two factors necessitates that, with the exception of stranded particles, most groundwater exits each discontinuity by flowing into intersecting ones, or, in the case of discontinuities near a groundwater discharge boundary, to surface water.

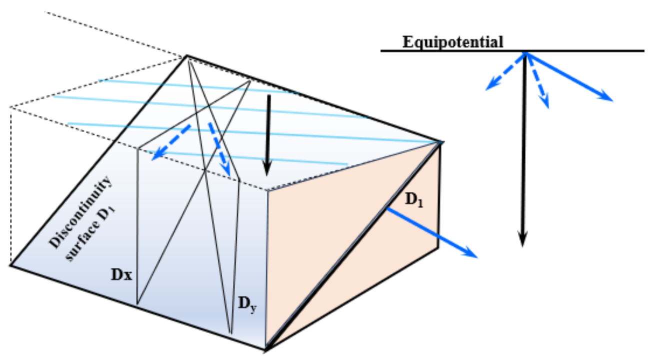


Figure 11. Schematic of available flow path orientations within a discontinuity network

Because all discontinuities below the phreatic surface are members of a connected network and are, by definition saturated with particles of groundwater, each of which possess a total hydraulic potential consistent with the potential of the flow field at that point and measurable as an elevation and pressure head with a total potential manifest as the elevation of the phreatic surface at that location, flow occurs in all available planar pore spaces in a composite direction generally consistent with the potential field. That is especially the case at the intersections between a discontinuity of one set with a discontinuity from another; e.g., a bedding plane parting with a joint. Because the joints are pervasive and connect with bedding plane partings (Lacombe and Burton, 2010), the total hydraulic potential of groundwater particles near the intersections must be identical in both types of planes, so flow in each type is controlled by the orientation of the in-plane gradients as resolved into each discontinuity (Figure 6).

Within any discontinuity (e.g., D_1, Figure 11), the distance a particle of groundwater can travel in a direction other than the field hydraulic gradient (black arrow) is limited by both the finite length of the discontinuity in the direction of the in-plane hydraulic gradient, and by the mean spacing of outlets from that plane in the form of intersecting discontinuities ($D_{(x,y)}$ in Figure 11) which provide flow pathways along other, unique azimuths, each of which serves as a correction factor for flow along a discontinuity strike direction at some azimuthal angle to, and at a lesser gradient than, the field hydraulic gradient (Figure 4). Because there are few situations in nature in which a discontinuity set in a network is oriented directly parallel to the field hydraulic gradient (Figure 4), each particle of water follows an indirect pathway as it moves from discontinuity to discontinuity, always in a direction which takes it from points of higher hydraulic potential to those of lower potential and at each discontinuity point intersection with a theoretical tendency to enter the discontinuity with a strike azimuth closest to the field hydraulic gradient vector and, consequently, the planes with in-plane gradients nearest the field hydraulic gradient. That inter-discontinuity flow occurs sub-parallel to the strikes of the planes (Figure 3) regardless of their respective dip angles.

The orientations of the different discontinuity sets within a network and their angular relationships with the field hydraulic gradient vector result in multiple in-plane gradients on the scale of the representative elemental volume, providing for differing degrees of potential anisotropy. Total anisotropy would occur in two dimensions in an orthogonal discontinuity set pair where the strike of one set is parallel to the field hydraulic gradient vector and the strike of the other set is parallel to groundwater contour lines. Conversely, isotropy would occur in any pair of sub-orthogonal discontinuities where the strikes of each set are equi-angular to the azimuth of the field hydraulic gradient (Smith and Schwartz, 1993), with varying degrees of potential anisotropy resulting from intermediate orientations or from the addition of another discontinuity set. In the former situation, groundwater in the planes oriented normal to the field hydraulic gradient would only flow at times of directional variation of the flow vector, typically after groundwater recharge events or during seasonal fluctuations. For the same reasons of recharge and seasonal variations, some anisotropy would occur in the latter situation. In nature, discontinuities within any set are not precisely parallel but occur in statistically defined sets, the strike of individual planes falling within a range of azimuths. Therefore, there is no condition wherein there is consistently no flow in one set (direction) and all flow is in another.

Although the strike of one set of discontinuities might be oriented closer to the field hydraulic gradient than other sets and therefore possessed of a higher in-plane gradient with a higher potential to convey more flowing water, there are two limiting conditions to the amplification of the inherent anisotropy at the representative elemental volume scale to a pronounced anisotropy on the scale of the hydrogeologic domain:

1. discontinuities of all types are of finite length (Zakharova, et. al., 2016). Groundwater is generally not conveyed in directions other than the field hydraulic gradient over distances greater than the mean discontinuity plane length as measured parallel to the in-plane gradient. That metric is a function of the mean surface area of the planes within that discontinuity set;
2. virtually all discontinuities are connected within a three-dimensional network of structural and stratigraphic planar discontinuities so discharge from the planes of the discontinuity set with the highest gradient is into planes of the set(s) with lower gradient(s) and, consequently,

lower water conveyance potential(s); i.e., no more water can flow through a high-gradient discontinuity than can be received from that discontinuity into intersecting discontinuities of lower gradient and, consequently, lower conveyance capacity.

Figure 12 is a two-dimensional representation similar to Figure 4 with the exception that the assumption of spatial continuity of Discontinuity 1 along a theoretically infinite length along the downgradient scale of the domain has been eliminated with the result that water cannot be conveyed in that specific discontinuity farther than Point C. The result is that the anisotropic distribution of a solute in the direction of the hypotenuse, d, along Discontinuity 1 can not be farther than the cross-gradient distance A – C. Although there is an apparent preference for movement in the set of discontinuities depicted by Discontinuity 1 in Figure 12, water can only flow from points of higher to those of lower potential at a rate and in volumes which can be accommodated by the discontinuities of Set 2.

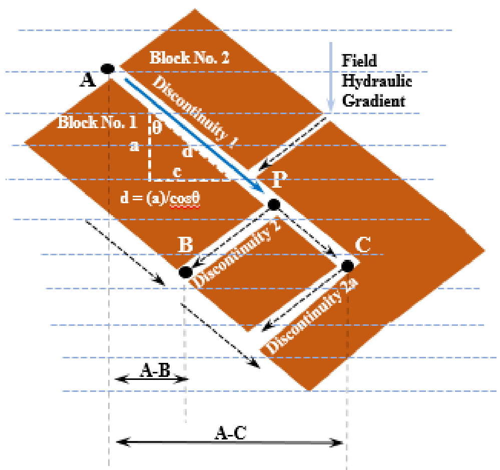


Figure 12. Two-dimensional schematic of flow in a network similar to that depicted in Figure 4 but with the truncation of Discontinuity 1, preventing flow farther along direction d farther than Point C. Continued flow, required by the continuity of the flow field must be into Discontinuity 2a

Figure 12 depicts a condition in which the in-plane gradients of the two discontinuity sets (1 and 2) are essentially equal, resulting in a phenomenon known as the *porous medium equivalent* because the potential velocity in both sets is essentially the same and there is no limiting condition; i.e., the water conveyed down the planes of either discontinuity set can be accommodated by flow into the other (Smith and Schwartz, 1993). In Figure 13 the orientation of the field hydraulic gradient in relation to the two discontinuity sets results in a potential for anisotropic partitioning into the two in-plane hydraulic gradients.

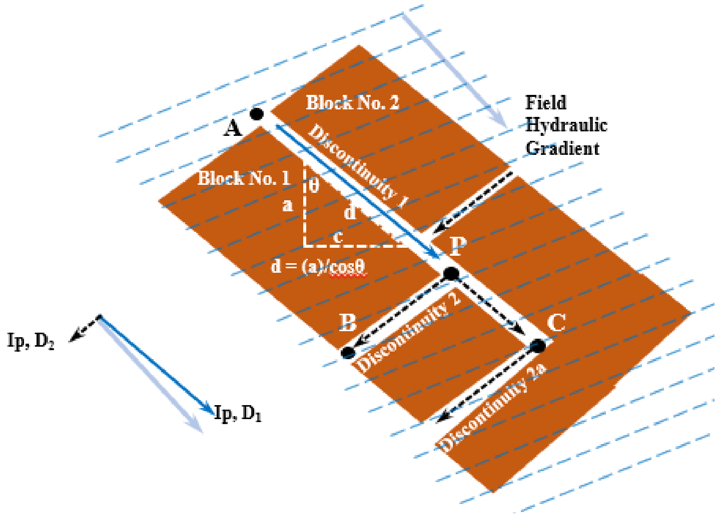


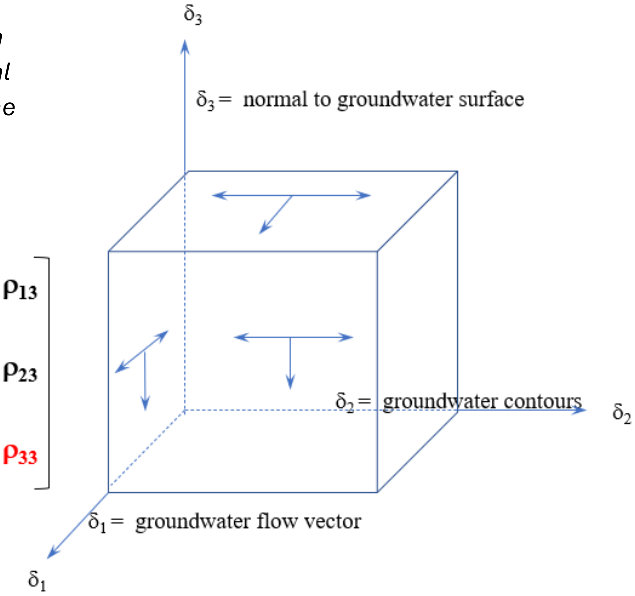
Figure 13. Flow through a discontinuity network in which there is extreme anisotropy between the resolved in-plane gradients and the field hydraulic gradient.

The anisotropy between the two in-plane gradients does not, however, result in an anisotropy in flow velocities between Discontinuities 1 and 2 because the orientation of the in-plane gradient vector of the latter is the limiting condition on flow out of the former; groundwater can only exit Discontinuity 1 at the rate it can be conveyed in the discontinuities of Set 2.

In the configurations depicted in Figures 12 and 13, it is not possible for groundwater to escape from Discontinuity 1 at Point C by moving normal to the plane of the page. Figure 14 is a simplified example of one rock block from Figure 12 arranged so the orientations of planes are in the end-member configuration in which one of the sub-orthogonal plane sets is vertical and parallel to the field hydraulic gradient vector, the second is normal to the field gradient (parallel to the groundwater contours) and a third is horizontal.

Figure 14. Flow along a rectangular block oriented with the FHG. The second order tensor of three-dimensional anisotropic flow on the scale of the REV is defined in the matrix in which the red factors are directions in which flow is not possible.

$$\begin{bmatrix} \rho_{11} & \rho_{12} & \rho_{13} \\ \rho_{21} & \rho_{22} & \rho_{23} \\ \rho_{31} & \rho_{32} & \rho_{33} \end{bmatrix}$$



In Figure 14, it can be seen that flow along any face of the block within a discontinuity of finite thickness consists of two components parallel to two of the directions of the three possible in three-dimensional space but not all are possible hydraulically (red designations in the matrix). Rotating the rock block (Figure 15) so that no bounding discontinuity is parallel to the field hydraulic gradient or groundwater contours and such that the upper bounding discontinuity is no longer horizontal but at some definite angle (Figure 15a) establishes the realistic condition that no discontinuity set is parallel to the field hydraulic gradient. Having established the relationship between the planes and the field hydraulic gradient, the block is rotated back to coincide with a map view (Figure 15b) along with a concomitant rotation of the hydraulic coordinate system. In this configuration, the phreatic surface can once again be depicted similar to the manner shown in Figures 6 and 10 (Figure 15c) and the resolutions into the planes can be calculated.

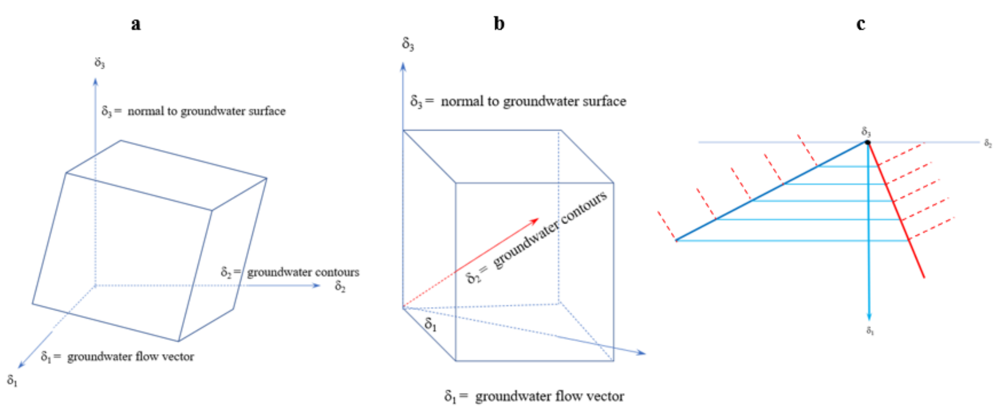


Figure 15. Resolution of flow around a rectangular rock block into two components of flow per face, as described in the text.

Combining the implications of Figures 14 and 15, flow within the confines of a discontinuity of finite thickness consists of a maximum of two components, both parallel to the faces of the bound rock blocks. The relevance to the current matter is that flow at Point C of Figures 12 and 13 can not be in a direction normal to the plane of the page and the rate of flow is limited by the capacity of Discontinuity 2a to convey the water from Discontinuity 1.

Flow in Discontinuity Networks on the Scale of the Hydrogeologic Domain

Despite the conclusion based on the microcosm of an aquifer presented in the foregoing, it is a well-known phenomenon that there are discrete linear or planar zones in bedrock aquifers, often referred to as *water-bearing zones* but hereinafter referred to as high-conveyance-capacity zones, which appear to convey most of the water through an aquifer. Such zones tend to form along structural and/or stratigraphic trends such as fault zones which tend to convey water preferentially along strike but typically act as barriers to flow in cross-strike directions (Gillespie, 2023). As reported by Parizek (2005), groundwater flow can be highest along lineations formed where a fault plane (zone) intercepts another open planar feature, either, e.g., another fault or an open formation contact. They can also occur within conductive strata, as discussed below.

Figure 16 is an idealized cross-sectional conceptualization of a hypothetical high-conveyance-capacity zone of finite width and thickness (i.e., a linear zone) but of theoretically infinite length along strike (into the plane of the page). Such high-conveyance-capacity zones do not occur in isolation but, rather, intercept innumerable, saturated discontinuities of the pervasive, penetrative, three-dimensional structural-stratigraphic network as described above herein. Similar to a surface water stream, the water which enters and is conveyed through such high-conveyance-capacity zones derives from the integrated inflow from the lower-capacity discontinuities which contact the zone and which are in hydraulic communication with the entirety of the surrounding three-dimensional discontinuity network.

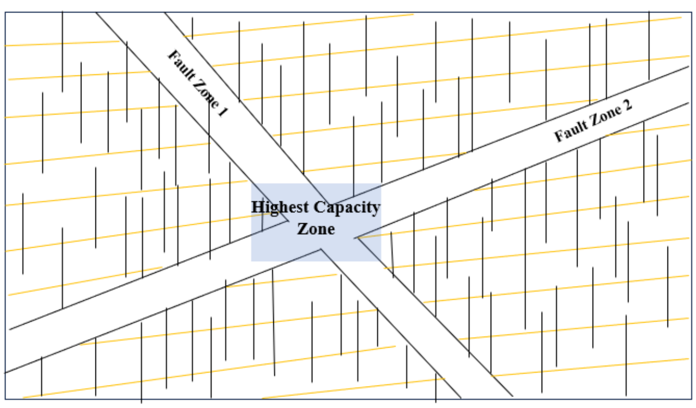


Figure 16. Idealized schematic of high-conveyance-capacity zone formed at the intersection of two fault zones of finite width and thickness but of infinite extent along strike. Groundwater flow is out of the plane of the page.

Such a condition can be modeled on the domainal scale with equipotential lines in the same manner unconfined aquifers can be modeled (Figure 17).

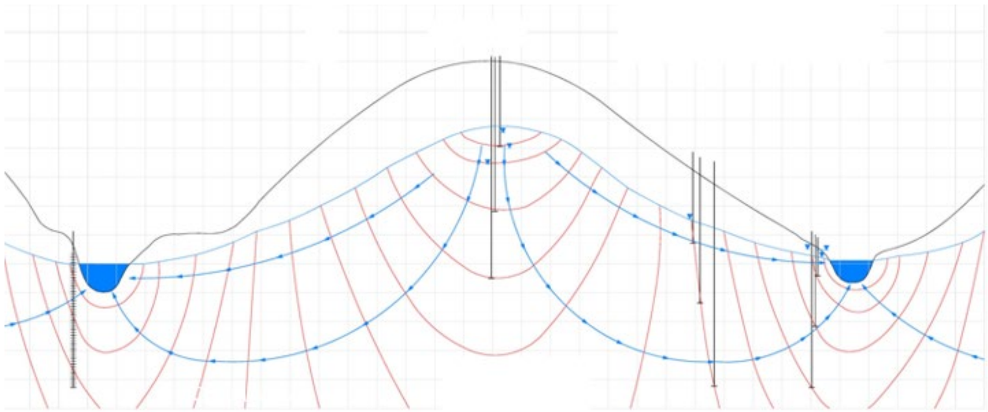


Figure 17. Idealized equipotential field in an unconfined aquifer. Blue lines are groundwater flow lines. Red lines are equipotential lines. Flow within the aquifer has both horizontal and vertical components whether it is an unconsolidated porous medium or bedrock system.

Unlike the situation in the unconfined aquifer of Figure 17 which is bounded at the upper surface and has the lowest hydraulic potential at the surface water discharges, a high-conveyance-capacity zone embedded within the phreatic zone does not have an upper boundary condition (unless it is at a shallow depth), water is conveyed to the zone from all directions (Figure 18) and the lowest hydraulic potential in the local flow field is within the high-conveyance-capacity zone (analogous to the surface stream in Figure 17). It is also possible that there is a lower boundary condition, both of which boundary conditions would limit the vertical development of the equipotential lines depicted in Figure 18.

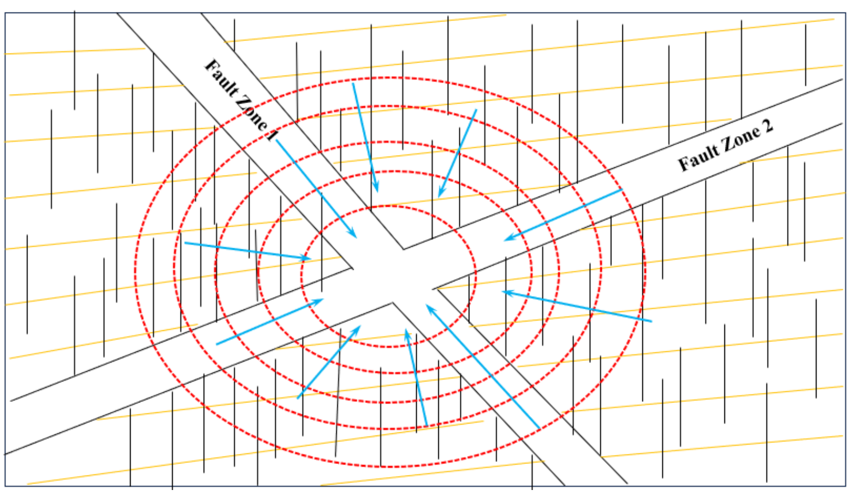


Figure 18. Two-dimensional schematic representation of a three-dimensional equipotential field in an aquifer around a discrete, linear high-conveyance-capacity zone. Blue lines are groundwater flow lines. Red lines are equipotential lines. Flow is toward the viewer.

The hydraulic condition depicted in Figure 18, however, does not exist except in situations in which the high-conveyance-capacity zone is connected to other, downgradient, high-conveyance-capacity zones or extends along-strike far enough that the zone is connected directly to a groundwater discharge. In the absence of an outlet for the water, the volume of water actually conveyed under natural hydrologic conditions through high-conveyance-capacity zones is constrained by the receiving capacity of downgradient zones of the aquifer; i.e., beyond the along-strike extension of the geologic feature(s) which create the high-conveyance-capacity potential. Under conditions where the zone exists but there is no outlet for the water other than the discontinuities of the pervasive, penetrative sets of the three-dimensional networks possessed of a lower bulk hydraulic conductivity, the equipotential field depicted in Figure 18 does not develop and flow is through the discontinuity network as described previously herein.

It is often reported that a monitoring well has encountered discrete high-conveyance-capacity zones and it is assumed that the conveyance of groundwater through the aquifer under natural conditions is predominantly through such zones. It is undeniable that most of the water extracted from such wells during pumping or monitoring derives from those identified zones. However, a well represents a groundwater discharge pathway at those times when observations are being made; i.e., when the well is being purged for sampling or during aquifer testing (Zakharova, et. al., 2016). The presence of the well creates a potential high-conveyance zone or outlet and can create connections between vertically-separated zones which were not otherwise in hydraulic communication naturally (Heisig, 2010). It is not necessarily the case, however, that the high-capacity zones thus identified represent the flow pathways of most groundwater in the absence of the outlet and artificial hydraulic conditions created by the well, although it is possible depending on downgradient conveyance capacities, on the connectivity of such zones with other, downgradient zones either at the same or different elevations within the aquifer and the location of the well within the hydraulic potential field (Figure 17).

Except in a well which is being pumped, the phreatic surface (the physical manifestation of the integrated total hydraulic potential of all particles of water at all points below the phreatic surface) describes a low-angle, planar, dipping surface. In such a situation, there is no hydraulic evidence of the presence of a zone of high conveyance potential. If such as zone is conveying groundwater at a rate higher than the bulk flow rate of the aquifer, it would be measurable as a linear depression parallel to the in-plane gradient of the feature; i.e., along its strike, or, in the case of a planar high-conveyance-capacity zone, a low area on the phreatic surface.

Despite the convergence of flow lines in the profile view of Figure 18, flow along individual discontinuities remains sub-parallel to the strikes of individual planar discontinuities pursuant to the hydraulic requirements as outlined above and in Figures 3 and 5. An analogy to a surface water-groundwater couple is presented in Figure 19 in which the flow lines as depicted in cross section (upper block diagram) are actually sub-horizontal flow lines (lower map view diagram).

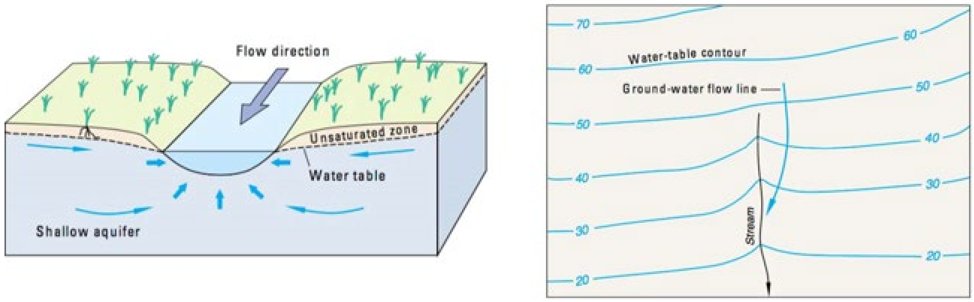


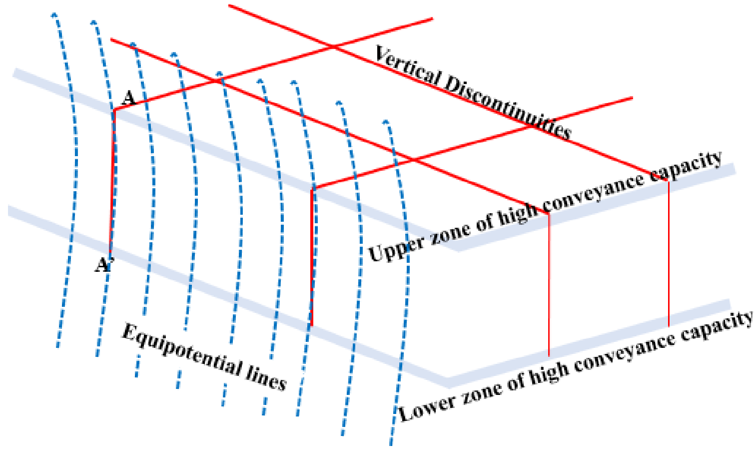
Figure 19. Groundwater flow and discharge to a surface water stream. Flow is dominated by the horizontal component even below the stream with flow lines nearly parallel to the thalweg with an upward component bringing water from lower elevation but higher potential into the stream bed. Original from USGS

Flow into deeper high-conveyance-capacity zones from overlying portions of the aquifer (Figure 18) does not occur via vertical seepage down open discontinuity planes. In the context of this analysis, the term seepage is used in the sense as defined in Poehls and Smith (2009): *"The slow movement of water through unsaturated* [geologic media] *into or out of a body of surface or subsurface water..."* A hypothetical particle of groundwater originating at a point below the phreatic surface in the volume of aquifer vertically above a high-conveyance-capacity zone (Figure 18) is possessed of a total hydraulic potential consistent with the elevation of the phreatic surface at that point and occurs on a equipotential line (Figures 17 and 18). The continuum of hydraulic potential between overlying groundwater and groundwater in such underlying high-conveyance-capacity zones is measurable with hydraulic observation points (Figure 17) and is the basis of contours constructed to depict a phreatic surface which is essentially horizontal at any point with gradients similar to aquifers at any location (Figure 19); i.e., typically on the order of 0.01 or less (Gillespie, 2013).

Figure 17 depicts several hydraulic regimes including recharge zones, discharge zones and intervening zones of near-horizontal flow. The zone of near-horizontal flow (between recharge and discharge areas) is the only zone where equipotential lines are essentially vertical and bulk groundwater flow can be sub-parallel to the strikes of discontinuities, whether stratigraphic or structural. If a site is in either a recharge or discharge area, flow has a significant vertical component and can not, in consequence, be sub-parallel to the strike of a conveying discontinuity, including bedding plane partings. The two components of flow (horizontal and vertical - Figures 14 and 15) are accommodated by flow through all discontinuity sets and flow is not controlled solely by the strike of either bedding plane partings, formation/member contacts or joints but is affected significantly by the potential field (gradient) at that point.

Within a zone of near-horizontal flow (i.e., flow along strike), two hypothetical particles of groundwater at the same geographic location but at different elevations (e.g., as measured in nested well sets) are located on the same equipotential and consequently have identical total hydraulic potentials (Figure 20). In that situation, groundwater flow within individual discontinuities is very nearly parallel to the strikes of all discontinuities (Figures 3 and 5) and the hydraulic potential at the top of a saturated discontinuity which connects two vertically-separated high-conveyance-capacity zones is identical to the potential at the bottom of that same discontinuity (Figure 20). In that situation, vertical flow is not possible because there could be no loss of potential (Toth, 2009, Hubbert, 1940). Therefore, at locations in an aquifer where flow is sub-parallel to the strike of the containing discontinuity (where the is no significant vertical flow component), there can be no vertical flow down the dips of steeply-dipping or sub-vertical, connecting discontinuities between high-conveyance-capacity-zones.

Figure 20. Block diagram depicting two high-conveyance-capacity zones separated by saturated sub-vertical discontinuities in a hydrologic location between recharge and discharge areas characterized by near-horizontal flow (Figure 17). In this situation, the total hydraulic potential at Points A and A' are identical so there can be no vertical flow.



In recharge and discharge areas (Figure 17), the hydraulic potentials at the tops and bases of discontinuities which connect vertically separated high-conveyance-capacity-zones are higher and lower, respectively (e.g., Heisig, 2010). The corollary is that, in hydrogeologic zones where vertical flow down steeply-dipping to sub-vertical discontinuities is possible (groundwater recharge and discharge areas) flow is not sub-horizontal and not along the strike of any planar discontinuity. That is the hydraulic condition which provides for both aquifer recharge and discharge (Zakharova, et. al., 2016). That recharge and discharge, however, occurs via saturated flow along field hydraulic gradient vectors, modified at the scale of the representative elemental volume by the development of in-plane gradients which have components of both horizontal and vertical flow (Figures 4 and 21) consistent with the conditions depicted in Figures 14 and 15 and with the analogous concept of groundwater discharge to surface water (Figure 19).

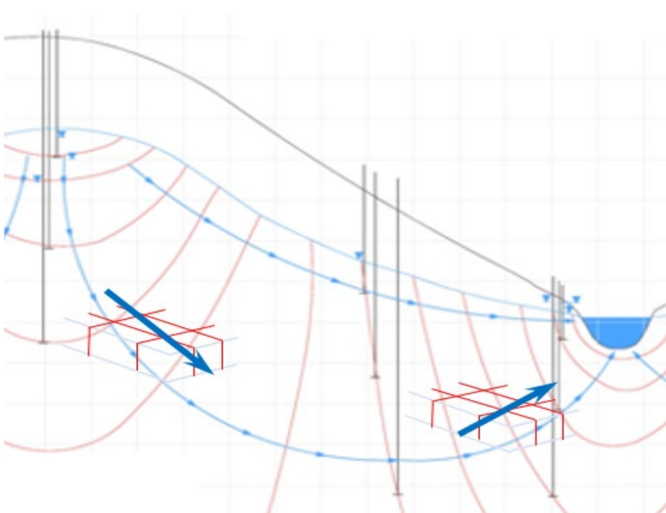
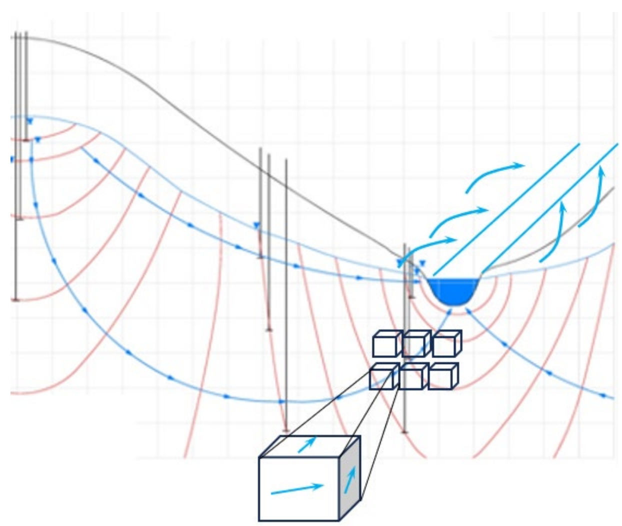


Figure 21. Translation of the block diagram of Figure 20 into recharge and discharge areas from Figure 17. In both end-member situations, there is significant vertical flow which occurs along vertically-oriented discontinuities.

Completely vertical flow through open, connected discontinuities in such a situation could only occur as vadose flow which, if actually measured in the field, would present an irresolvable conundrum because vadose flow occurs at pressures lower than atmospheric and in unsaturated conditions, whereas, at depths below the phreatic surface, all pore spaces are saturated and every particle of water is possessed of a total hydraulic potential at pressures above atmospheric. Because the phreatic surface at a point is the measurable manifestation of the integrated total hydraulic potential of every particle of water in a vertical section of the aquifer at that point, each particle of water is affected by, and exerts a hydraulic effect on, every other particle of water within the field. It is not hydraulically possible in that situation that groundwater in non-vertical two-dimensional pore spaces within the phreatic zone flows under a sub-horizontal hydraulic gradient at an azimuth sub-parallel to the strike of the discontinuities (i.e., ‘flow is along strike’) while flow in the same phreatic zone (same potential field) is down the dip of connected sub-vertical discontinuities. Such a hypothetical situation would necessitate simultaneous flow along two separate hydraulic gradients within the same potential field, or, as above, a vadose zone below the phreatic surface. The hypothetical condition presented here, for illustrative purposes only, differs from that of the refraction of flow lines between aquifers and aquitards (Freeze and Cherry, 1979; Hubbert, 1940) in which the bulk flow is via primary porosity between high-conductivity and low-conductivity strata.

As a result of the configuration of equipotential lines in Figure 21, the water table surface in the area adjacent to the discharge slopes downward toward the stream, but on the scale of the representative elemental volume at the location of the block diagram at depth, a series of infinitesimally spaced observation points intercepting a similar number of equipotential lines would describe decreasing hydraulic potential from depth toward the land surface, so net flow is sub-parallel to the strike of the planes of individual discontinuities with an upward component, (Figure 22), as depicted in Figures 14 and 15 (Heisig, 2010).

Figure 22. In its flow toward a surface water discharge, groundwater must flow around every matrix block (blue arrows) with an upward flow component in sub-vertical or steeply dipping planes (Figures 14 and 15), but little to no upward flow within sub-horizontal planes because of the constraint of the overlying matrix block unless the surface water discharge is either up-dip or along strike.



Groundwater can flow in any discontinuity only in the direction which results in a loss of hydraulic potential. In a case of jointed sedimentary rock in which there are two predominant, sub-vertical, sub-orthogonal extension joint sets and bedding plane partings/formation contacts are at a low dip angle in a homoclinal configuration (e.g., rocks of the Newark Basin), it is the combination of the field hydraulic gradient and the strike directions of each discontinuity set which exerts the controlling factor on groundwater flow anisotropy on the scale of the representative elemental volume (Surrette and Allen, 2008; Bear, 1993; Smith and Schwartz, 1993; and in Figures 3 through 6 herein). Figure 23 depicts a configuration in which two sub-orthogonal joint sets are mutually orthogonal to bedding and the strikes of all discontinuities do not coincide. This differs somewhat from many locales in the Newark Basin in which the strike of one joint set is very near, or in some cases, coincident with the strike of bedding. The configuration depicted was selected for ease of illustrative purposes, but the concepts discussed below apply equally to configurations in which the resulting rock blocks are more rectangular than the triangular segmentation depicted in Figures 23 through 25 (e.g., Figure 1a).

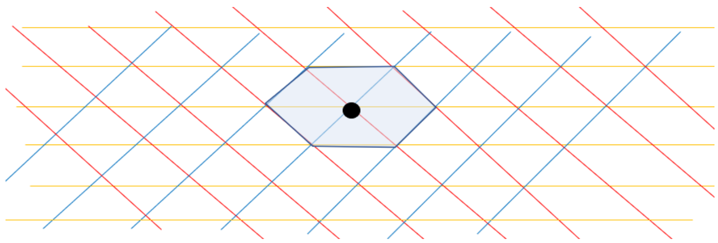


Figure 23. Schematic map view of three idealized sets of planar discontinuities: red and blue are sub-vertical joints and yellow is homoclinally dipping bedding plane partings. The shaded area is a hexagonal region within which all three discontinuity sets intersect. Each hexagonal area overlaps with other adjacent hexagons with each intersection at the locus of the meeting of six triangular prismatic blocks of rock. The diagram has been simplified to eliminate the differences between systematic and non-systematic joints common in the Newark Basin.

In a case below the phreatic surface where all discontinuity planes are saturated and every particle of water is affected by the potential field, the angular relationship between the field hydraulic gradient and the several sets of discontinuities differ, with a resultant difference in flow path lengths and gradients (Figures 24 a, b and c) as depicted in Figures 7 and 8. In the configuration of Figure 23 and 24, each triangular block can be considered a representative elemental volume. However, because it is at the intersections of the six adjacent triangular blocks that groundwater flow anisotropy can initiate (Surrette and Allen, 2008), each hexagonal segment of the aquifer is considered a representative elemental volume.

