Obtaining Site-Derived Parameters Supporting DFM Transport Modeling In Fractured Sedimentary Rock

10th International Groundwater Quality Conference
9-12 September 2019, Liege, Belgium

Kenley Bairos MASc
Research Associate, G360 Group, University of Guelph
Collaborators: Dr. Beth Parker, Dr. Patryk Quinn, Pete Pehme.

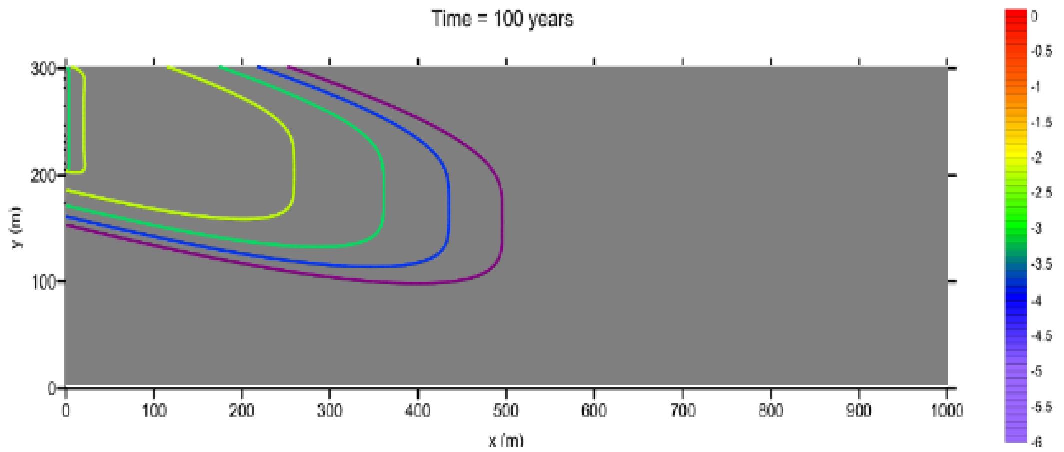
Groundwater Quality 2019

Transport Modeling in Contaminant Hydrogeology

EPM vs DFM

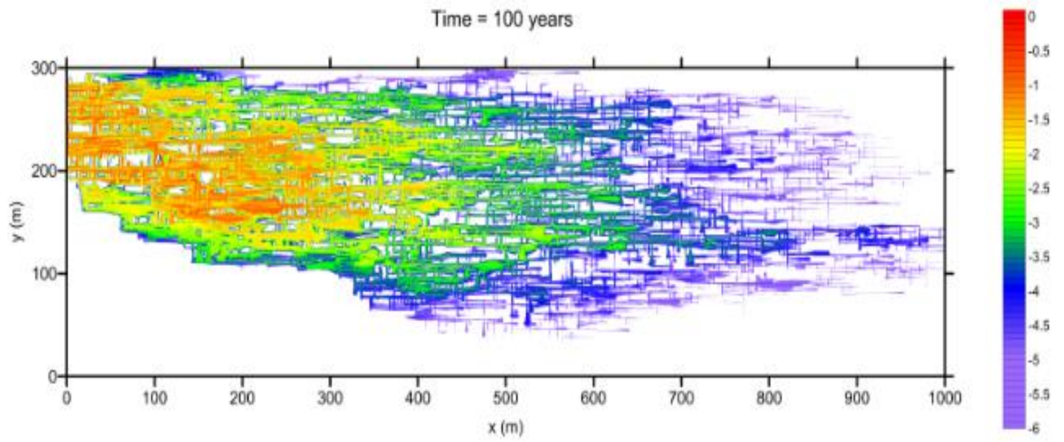
Equivalent Porous Media (EPM)

- Averaged fracture matrix properties
- neglects controlling processes
- inadequate for transport in fractured rock



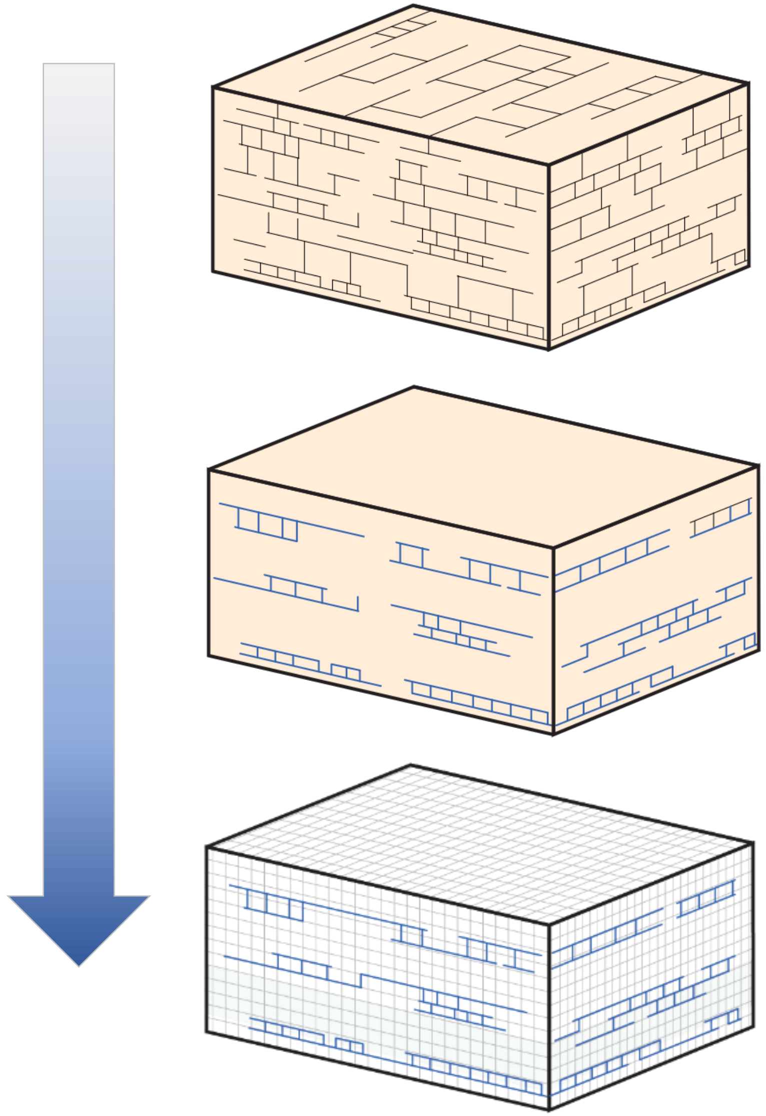
Discrete Fractured Matrix (DFM)

- most rigorous approach
- field ground truthing (profile comparisons)
- computationally demanding
- Difficult to parameterize with standard methods
- A DFM Field Approach provides inputs



Outline of Talk

Applying our DFM approach for model parameterization



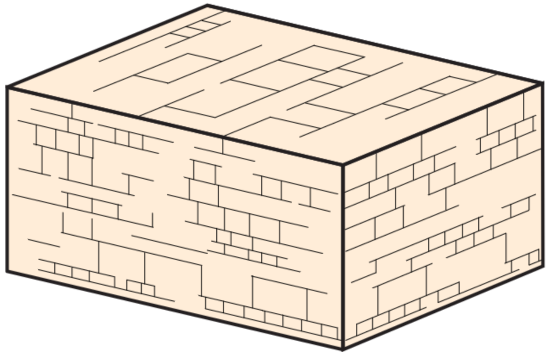
1) **Parameterizing the static fracture network**
   - Methods for Identifying mechanical units

2) **Identifying the “active” fracture network**
   - New methods for Identifying and representing active fractures in model – *Critical Reynolds Number (Re_c) Approach*

3) **Model Runs**
   - Example Results of 2D / 3D Flow & Transport simulations using DFM paramaterization

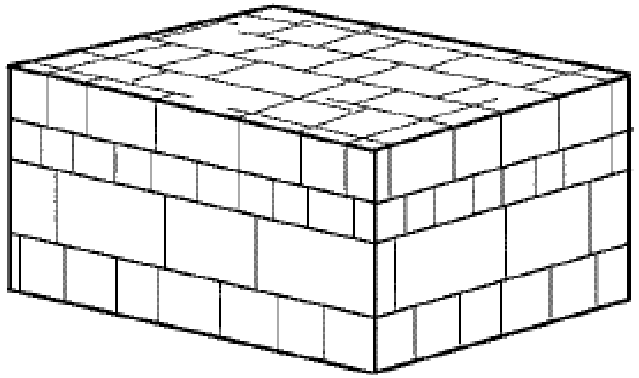
Development of DFM model

Applying a DFM approach for model parameterization

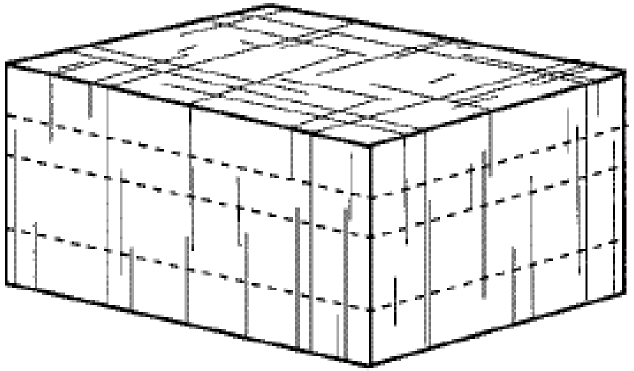


1) **Parameterizing the static fracture network**
    - Methods for Identifying mechanical units

Types of Joint Systems



Stratabound joint system
Joints are largely confined to individual beds, their size is limited to a narrow range and spacing is regular



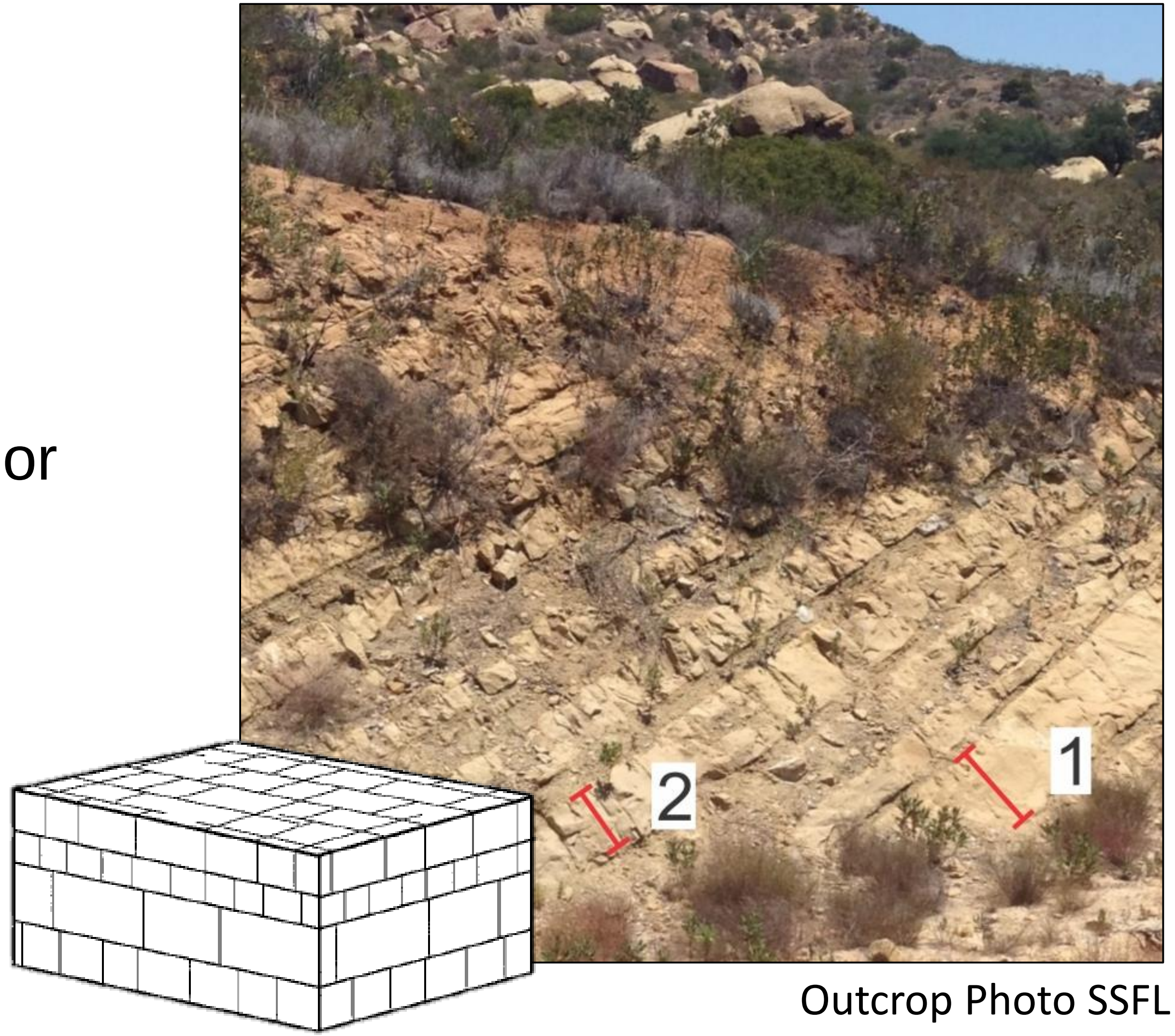
Non-Stratabound joint system
Joints cover a wider range, fractures cross cut bedding and spacing tends to be clustered

(Odling et. al, 1999)

Joint network at sedimentary rock research sites exhibit the characteristics of a *stratabound* system

