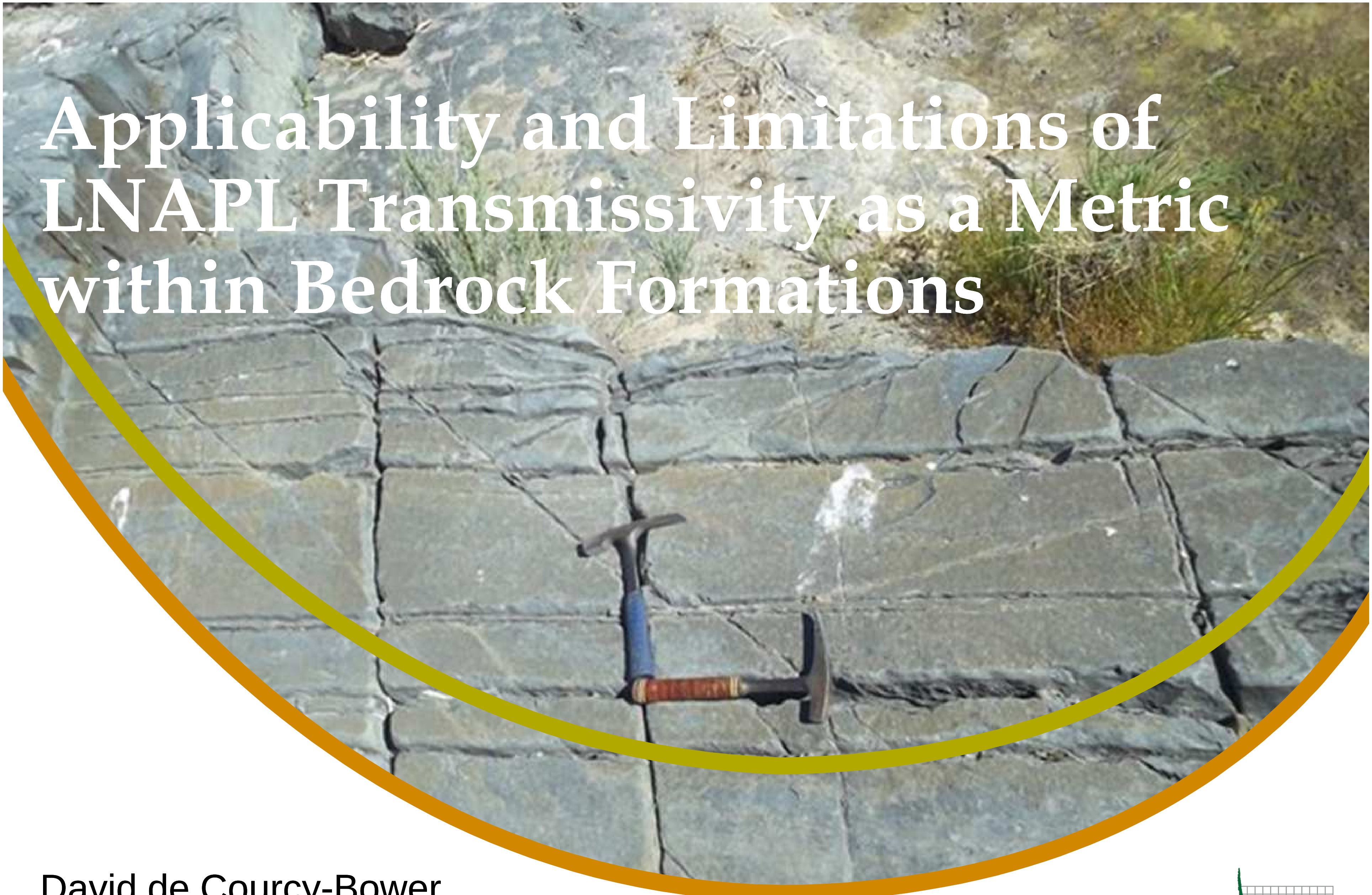
Applicability and Limitations of LNAPL Transmissivity as a Metric within Bedrock Formations



David de Courcy-Bower
and Samuel Mohr

The world's leading sustainability consultancy

Contents

- Bedrock Overview
- Transmissivity
  - Theory
- Case Studies

"Contaminant transport and fate is fundamentally different in fractured rock than in unconsolidated (sand and gravel) aquifers. Significantly more uncertainty exists as to the direction and rate of contaminant migration"

Source: USGS (2013)

Source: David de Courcy-Bower, ERM

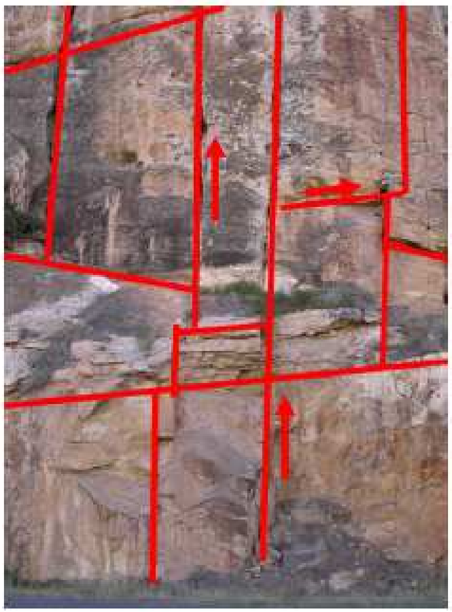
Fractured Bedrock

- Fractured bedrock is a complex anisotropic, heterogeneous environment
- All fractures are NOT created equally

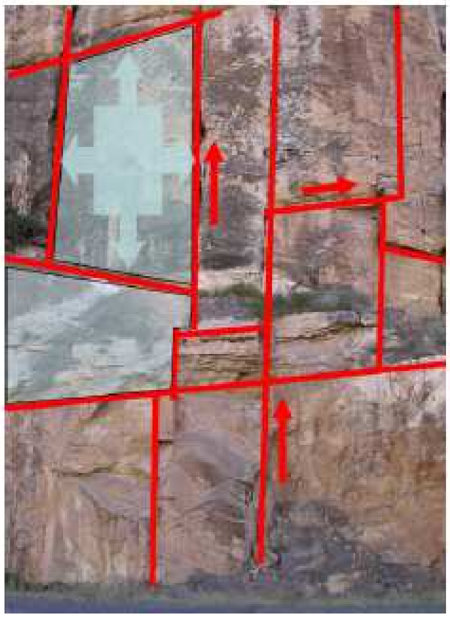
Fractures ≠ groundwater flow

- Defining hydraulically inter-connected transmissive fractures is the key to understanding LNAPL transport
- Matrix diffusion can result in dissolution of LNAPL and development of a secondary source area

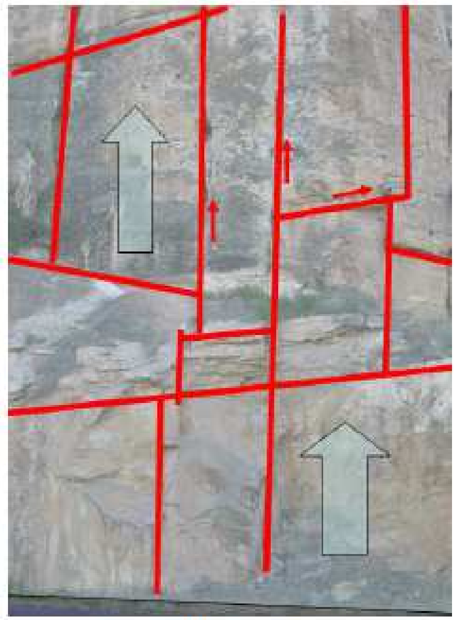
Bedrock - Fractures and Matrix



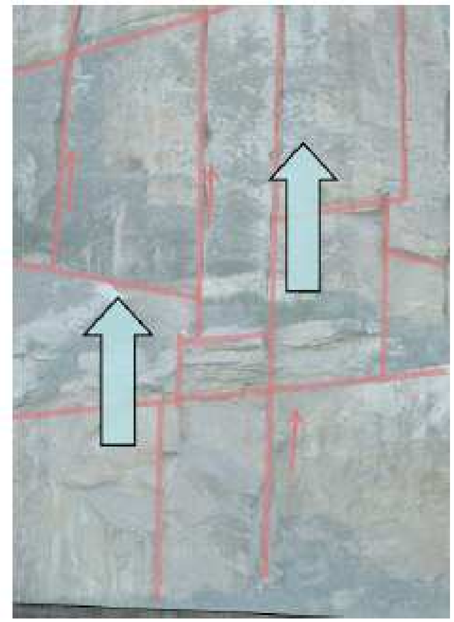
Type 1: Flow and Storage only in Fractures (Single Porosity)



Type 2: Fracture Flow Only, Matrix Storage (Dual Porosity)



Type 3: Flow in Fractures and Matrix, Storage in Matrix (Dual Permeability)