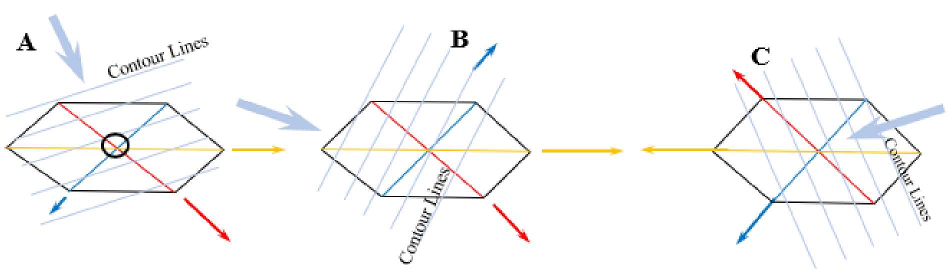


Figure 24. the representative elemental volume of Figure 20 in three configurations of Field Hydraulic Gradients. In each configuration, groundwater is conveyed through all three semi-planes of each discontinuity set, establishing the constraint on solute transport at discontinuity intersections.

Each planar discontinuity set depicted in Figure 23 and 24 is at some angle to the field hydraulic gradient and each set within any hypothetical representative elemental volume is at the same elevation and same depth below the phreatic surface, so flow, constrained by the flow field defined with equipotential nets, occurs in each set. Starting at the intersections of planes, there are two semi-planes for each discontinuity at the center of each hexagonal representative elemental volume. In each set, flow must be along the semi-plane which is at an obtuse angle to the gradient; that is, the pathway along which a loss of potential energy can occur. Using schematic A in Figure 24 as exemplar (Figure 25), the change of total hydraulic potential from the central point intersection of each plane to the respective "downgradient" ends (in-plane gradients) are different, as presented previously herein.

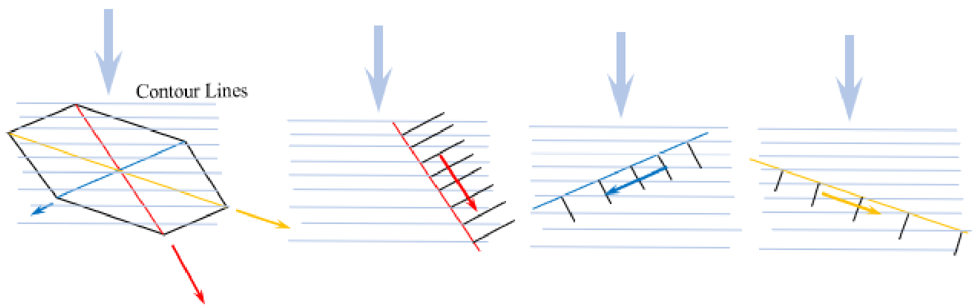


Figure 25. Example of the difference in in-plane gradients resolved from the FHG using the configuration of diagrammatic conditions of Figure 24A.

The significant differences of in-plane gradients results in lateral dispersion but can also magnify anisotropy from the scale of the representative elemental volume to that of the hydrogeologic domain, depending on a number of permutations of the variables, including, but not limited to: discontinuity orientation with respect to the field gradient; mean surface areas of the discontinuity sets; network connectivity; direction and distance to groundwater discharges, including sub-surface high-conveyance-capacity-zones (as described herein); downgradient conveyance capacity as well as factors such as differential discontinuity aperture and/or roughness.

The often-cited observation that groundwater flow can be sub-parallel to the strike of bedding plane partings is possibly a result of the predominance and aerial continuity of that set of discontinuities in some members of the Newark Basin formations compared with the frequency and spatial continuity of joint planes. However, as reported by Vecchioli (1969) and Lacombe and Burton (2010), the high-conveyance-capacity zones are possessed of high densities of both stratigraphic and structural discontinuities. In such conditions, flow in all discontinuity planes is sub-parallel to the strikes of the planes and there have been no systematic observations supporting a conclusion that all planes do not convey groundwater to a well or discharge. In fact, such must be the case because a well with a partially penetrating screen extracts groundwater from the full 360° area surrounding the casing, as well as from depths above and below the open interval (Hubbert, 1940; Freeze and Cherry, 1979; Fetter, 2001).

The differential disparities in the spatial distribution of all discontinuities is not uniform across the Basin, however, as depicted in Figure 1a, which is a photograph of the Lockatong Formation. There are members of the Passaic Formation in which the bedding plane partings appear to be more frequent than the sub-vertical joints to the degree that the rock is nearly fissile in directions parallel to bedding. However, the high-conveyance capacity zones even in such members tend to be those in which steeply-dipping to sub-vertical joint planes also occur at high frequency and close spacing

(Vecchioli, 1969; Lacombe and Burton, 2010) although they are obscured by the extreme fragmentation of the rock (Gillespie, unpublished data). As observed by Vecchioli (1969), producing zones are lithologically similar to non-producing zones but are distinctly jointed; i.e., the ability of such producing zones to store and convey groundwater (under pumping conditions) is a function of the combined porosity and permeability effects of finely laminated bedding plane partings and closely spaced structural planar discontinuities. That is consistent with the findings of Lacombe and Burton (2010) who report that the degree of fracturing (bedding plane and structural) is directly related to the hydraulic conductivity of strata; i.e., groundwater flow is through both stratigraphic and structural discontinuities.

In such high-conveyance-capacity zones, the limiting condition on flow velocity and anisotropy, reported above to be caused by the inability of low-gradient discontinuities to accept water at the rate of the conveyance capacity of high gradient discontinuities, is eliminated by the high stratigraphic and structural discontinuity densities. In such situations, flow is most similar to that of the porous medium equivalent, as documented by Vecchioli (1960) in which strong responses were recorded both along strike and down dip in contiguous high-conveyance-capacity strata.

Examination of Conceptualizations of Anisotropy

The presence of high-conveyance-capacity zones has been demonstrated by numerous investigators. Such zones in the Newark Basin are finite in both thickness and aerial extent (Zakharova, et. al.,2016), although some lithostratigraphic units can be correlated on the square kilometer scale (e.g., Olsen, et. al., 1996; Kent, et. al., 1995). High-conveyance-capacity zones, however, are possessed of *“significant lateral heterogeneity in hydraulic as well as lithologic properties”* (Zakharova, et. al. (2016).

Those high-conveyance-capacity zones have been reported variously as independent, leaky aquifers by, e.g., Michalski and Britton (1997) or as *producing zones* by, e.g., Vecchioli, et. al. (1969). It is unambiguous that, under the induced stress of pumping, groundwater extracted from the bedrock formations of the Newark Basin derives in large part from specific, finite, structural or stratigraphic zones (Zakharova, et. al., 2016) possessed of high secondary porosity in the form of discontinuities, including both bedding planes and structural planes (Vecchioli, 1969), high storage potential (Heisig, 2010), and, in the case of stratigraphic zones, a strata-parallel permeability higher than surrounding rock of more massive texture (Zakharova, et. al., 2016). What does not follow from that consistent observation is a conclusion that:

> *“If the water is able to move more freely in the direction of strike than in other directions* [during aquifer testing]*, then the facility for the spread of a contaminant would be greatest along strike.”* (Vecchioli, et. al., 1969)

That specific conclusion is not wholly incorrect in that Vecchioli refers to the *facility* for the spread of contaminants and does not imply that such an outcome is universally the case, although it is the presumption of many investigators and regulators (see below). Unlike the hydraulic behavior within high-conveyance-capacity-zones during aquifer testing, under non-pumping conditions (i.e., the natural prevailing field hydraulic gradient) on the scale of the hydrogeologic domain, groundwater:

- can only flow at the rate of the measured hydraulic characteristics of such high-conveyance-capacity-zones if the zone is connected to an equally transmissive downgradient zone or to a surface water discharge, as described above, herein;

  and

- flows in a direction on the hydrogeologic domain scale constrained by the resolution of the field hydraulic gradient into the various planar discontinuities which results in angular disparities between the field hydraulic gradient and the mean orientation of each discontinuity set considered collectively; the spatial distribution of the discontinuity sets; the connectivity of sets within the network; and the mean surface areas of individual, finite discontinuities in each set within the confines of a specific high-conveyance-capacity-zone.

Considering that all discontinuities in three-dimensional networks are saturated and convey groundwater within the hydraulic constraints of the prevailing potential field, a position that groundwater flow is controlled by "the strike" must be evaluated by first asking: "The strike of what?" The hydraulic constraints on flow through discontinuity networks established previously herein require flow through all discontinuities in the network (Lacombe and Burton, 2010) which means that all discontinuities in a three-dimensional network potentially affect flow, whether isotropic or anisotropic. That is especially the case in those Newark Basin formations/members where the disparity in discontinuity spatial distribution between the sets of a network is not high (e.g., Figure 1).

The nomenclature, "producing zone" as described by Vecchioli, et. al. (1969) is perhaps the most accurate representation of the high-conveyance-capacity stratigraphic zones in Newark Basin formations where high conveyance along strike has been measured. Production refers to the rate at which groundwater can be produced via a well and it is the case that under pumping stresses such zones produce more water than other zones. That production, however, does not occur exclusively along the strike of the strata. Vecchioli reported hydraulic responses in down-dip wells which intercepted the high-conveyance-capacity stratum being pumped.

Accordingly, and considering the findings of Lacombe and Burton (2010) and Vecchioli (1969) that the highest producing strata are those which contain a higher proportion of stratigraphic/structural discontinuities than in other strata in a study area, there appears to be no unique relationship between high groundwater production, hydraulic responses to extractive stress, and the strike of a formation's bedding plane partings or formation/member contacts. That finding calls into question the companion conclusion that contaminant distribution is preferentially along strike (Vecchioli, 1969). The most pronounced and rapid hydraulic responses are measured in directions along the strike of bedding for the same reasons as described in the foregoing sections of this current report: flow within the several member sets of discontinuities in a network, and, indeed, along individual discontinuities, is in directions sub-parallel to the strikes, whether that flow occurs under the influence of a prevailing natural field hydraulic gradient or under the stress of an induced gradient during aquifer testing.

As reported by Vecchioli (1969) the anisotropy observed as preferential flow along bedding plane partings during aquifer testing results from the difference in contribution to well discharge between highly fractured strata, including structural discontinuities (e.g., Lacombe and Burton, 2010) and more massively-bedded strata within the same or adjacent formations. As established by Lacombe and Burton (2010) in finely-bedded members the integrated hydraulic conductivity of the prevalent bedding plane partings as measured in aquifer tests is higher than the collective conductivity of the relatively sparser strata-bound joint planes. The hydraulic response, however, is not restricted to along-strike directions, as reported by Vecchioli (1969) so that which is being recorded is less of a strike-controlled response than it is a general response to a hydraulic stress across a zone of higher bulk hydraulic conductivity than surrounding rock zones, within which hydraulic responses were also recorded, both along strike and down dip, but to a lesser degree (Vecchioli, 1969). Highly conductive zones, such as those described by Vecchioli (1969) and by Lacombe and Burton (2010) are many times composed of thinly bedded rock with closely spaced joints with resultant representative elemental volumes on the scale of a centimeter. In such cases, the aquifer can best be characterized as a porous medium equivalent (Gillespie, 2023) and the effects of the resolution of the field hydraulic gradient into the various planar discontinuities disappear (Figure 7). That condition also contributes to the high production, resulting from high storage, and rapid responses along the strike of bedding, although similar responses have been recorded down dip in the same unit.

That latter condition is consistent with the condition depicted in Figure 18 in which the high potential flows within the linear preferential flow pathway derives its water from the innumerable intersecting, smaller-scale water-conveying discontinuities of the three-dimensional network and from directions constrained by the field potential in and around the preferential conveyance zone. That is also the finding of Lacombe and Burton (2010) who found that, because joints in the Lockatong Formation are strata-bound, the measurement of hydraulic conductivity is predominantly attributable to along-bedding-strike partings and/or formation/member contacts which occur with a higher frequency, are individually more aerially contiguous on the scale of the domain and collectively represent the most prevalent water-bearing discontinuities with the highest collective surface area along which flow can occur compared with the strata-bounded joint planes. The implications for anisotropy are less applicable, or not at all, in members in which the spacing and frequency of all discontinuity sets are equivalent (e.g., Figure 1). The Lacombe and Burton study focused on the Lockatong Formation in which joints, although pervasive, are not penetrative to the same scale of observation as is the case in the other formations of the basin (Gillespie, unpublished data). Accordingly, the representative elemental volume in the Lockatong tends to be statistically larger than is the case in the other formations of the basin and the potential for anisotropy is greater at the scale of the representative elemental volume, as described previously herein.

What has not been addressed within the context of the conceptualizations discussed in the foregoing is the distribution of solutes under the influence of natural field hydraulic gradients through three-dimensional networks of planar discontinuities within and through groundwater drainage areas; i.e., under the prevailing hydraulic conditions within a single area consisting of both recharge and discharge areas with some zone, or at least inflection plane, where near-uniform lateral flow occurs. It is a premise of the conceptualization in which preferential flow is compartmentalized stratigraphically, that flow is *along the strike of bedding*. In order for the premise to hold, either nearly all sites would have to be located in zones of near-horizontal flow between recharge and discharge areas (demonstrably not the case) or flow in the high-conveyance-capacity zones in recharge or discharge areas is not actually along the strike but consists of significant vertical flow components which must be accommodated by flow through non-bedding discontinuities (Gillespie, 2023). In that latter case, there is no hydraulic rationale which could be applied to conclude that the distribution of flow into all discontinuities of a network does not also occur in the zones of sub-horizontal flow between recharge and discharge areas.

It is not uniformly the case that under non-pumping conditions, discovered solutes became distributed into distinct stratigraphic zones. Many examples can be cited in the Newark Basin in which a plume of contaminants is not distributed coincident with the strike of a stratum but, rather, is distributed in a direction consistent with the field hydraulic gradient with either:

- some degree of anisotropy resulting from preferential flow into one of the discontinuity sets in the network;

  or

- isotropy, in which there is no preferential orientational resolution of the field hydraulic gradient into the several discontinuity sets – the condition of the porous medium equivalent.

Figure 26 is a reproduction from a case study in the Newark Basin (Gillespie, 2013) in which the NJDEP concluded, based on groundwater extraction testing conducted by its own contractor, that the direction of flow was along the red arrow (Figure 26a) which is generally parallel to the mean strike of bedding. That conclusion was contrary to the factual evidence that the hydraulic gradient, as mapped quarterly with groundwater elevation contours (equipotential lines in Figure 26b) in approximately 25 monitoring wells over a 30-year period (120 episodes), was consistently oriented with a gradient along the blue arrow (Figure 26a) at an azimuth 40° from the NJDEP-presumed, along-strike flow direction. Flow as conceptualized by NJDEP would require groundwater contours as depicted in Figure 26c, which differs significantly from the contours based on the monitoring data (Figure 26b). Contours consistent with the monitoring data (Figure 26b) are also consistent with the hydrologic function of the perennial stream as a groundwater discharge. Figure 26c depicts a hydrologic condition contrary to the established groundwater-surface water couple in an effluent stream situation. NJDEP defended the conceptualization based on the detection of one compound (of many) in one well in a single monitoring episode at Point A (Figure 26a), the concentration of which was higher than at any monitoring location in any episode near the source (apex of arrows, Figure 26a) and separated from the source by an expanse of uncontaminated groundwater more than a half mile long in which that compound had never been detected.

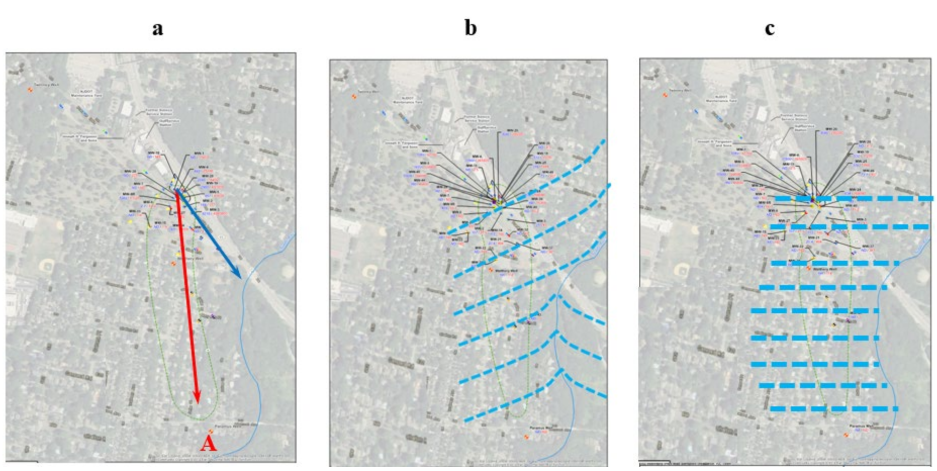


Figure 26. reproduction of results of a field investigation in which the NJDEP, based on a groundwater extraction test, concluded that solute transport and, necessarily groundwater flow, occurred at an angle 41° from the consistently measured hydraulic gradient. From: Gillespie, 2013

Evaluating groundwater flow within the three dominant sets of discontinuities present at the site pursuant to the methods described herein resulted in a predicted plume consistent with the measured field hydraulic gradient and with long term groundwater quality data; i.e., the actual plume was oriented with the gradient depicted in Figure 26b.

The NJDEP, in support of its effort to fit the data to its presumptive conceptualization, presented a distance-drawdown curve based on the aquifer testing which, contrary to its conclusion, was consistent with a single groundwater system, despite the agency's designation of multiple stacked aquifer units which the presumptive conceptualization treated as separate and hydraulically distinct water-bearing zones (Figure 27). Most significantly, the hydraulic responses to the aquifer test were measured in wells arrayed normal to the strike of the strata, across bedding plane partings and in strata which the Department had designated as different hydrologic units.

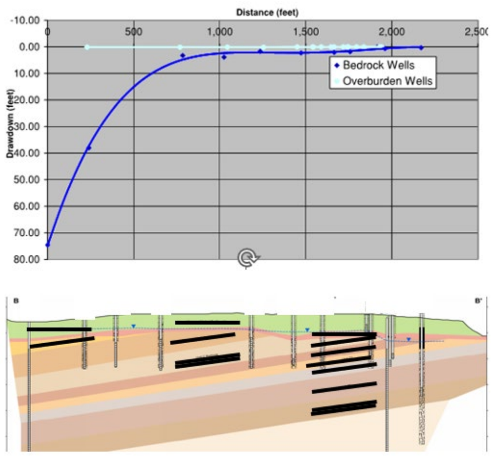


Figure 27. Reproduction distance-drawdown plot and cross section (a non-right-section) in which the wells monitored were completed into rock designated as comprising individual, isolated aquifer units (lower figure), but which were shown by the aquifer test (upper graph) to be part of a single saturated system. From Gillespie, 2013.

In addition to the absence of hydraulic or groundwater quality data to support multiple, distinct aquifer zones (which were, indeed, zones of high production under pumping) the cross section NJDEP presented to support the conceptualization (Figure 27) was not constructed as a right section and the effects of vertical exaggeration between the map and profile scales was not accounted for, both of which errors rendered the geometric basis of establishing contiguous dipping aquifer zones incorrect and, consequently, invalid. Such ostensible hydrologic zones over the scale of the study area (~350 acres) can not be demonstrated to comprise single high-conveyance-capacity zones within the scope of a site investigation (Zakharova, et., al., 2016) – a conclusion supported by the results of the aquifer test (Figure 27).

In the case in the example of Figure 26, NJDEP concluded that flow at an azimuth more than 40° from the field hydraulic gradient was a valid conceptualization because that direction was near (not exactly coincident with) the strike of strata. The effects of planar discontinuities of two pervasive and penetrative joint sets were ignored, despite the fact that one of the joint sets is parallel to the field hydraulic gradient, parallel to the measured plume and coincident with the hydraulic response to the aquifer test (Figure 27).

The presumption that a formation is possessed of, and can be hydraulically characterized by a single *strike* direction which is presumed to control the hydrology of a study area has become a default conceptualization of investigators and regulators involved in cases with potential contamination of the sedimentary bedrock aquifers in the Newark Basin of New Jersey. That conceptualization is based on a presumption that bedding plane partings and contacts are of significant aerial extent across the scale of the hydrogeologic domain. Although one or both of the presumptions of that conceptualization might be correct, the entire conceptualization ignores that the formations of the Basin are lithologically and hydraulically variable in both vertical and horizontal (down-dip) directions (Zaklharova, et., al., 2016), contain at least three sets of planar discontinuities at any location (Herman, 2001) and that:

- each discontinuity set has a statistically consistent strike direction;
- each discontinuity set is pervasive and penetrative across all hydrogeologically relevant domains of interest in site investigations;
- the geometric and spatial relationship between sets is the basis for the definition of the representative elemental volume;
- all discontinuity planes are saturated;
- every particle of water is possessed of a total hydraulic potential consistent with, and accordingly contributive to, the hydraulic potential field, including the elevation and configuration of the phreatic surface, which, as depicted in Figure 27, incorporates potentials measured across the three-dimensional extent of the study area including along strike and down dip locations.

In terms of the effects of aquifer framework anisotropy on the distribution of solutes which occurs under the hydraulic conditions dominated by natural field hydraulic gradients, the characteristic which must be determined is the anisotropy under non-pumping conditions, if any. It is often times the case that an apparent anisotropy is an artefact of the investigation methods. This is illustrated in Figure 28 which presents a schematic of an analogous situation in a porous medium aquifer. An aquifer test in the sand and gravel aquifer would yield an estimation of the groundwater flow velocity consistent with measured hydraulic conductivity and transmissivity values typical of formations of similar lithology. The rate of groundwater flow into, through and out of the sand and gravel unit, however, is constrained by the conveyance capacity of the surrounding formation with conductivity values orders of magnitude lower. Within the context of the elements depicted, if a more rapid and stronger hydraulic response was measured during an aquifer test in the observation well located within the higher-conductivity paleochannel, as compared with responses in the other observation points, it could not be interpreted that groundwater flow and solute distribution under the influence of the pre-test natural hydraulic gradient had occurred in the direction from the pumped well to that observation point; solutes in groundwater from a source location near the pumping well would have been transported in the downgradient direction despite the presence of a higher-conveyance-capacity zone (the paleochannel) near the source.

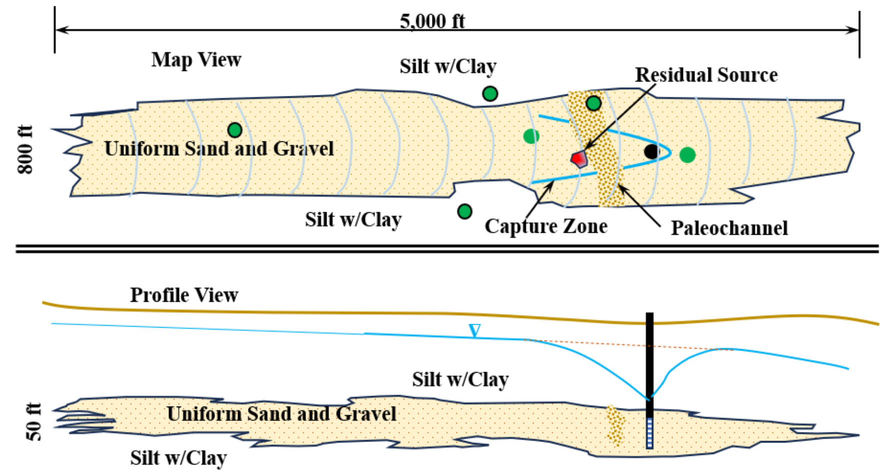


Figure 28. Porous medium analogue of high-conveyance-capacity zones in bedrock aquifers.

As described above herein, a geologic condition which has higher intrinsic conveyance capacity does not cause groundwater to flow in a direction which does not result in a loss of total hydraulic potential. In the case of the example in Figure 28, flow into the paleochannel from the direction of the pumped well under non-pumping conditions would not be possible because there would be no loss of potential; flow in that hypothetical situation would had to have occurred in a direction parallel to the contour lines which is not possible. Analogously, the measurement of a hydraulic response to extraction of groundwater from a high-capacity stratigraphic horizon in a consolidated formation of the Newark Basin reveals nothing about the conditions under which solute distribution occurred under the natural field hydraulic gradient.

There are circumstances in which the distribution of solutes under natural field hydraulic gradients not coincident with the strike of bedding has been along the strike of bedding. In such circumstances, however, the controlling factors must be that:

- there is a degree of coincidence of the field hydraulic gradient and the bedding strike (an exact parallel is not necessary nor is such implied) such that there is continuous loss of hydraulic potential along the flow pathway;
- the aerial extent of the stratum is significant on the scale of the hydrogeologic domain such that the factors of anisotropy enumerated herein result in the observed anisotropic distribution, As demonstrated by Zakharova, et. al., (2016) such aerial continuity of lithology or hydraulic characteristics is not a common condition in the Newark Basin;
- the stratum is connected to either a downgradient conveyance condition (e.g., a fault zone) of similar conveyance capacity or to a surface water discharge, both of which are common and likely the reason that flow generally along the strike of bedding is not uncommon but also not universally the case.

The fundamental role of hydrogeology in groundwater contamination investigations in bedrock aquifers is to determine how solutes became distributed under the field hydraulic gradient. That determination can then be applied to predict if the mechanisms of the extant distribution are still operational and, if so, to what extent:

- further distribution is possible and what specific receptors could be at risk;
- the distribution mechanisms can be reversed and the solutes recovered;
- the distribution mechanisms can be interrupted to reduce further transport;
- a reagent can be distributed uniformly through the same transport pathways under different hydraulic conditions and in a manner which will result in the reagent encountering the entire plume of solutes, rendering it harmless.

The methods described herein can be applied in combination with formation structural data on the scale of both the representative elemental volume and the domain to develop a reasonable estimate of natural anisotropy. In the absence of structural/stratigraphic data and within the scope of an investigation which does not provide for the gathering of such data, the conceptualization presented herein provides the basis to conclude that the measured distribution of solutes in an extant plume is the physical manifestation of the natural anisotropy which should be the guiding data in any remedial decision (e.g., example depicted in Figure 26).

The foregoing conclusion is obvious on face value, but it is commonly the case that a contaminant plume has been delineated pursuant to regulations and consistent with hydrologic theory but NJDEP has required additional wells installed in directions parallel to groundwater contour lines directly cross-gradient of a residual source zone, citing the indefensible and irrational rationale that the direction to those required additional wells coincided with "the strike" of the formation. In such situations (e.g., Gillespie, 2022), flow and transport in a sedimentary formation in the Newark Basin has been demonstrated to be in the down-dip direction, controlled by the natural field hydraulic gradient flowing in three-dimensions through all discontinuity sets.

Such a presumption of directional anisotropy as a default conceptualization despite being hydrologically impossible, necessitating simultaneous operation of multiple gradients within a single potential field, can result in a case of "shoe-horning" investigation designs and results into the conceptual model rather than conceptualizing hydrogeologic conditions based on site-specific geologic data and structural data in particular. The risks associated with interpreting site data in the context of a pre-determined or default conceptualization are that:

- money and time are wasted attempting to prove inapplicable premises;
- delays to project compliance accrue when predicted/expected findings are not realized, resulting in further field efforts;
- remedial actions are either protracted or abandoned in favor of alternatives, but only after additional resources are brought to bear to develop the alternatives.

Summary

Anisotropy in a bedrock aquifer is a direction-dependent characteristic resulting from the preferential directional flow of groundwater within a hydraulic potential field into and through a network of planar discontinuities which occur in non-randomly-oriented sets, typically none of which are orientationally coincident with the local field hydraulic gradient. Anisotropy manifests when flow is not distributed equally into the various sets of pervasive, non-randomly-oriented discontinuity sets. Development of anisotropy is a function of: the angular disparity between the field hydraulic gradient and the in-plane gradients of each discontinuity set considered collectively; the spatial distribution of the discontinuity sets; the connectivity of sets within the network; and the mean surface areas of individual, finite discontinuities in each set.

Natural formation anisotropy can be altered by the installation of long boreholes which connect vertical aquifer zones possessing different hydraulic potentials (i.e., in recharge or discharge areas) or by conducting an aquifer test in which both the direction and magnitude of the hydraulic gradient are altered compared with the field hydraulic gradient. Both are examples of what is referred to in the field of particle physics as the "observer effect" in which, by conducting an experiment (e.g., installing a well) investigators alter the physical conditions being observed. The anisotropic distribution of an established plume, if any, would have resulted from the resolution of the field hydraulic gradient into the several discontinuity sets which comprise the network of hydraulically-connected, two-dimensional flow pathways, as amplified from the scale of the representative elemental volume to that of the hydrogeologic domain; the observation of the hydraulics of the system under altered conditions results in an incomplete and sometimes incorrect characterization of contaminant fate and transport and possibly incorrect remedial decisions.

There is no single or universally applicable conceptualization of groundwater flow in the bedrock aquifers of the rift basins inboard of the Atlantic Coastal Plain. The conceptualization prevalent in New Jersey, although valid in some aspects and site-specific conditions, is not universally applicable. As an example, that specific conceptualization is not recognized in other states in which sibling basins occur, all of which are possessed of similar stratigraphic and structural components as the Newark Basin (including the same basin in Pennsylvania)., In those other states investigators and regulators evaluate, delineate, test, monitor, model and remediate contamination successfully using different but equally valid conceptualizations of the hydrogeology of the respective and hydrogeologically identical basins.

Within New Jersey where the conceptualization of bedding strike control of solute distribution is presumptive, data actually support a conclusion that the direction of strike of bedding exerts less control on solute distribution than does the degree of fragmentation of the rock of the high-conveyance-capacity strata by a combination of densely spaced bedding plane partings and joints. In such high storage, conductive strata, hydraulic responses have been recorded both along strike and down dip in those situations where wells intercepted the same high-conveyance-capacity zone; in other cases (e.g., Figures 26 and 27), hydraulic responses have been recorded across strikes, across strata and across zones designated as individual hydrologic units (Gillespie, 2013).

Within the Newark Basin in New Jersey there are members of the formations which are massively bedded and in which the spatial distribution of sub-vertical joints are equivalent to, or even exceed in frequency, that of bedding. In those situations, the hydraulic conditions developed herein and as documented by, e.g., Zakharova, et. al., (2016), Lacombe and Burton (2010), Vecchioli, et. al., (2969) Heisig, (2010) and as modeled by e.g., Surrette and Allen (2008), Bear (1993), Smith and Schwartz (1993), Fogg (1990) and Gillespie, (2013, 2022, 2023) prevail and the presumption of preferential distribution into densely fragmented strata, as observed in some locations, does not apply. Rather, in those situations, it is flow within three-dimensional flow fields into and through three-dimensional discontinuity networks as described herein that constrains flow, and to a large degree normalizes anisotropic distribution of solutes measurable on the representative elemental volume scale over the scale of the hydrogeologic domain.

In preference to presumptive conceptualizations, it is herein advocated that there should be scope for the initial guiding conceptualizations of aquifer conditions to be refined or modified after hydrostructural data have been gathered and evaluated. That approach provides for the greatest degree of flexibility in reaching remedial decisions by eliminating pre-conceived expectations on the part of agency reviewers from the calculus of the compliance process. In many circumstances, the requisite hydrostructural data are available and can be incorporated into the preliminary stages of site investigation to reduce the collection of data not relevant to the most accurate determination of hydrogeologic conditions.

Acknowledgments

The author expresses gratitude to Gilmore & Associates for providing the opportunity to pursue the research reported herein. Many thanks are extended to Charles McLane, Ph.D. and Peter Robelin for graciously giving their time to review and critique drafts of this paper. The author also thanks the Pennsylvania Council of Professional Geologists for the many opportunities to vet ongoing research findings to its professional geologist members who have provided invaluable insights to findings presented at PCPG venues throughout the many years over which the research process has been conducted.

Errata

Pg 25, first full paragraph is amended to read:

"In terms of the effects of aquifer framework anisotropy on the distribution of solutes which occurs under the hydraulic conditions dominated by natural field hydraulic gradients, the characteristic which must be determined is the anisotropy under non-pumping conditions, if any. It is often times the case that an apparent anisotropy is an artefact of the investigation methods." That is consistent with the findings of Gudmundsson (2011) who reports that "rocks are often highly permeable along bedding planes in layered sedimentary rocks…" Such high permeability compared with strata-bound extension discontinuities can account for the observed responses in aquifer tests.

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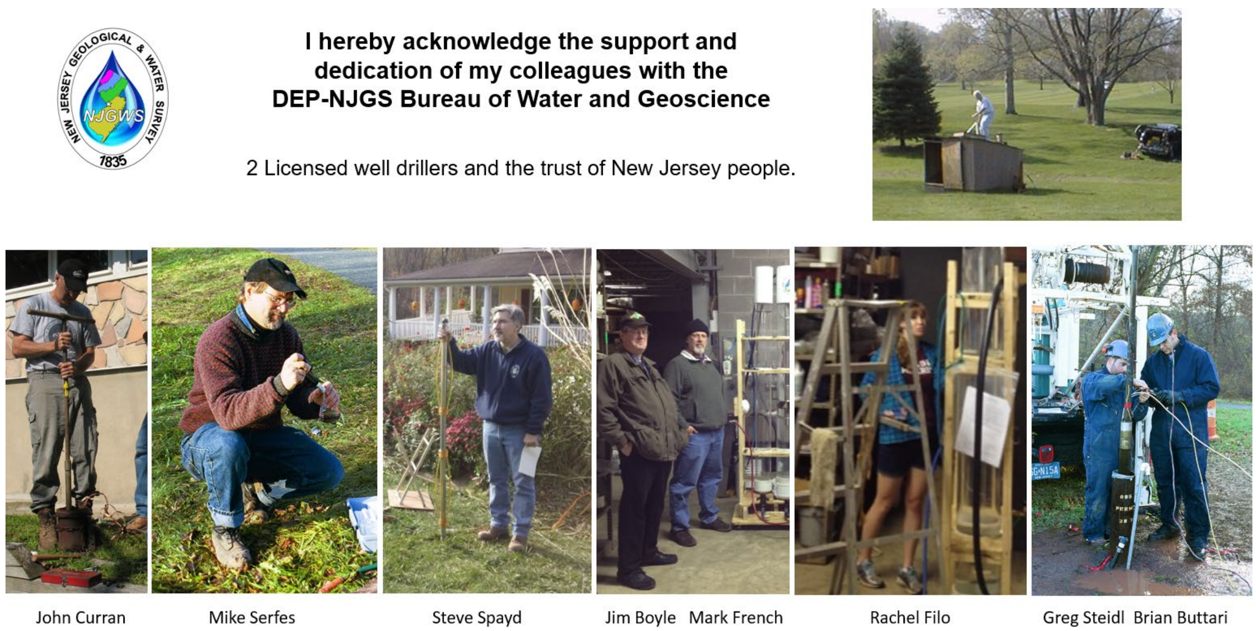
5. NJGS Bulletin 77 Summary of Fractured-Bedrock Aquifer Borehole Research in the Eastern Half of the Newark Basin

Gregory C. Herman, PhD; Trap Rock Industries

Fourteen Years of Hydrogeologic Research into the Nature of Fractured-Bedrock Aquifers of the Newark Basin, NJ, Fourteen Years Afterwards

NJ Geological Survey Bulletin 77 is a compendium of scientific articles covering the geology and hydrogeology of the Newark basin. Chapter F and Appendices 1 to 4 summarize the results of 36 hydrogeologic research projects featuring 128 water wells in the Newark basin that I logged using borehole geophysics (fig. 1). The geophysical records characterize the sedimentary and igneous aquifers containing stratigraphic and structural water-bearing features (WBFs) and water-bearing zones (WBZs). The orientations and structural interactions of water-transmitting features were identified using optical borehole imaging sondes, heat-pulse flowmeters, traditional geophysical logs, rock cores and outcrops. Fractured-bedrock aquifers in the Newark Basin generally reflect long-term climate cycles characterized by Milankovitch theory. Each aquifer contains rhythmic accumulations of detritus, with the older Stockton and Lockatong aquifers equaling the respective formations. The younger Brunswick aquifer contains the red-bed dominated sedimentary rocks of the Passaic Formation together with the igneous lava flows of the early Jurassic Watchung Zone including three interbedded sequences of mudstone to sandstone. Early Jurassic diabase dikes and sills also locally intrude the Triassic rocks. Most WBFs are tectonic fractures but both sedimentary bedding and igneous layering are most transmissive over long distances. Coarse-grained red beds have more bed-transmitting horizons with tectonic fractures providing intervening leakage. Structural intersections between bedding partings and tectonic fractures are most abundant near large faults where groundwater transport directions can parallel fault strikes. Gently tilted beds cropping out in ridge and swale topography demonstrate robust cross flow approaching 10 GPM in 6”-diameter water wells with upward, downward or both cross-flow directions occurring naturally without pumping, and dependent upon relief changes over the recharge zone. Red paleosol horizons in red mud rock contain abundant, secondary, diagenetic minerals that are prone to dissolution in weathered bedrock and can be highly transmissive over large areas. Red beds with paleosol horizons near the border faults have slight angular unconformities that can hinder recharge and the aquifer’s productivity.