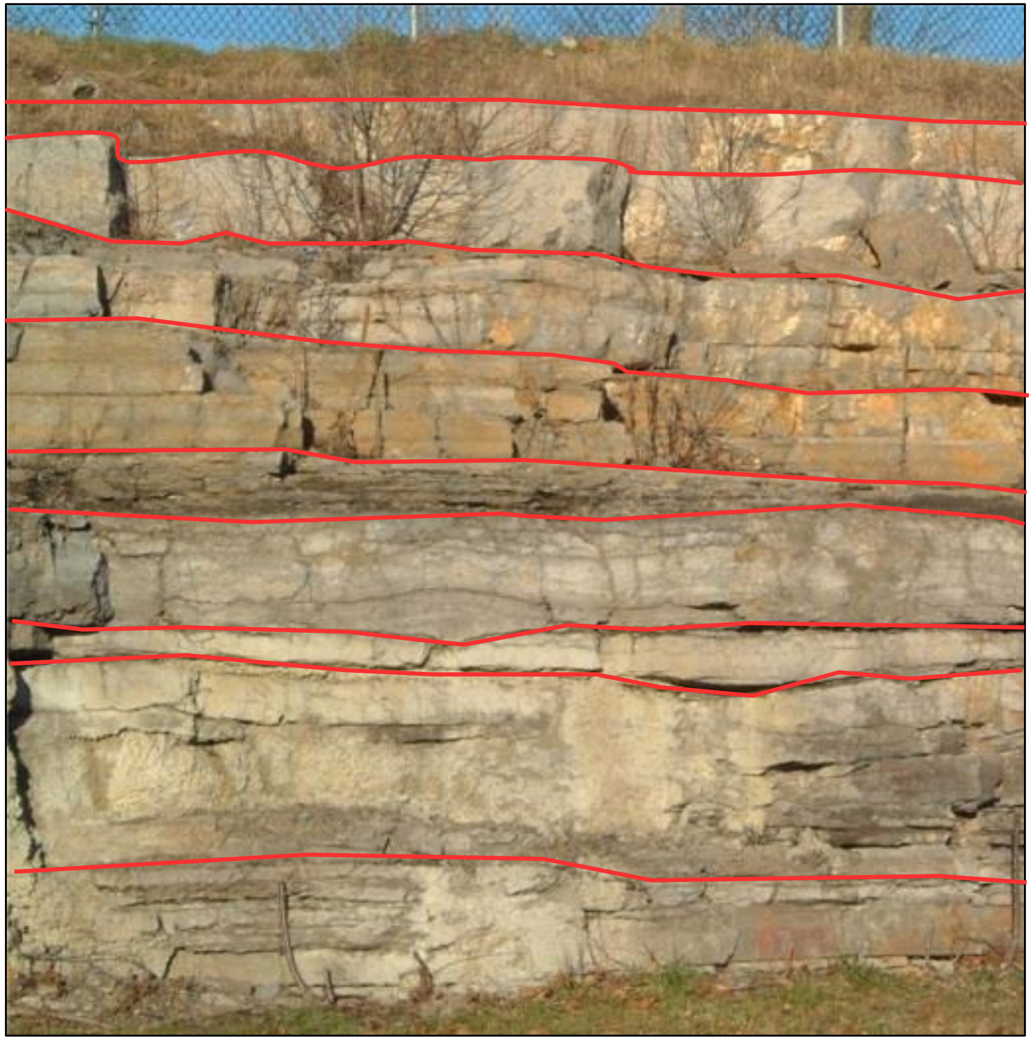
Joints are:

- confined to individual beds separated by fine grained unit or bedding plane features



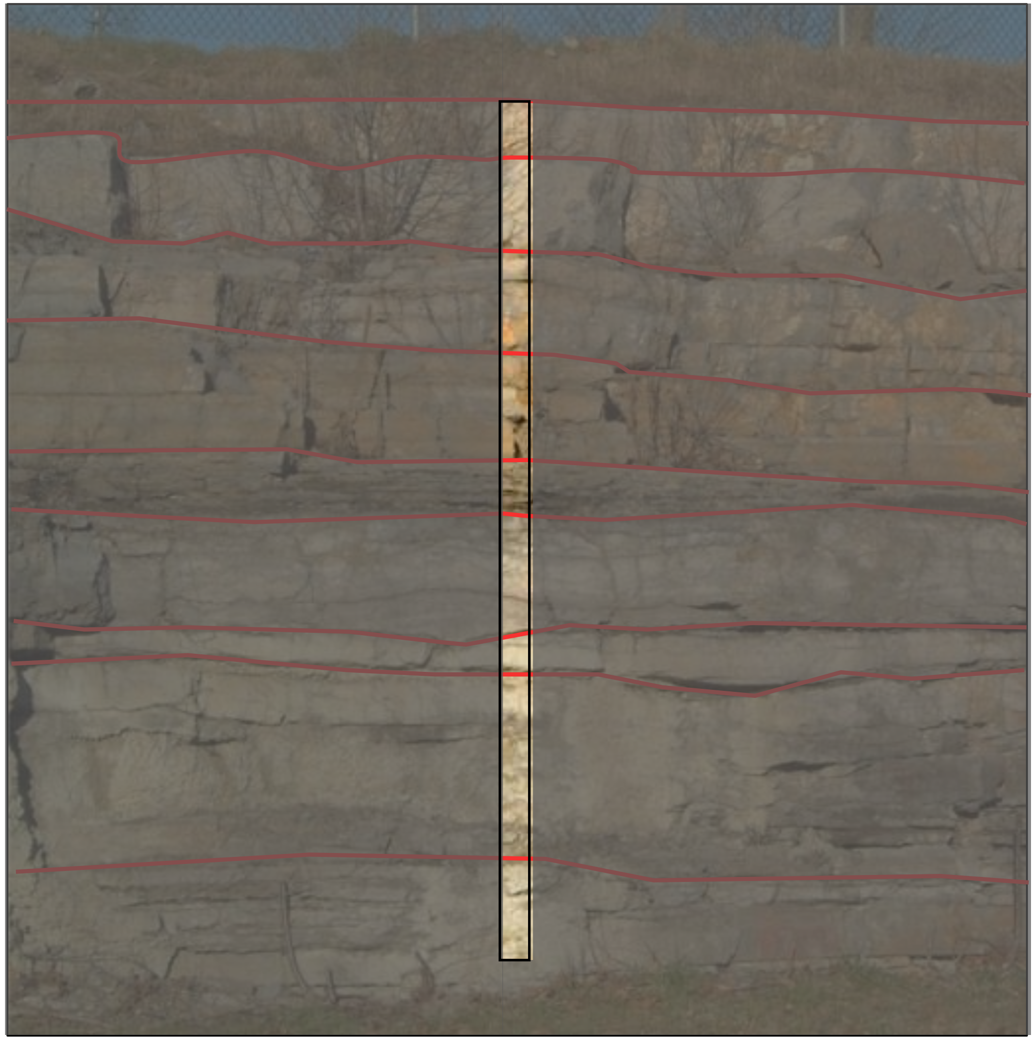
Outcrop Photo SSFL

What are Mechanical Units?



- Groups of layers displaying regularly spaced joints
- All (most) joints start and end at the boundaries of the unit itself.
- Most commonly identified using outcrops but can also be obtained using borehole data.

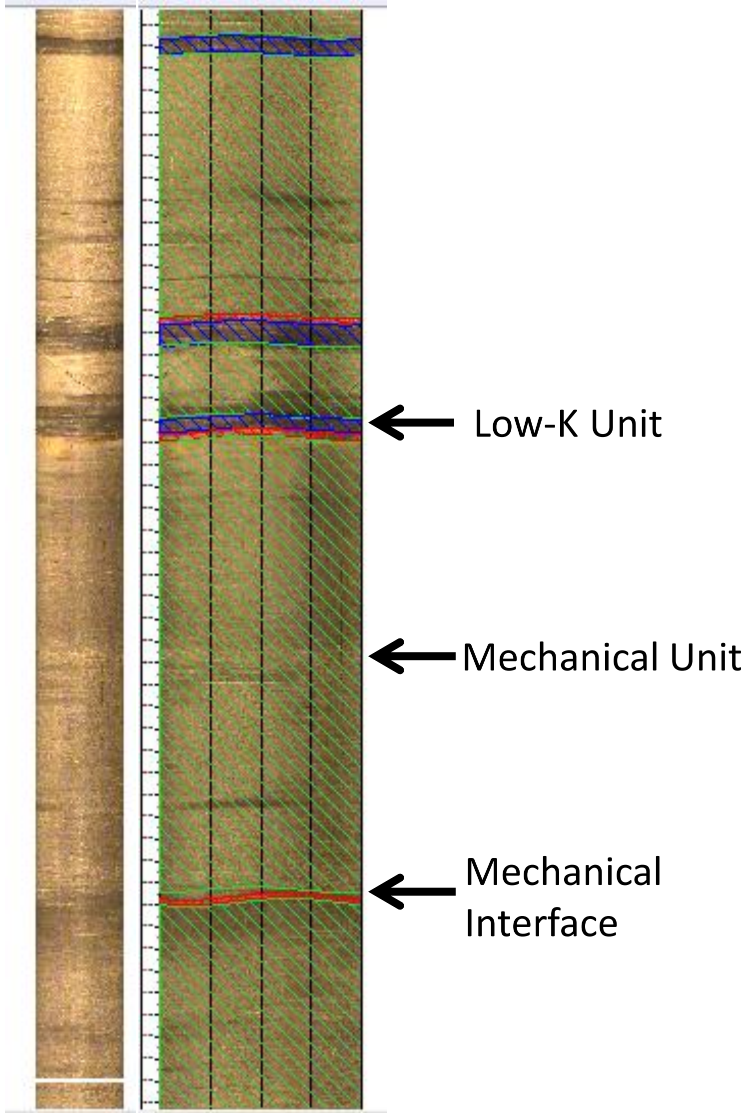
Challenge - Establishing Mechanical Unit Distribution in Subsurface



- Outcrops most often cannot offer information regarding mech units in subsurface
- Must rely on borehole data to identify mechanical units distribution with depth
- Horizontal continuity exhibited by mechanical units means borehole data useful despite small sample size.

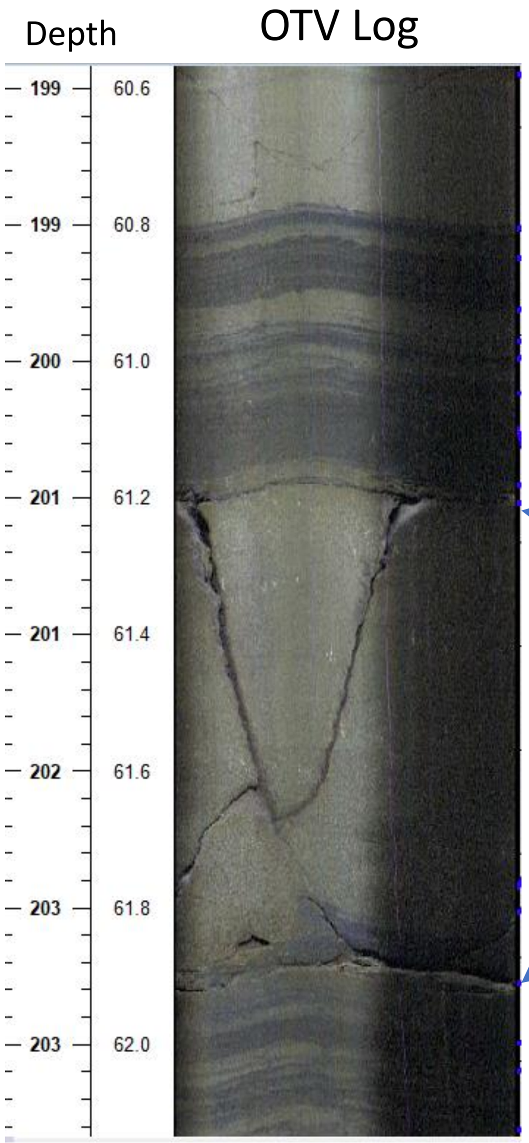
Identifying Mechanical Units using OTV/ATV Logs

RD-107 – OTV Log



- Mechanical Units can be identified using borehole imaging tools.
- Like outcrop analysis, potential mechanical unit interfaces are identified by low K units or bedding plane features.
- Offers location/depth specific Mechanical Unit distribution