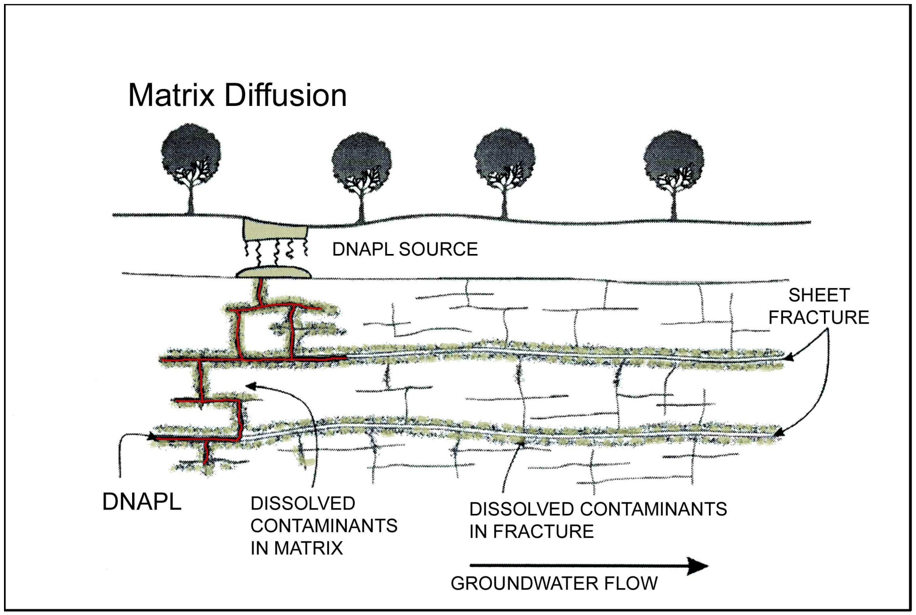


Type 4: Flow and Storage in Matrix, Fractures Assist Flow (Single Porosity)

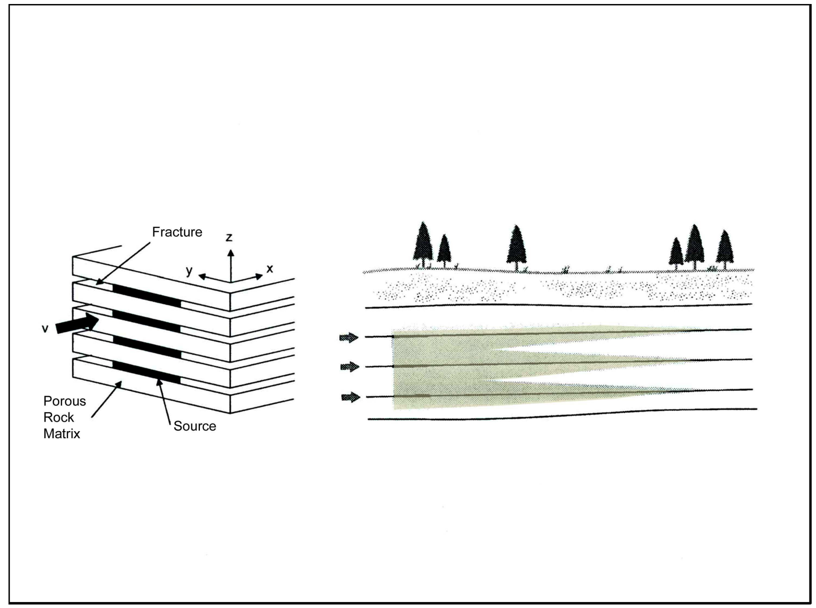
Source: Fractured Bedrock Field Methods and Analytical Tools - Science Advisory Board for British Columbia

Principles of Fractured Bedrock Hydrogeology

Moderate Primary Porosity



High Primary Porosity



Dr. Bernie Kueper, 2007

Fractured Bedrock – Investigative Methods

- Bedrock Characterization
  - Determine geological setting (geological literature review)
  - Evaluate structural fabric (lineament and/or fracture trace analysis)
  - Identify types, styles and orientation of fracturing (above methods plus core logging and/or geophysical borehole logging)
  - Define transmissive fractures (hydrophysical borehole logging, packer testing, and/or FLUTe hydraulic conductivity profiling)
  - Define hydraulic interconnectivity of transmissive fractures (hydraulic testing using pressure transducers)
  - Develop conceptual bedrock structure model

LNAPL Transmissivity in Bedrock

LNAPL Transmissivity

- **Matrix**
  - High primary permeability
  - Weathered – almost unconsolidated

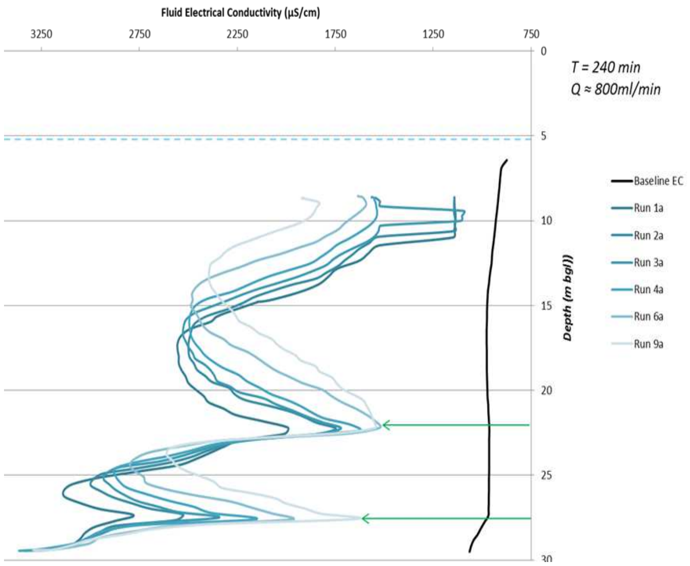
$$T_o = K_o \cdot B_o$$

- **Fracture Flow**
  - Parallel plate theory
  - Tn dominated by fracture aperture (cube)

$$T_f = (2b)^3 \frac{\rho g}{12\mu}$$

Where:
Tf = individual fracture transmissivity
2b = fracture aperture
ρ = fluid density
μ = fluid viscosity

$$\sum T_f = T_{to}$$



Source: Samuel Mohr , ERM

Idealized Fracture Flow

m^3 **kg/m^3** **m/s^2**

$$T_f = (2b)^3 \frac{\rho g}{12\mu}$$

kg/m·s

Tn for 15mm ~ 480,000 m2/day

Tn for 1.5mm ~ 480 m2/day

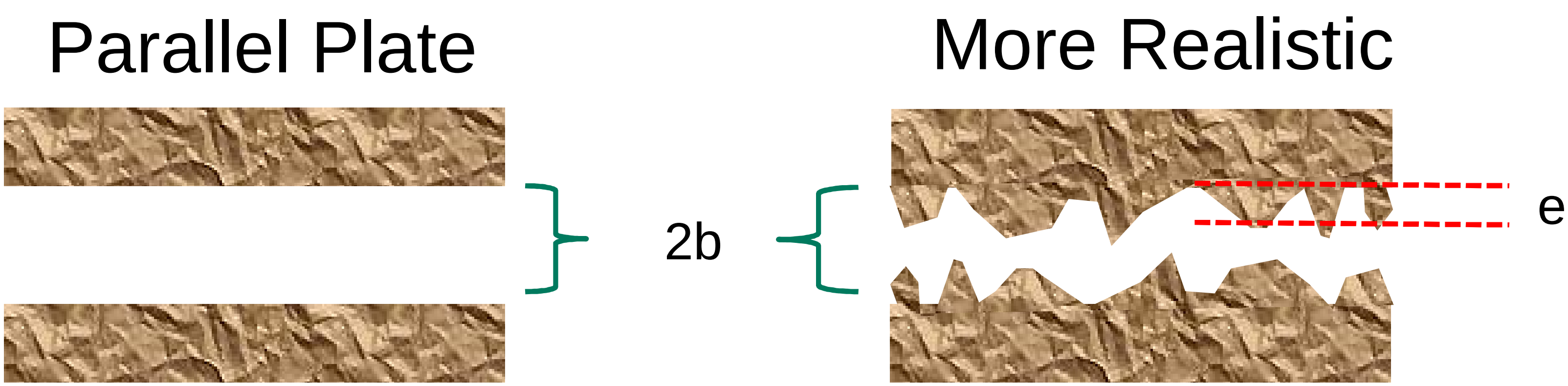
Tn for 0.15mm ~ 0.48 m2/day

Assumptions:

1) **Fracture is uniform width**
2) **Fracture plain surface is smooth**
3) **Fracture is completely filled with LNAPL**