Optical borehole imaging is a very valuable tool that directly sheds light on the geological nature of subsurface structures, especially when placed into context with other traditional geophysical sondes including fluid conductivity/resistivity, gamma logs, and borehole caliper readings among others. Heat-pulse flowmeter technologies are fickle but very useful when placed into context with nearby topographic and pumping influences. Although natural cross flows can exceed the designed threshold limits of HPFMs (~1.5 GPM flow rates), research has shown that they can be deployed using customized flow divertors to attain reliable cross flow measurements. In summary, this research used modern tools to discreetly map and characterize the subsurface in areas underlain by varying lithologies and structures. The most informative studies stemmed from having multiple wells clustered together like that at the Watershed Research Institute, one of the first research wellfields in the United States that I used to gain familiarity with subsurface logging instruments early on, and to further our understanding of the manner in which fractured rock stores and transmits groundwater. The following 24 figures capture the key aspects of this body of research and are part of Friday's oral presentation.



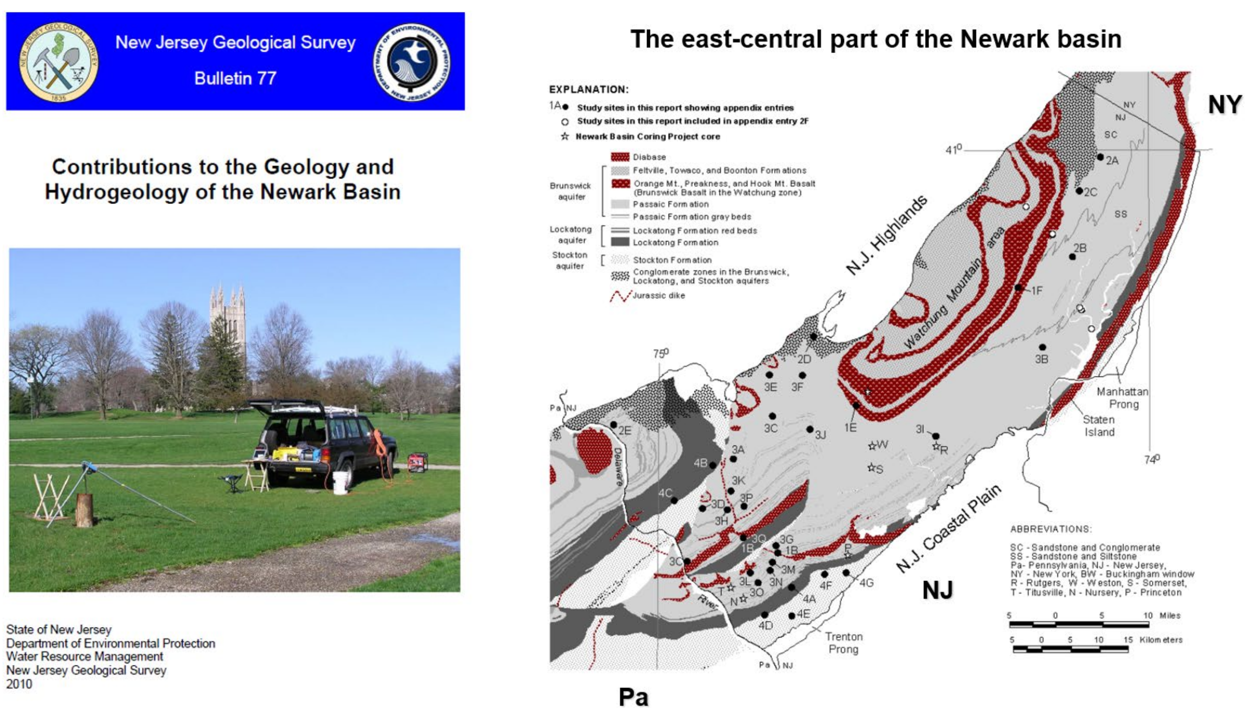


Figure 1. The cover of NJGS Bulletin 77 (left) that captured deployment of the Robertson Geologging Ltd. suite of equipment at the Spring Meadows Glub Club, Princeton University. The geological map to the right summarizes the study locations and numbers in the easter-central part of the Newark Basin. The link to a PDF of Bulletin 77 is https://dep.nj.gov/wp-content/uploads/njgws/techincal-publications-and-reports/bulletins-and-reports/bulletins/bulletin77.pdf.

Contents

[1]US Geological Survey, [2]Oberlin College, [3]West Virginia Dept. of Environmental Protection, [4]Lafayette College, [5]Michalski & Associates, Inc., [6]NJ Geological Survey, [7]Rutgers University

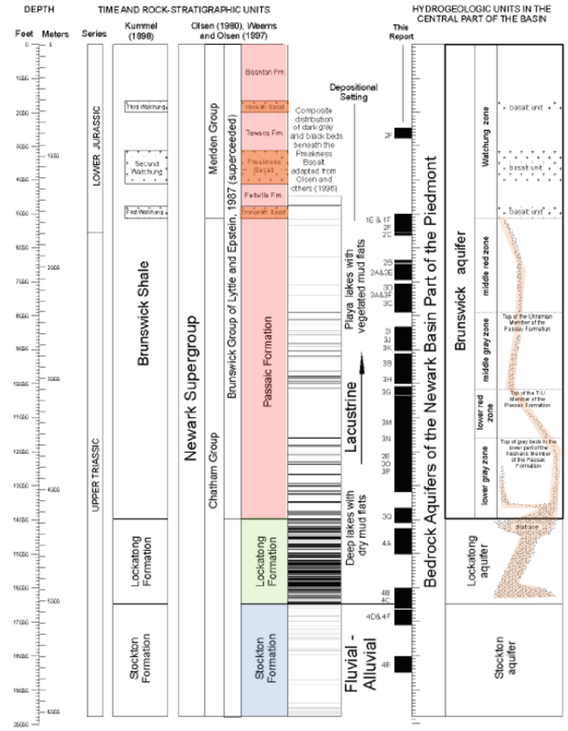


Figure AP2. Summary of time, rock and hydrogeologic units in the central part of the Newark basin showing approximate stratigraphic intervals covered by each study.

Figure 2. Bulletin 77 table of contents (left) and aquifer classification (right).

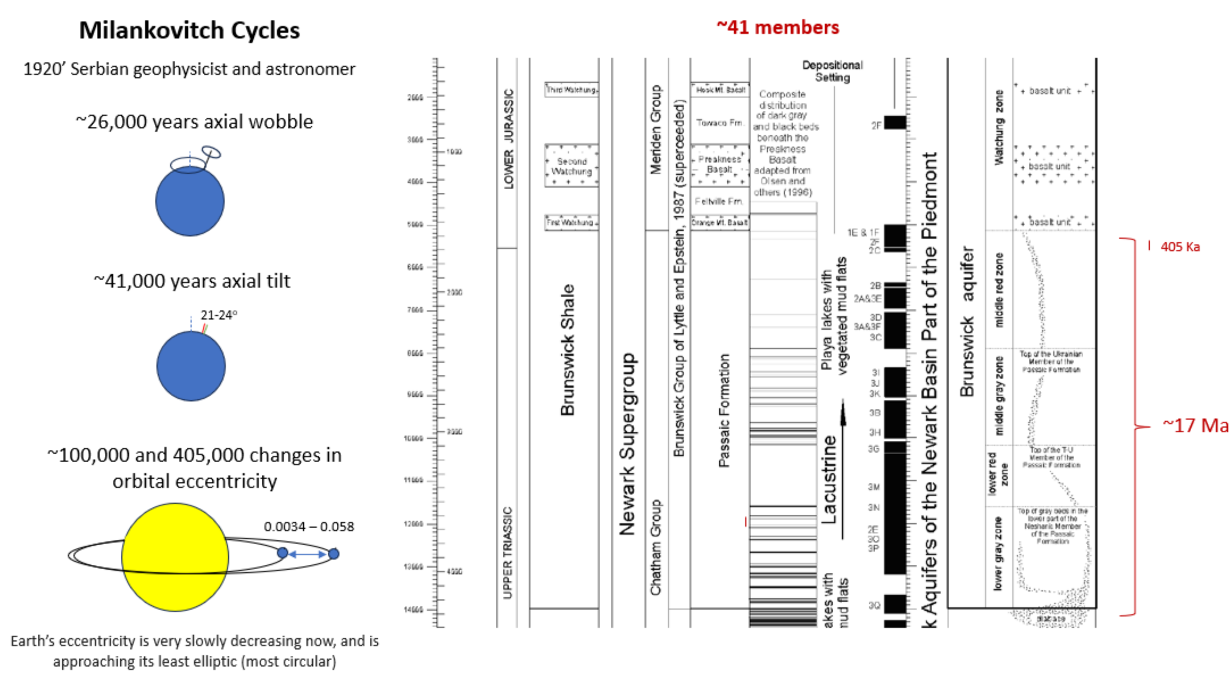


Figure 3. Newark basin sedimentation is rhythmic, reflecting Milankovitch climate forcing from celestial mechanics. The Passaic Formation spans about 17 million-years of time (Ma) and contains over 40 informal members correlated with the 405,000-year elliptic climate cycle from systematic, gravitational interaction with Venus and Jupiter (Olsen and others, 1996).

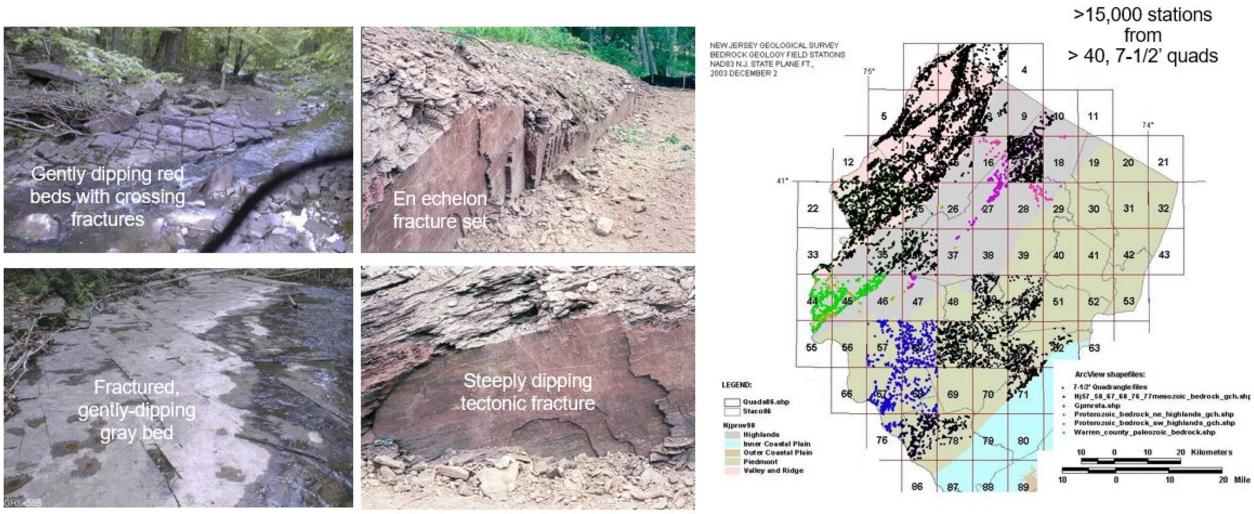


Figure 4. Photographs from outcrops showing gently titled sedimentary beds containing tectonic fractures (joints). The map to the right summarizes the bedrock outcrops mapped and catalogued at the NJGS during my time there with D. Montverde and R. Volkert among others.

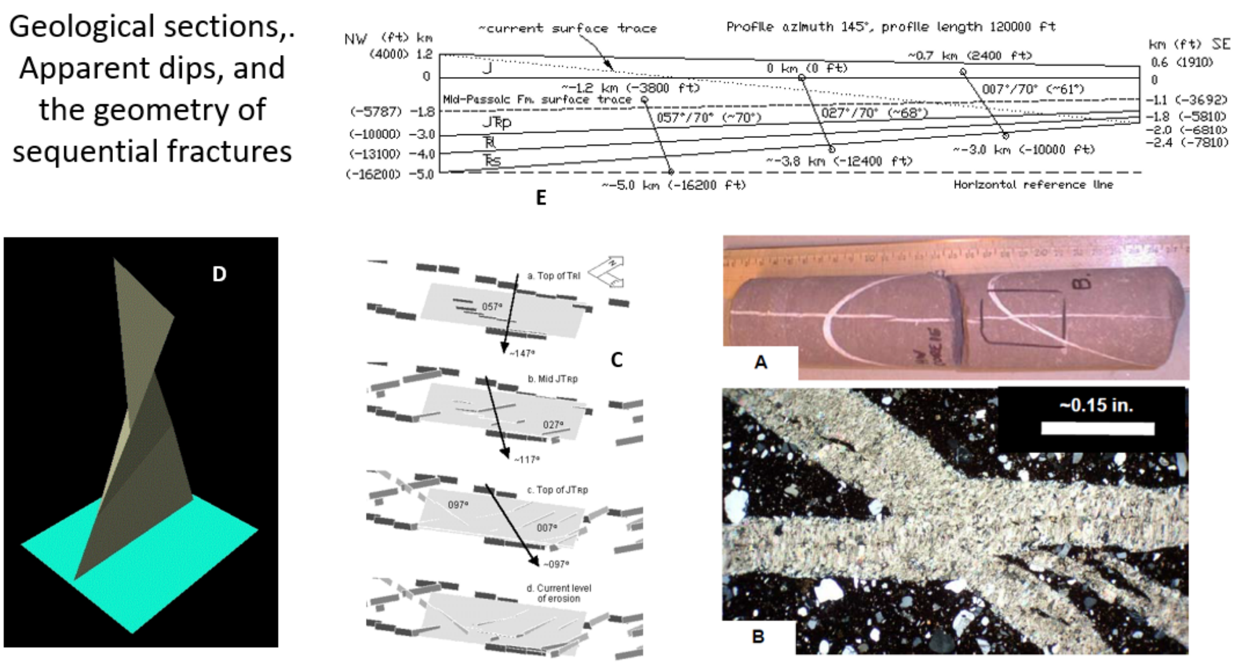


Figure 5. Photograph A shows a piece of a core from the Hopewell Boro groundwater study and B is a photomicrograph of the area outlined in A showing cross-cutting, healed fractures with a younger (S2) and older (S1). Figure C depicts overlapping fracture sets that evolved with clockwise rotation of the stretching direction over time from southeast to east. D and E shows the consequence of having a rotating plate with overlapping tensional fractures opening in different directions at different times and at different stratigraphic levels in the basin.

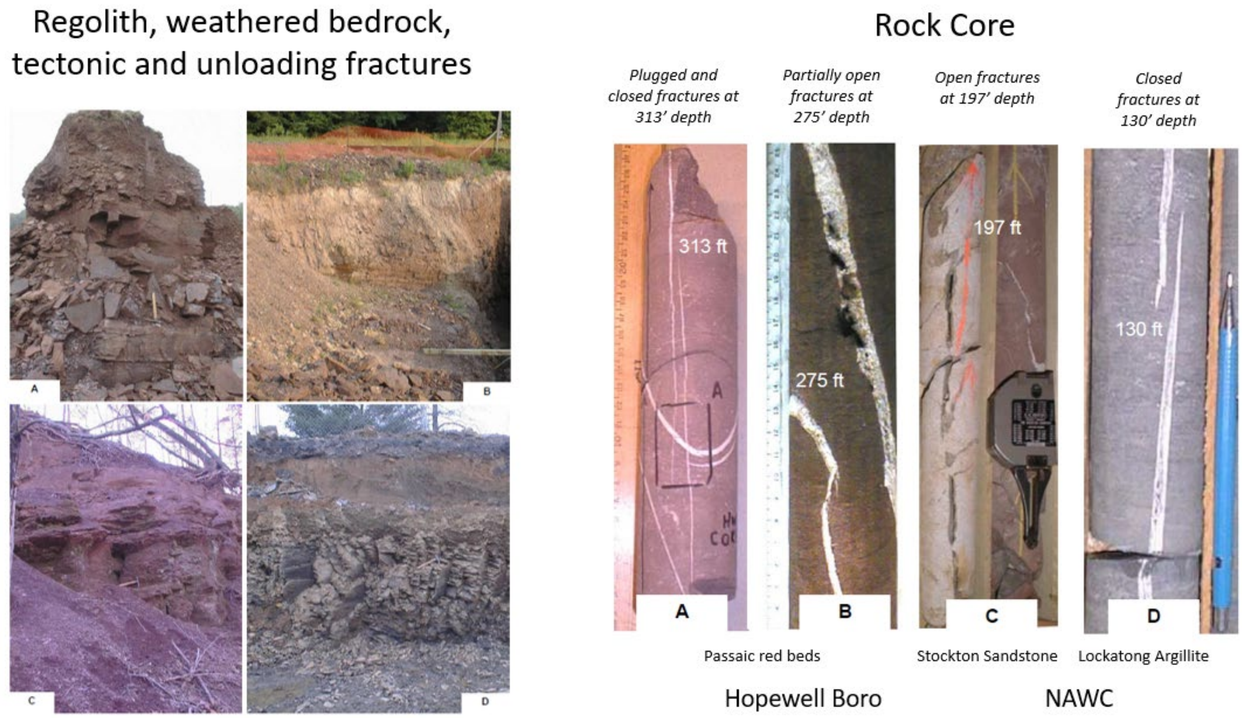


Figure 6. Photographs of weathered bedrock and regolith (left) and rock cores (right). The two core photos on the outside have sealed fractures whereas those in the center have varying degrees of dissolution of fracture-filling soluble minerals.

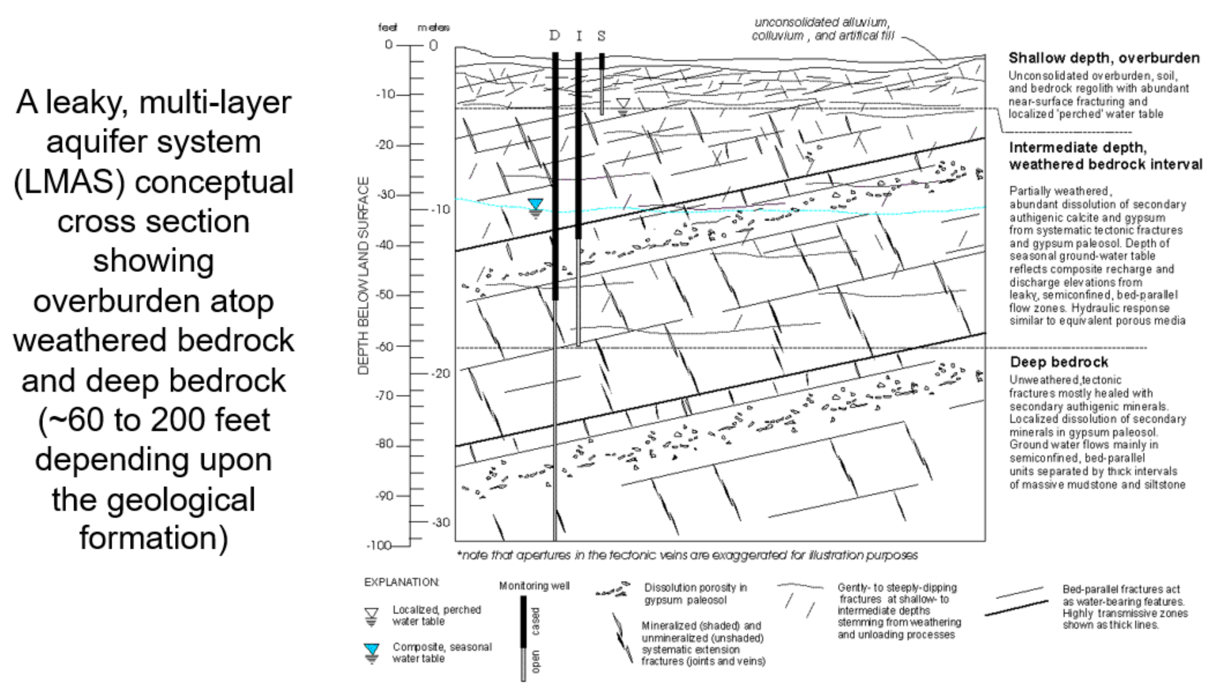


Figure 7. A diagram conceptualizing shallow, intermediate, and deep bedrock. Soluble, secondary, authigenic minerals filling rock pores and tectonic fractures in gently inclined beds are locally dissolved.

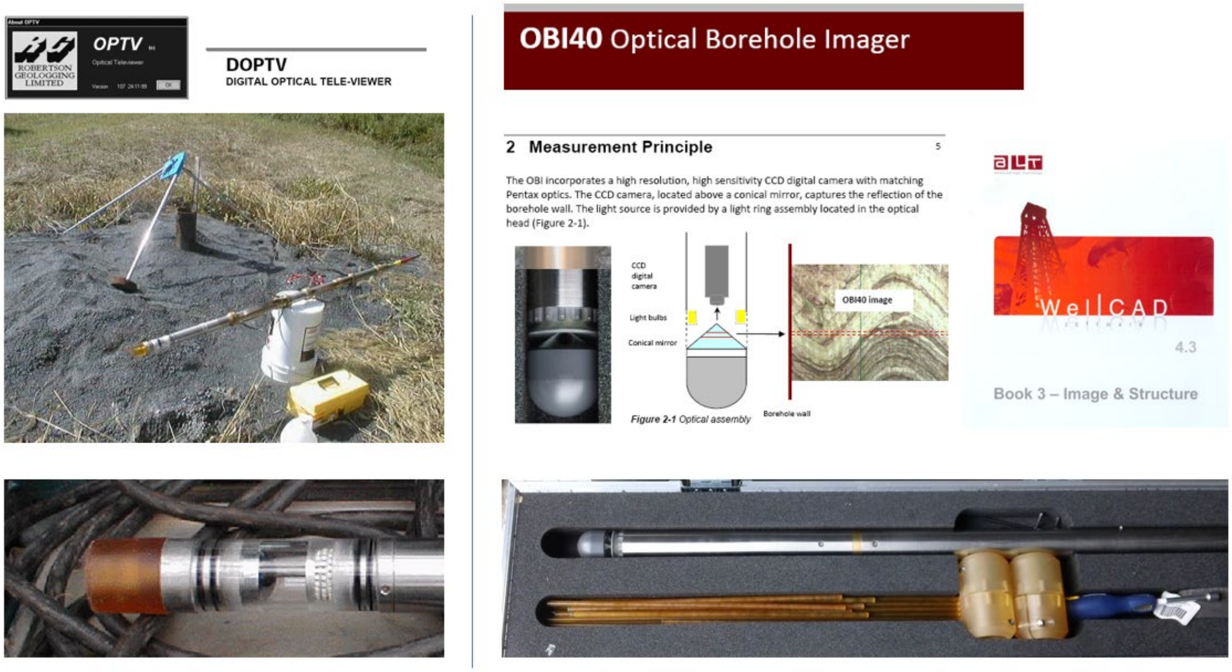


Figure 8. An optical televiewer or optical borehole imaging tool generates a photographic scan of the borehole. The older (left) and newer (right) optical-imaging probes (OPTV and OBI) used by the NJGWS.

OPTICAL TELEVIEWER (OPTV or OBI)

OPTV radial scan of 360 or 720 pixels per 1mm depth

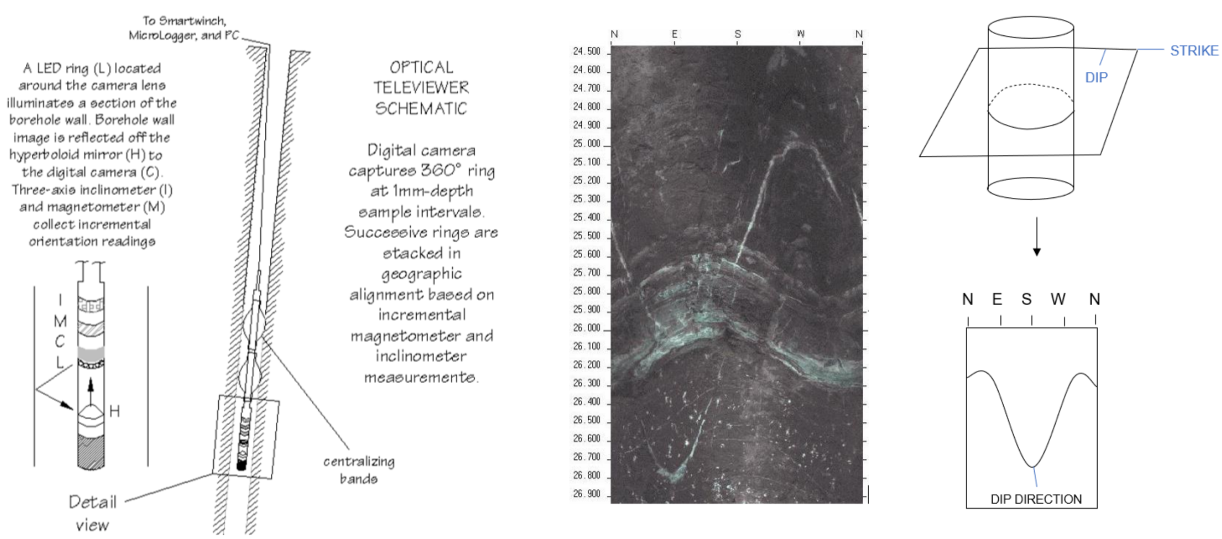


Figure 9. Image-processing software can unwarp the image for structural analysis by fitting vector planes to observed features.

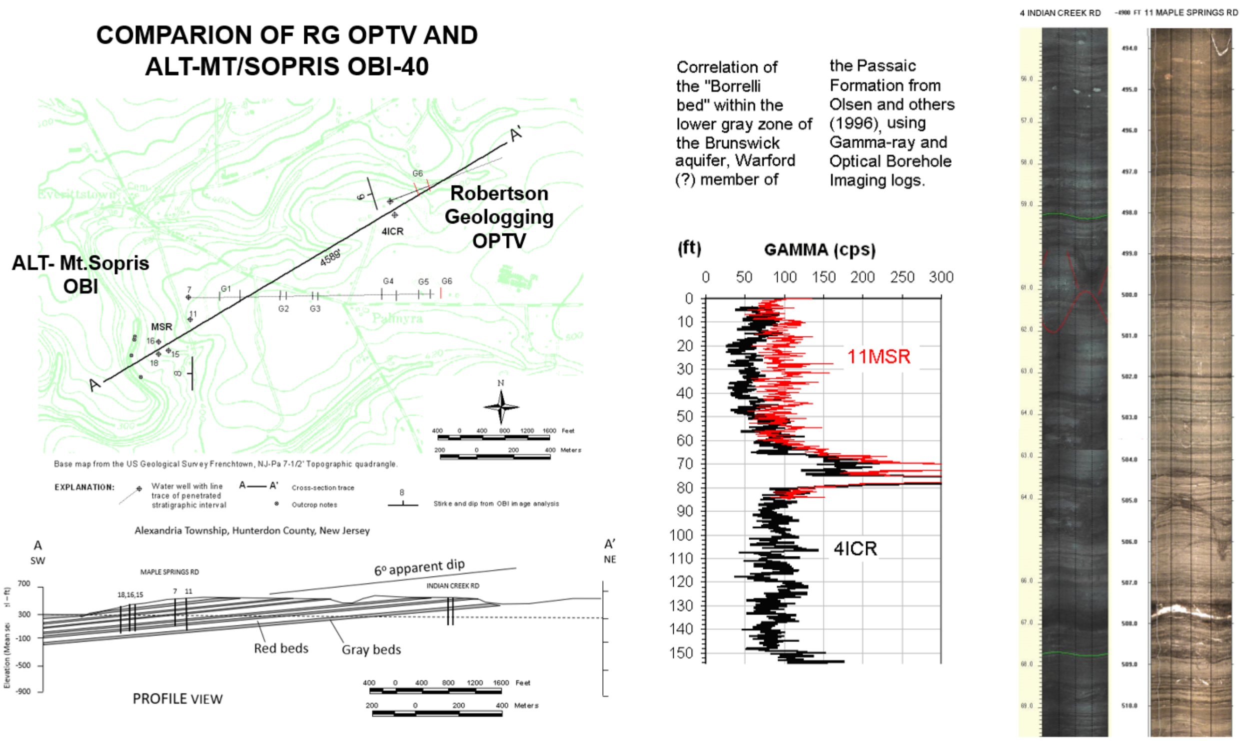


Figure 10. A hydrogeological framework was developed in an area of Hunterdon County having elevated levels of Arsenic and Boron in groundwater. The study began in one neighborhood and continued years later nearby in another sharing the same black and gray sequence of shale having high gamma counts. This study provided a comparison of older (left) and newer (right) televiewer technologies and records.

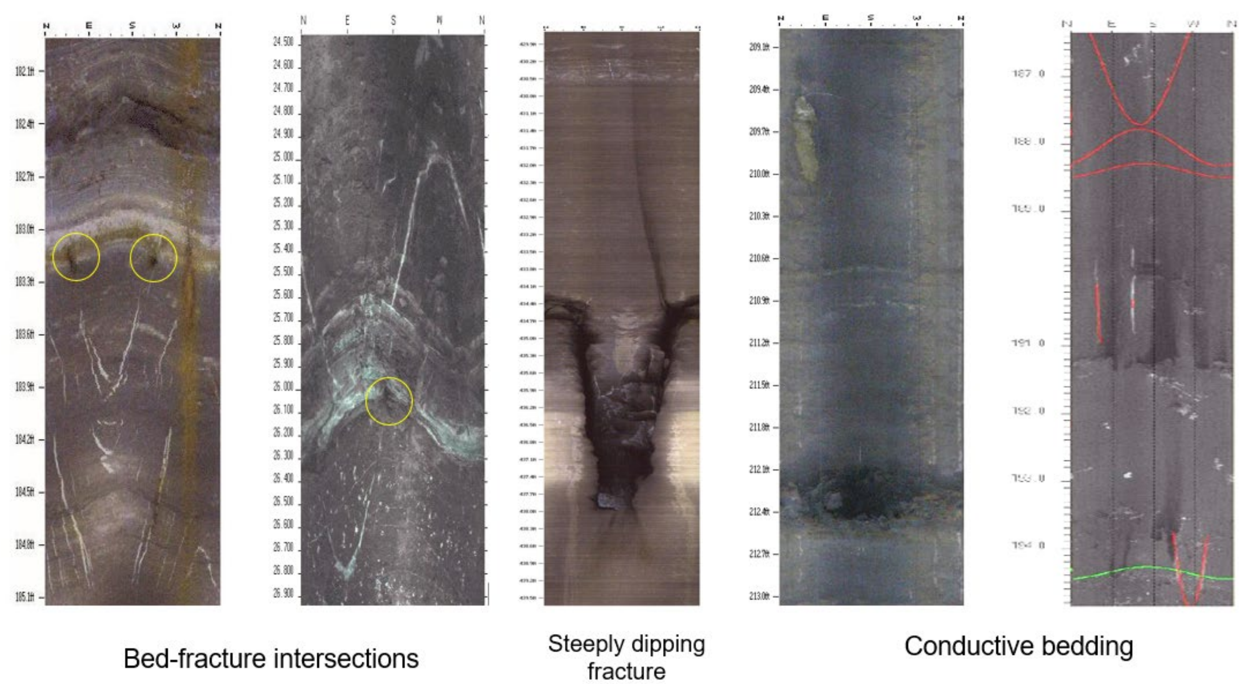


Figure 11. Example WBFs in red and gray mudstone.

Figure 12. Heat-pule flowmeters used by the NJGS. The older (left) and newer (right) HPFMs used by the NJGWS.

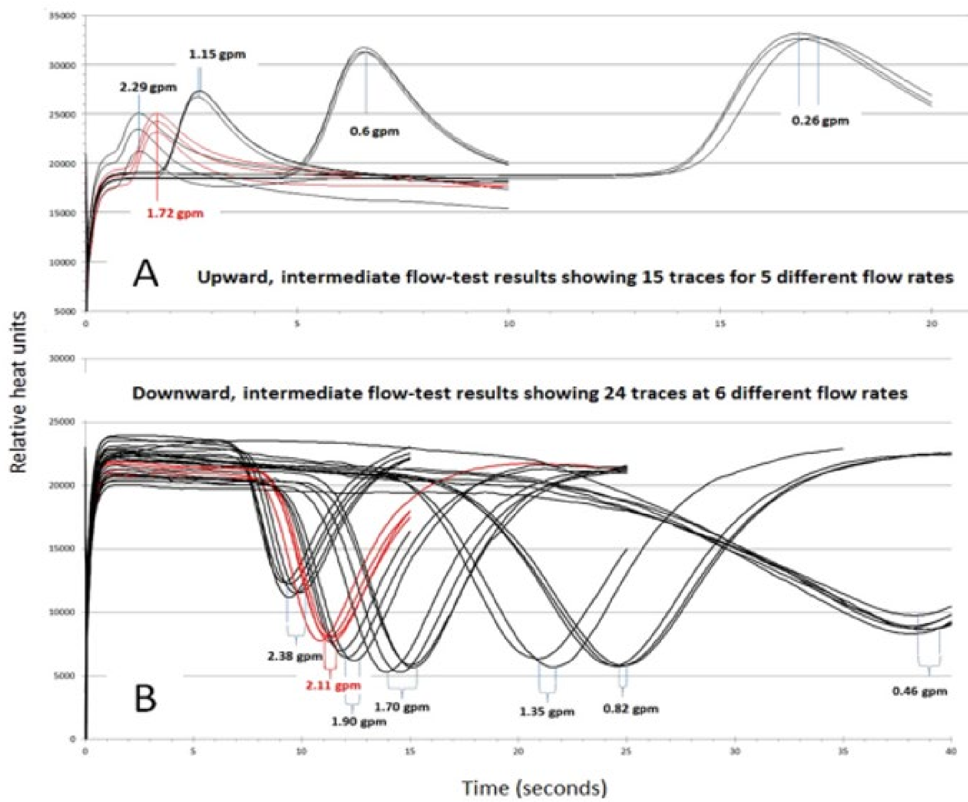


Figure 13. The results of HPFM testing with customized divertors showing timed responses and calculated flow rates for upward (top) and downward (bottom) flow tests.

