Historical Bedrock & DNAPL Investigations M52 Operable Unit 1

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Outline

- Overview of DNAPL behavior in subsurface
- Overview of historical bedrock & DNAPL investigations in Operable Unit 1 (OU1) area
- Summary
- Next Steps

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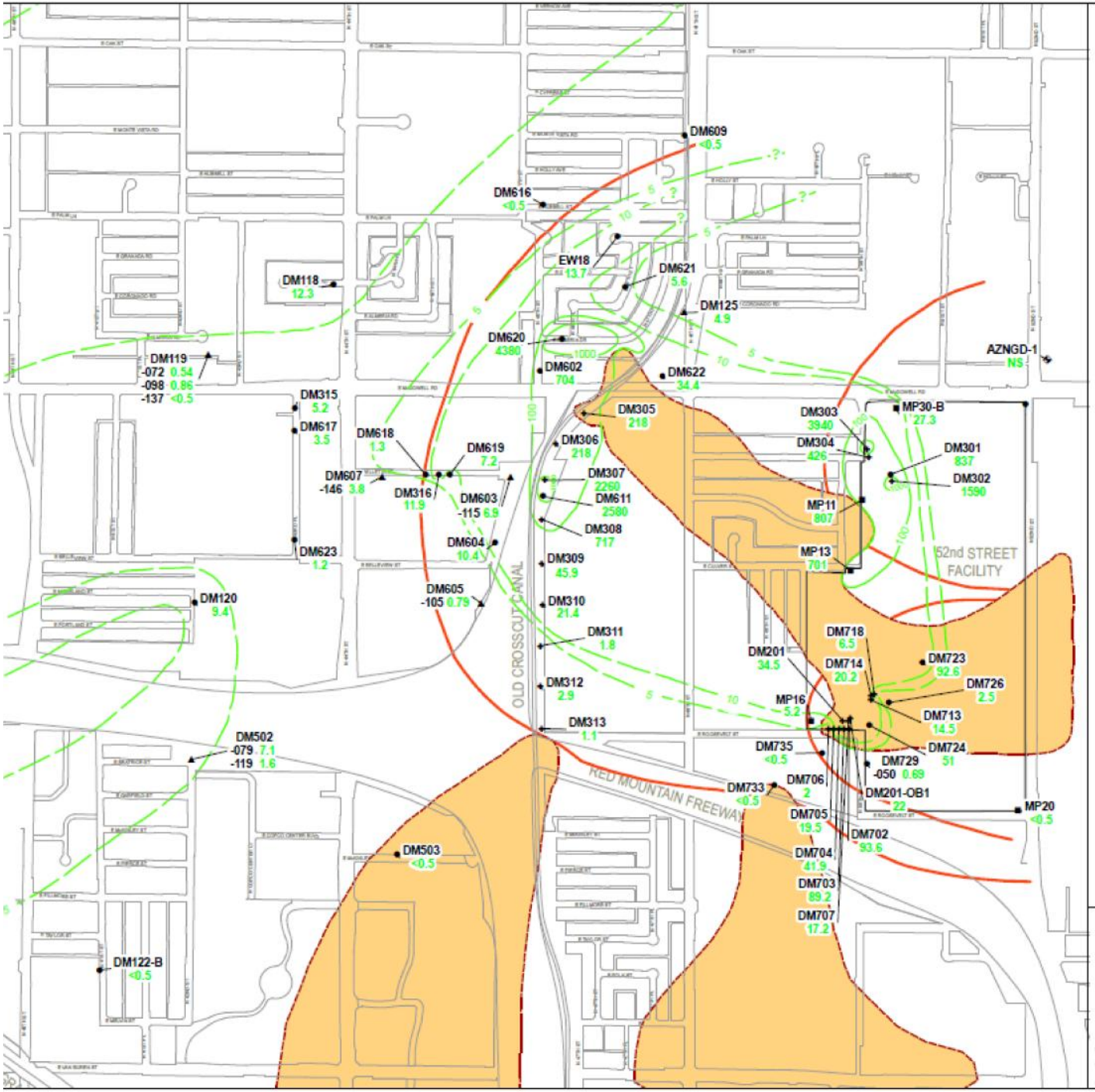

TCE: Trichloroethylene

LEGEND:

SYMBOL	WELL TYPE
●	CONVENTIONAL
✦	EXTRACTION
■	MULTIPORT
▲	WESTBAY or FLUTe
✦	PRIVATE

▲ DM502 -079 7.1 -119 1.6 — WELL NAME; Depth of Westbay or FLUTe well sample port (in feet bgs) or completion interval designation. TCE concentration (ug/l)

● DM120 9.4 — WELL NAME; TCE concentration (ug/l)

Approximate area of capture

10 — TCE concentration contour (ug/l)

NS — Not sampled

Approximate area of bedrock above December 2013 water table.

52nd Street Facility

NOTE:

The TCE contours drawn on this figure are approximate and are represented to illustrate general concentrations of TCE in alluvium in the area. Contours are dashed where approximate or conjectured.

Wells DM311, DM312, and DM313 are currently used as monitor wells only.

Wells DM616, DM617, DM618, DM619, DM620, DM621, DM622, and DM623 were completed in November - December 2013. Water quality data are from December 2013.

Wells DM315 and DM316 were completed in November-December 2013. These wells will be used as aquifer test wells.