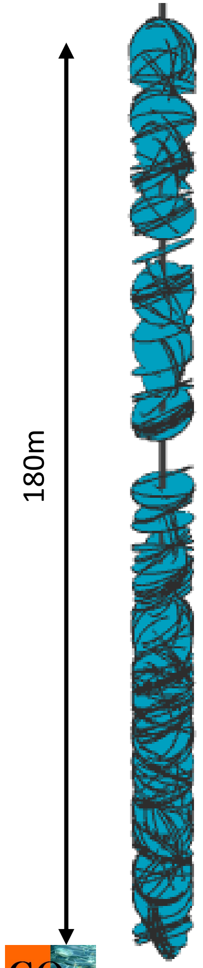
IDENTIFYING MECHANICAL UNITS USING OTV/ATV LOGS

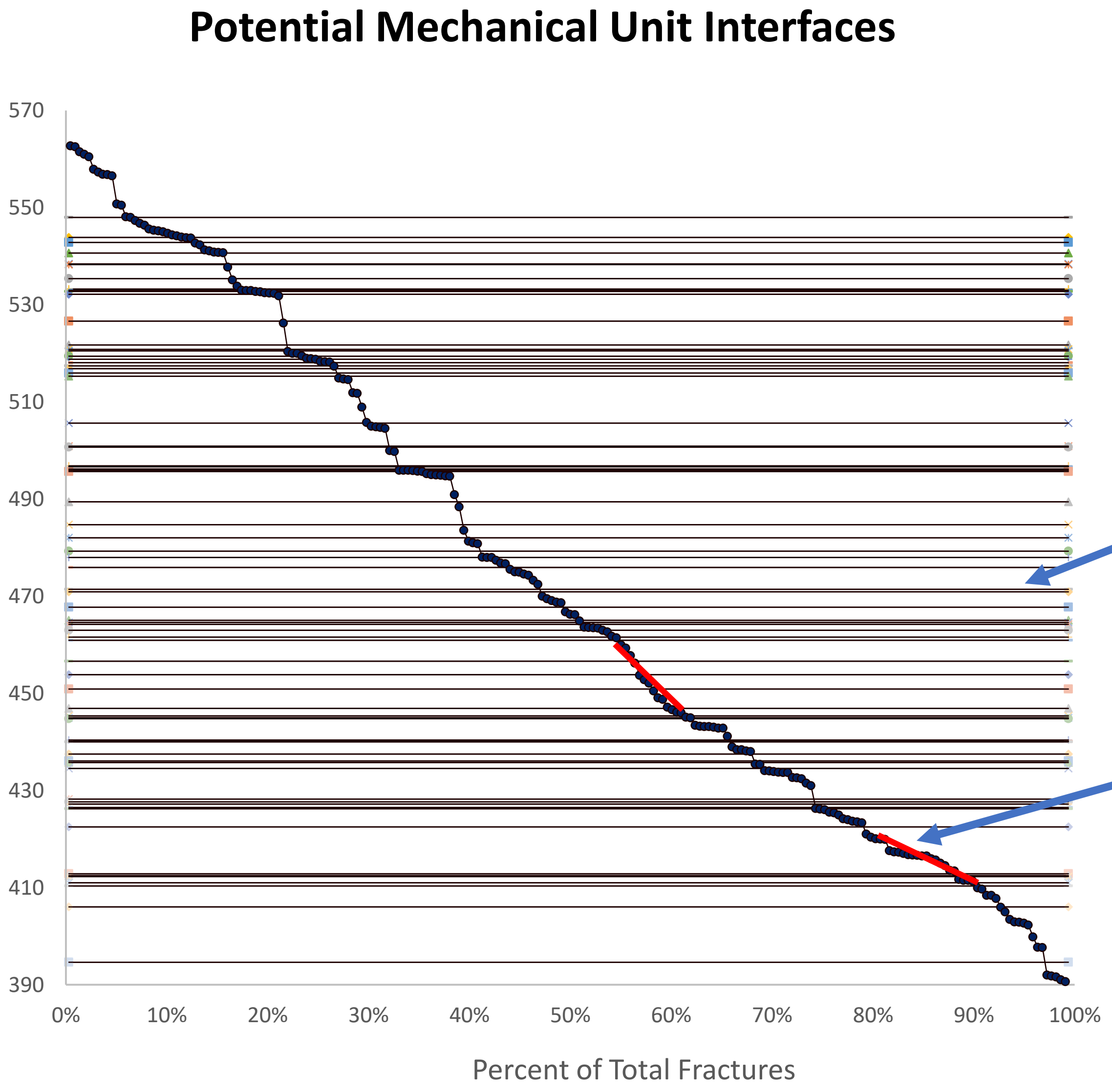


Example of fracture termination at bedding plane partings located at lithology boundaries.

Cumulative Fracture Intensity Plot and Potential Mechanical Boundaries (Borehole Image Derived)

OTV Fractures





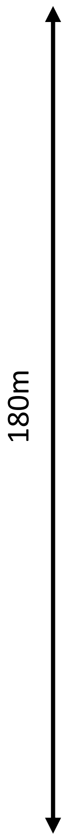
Plot Cumulative Fracture Frequency with Depth

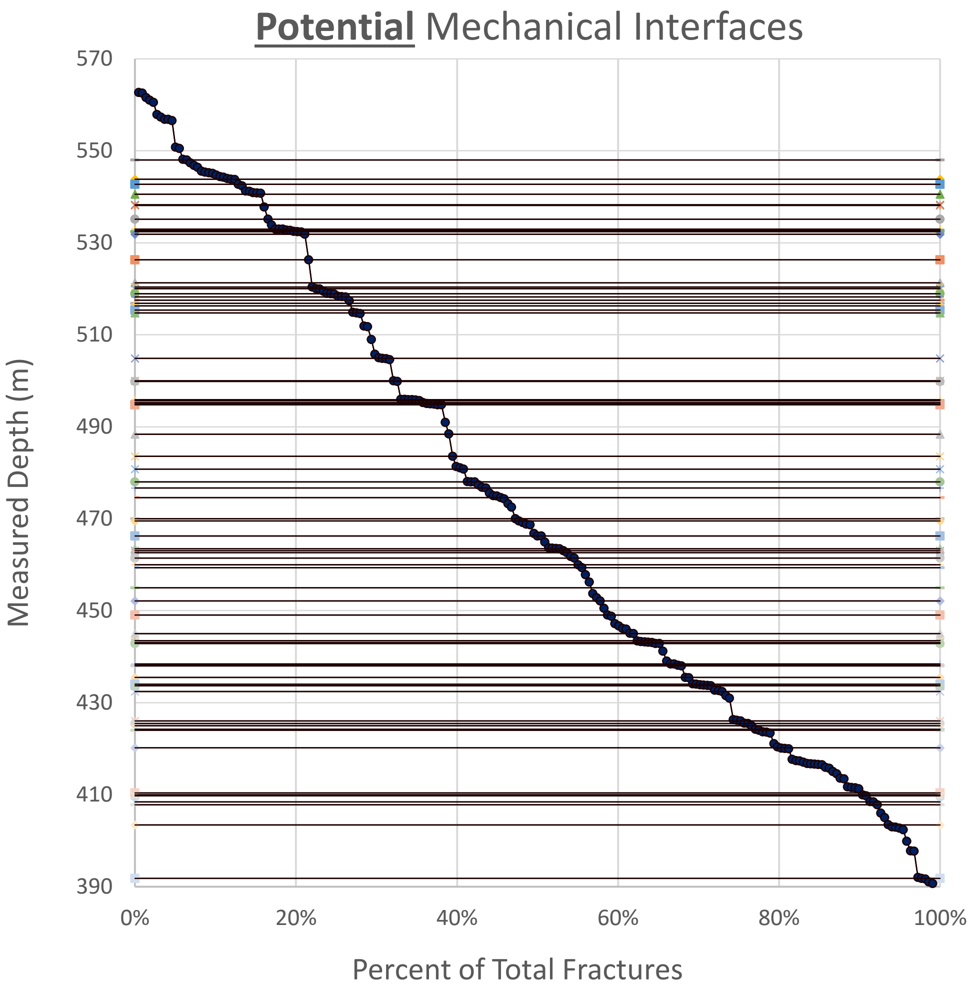
Overlay potential mechanical unit interface

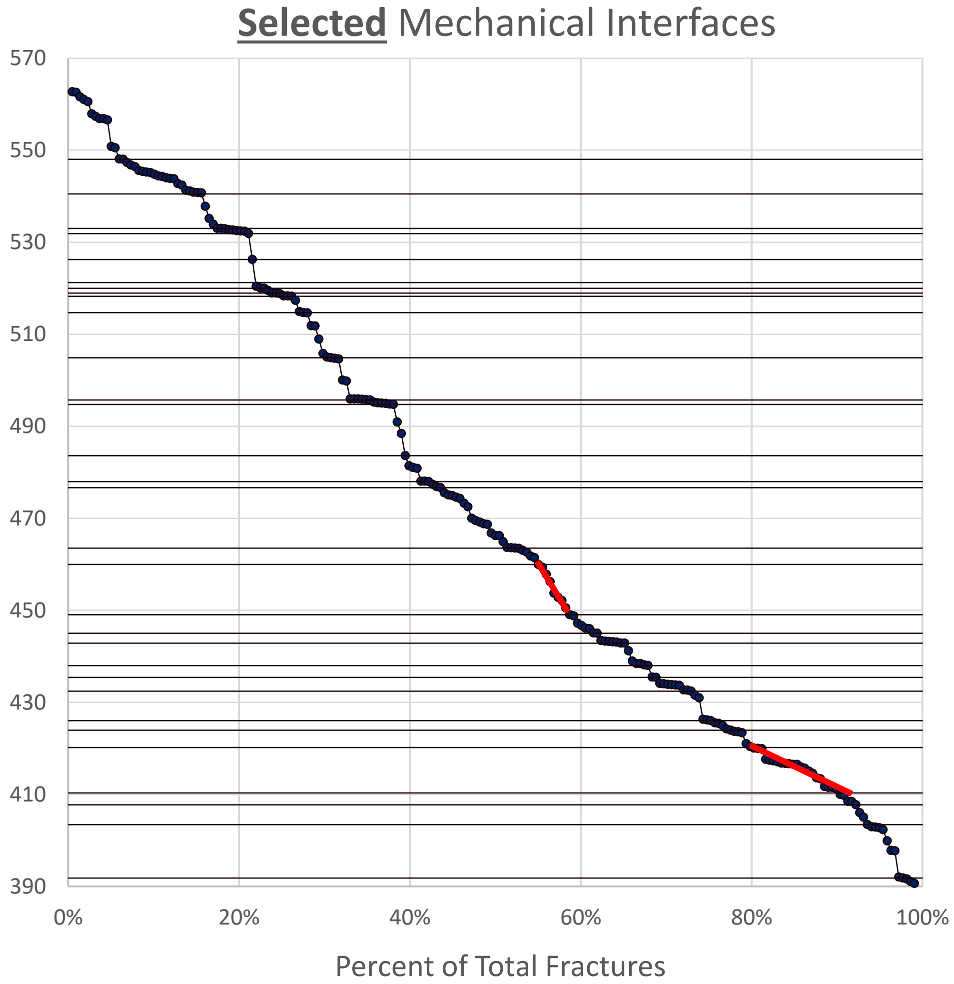
Consistent slope in fracture frequency plot is also evidence of a mechanical unit