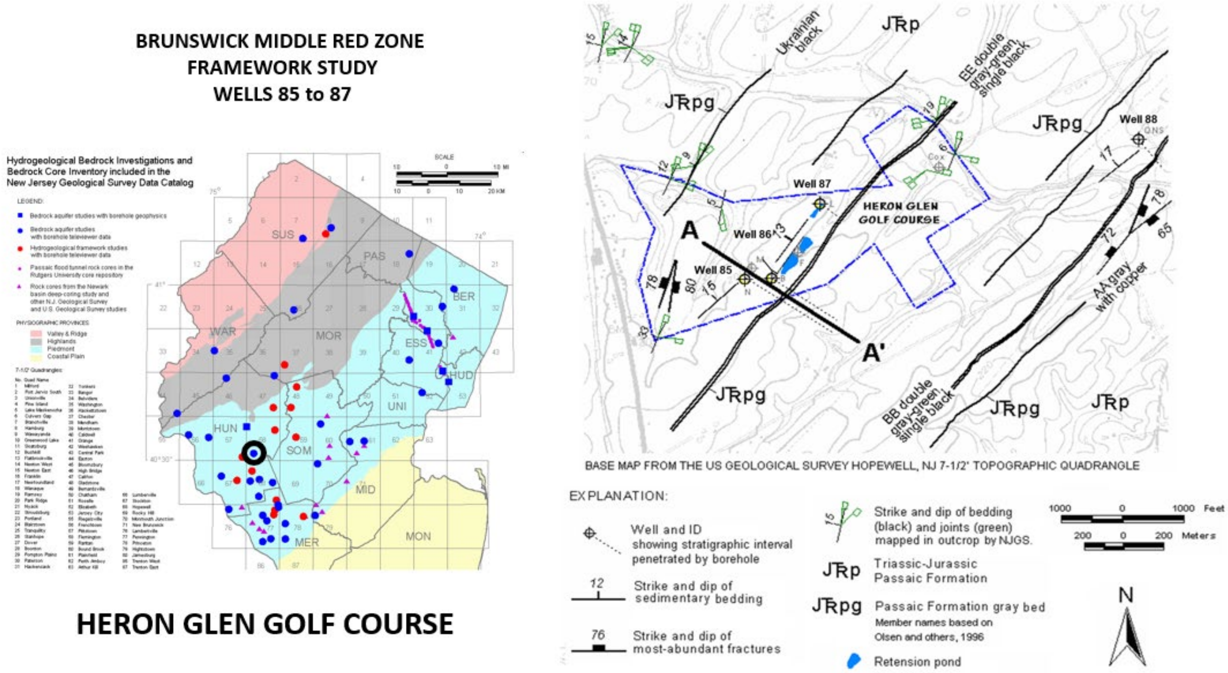


Figure 14. Location map of the Hunterdon County Heron Glen Gold Course on the left and topographic map on the right showing the locations of observation wells near the ponds.

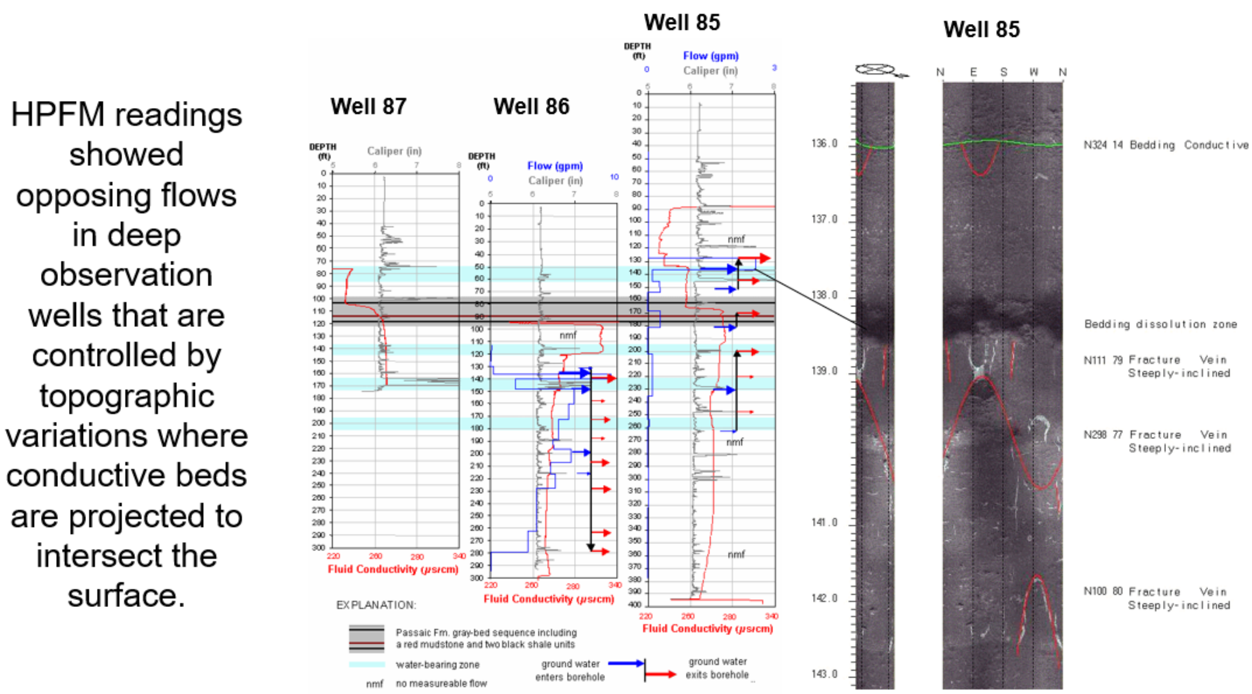


Figure 15. Their observation wells show non-pumping borehole crossflows reflecting variable topography covering the aquifer-recharge zone. Geophysical logs of the observation wells show how gray beds are confining units that affect water quality and cross flows.

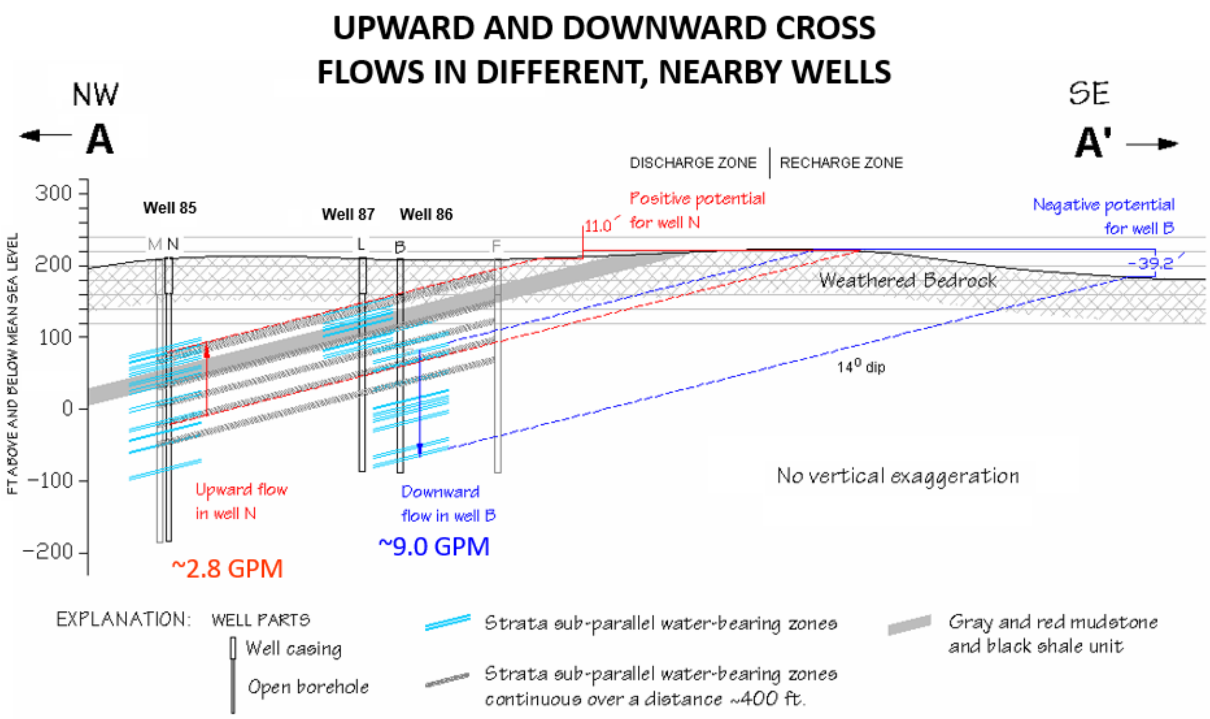


Figure 16. WBFs and WBZs at Heron Glen Golf Course exchange groundwater in the open boreholes because transmissive beds are recharged up dip at different topographic elevations resulting in predictable cross-flow directions.

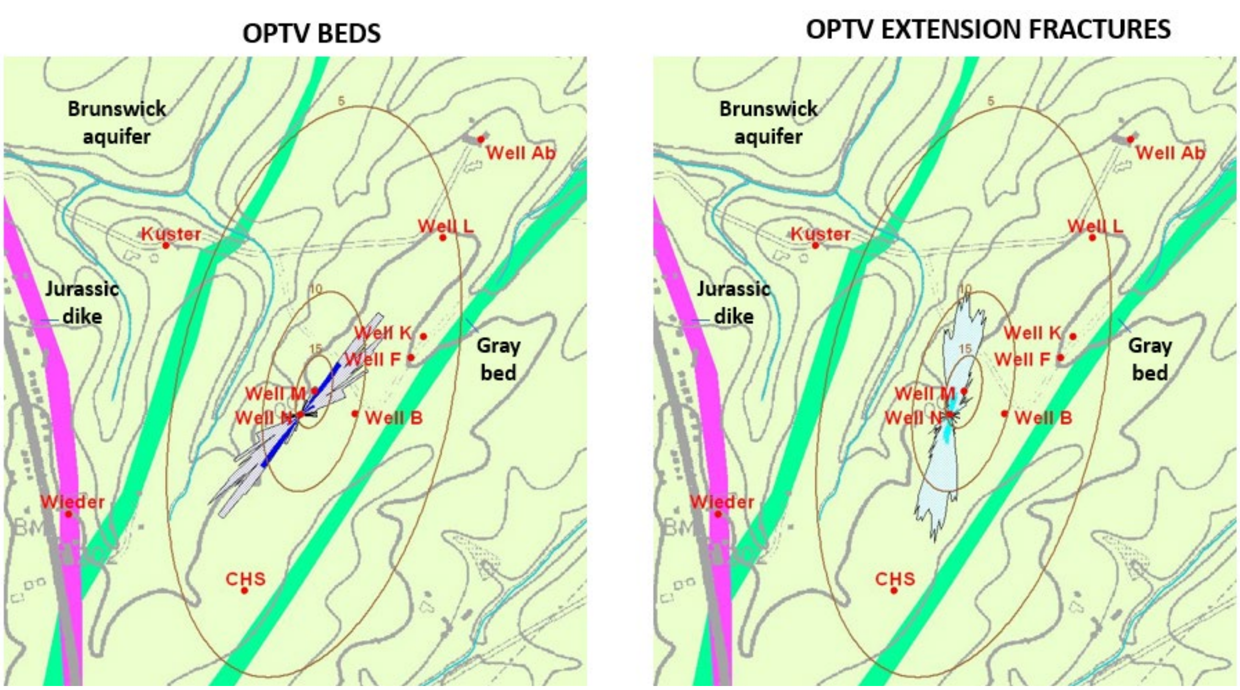
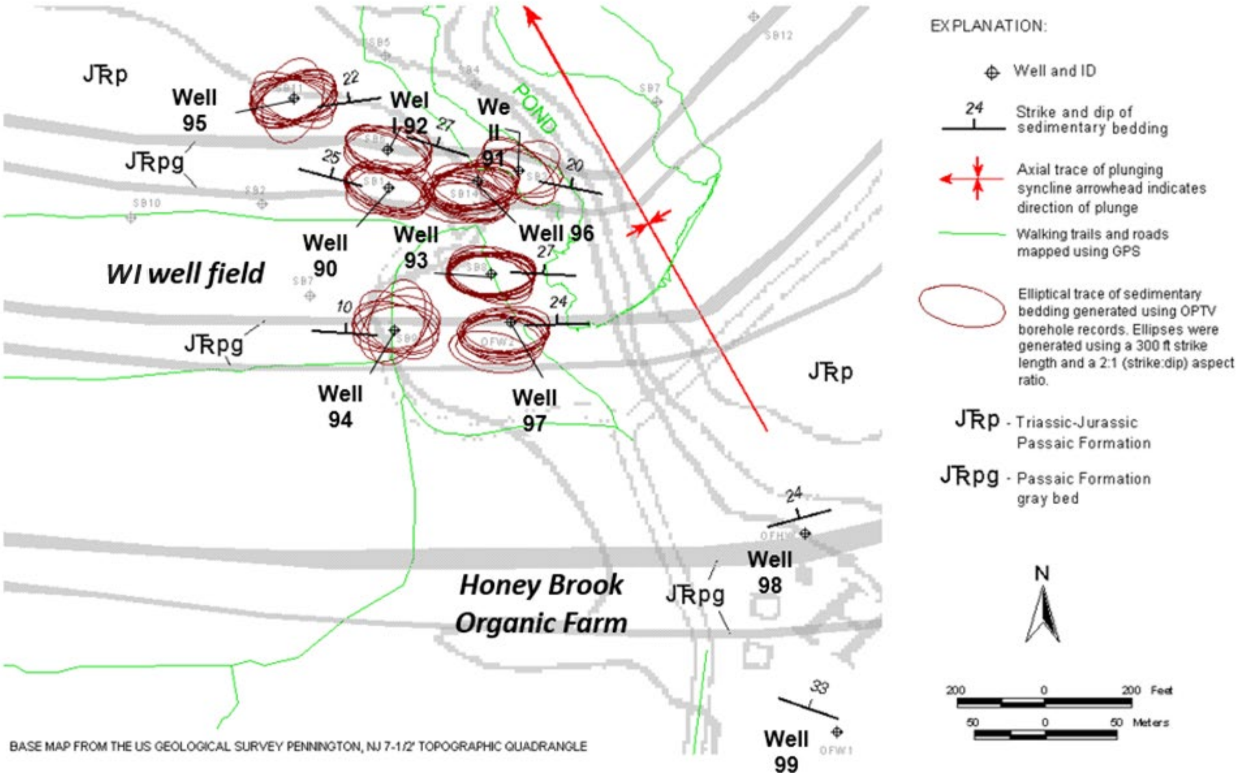


Figure 17. Pumping drawdown predicted by aquifer-test analysis favors fracture-dominated flow occurring within 2 miles of the major, intrabasin Flemington fault.



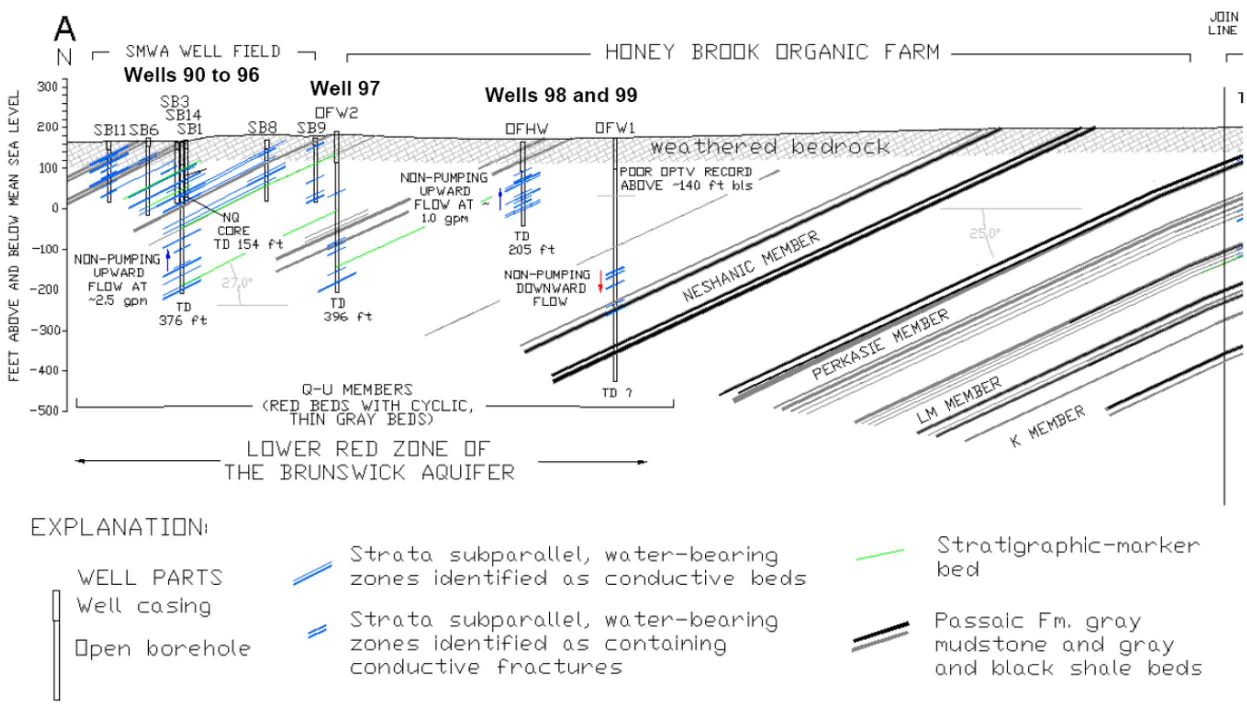


Figure. 18. The former Stonybrook-Millstone Watershed Association (SMWA) research wellfield at the Watershed Institute (WI), Pennington, NJ. Top map shows the wells logged by the NJGWS and elliptical traces of beds measured in each. Average bed strike and dip readings for each well placed next to well locations. Bottom hydrogeological framework summarizes natural cross flows, WBFs, and WBZs.

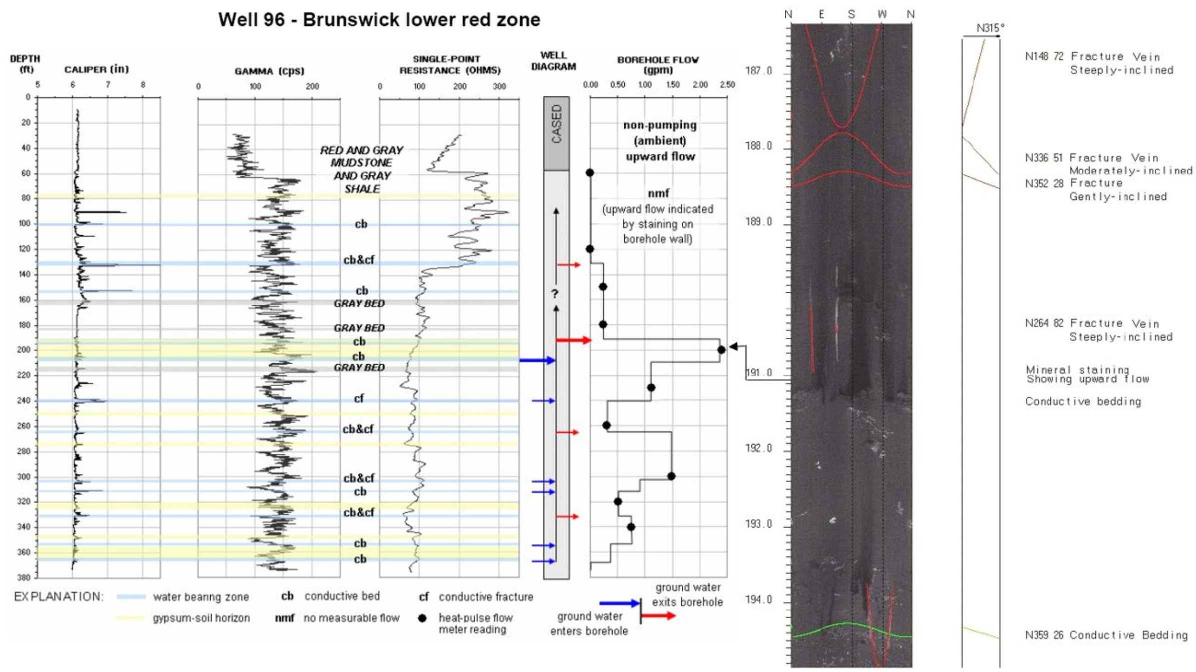


Figure 20. A representative borehole diagram for the WI wellfield showing upward-directed flow stains from the natural cross flows occurring within the mineralized paleo-soils with local mineral dissolution.

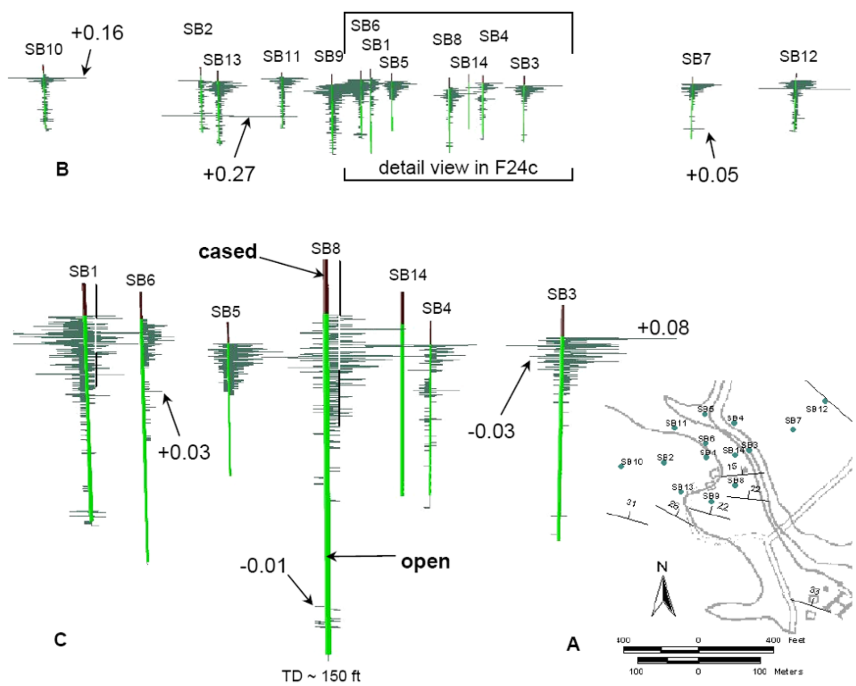


Figure 21. 3D borehole diagram of the WI wellfield using U.S. Geological Survey fluid-temperature logs. The sideways spike plot differences in successive fluid-temperature readings that serve as good indicators of borehole inflow and outflow points. These plots show that the weathered-bedrock intervals extend to below 60 ft. in the lower red zone of the Brunswick aquifer.

Most abundant WBFs are non-bedding fractures

The % of WBFs paralleling beds and layers are highest in coarse-grained beds and basalt.

Fractures are the highest % of WBFs in the gray and black beds

Aquifer	Zones, units and groups	No. of wells	Type 1	Type 2	Type 3	Total	%1	%2	%3
Diabase…..	………	7	11	32	2	45	24	71	4
Brunswick..	………	93	181	247	54	482	38	51	11
Lockatong..	………	10	8	31	6	45	18	69	13
Stockton…..	………	12	13	25	10	48	27	52	21
TOTAL[2]…..	………	**119**	**213**	**335**	**72**	**620**	**34**	**54**	**12**
Brunswick	Basalt units in the Watchung zone (BWB)……..	4	15	10	4	29	52	34	14
Brunswick	Conglomerate and Sandstone (BC and BSC)…..	20	37	21	22	80	47	26	26
Brunswick	Sandstone (BSS)………	3	9	5	1	15	60	33	7
Brunswick	Middle Red zone (BMR)………	33	70	79	5	154	45	51	3
Brunswick	Middle Gray zone (BMG)………	14	21	48	3	72	29	67	4
Brunswick	Lower Red zone (BLR)………	11	20	34	9	63	32	54	14
Brunswick	Lower Gray zone (BLG)………	10	9	50	10	69	13	72	14
Brunswick	Coarse-grained units (BC, BSC and BSS)………	23	46	26	23	95	48	27	24
Brunswick	Fine-grained units (BMR, BMG, BLR and BLG)..	68	120	211	27	358	33	59	8
Brunswick	Red Units (BC, BSC, BSS, BMR and BLR)……..	67	136	139	37	312	43	45	12
Brunswick	Gray Units (BMG and BLG)………	24	30	98	13	141	21	70	9
	Igneous rocks (diabase and basalt)………	11	26	42	6	74	35	57	8
	Sedimentary rocks………	110	187	295	67	549	34	54	12

[1]Type 1 – bedding planes and layers, Type 2 – fracture planes, Type 3 – linear intersections of bed and fracture planes

[2] Some wells penetrate more than one aquifer, group or unit so that the total number of wells and WBFs may not equal column totals.

Figure 22. Bulletin 77 summary of WBFs logged in all wells by geologic zones, units, and groups.

- Cross flows in open boreholes are predictable when considering the dip of beds and the nature of the nearby topography
- Wells drilled into beds dipping down topographic slopes commonly have upward cross flows
- Wells drilled into beds dipping opposite to topographic slopes commonly have downward cross flows

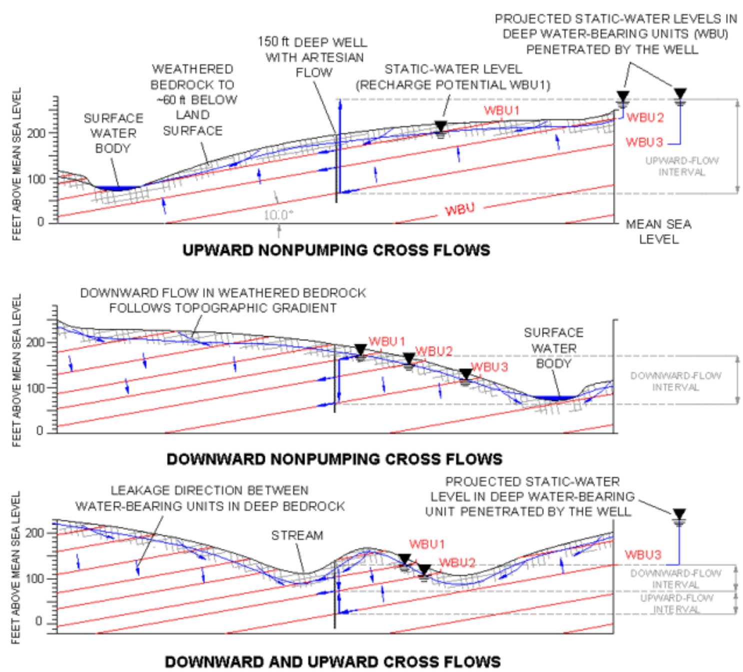
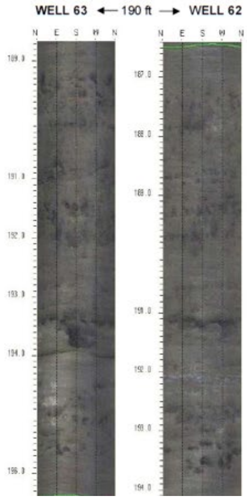
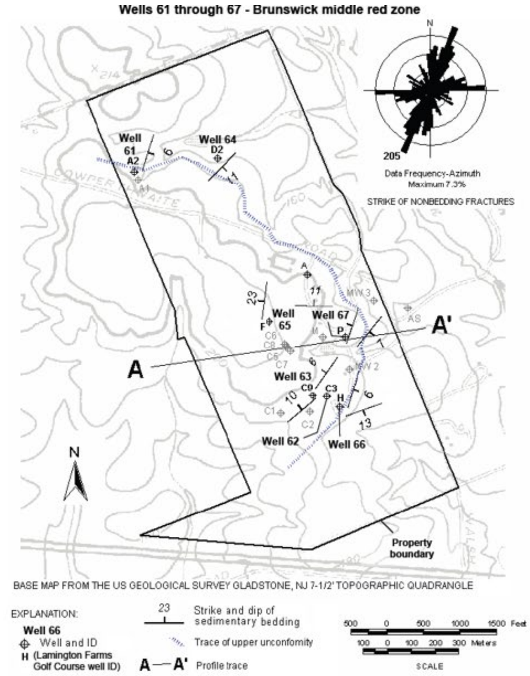


Figure 23. Bulletin 77 cross sections illustrating the hydrogeological nature of borehole cross flows in open boreholes intercepting gently inclined beds recharging at various topographic elevations.

Brunswick middle red zones; Framework study Wells 61 to 67





Stratigraphic unconformities in red mudstone with gypsum soils can hinder groundwater recharge

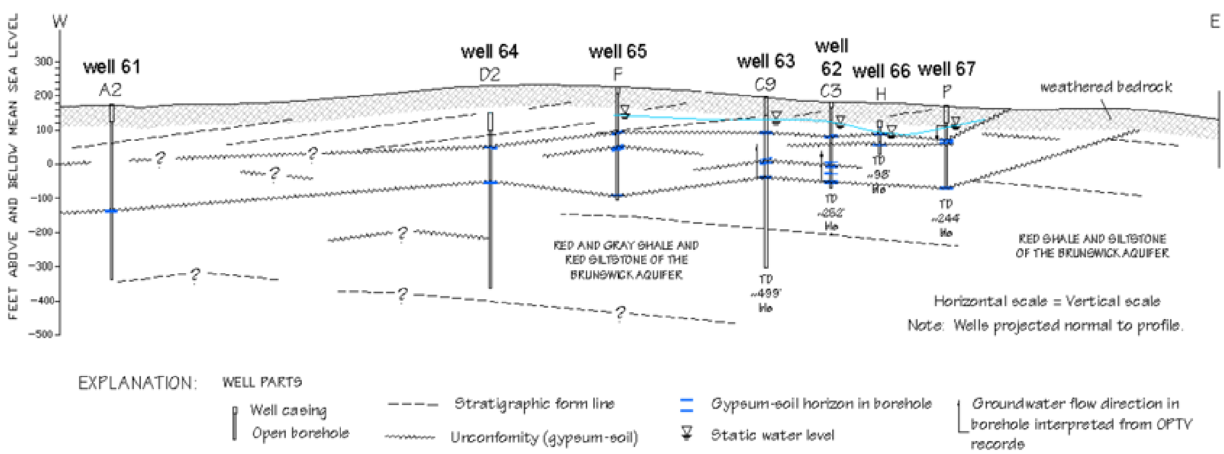


Figure 24. Top maps and core from Lamington Farms at the old DeLorean estate that became Trump National Golf Club at Bedminster. Lamington Farms well test failed to yield adequate supplies because of the geological nature of the red beds. Optical televiewer records indicated the occurrence of angular unconformities along paleosol horizons having good shallow transmission but poor yield from deep beds that are cut off from recharge by angular unconformities.

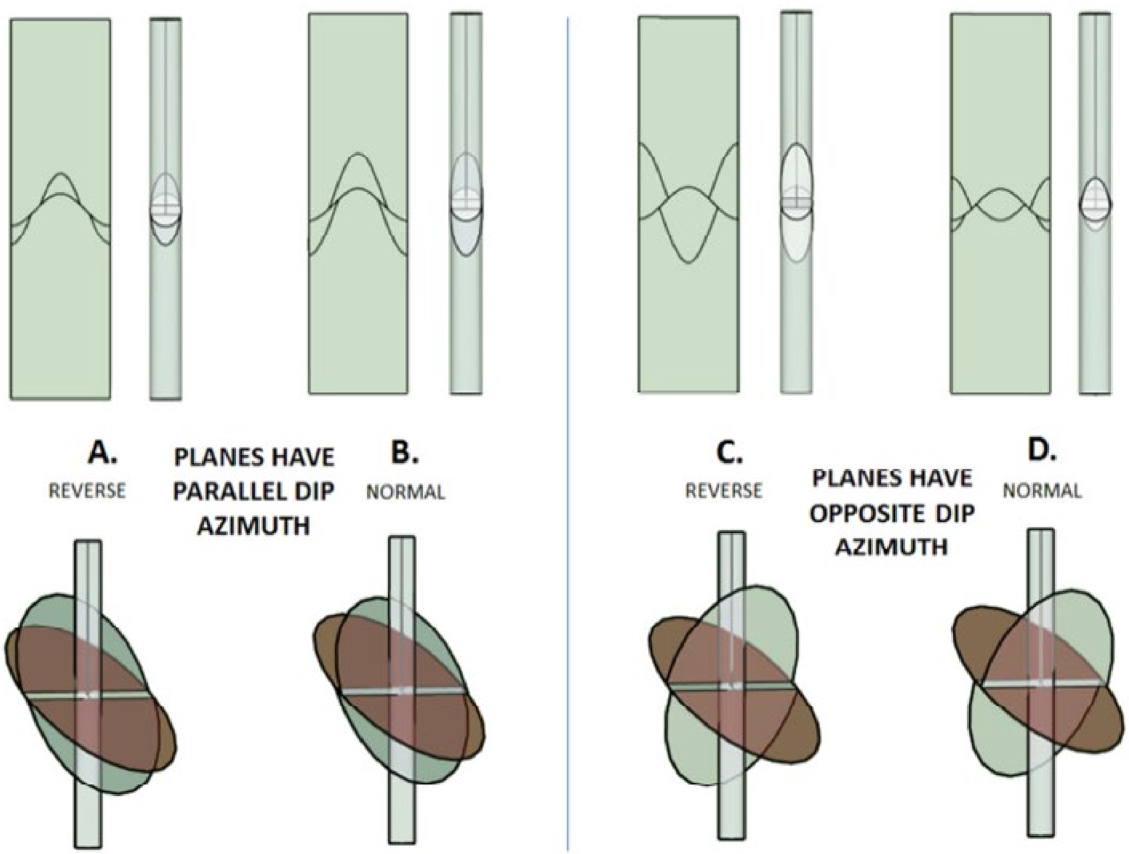


Figure 25. This final figure is reproduced from Herman (2016) from GANJ 33 that serves as a reference for interpreting BTV records having cross cutting fractures and faults. SketchUp Pro 2015 software was used to generate a series of borehole models with shear planes dipping 45° that offset extension fractures dipping 70° and in different directions to serve as a visual aid when interpreting kinematic indicators in BTV records. Each borehole segment was modelled using a 6-inch diameter borehole section that intersects two cross-cutting planes. The dip separation on each shear plane is 2 inches. The borehole walls were next unrolled and flattened into rectangles (top). The four models cover end-member structural scenarios where cross-cutting planes dip in the same (A. and B.) and opposing (C. and D.) directions and have either reverse or normal dip separation.

