Site Characterization Using Physical and Chemical Methodologies

Kent Novakowski

Queens University

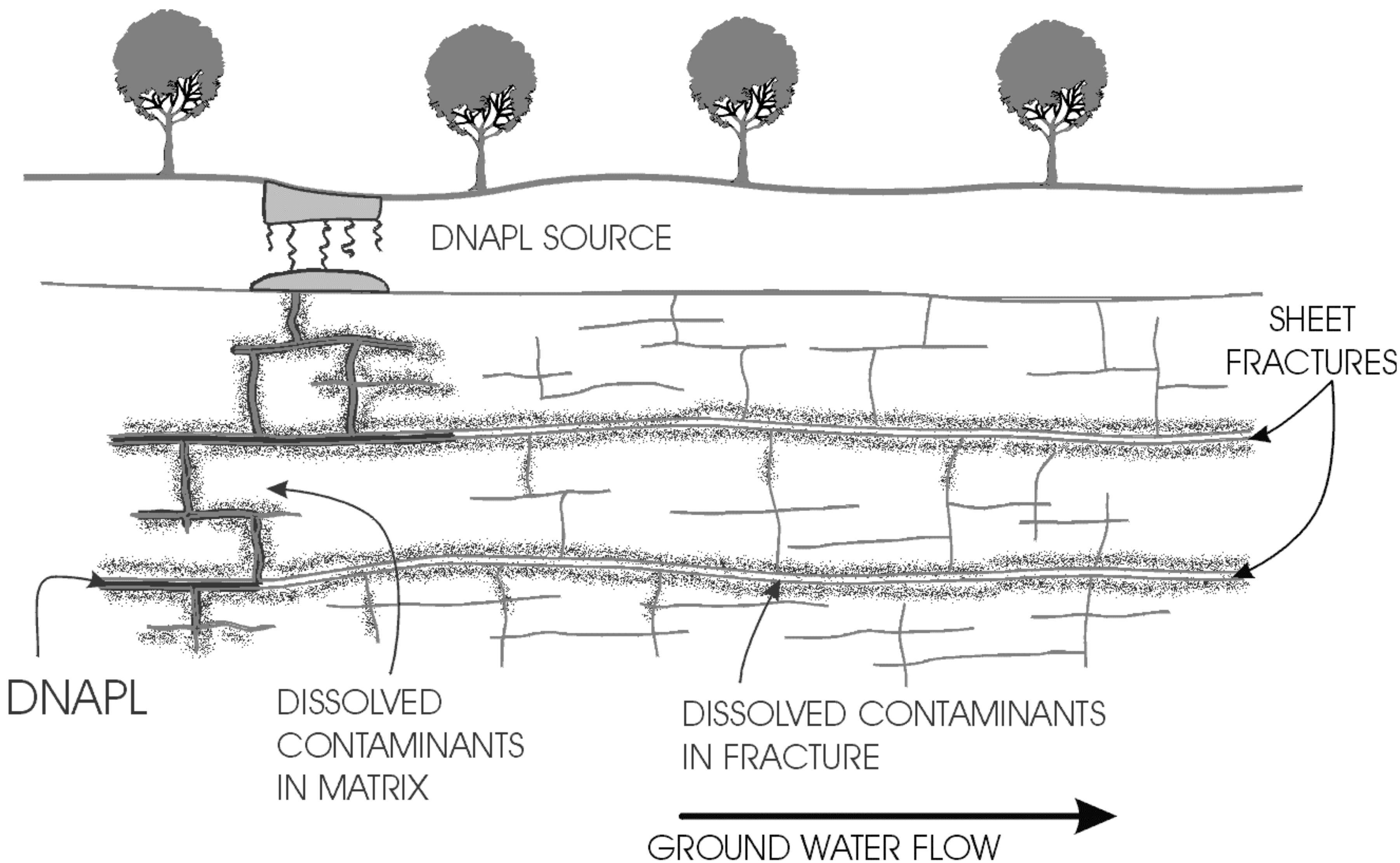
Kingston, ON

EPA Fractured Bedrock Workshop

United States Environmental Protection Agency

"...to protect human health and to safeguard the natural environment..."

