Atlas 12 - Fracture-Emplacement and 3D Mapping of a Micro-Iron/Carbon Amendment in TCE-Impacted Sedimentary Bedrock

Presented by:
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About TOTERRA Remediation

- Environmental service contractor focused on advanced *in situ* remediation and landfill gas recovery enhancement
- TOTERRA has been remediating sites since 1995
- Offices in Buffalo, Dallas, Toronto, Calgary, Edmonton, and Berlin, Germany
- International scope - with a broad portfolio of successful projects around the world
- SAFETY is our first value; TRIR of 0.0 since inception
Outline

- Background:
  - What is Environmental (Hydraulic) Fracturing and what are its applications?

- Environmental Fractures Exposed (Visuals)

- Applying Environmental Fracturing
  - When does it make sense?

- Atlas 12 Case Study
  - Fracture Emplacement and 3D Mapping of a Micro-Iron-Carbon Amendment in Bedrock
What is Hydraulic Fracturing?

Petroleum Industry Definition:
Process of transmitting pressure by fluid to create cracks, or to open existing cracks in hydrocarbon bearing rocks, thousands of feet below the ground surface.
Environmental

Why Do It? To facilitate the in-place treatment or extraction of subsurface contaminants
Visualizing Hydraulic Fracturing
Evolution of Environmental Fracturing

In Canada - adapted and modified from research into fracturing of oil sands (Global Engineering Consultancy) in late 1980s

In the U.S.A. - from research into environmental applications for hydraulic fracturing at University of Cincinnati and New Jersey Institute of Technology in late 1980s - studies sponsored by US EPA

Commercial environmental fracturing services for in situ remediation of contaminated industrial, commercial, retail, Federal, and brownfield sites available since 1993.
# Environmental Fracturing - Hydraulic vs. Pneumatic

<table>
<thead>
<tr>
<th>CONSIDERATIONS</th>
<th>FRACTURING METHOD</th>
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<tbody>
<tr>
<td></td>
<td>HYDRAULIC</td>
<td>PNEUMATIC</td>
</tr>
<tr>
<td>“Leak Off”</td>
<td>• Low</td>
<td>• High</td>
</tr>
<tr>
<td>Fracture Tendency</td>
<td>• Creates new fractures</td>
<td>• Propagate along existing patterns</td>
</tr>
<tr>
<td>Lithology</td>
<td>• Silts, clays &amp; bedrock (including swelling clays)</td>
<td>• Suited to self-propping bedrock</td>
</tr>
<tr>
<td>Solid Amendment Delivery Capacity</td>
<td>• High</td>
<td>• Low</td>
</tr>
<tr>
<td>Target Depth &amp; Spacing</td>
<td>• Typically applied between 2-100 m bgs</td>
<td>• Typically applied between 3-25 m bgs (without proppant)</td>
</tr>
<tr>
<td></td>
<td>• Can space 12” apart</td>
<td></td>
</tr>
<tr>
<td>Other</td>
<td>• 3D mapping available</td>
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Environmental (Hydraulic) Fracture Fluid

Environmental Fracture Fluid: Potable water and biodegradable polysaccharide (i.e. sugar based) guar polymer (non toxic)
Environmental Fractures Exposed

Sand-filled permeable treatment pathway in clay
Environmental Fractures Exposed

Brown-coloured oxidation front

Horizontal permeable treatment pathways in low permeability soils
Environmental Fractures Exposed

Narrowly spaced permeable treatment pathways in low permeability soils
Environmental Fractures Exposed

Upon injection into (or co-emplacement with) the permeable treatment network, amendments radiate out from the pathway, creating a zone of influence many times the thickness of the pathway.
Determining When to Apply Envirofracking

Key Considerations:

1. Contact area & lithology, which drive:
   - Efficiency of extraction/delivery
   - Whether the amendment can pass through the pore throat

2. Site surface conditions
   - Presence of infrastructure
   - Potential for disruption of surface operations
Efficiency: Fracture Emplacement vs. Direct Push

Hydraulic Fracturing provides a relatively large horizontal distribution

Direct Push Injections provide a relatively small horizontal distribution
Injection only works if the amendment can pass through the mean pore throat diameter of a soil, i.e. when:

Amendment Particle size:

$$Ps < \sqrt{\frac{K}{7}}$$

Ps in microns and K in md (Harris and Odom, 1982)