Conclusions

- WBFs include stratigraphic beds and layers, tectonic and unloading fractures, faults and their intersections.
- WBFs penetrated by wells in bedrock are about 1/2 fractures and 1/3 bedding and layering, with the remaining 1/6 plane intersections.
- High-yielding, area-extensive water-bearing units with high transmissivities are mostly stratigraphic beds and layers (LMAS).
- In water wells open to bedrock, water is constantly exchanged between semi-confined horizons recharging at different topographic elevations
- Water-supply wells should be cased to a minimum 60-100 ft depth range in order to prevent surface-born pollutants from being drawn into nearby wells

- Cross-bedding and fracturing affect hydraulic conductivity and recharge potential by imparting stratigraphic and structural heterogeneity

5 Key Takeaway Points

1. Borehole cross flows in well are systematic and commonly related to red and gray bed stratigraphy
2. WBFs and WBZs in gray beds are more concentrated in non-bedding fractures whereas those in red beds and especially coarser-grained units have more bed-parallel WBFs and Zs.
3. The massive mudstone units have about an equal number of type 1 and 2 WBFs, but the bed-parallel WBZs are higher transmissivities over longer distances.
4. Gray and Black shale units are confining beds to the red-bed aquifers.
5. The depth of weathering in bedrock is commonly 60 – 100 ft below land surface, so having more than 50-ft of casing for supply wells is advised

6. Utility of the LMAS Model to Resolve Responsibility for Off-Site Groundwater Contamination in Bedrock

Rich Britton, PG, LSRP

Abstract

This case history involves two adjacent industrial sites located in Central NJ along the same bank of a major river, with a rather thin saturated overburden overlying the Passaic Formation bedrock. PCE and TCE were common groundwater contaminants at both sites. Unexpectedly, chemicals uniquely associated with the more downstream site were detected in lower overburden wells installed on the opposite side of the river at locations that were not only upstream but also nominally upgradient of both sites. This finding defied groundwater flow patterns claimed by consultants for the more downstream site who relied on an outdated conceptual model for bedrock featuring the shallow, intermediate and deep horizontal flow zones.

To explain a contaminant transport mechanism causing this apparent oddity, a conceptual model of bedrock as a Leaky Multi-unit Aquifer System (LMAS) has been employed. This model features very few transmissive bedding fractures conveying the bulk of groundwater flow through the dipping bedrock. It has brought our attention to the role of an inactive 400 ft deep municipal wellbore, located upstream and structurally down-dip of both sites, might play in the spread of contamination in the nominally upstream and upgradient direction from the more downstream site that formerly used bedrock supply wells.

Our comprehensive bedrock groundwater investigation shows that the old municipal wellbore short-circuited the transmissive bedding fractures, capturing and redistributing the bedrock contamination from the more downstream site. Although it was not possible to directly access the wellbore for testing, a shallower test hole installed nearby documented a large upward flow and the presence of contaminants uniquely associated with the more downstream site. Packer testing with pressure transducers deployment throughout the study area confirmed the continuity of the transmissive bedding fractures identified as wells as bedrock-overburden interactions. The presented case illustrates the utility of the LMAS as the only viable model when conducting bedrock investigations in complex bedrock situation in the Newark Basin.

UTILITY OF LMAS MODEL TO RESOLVE REPONSIBILITY FOR OFF-SITE GROUNDWATER CONTAMINATION IN BEDROCK

Richard Britton, PG, LSRP
Matrix New World Engineering

Geological Association of New Jersey
October 18, 2024

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Project Background

- Site A and Site B located in Central, NJ
- PCE and TCE were a common groundwater contaminant at both facilities.
- Site A and B located adjacent to regional river which acts as a discharge boundary to overburden flow on both sides of the regional river.

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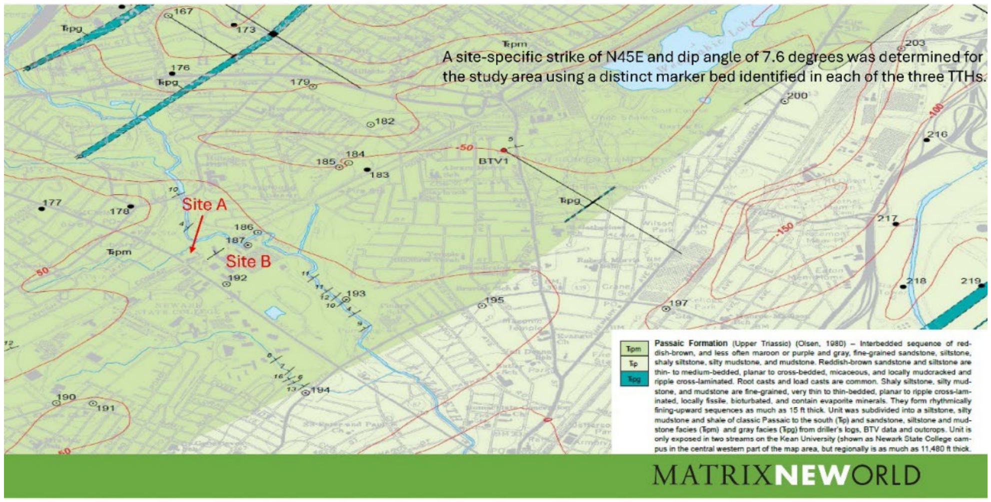
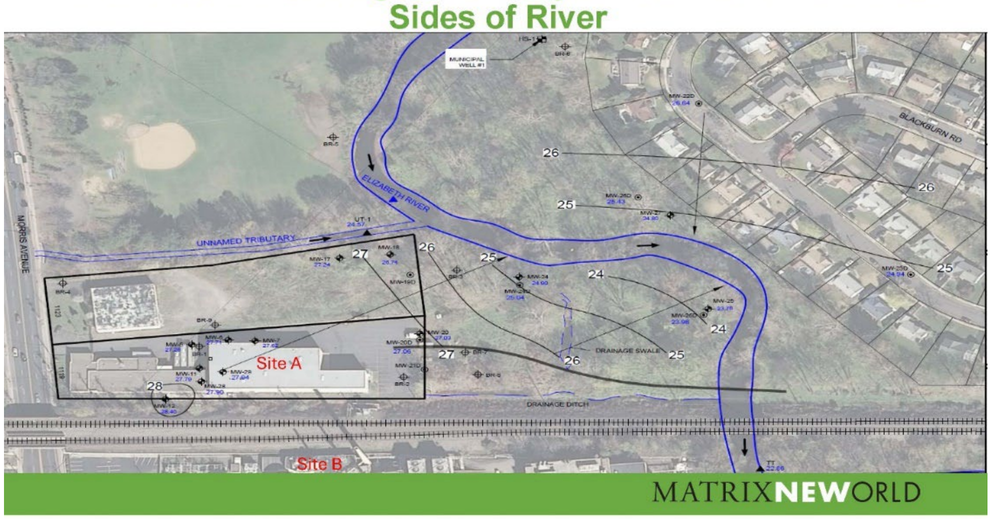
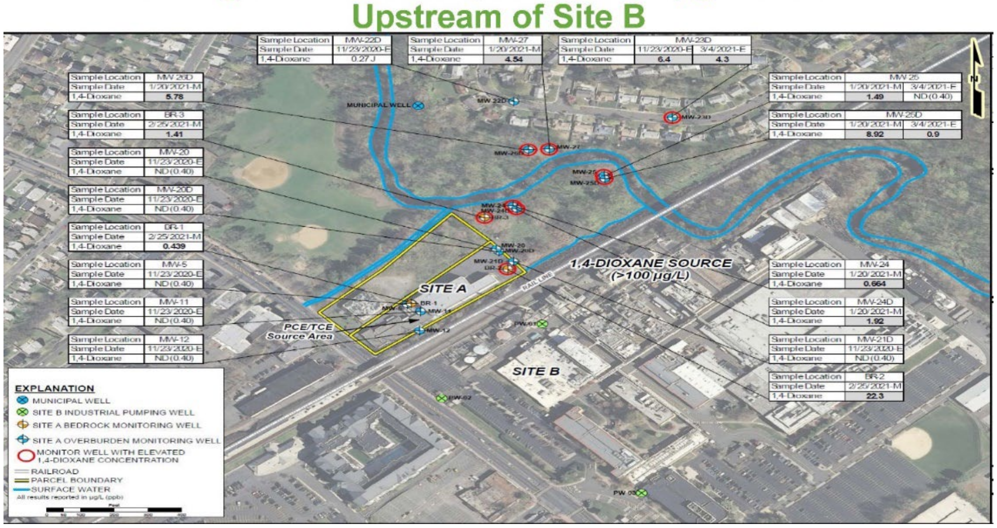
Bedrock Geologic Map



River Acts a Discharge Boundary for OB Flow From Both Sides of River



Puzzling Presence of 1,4-Dioxane Upgradient and Upstream of Site B



Site B Operated Three Deep Bedrock Production Wells

- Site B operated three deep bedrock production wells at its manufacturing facility adjacent to Site A. Production well PW-1, which is nearest to the Site A was installed in 1939. Well PW-2, was installed in 1945, and well PW-3 was installed in 1955 near the center of Site B.
- The reported total pumping rate from these three bedrock production wells was 340 gpm under full plant operation. It increased to 450 gpm under maximum operating conditions.
- Other relevant characteristics of these former production wells are as follows:

Well No.	Open Hole Interval Feet below grade	Well Yield Gallons per minute	Decommissioning Date
PW-1	50-600	225	1985
PW-2	80-676	575	10/4/2014
PW-3	50-475	550	10/8/2014

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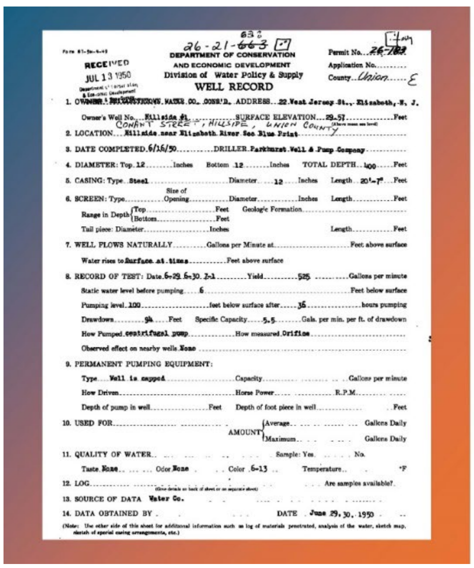
Form 81-5a-6-49
RECEIVED JUL 13 1950 Department of Conservation & Economic Development
26-21-663 (683)
DEPARTMENT OF CONSERVATION AND ECONOMIC DEVELOPMENT
Division of Water Policy & Supply
WELL RECORD
Permit No. 26-183
Application No.
County Union E

1. OWNER: ELIZABETHTOWN WATER CO. CONS'D. ADDRESS 22 West Jersey St., Elizabeth, N. J.
Owner's Well No. Hillside #1 SURFACE ELEVATION 29.57 Feet (Above mean sea level)
2. LOCATION Hillside near Elizabeth River See Blue Print — CONANT STREET, HILLSIDE, UNION COUNTY
3. DATE COMPLETED 6/16/50 DRILLER Parkhurst Well & Pump Company
4. DIAMETER: Top 12 Inches Bottom 12 Inches TOTAL DEPTH 400 Feet
5. CASING: Type Steel Diameter 12 Inches Length 20'-7" Feet
6. SCREEN: Type Size of Opening Diameter Inches Length Feet
Range in Depth Top Feet Bottom Feet Geologic Formation
Tail piece: Diameter Inches Length Feet
7. WELL FLOWS NATURALLY Gallons per Minute at Feet above surface
Water rises to Surface at times Feet above surface
8. RECORD OF TEST: Date 6-29 6-30 7-1 Yield 525 Gallons per minute
Static water level before pumping 6 Feet below surface
Pumping level 100 feet below surface after 36 hours pumping
Drawdown 94 Feet Specific Capacity 5.5 Gals. per min. per ft. of drawdown
How Pumped centrifugal pump How measured Orifice
Observed effect on nearby wells None
9. PERMANENT PUMPING EQUIPMENT:
Type Well is capped Capacity Gallons per minute
How Driven Horse Power R.P.M.
Depth of pump in well Feet Depth of foot piece in well Feet
10. USED FOR AMOUNT Average Gallons Daily Maximum Gallons Daily
11. QUALITY OF WATER Sample: Yes No
Taste None Odor None Color 6-13 Temperature °F
12. LOG (Give details on back of sheet or on separate sheet) Are samples available?
13. SOURCE OF DATA Water Co.
14. DATA OBTAINED BY DATE June 29, 30, 1950
(Note: Use other side of this sheet for additional information such as log of materials penetrated, analysis of the water, sketch map, sketch of special casing arrangements, etc.)

Abandoned Municipal Well Located Downdip and Nominally Upgradient of Sites A and B

- 400 feet deep.
- Steel casing to 20'-7"
- 12-inch diameter steel casing and open borehole.
- Completed June 16, 1950-never used due high levels of bacteria.
- Yield – 525 gpm w 94 ft. drawdown.
- No credible record of decommissioning.

Bedrock Investigation

- Bedrock hydrogeology of the Site A was evaluated in the context of a Leaky Multi-unit Aquifer System (LMAS) concept, the default conceptual groundwater flow model for contaminated bedrock sites in the Passaic Formation (NJDEP, 2012).
- A different, outdated concept was employed during the bedrock investigation at Site B, the adjacent neighboring industrial facility.
- Only the LMAS model can explain the puzzling presence of 1,4-dioxane upgradient and upstream of Site B and on the opposite side of a regional river.

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Site A was Evaluated Using LMAS CSM

(proposed by Michalski,1990)

- The scope of the comprehensive bedrock investigation followed NJDEP's guidance on conducting bedrock groundwater investigations in the context of a Leaky Multi-unit Aquifer System (NJDEP, 2012). It included:
- Installation of three deep Temporary Test Holes (TTHs)
- Geophysical logging of the TTHs
- Salt tracer testing

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Site A was Evaluated using LMAS CSM

(proposed by Michalski, 1990)

- Depth-discrete grab sampling
- Packer sampling and testing with pressure transducers deployed in other TTHs and wells.
- Conversion of TTHs to permanent monitoring wells
- Synthesis of data into a site-specific bedrock flow model and its verification through short-term pumping tests
- Installation of additional bedrock wells targeted to transmissive aquifer units of interest.

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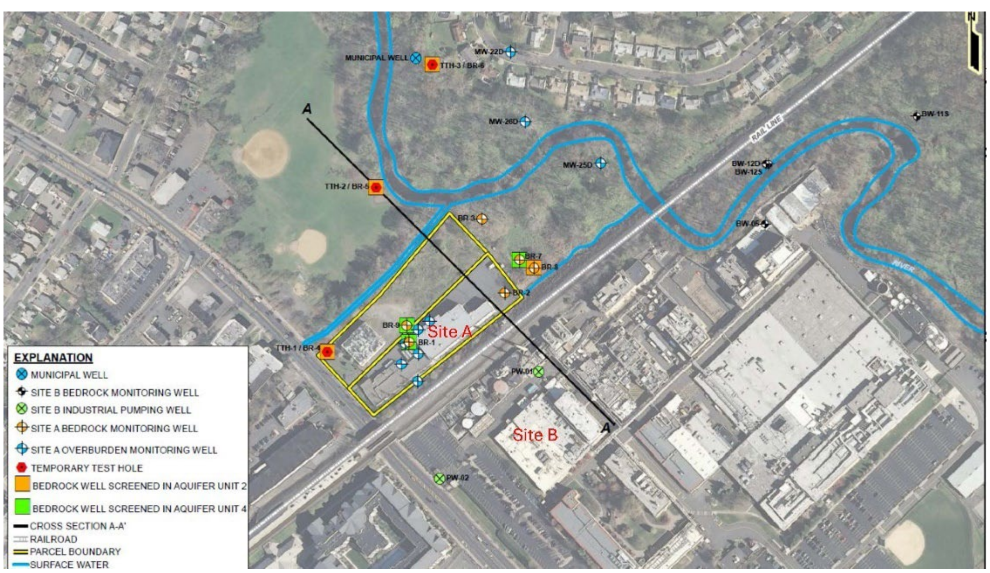
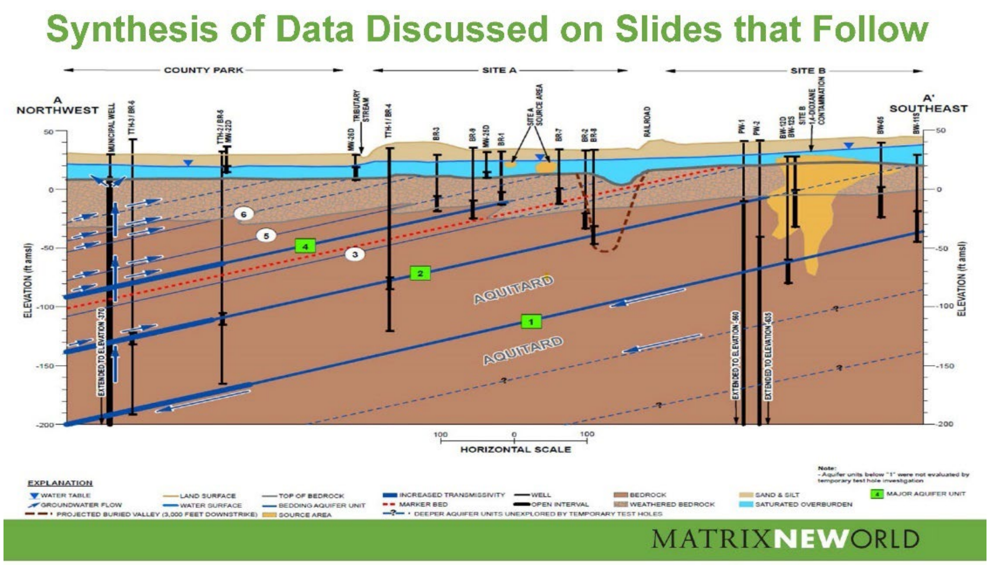
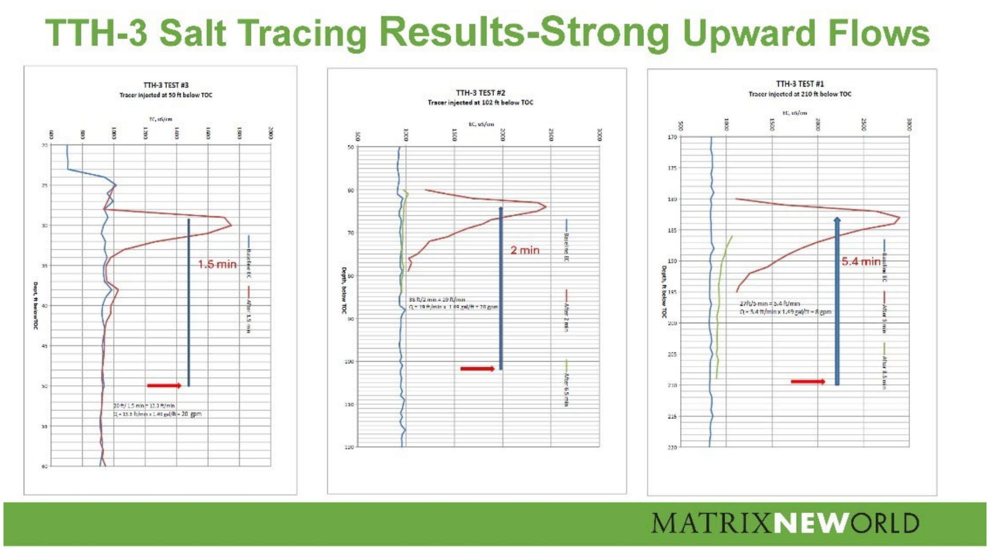



Synthesis of Data Discussed on Slides that Follow
COUNTY PARK
SITE A
SITE B
A
NORTHWEST
A'
SOUTHEAST
ELEVATION (ft amsl)
AQUITARD
AQUITARD
HORIZONTAL SCALE
EXPLANATION
MATRIXNEWORLD


TTH-3 Salt Tracing Results-Strong Upward Flows
TTH-3 TEST #3
Tracer injected at 50 ft below TOC
1.5 min
TTH-3 TEST #2
Tracer injected at 102 ft below TOC
2 min
TTH-3 TEST #1
Tracer injected at 210 ft below TOC
5.4 min
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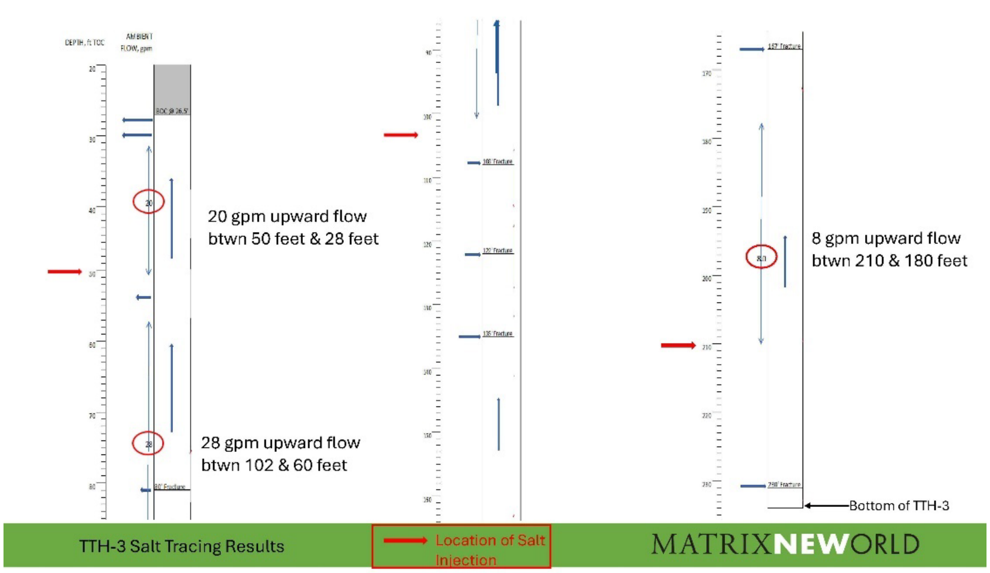
20 gpm upward flow
btwn 50 feet & 28 feet
28 gpm upward flow
btwn 102 & 60 feet
8 gpm upward flow
btwn 210 & 180 feet
Bottom of TTH-3
TTH-3 Salt Tracing Results
Location of Salt Injection
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Packer Test Transmissivity and Head Profiling

SUMMARY OF PACKER TESTING DATA FOR TTH-3

Zone No.	Depth Interval (ft)	Zone Elevation Range (ft, msl)	Depth to Water from TOC (ft)	Water Elevation (ft msl)	Head Difference (ft*)	Head Elevation (ft, msl)	Pumping Rate (gpm)	EC (mS/cm)	Temperature (deg C)	Drawdown (ft)	Transmissivity (gpd/ft**)	Analytical Results (ug/L) 1,4-Dioxane	Tetrachloroethene	Trichloroethene	cis-1,2-Dichloroethene	1,1-Dichloroethene	Comments
7	52-63.3	-9.6 to -20.9	10.83	31.54							8						Tight zone, not pumpable
6	75-86.3	-32.6 to -43.9	10.83	51.54	-3.0	28.5	2	398	15.2	67	26	6.55	79.9	37.3	20.0	3.7	
5	104-115.3	-61.6 to -72.9	10.85	31.52	0.5	32.0	8	440	14.3	26.5	264	3.97	99.2	51.1	9.7	5.9	
4	117-128.3	-74.6 to -85.9	10.84	31.53	0.6	32.1	6	445	14.7	10.6	495	2.64	81.9	61.1	8.2	5.8	Carbon tet detected at 0.93 J
3	131-142.3	-88.6 to -99.9	10.83	31.54	0.7	32.2	10	395	14.3	10.7	817	4.06	115	72.1	20.4	5.3	
2	162-173.3	-119.6 to -130.9	10.83	31.54	2	33.5	15	324	14.0	5.5	2,384	18.3	48.8	30.5	70.5	1.6	
1B	209-234	-166.6 to -191.6	10.85	31.52	3.3	34.8	12	319	14.1	4.9	2,140	3.84	151	13.7	9.7	ND (0.59)	Bottom at ~234 ft, below TOC
1A	209-220.3	-166.6 to -177.9	10.85	31.52	1.8	33.3	1			>200	<4						Pumping stopped; tight zone
								Total Transmissivity			6,134						

Notes:

Top of Casing Elevation = 42.37 ft, msl

* Relative to ambient water level prior to inflation of the packers

** For tight zones, transmissivity value derrived from slug tests

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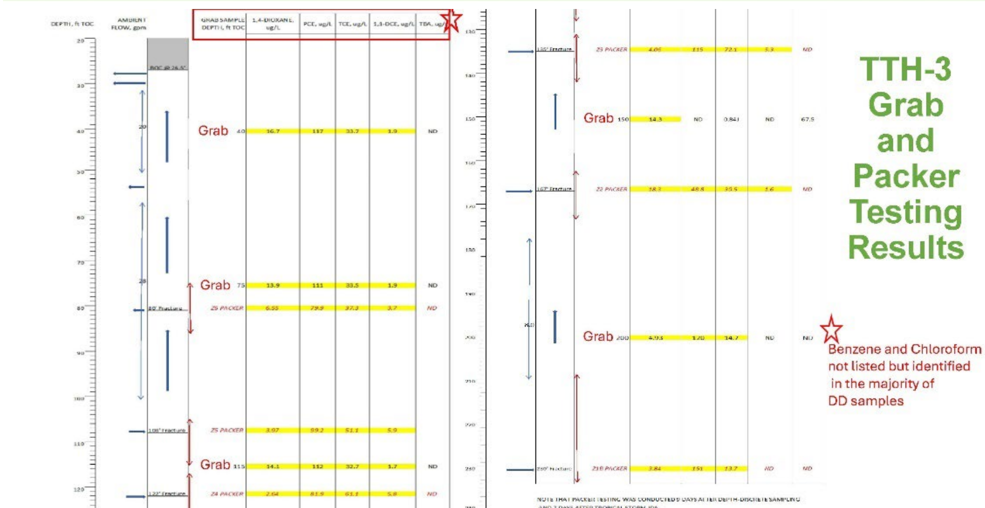

Packer Test Transmissivity and Head Profiling

SUMMARY OF PACKER TESTING DATA FOR TTH-2

Zone No.	Depth Interval (ft)	Zone Elevation Range (ft, msl)	Depth to Water from TOC (ft)	Water Elevation (ft msl)	Head Difference (ft*)	Heat Elevation (ft, msl)	Pumping Rate (gpm)	EC (mS/cm)	Temperature (deg C)	Drawdown (ft)	Transmissivity (gpd/ft)	Analytical Results (ug/L) 1,4-Dioxane	Tetrachloroethene	Trichloroethene	cis-1,2-Dichloroethene	1,1-Dichloroethene	Comments
6	52-63.3	-19.7 to -31.0	0.38	31.91	-2.7	29.2	2.2	338	16.2	20	96	25.3	7.2	6.3	40.4	1.2	
5	75-86.3	-42.7 to -54.0	0.42	31.87	-1.7	30.2	0.8	335	17.1	79	9	12.9	7.6	15.9	40.9	3.3	
4	92-103.3	-59.7 to -71.0	0.38	31.91	0.05	32.0	7.5	353	15.0	4.6	1,425	18.4	13.3	15.1	40.3	4.2	
3	105-116.3	-72.7 to -84.0	0.38	31.91	0.05	32.0	3.0	462	15.6	10	262	18.3	38.1	25.1	42.9	1.5	
2	137-148.3	-147.7 to -159.0	0.30	31.99	0.74	32.7	7.2	378	14.8	32	197	31.4	ND (0.90)	2.0	41.8	0.60 J	
1	180-205.3	-147.7 to -159.0	0.25	32.04	0.3		0.7			185	3						Test terminated - tight zone
								Total Transmissivity			1992						

Notes:

Top of Casing Elevation = 32.29 ft, msl

* Relative to ambient water level prior to inflation of the packers

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Packer Test Transmissivity and Head Profiling

SUMMARY OF PACKER TESTING DATA FOR TTH-1

Zone No.	Depth Interval (ft)	Zone Elevation Range (ft, msl)	Depth to Water from TOC (ft)	Water Elevation (ft msl)	Head Difference (ft*)	Head Elevation, ft msl	Pumping Rate, gpm	EC, mS/cm	Drawdown, ft	Transmissivity (gpd/ft**)	1,4-Dioxane	Tetrachloroethene	Trichloroethene	cis-1,2-Dichloroethene	1,1-Dichloroethene	Toluene	Comments
5	52-63.3	-14.3 to -25.6	5.29	32.39	0	32.4	2.0	287	32	55	0.274 J	2.2	5.4	1.7	ND (0.57)	0.96 J	
4	66-77.3	-28.3 to -39.6	5.22	32.46	0.1	32.6	7.1	275	24	259	0.224 J	4.9	1.9	1.8	0.85 J	0.98 J	
3	79-90.3	-41.3 to -52.6	5.2	32.48	0.2	32.7	0.4	274	37	9	0.711	16.3	5.7	8.1	3.0	4.9	
2	112-123.3	-74.3 to -85.6	5.19	32.49	0.4	32.9	2.3	265	45	45	0.840	9.8	5.1	8.3	3.3	0.72 J	
1	145-164	-107.7 to -119.0	5.13	32.55						18							Tight zone, no pumping
							Total Transmissivity			385							

Notes:

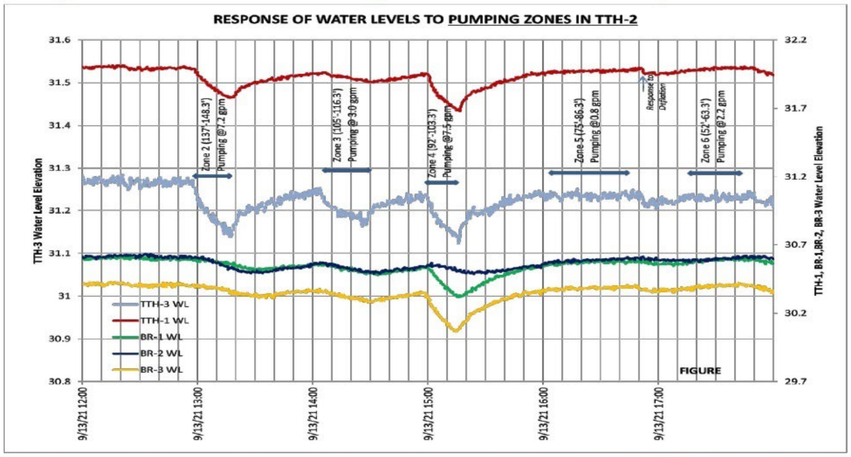
Top of Casing Elevation = 37.68 ft, msl

* Relative to ambient water level prior to inflation of the packers

** For tight zones, transmissivity value derrived from slug tests

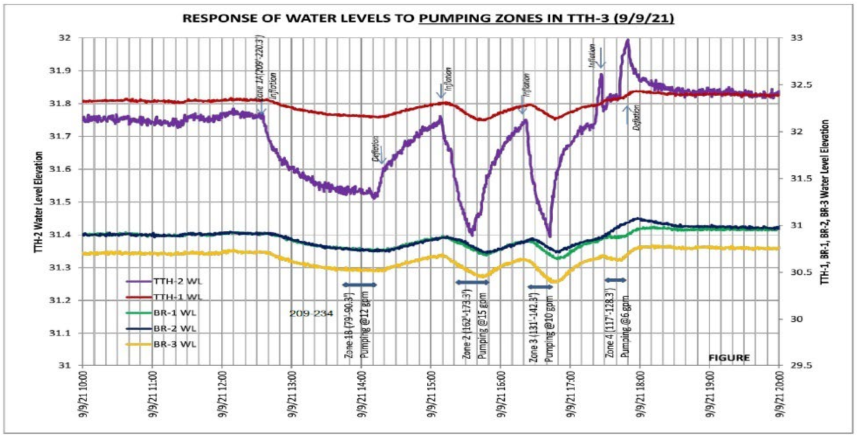
MATRIXNEWORLD

Hydraulic Continuity of Identified Aquifer Units



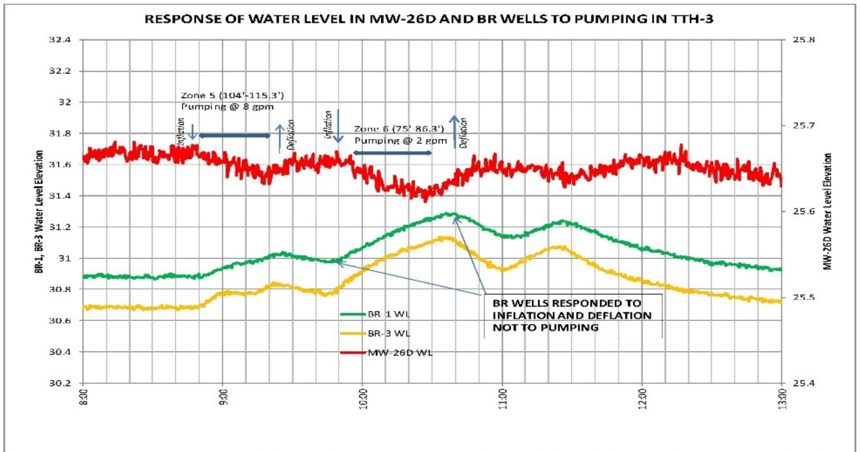
MATRIXNEWORLD

Hydraulic Continuity of Identified Aquifer Units

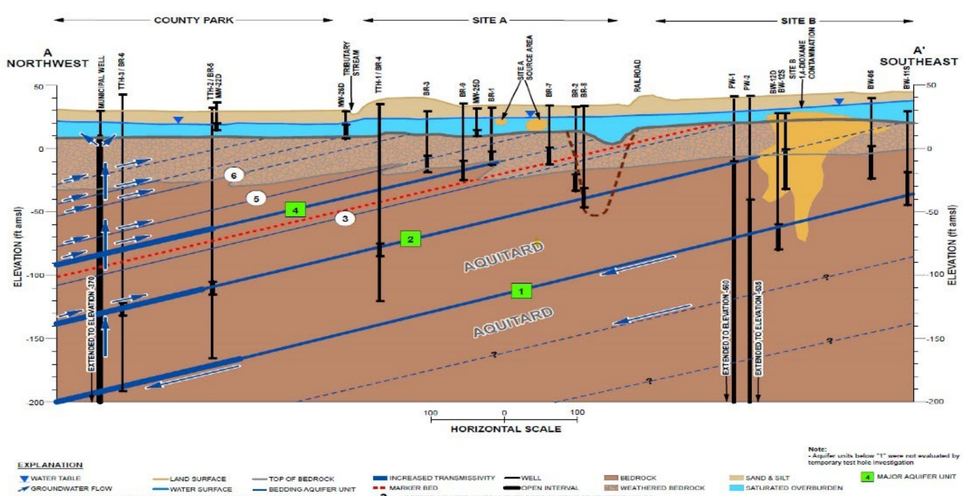


MATRIXNEWORLD

Hydraulic Connection TTH-3 and Overburden Well MW-26D



MATRIXNEWORLD



MATRIXNEWORLD

Synthesis of Data into a Site-Specific Bedrock Flow Model/Hydraulic Impact of Municipal Well

- The short-circuiting effects of the open hole interval of the municipal well has been documented by the data collected at TTH-3, a shallower surrogate for the municipal well.
- The bedrock investigation showed that the long open borehole of the former municipal supply well cross-connects transmissive bedding planes (AUs 1-6) with different hydraulic heads creating an internal upward flow estimated to be more than 100 gpm. This vertical conduit provides an elevator-like transfer of contaminated groundwater from the deep AUs under higher heads through the overlying shallower AUs and into the overburden and the river, which are at lower hydraulic heads.