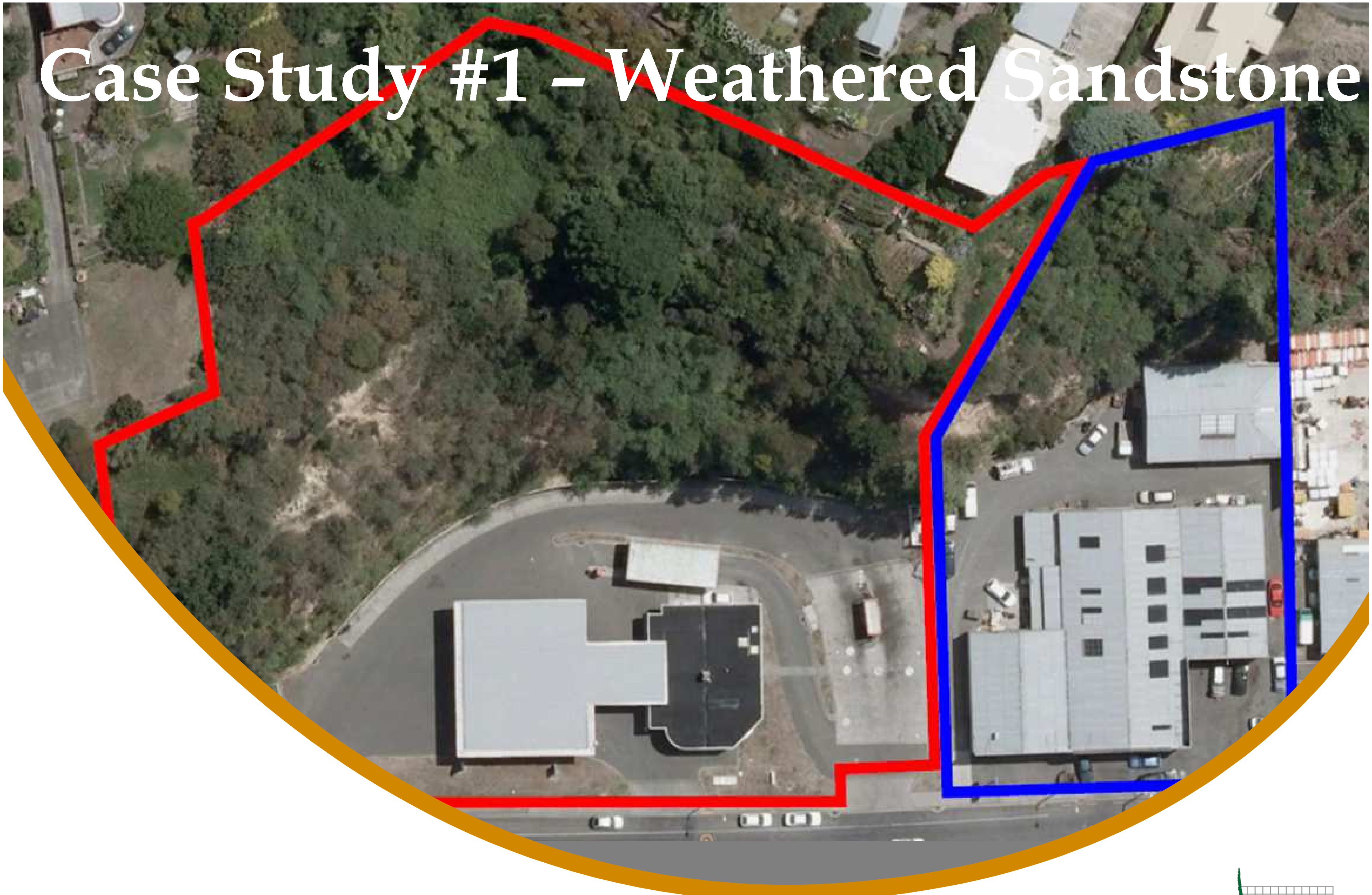
IS THIS REALITY?

More Realistic Fracture Flow

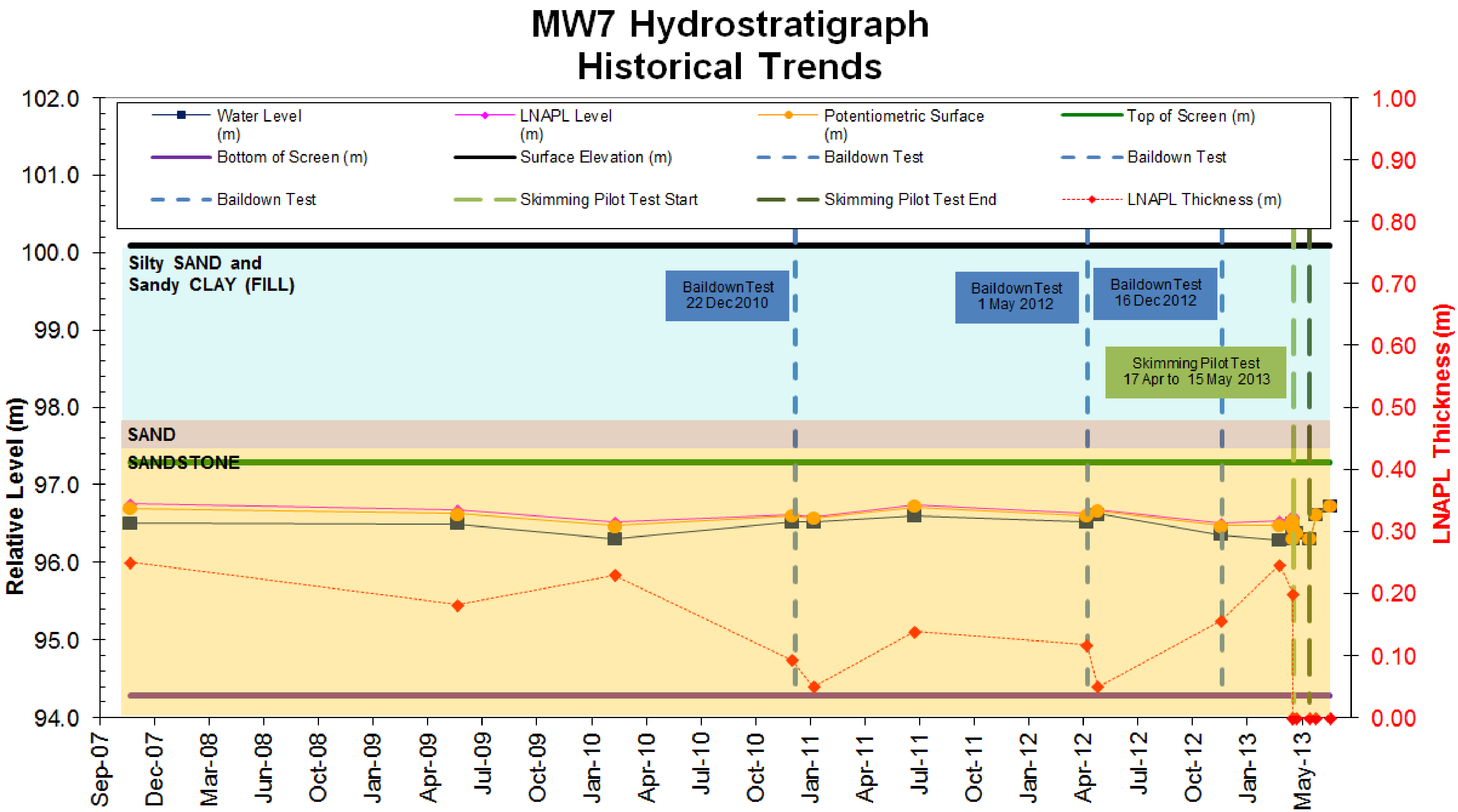


- More Real
  - Flow is more restricted due to surface friction. (Louis 1974) Friction Factor (f) = e / 2*2b
  - Flow follows preferential paths because of the variation in fracture aperture.