● Fracture Identified in Borehole

Final Mechanical Stratigraphy Defined Using Borehole Image Analysis and CFI Plot





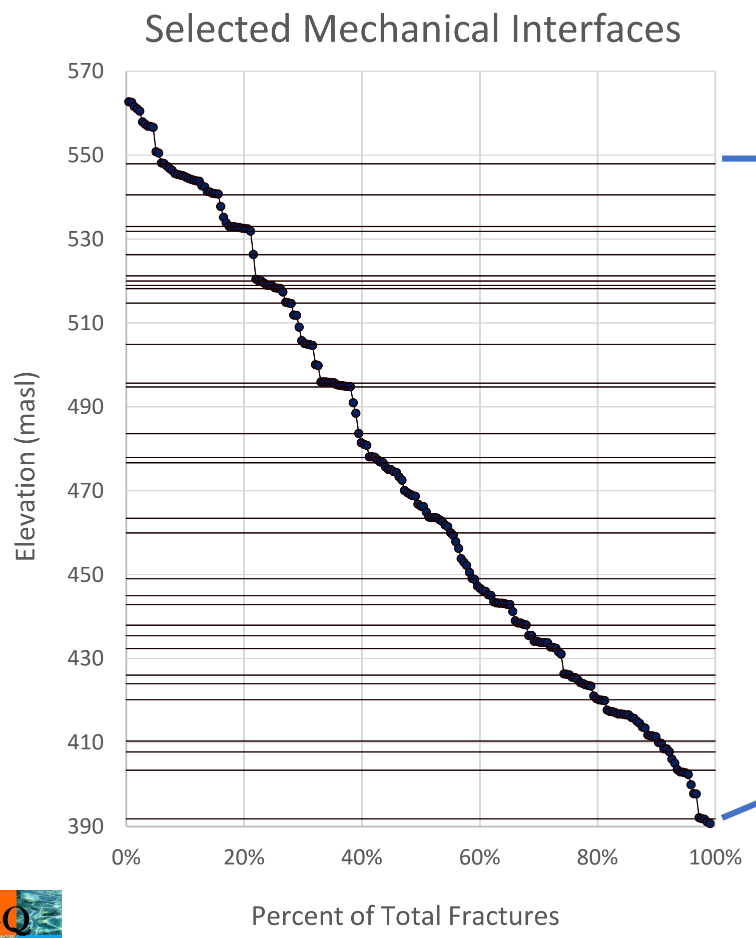


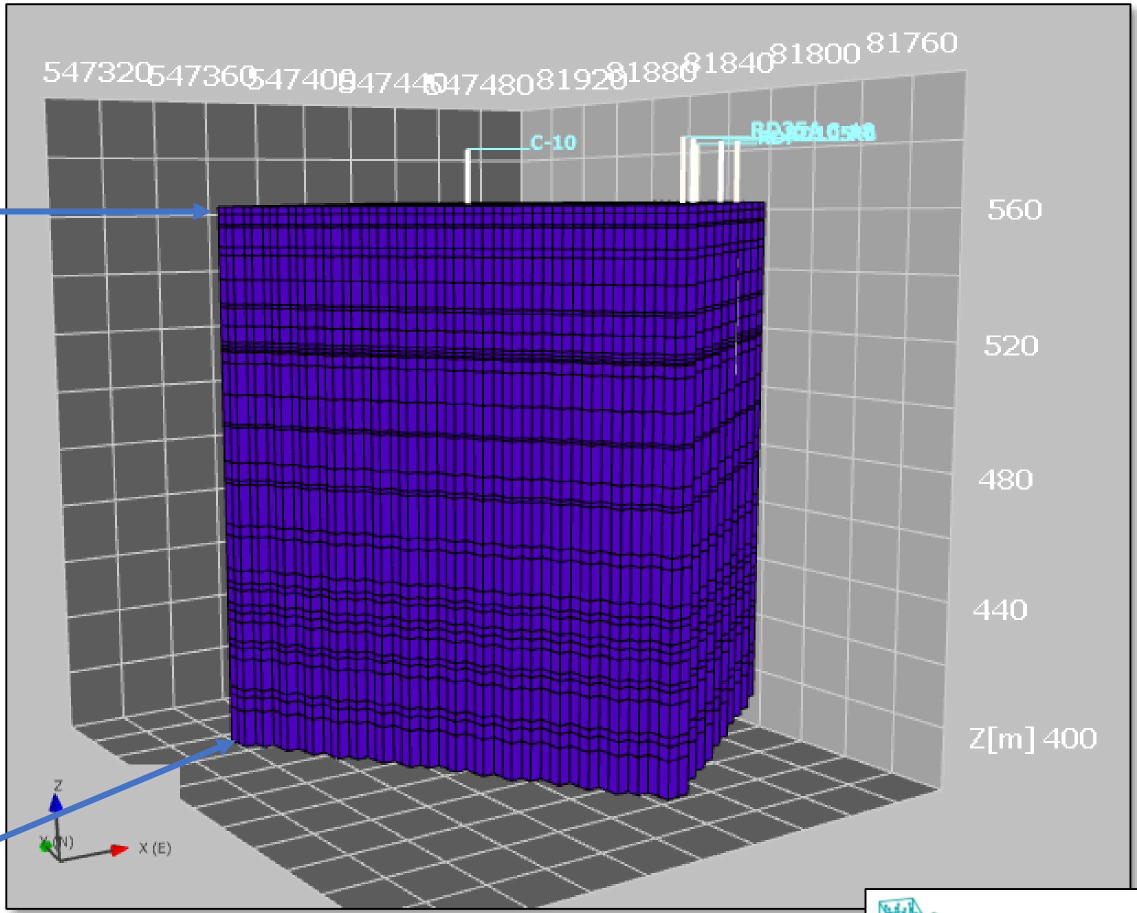
73 Interfaces

Informed Selection

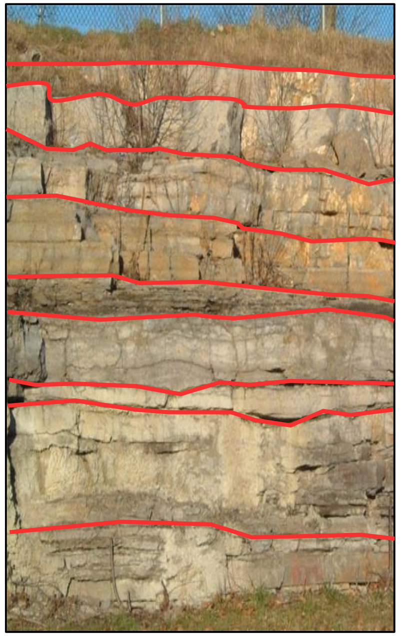
31 Interfaces

Mechanical Units Used to Define Fracture Generation Grid



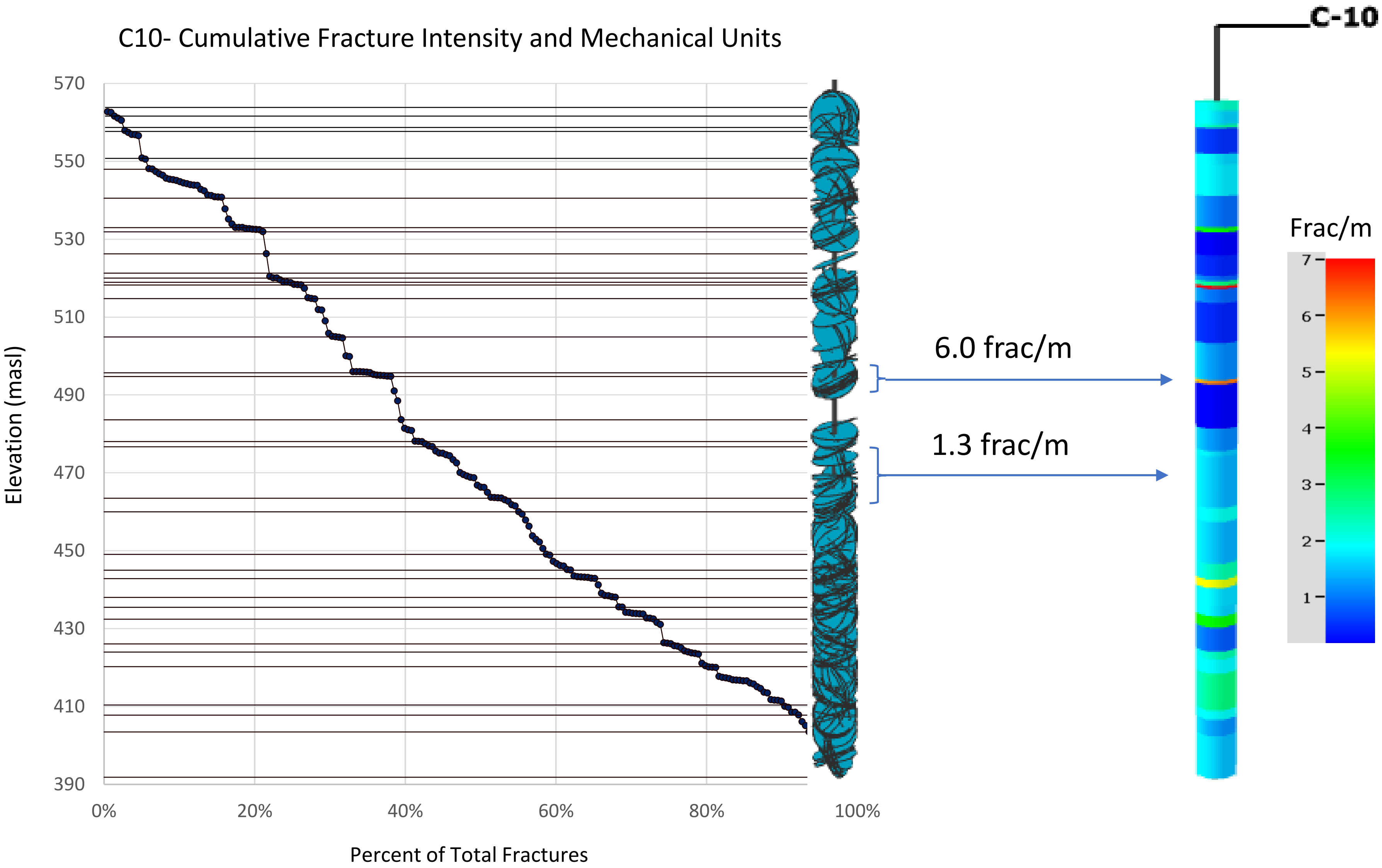


Domain = 160m x 160m x 180m

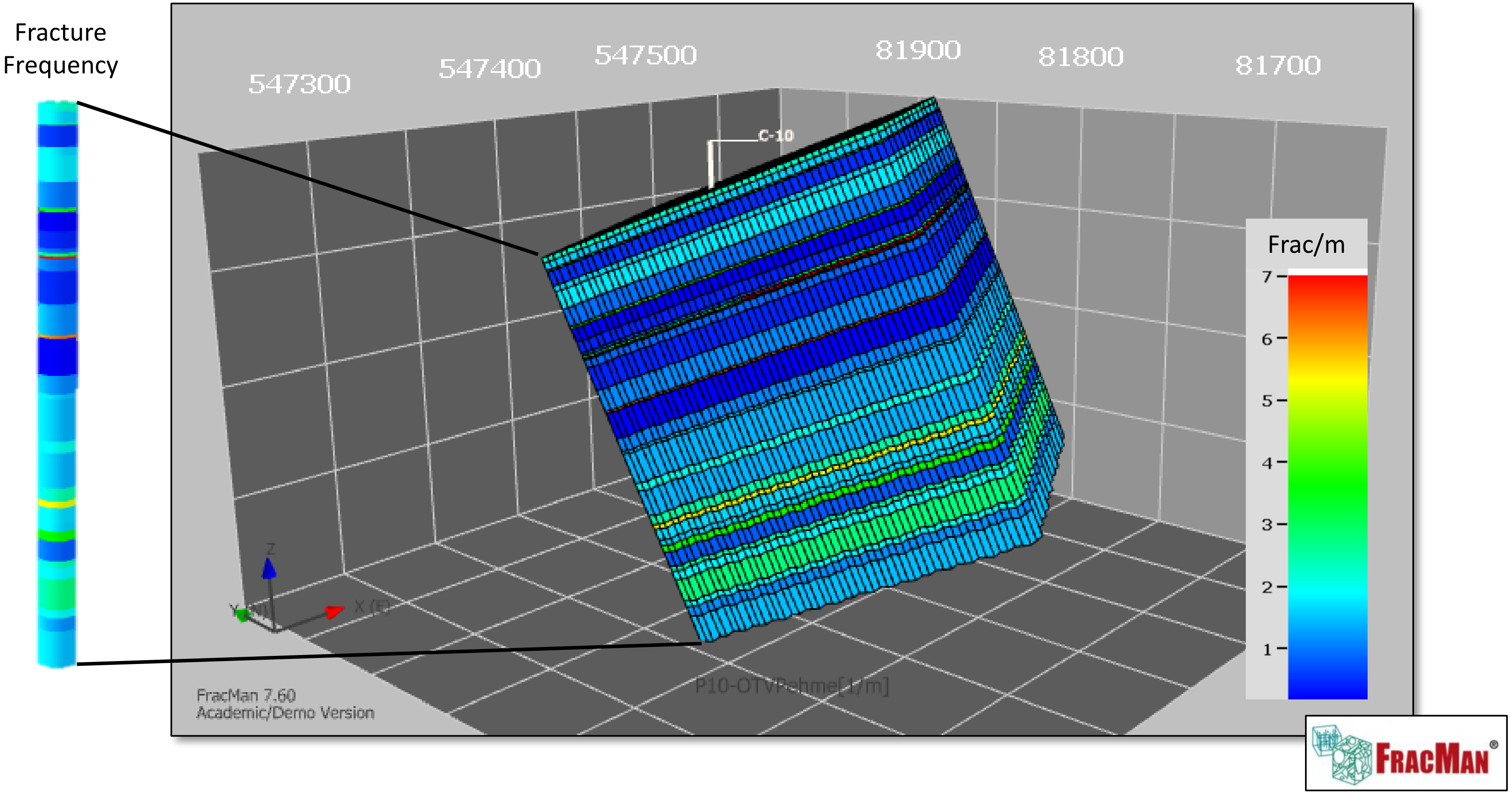


Example of Outcrop

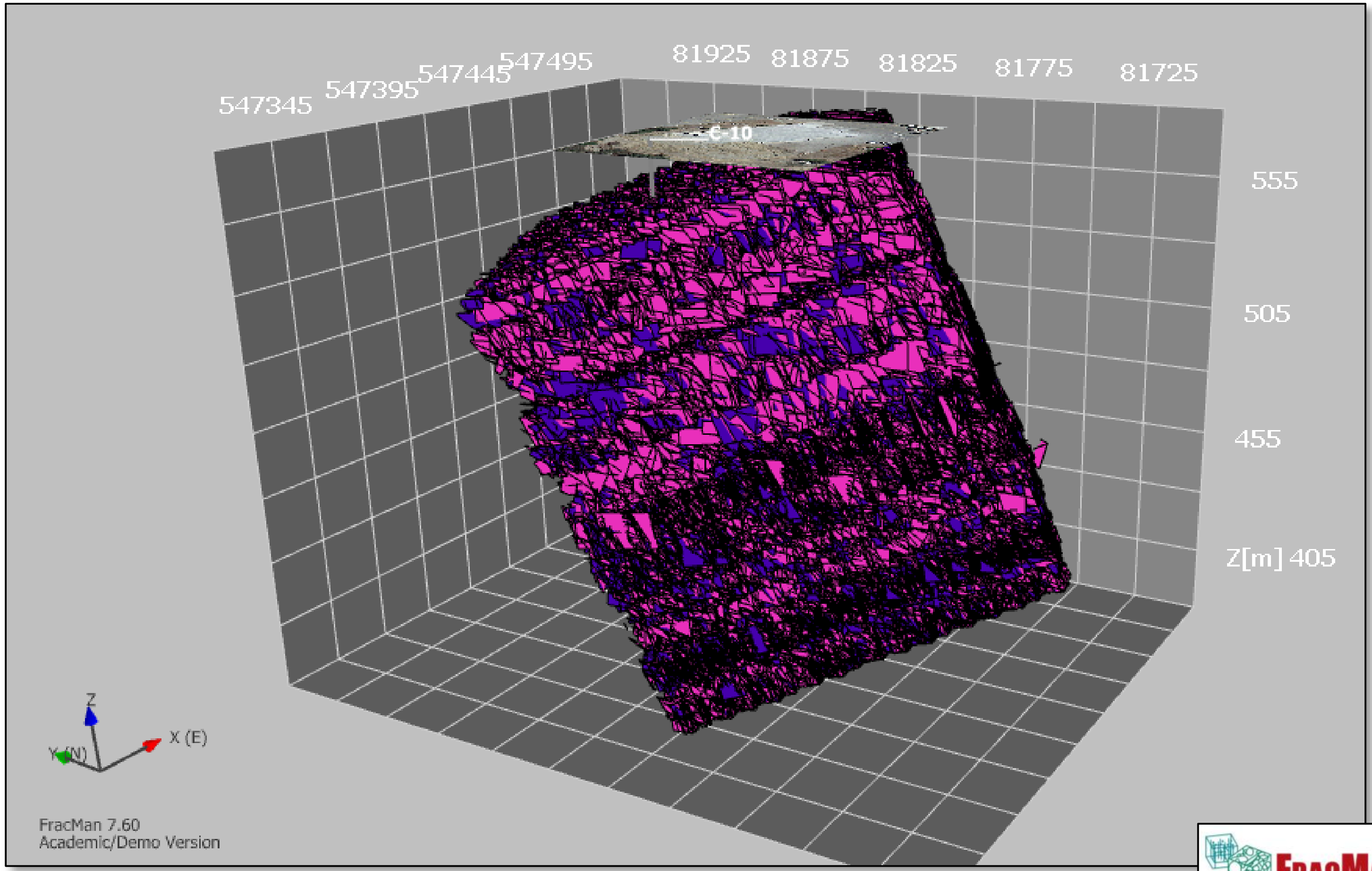
Fracture Frequency of Each Mechanical Unit Calculated