0 500 1,000 2,000 Feet

TCE CONCENTRATIONS ALLUVIAL AQUIFER PLAN VIEW SEPTEMBER 2013

Figure 25

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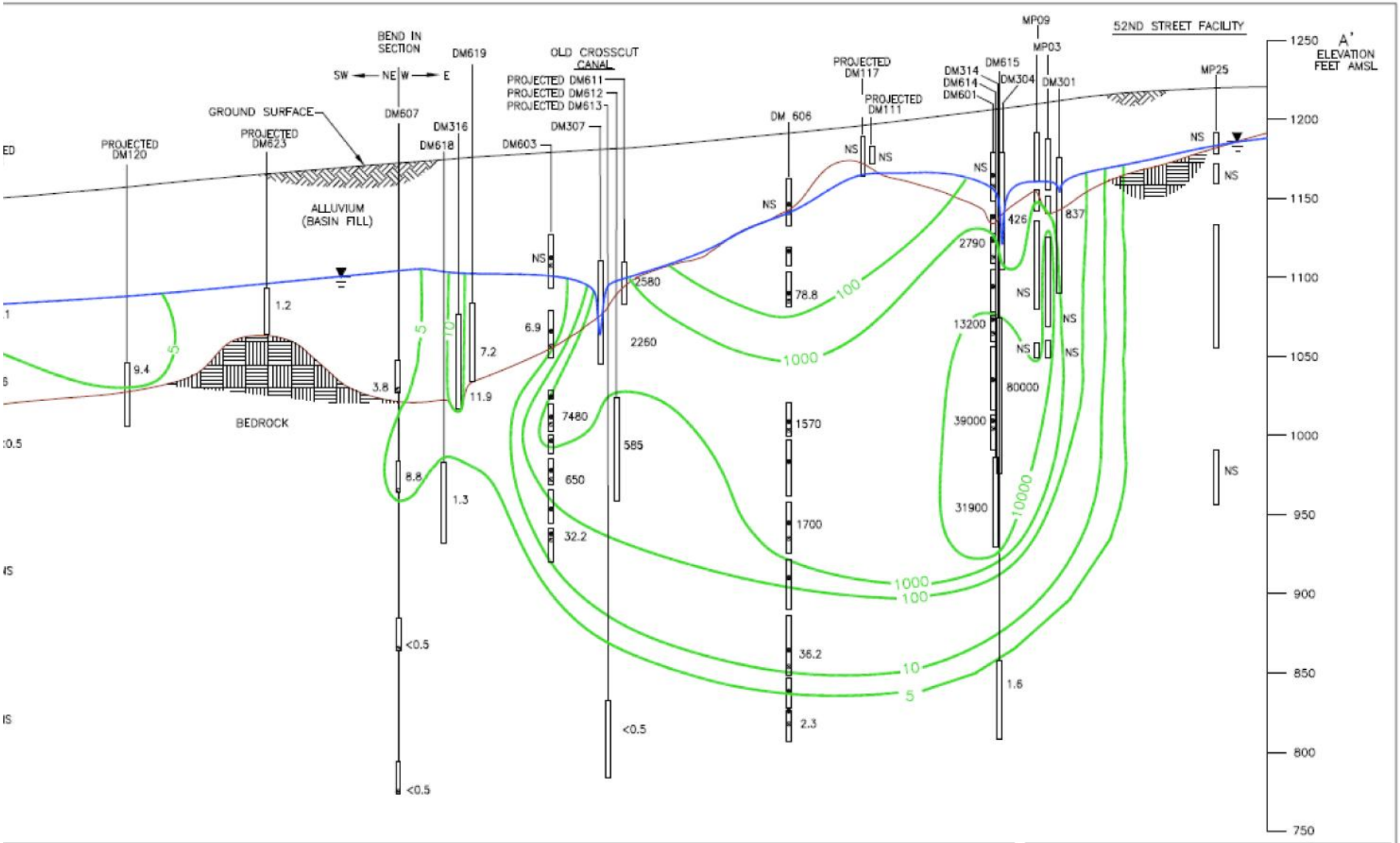

OF WELL
ND SURFACE
OCK CONTACT
WATER TABLE
OR ZONE
UREMENT PORT

OR ZONE

7.4 TCE CONCENTRATION IN ug/L

NS NOT SAMPLED

5 TCE CONCENTRATION CONTOUR (ug/L)

NOTES:

1. LOCATION OF SECTION A–A' IS SHOWN ON FIGURE 1 AND 24. SOME WELLS IN CLOSE PROXIMITY TO SEC. A–A' HAVE BEEN PROJECTED TO THE CROSS SECTION. FIGURE 1 SHOWS THE APPROXIMATE AND RELATIVE DISTANCE OF THE PROJECTED WELLS.
2. THE SPECIFIC DEPTHS/LOCATIONS OF MEASUREMENT AND PUMPING PORTS, AND MONITOR ZONES ARE PROVIDED IN THE MI52 1992 FR RI REPORT AND OTHER RELATED DOCUMENTS. THE ENTIRE WELL CONSTRUCTION IS NOT SHOWN ON THIS FIGURE.
3. THE WATER TABLE WAS PLOTTED USING DECEMBER 2013 DATA.
4. WELL DM307 IS A PUMPING WELL. THE WATER LEVEL HAS BEEN ADJUSTED FOR WELL EFFICIENCY.
5. WELLS DM316, DM618 AND DM619 WERE SAMPLED IN DECEMBER 2013.

HORIZONTAL SCALE
0 600 1200
IN FEET
VERTICAL EXAGGERATION 10X

TCE CONCENTRATIONS SEPTEMBER 2013 SECTION A-A'

Figure 28

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OU1 EFFECTIVENESS REPORT
2013 OPERATIONS
MARCH 2014

DNAPL 101 – What are DNAPLs?

- **D**ense (heavier than water [i.e. specific gravity >1])
- **N**on**a**queous **P**hase **L**iquids (free-phase product)

- TCE has a specific gravity of 1.46 and is less viscous (0.42) than water (1.0):
  - TCE quickly moves vertically downward (sinks) through an aquifer and spreads out laterally on lower permeability materials
  - Low interfacial tension between TCE (and other chlorinated solvents) and water allows solvents to penetrate smaller aperture fractures and pore spaces – meaning there is deeper penetration of solvent for given volume of rock
- TCE and other chlorinated solvents are relatively insoluble in water on a physical chemistry basis, BUT, solubility limit (1,100 mg/L) is high compared to health based regulatory levels (0.005 mg/L or 5 ppb)
  - Residual TCE as a NAPL or adsorbed contaminant represents a long-term source of contamination