Case Study #1 – Weathered Sandstone



Case Study #1 – Weathered Sandstone

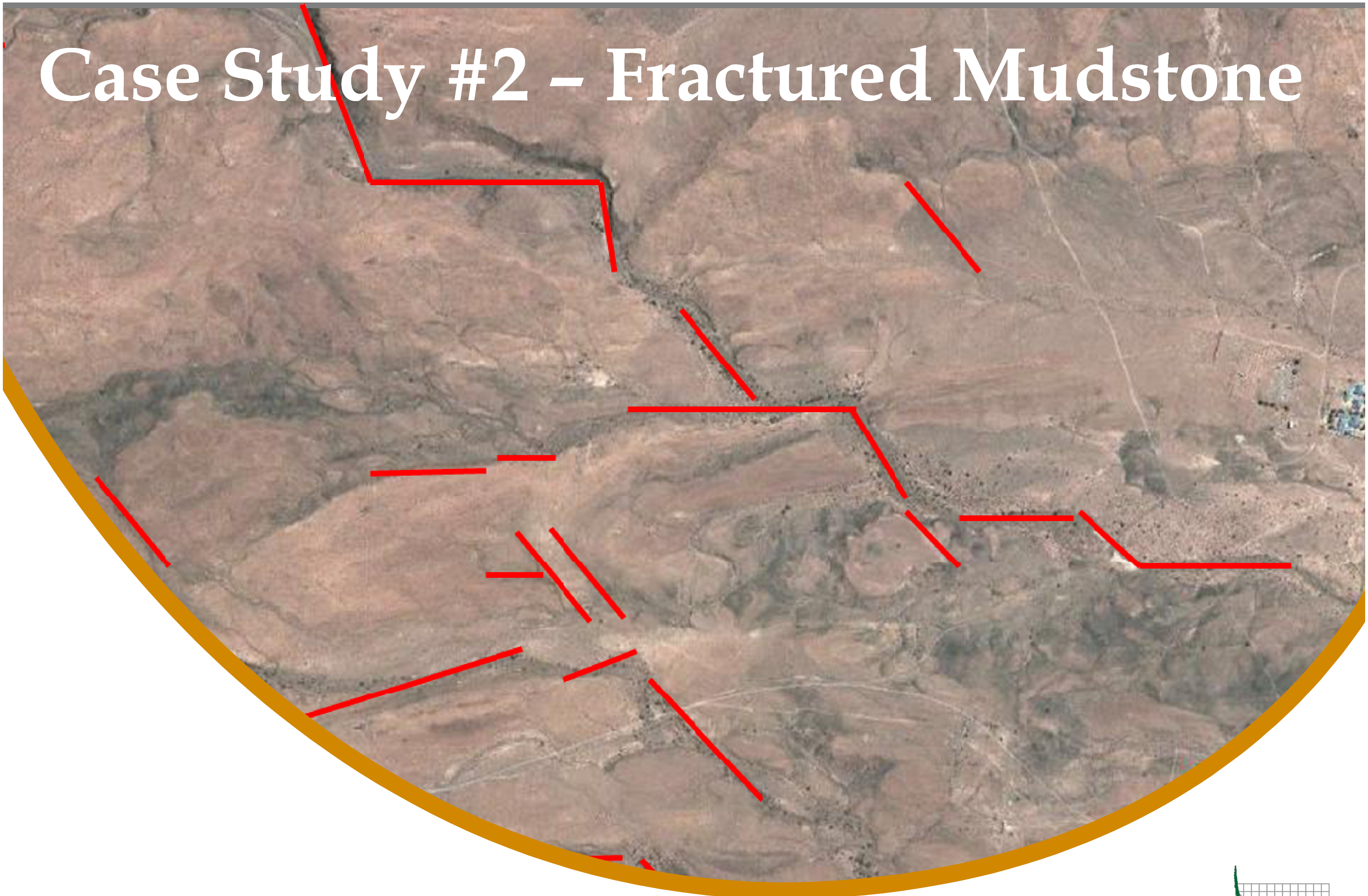


Case Study #1 – Weathered Sandstone

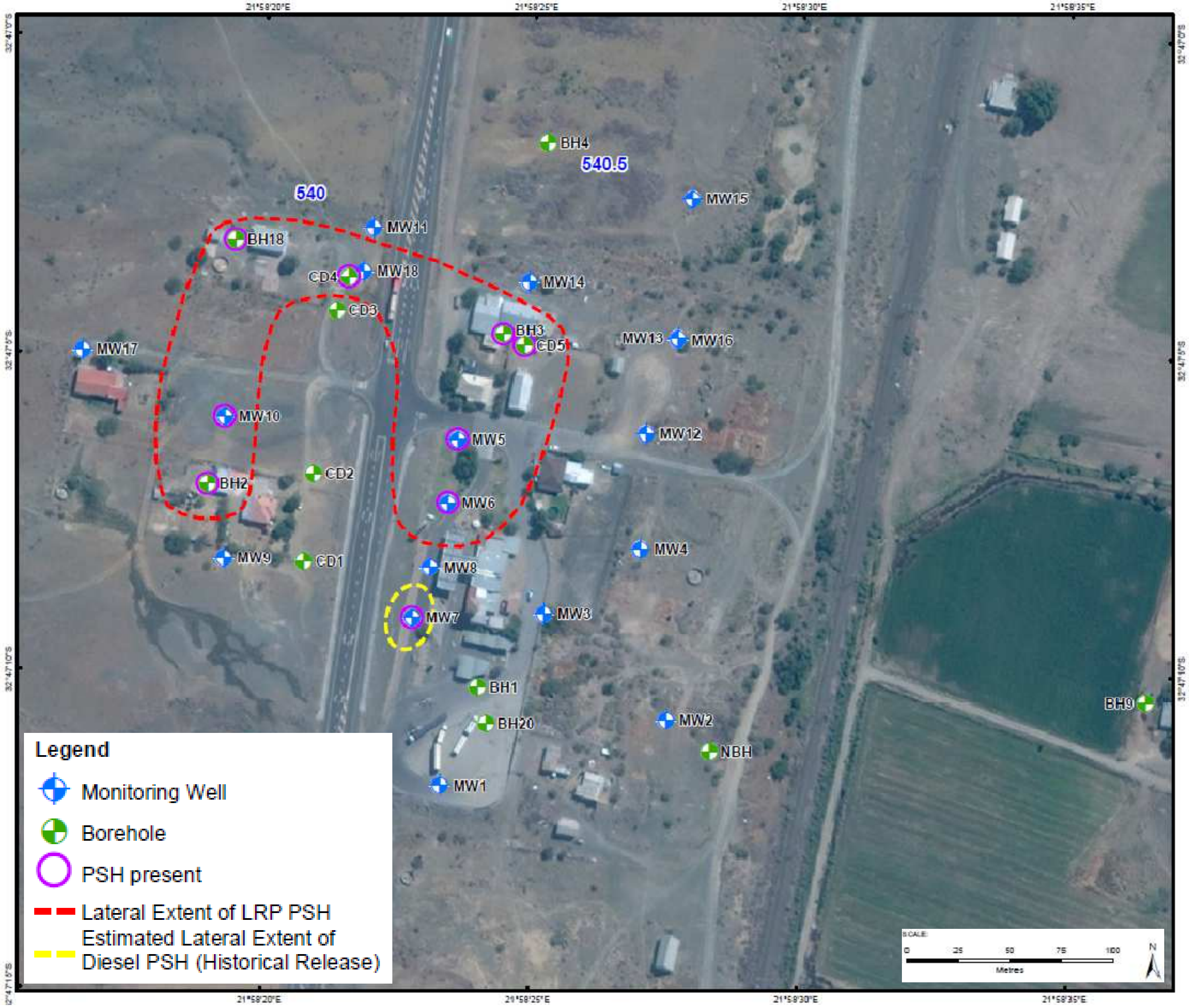
- Baildown Testing
  - ~0.3m LNAPL gauged
  - LNAPL Tn ~ 0.006 m2/day ~ 0.06 ft2/day
  - Behaved like unconfined conditions

- Skimming Test (1 month period)
  - Validated baildown test data
  - Confirmed low Tn

