Field Studies of Chlorinated Solvent Plume Behaviour in Sedimentary Rock: From Source to Discharge Zones

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• Many research associates, technicians and students:
  – Chapman, Pierce, Meyer, Pehme, Quinn, Munn and others

• Site owners, consultants and regulators
Nature of Contamination in Fractured Sedimentary Rock

Source Zone

Plume Zone

vadose zone

groundwater zone

Plume Front
This Talk Shows…

• An example of an intensive field study of chlorinated solvent contamination in fractured Cretaceous sandstone

• Strong plume retardation and attenuation due to matrix diffusion
Bedrock Groundwater Research
Started in 1996
Santa Susana Field Laboratory:
2800-acre industrial facility located
~50 km northwest of Los Angeles
Upland Site Between Communities

- Simi Valley
- Runkle Canyon
- SSFL
- Black Canyon
- Bell Canyon
- Chatsworth
- West Hills
Uplifted Late Cretaceous Turbidite Sandstone
Deep Marine Turbidite Deposit: Interbedded Sandstone and Shale

Bedding Plane Fracture

Vertical Fractures (Joints)
Nature of the Problem

At first glance the site is complex:

- Fractures
- Faults
- Dipping beds
- Numerous contaminant input areas
- DNAPL

Value of site conceptual model approach
High water table and groundwater flow in fractures
Why does the SSFL groundwater level stay high above the surrounding valleys?

The water table stands ~1000 ft above the valleys.
Groundwater mound forms a long ridge of constant cross section.

\[ K_b = \frac{R \cdot L^2}{h^2} \]

- \( K_b \) = bulk hydraulic conductivity
- \( R \) = recharge rate
- \( L \) = width of mound
- \( h \) = height of mound at center

\[ K \sim 10^{-5} \text{ cm/s} \]
Dual Permeability System

Matrix Porosity: 2-20%

Fracture Porosity: 0.01 to 0.001%

Microscopic view of rock matrix

DETAIL A

mineral particle
Fast Average Linear Groundwater Velocity in Fractured Rock

\[ \bar{\nu}_f = \frac{K_b i}{\phi_f} \]

\( \bar{\nu}_f \) represents line path from A to B
Virtually all groundwater is present in the low permeability matrix.

Matrix porosity $\sim 13\%$

Matrix permeability $\sim 10^{-6}$ to $10^{-11}$ cm/s
Approximately 50% of Recharge Discharges at Seeps

S = Discharge to seeps and phreatophytes

R = S + D

D = Deep flow discharges beyond mountain
Two Primary Functions at SSFL

Rocket Engine Testing for NASA
• 1949-2006
• Six Test Stands – 17,000 Rocket Engine & Component Tests
• Last test March 3, 2006

Nuclear Research & Liquid Metal Research for DOE
• Nuclear Power Research: 1956-1983
• Ten reactors
• Sodium component test facilities
• DOE Program ends 1988
How Did Contaminants Get Into SSFL Groundwater?

**DNAPL Infiltration**
- Trichloroethene
- Perchloroethene
- Trichloroethane

**Leaching of Solids**
- Perchlorate (ClO$_4^-$)
- Metals

**Water Infiltration**
- Nitrate
- Chloride
- Tritium
- Dissolved Solvents

Plume

Septic System

Retention Pond
Residents Criticize Pollution Study

Residents file a class-action suit against the parent company of Rocketdyne in Los Angeles County Superior Court, claiming that the company's emissions have caused health and environmental problems.

Rocketdyne Field Lab Neighbors Sue Boeing

An attorney representing a group of neighbors filed a class-action lawsuit against Boeing, alleging that the company's emissions from its Los Angeles facility have caused health and environmental problems.

County

SSFL in Public Eye

The SSFL is facing public pressure to address environmental concerns. A group of residents has filed a class-action lawsuit against Boeing, alleging that the company's emissions from its Los Angeles facility have caused health and environmental problems.