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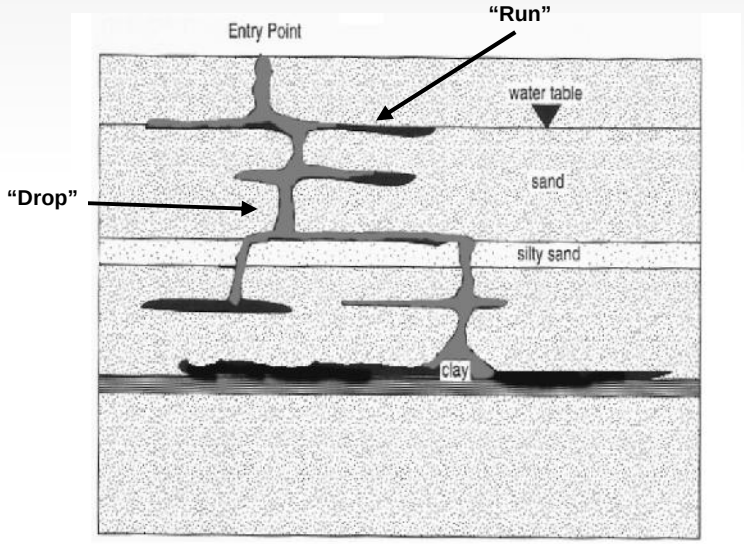
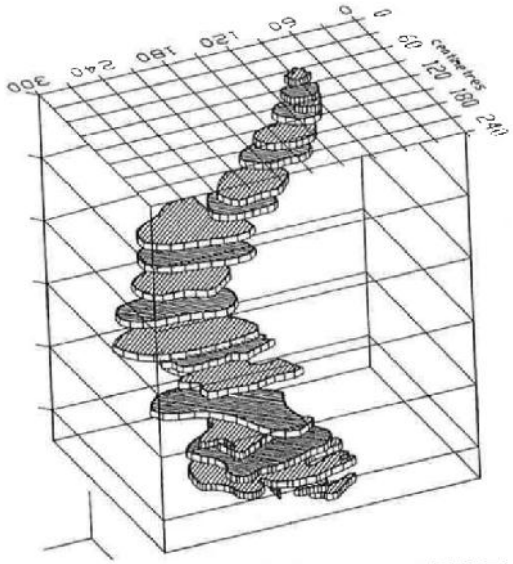
DNAPL 101 – cont'd

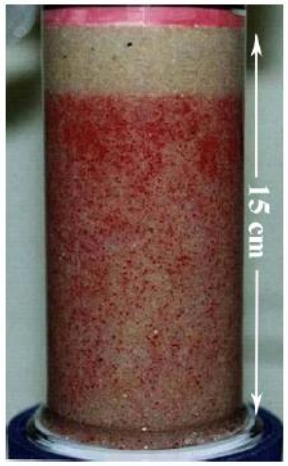
- DNAPL migration in subsurface is complex, with multiple "runs" (lateral spreading) and "drops" (vertical migration) even in seemingly homogeneous aquifers



From NRC, 2005



Cartoon depicting "Drip-like" infiltration of PCE into Borden sand (Pankow & Cherry, 1995 reprint of Poulsen and Keuper, 1992)



Colored PCE in vial of clean coarse sand (NRC, 2005)

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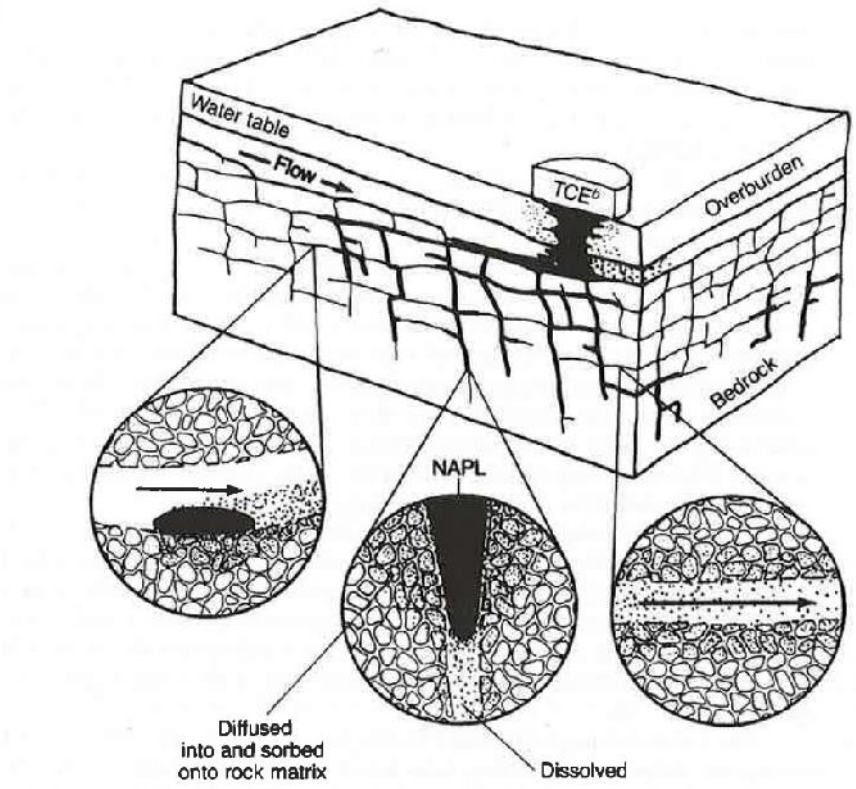
DNAPL 101 – cont'd



From Pankow & Cherry, 1995

- Migration and distribution in subsurface is complex both on the "regional" scale and on the pore/fracture scale
- Due to their density and other physical attributes, thick pools of chlorinated solvent DNAPLs are rare
  - Accumulated DNAPL enters fractures or pore spaces leaving thin small layers, disconnected globules and ganglia (or fingers)
- DNAPL, contaminants in no-flow zones and sorbed into matrix represent continuing sources

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Overview of Key Points

- Based on their attributes and subsurface behavior, identification of DNAPL is challenging. Most sites rely on evaluation of other factors to infer DNAPL presence (from EPA 1993)
  - Industry / operations type
  - Waste management practices
  - Site chemical usage history
  - Release type (e.g. direct solvent release or in aqueous solution)
  - Groundwater data (e.g. maximum concentration, temporal trends, spatial patterns, direct observation)
- Motorola 52nd Street facility is a “confirmed” DNAPL site with DNAPL observed in fractured bedrock at monitoring well MP03-D

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Overview of Bedrock/DNAPL Investigations

- Evaluation of bedrock has been an integral component of the investigation and remediation efforts in the OU1 area since work began in 1983
- M52 investigators recognized and considered non-aqueous phase liquids in the OU1 area as early as 1985
  - "Dense Chlorinated Solvents in Porous and Fractured Media" 1988 English Translation by James Pankow of 1984 Schwille publication in German
  - "Ground Water Issue – Dense Nonaqueous Phase Liquids" EPA 540/4-91-002, 1991
  - "Estimating Potential for Occurrence of DNAPL at Superfund Sites" OSWER 9355.4-07FS, 1992.
  - "Evaluation of the Likelihood of DNAPL Presence at NPL Sites" OSWER 9355.4-13. 1993.
  - "DNAPL Site Evaluation" Cohen and Mercer, 1993
  - "Dense Chlorinated Solvents and other DNAPLS in Groundwater" Pankow and Cherry, 1996.