Case Study #2 – Fractured Mudstone

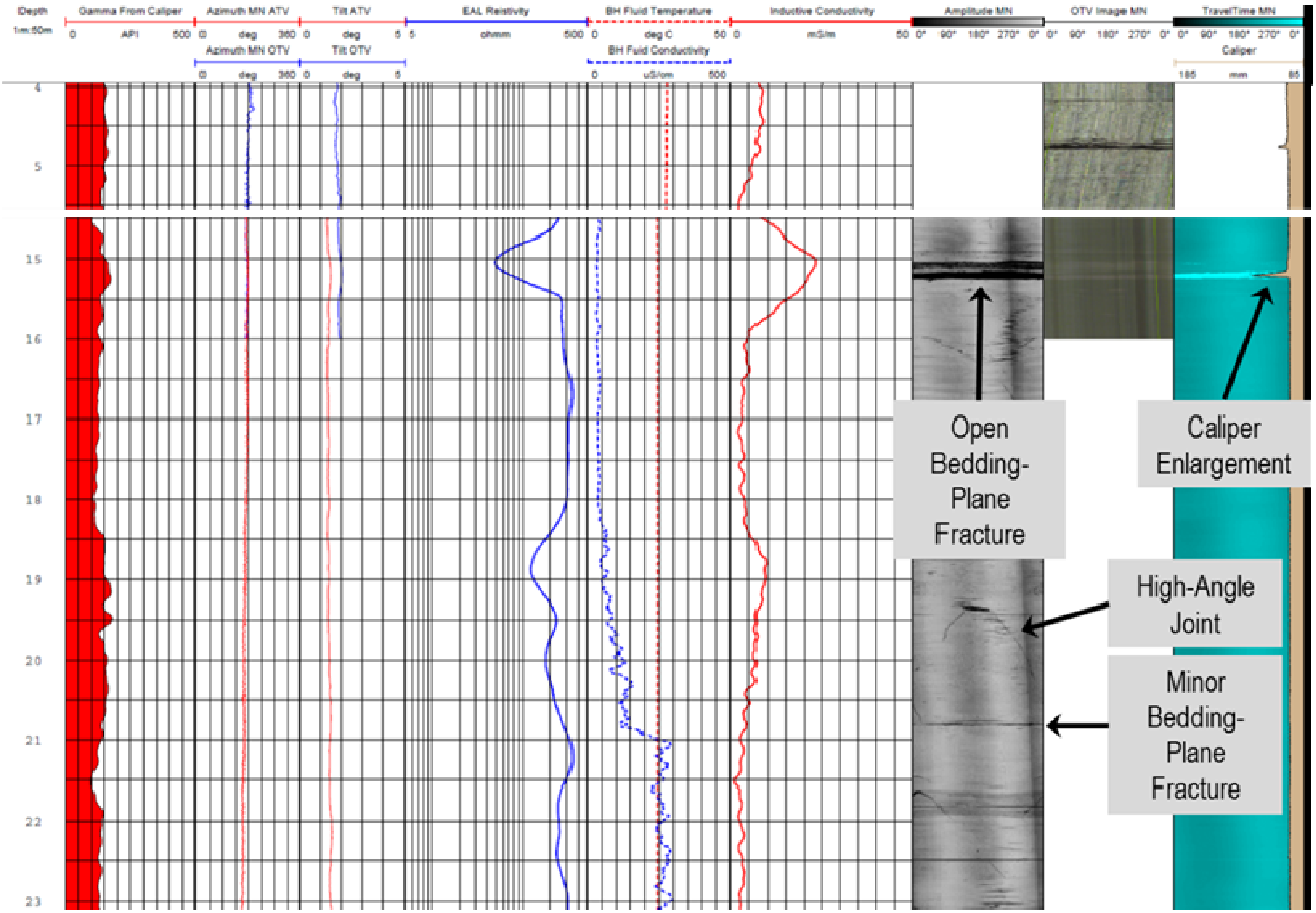


Site Overview

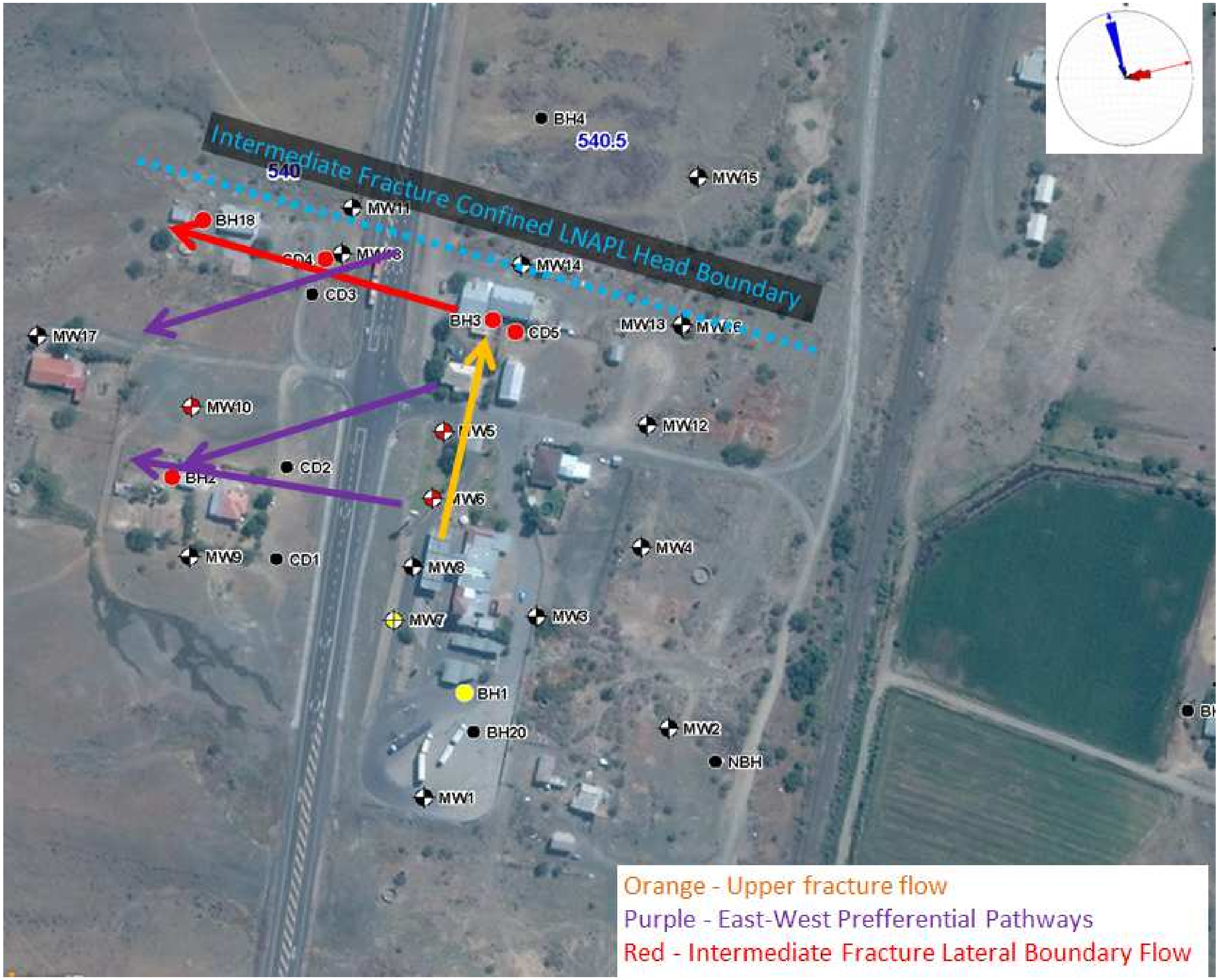


Fractured Mudstone

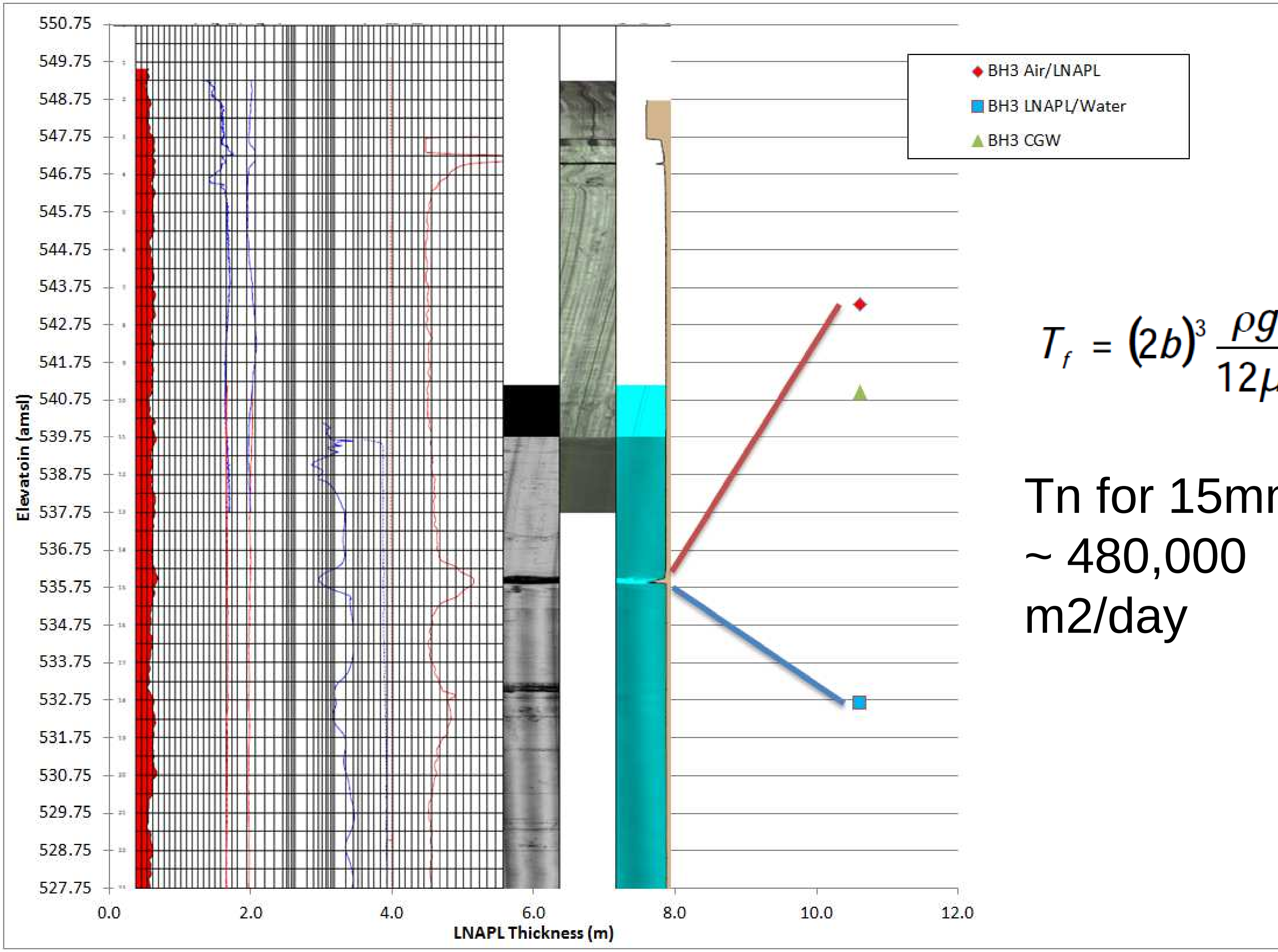
Geophysical Interpretation (down-hole)