Fracture Frequency of Each Mechanical Unit Assigned to Respective Layer in Model Grid



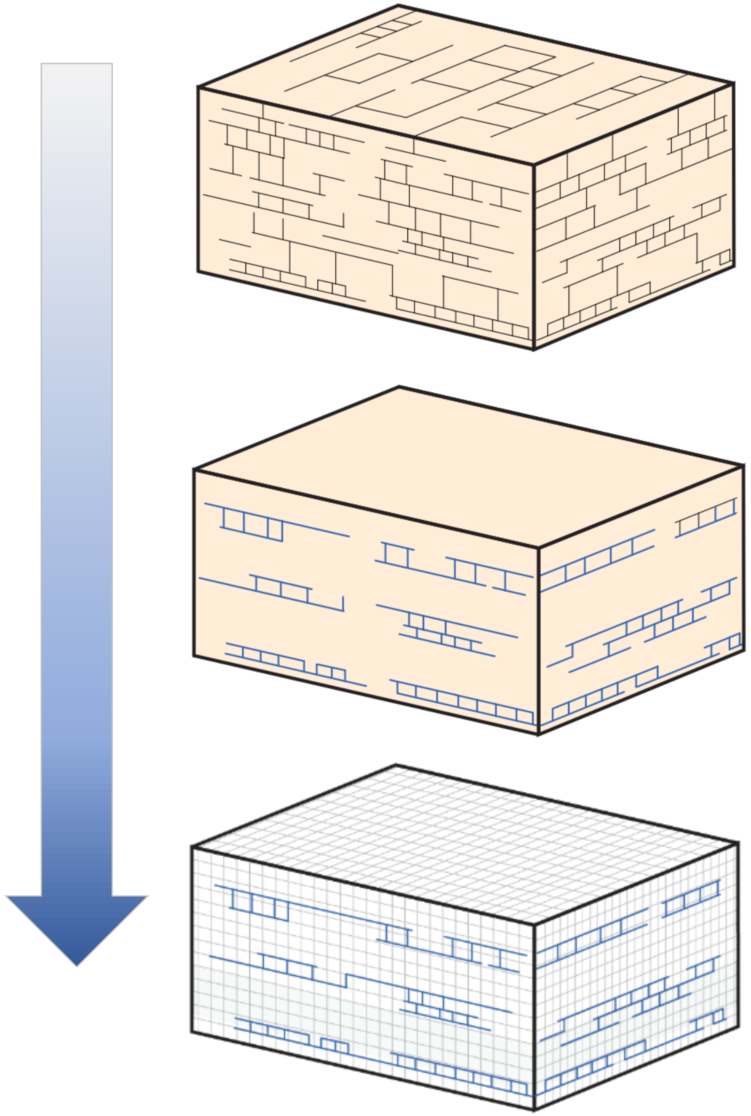
Static Fracture Model Informed by OTV Fracture Data



73,430 Simulated Fractures
Domain = 160 x 160 x 180m

Development of DFM model

Applying a DFM approach for model parameterization



1) Methods for Identifying / modeling mechanical stratigraphy

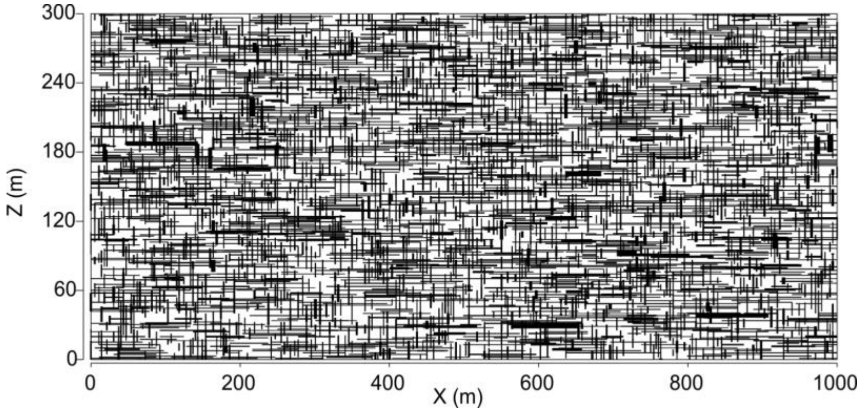
2) New Methods for Identifying and representing active fractures in model – Critical Reynolds Number (Re_c) Approach

3) Results: Run 2D / 3D Flow & Transport simulation using the active fracture system.

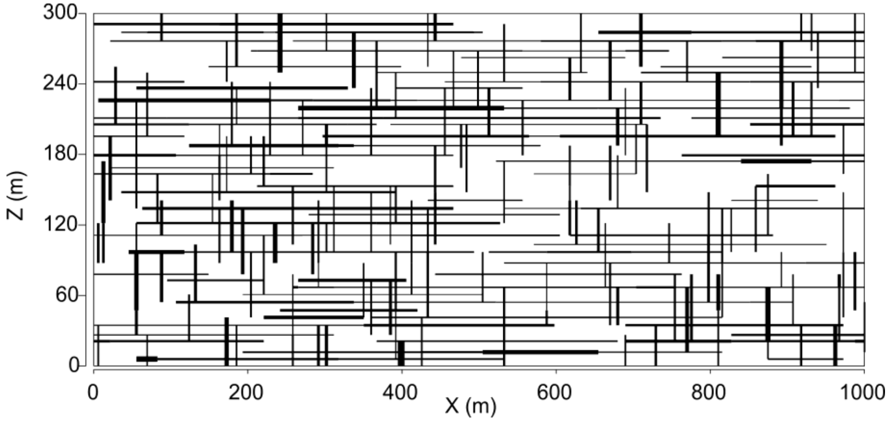
GQ 19
Groundwater Quality 2019

Number of Active Fractures Controls Plume Migration Distances

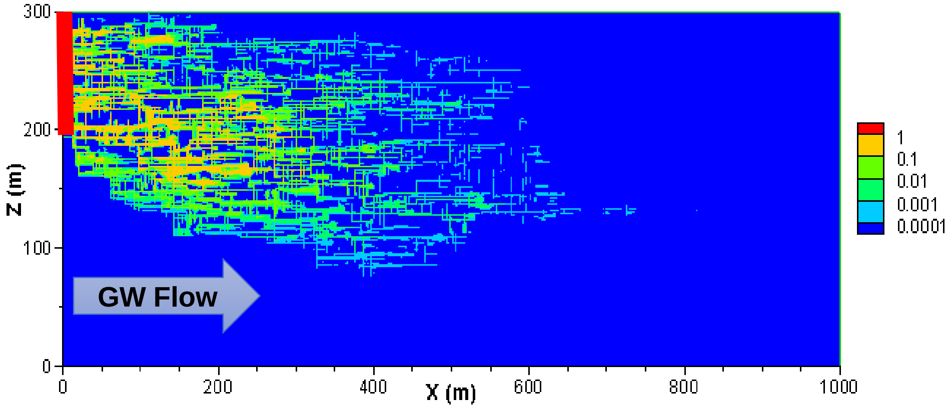
Dense Network



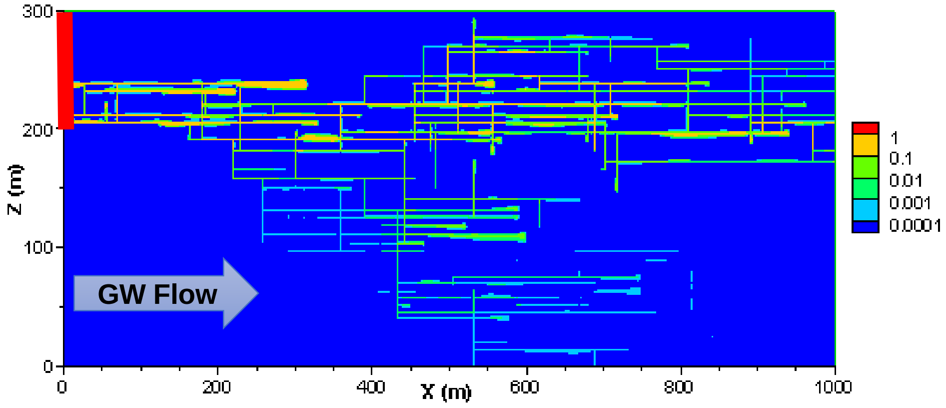
Sparse Network



Source 50 years



Source 50 years



Same bulk K but very different contaminant distribution

Borehole Fracture Identification Methods

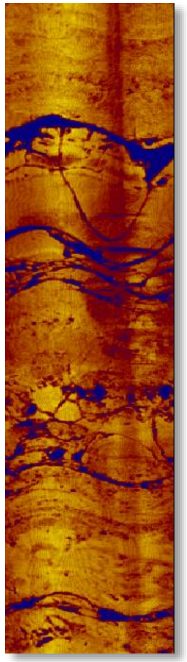
Static

Core Logging

Date (dd/mm/yy)	Core Run #	Dist. to Start of Feature	Dist. to End of Feature	Fracture	Hairline Fracture	Series of Fxs	Irreg micro Fx	BPP bed plane	Mineral	Rubble	Lithology Change	Colour Change	Other, vug,
28/11/12	1	0.3	0.3	X									
	1	0.6	0.6										
		0.85	0.85										
		1.1	1.1										
		1.3	1.3										
		1.55	1.55										
		1.75	1.75										
		2	2										
		2.35	2.35										
		2.65	2.65										
		3.7	3.75	X									
		3.85	—	X									
	2	0.05	0.15	X									
		0.35	—										
		0.60	0.90	X									
		0.90	0.95	X				X			X		
		1.35	1.40	X				X					
		1.65	1.70	X				X					
		1.75	1.80	X				X					
		1.95	2.0	X				X					
		2.2	2.45	X				X					
		2.3	2.4	X				X			X		
		2.8	—	X									
		3.6	3.7	X								X	
	3	0.35	—	X									

Borehole Imaging

Optical Televiewer



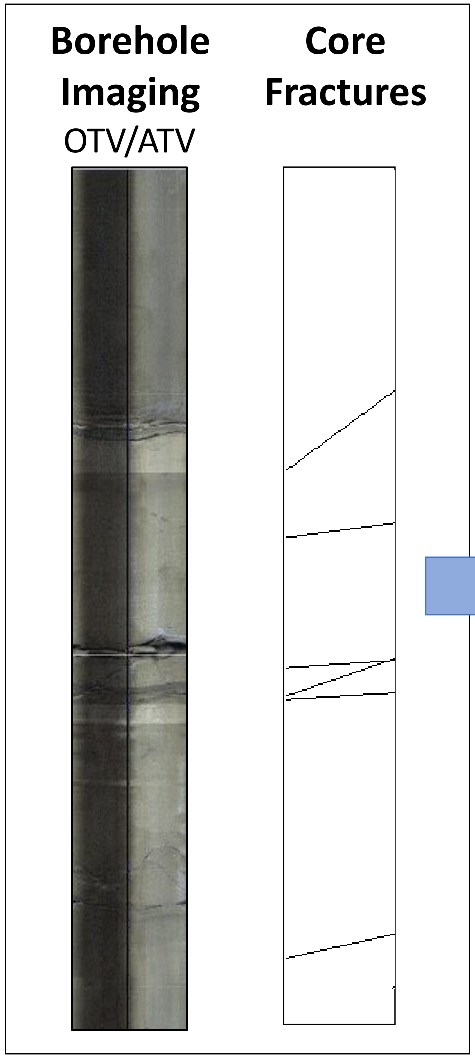
Acoustic Televiewer

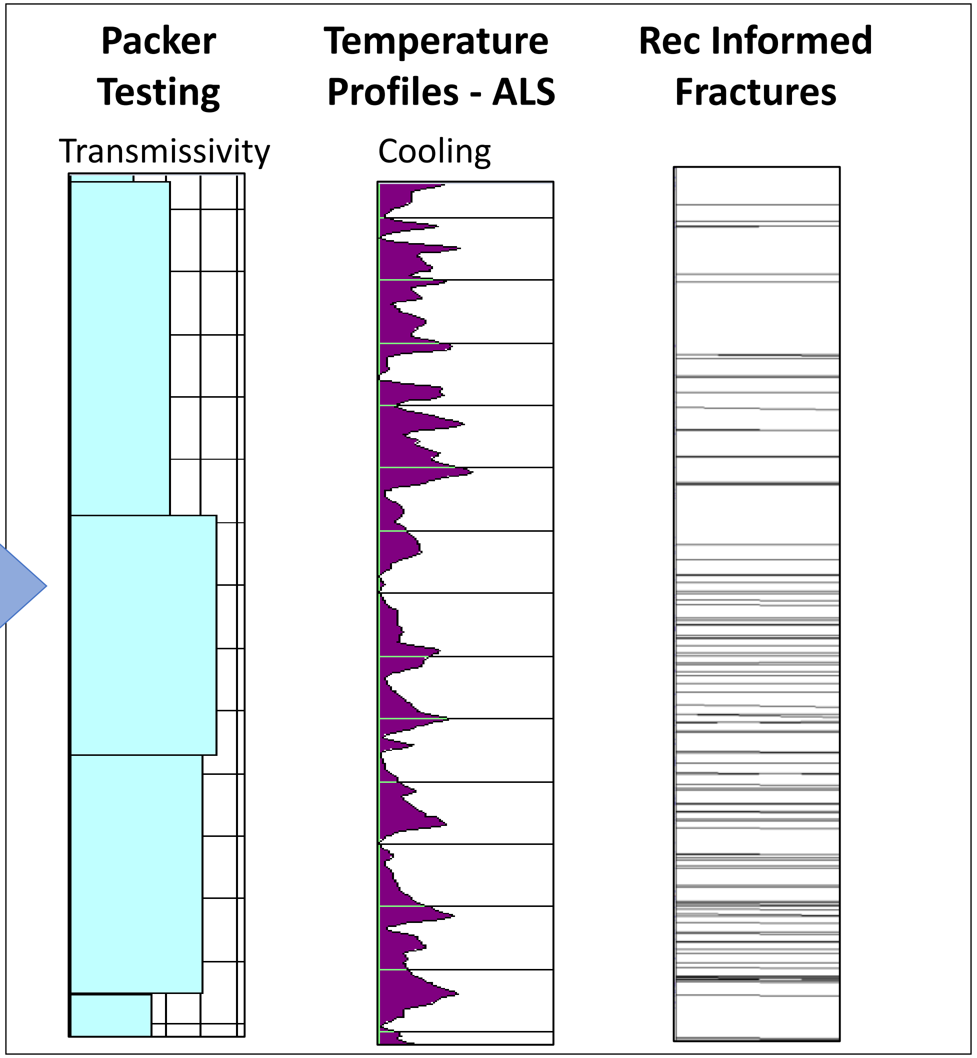
- Good for observing distribution of fractures in boreholes
- Provide limited information regarding which fractures have active flow