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OU1 By the Numbers

- Approx. 21,700 vertical feet (4.1 miles) of borehole have been drilled in OU1 area to date
  - Of that, over 12,700 feet (2.4 miles) have been drilled in bedrock including collection of over 4,300 feet of rock core
- Some 327 monitoring points have been installed over time in the OU1 area
  - Of that, some 246 were completed across the alluvium/bedrock interface or within bedrock
- Through 2013, approx. 3.55 billion gallons of water have been treated and an estimated 23,635 pounds of VOCs (or 1,941 gallons as TCE) have been recovered
  - Of the total mass recovery, approx. **279 pounds have been recovered as DNAPL** and saturated groundwater from monitoring well MP03-D

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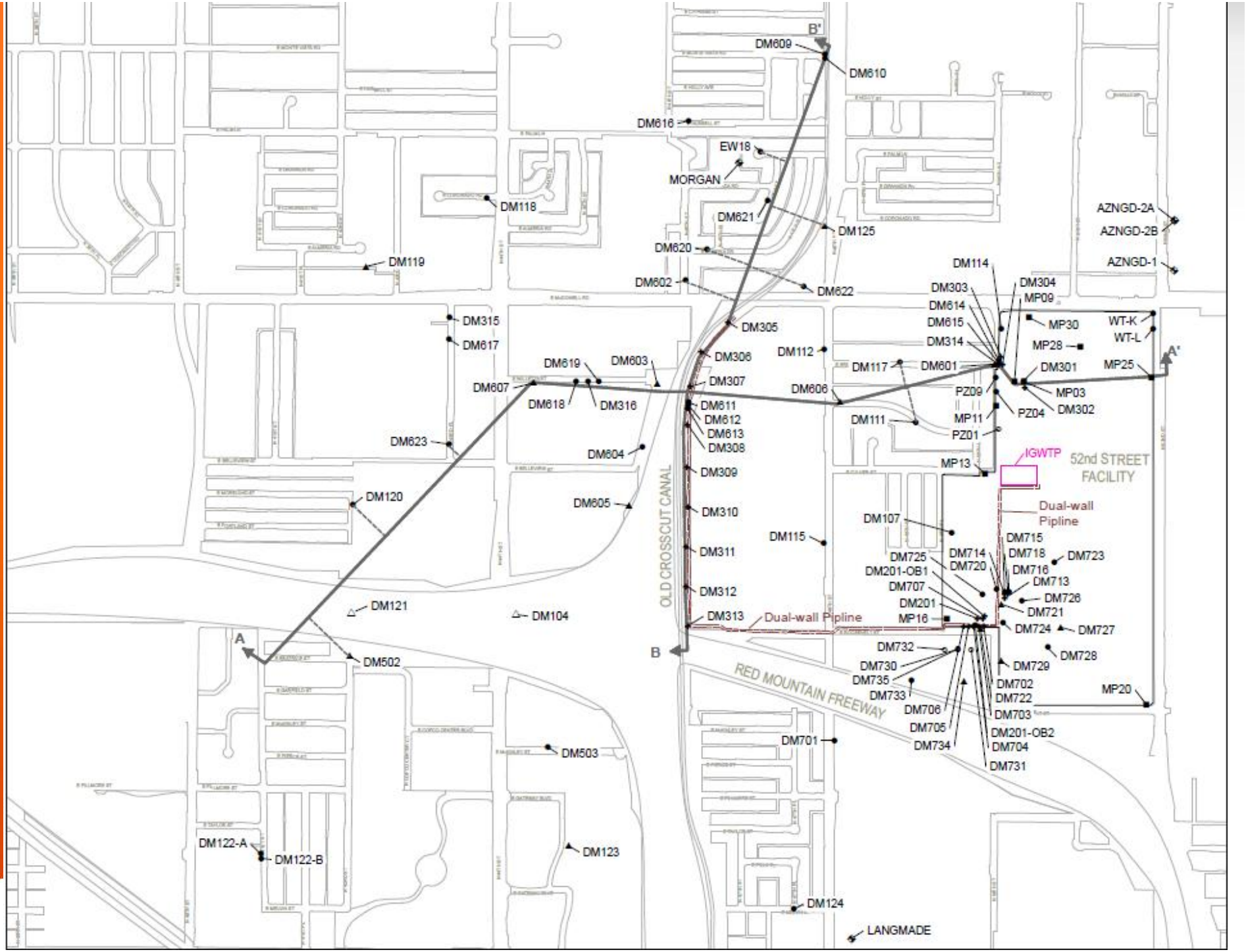
B'
DM609
DM610
DM616
EW18
MORGAN
DM118
DM621
DM125
DM620
DM622
DM602
DM119
AZNGD-2A
AZNGD-2B
AZNGD-1
DM114
DM303
DM304
MP09
DM614
DM615
DM314
MP30
WT-K
WT-L
MP28
A'
DM315
DM617
DM305
DM112
DM306
DM619
DM603
DM307
DM607
DM618
DM316
DM117
DM601
DM301
MP25
DM606
PZ09
MP03
PZ04
DM302
DM611
DM612
DM613
DM308
DM111
MP11
PZ01
DM623
DM604
MP13
IGWTP
52nd STREET FACILITY
DM309
DM120
DM605
DM310
Dual-wall Pipline
DM107
DM115
DM715
DM718
DM723
DM725
DM714
DM720
DM716
DM201-OB1
DM713
DM707
DM726
DM311
DM201
DM721
DM312
DM121
DM104
DM313
Dual-wall Pipline
MP16
DM724
DM727
A
B
DM732
DM728
DM730
DM729
DM735
DM733
DM702
DM722
MP20
DM706
DM703
DM705
DM201-OB2
DM734
DM704
DM731
DM701
DM502
OLD CROSSCUT CANAL
RED MOUNTAIN FREEWAY
DM503
DM122-A
DM122-B
DM123
DM124
LANGMADE