LNAPL Migration



Gauging Data ~10.5 m



$$T_f = (2b)^3 \frac{\rho g}{12\mu}$$

Tn for 15mm ~ 480,000 m2/day

Case Study Pilot Test - Skimming

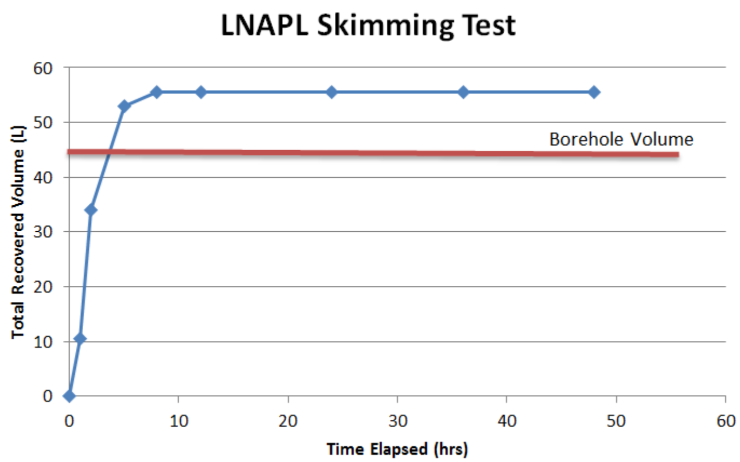
- Skimming Test
  - Initially high recovery
  - Rapid decline
- Well # 1 (1.3L in borehole)
  - 10.5 L/hr (1hr)
  - Tn ~ 11 m2/day (~110 ft2/day)
- Well # 2 (45L in borehole)
  - 11.1 L/hr (5 hrs)
  - Tn ~ 2.5 m2/day (~25 ft2/day)

$$T_n = \frac{Q_n \ln\left(\frac{R_{oi}}{r_w}\right)}{2\pi s_n}$$

$$s_{n\_unconfined} = b_n(1 - \rho_r)$$

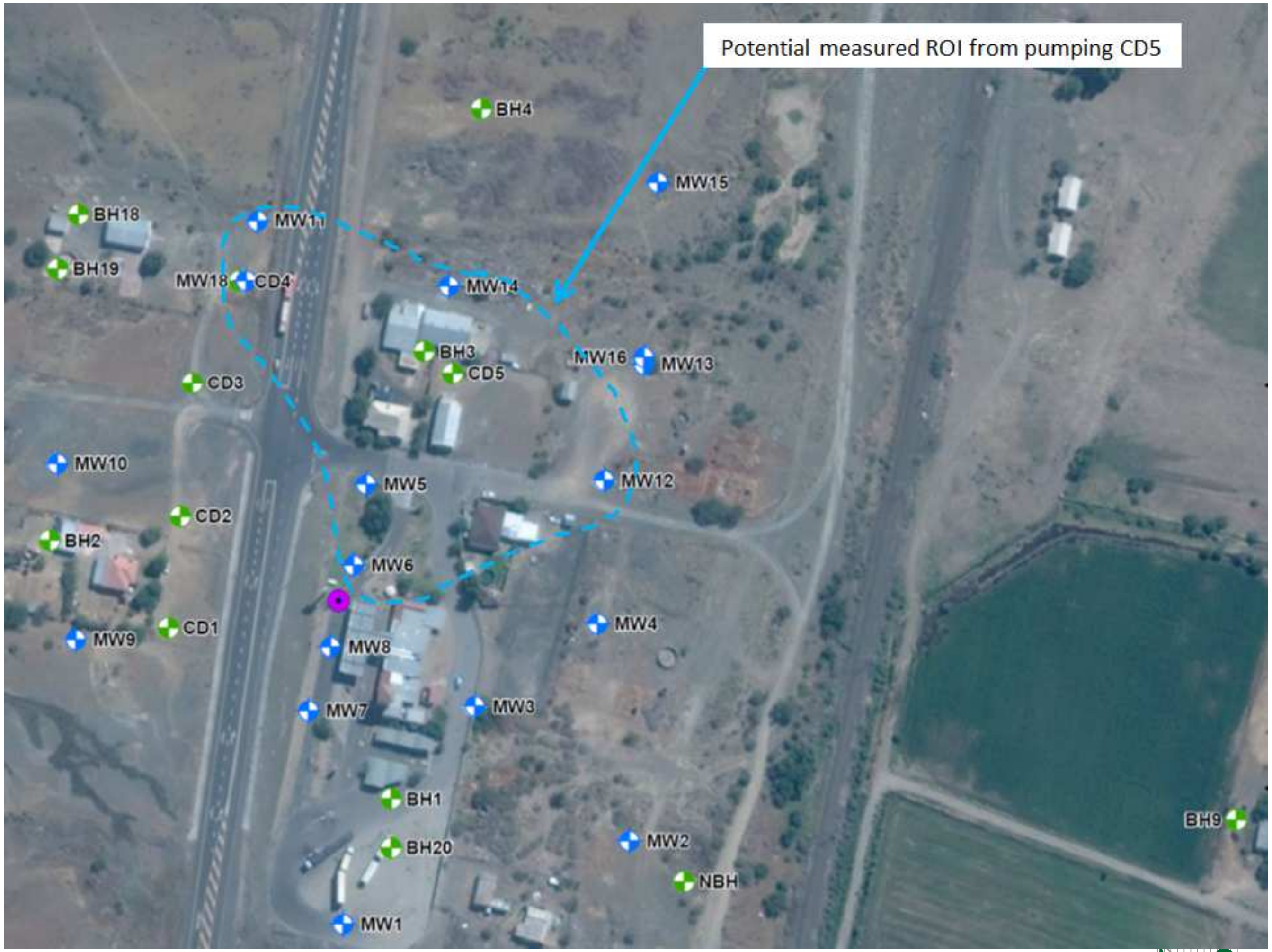
$$s_{n\_confined} = b_{nf}\frac{1 - \rho_r}{\rho_r}$$

$$s_{n\_perched} = b_{nf}$$

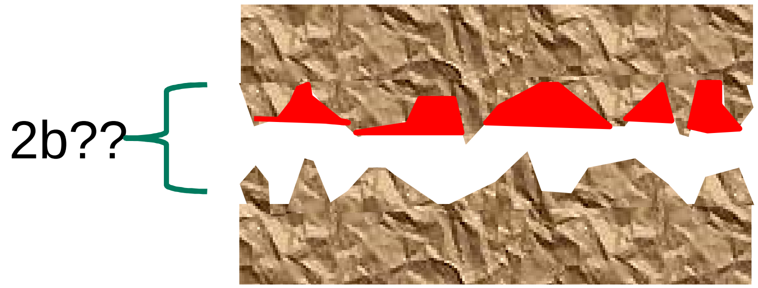


Case Study Pilot Test – Total Fluids Extraction

- Total Fluids Extraction
  - Large ROI
    - Not linear
  - Slight Increase in LNAPL/Water recovery



More Realistic Fracture Flow for LNAPL?



- LNAPL Reality
  - Larger fractures not fully saturated
  - LNAPL “trapped/pools” due to fracture roughness
  - LNAPL migration can be significant and unpredictable
  - Target intersections of sub-vertical and bedding plane fractures

Bedrock LNAPL Transmissivity Observations

- High Primary Porosity
  - Similar to unconsolidated
  - Unconsolidated methods appear valid

- Fractured Conditions
  - LNAPL Transmissivity can be very high
  - Rapid change from high Tn to low Tn
    - Lower ability to predict future
    - Possible to mobilize “trapped” LNAPL
  - Ongoing lateral migration can occur
    - Low Tn does not indicate Tn will remain low

Questions?