Queen's University

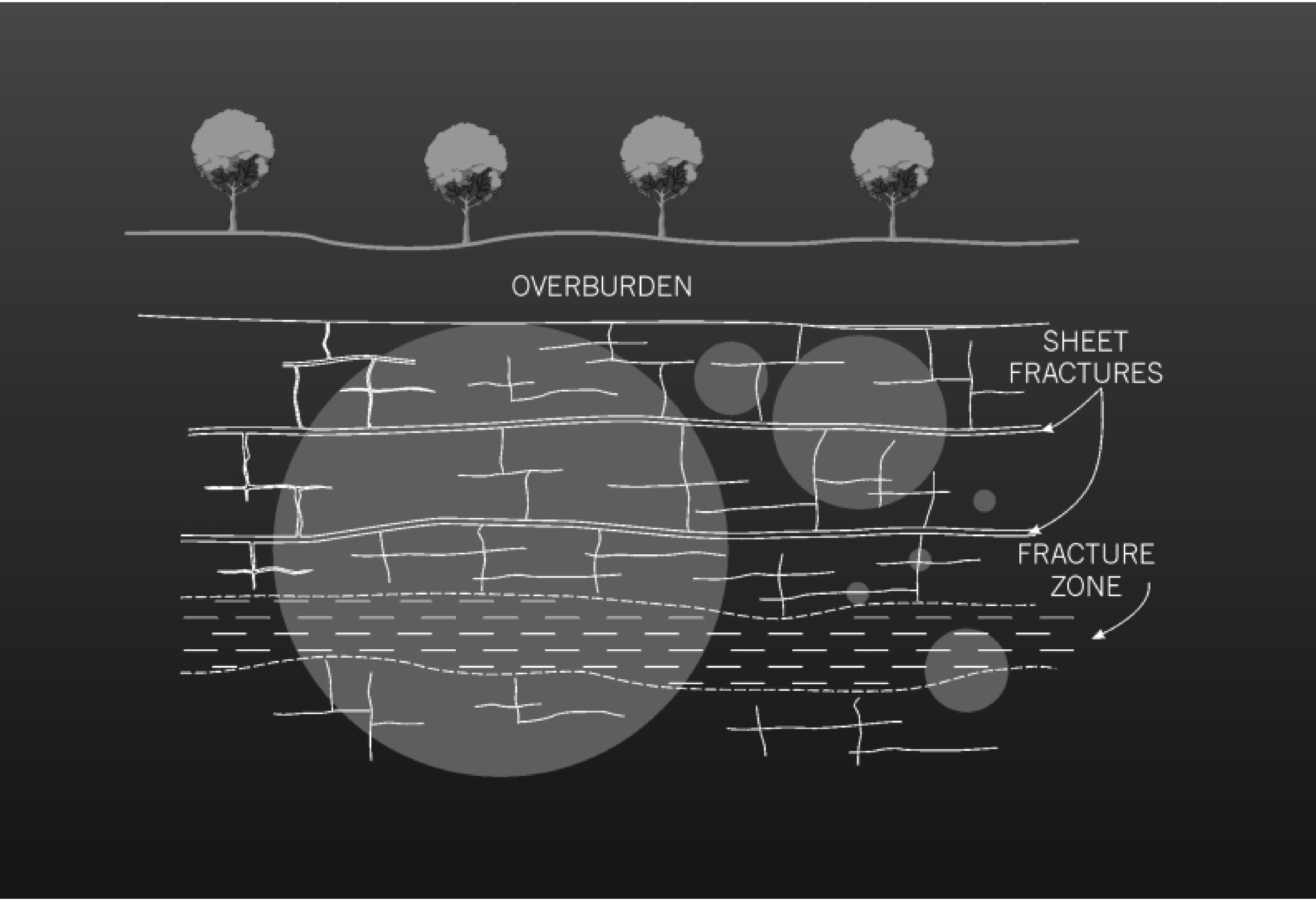

DNAPL SOURCE
SHEET
FRACTURES
DNAPL
DISSOLVED
CONTAMINANTS
IN MATRIX
DISSOLVED CONTAMINANTS
IN FRACTURE
GROUND WATER FLOW