Historical Bedrock / DNAPL Investigations

- Preliminary Report, Chemical Leak Project. Guitierrez Palmenberg, Inc. 1983
  - Work primarily conducted on-site
  - Electrical resistivity survey to identify subsurface conditions for evaluation of well locations
  - Drilled boreholes, collected geologic core, evaluated bedrock fractures, and installed multi-point wells completed in the alluvium, the interface-shallow bedrock and deep bedrock
  - Conducted 2 constant rate tests (one in bedrock) and multiple borehole pressure tests in alluvium and bedrock borings
  - Developed initial bedrock lithology and surface contour map with preliminary identification of fault
  - Developed geologic fence diagram

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Historical Bedrock / DNAPL Investigations

- Preliminary Report, Chemical Leak Project. Guitierrez Palmenberg, Inc. 1983
  - Identification of potential source areas and chemicals
  - Preliminary water level and water quality results
  - Recognized that other factors, incl. the geologic “trough”, appeared to influence contaminant distribution
  - Recognized that density of TCE may affect its migration through unsaturated zone and along alluvium/bedrock interface
  - Sought an explanation for the detection of TCE at concentrations greater than its saturation limit
  - Dames & Moore developed initial three-dimensional groundwater flow and transport model of alluvium and bedrock

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Historical Bedrock / DNAPL Investigations

- Stratigraphic Boring / Monitoring Wells Report. Dames & Moore, 1985.
  - Documented findings stratigraphic boring and geologic logging to characterize the geologic and hydrogeologic conditions of alluvium and bedrock in OU1 area
  - Detailed logs of corehole, including:
    - % recovery (recovered length ÷ core barrel length)
    - Rock quality designation (RQD) [% recovery of solid core greater than 4 in]
    - Rock hardness
    - Fractures per interval
    - Fracture description (orientation, open, healed, description of in-fill material)
    - Graphic log
    - Lithologic description
  - Presented lithologic and structural geology history for region and for OU1 area based on observed core
  - Lineament analysis of Motorola plant site and surrounding area
    - **Concluded not related to geologic structures**
  - Identified structural features in bedrock in OU1 area
  - **Identified alluvium / bedrock interface as potential primary transport pathway**

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Historical Bedrock / DNAPL Investigations

- Physical Chemical Investigation Report. Dames & Moore, 1986.
  - Identified nonaqueous phase liquids as being observed at the Motorola facility
  - Evaluated considerations of phase separated liquids in support of contaminant transport modeling
    - Two-fluid flow considerations
    - Viscosity and density
    - Interfacial tension
    - Partitioning and solubility limits
    - Adsorption
  - Recognized that NAPL represents a continuing source

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Historical Bedrock / DNAPL Investigations

- Remedial Investigation Report. Dames & Moore, 1987.
  - Summary of all investigations conducted to date
  - Lithologic and geophysical logging results of bedrock boreholes
  - Detailed logs of corehole, including:
    - % recovery
    - Rock quality designation (RQD) [% recovery of solid core greater than 4-in]
    - Rock hardness
    - Fractures per interval
    - Fracture description (orientation, open, healed, description of in-fill material)
    - Graphic log
    - Lithologic description
  - Key findings:
    - **Although extensively fractured, most of the fractures are filled with clay or secondary mineralization**
    - **RQD increases and fracture density decreases with depth indicating a decreased permeability with depth**

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Historical Bedrock / DNAPL Investigations

Bedrock Cores of fractured granite showing in-fill

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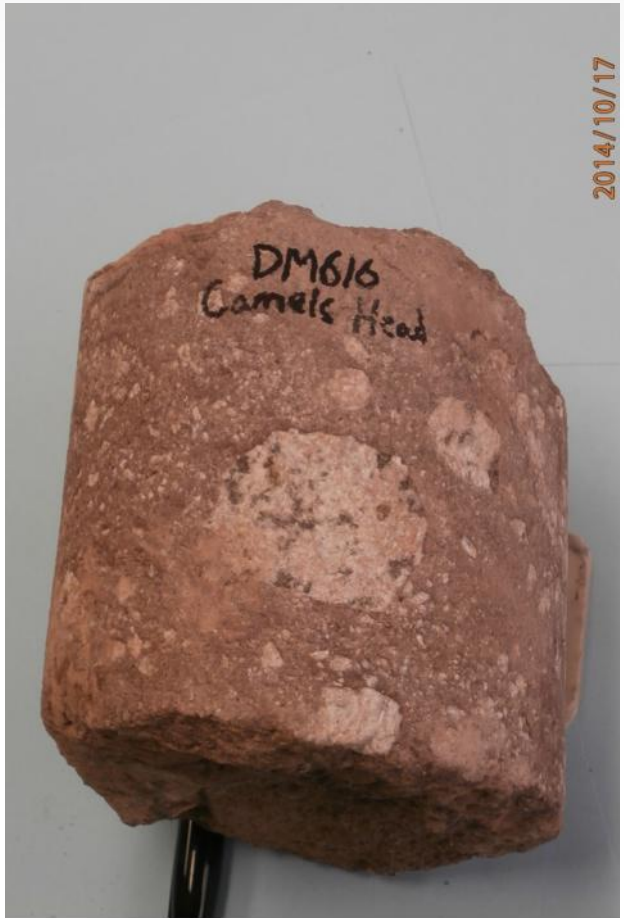
Historical Bedrock / DNAPL Investigations

Bedrock Cores of Tempe Beds (left) and Camelshead Formation (right)



Historical Bedrock / DNAPL Investigations

- Remedial Investigation Report. Dames & Moore, 1987.
  - Updated geologic maps
    - Bedrock types
    - Bedrock surface contours
    - Updated structural features
    - Geologic cross sections
  - Results of aquifer testing – including testing of bedrock well DM201 in the Southwest Parking Lot (SWPL) area
  - Updated alluvium/bedrock groundwater flow and contaminant transport model
  - Documented findings of source verification studies and evaluated the potential for associated presence of residual NAPL
  - Report on DNAPL in MP03-D and assessment that non-aqueous phase liquid was likely not mobile

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Historical Bedrock / DNAPL Investigations

- Feasibility Study Report. Dames & Moore, 1987.
  - Evaluation of remedial alternatives to contain and treat contaminated groundwater in both the alluvium and bedrock
  - Recognizes that undissolved solvents represent a continuing source and
  - Bedrock contamination defined to west of Old Crosscut Canal
  - Identified and evaluated remedial objectives
  - Recommends “Alternative C” (continuation of the on-site remedy implemented in 1986 and pumping from the alluvium and bedrock at the Old Crosscut Canal for hydraulic containment)