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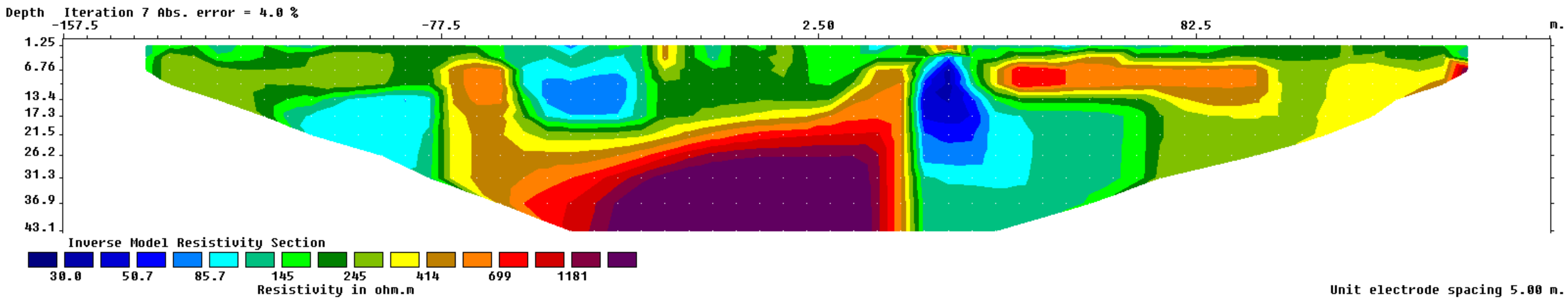
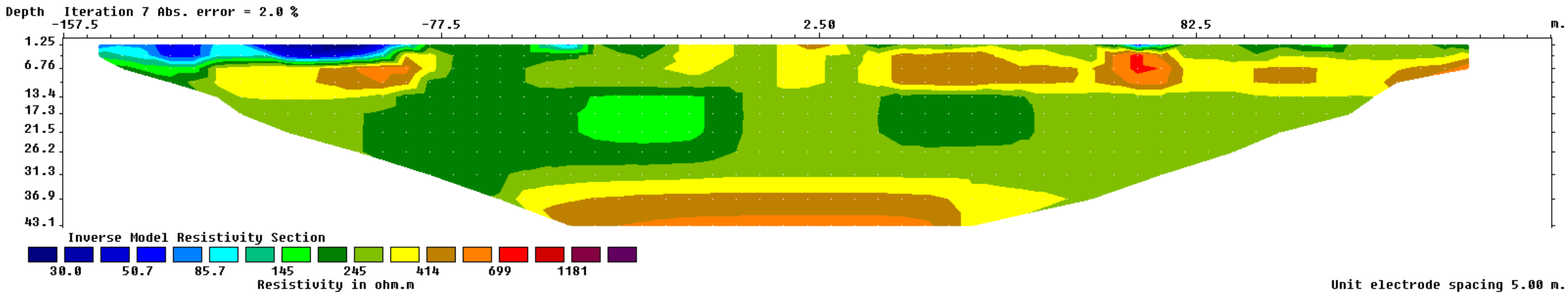
Case Study

ERM

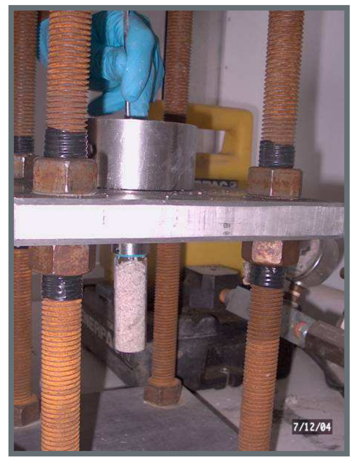
Surface Geophysics: 2D Resistivity

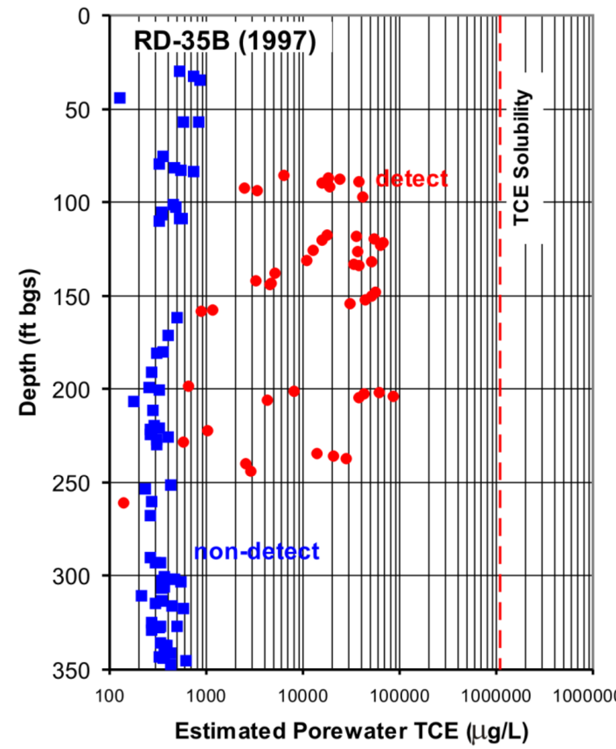




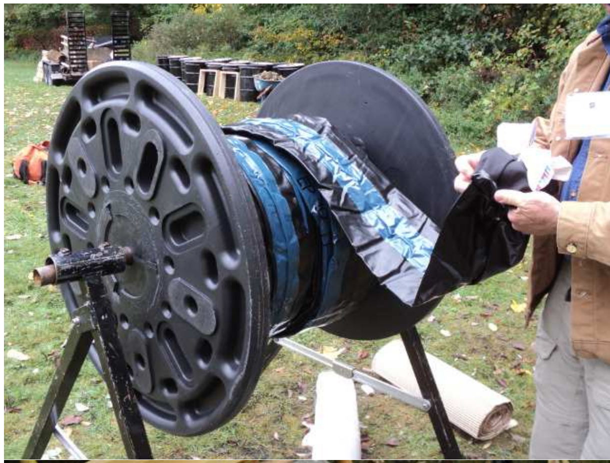
Rock Core Analyses

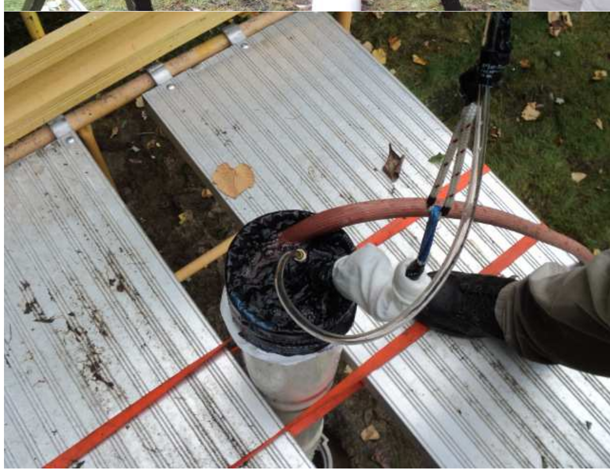
- Matrix porosity
- Pore water contaminant analysis
- Fraction of organic carbon (foc)
- Mineralogical content / whole rock analysis