EPA: Rocketdyne cleanup OK'd

The EPA has approved a cleanup plan for the SSFL, which is facing public pressure to address environmental concerns. The plan includes the installation of air pollution control systems and the removal of hazardous materials from the site.

State Begins Study of Field Lab's Toxic Path

A state study is being conducted to assess the environmental impact of the SSFL. The study will evaluate the potential risks to public health and the environment posed by the site.

Opinion

Rocketdyne\'s gas turbine engines are controversial, and the company is facing public pressure to address environmental concerns. The future of the SSFL is uncertain, and the state is conducting a study to assess the potential risks to public health and the environment.

As a result of the ongoing controversy, the SSFL is facing public pressure to address environmental concerns. The state is conducting a study to assess the potential risks to public health and the environment, and the future of the SSFL is uncertain.
Surficial Media Contaminated Areas

Areas recommended for corrective measures study based on suburban residential land use
Groundwater Monitoring Network

428 wells used to define extent of groundwater contamination
Much TCE DNAPL Went into the Ground – What Happened to it?

CH2M Hill Estimate (1993) ~ 500,000 gallons

Rocket Engine Tests at Stands 1954 - 1983

Number of Tests

Year


0 500 1000 1500 2000 2500 3000 3500

135 614 662 732 533 801 354 64 67 56 99 78 120 614 67 56 99 78 120 64 41 58 62 88 76 39 13 15 30 73 49
Nature of Contamination in Fractured Sedimentary Rock

- Source Zone
- Vadose Zone
- Groundwater Zone
- Plume Zone
- Plume Front
TCE is Most Mobile Contaminant Due to DNAPL

Water  Tritium  Dissolved Perchlorate  Dissolved TCE  TCE DNAPL

Plug Flow Position  Detection Limits (MCL)  DNAPL
Rock Core Sampling to Find Contaminants

Fractures core samples analyzed:
- Fractures with Diffusion halos
- non-detect
Rock Core Drilling at C-2, Canyon Test Stand
Rock Porewater TCE Profile

RD-35B

Rock Porewater TCE (mg/L)

Below detection limit

TCE Solubility

Depth (m)

R=3.3
\( \phi = 13\% \)

S. Sterling et al., Groundwater 2005
Total of 20 Coreholes at 18 Locations
TCE Concentrations Decline with Depth

> 7,000 Rock Core Samples in 20 Core Holes
Source Zone / Plume Evolution Conceptual Model

Early Time
- DNAPL reaches stationary phase in fractures

Intermediate Time
- Much DNAPL disappeared, diffusion into matrix in source and plume zones

Late Time
- No DNAPL remains and most mass occurs in the matrix, diffusion and other processes cause strong plume attenuation
Key Issues:
How many active fractures?
What is their Interconnectivity?

Dense Network

Sparse Network
Interplay Between Matrix and Fractures Controls Plume Behavior

Same bulk K but dissimilar plumes
Focused Look at Northeast Plume

- Tritium
- TCE
- Perchlorate
Groundwater Flow Direction

Source Zone Transect
Total Equivalent Porewater Concentration along Source Zone Transect

Concentration averaged over 20 ft intervals (µg/L Porewater)

*Ordinary kriging with anisotropy ratio = 5, anisotropy angle = 20 degrees*
Northeast Plume Longsect

Source Transect

Plume Longsect

Groundwater Flow Direction

Plume Transect

Site Boundary

Legend

- Faults
- Deep Cored
- Shallow Cored
- Monitoring Wells
- Site Polyline

SSFL Rock Core VOC NE Plume Coreholes

Groundwater Flow Direction

A

B

C
TCE Migration @ 60 yr since initial releases

(estimated porewater concentrations from rock core VOC subsampling averaged over 6 m intervals)
Concentrations Decline Rapidly with Distance from Source

Maximum Equivalent TCE along Longsect

Semi-Log Plot
Plume concentrations decline rapidly with distance in the direction of groundwater flow.
General Modeling Approaches for Fractured Rock

Spatial Representation

Equivalent Porous Media (EPM)
(averaged fracture and matrix properties)

Dual Porosity (DP)
(coupled mobile and immobile zones; exchange terms)

Discrete Fracture Network (DFN)
(distinct fracture and matrix entities; rigorous simulation of interactions)

Complex Rock Mass
Commercially Available DFN Models

FRAC3DVS
FRAC3DVS is a 3D finite element model for steady-state/transient, variably-saturated flow and advective-dispersive solute transport in porous or discretely-fractured porous media.