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Historical Bedrock / DNAPL Investigations

- Bedrock Data Report. Dames & Moore, 1991
  - **Compiled and re-analyzed bedrock specific boring logs, text, tables and figures from previous reports**
  - Second lineament study of Motorola plant site and surrounding area
    - Based on 1936 and 1954 aerial photos
    - None of lineaments appear associated with identified (NW trending) faults
    - Most lineaments oriented NE (typical of arroyos off Papago Buttes)
  - Results of hydraulic conductivity tests performed in bedrock, summary of completion intervals of bedrock wells, an identification of lost circulation zones in bedrock wells
  - Review of hydraulic conductivity tests for evidence of open fractures and hydraulic connection between alluvium and bedrock
    - 218 packer, pump, and rising head tests in 25 bedrock wells
    - No correlation observed between increased values of hydraulic conductivity to logged geologic structures (e.g. Increased fracture frequency, openness of reduced core recovery)
    - No response in alluvium as a result of pumping in bedrock or vice versa
      - Rates and duration of tests were small compared to more than three orders of magnitude differences in hydraulic conductivity
      - Long-term operations show a connection – but at a very low rate
  - Review of alternatives presented in the Feasibility Study that included bedrock pumping wells
  - **Re-affirmed conclusions in FS Report regarding proposed remedy**
    - Bedrock specific alternatives would result in reduced removal efficiency and increased construction and O&M costs as compared to proposed plan

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Historical Bedrock / DNAPL Investigations

- Final Remedy Remedial Investigation Report (including Southwest Parking Lot Attachment). Dames & Moore, 1992.
  - Included information provided in 1991 Bedrock Data Report
  - Updated geologic and hydrogeologic information obtained from drilling and hydraulic testing of 6 new wells in OU1 area, 11 new OU1 extraction wells (2 on-site, 9 at OCC) 10 wells in OU2 area, and 1 well south of the 52nd St facility / SWPL area
  - Evaluation of vertical flow between the alluvium and bedrock in the OU1 and OU2 areas
  - Results of source investigation and multi-well bedrock pumping test in the SWPL area
    - Coring to collect soil samples inside AD Building near solvent sump
    - Work to install additional SWPL area extraction wells begins in Jan 1992

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Historical Bedrock / DNAPL Investigations

- Southwest Parking Lot Remedial Investigation Report. Dames & Moore, 1993.
  - Installation of two multiport Westbay wells and four conventional wells in bedrock to define extent of contamination in SWPL area
    - Collection and description of bedrock core
    - Standard geophysical logs (gamma, spontaneous potential, density, caliper, resistivity)
    - Updated geologic and hydrogeologic information obtained from drilling and hydraulic testing of new wells
  - Specialty logging of one borehole near AD Building sump for more detailed fracture and fluid migration analysis
    - Temperature and fluid resistivity
    - Full wave form sonic
    - Acoustic televiewer
  - Identification of fracture network controlling flow near AD Building sump
  - Identification of data gaps

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Historical Bedrock / DNAPL Investigations

- Addendum to Southwest Parking Lot Remedial Investigation Report. Dames & Moore, 1994.
  - Summarized completion of RI in SWPL Area
  - Installation of 6 multiport Westbay wells and 2 conventional wells in bedrock to address data gaps identified in SWPL RI and define extent of contamination in SWPL area
    - Collection and description of bedrock core
    - Standard geophysical logs (gamma, spontaneous potential, density, caliper, resistivity)
    - Updated geologic and hydrogeologic information obtained from drilling and hydraulic testing of new wells
  - Bedrock groundwater remedy in place since 1991 consists of 12 bedrock extraction wells pumping at combined average rate of 1.3 gpm

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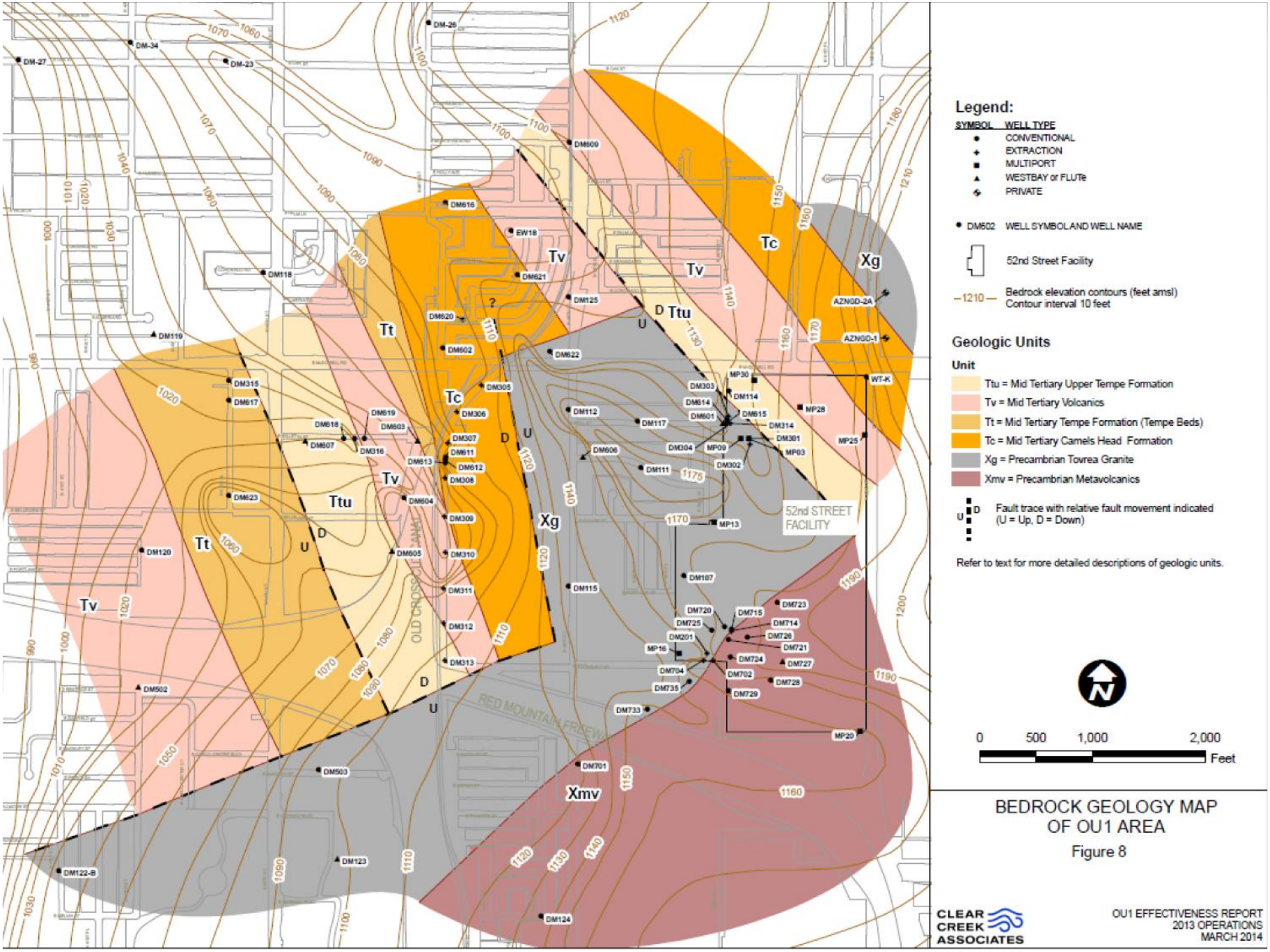
Legend:
SYMBOL WELL TYPE
CONVENTIONAL
EXTRACTION
MULTIPORT
WESTBAY or FLUTe
PRIVATE
DM602 WELL SYMBOL AND WELL NAME
52nd Street Facility
1210 Bedrock elevation contours (feet amsl)
Contour interval 10 feet
Geologic Units
Unit
Ttu = Mid Tertiary Upper Tempe Formation
Tv = Mid Tertiary Volcanics
Tt = Mid Tertiary Tempe Formation (Tempe Beds)
Tc = Mid Tertiary Camels Head Formation
Xg = Precambrian Tovrea Granite
Xmv = Precambrian Metavolcanics
U D Fault trace with relative fault movement indicated (U = Up, D = Down)
Refer to text for more detailed descriptions of geologic units.
52nd STREET FACILITY
OLD CROSSCUT CANAL
RED MOUNTAIN FREEWAY
0 500 1,000 2,000
Feet
BEDROCK GEOLOGY MAP
OF OU1 AREA
Figure 8
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OU1 EFFECTIVENESS REPORT
2013 OPERATIONS
MARCH 2014