MATRIXNEWORLD

Synthesis of Data into a Site-Specific Bedrock Flow Model/Hydraulic Impact of Municipal Well

- The hydraulic connection created by the long open borehole of the municipal supply well, is analogous to a slanted hydraulic U-tube: The municipal supply wellbore acts as the neck of the U-tube, while the highly-transmissive bedding-plane separation identified as AU-1 (and deeper unexplored AUs below it) provide an arm of downdip flow, and AU-3 through 6 an arm of updip flow.
- The 2014 decommissioning of Site B production wells, combined with the short-circuiting conduit created by the municipal supply well has allowed deep-seated contamination from Site B, migrating under post-Site B production well closure natural gradients, into the deeper segments of the municipal wellbore where it is redistributed up dip.

MATRIXNEWORLD

LMAS is the Only Viable Model for Complex Bedrock Investigations in the Newark Basin

- The short-circuiting/capture and redistribution of Site B's bedrock contamination accounts for the overburden and subslab soil gas contamination identified on the opposite site of the regional river.
- No other transport mechanism has been identified to explain the presence of contaminant compounds uniquely associated with Site B on the opposite side of the river.
- The presented case study illustrates the utility of the LMAS model as the only viable model when conducting bedrock investigations in complex bedrock situations in the Newark Basin.

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Questions?

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7. Vertical Delineation of the Weathered Bedrock Geological and Hydrogeological Unit in Central New Jersey

Paul Trudell, P. Eng.; WSP USA Solutions, Valerie Holliday; GeoLogos & Jeffrey J. Frederick; WSP USA Solutions

Introduction

Contaminated bedrock groundwater investigations require an understanding of the groundwater flow paths that yielded the present contaminant distribution. In the most basic sense, the conceptual site model summarizes the groundwater flow paths by delineating the saturated subsurface into aquifers – water bearing units and aquitards – impeded groundwater flow zones between aquifers.

In the Newark Basin, there has been considerable effort to develop the regional conceptual model for groundwater flow paths. The regional geological framework is comprised of unconsolidated residual soils overlying weathered bedrock and competent (un-weathered) bedrock. Michalski (1990) detailed when the near-surface experiences weathering processes, the bedding plane partings experience reduced transmissivity due to clogging with clay. With an observed trend of increasing hydraulic conductivity with depth, Michalski advised to install monitoring screens in a trial and error approach to reduce vertical cross-connection across the weathered bedrock. Michalski & Britton (1997) incorporated the weathered (transition) zone between the overburden and un-weathered bedrock in the fifth iteration of leaky multi-aquifer system conceptual site model for Newark Basin sites, highlighting the enhanced storage of this zone. Despite these advancements, Herman (2010) indicated that the hydrogeological properties of weathered bedrock are not well documented and that water well casings are not typically isolating the weathered bedrock from the competent bedrock hydrogeological units.

This talk involves analyzing two pairs of bedrock borehole instrumented as multilevel monitoring for a remedial investigation for indications of weathered bedrock from the central New Jersey DNAPL site.

Methodology

The remedial investigation involved applying the Discrete Fracture Network (DFN) Approach (Parker et al., 2012) to characterize the nature and extent of contamination in the bedrock. This approach involves collecting a diverse range of datasets (physical, suite of geophysical logs, hydrophysical, hydraulic head profiling, and rock core contaminant analysis) from coreholes to understand the nature & extent of contamination. In particular this characterization approach utilizes vertical head profiles from multilevel monitoring systems (MLS) to delineate distinct hydrogeological units of groundwater flow systems (Meyer et al., 2008)

This talk focuses on characterizing the thickness and degree of weathering using the DFN approach. The data was collected as part of a remedial investigation of an industrial facility with an operational water supply well where there was a dense non-aqueous phase liquid release at surface. As part of the investigation, a traditional overburden and bedrock wells were paired with DFN coreholes down to the depth of interest at two locations with the study area. Due to a groundwater classification exception area from an upgradient property, the DFN coreholes were advanced as a shallow and deep pair. The range of DFN datasets were used to design MLSs for the completion of each corehole. At location A, there were 9 multilevel screens of 5-10 ft length installed (between 2 MLSs) at depths between 40 and 370 feet below ground surface (bgs). At location B, there were 11 multilevel screens of 2-10 feet length installed (between 2 MLSs) at depths between 40 and 365 feet bgs. The MLSs were gauged and sampled over three for three events and gauged during a fourth event.

Results

Over the four gauging events, a reproducible transition in vertical hydraulic head transition was observed from the overburden through to 100+ feet below ground surface at both locations. The largest difference in hydraulic head was found to be between the overburden and first MLS monitoring interval. Across each subsequent monitoring interval, the gradient decreased to a depth of over 100 feet. Practically, this means that the installed well casings did not completely isolate the transition in hydraulic head between the overburden and un-weathered bedrock; the well casing isolated the bulk of the hydraulic transition, but a subtle hydraulic transition continues for approximately 75 feet below the well casing.

Analysis

The complementary DFN datasets were assessed for both primary reasoning for the upper bedrock transition in hydraulic head and for correlation with complementary logs.

The fractures were assessed within the acoustic televiewer log for indications of weathering. The results indicate that in the hydraulic transition zone, the fractures are of less integrity than the underlying fractures. Furthermore, the bulk media integrity profile derived from the ATV amplitude indicate an increase in rock integrity with depth that correlates with the transition in hydraulic head.

The transitional zone was assessed for hydraulic conductivity properties relative to the underlying bedrock. The continuous transmissivity profile and heat-pulse flow meter indicates that the highest hydraulic conductivity through the sequence was measured in the hydraulic transition zone. The cumulative transmissivity profile indicates that the hydraulic transition zone has distinct transmissivity features separated by thick sequences with menial transmissivity.

Findings

The results from this project suggests that weathered bedrock hydrogeological unit is comprised of an abrupt transition from the overburden underlain by a gradual transition into the competent (un-weathered) bedrock. Ultimately, this study proposes using multiple lines of evidence to characterize the weathered bedrock as a distinct geological unit and hydrogeological unit that should not be overlooked when developing a conceptual site model at contaminated bedrock sites in the Newark Basin.

References:

Herman, G. (2010). Hydrogeology and Borehole Geophysics of Fractured-Bedrock Aquifers, Newark Basin, *New Jersey Geological Survey Bulletin 77*. https://dep.nj.gov/wp-content/uploads/njgws/techincal-publications-and-reports/bulletins-and-reports/bulletins/bulletin77.pdf

Meyer, J.R., Parker, B.L., Cherry, J.A. (2008). Detailed hydraulic head profiles as essential data for defining hydrogeologic units in layered fractured sedimentary rock

Michalski, A. (1990). Hydrogeology of the Brunswick Passaic Formation and Implications for Ground Water Monitoring Practice. *Groundwater Monitoring & Remediation*, 134–141.

Michalski, A. and R. Britton. (1997). The Role of Bedding Fractures in the Hydrogeology of Sedimentary Bedrock – Evidence from the Newark Basin, New Jersey. *Ground Water*, 318–327.

Parker, B.L., Cherry, J.A., Chapman, S.W. (2012). Discrete Fracture Network Approach for Studying Contamination in Fractured Rock. AQUA mundi, 101-116.

8. Application of Environmental Sequence Stratigraphy to Sedimentary Bedrock Aquifers with Commingled and Co-located VOC and PFAS Plumes

Bob Bond, PG with Matthew Morris, PG & Kevin Kelly, PG; Langan

Abstract

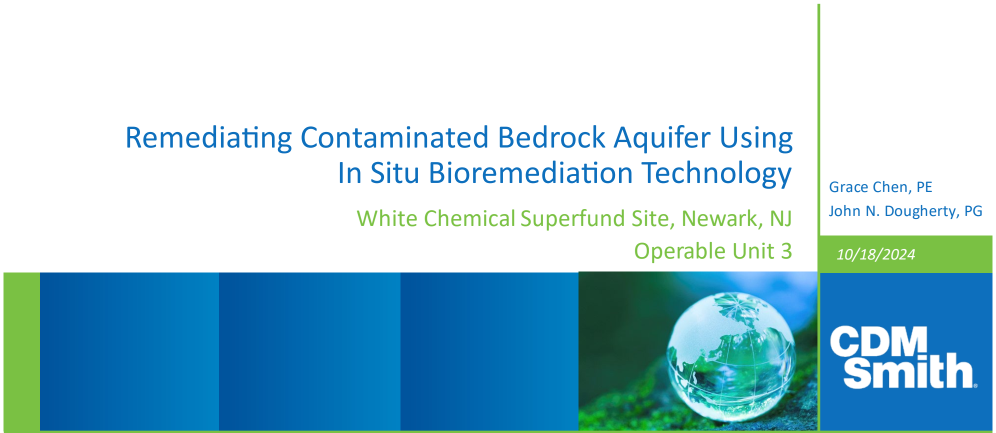
The Newark basin in Connecticut, New York, New Jersey, and Pennsylvania contains cyclically sequenced sedimentary bedrock with monoclinally dipping bedding that imparts first-order control on groundwater flow. Preferential flow along strike direction in discrete tabular aquifer units is described by the leaky multi-aquifer system model, which is generally accepted by state and federal regulators. Identifying, characterizing, and correlating dipping bedrock hydrostratigraphic units is key to developing a conceptual site model (CSM) that can be effectively used to determine migration pathways and identify on and off-site sources. We will present two case studies where conventional CSMs struggled for over a decade to explain head data from monitoring wells, groundwater flow directions and the sources of VOCs as well as new contaminants of concern; PFAS and 1,4-dioxane. We will present how we used environmental sequence stratigraphy to update the CSMs and map tabular aquifer units thousands of feet, including to off-site source areas.

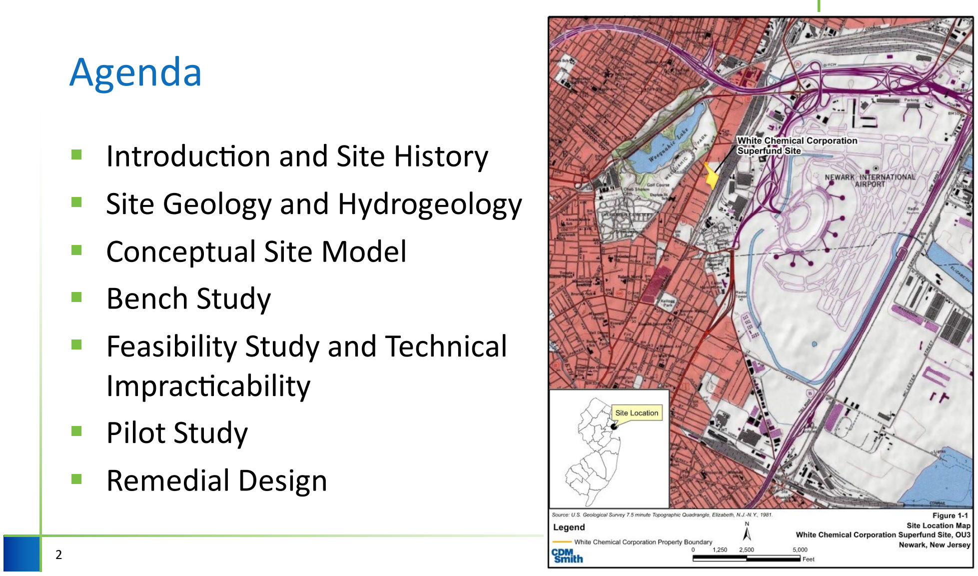
The original CSMs used a depth-based aquifer zonation approach described as shallow, intermediate, and deep bedrock aquifer units and inferred contaminant pathways using plan view plume distribution maps. Using environmental sequence stratigraphy, a geology-based forensic method, we performed detailed hydrostratigraphic mapping utilizing borehole geophysics, drilling logs and outcrop data. Our site borehole sequencing was correlated with logs from off-site industrial and commercial sites up to 2,000 feet away along strike, which are contributing to the commingled plumes. The Newark basin sedimentary rocks are profoundly cyclical, with four overlapping depositional cycles ranging from 20 thousand years to 2 million years. Bedding expression can be very subtle and difficult to follow; however, the stacking patterns of strata expressed in gamma logs, and associated water-bearing bedding-parallel fractures, can be correlated between cores by a trained geologist. To confidently identify and correlate sequences, which repeat and look very similar, we tied our model to the borehole data from the National Science Foundation–funded Newark Basin Coring Project (NBCP), which produced 6,770 meters of continuous core and geophysical logging. The cycles in the NBCP cores have been worked out and interpreted in great detail (centimeter scale) by others and traced over more than 100 kilometers.

Our improved CSMs, which included integration of head and chemical data and pumping and packer test findings, was an important part of our environmental forensic analyses that resulted in the determination of contaminant (VOCs, 1,4-dioxane and PFAS) sources, both on and off-site, and an understanding of stratigraphic flux and associated contaminant transport. Our presentation will include descriptions of the methods, correlation graphics, maps, cross-sections, and 3D EVS visualizations, and describe the value of improving hydrostratigraphic CSMs using environmental sequence stratigraphy to integrate hydrogeology and contaminant data.

9. Remediating Contaminated Bedrock Aquifer Using In Situ Bioremediation Technology

Grace Chen, PE & John N. Dougherty, PG; CDM Smith





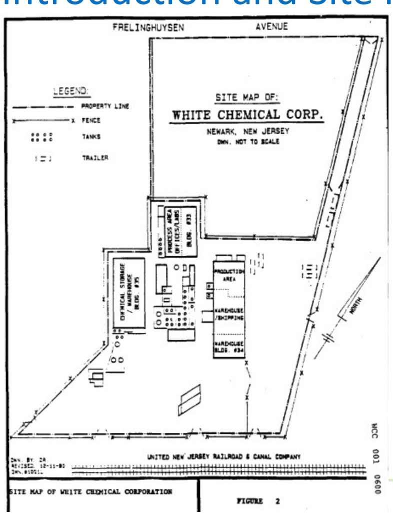
Introduction and Site History

- 1983 to 1990, White Chemical Corporation (WCC) in operation
  - Produced three major groups of chemical products: acid chlorides, brominated organics (both aliphatic and aromatic) and mineral acids, most notably hydriodic acid.
- September 1991, listed on NPL and issued OU1 ROD
  - Site stabilization, removed drums, lab containers, gas cylinders
- September 2005, OU2 ROD
  - Address contaminated surface and subsurface soil, demolition and disposal of onsite buildings and above-ground storage tanks
  - Excavation to water table
- September 2012, OU3 ROD
  - Address contaminated groundwater

Introduction and Site History

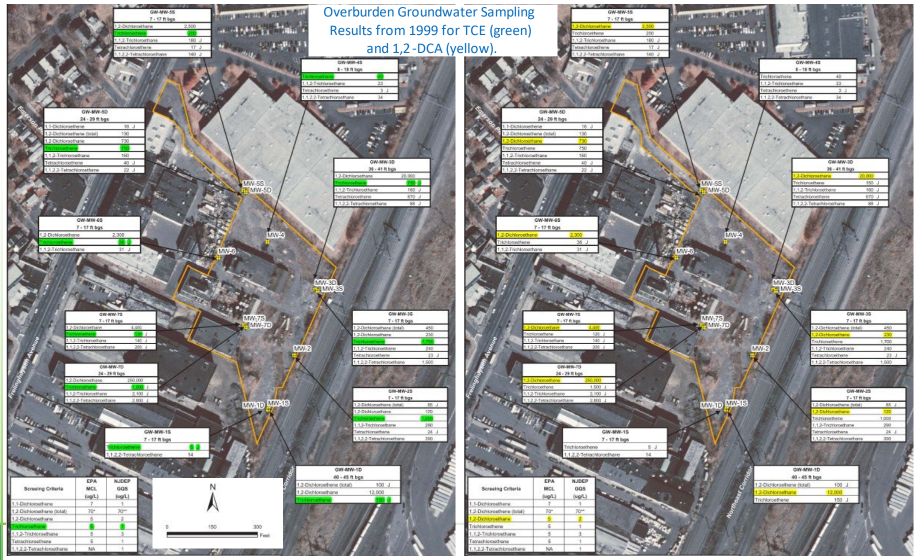
- OU2 – under USACE Philadelphia District
  - 2008 completed remedial design
  - 2009 completed Remedial Action Report
- OU3 – under USACE Kansas City District
  - 2009 to 2012 completed remedial investigation
  - 2011 to 2012 completed feasibility study including the technical impracticability evaluation
  - 2011 to 2012 completed a bench scale treatability study
  - 2014 to 2016 completed pilot study and remedial design
  - 2022 to 2023 completed remedial design update
  - Currently providing engineering support for remedial action construction

Introduction and Site History



Pim Van Hemmen/The Star -Ledger
Workers in protective clothing inventory some of the approximately 9,000 barrels of chemicals, which the EPA will be removing from the White Chemical Corp. site in Newark, in this 1990 file photo

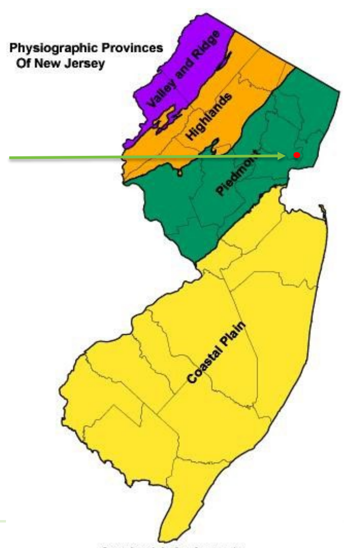
Source
https://www.nj.com/essex/2012/09/epa_to_spend_at_least_25m_to_c.html



Site Geology and Hydrogeology

Physiographic Province

White Chemical Superfund Site



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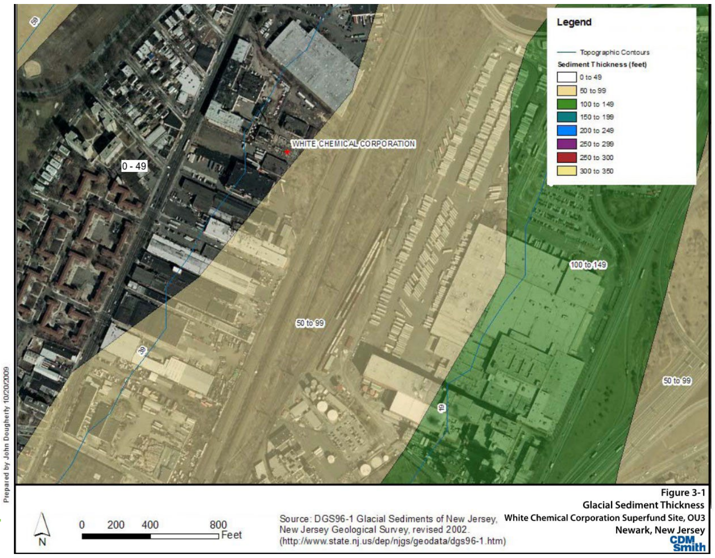


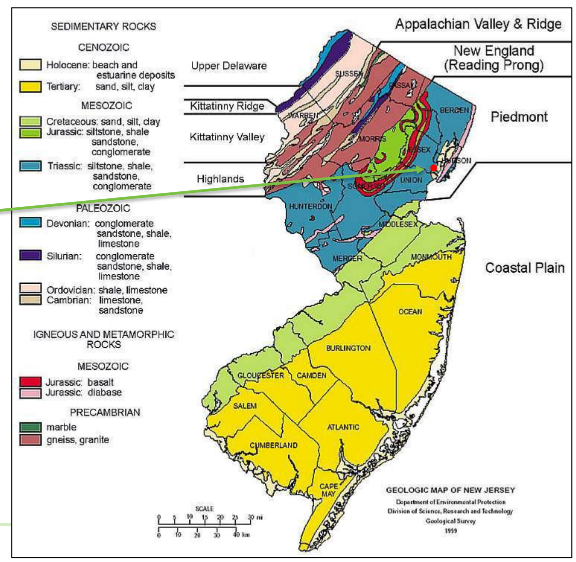
9

Bedrock Geologic Map

White Chemical Superfund Site

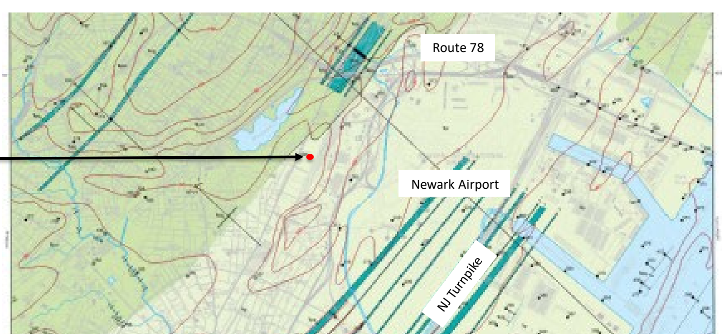
Passaic Formation (Lower Jurassic and Upper Triassic) – Sandstone, siltstone and shale; reddish-brown to purple and gray.

NJGWS 2014. *Bedrock Geologic Map of New Jersey* . Trenton: New Jersey Geological and Water Survey. NJDEP - NJGWS - Bedrock Geologic Map of New Jersey, 2014, Scale 1:250,000.



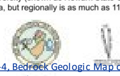
10

White Chemical Superfund Site



Ꞧpm	Ꞧp	Ꞧpg

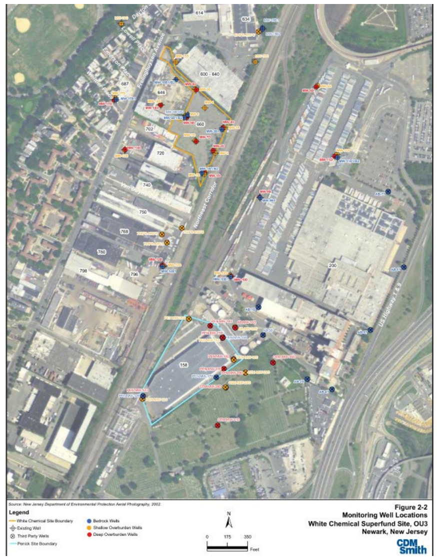
Passaic Formation (Upper Triassic) (Olsen, 1980) – Interbedded sequence of reddish-brown, and less often maroon or purple and gray, fine-grained sandstone, siltstone, shaly siltstone, silty mudstone, and mudstone. Reddish-brown sandstone and siltstone are thin- to medium-bedded, planar to cross-bedded, micaceous, and locally mudcracked and ripple cross-laminated. Root casts and load casts are common. Shaly siltstone, silty mudstone, and mudstone are fine-grained, very thin to thin-bedded, planar to ripple cross-laminated, locally fissile, bioturbated, and contain evaporite minerals. They form rhythmically fining-upward sequences as much as 15 ft thick. Unit was subdivided into a siltstone, silty mudstone and shale of classic Passaic to the south (Ꞧp) and sandstone, siltstone and mudstone facies (Ꞧpm) and gray facies (Ꞧpg) from driller's logs, BTV data and outcrops. Unit is only exposed in two streams on the Kean University (shown as Newark State College campus in the central western part of the map area, but regionally is as much as 11,480 ft thick.



Bedrock Geologic Map of the Elizabeth Quadrangle
Essex, Hudson and Union Counties, New Jersey

by
Donald H. Monteverde and Gregory C. Herman
2015

11 NJDEP - NJGWS - GMS 15-4, Bedrock Geologic Map of the Elizabeth Quadrangle, Essex, Hudson and Union Counties, New Jersey.


Legend
White Chemical Site Boundary
Existing Well
Third Party Wells
Pierce Site Boundary
Bedrock Wells
Shallow Overburden Wells
Deep Overburden Wells
Figure 2-2
Monitoring Well Locations
White Chemical Superfund Site, OU3
Newark, New Jersey
CDM Smith

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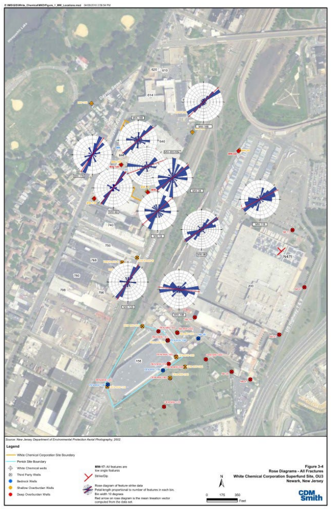
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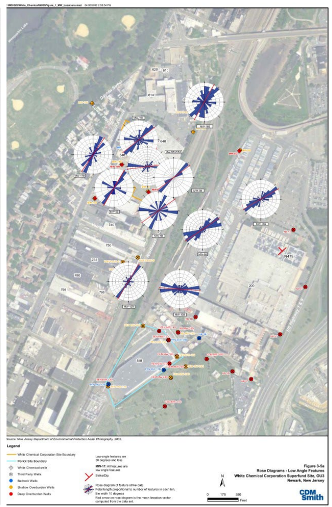
CDM Smith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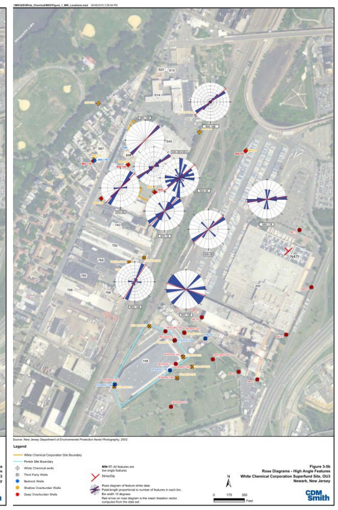
CDM Smith


Legend
CDM Smith

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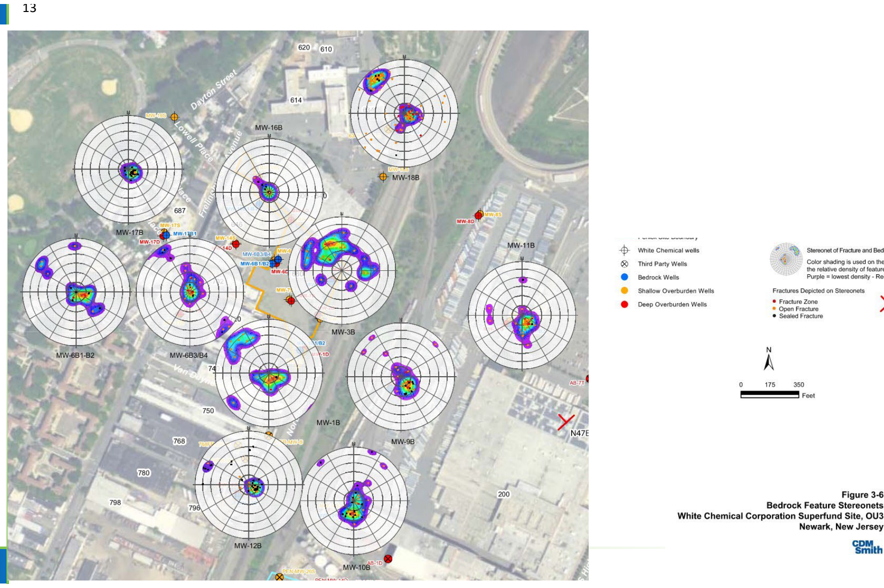
620
610
614
Dayton Street
MW-16B
MW-17B
MW-18B
687
MW-11B
MW-6B1-B2
MW-6B3/B4
MW-3B
MW-1B
MW-9B
750
768
780
798
796
MW-12B
MW-10B
200
N47E
White Chemical wells
Third Party Wells
Bedrock Wells
Shallow Overburden Wells
Deep Overburden Wells
Stereonet of Fracture and Bedding Plane Orientation.
Color shading is used on the stereonets to indicate the relative density of feature data.
Purple = lowest density - Red = highest density
Fractures Depicted on Stereonets
Fracture Zone
Open Fracture
Sealed Fracture
Bedding Strike/Dip
N
0
175
350
Feet
Figure 3-6
Bedrock Feature Stereonets
White Chemical Corporation Superfund Site, OU3
Newark, New Jersey
CDM Smith

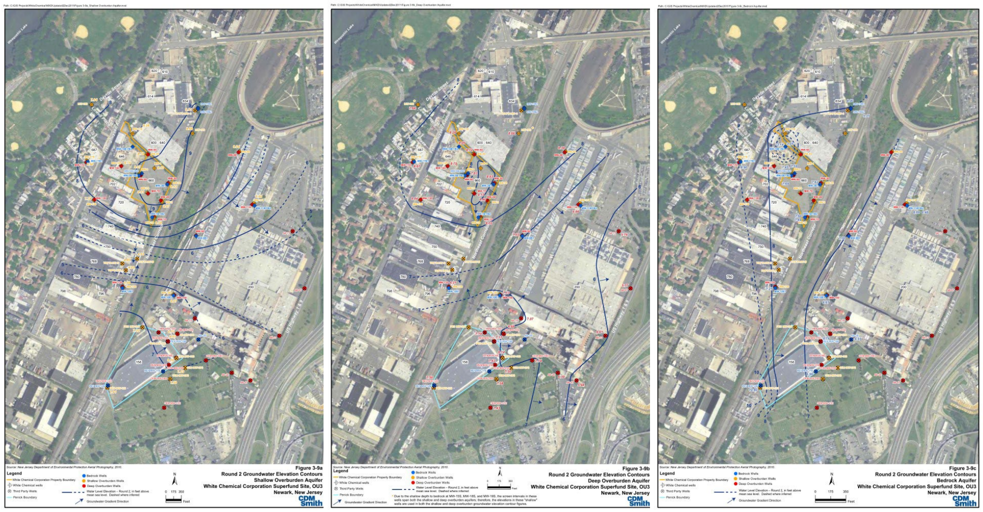
Figure 3-9a
Round 2 Groundwater Elevation Contours
Shallow Overburden Aquifer
White Chemical Corporation Superfund Site, OU3
Newark, New Jersey
Figure 3-9b
Round 2 Groundwater Elevation Contours
Deep Overburden Aquifer
White Chemical Corporation Superfund Site, OU3
Newark, New Jersey
Figure 3-9c
Round 2 Groundwater Elevation Contours
Bedrock Aquifer
White Chemical Corporation Superfund Site, OU3
Newark, New Jersey
CDM Smith

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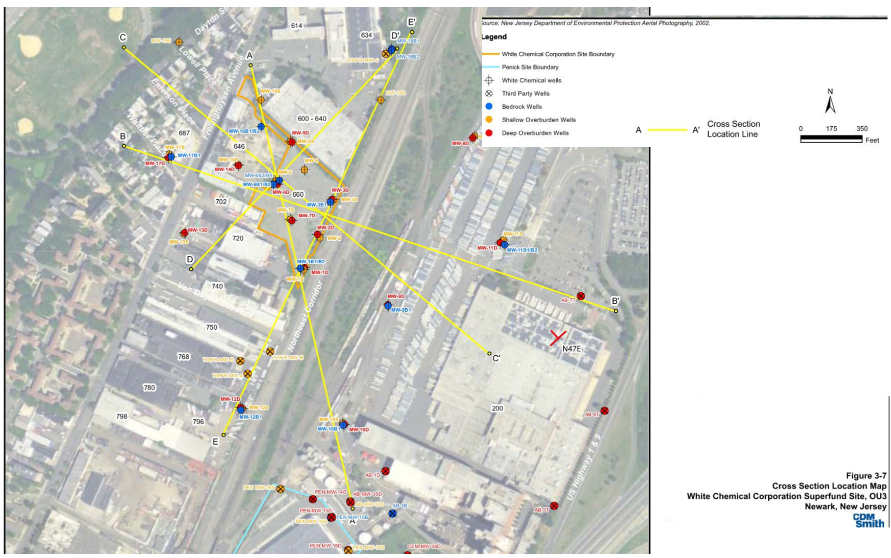
Source: New Jersey Department of Environmental Protection Aerial Photography, 2002.
Legend
White Chemical Corporation Site Boundary
Penick Site Boundary
White Chemical wells
Third Party Wells
Bedrock Wells
Shallow Overburden Wells
Deep Overburden Wells
A — A' Cross Section Location Line
0 175 350
Feet
N
Figure 3-7
Cross Section Location Map
White Chemical Corporation Superfund Site, OU3
Newark, New Jersey
CDM Smith

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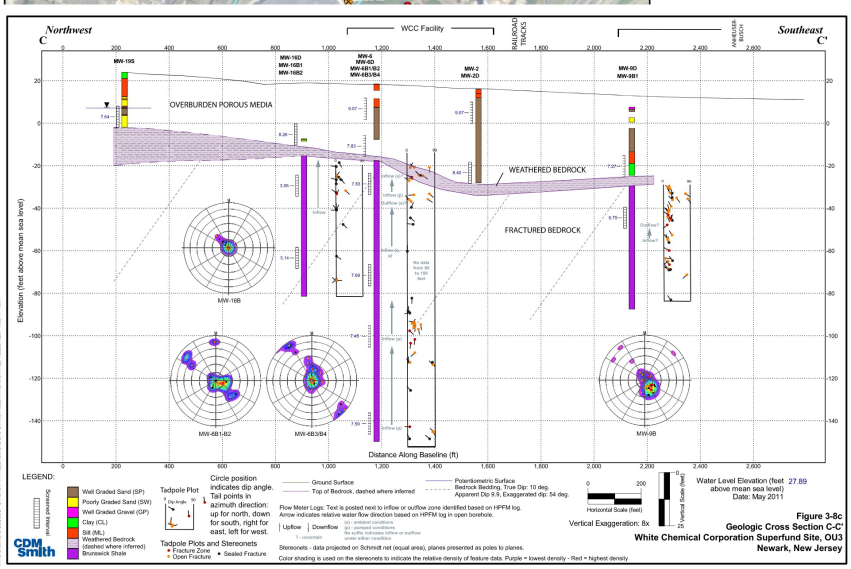
Northwest
Southeast
C
C'
WCC Facility
RAILROAD TRACKS
OVERBURDEN POROUS MEDIA
WEATHERED BEDROCK
FRACTURED BEDROCK
Elevation (feet above mean sea level)
Distance Along Baseline (ft)
MW-19S
MW-16D
MW-16B1
MW-16B2
MW-6
MW-6D
MW-6B1/B2
MW-6B3/B4
MW-2
MW-2D
MW-9D
MW-9B1
MW-16B
MW-6B1-B2
MW-6B3/B4
MW-9B
LEGEND:
Well Graded Sand (SP)
Poorly Graded Sand (SW)
Well Graded Gravel (GP)
Clay (CL)
Silt (ML)
Weathered Bedrock (dashed where inferred)
Brunswick Shale
Tadpole Plot
Circle position indicates dip angle. Tail points in azimuth direction: up for north, down for south, right for east, left for west.
Tadpole Plots and Stereonets
Fracture Zone
Open Fracture
Sealed Fracture
Ground Surface
Top of Bedrock, dashed where inferred
Potentiometric Surface
Bedrock Bedding, True Dip: 10 deg. Apparent Dip 9.9, Exaggerated dip: 54 deg.
Flow Meter Logs: Text is posted next to inflow or outflow zone identified based on HPFM log. Arrow indicates relative water flow direction based on HPFM log in open borehole.
Upflow
Downflow
Stereonets - data projected on Schmidt net (equal area), planes presented as poles to planes.
Color shading is used on the stereonets to indicate the relative density of feature data. Purple = lowest density - Red = highest density
Horizontal Scale (feet)
Vertical Exaggeration: 8x
Vertical Scale (feet)
Water Level Elevation (feet above mean sea level) 27.89
Date: May 2011
Figure 3-8c
Geologic Cross Section C-C'
White Chemical Corporation Superfund Site, OU3
Newark, New Jersey
CDM Smith