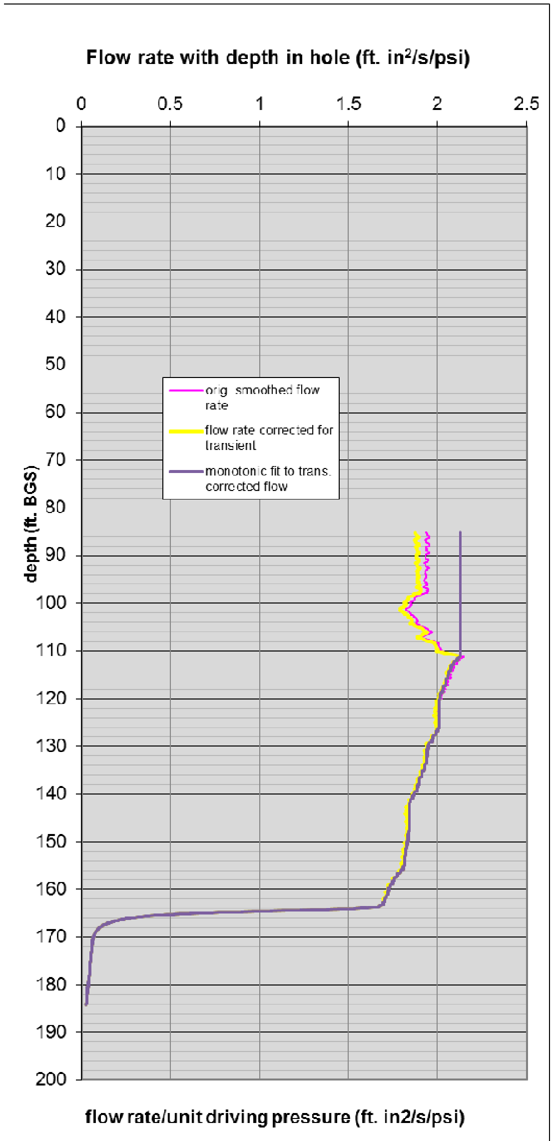
FLUTe Tools

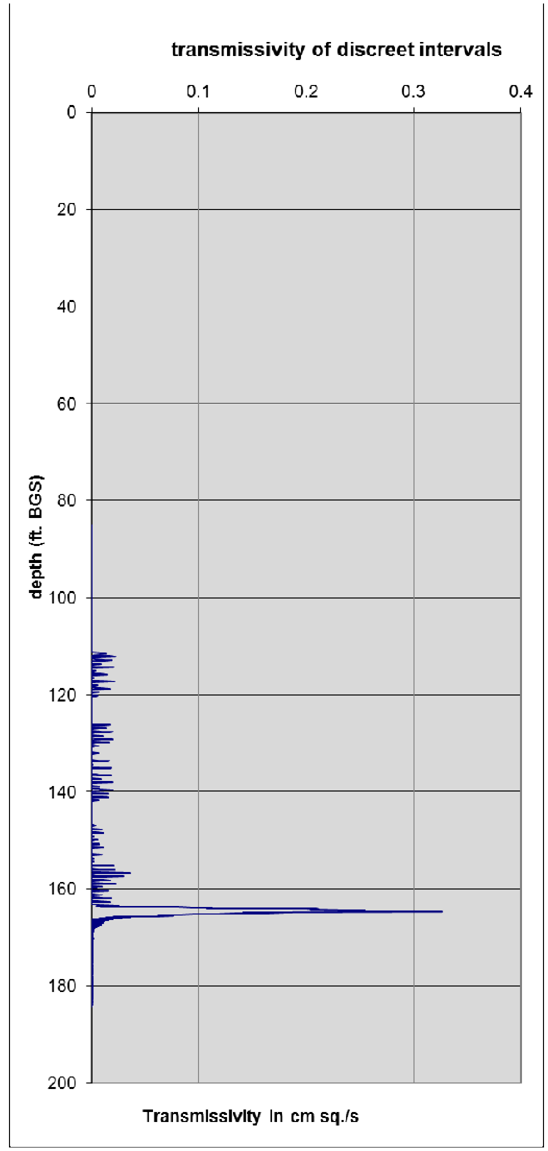




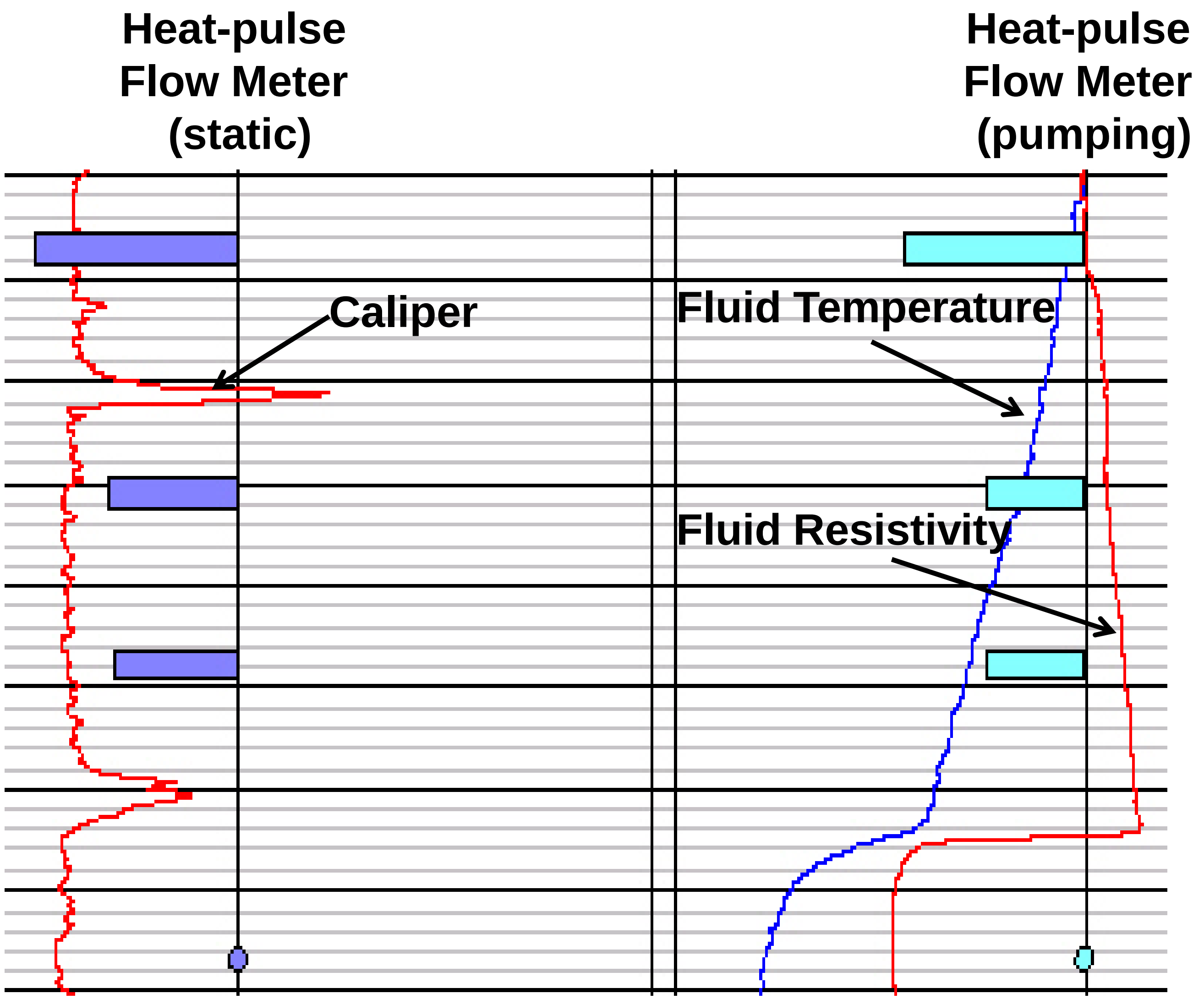
FLUTe Tools: NAPL and FACT liners

FLUTe Tools: Continuous Transmissivity Log



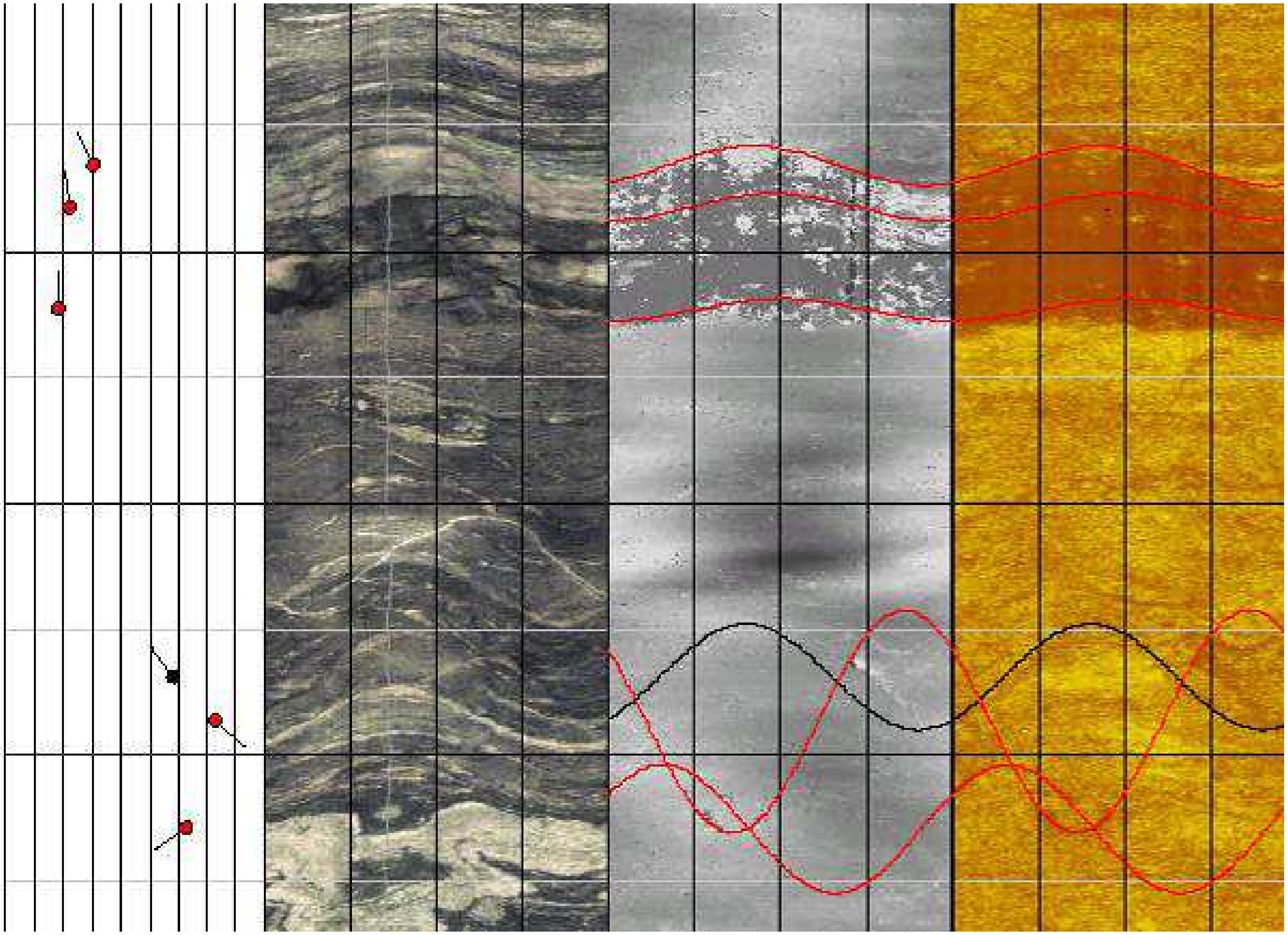


Borehole Geophysical Logging Tools



Borehole Geophysical Logging Tools

Fracture Orientations **Optical Televiewer** **AcousticTeleviewer**



Packer Testing

Pumping Tests