Fracture Identification Methods

Hydraulic

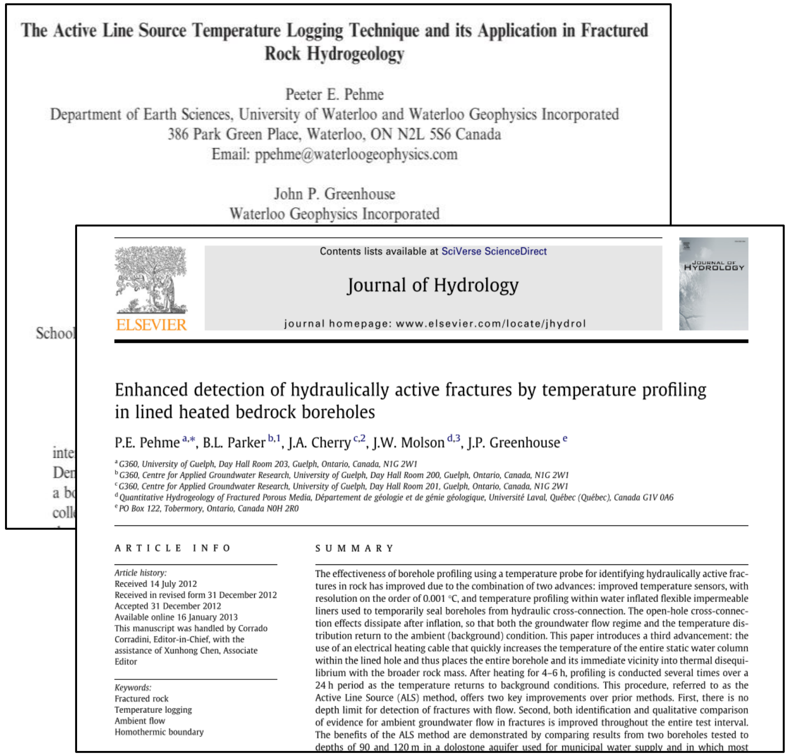
Visual Interpretation of fractures combined with evidence of flow to identify "active" fractures





ALS - High Resolution Temperature Logging Technique for Identifying Flowing Features in Lined Borehole

Pehme, P. E., et al. (2007). *Journal of Environmental & Engineering Geophysics*,



The Active Line Source Temperature Logging Technique and its Application in Fractured Rock Hydrogeology

Peeter E. Pehme
Department of Earth Sciences, University of Waterloo and Waterloo Geophysics Incorporated
386 Park Green Place, Waterloo, ON N2L 5S6 Canada
Email: ppehme@waterloogeophysics.com

John P. Greenhouse
Waterloo Geophysics Incorporated

Contents lists available at SciVerse ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Enhanced detection of hydraulically active fractures by temperature profiling in lined heated bedrock boreholes

P.E. Pehme [a,*], B.L. Parker [b,1], J.A. Cherry [c,2], J.W. Molson [d,3], J.P. Greenhouse [e]

[a] G360, University of Guelph, Day Hall Room 203, Guelph, Ontario, Canada, N1G 2W1
[b] G360, Centre for Applied Groundwater Research, University of Guelph, Day Hall Room 200, Guelph, Ontario, Canada, N1G 2W1
[c] G360, Centre for Applied Groundwater Research, University of Guelph, Day Hall Room 201, Guelph, Ontario, Canada, N1G 2W1
[d] Quantitative Hydrogeology of Fractured Porous Media, Département de géologie et de génie géologique, Université Laval, Québec (Québec), Canada G1V 0A6
[e] PO Box 122, Tobermory, Ontario, Canada N0H 2R0

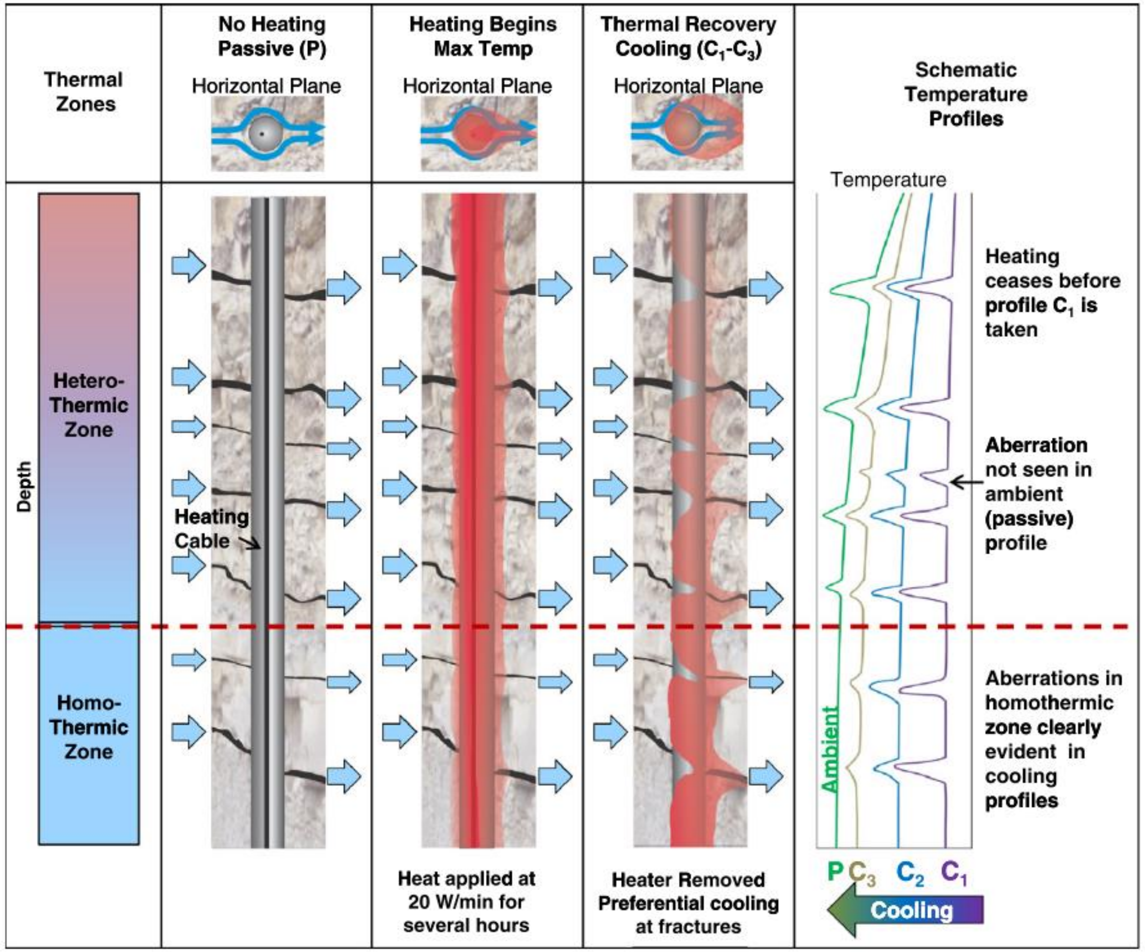
ARTICLE INFO

Article history:
Received 14 July 2012
Received in revised form 31 December 2012
Accepted 31 December 2012
Available online 16 January 2013
This manuscript was handled by Corrado Corradini, Editor-in-Chief, with the assistance of Xunhong Chen, Associate Editor

Keywords:
Fractured rock
Temperature logging
Ambient flow
Homothermic boundary

SUMMARY

The effectiveness of borehole profiling using a temperature probe for identifying hydraulically active fractures in rock has improved due to the combination of two advances: improved temperature sensors, with resolution on the order of 0.001 °C, and temperature profiling within water inflated flexible impermeable liners used to temporarily seal boreholes from hydraulic cross-connection. The open-hole cross-connection effects dissipate after inflation, so that both the groundwater flow regime and the temperature distribution return to the ambient (background) condition. This paper introduces a third advancement: the use of an electrical heating cable that quickly increases the temperature of the entire static water column within the lined hole and thus places the entire borehole and its immediate vicinity into thermal disequilibrium with the broader rock mass. After heating for 4–6 h, profiling is conducted several times over a 24 h period as the temperature returns to background conditions. This procedure, referred to as the Active Line Source (ALS) method, offers two key improvements over prior methods. First, there is no depth limit for detection of fractures with flow. Second, both identification and qualitative comparison of evidence for ambient groundwater flow in fractures is improved throughout the entire test interval. The benefits of the ALS method are demonstrated by comparing results from two boreholes tested to depths of 90 and 120 m in a dolostone aquifer used for municipal water supply and in which most



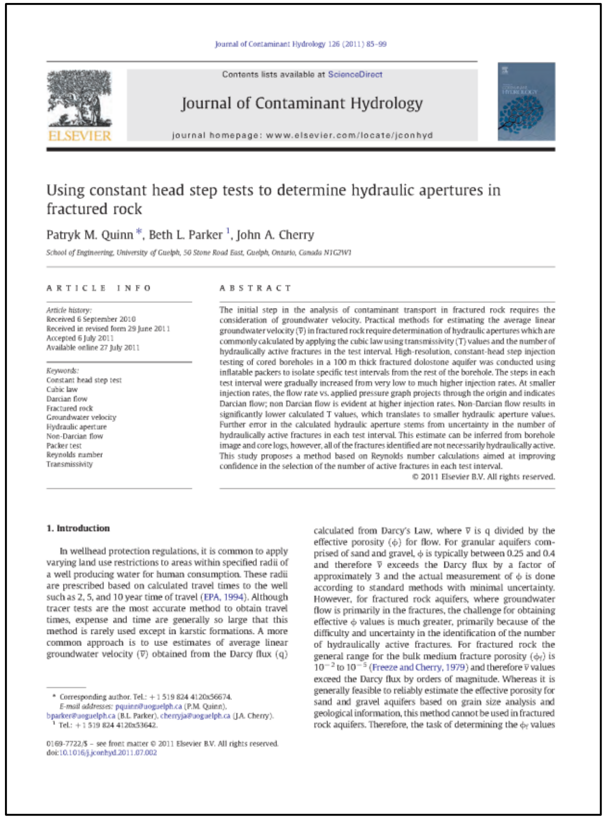
Pehme, P. E., et al. (2013). *Journal of Hydrology*

NEW CRITICAL REYNOLDS NUMBER (RE_C) ANALYSIS FOR ESTIMATING DISTRIBUTION OF PERMEABLE FRACTURES IN BOREHOLES

- Quantifying the distribution of permeable fractures using <u>fluid mechanical behaviour</u> – Onset of non-Darcian flow : Critical Reynolds Number (Re_c)

- Requires Constant Head Step Tests in short isolated packer intervals

- Uses visual physical fractures (Core, OTV, ATV) to constrain analysis.



Journal of Contaminant Hydrology 126 (2011) 85–99

Contents lists available at ScienceDirect

Journal of Contaminant Hydrology

journal homepage: www.elsevier.com/locate/jconhyd

Using constant head step tests to determine hydraulic apertures in fractured rock

Patryk M. Quinn *, Beth L. Parker [1], John A. Cherry

School of Engineering, University of Guelph, 50 Stone Road East, Guelph, Ontario, Canada N1G2W1

ARTICLE INFO

Article history:
Received 6 September 2010
Received in revised form 29 June 2011
Accepted 6 July 2011
Available online 27 July 2011

Keywords:
Constant head step test
Cubic law
Darcian flow
Fractured rock
Groundwater velocity
Hydraulic aperture
Non-Darcian flow
Packer test
Reynolds number
Transmissivity

ABSTRACT

The initial step in the analysis of contaminant transport in fractured rock requires the consideration of groundwater velocity. Practical methods for estimating the average linear groundwater velocity ($\overline{v}$) in fractured rock require determination of hydraulic apertures which are commonly calculated by applying the cubic law using transmissivity (T) values and the number of hydraulically active fractures in the test interval. High-resolution, constant-head step injection testing of cored boreholes in a 100 m thick fractured dolostone aquifer was conducted using inflatable packers to isolate specific test intervals from the rest of the borehole. The steps in each test interval were gradually increased from very low to much higher injection rates. At smaller injection rates, the flow rate vs. applied pressure graph projects through the origin and indicates Darcian flow; non Darcian flow is evident at higher injection rates. Non-Darcian flow results in significantly lower calculated T values, which translates to smaller hydraulic aperture values. Further error in the calculated hydraulic aperture stems from uncertainty in the number of hydraulically active fractures in each test interval. This estimate can be inferred from borehole image and core logs, however, all of the fractures identified are not necessarily hydraulically active. This study proposes a method based on Reynolds number calculations aimed at improving confidence in the selection of the number of active fractures in each test interval.