FRACTRAN
FRACTRAN is a 2D finite element model for simulating steady-state groundwater flow and time-variant contaminant transport in discretely-fractured, fully-saturated porous media.

FracMan
FracMan® is the premier software for analysis and modeling of heterogeneous and fractured rock masses.

HydroGeoSphere
HydroGeoSphere is a Three-dimensional Numerical Model Describing Fully-integrated Subsurface and Surface Flow and Solute Transport.

Waterloo Hydrogeologic, Inc.

FEFLOW
Advanced 3D Finite Element Groundwater Flow, Heat & Contaminant Transport Modeling!

WASY
Simulate Plume Using DFN Numerical Model
Discrete Fracture Network (DFN) Approach
Characterization of Contaminated Bedrock

Initial Site
Conceptual Model

Drill Corehole in and Near Contaminated Area

ROCK MATRIX
Use rock samples from continuous rock core for property measurements:
• Contaminants
• Physical
• Chemical
• Microbial

BOREHOLE
Use the borehole to acquire hydraulic data and water samples

Conceptual and mathematical modeling

Prepared by B.L. Parker
Discrete Fracture Network (DFN) Approach

Use of Rock Core

Drill in or near Contaminated Areas

Use of Drill Holes

Measurements during drilling

Measurements in completed hole

Field Geologic Core Examination

Open Hole (minimize)

Lined Hole (maximize)

Short Term

Laboratory Measurements

Core physical, mineralogical, and microbial measurements

Degradation microcosms

GW Sampling

Geophysics

Packer Testing

Flow Metering

Temperature

Analysis: fracture frequency, apertures, porosity

Long Term

Lined Hole (maximize)

Design Multilevel Systems

Vertical Profiles: Hydraulic Head, K, Flux, Chemistry

Prepared by B.L. Parker

Laboratory Measurements

Core Contaminant Analyses

Partitioning calculations for phase and mass distribution

Modeling

Static Modeling (spatial distribution)

Dynamic modeling (flow, transport, reaction)

Design network for long-term site monitoring

Assess transport, fate, and impacts to receptors
Overview of DFN Methods

- Rock Core Chemical Analyses
- Improved Borehole Geophysics
- Impermeable Flexible Liner (FLUTE™)
- High Resolution Temperature Logging
- Improved Hydraulic Tests Using Straddle Packers
- High Resolution Multilevel Monitoring Systems

Multiple Methods Applied in Boreholes
Site - Derived Parameters

- **\( f_{oc} \)**
  - Box = 50% of data
  - Bar = geometric mean
  - Diamond = median
  - Whiskers = 10th & 90th percentiles
  - X = minimum and maximum
  - (N) = number of samples

- **\( \phi_m \)**
  - Gravimetric method mean (no. of samples)
  - ±Gravimetric method standard deviation
  - Gravimetric method minimum & maximum
  - Thin-section method mean (no. of samples)
  - Total No. of Measurements 230

- **\( K_m \)**
  - Boxes = 50% of data
  - Bars = geometric mean
  - Diamonds = median
  - Whiskers = 10th & 90th percentiles
  - X = minima and maxima
  - (N) = number of samples

- **\( K_b \)**
  - Boxes = 50% of data
  - Bars = geometric mean
  - Diamonds = median
  - Whiskers = 10th & 90th percentiles
  - X = minima and maxima
  - (N) = number of measurements

Source: Hurley et al., 2009
FRACTRAN Domain: Vertical Cross-Section
Tailored to Conditions along Plume Longsect