Historical Bedrock / DNAPL Investigations

- University Consortium, Solvents in Groundwater Research Program 1995-2001
  - Research activities at four principal universities :
    - University of Waterloo [Dr. Cherry, Dr. Gillham, Dr. Parker],
    - Colorado State University [Dr. McWhorter, Dr. Sale]
    - Oregon Graduate Institute [Dr. Johnson, Dr. Pankow]
    - Queen's University [Dr. Keuper]
  - Originally began in 1988 to study the subsurface behavior and fate of chlorinated solvents in groundwater. By mid-1990s had evolved to focus on research of emerging treatment technologies and approaches and technologies for characterizing site conditions and remedial performance
  - Motorola was corporate member 1995-96; Research chair from 1997-2001
    - **Sponsorship provided early access to research efforts and chance to confer with leading DNAPL investigators**
    - Research chair (Dr. Gillham) focused on zero-valent iron and bi-metal (e.g. iron-nickel) remediation technologies
      - Emplacement to depth and in fractured media has been a key limitation

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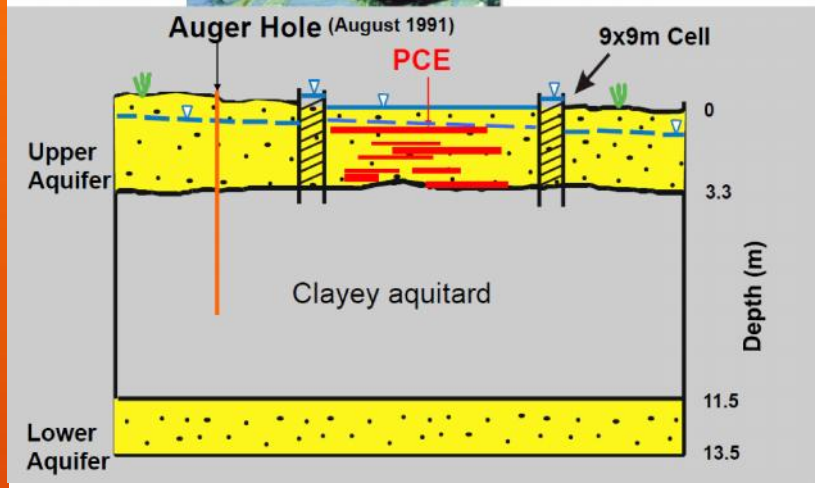
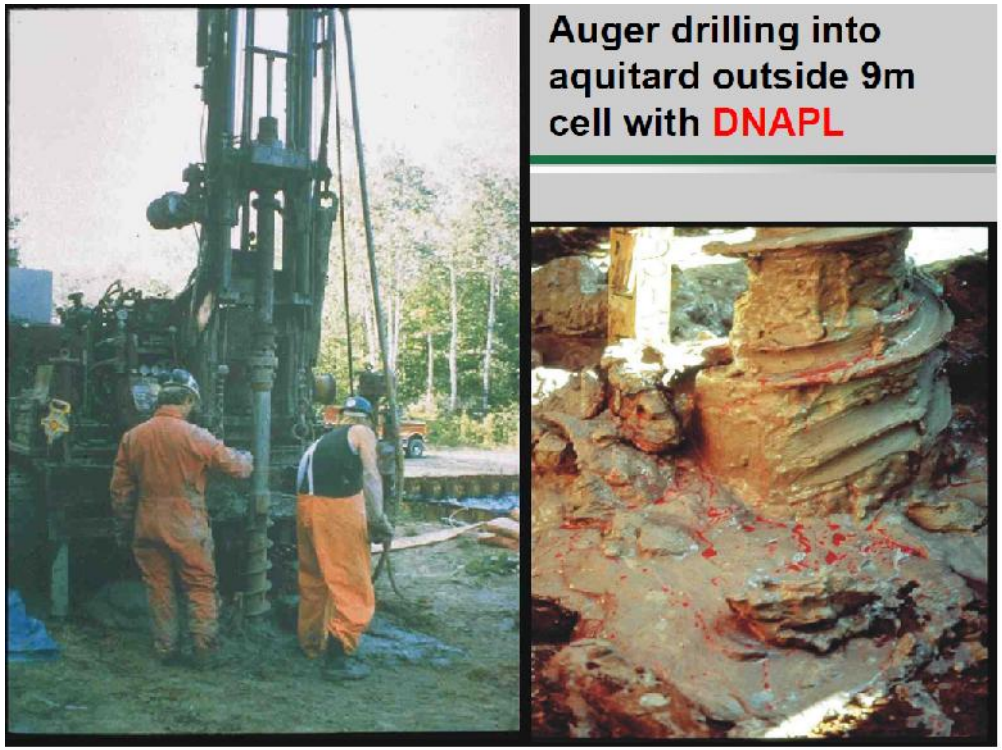
Historical Bedrock / DNAPL Investigations