© 2011 Elsevier B.V. All rights reserved.

1. Introduction

In wellhead protection regulations, it is common to apply varying land use restrictions to areas within specified radii of a well producing water for human consumption. These radii are prescribed based on calculated travel times to the well such as 2, 5, and 10 year time of travel (EPA, 1994). Although tracer tests are the most accurate method to obtain travel times, expense and time are generally so large that this method is rarely used except in karstic formations. A more common approach is to use estimates of average linear groundwater velocity ($\overline{v}$) obtained from the Darcy flux (q) calculated from Darcy's Law, where $\overline{v}$ is q divided by the effective porosity (ϕ) for flow. For granular aquifers comprised of sand and gravel, ϕ is typically between 0.25 and 0.4 and therefore $\overline{v}$ exceeds the Darcy flux by a factor of approximately 3 and the actual measurement of ϕ is done according to standard methods with minimal uncertainty. However, for fractured rock aquifers, where groundwater flow is primarily in the fractures, the challenge for obtaining effective ϕ values is much greater, primarily because of the difficulty and uncertainty in the identification of the number of hydraulically active fractures. For fractured rock the general range for the bulk medium fracture porosity (ϕ_f) is 10^{-2} to 10^{-5} (Freeze and Cherry, 1979) and therefore $\overline{v}$ values exceed the Darcy flux by orders of magnitude. Whereas it is generally feasible to reliably estimate the effective porosity for sand and gravel aquifers based on grain size analysis and geological information, this method cannot be used in fractured rock aquifers. Therefore, the task of determining the ϕ_f values

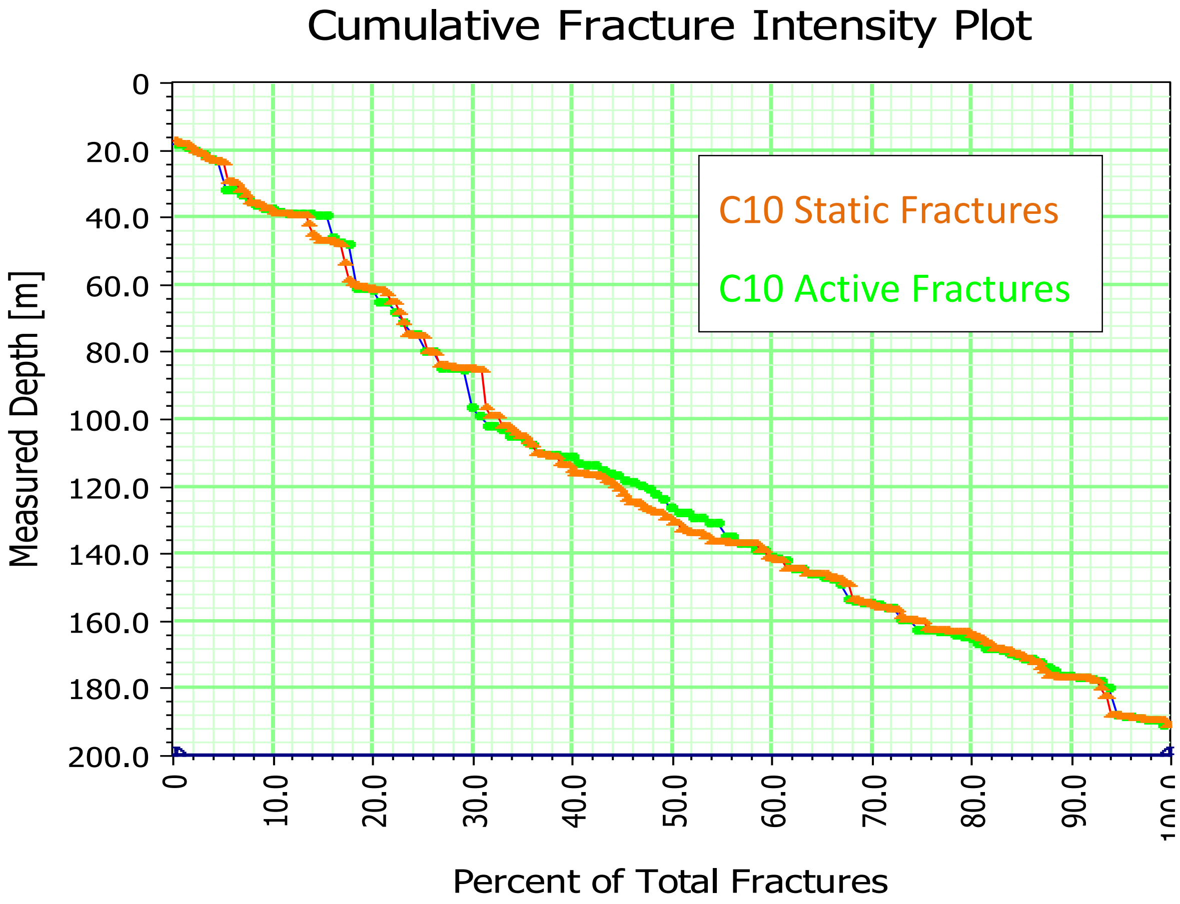
* Corresponding author. Tel.: +1 519 824 4120x56674.
E-mail addresses: pquinn@uoguelph.ca (P.M. Quinn), bparker@uoguelph.ca (B.L. Parker), cherryja@uoguelph.ca (J.A. Cherry).
[1] Tel.: +1 519 824 4120x53642.

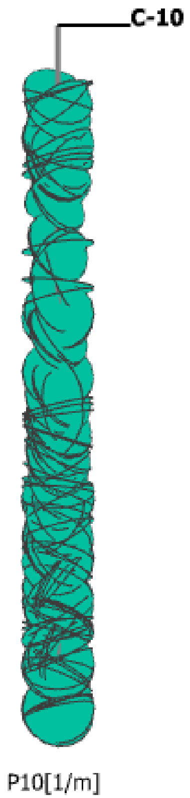
0169-7722/$ – see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.jconhyd.2011.07.002

Quinn et. al. 2011
Journal of Contaminant Hydrology

ACTIVE VS STATIC FRACTURE DISTRIBUTION

- ALS/Re_c analysis produced a 58% reduction from OTV fractures
- General pattern of fracture intensity (mechanical units) remains unchanged

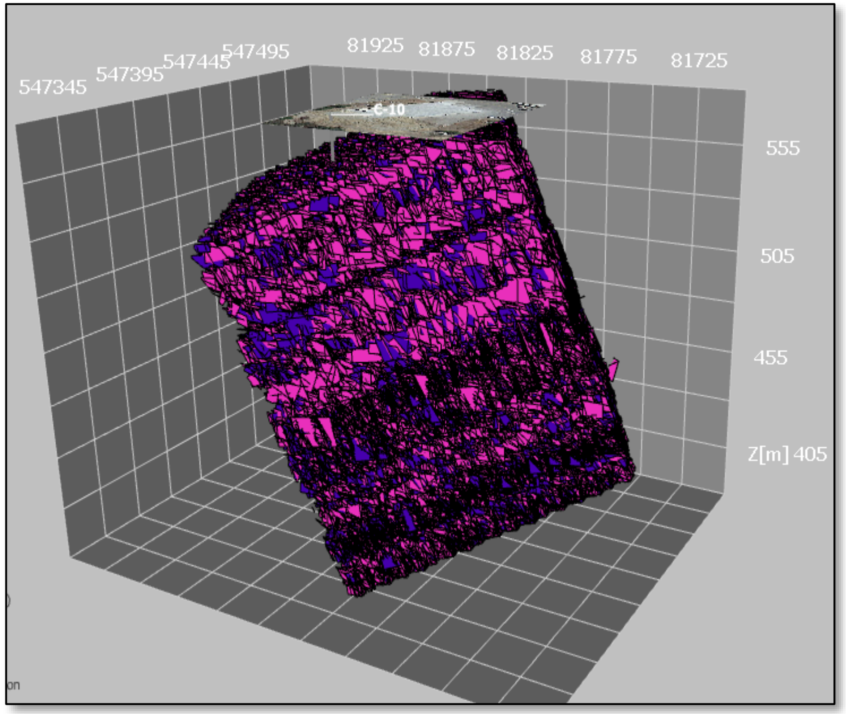




Re_c Informed Fractures Visualized in FracMan

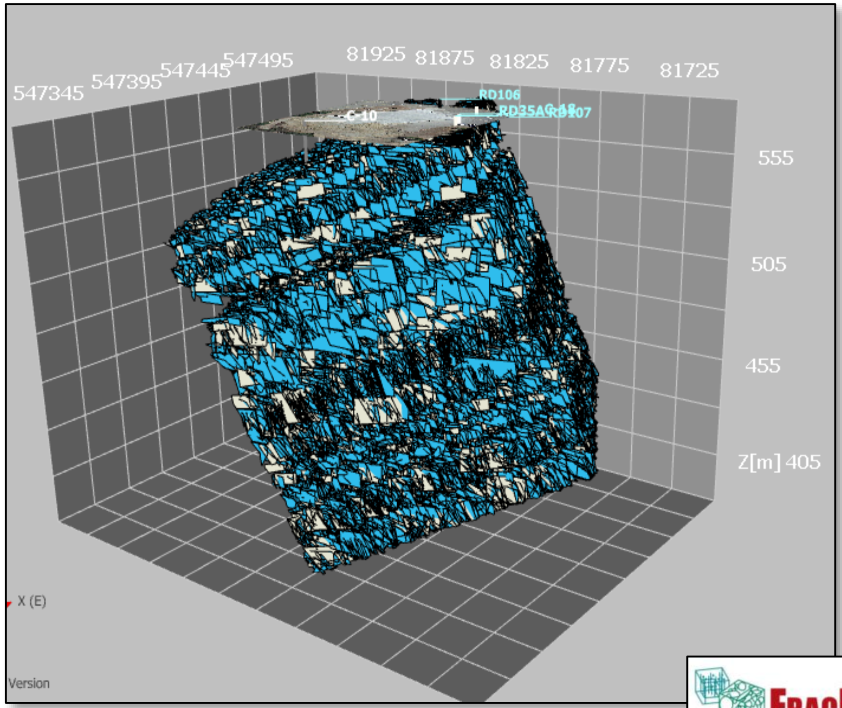
Field Informed Active Fracture Network Represented in 3D Model (FracMan)