Fracture Statistics

<table>
<thead>
<tr>
<th></th>
<th>Horizontal</th>
<th>Vertical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean aperture (microns)</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Length range (m)</td>
<td>20 - 100</td>
<td>5 - 20</td>
</tr>
<tr>
<td>Fracture density (fracs/m²)</td>
<td>0.007</td>
<td>0.010</td>
</tr>
<tr>
<td>Average fracture spacing (m)</td>
<td>~3</td>
<td>~10</td>
</tr>
</tbody>
</table>

$\phi_f = 5 \times 10^{-5}$

Darcy Flux Constraint
Simulated Hydraulic Head Distribution

Hypothetical Borehole
X=500m

Average Hydraulic Gradients:

1%  1.5% ↓

Average GW Velocity in Fracture Network:

\[ v_f = \frac{K_b}{\phi_f} i \sim 2500 \text{ m/yr} \]
Point concentrations extracted at 50 m intervals along flowpath, averaged vertically over 5 m intervals and resulting dataset kriged.
Comparison of FRACTRAN versus Field Results along Plume Longsect

Field Plume Longsect (averaged)

FRACTRAN @ 60 yr (averaged)

Field and model show similar bulk plume style and extent
Simulated Northeast Plume

No degradation included

Plumes are nearly stable after 50 years
FRACTRAN results suggest plume front nearly stationary (physical processes only)

FRACTRAN Simulated Plume Front Velocity

Plume Front Assumed at $C/C_0 = 10^{-4}$

Nearly stable plume (without degradation)
Well-Interconnected Fractures

TCE Degradation

20 year DNAPL Source
No Degradation
50 years

20 year DNAPL Source
Degradation (5 yr half life)
50 years
Mountain Scale 3-D FEFLOW EPM Model

- 8 km x 8 km domain
- 250,000 elements per layer
- 46 layers
- 11.5M elements total
- average element area ~ 256 m²
- average layer thickness ~10 m

Site Macro-Complexity
- major hydrogeologic units
- faults, dipping beds
- hydraulic head
- water balance
Forward Particle Tracks in Bedrock

FEFLOW 3D Groundwater Flow Model

1000 m particle tracks under non-pumping conditions
Have plumes migrated to off-site receptors?
Study of Groundwater Discharging at Seeps along Mountain Bedrock Slopes: Searching for Contaminant Plumes

Beth Parker, Amanda Pierce, John Cherry, and Robert Ingleton
Seep

- Transpiration
- Evaporation
- Phreatophytes
- Water Table
Most seeps are located in ephemeral hill streams and/or drainages.
Seeps
154 seeps identified by ground reconnaissance on mountain slopes surrounding site
Purpose of Seeps Investigation

- Search for contaminants discharging along mountain slopes
- Understand groundwater flow system
Seeps are Potential Receptors for Contaminants

Contaminant Plume

Groundwater Flow

Seep

Seep

Seep
Seeps water can be a mixture from different groundwater travel paths.
Approach: Use Portable Drills to Instrument Seeps With Monitoring Wells
Approach

• Advance coreholes to depths ranging from 5 to 60 ft using portable drilling equipment.
  – Shaw Portable Core Drill
  – Winkie Drill

• Installation of small diameter wells for:
  – water level measurements
  – sampling
Terrain Enroute to Seeps
Shaw Portable Core Drill
www.backpackdrill.com

Depths: 20 to 40 ft
Corehole Diameters: 1.65 or 2.00-inches
Run Length: 1.5 to 2 ft

Neil Shaw
Inventor of the Shaw Drill

Shallowest Drilling
Fred Wink (1914-2007)
Inventor of the Winkie Drill

Winkie Drill
www.minex-intl.com (sole manufacturer)

Depths: 50 to 75 ft
Corehole Diameter: 1.87”
Run Length: 5 ft
Winkie Drill Field Set-up