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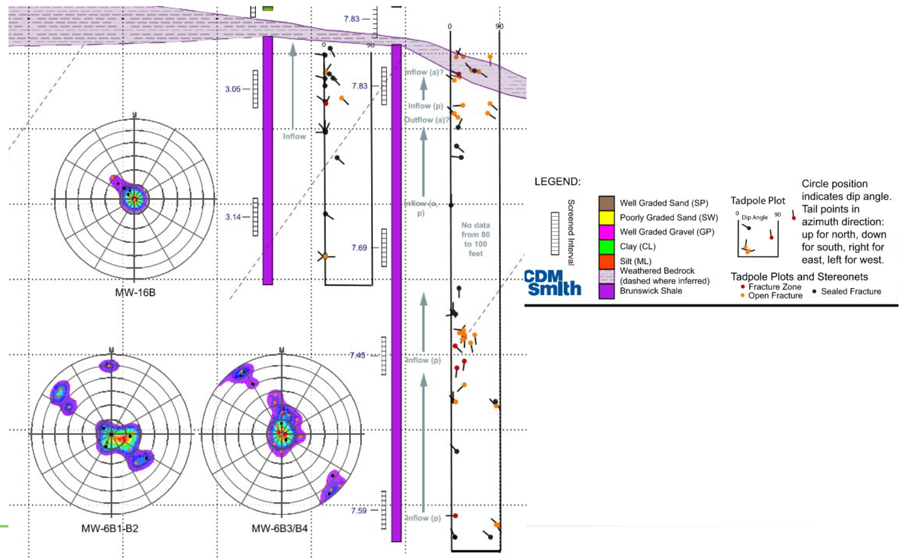

MW-16B
MW-6B1-B2
MW-6B3/B4
Inflow
Inflow (a)?
Inflow (p)
Outflow (a)?
No data from 80 to 100 feet
LEGEND:
Screened Interval
Well Graded Sand (SP)
Poorly Graded Sand (SW)
Well Graded Gravel (GP)
Clay (CL)
Silt (ML)
Weathered Bedrock (dashed where inferred)
Brunswick Shale
Tadpole Plot
Circle position indicates dip angle. Tail points in azimuth direction: up for north, down for south, right for east, left for west.
Tadpole Plots and Stereonets
Fracture Zone
Open Fracture
Sealed Fracture
CDM Smith

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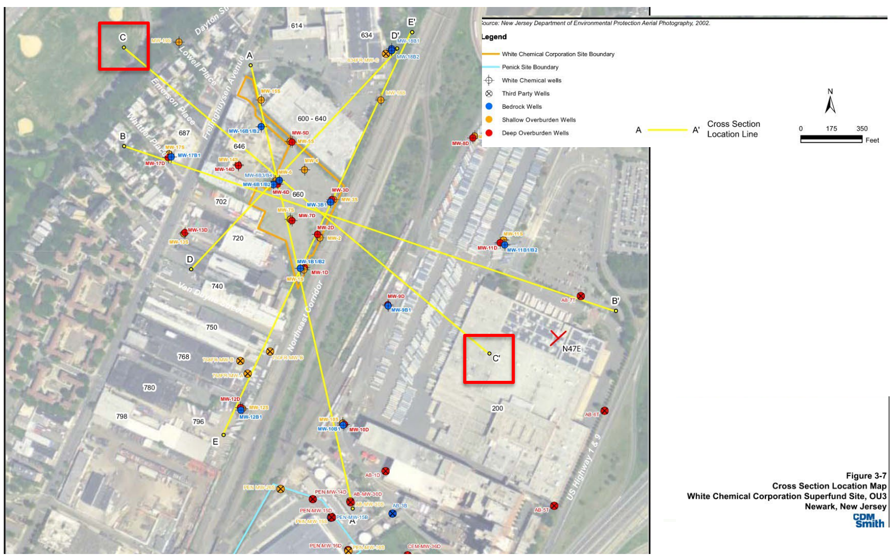
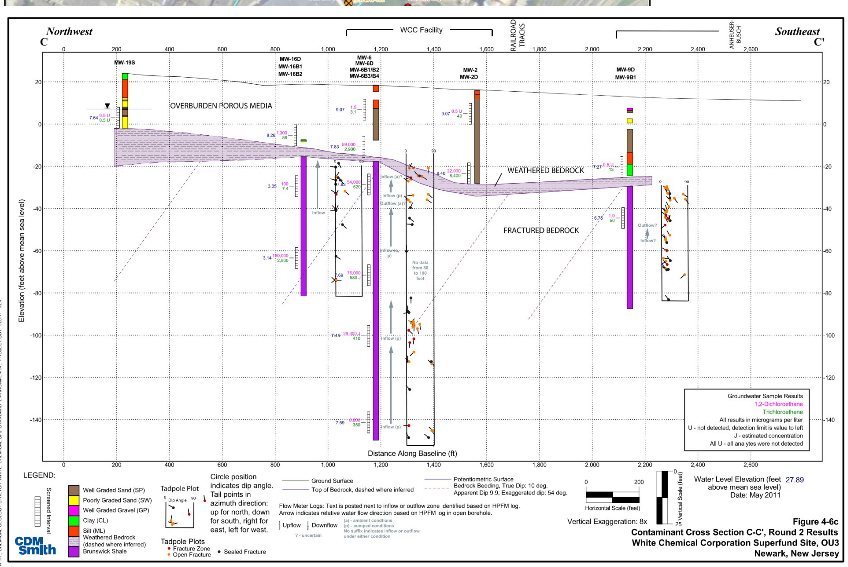
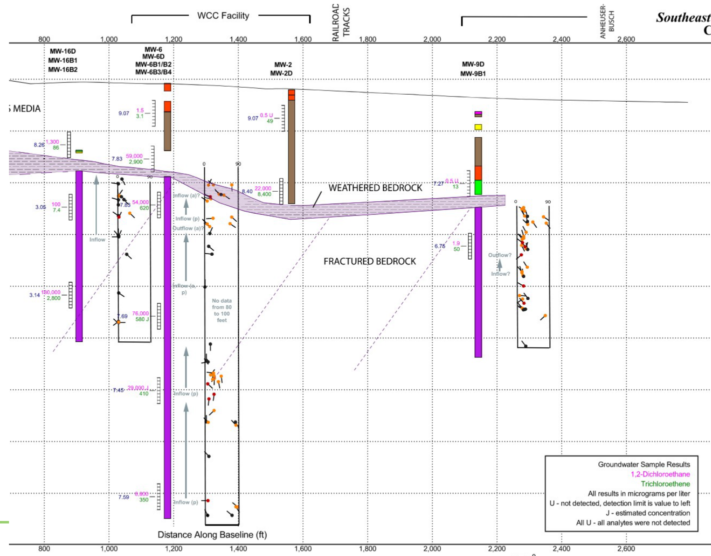


Source: New Jersey Department of Environmental Protection Aerial Photography, 2002.
Legend
White Chemical Corporation Site Boundary
Penick Site Boundary
White Chemical wells
Third Party Wells
Bedrock Wells
Shallow Overburden Wells
Deep Overburden Wells
Cross Section Location Line
0 175 350 Feet
Figure 3-7
Cross Section Location Map
White Chemical Corporation Superfund Site, OU3
Newark, New Jersey
CDM Smith

20

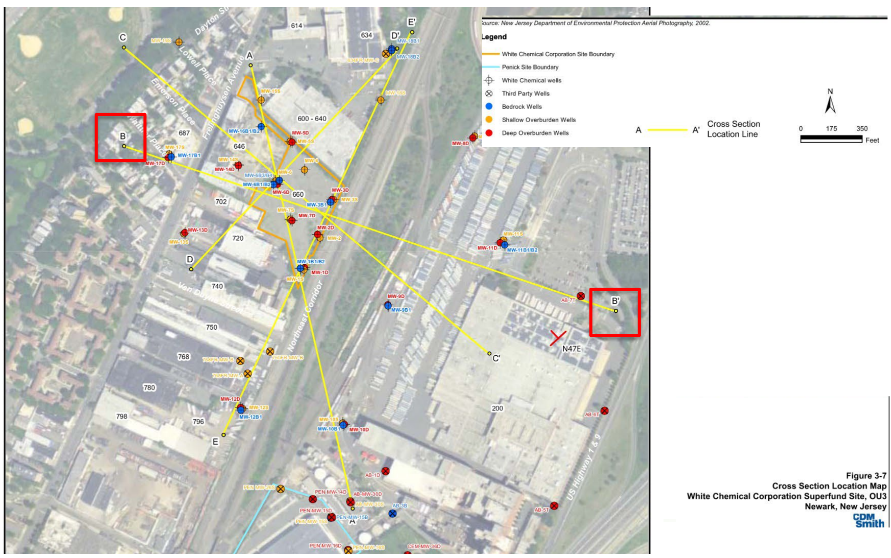


Northwest C
Southeast C'
WCC Facility
RAILROAD TRACKS
OVERBURDEN POROUS MEDIA
WEATHERED BEDROCK
FRACTURED BEDROCK
Elevation (feet above mean sea level)
Distance Along Baseline (ft)
Groundwater Sample Results
1,2-Dichloroethane
Trichloroethene
All results in micrograms per liter
U - not detected, detection limit is value to left
J - estimated concentration
All U - all analytes were not detected
LEGEND:
Ground Surface
Top of Bedrock, dashed where inferred
Potentiometric Surface
Bedrock Bedding, True Dip: 10 deg. Apparent Dip 9.9, Exaggerated dip: 54 deg.
Water Level Elevation (feet above mean sea level) Date: May 2011
Vertical Exaggeration: 8x
Figure 4-6c
Contaminant Cross Section C-C', Round 2 Results
White Chemical Corporation Superfund Site, OU3
Newark, New Jersey



Southeast
C'
WCC Facility
RAILROAD TRACKS
ANHEUSER-BUSCH
MW-16D
MW-16B1
MW-16B2
MW-6
MW-6D
MW-6B1/B2
MW-6B3/B4
MW-2
MW-2D
MW-9D
MW-9B1
WEATHERED BEDROCK
FRACTURED BEDROCK
No data from 80 to 100 feet
Groundwater Sample Results
1,2-Dichloroethane
Trichloroethene
All results in micrograms per liter
U - not detected, detection limit is value to left
J - estimated concentration
All U - all analytes were not detected
Distance Along Baseline (ft)

21



Source: New Jersey Department of Environmental Protection Aerial Photography, 2002.
Legend
White Chemical Corporation Site Boundary
Penick Site Boundary
White Chemical wells
Third Party Wells
Bedrock Wells
Shallow Overburden Wells
Deep Overburden Wells
A — A' Cross Section Location Line
N
0 175 350
Feet
Figure 3-7
Cross Section Location Map
White Chemical Corporation Superfund Site, OU3
Newark, New Jersey

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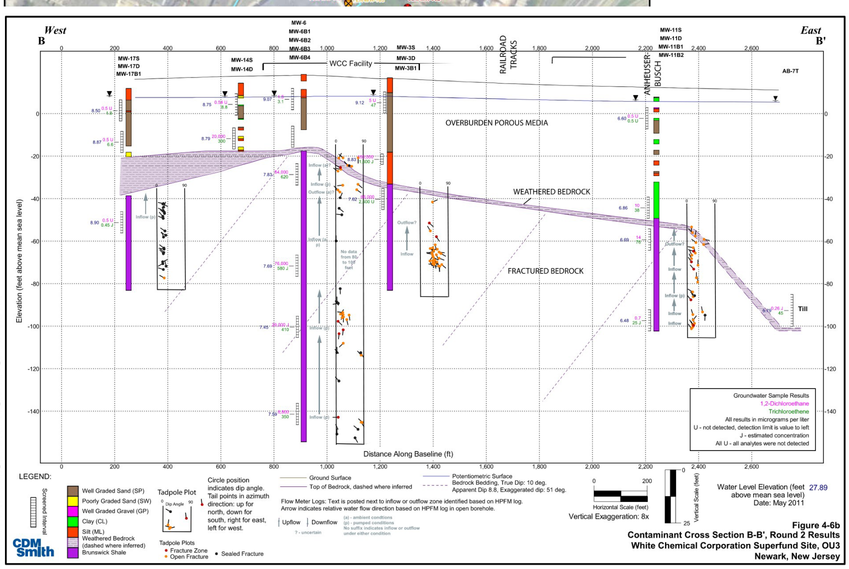

West
B
East
B'
WCC Facility
RAILROAD TRACKS
ANHEUSER-BUSCH
MW-17S
MW-17D
MW-17B1
MW-14S
MW-14D
MW-6
MW-6B1
MW-6B2
MW-6B3
MW-6B4
MW-3S
MW-3D
MW-3B1
MW-11S
MW-11D
MW-11B1
MW-11B2
AB-7T
OVERBURDEN POROUS MEDIA
WEATHERED BEDROCK
FRACTURED BEDROCK
Till
Elevation (feet above mean sea level)
Distance Along Baseline (ft)
Groundwater Sample Results
1,2-Dichloroethane
Trichloroethene
All results in micrograms per liter
U - not detected, detection limit is value to left
J - estimated concentration
All U - all analytes were not detected
LEGEND:
Screened Interval
Well Graded Sand (SP)
Poorly Graded Sand (SW)
Well Graded Gravel (GP)
Clay (CL)
Silt (ML)
Weathered Bedrock (dashed where inferred)
Brunswick Shale
Tadpole Plot
Circle position indicates dip angle. Tail points in azimuth direction: up for north, down for south, right for east, left for west.
Ground Surface
Top of Bedrock, dashed where inferred
Potentiometric Surface
Bedrock Bedding, True Dip: 10 deg. Apparent Dip 8.8, Exaggerated dip: 51 deg.
Flow Meter Logs: Text is posted next to inflow or outflow zone identified based on HPFM log. Arrow indicates relative water flow direction based on HPFM log in open borehole.
Uplow
Downflow
Horizontal Scale (feet)
Vertical Exaggeration: 8x
Vertical Scale (feet)
Water Level Elevation (feet above mean sea level) 27.89
Date: May 2011
Figure 4-6b
Contaminant Cross Section B-B', Round 2 Results
White Chemical Corporation Superfund Site, OU3
Newark, New Jersey

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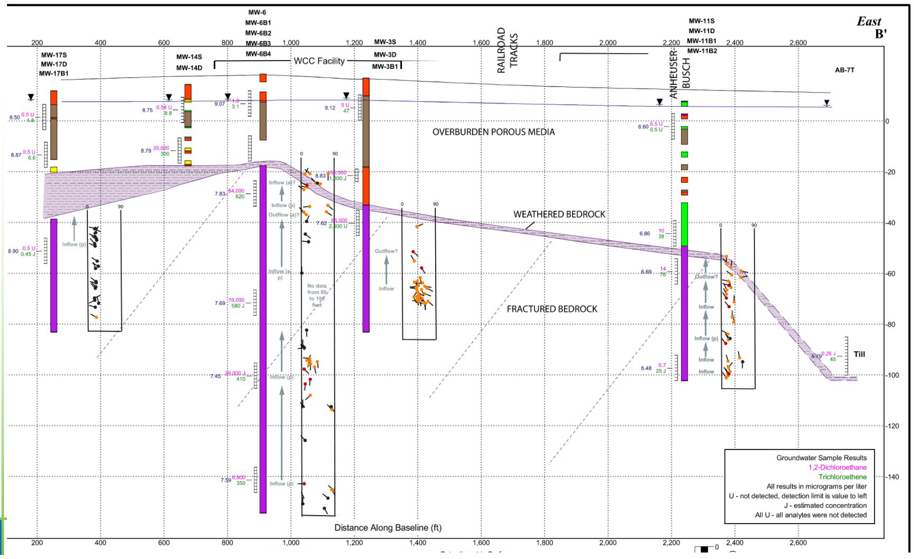


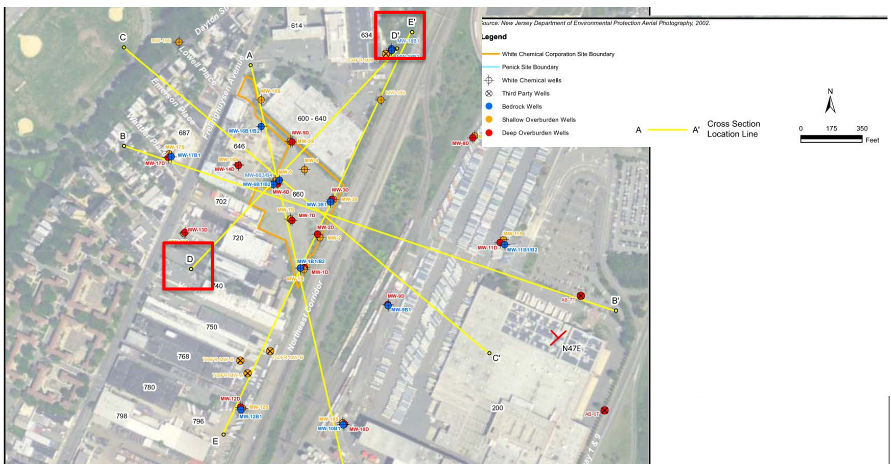


Figure 3-7
Cross Section Location Map
White Chemical Corporation Superfund Site, OU3
Newark, New Jersey

25

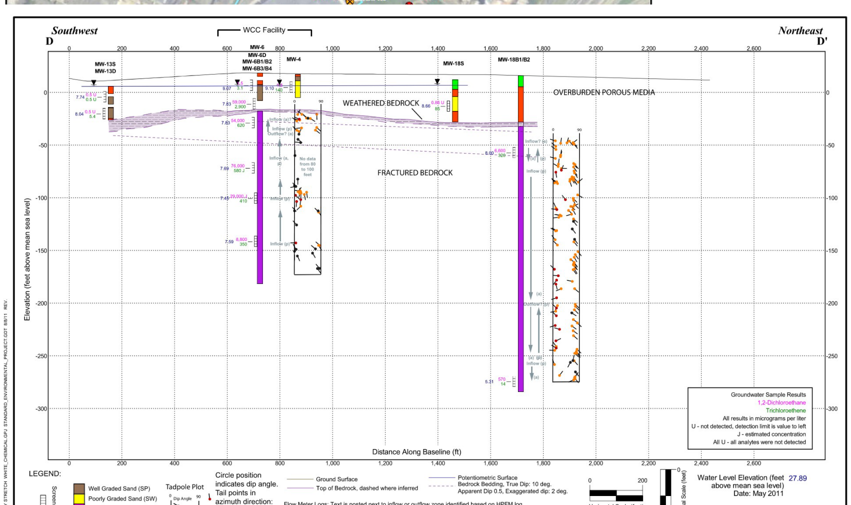
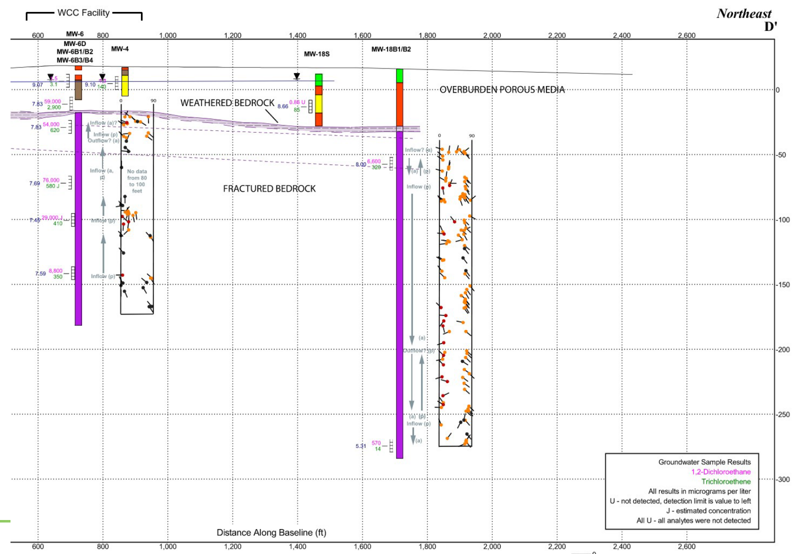
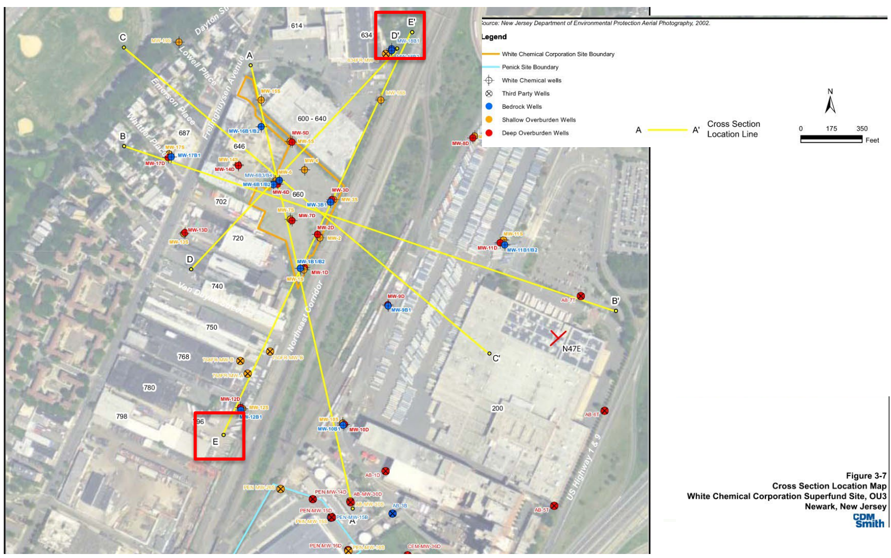


Figure 4-6d
Contaminant Cross Section D-D', Round 2 Results
White Chemical Corporation Superfund Site, OU3
Newark, New Jersey

26


WCC Facility
Northeast
D'
MW-6
MW-6D
MW-6B1/B2
MW-6B3/B4
MW-4
MW-18S
MW-18B1/B2
WEATHERED BEDROCK
OVERBURDEN POROUS MEDIA
FRACTURED BEDROCK
Groundwater Sample Results
1,2-Dichloroethane
Trichloroethene
All results in micrograms per liter
U - not detected, detection limit is value to left
J - estimated concentration
All U - all analytes were not detected
Distance Along Baseline (ft)

27


Source: New Jersey Department of Environmental Protection Aerial Photography, 2002.
Legend
White Chemical Corporation Site Boundary
Penick Site Boundary
White Chemical wells
Third Party Wells
Bedrock Wells
Shallow Overburden Wells
Deep Overburden Wells
Cross Section Location Line
Feet
Figure 3-7
Cross Section Location Map
White Chemical Corporation Superfund Site, OU3
Newark, New Jersey

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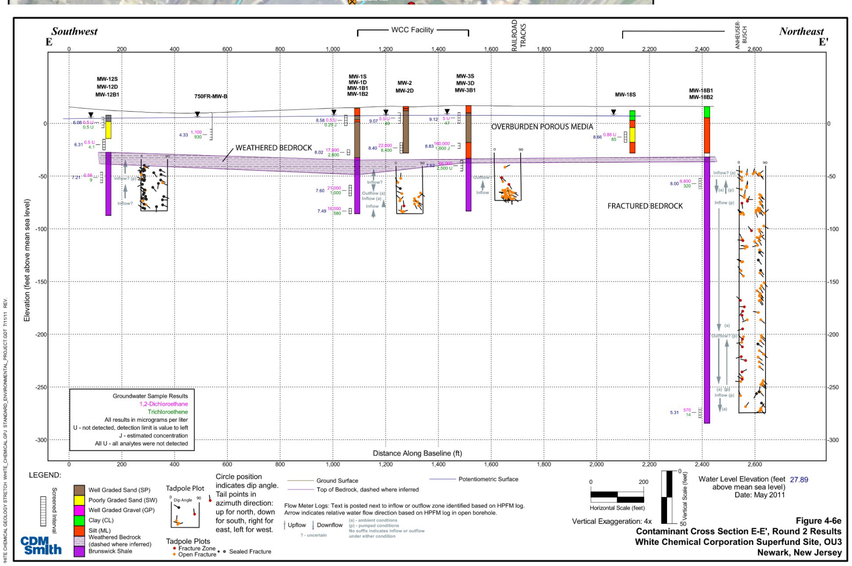
Southwest
E
WCC Facility
RAILROAD TRACKS
Northeast
E'
MW-12S
MW-12D
MW-12B1
750FR-MW-B
MW-1S
MW-1D
MW-1B1
MW-1B2
MW-2
MW-2D
MW-3S
MW-3D
MW-3B1
MW-18S
MW-18B1
MW-18B2
WEATHERED BEDROCK
OVERBURDEN POROUS MEDIA
FRACTURED BEDROCK
Elevation (feet above mean sea level)
Groundwater Sample Results
1,2-Dichloroethane
Trichloroethene
All results in micrograms per liter
U - not detected, detection limit is value to left
J - estimated concentration
All U - all analytes were not detected
Distance Along Baseline (ft)
LEGEND:
Well Graded Sand (SP)
Poorly Graded Sand (SW)
Well Graded Gravel (GP)
Clay (CL)
Silt (ML)
Weathered Bedrock (dashed where inferred)
Brunswick Shale
Screened Interval
Tadpole Plot
Circle position indicates dip angle. Tail points in azimuth direction: up for north, down for south, right for east, left for west.
Tadpole Plots
Fracture Zone
Open Fracture
Sealed Fracture
Ground Surface
Top of Bedrock, dashed where inferred
Potentiometric Surface
Flow Meter Logs: Text is posted next to inflow or outflow zone identified based on HPFM log. Arrow indicates relative water flow direction based on HPFM log in open borehole.
Upflow
Downflow
Horizontal Scale (feet)
Vertical Scale (feet)
Vertical Exaggeration: 4x
Water Level Elevation (feet above mean sea level)
Date: May 2011
Figure 4-6e
Contaminant Cross Section E-E', Round 2 Results
White Chemical Corporation Superfund Site, OU3
Newark, New Jersey

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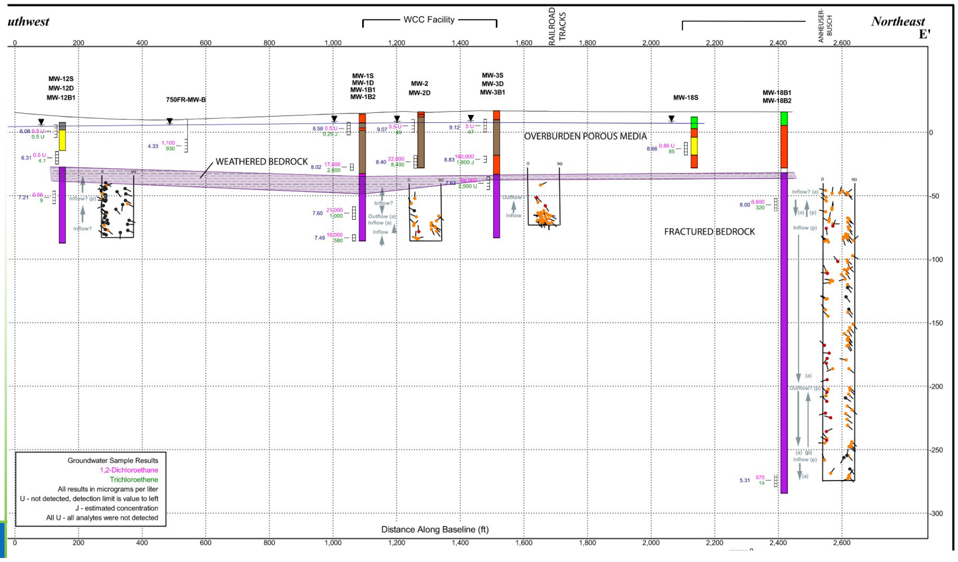
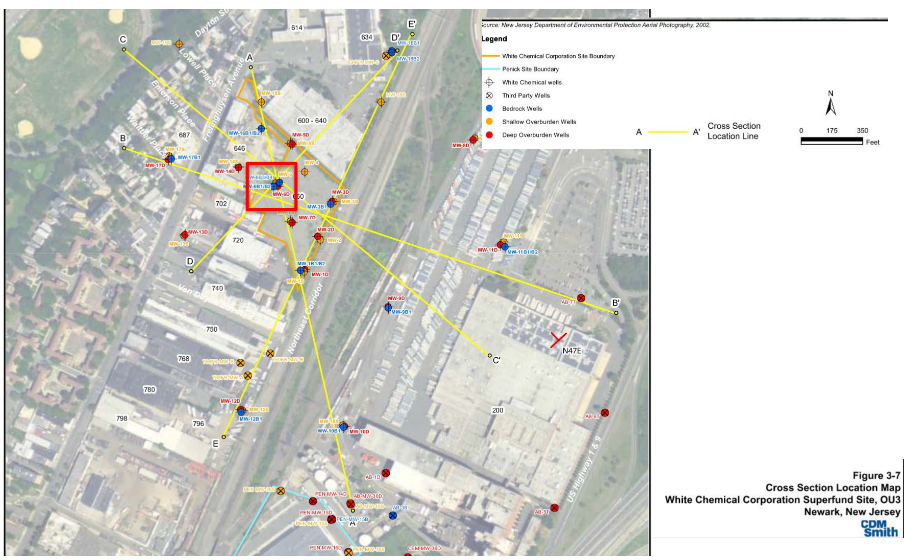
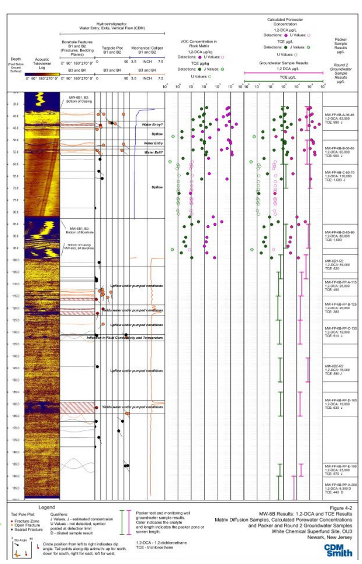


31



Rock Matrix Diffusion Study



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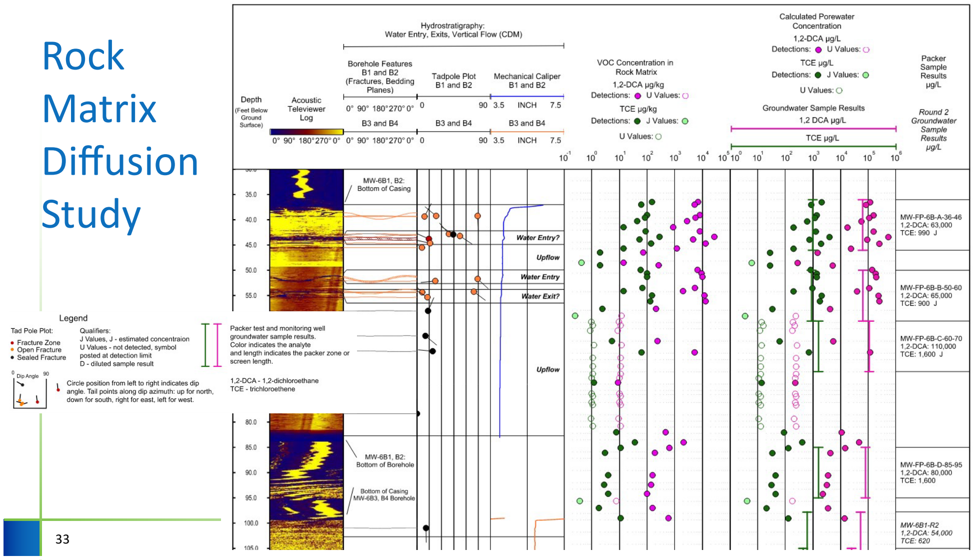
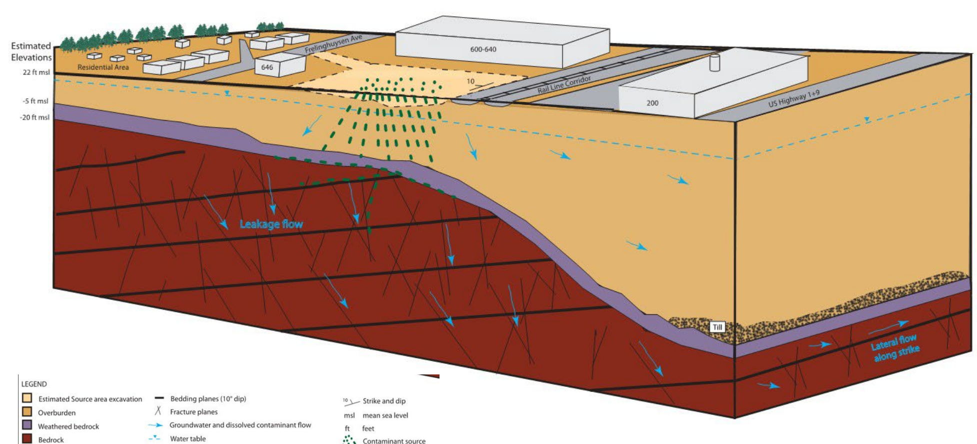
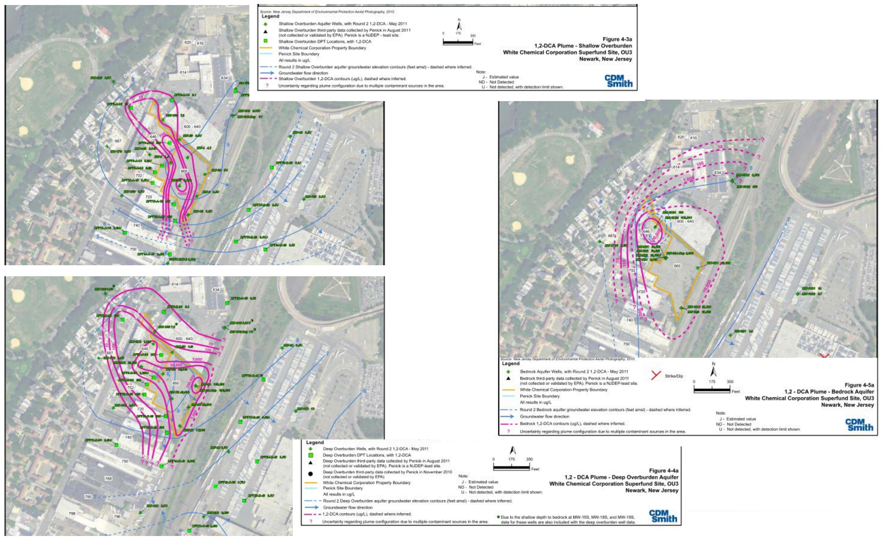
Rock Matrix Diffusion Study



Conceptual Site Model

Conceptual Site Model





Technical Impracticability Evaluation

Feasibility Study – Technology Screening

Technologies	Overburden Aquifer	Bedrock Aquifer
Institutional Control	✓	✓
Long-Term Monitoring	✓	✓
Monitored Natural Attenuation	✓	✓
Pump and Treat	X	X
Air Sparging	X	NA
In Situ Thermal Remediation	✓	✓
In Situ Chemical Oxidation/Reduction	✓	✓
In Situ Bioremediation	✓	✓

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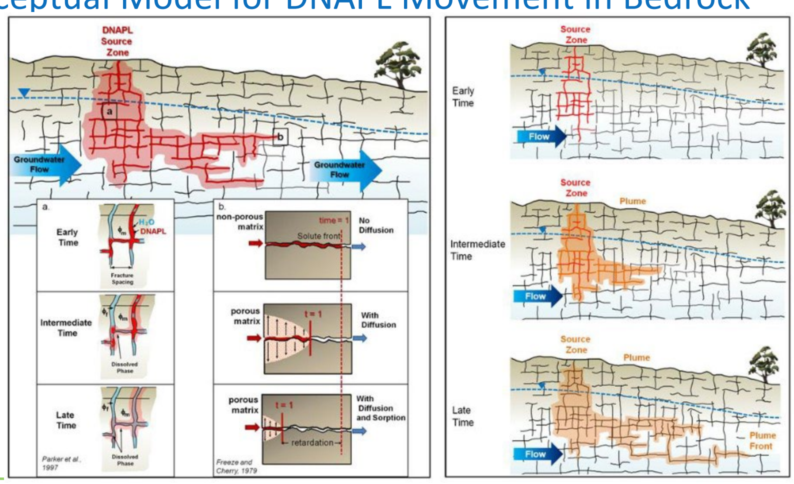
Technical Impracticability Evaluation

1. Specific ARARs or media cleanup standards that cannot be attained
   - NJ Class IIA groundwater quality standards, NJ drinking water standards, and Federal MCLs
2. Spatial area of TI decision
   - Weathered and fractured bedrock aquifer and the aquifer below the rail line corridor with contamination contributed by WCC

Technical Impracticability Evaluation

3. Conceptual site model - geologic, hydrogeologic and contaminant-related Factors inhibit groundwater restoration
   - Complex fracture and flow system
   - Historical DNAPL release – complex contaminant distribution
   - Contaminants in rock matrix - diffusion controlled process

Conceptual Model for DNAPL Movement in Bedrock



ITRC. 2015. *Integrated DNAPL Site Characterization and Tool Selection*. Washington, DC: ITRC. https://projects.itrcweb.org/DNAPL-ISC_tools-selection/

Technical Impracticability Evaluation

4. Restoration potential from engineering perspective
   - Source treatment or containment
     - Contamination sources will be removed to the extent practicable (excavation of unsaturated soil and treatment of overburden aquifer)
     - Mass reduction of currently known contamination in bedrock aquifer
     - Some indication of on-going natural occurring degradation
   - Predictive model analysis indicated that it may require 188 years to 1,885 years to reach 1,2-DCA groundwater quality standard
   - Limited effectiveness of remedial technologies to reliable, logically and feasibility attain the cleanup levels within a reasonable timeframe

Record of Decision

OU3 Record of Decision

- Selected Remedy:
  - In-situ bioremediation of the groundwater in the shallow and deep aquifers by reducing site contaminant concentrations to federal MCLs and New Jersey GWQSs to the extent practical
  - Treatment of the bedrock aquifer in an effort to decrease contaminant mass to the extent practical
  - The establishment of a CEA to minimize the potential for exposure to contaminated groundwater; and
  - Implementation of a long-term sampling and analysis program to monitor the contamination at the site to assess groundwater migration and to establish whether contaminants are meeting the appropriate NJ GWQC or MCLs, whichever is lower

OU3 Record of Decision

- TI Waiver:
  - EPA evaluated alternatives for restoration of the shallow and deep overburden aquifers below the rail-line corridor and the bedrock aquifer to Applicable or Relevant and Appropriate Requirements (ARARs) and concluded that no practical alternatives could be implemented. Consequently, EPA is invoking an ARAR waiver for portions of the groundwater at the Site due to Technical Impracticability.