Core/ATV/OTV Informed
"Static" Fracture Network

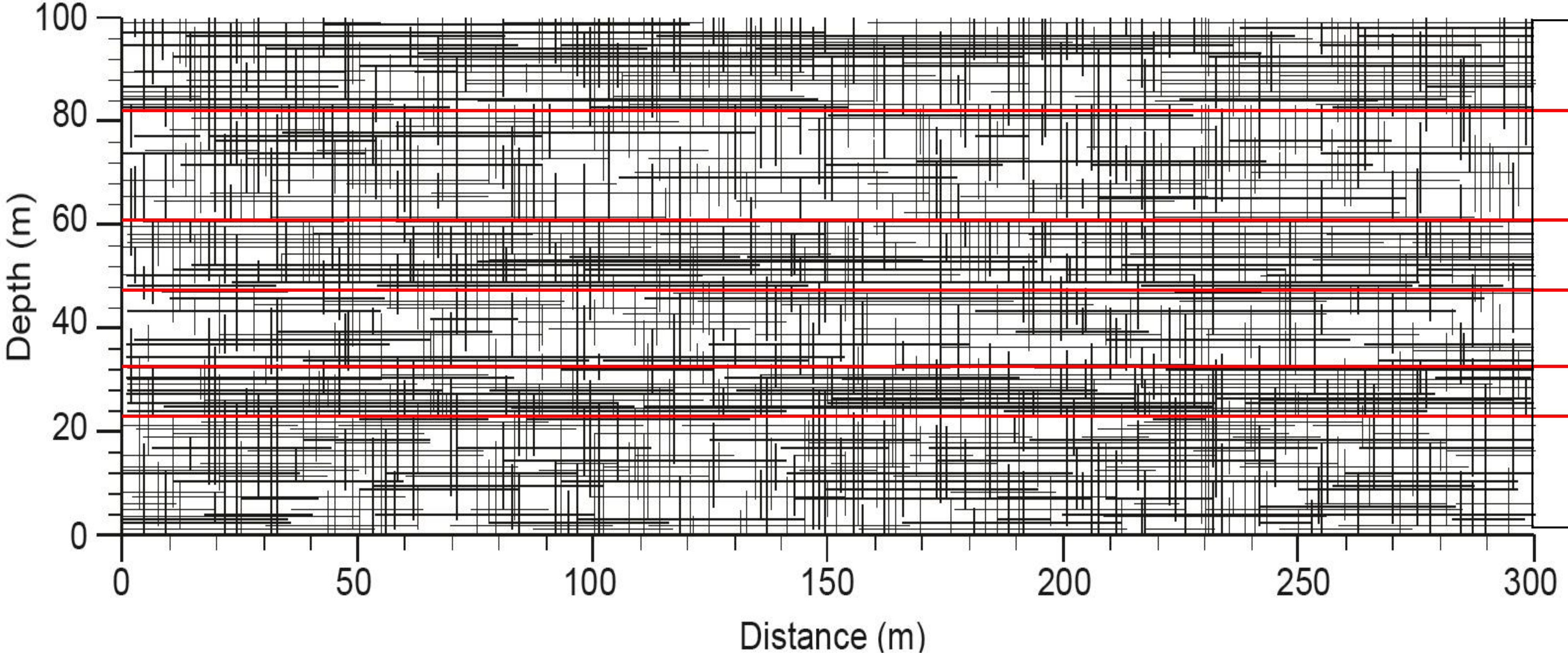


58% Reduction
In Fractures

Re_c / ALS Informed
"Active" Fracture Network

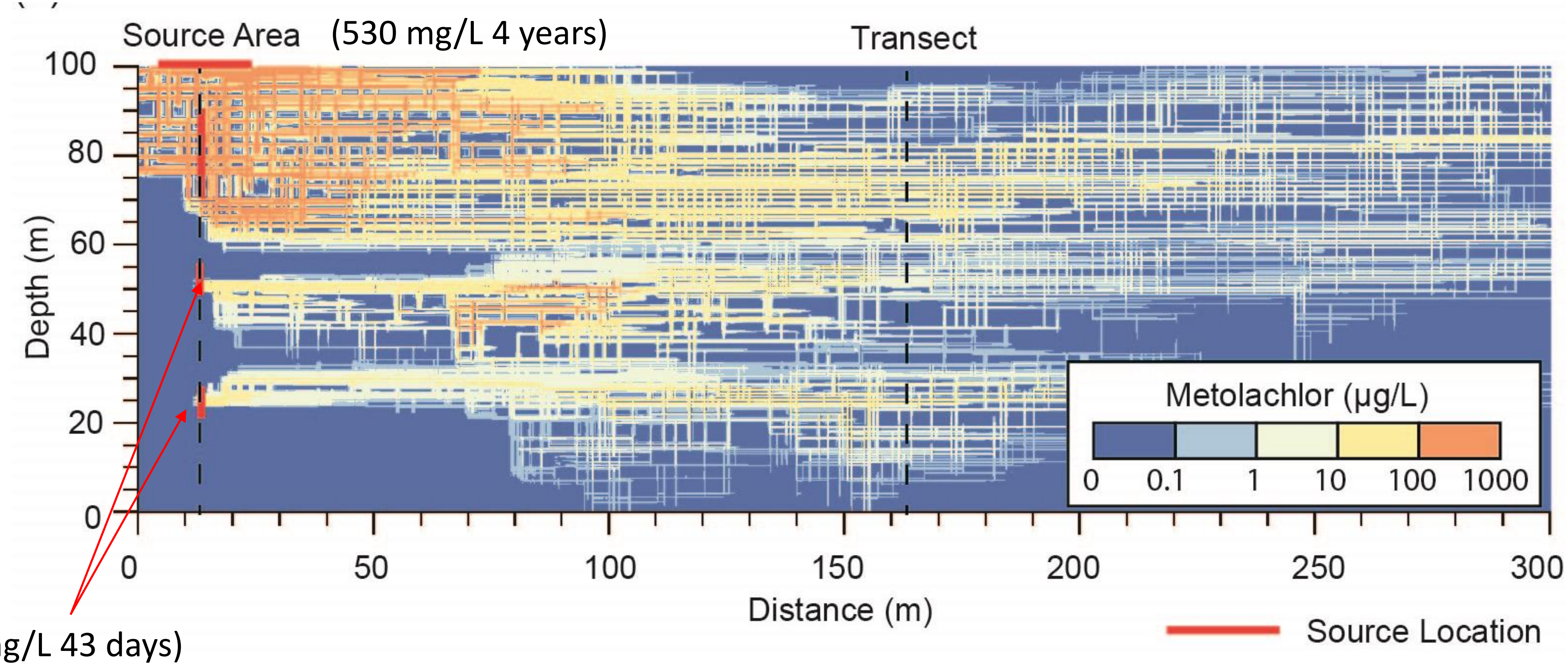


Field Informed "Active" Fracture Network Represented in 2D DFM Transport Model (FRACTRAN)



Mech. Unit	Mean Frequency (frac/m)
1	1.5
2	0.7
3	0.9
4	0.6
5	1.1
6	0.4

2D DFN Transport Model For Industrial Site in Cambridge, Ontario, Canada

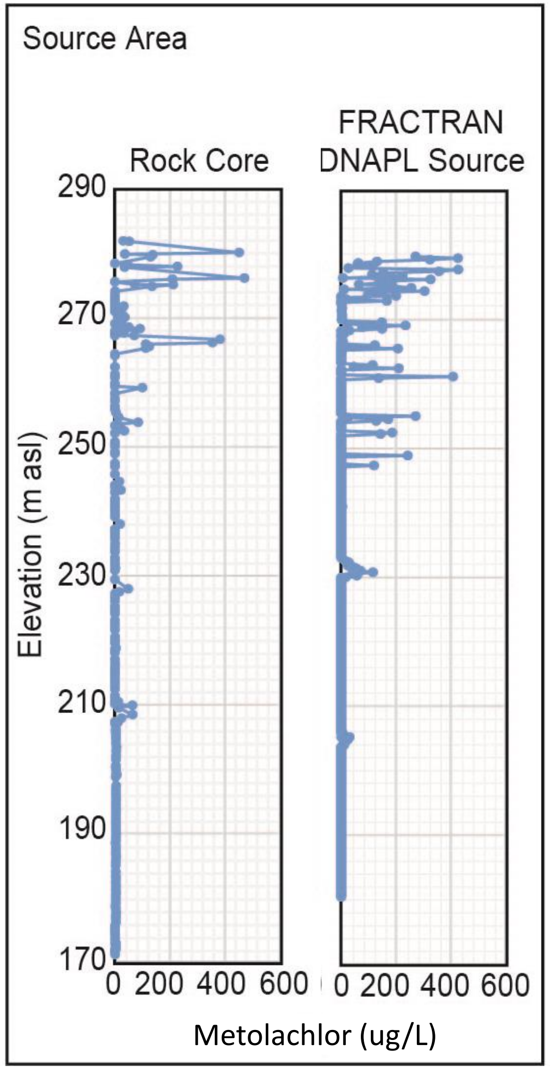


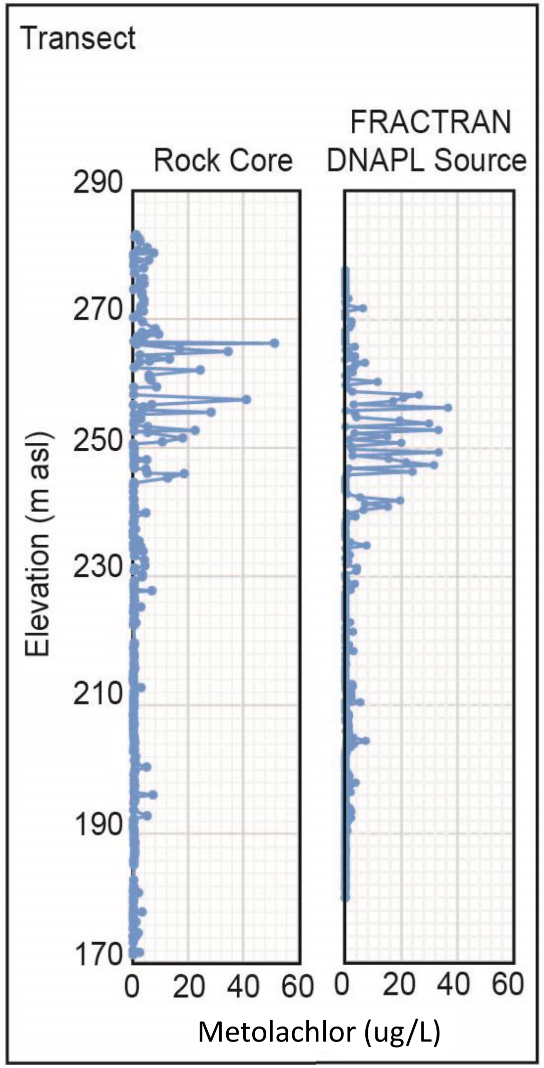
(530 mg/L 43 days)
Placed where highest
Concentrations of MET
Detected in rock core.

Ground Truthing DFM Model

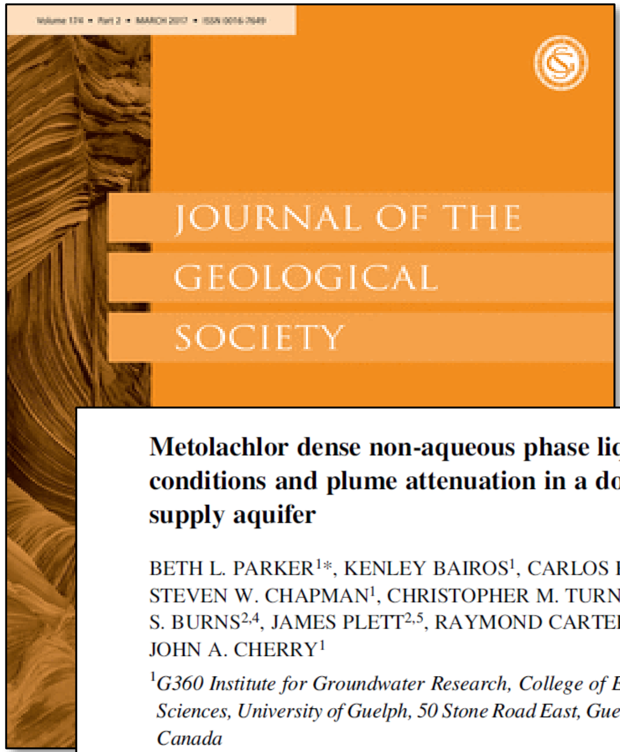
Simulated Contaminant Distribution vs Rock Pore Water Concentrations

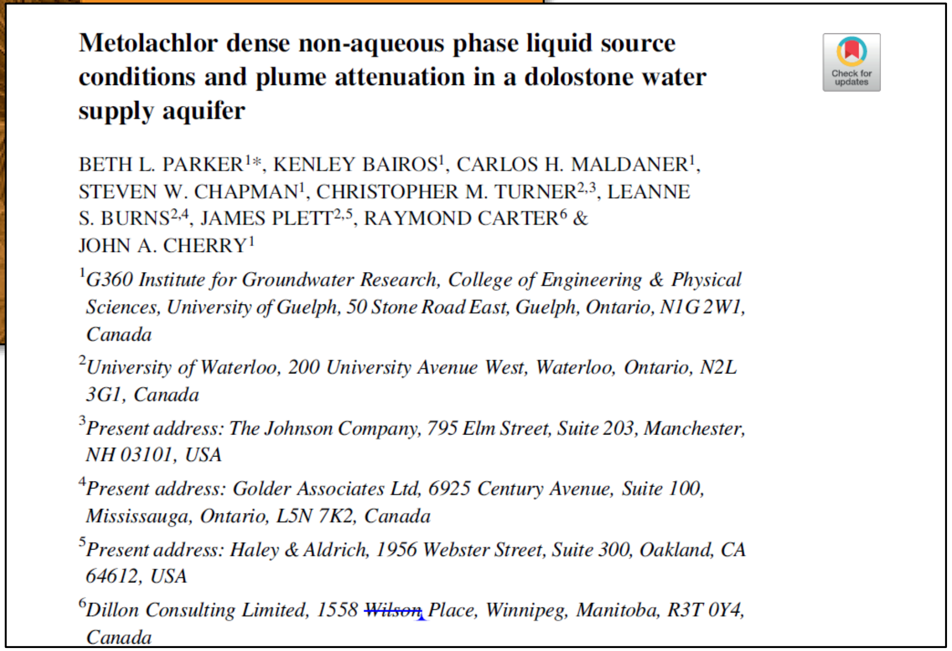
Field informed DFM model reproduces the vertical distribution of contamination observed in rock core.





PUBLISHED IN JOURNAL OF THE GEOLOGICAL SOCIETY OF LONDON





Metolachlor dense non-aqueous phase liquid source conditions and plume attenuation in a dolostone water supply aquifer

BETH L. PARKER[1]*, KENLEY BAIROS[1], CARLOS H. MALDANER[1], STEVEN W. CHAPMAN[1], CHRISTOPHER M. TURNER[2,3], LEANNE S. BURNS[2,4], JAMES PLETT[2,5], RAYMOND CARTER[6] & JOHN A. CHERRY[1]

[1]*G360 Institute for Groundwater Research, College of Engineering & Physical Sciences, University of Guelph, 50 Stone Road East, Guelph, Ontario, N1G 2W1, Canada*

[2]*University of Waterloo, 200 University Avenue West, Waterloo, Ontario, N2L 3G1, Canada*

[3]*Present address: The Johnson Company, 795 Elm Street, Suite 203, Manchester, NH 03101, USA*

[4]*Present address: Golder Associates Ltd, 6925 Century Avenue, Suite 100, Mississauga, Ontario, L5N 7K2, Canada*

[5]*Present address: Haley & Aldrich, 1956 Webster Street, Suite 300, Oakland, CA 64612, USA*

[6]*Dillon Consulting Limited, 1558 ~~Wilson~~ Place, Winnipeg, Manitoba, R3T 0Y4, Canada*

Parker *et. al.* 2018

Presents site conceptual model using high resolution DFM data sets and numerical modeling to show site source and plume evolution

Conclusions

- DFM Models are excellent tools for simulating transport in fractured rock, exploring uncertainty and testing conceptual models

- Require rigours DFM focused field approach to properly parameterize the fracture network

- Important to represent mechanical unit distribution and active fracture network for accurate representation of plume

Groundwater Quality 2019

Thank You

Acknowledgments

Beth Parker

Patryk Quinn (G^{360})

Pete Pehme (G^{360})

Boeing

NSERC

Syngenta

kbairos@g360group.org

www.g360group.org