Otherwise, you are fracturing!!!
When to Apply Envirofracking

<table>
<thead>
<tr>
<th>COMMON IN SITU TREATMENT AMENDMENTS</th>
<th>MODE OF AMENDMENT EMLACEMENT INTO SUBSOILS AND BEDROCK</th>
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<tbody>
<tr>
<td></td>
<td>&lt;10^-2 m/s</td>
</tr>
<tr>
<td></td>
<td>GRAVEL: coarse</td>
</tr>
<tr>
<td>FRAC SAND (20-40)</td>
<td>INJ</td>
</tr>
<tr>
<td>ZERO VALENT IRON</td>
<td>INJ</td>
</tr>
<tr>
<td>MICRO IRON</td>
<td>INJ</td>
</tr>
<tr>
<td>PEROXYGEN/PERMANGANATE SLURRIES</td>
<td>INJ</td>
</tr>
<tr>
<td>SOLUTION OXIDANTS</td>
<td>INJ</td>
</tr>
<tr>
<td>SOLUTION BIO-AMENDMENTS</td>
<td>INJ</td>
</tr>
<tr>
<td>LACTATES, MOLASSES, VEGETABLE OIL EMULSIONS</td>
<td>INJ</td>
</tr>
<tr>
<td>CELLULOSE, CHITIN</td>
<td>INJ</td>
</tr>
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Note:
- INJ: Permeation Injection is the primary mode of amendment emplacement
- FRAC: Fracturing is the primary mode of amendment emplacement
ATLAS 12 CASE STUDY:
ZVI-Carbon Emplacement for Remediation of TCE in Bedrock

- Former USAF “Atlas 12” Missile Site, Colorado
- Operational disposals of TCE (1960-1965) resulted in impacts in underlying sandstone aquifer to 60 ft. depth
- Widespread TCE concentrations in groundwater upwards to 4,000 ug/L
TCE Dechlorination Pathways

- EHC-G consists of a complex carbon amendment “Daramend” and zero valent iron (ZVI)
  - *Carbon amendment* facilitates Anaerobic Reductive Dechlorination (ARD) Pathways
  - *ZVI* facilitates Chemical Dechlorination Pathways

**ARD Pathways**

**Chemical Dechlorination Pathways**

- ZVI particles provide reactive surface areas that stimulate direct chemical dechlorination of TCE

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Modified from Wiedemeier et al., 1996
Groundwater Monitoring Parameters

**ARD Parameters**
- TOC (total organic carbon)
- Redox Parameters
- TCE and degradation products
- Microbial (*Dehalococcoides* spp.)

**Chemical Dechlorination Parameters**
- TCE
- Ethene

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*β-Elimination Pathway*

*Hydrogenolysis Pathway*
Atlas 12 Pilot Test
ZVI Distribution

Source Area:
- 7 Fracture Boreholes

Dissolved Phase
Plume:
- 2 Fracture Boreholes

EHC-G Emplacement:
- April 20 to May 19

Legend
- Monitoring Well Fox Hill Sandstone
- Pilot Test Fracture Borehole/Monitoring Well
- Fox Hill Sandstone
- Buildings
- Fence
- Former Retention Pond

Mass of EHC-G per Borehole; Number of Fracture Depths

- 5,700 lbs; 4 depths
- 8,200 lbs; 4 depths
- 24,000 lbs; 4 depths
- 24,000 lbs; 4 depths
- 32,000 lbs; 5 depths
- 32,000 lbs; 5 depths
- 32,000 lbs; 6 depths
- 24,000 lbs; 6 depths
Fracture Mapping using Tiltmeter Geophysics

Tiltmeters are ground surface sensors that detect tilt angle and tilt direction in response to a fracturing or injection event in the subsurface.
Mapping of ZVI-Filled Fractures

Conducted for 7 boreholes in source area
Mapping of ZVI-Filled Fractures

From MW-22 looking west

North-South extent of continuous ZVI/C coverage is approximately 450 ft, effectively comprising a treatment barrier
TCE Treatment Performance after 21 Months

Source Area:
- Starting TCE levels: >2000 to 4,000 ug/L
- After 12 months: <400 ug/L (5 of 7 wells)
- After 21 months: <100 ug/L, generally

Dissolved Plume Area:
- Starting TCE levels: 500 to 700 ug/L
- After 21 months: 200 to 400 ug/L
21 Month Performance Evaluation

- 94% of Source Area below RMC of 100 ppb TCE
- 82% of Dissolved Plume Area below TCE RMCs
- Phase 2 delivery of another 40 tons ZVI completed in August 2011; TCE is ND to 100 ug/L
- Treatment cost equivalent: $8 per ton

(Journal of Remediation, Spring, 2012).
Thank You

Please come see us at Booth 20

TOTERRAREMEDIATION.COM
Additional Background Slides
What Controls Fracturing?

Mother Nature!!