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Bench Scale Treatability Study

Bench Scale Treatability Study

Test Condition	Amendments	Culture	Results
1	Lactate + Whey	----	Initiated degradation at the end of testing period
2	Lactate + Whey	SDC-9 + TCA-20	Effective
3	EOS598	----	Not effective during testing period
4	EOS598	SDC-9 + TCA-20	Not effective during testing period
5	EHC	----	Significant removal, some intermediates remain
6	EHC	SDC-9 + TCA-20	Most Effective
7	----	SDC-9 + TCA-20	
8	----	----	

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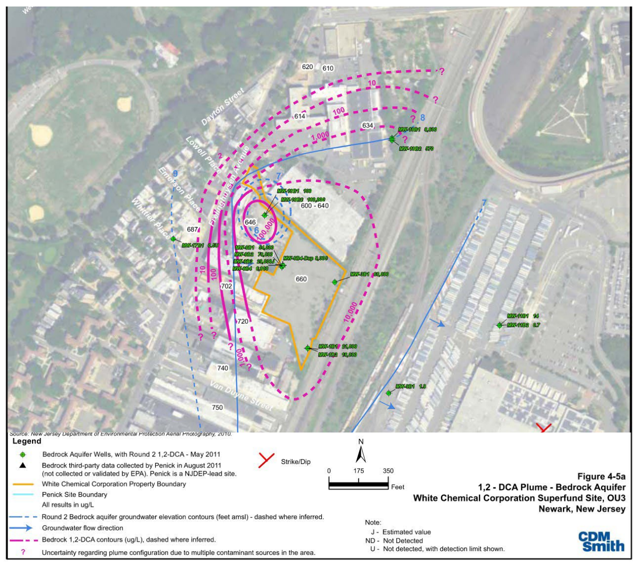
Pilot Study

Gravity Injection at 9 Bedrock Wells



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Bedrock Injection Pilot Study

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Bedrock Injection Pilot Study

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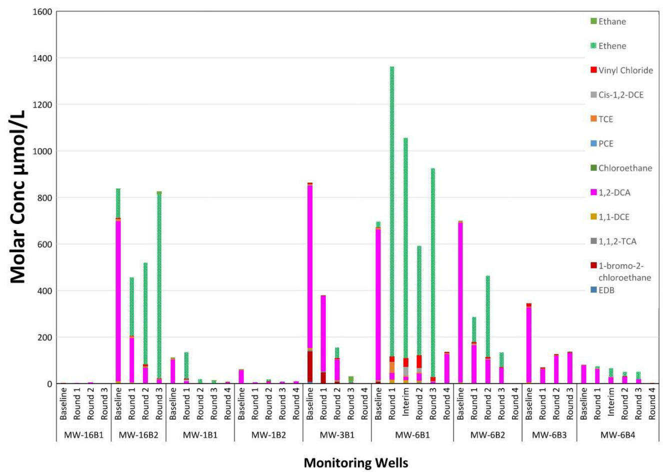
Bedrock Pilot Studv Results

Sampling Events
- Baseline
- R1-8 months
- R2-16 months
- R3-25 months
- R4-87 months

*R1 to R4 after injection, MEE not collected in R4



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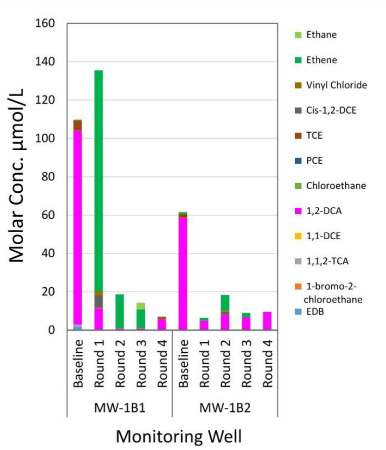
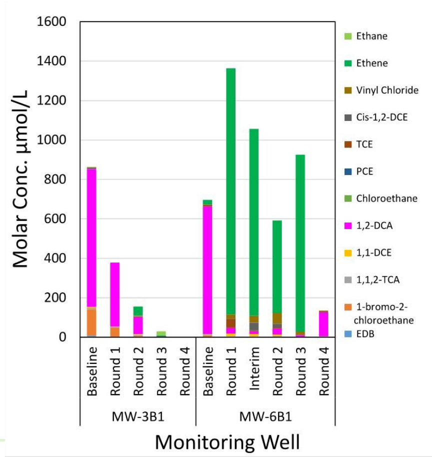
Bedrock Pilot Study Results





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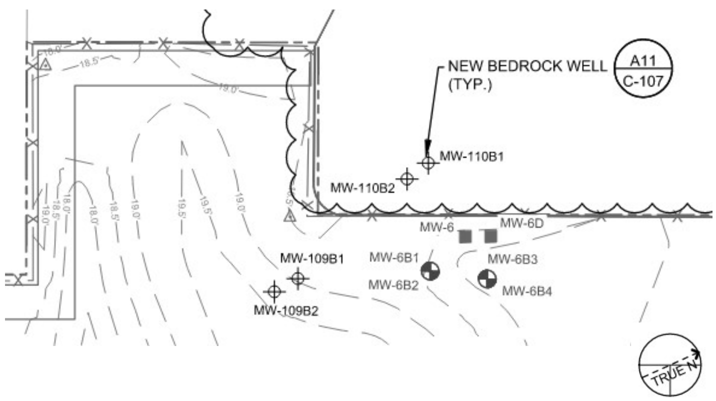
Remedial Design

Remedial Design



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Questions

Proceedings XL (40) – Field Demonstrations

1. Multi-parameter Geophysical Logging

Timothy J. Hull, PG, LSRP; Princeton Geoscience, Inc.

Of the many investigative techniques to evaluate groundwater flow and contaminant fate and transport, borehole geophysics provides one of the best in-situ evaluations of subsurface conditions. Borehole geophysics can result in a wide range of information, using a diverse suite of logging tools, and is applicable at many stages of investigation and remediation. Borehole geophysics can be used to evaluate hydrogeologic properties at a single location, to inform or update a Conceptual Site Model (CSM), or to develop or evaluate regional hydrogeologic models, including as was done at the Watershed wellfield in the late 1960s to better understand anisotropic transmissivity of the dipping sedimentary rocks. Several further studies were completed by the US Geological Survey (USGS) and the NJ Geological Survey (NJGS) through the early 2000s at the Watershed wellfield. A field demonstration will demonstrate several of the logging tools – both standard and specialty tools – along with discussion of how the results are processed and interpreted, and then used in applying or developing hydrogeologic frameworks.


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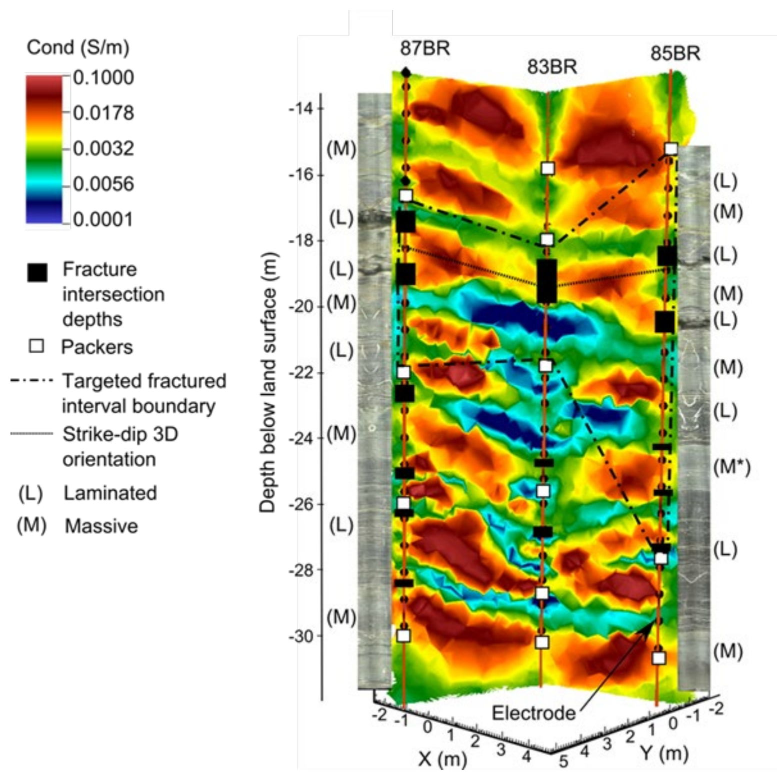
2. Cross-Borehole Electrical Resistivity Tomography Survey

Lee Slater, PhD; Rutgers University

Advancing Hydrogeophysical Characterization of the Newark Basin: High Resolution Electrical Tomography Characterization of the Former Naval Air Warfare Center (NAWC) Site

Hydrogeophysical technologies have evolved in recent years to improve aquifer characterization and transport monitoring across multiple scales beyond the borehole wall. In particular, electrical tomographic geophysical imaging methods have evolved to allow 4D (in space and time) assessment of contaminant transport, amendment delivery and the progress of remediation treatments (Figure 1). This presentation highlights results of the application of 4D electrical resistivity tomography to improve understanding of the fate and transport of trichloroethylene (TCE) contamination of the groundwater of Newark Basin sediments at the former Naval Air Warfare Center (NAWC) site located in W. Trenton, New Jersey. The presentation demonstrates how cross-borehole electrical tomography was used to (1) image permeable fracture zones between alternating laminated and massive mudstone layers, and (2) improve understanding of amendment delivery and fate following injection into a primary fracture zone. The use of other geophysical methods at former Naval Air Warfare Center (NAWC) will also be discussed. A full field-demonstration of state-of-the-art surface and cross-borehole electrical tomographic imaging instrumentation will also be included in the activity. Principles of data acquisition will be discussed, and geophysical inversions of dataset acquired at the field-site will be performed in real time.

A 3D inversion for electrical conductivity (Cond) structure between an array of boreholes at the former Naval Air Warfare Center (NAWC) site, W. Trenton, NJ. Fracture intersection depths, packers used for hydraulic tests, strike/dip of orientation shown. The resistivity inversion highlights alternating conductive and resistive layering partly resulting from the alternating laminated and massive mudstones at the site. The optical televiewer (OTV) log for two boreholes (85BR and 87BR) is shown for comparison. After Robinson et al. (2016).



Reference

Robinson, J., Slater, L., Johnson, T., Shapiro, A., Tiedeman, C., Ntarlagiannis, D., Johnson, C., Day-Lewis, F., Lacombe, P., Imbrigiotta, T. and Lane, J., 2016. Imaging pathways in fractured rock using three-dimensional electrical resistivity tomography. *Groundwater*, 54(2), pp.186-201.

3. USGS Naval Air Warfare Center Fractured Bedrock Research Findings and Rock Core Review

Pierre LaCombe; USGS, retired & Alex Fiore, PhD; USGS

Abstract

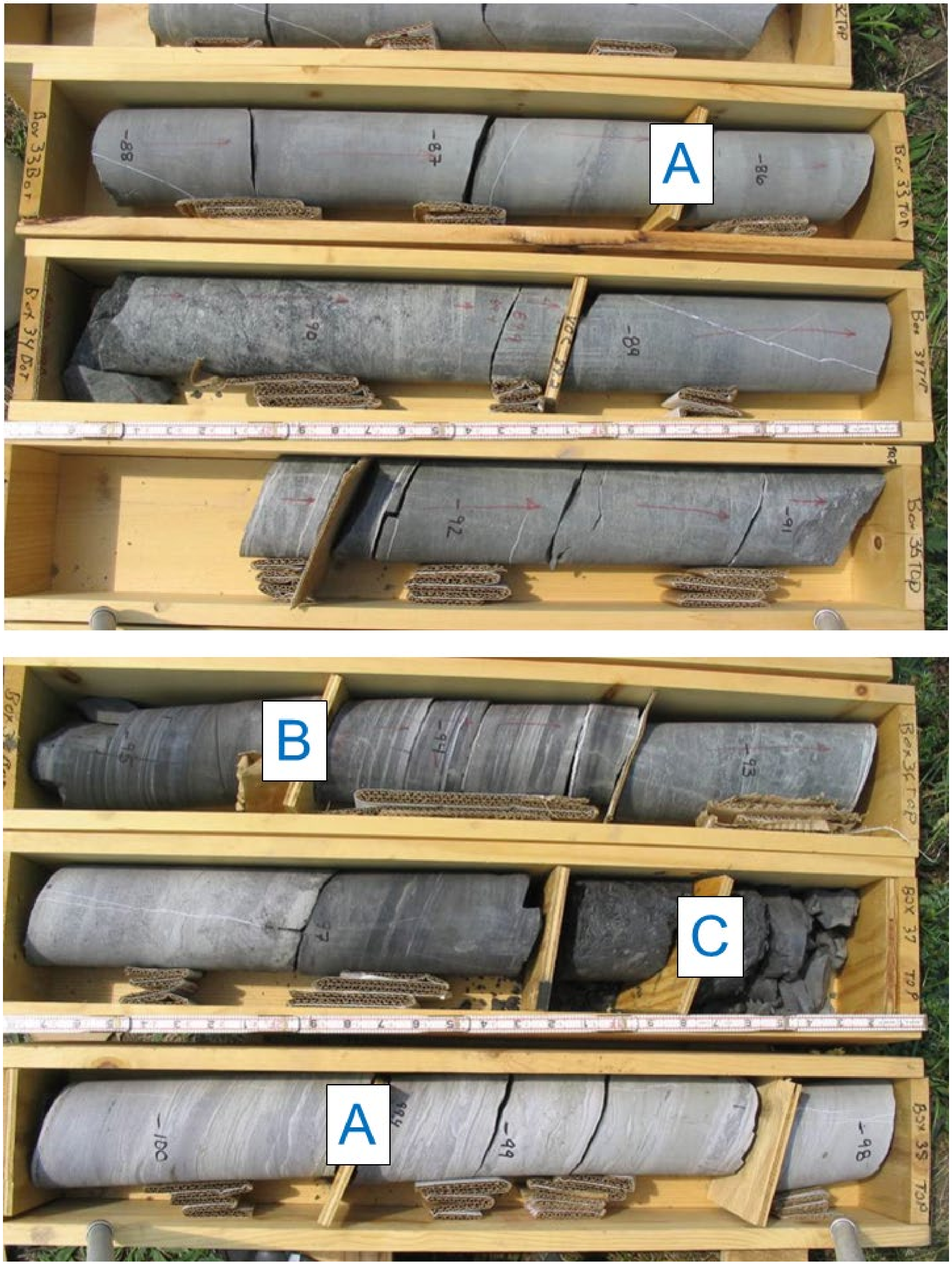
In 2002, the US Geological Survey Toxic Substances Hydrology Program created a program to select a national research site to investigate remediation of recalcitrant contamination in fractured bedrock. Among the 14 sites nationwide that were submitted for consideration, the Toxics Substances Program selected the Naval Air Warfare Center (NAWC) contamination site in West Trenton, N.J. for three major reasons. 1) The site consisted of mudstone. In America, two- thirds of exposed bedrock is sedimentary and two-thirds of the sedimentary rock is mudstone. This site represented a major rock type for research. 2) The site had only one major type of recalcitrant contamination, Trichloroethylene (TCE) with its degradation products DCE and VC. This site could be used to investigate a singular recalcitrant contaminate and not a massive mixture of contamination issues. 3) The hydrogeologic framework, groundwater flow, and groundwater contamination plumes were well defined. Researchers could enter the site and be quite confident that the laboratory site that they were using to investigate their particular tool of methodology did not require a great deal of preliminary framework evaluation and definition.

The purpose of the 2024 GANJ Field Demonstration is to show rock cores collected at the NAWC site. The three stratigraphic features found in the rock core are the 1) dipping geologic strata, 2) flat-lying, differential offloading strata, and 3) flat-lying differential weathering strata.

More than 60 ft of core will display black carbon rich strata, massive red and gray strata, banded/fine bedded strata, salt crystal replaced via analcime strata, migrated bitumen rich strata, multiple cyclicals of desiccation strata and other unweathered, indurated, competent strata found at depth. Shallower rock cores will show the effects of offloading such as fissile and indurated strata. Shallower rock core also shows the effects of physical, chemical, and biological weathering and it impacts on the multiple types of deep indurated geologic strata.

Most rock cores have been kept protected from the elements in core boxes in a core shed for more than a decade. One length of rock core that has been purposefully exposed to the elements for decades to show the impact of physical, chemical, and biological weathering has on originally indurated cores. The demonstration will compare and contrast the impact to the core caused by time of exposure under research conditions.

The in situ and fractured bedrock at the NAWC transmitted or held TCE or its degradation compounds as DNAPL phase, aqueous phase and sorbed phase. The demonstration will explain the various transport routes or sinks for entrainment of the TCE, DCE, and VC in the bedrock using the cores samples. The transports and sinks will include connected bedding fractures, major non-connected strata-bound fractures, indurated rock with microfractures, analcime, and carbon-rich strata.



Example core from former Naval Air Warfare Center, West Trenton, NJ, showing (A) light gray massive mudstone, (B) dark gray laminated mudstone, and (C) black, carbon-rich, fissile mudstone.

4. Review of Core and Geophysical Logs from a Central NJ DNAPL Site

Valerie Holliday, PG; Geologos, LLC

Field Demonstration Abstract

Dissolved chlorinated solvent contamination was found throughout the fractured bedrock aquifer sequence beneath a well-characterized industrial site in Middlesex County NJ. Continuous rock cores collected to depths exceeding 300 feet bgs during hydrogeological investigations are available for examination and comparison to an unusually comprehensive multi-mode data set. Shallow/deep bedrock monitoring well pairs were continuously cored and rock samples taken for high-resolution vertical characterization of diffused/sorbed VOC concentrations, with highest levels of matrix contamination found in discreet zones. Borehole geophysical surveys, including ATV, OTV, and HPFM tools, and vertical transmissivity profiling informed the design of the multilevel monitoring systems installed in each borehole. Multi-zone hydraulic monitoring and groundwater sample collection followed. In addition, the Rutgers Core Repository (RCR), current custodian of the cores, recently added to the data set by scanning individual cores with the Minalyzer drill core XRF scanner to provide comprehensive chemical, structural, density and photographic information. The cores present a rare opportunity to view a diverse body of high-resolution data, compare it to visible sedimentary structures, and perhaps gain new insights into weathered and fractured bedrock investigation methods.

5. Review of ongoing Research by Rutgers / LDOE Geological Core Laboratory Repository Scientists

Sean T. Kinney, PhD; Rutgers University

The ~6.7 km (+30 Myr) predominately lacustrine sequence that comprises the stratigraphy of the Newark Basin provides an unparalleled view into the evolution of the Earth system during the early Mesozoic. Here, we present the initial data product from a large-scale project where we have produced a continuous whole rock geochemical record of nearly the entire stratigraphy of this sequence basins from legacy cores, where we show that chemical proxies of lake depth and monsoonal climate can be tied directly to initial depositional environments and their subsequent history. This data product includes a library of the stratigraphic distribution of metals, including arsenic and uranium, that could ultimately be a source of geogenic groundwater contamination. These results also provide a baseline understanding of their vertical/lateral distributions that can ultimately aid in the development of predictive models of transport based on paleoclimate-driven lithological variations that exist at both member and bed levels. Our field demonstration will include a showcase of major results relevant to both an improved understanding of fundamental Earth system processes as well as applications to environmental science and engineering. Participants will have the opportunity to view and interact with the entire data product at workstations and examine representative sections of core from the Newark Basin Coring Project.

6. Correlation of Geophysical Logs—A Crucial and Underutilized Geological Skill

James L. Peterson, PG, LSRP; Princeton Geoscience, Inc.

Field Demonstration Abstract

Although the use of sophisticated borehole logging techniques has increased in recent years, the resulting data are frequently considered narrowly as mere high-resolution mapping of local conditions at the well or borehole, rather than as resources for the establishment of an interpreted, site-wide framework. Without doubt, borehole geophysics provides data invaluable to the planning of packer testing, grab sampling, well design and other activities which take place in, and require detailed understanding of, boreholes. But the larger goal is to understand the aquifer system, so it's necessary to ensure that characterization activities are performed with a framework in mind. Correlation is needed to establish that framework.

In a dipping sedimentary bedrock setting such as the Newark Basin, correlation consists of identifying distinctive stratigraphy-associated features (designated Markers) and tracking those features from one geophysical logging location to another by comparing the logging traces. If such correlation can be established, elevations of the correlated Markers can be used to evaluate (based on completion of 3-point problems yielding structural contours for the Marker) the site-scale strike and dip of sedimentary bedding, and therefore, of bedding-parallel fractures which are commonly of interest. In addition to providing a site-scale understanding of overall rock structure, log correlation efforts can, in favorable circumstances, lead to development of a "stratigraphy" of lithostratigraphic Marker units which can be used as points of reference in developing and tracing hydrostratigraphic units along strike, up- and down-dip from source areas to potential receptors or points of discharge (surface water bodies or wells).

Integral as they are to site characterization and to all remediation which relies on that characterization, correlation work products must be accurate and demonstrably so. This demonstration will show, with data from New Jersey remediation sites, the steps involved to achieve reliable correlations supporting framework development, using data from two New Jersey remediation sites underlain by Passaic Formation bedrock. One site will be from an area where more readily-correlated mudstone lithologies predominate, while a second will be from an area with interbedded sandstones and mudstones. The presentation will initially explore the practical implications of mis-correlation, followed by discussions focusing on use of existing data (e.g., geologic maps, NJ State-wide Lidar) to inform planning and initial correlation efforts; requisite geophysical logging data (types and distribution) to support a correlation effort; identifying suitable units for correlation; and some quality control

measures that may be applied to check upon the validity of the correlation and thereby support provision of correlation work products of known quality.

OUTLINE

I. Monitoring Challenges / Why Co rrelate Logs?
II. Preparing to Correlate
III. Structural Contour Mapping
IV. Quality Control Checks
V. Log correlation examples

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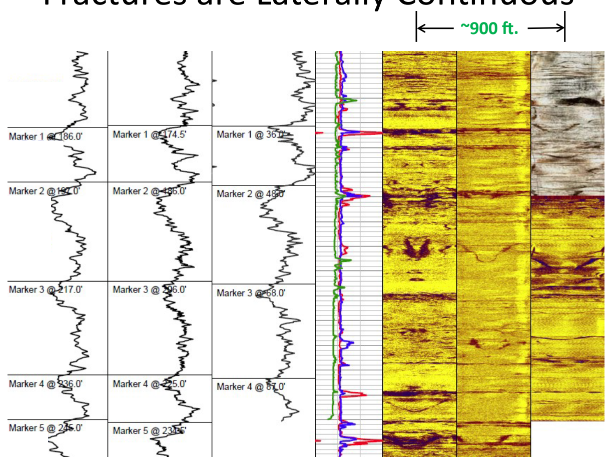
Correlated Logs Show that Bedding Fractures are Laterally Continuous



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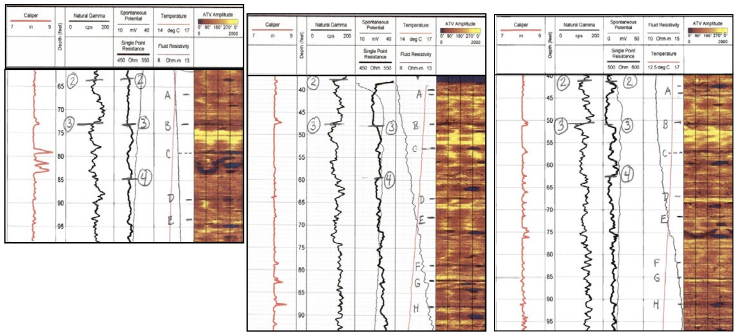
Logs Vertically Shifted to show Correlation; Individual Rock Units and Bedding Fractures can be Traced Hundreds of Feet across a Site in Mudstones

Boring Located Down-Dip | **Borings Positioned Nearly Along Strike from One Another**



Ground surface elevations at borings are similar, so <u>depths of markers</u> shown on logs give a good general indication of bedrock structure

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7. 3-D Visualization of Hydrogeologic Models Using Leapfrog

John N. Dougherty, PG; CDM Smith

As geologists we think about subsurface data in 3-dimensions but until recently it has not been easy to create 3-d visualizations of subsurface data to use in data analysis, decision support, and to share with colleagues, clients, and other stake holders. A 3-dimensional geologic model and conceptual site model of the fractured rock aquifer underlying the Watershed Institute, in Pennington, NJ was built in Leapfrog software using existing information including geologic maps, cross sections, boring logs, natural gamma logs, water level data, and sample results in both PDF and electronic format. Participants were able to use Seequent Onsite software on a mobile device to view the georeferenced model prepared in Leapfrog software.

8. Pumping-Stressed Hydraulic Monitoring (Well Interference) and Single Packer Hydraulic Monitoring

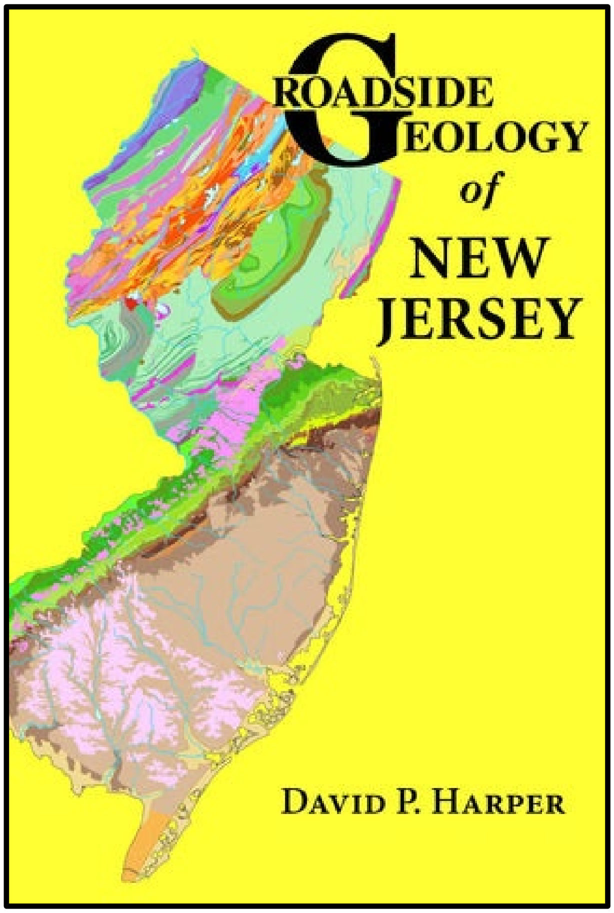
Gregory C. Herman, PhD; Trap Rock Industries, Timothy J. Hull, PG, LSRP; Princeton Geoscience, Inc., & Andrew Michalski, PhD, CGWP, PG

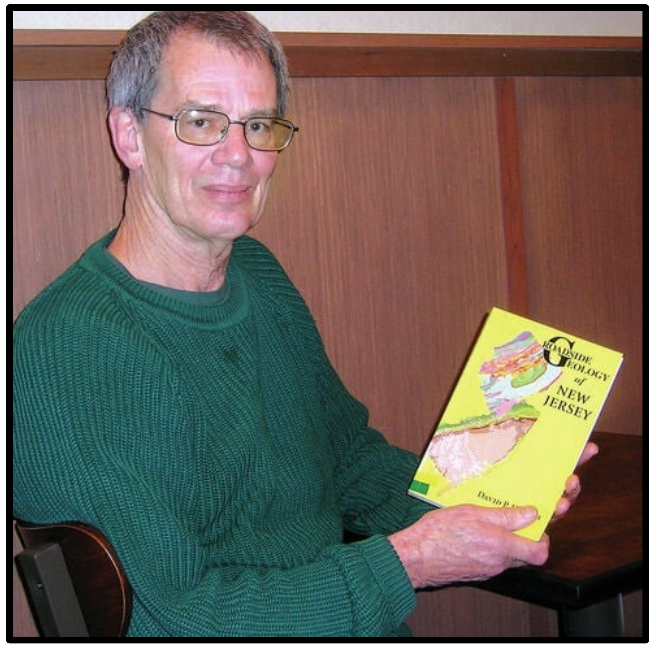
Abstract: Single-Packer and Short-Term Pumping Testing to Evaluate Hydrostratigraphy of the Multi-Unit Bedrock Aquifer System at the Watershed Institute Wellfield

The radial bedrock wellfield at the Watershed Institute consists of 13 wells that were drilled to depths of about 150', with about 20' of 6"-diameter steel casing. The wellfield was developed in 1966 to study the occurrence and movement of groundwater in the Passaic Formation bedrock for water supply applications (well interference, wellfield configuration and productivity). Discharge measurements during well drilling indicated that water occurs in discrete zones controlled by bedding, but no relation was apparent between well yield and the number of zones penetrated. When a central well was pumped and drawdowns were recorded in other wells, anisotropic drawdown response was observed, with a greater drawdown recorded in wells situated along strike and thus tapping common producing zones within dipping bedrock beds (Vecchioli and others, 1969).

While re-visiting this old wellfield, one needs to recognize significant subsequent developments. First, the Passaic Formation is now conceptualized as a Leaky, Multi-unit Aquifer System (LMAS). While bedding-parallel flow is dominant in this generic model, the bulk of this flow is concentrated within very few transmissive bedding fractures that are laterally extensive and separated by thick aquitards. Weathered bedrock provides major groundwater storage zone for the deeper bedrock flow. Second, contaminant hydrogeology requires an advanced bedrock characterization that starts with documenting discrete contaminant migration pathway from a source area into deeper bedrock. In this context, long open holes that penetrate multiple transmissive bedding fractures, alongside with resulting mutual interference of the wellfield wells, presents challenges for such advanced characterization.

The current field demonstration activities will involve 1) discussion of composite water levels measured in wellfield's open holes, and 2) continuous monitoring of hydraulic heads during ambient conditions and on-site testing periods. One of the planned tests includes inflating a single packer in one of the open holes while observing head responses in other wells to constricting of ambient vertical flow resulting from the inflation. It will be followed by a short-term pumping test using the on-site water-supply well (SB14 ~ 207 TD), paying attention to the rapidity and amount of drawdown responses in other wells as indicators of the continuity anisotropic nature of the bedrock system.





The Geological Association of New Jersey wishes to thank Dave Harper, author of **Roadside Geology of New Jersey** for his continual donation of part of the profits from sales of his book. This guide book should be part of any New Jersey geologist's library and can be purchased at most NJ books stores and on-line.

Dave worked with the New Jersey Geological Survey during 1974-1994 and with the New Jersey Site Remediation Program from 1994-2002. Dave taught geology classes at Rider University, Mercer County Community College, and New Jersey City University.

Dave was the President of the Geological Association of New Jersey in 2000 with his proceedings covering the ***Glacial Geology of New Jersey.***

Thank you Dave for your continued support