July 1991 release



August 1991 boring

- Solvents in Groundwater Consortium Work at Canadian Forces Base Borden
  - "Even though the Borden aquifer and aquitard are very simple and uniform, DNAPL releases result in much complexity of source zones and plumes." (From Dr. J. Cherry keynote address 2009 International Congress on Subsurface Environment.)



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Historical Bedrock / DNAPL Investigations

- Groundwater Remedial Alternatives Analysis and Addendum to Groundwater Remedial Alternatives Analysis. GeoTrans, Inc., 2005
  - Evaluation of potential modifications to OU1 groundwater remedy
  - Assessment of innovative technologies for potential DNAPL source zone reduction
  - State of the Science review of literature & case studies to evaluate feasibility of innovative source zone remediation technologies
    - In-situ chemical oxidation (ISCO)
    - Chemical reduction with zero-valent iron (ZVI)
    - Surfactant and co-solvent flushing
    - Thermal treatment
    - Enhanced In-situ bioremediation
  - Due to the complex setting and limitations of available technologies GeoTrans concluded that an innovative approach to source zone remediation was technically infeasible in OU1. Recommended enhanced hydraulic control with additional bedrock extraction on-site.

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Feet: 0 50 100 200
Meters: 0 10 20 40 60 80

EXPLANATION

- EXISTING WELL LOCATIONS
- ISCO, ZVI, OR ISB INJECTION WELL
- ESTIMATED AREA OF POTENTIAL DNAPL OCCURRENCE BASED ON TCE CONCENTRATIONS. (600-FT DIAMETER AROUND WELL MP-03)

NOTE:

WELL SPACINGS OF 20 FEET ON-CENTER ASSUMED FOR FRACTURED BEDROCK REMEDIATION.

DEFINITIONS:

ISCO: IN-SITU CHEMICAL OXIDATION
ZVI: ZERO-VALENT IRON CHEMICAL REDUCTION
ISB: IN-SITU BIOREMEDIATION

TITLE: **CONCEPTUAL GRID OF REQUIRED TREATMENT WELLS FOR ISCO, ZVI, OR ENHANCED ISB**

LOCATION: MOTOROLA / FREESCALE OU1

GeoTrans, Inc.

CHECKED	JR	FIGURE:
DRAFTED	CKG	5.3
FILE	3908.001	
DATE	12/07/05	

Historical Bedrock / DNAPL Investigations

- Clear Creek Assoc. Bedrock Pilot Study reports:
  - Bedrock Well Installation Letter report. 2009
  - Bedrock Pilot Preliminary Findings Report. 2010
  - Bedrock Pilot Operations Report. 2011
- Installation of dedicated bedrock extraction well and two adjacent monitoring wells
  - Standard geophysics (caliper, resistance, gamma)
  - Special geophysics (temperature, fluid resistivity, acoustic televiewer, optical televiewer) to identify potential fractures

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Historical Bedrock / DNAPL Investigations

- Clear Creek Assoc. Bedrock Pilot Study reports:
  - Heat pulse flowmeter (HPFM) testing capable of high resolution of low [0.02 gpm] flow
    - Single well testing in non-pumping and pumping conditions to identify potential fracture flows
      - No significant flow observed in wells
    - Cross-hole testing to identify interconnectivity of fractures
      - **No significant interconnectivity by fracture flow observed**
  - Step and constant rate pump tests
  - Evaluation of phased start-up of new and existing extraction wells showed varied/delayed response to extraction

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Historical Bedrock / DNAPL Evaluations

- OU1 Annual Effectiveness Reports
  - Dames & Moore (1993-1999)
  - Clear Creek Associates (2000-2014)
- Geologic Map (recent reports)
- Bedrock contour map
- Evaluation of effects of OU1 groundwater remedy on alluvium and bedrock hydraulic capture and water quality conditions
  - Comparison of 1991 Baseline to 2013 show improvement in bedrock quality downgradient of OCC but no significant change in the area between the 52nd Street facility and OCC
- Since 1994, record of DNAPL pumped from MP03-D

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Summary

- Evaluations of bedrock & DNAPL have been part of OU1 since investigations began in 1983
  - Over 12,700 feet of drilling in bedrock in OU1 area (including collecting 4,300 feet of rock core)
  - Extent of contamination generally defined
- Annual Effectiveness Reports report on:
  - Bedrock water quality and concentration trends
  - Contaminant mass removal
    - 23,655 pounds overall including 279 pounds as DNAPL from MP03-D
- Additional bedrock extraction well added on-site in 2009 to enhance bedrock hydraulic capture and mass removal
- New wells installed in 2013 provided additional detail on northern extent of bedrock ridge

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Next Steps

- Remedial Investigation Work Plan (late 2014 to early 2015)
  - Identify and address data gaps that need to be addressed to complete a Final Remedial Investigation in OU1
- Final Remedial Investigation (2015-2016)
  - Updated hydrogeologic understanding of OU1
  - Define nature and extent of contamination (alluvium and bedrock)
  - Human exposure conceptual model
  - Updated Baseline Human Health Risk Assessment
- Conduct Final Feasibility Study
  - **Identify and preliminary screening of alternatives (technologies / approaches)**
  - Identify any data gaps for completing Feasibility Study (e.g. bench scale testing)
  - Identify remedial objectives and Applicable or Relevant and Appropriate Requirements (ARARs)
  - Conduct detailed evaluation of selected alternatives
  - Complete comparative analysis and identify preferred remedy

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