She governs in situ stress conditions:

Ko and OCR

Fractures align perpendicular to the least principal stress, they cannot be "steered"
| $K_0$  
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<tbody>
<tr>
<td>$(\sigma_h/\sigma_v)$</td>
<td>Massive</td>
<td>Layered</td>
<td></td>
</tr>
<tr>
<td>$\leq 1$ (NC)</td>
<td>Vertical</td>
<td>Horizontal or Vertical</td>
<td></td>
</tr>
<tr>
<td>$&gt; 1$ (OC)</td>
<td>Horizontal or Vertical</td>
<td>Horizontal</td>
<td></td>
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Over consolidated soils, including glacial tills common in this geography, are very conducive to horizontal propagation of permeable treatment networks/discs.
## Comparison: Environmental Footprint

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Environmental</th>
<th>Oil and Gas</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of wells fractured</td>
<td>2,000 – 3,000</td>
<td>&gt; 2 million (M.J. Economides)</td>
</tr>
<tr>
<td>Drilling Depth</td>
<td>&lt; 100 m (vertical)</td>
<td>1,200 to 3,500 m (vertical) in AB up to 2,500 m (horizontal) in AB</td>
</tr>
<tr>
<td>Frac Volume (water)</td>
<td>0.5 to 10 m³ per frac; 3 to 50 m³ per well</td>
<td>100 to 3,600 m³ per frac; 10,000 to 70,000 m³ per well</td>
</tr>
<tr>
<td>Fracs per Well</td>
<td>5 to 10</td>
<td>30 to 50 per HDMSF well</td>
</tr>
<tr>
<td>Frac Dimensions</td>
<td>3 to 30 m (horizontal)</td>
<td>20 to 300 m in height (vertical)</td>
</tr>
<tr>
<td>Areal Footprint</td>
<td>Typically &lt; 1,000 m² No site preparation required</td>
<td>Acres to hectares; clearing and pad construction req’d</td>
</tr>
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## Potential Environmental Impacts

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<tr>
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<th>Oil and Gas</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frac Chemicals</td>
<td>Food grade chemicals (GRAS rated) biodegradable polysaccharides and surfactants. Passes microtox.</td>
<td>Industrial or saline quality water; Often hydrocarbon based; Additives may include biocides (toxic)</td>
</tr>
<tr>
<td>Creation of Contaminant Pathways to Aquifers</td>
<td>Fractures are created in already contaminated sediments to act as pathways for injecting treatment amendments to remediate contamination in soil and GW</td>
<td>Indirectly through poorly completed boreholes and poorly cemented well casings, or intersection of fracs with operational wells.</td>
</tr>
<tr>
<td>Water use</td>
<td>Potable water quality, minor volumes</td>
<td>Potentially large demand on local water sources</td>
</tr>
<tr>
<td>Frac Blowback</td>
<td>Minor, usually less than 5%, recycle</td>
<td>Can be significant – 25% to 40% Containerize, recycle or deep well inject</td>
</tr>
<tr>
<td>Ground Disturbance</td>
<td>Shallow fracturing can cause localized ground surface displacement (mms to cms)</td>
<td>Have been observed to cause Earth Tremors in some instances (magnitude 2.3 to 3.4, NE British Columbia)</td>
</tr>
</tbody>
</table>
Chemical Composition:

Water based Fracs, Oil and Gas

Many fracs in oil and gas based on other fluids: diesel, propane, CO2, liquid N, saline water, foam, etc.

Modified from: ALL Consulting, based on data from a fracture operation in the Fayetteville Shale, 2008
## Regulatory Perspective

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<th>Oil and Gas</th>
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<tr>
<td>Frac Chemicals</td>
<td>Food grade chemicals (GRAS rated) scrutinized by provincial, state, and water board environmental authorities – e.g. used for remediation in California aquifers.</td>
<td>Disclosure has not been provided in past due to propriety of fluid formulations; call for transparency has resulted in industry deciding on voluntary disclosure</td>
</tr>
<tr>
<td>Groundwater Protection</td>
<td>Fracturing confined to delineated areas of contamination in aquicludes, aquitards, and aquifers to remediate carcinogenic compounds in GW</td>
<td>3 U.S. EPA studies since 2004; ERCB Directive 27 for fracture offsets with respect to shallow gas fracturing; Fracfocus – U.S. and Canada</td>
</tr>
<tr>
<td>Moratoriums on Fracturing</td>
<td>None in place – fracturing has resulted in remediation of 100’s of contaminated sites in North America; U.S. EPA has acknowledged fracturing for environmental remediation applications since 2001; European countries researching environmental fracturing for remediation &amp; considering pilot projects – want to first see demonstrated success.</td>
<td>Quebec, Vermont, New York, France; other jurisdictions considering moratorium (e.g. New Brunswick, New Jersey, Germany)</td>
</tr>
</tbody>
</table>
Increasing Landfill Gas Yields for Bio-LNG Production Using Hydraulic Fracturing

- Sand fracture network is emplaced within existing landfill mass
- Gas gathers from below in the sand pathway network and flows into the drilled well. In this way a “guiding” circuit for landfill gas is created.
- With a 3 to 5 fold increase in gas production, economy of scale for bio-LNG production can be reached rapidly.
- This hydraulic fracturing method, combined with containerized upgrading and liquefaction units, offers huge potential for tens of thousands of landfills worldwide.
- The method is cost effective, especially at virgin landfills, but also at aging landfills with declining landfill gas reserves.