- Pump supplies water to drill
- Battery-powered winch
- Waste water containers
- 12 V Battery
- Tripod used to remove rods
- Contained Fuel
- Pond Liner used to catch all drilling fluids
Maximum Depths Drilled at SSFL

• Shaw Core Drill
  – Maximum depth drilled: 37 ft

• Winkie Drill
  – Maximum depth drilled: 54 ft
Monitoring Well Design

- One well screen at the bottom of each corehole
- Hole fully sealed above well intake
- No grout escapes into fractures
- No sand pack around well “screen”
Need for the ‘Grout Liner’

**No Liner**

Injected grout pushes outward into formation along fractures potentially disrupting local flow system.

**With Liner**

Grout is contained and more natural flow conditions maintained.
Grout liner is custom constructed using nylon material.
Completed Cluster in Drainage

SP-25A
Depth: 13 ft

SP-25B
Depth: 18 ft

SP-25C
Depth: 28 ft

SP-25D
Depth: 37 ft
3 Seep Clusters Installed in 2011 at Contaminated Seeps
Seep Well Cluster: SP-890

G
D
A
B

brown, fine to coarse, sandstone
dark grey, fine to medium, banded sandstone
grey, fine to coarse, sandstone

Elevation (ft amsl)

1630
1620
1610
1600
1590
1580
1570

20 ft

1630
1625
1630

A
G
C
D
A
B

A'
Results of Groundwater Sampling
SP-890 Cluster

Groundwater Sampling Dates

SP-890C → July 5, 2011
SP-890D → July 5, 2011
SP-890G → September 12, 2011

FDP-890
TCE: 200 µg/L
cDCE: 440 µg/L
tDCE: 18 µg/L
VC: 1.0 µg/L

Groundwater Release Dates

SP-890 Cluster

TCE: 920 µg/L
cDCE: 350 µg/L
tDCE: 12 µg/L

TCE: 770 µg/L
cDCE: 320 µg/L
tDCE: 11 µg/L

TCE: 1400 µg/L
cDCE: 740 µg/L
tDCE: 22 µg/L
VC: 4.3 J µg/L
Cross Section Across Fault Zone through Production Well, Seeps, and Cluster Wells

- TCE
- cis-DCE
- trans-DCE
- Vinyl Chloride
- Values in ug/l.

RS-13 & WS-9A screened below approx. 17 & 20 ft bgs, respectively.
WS-9A minimum water levels occurred 1990-91 at approx. 1,300 ft msl.

Concentrations higher at depth.

Burro Flats Fault Zone

Cluster wells SP-890, SP-881, & SP-882 screened approx. 1 foot at bottom.
Sampled July & September 2011.

Seeps sampled 2006-09.

Vertical Exaggeration = x3
Annual rainfall 18.6 inches

Water table near mountain top

About half of the groundwater originating on the SSFL discharges along slopes at seeps and phreatophytes, and no contaminants found offsite.

Perched groundwater occurs locally, flows into deeper groundwater

Santa Susana Field Laboratory
Located on top of a sandstone mountain (2850 acres)

Annual Recharge ~ 60 to 200 gpm

Shallow perchlorate and tritium plumes

Sandstone has low matrix K and low to moderate bulk hydraulic conductivity

TCE is Deepest: no DNAPL remains now

Contaminants degrade or decay

Fresh water – ocean salt flushed away over millions of years

Nearly immobile brackish water – relic ocean salt

Shale zones generally lower bulk K

Fault

Schematic cross section with vertical exaggeration (Not-To-Scale)
Prepared by SSFL Groundwater Panel December 2009
Summary of Key Findings

• Diffusion of contaminants readily occurs in sandstone and shale and is a very important process at SSFL.

• Nearly all the contaminant mass is in the low permeability rock matrix.

• Most of the contamination is found close to where it went into the ground.

• Groundwater plumes are now stable and plume fronts are nearly stationary.

• Contamination has not been found at offsite seeps consistent with lack of atmospheric tritium.
Thank You

Questions?
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