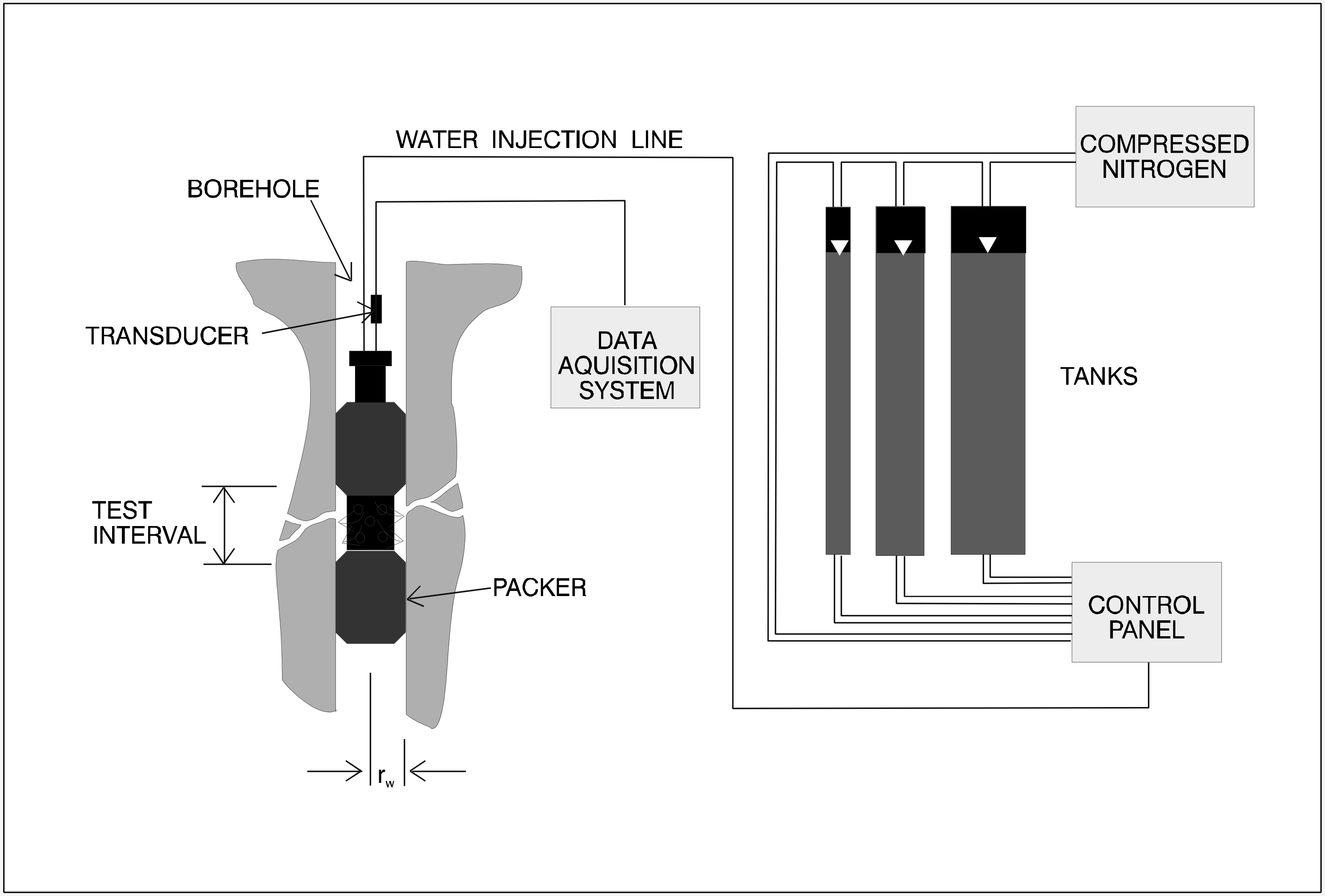
Conceptual Model Development

- Transport through discrete fracture pathways
- Pathway inter-connectivity
- Groundwater velocity
- Matrix diffusion
- Vertical fractures
- Modeling

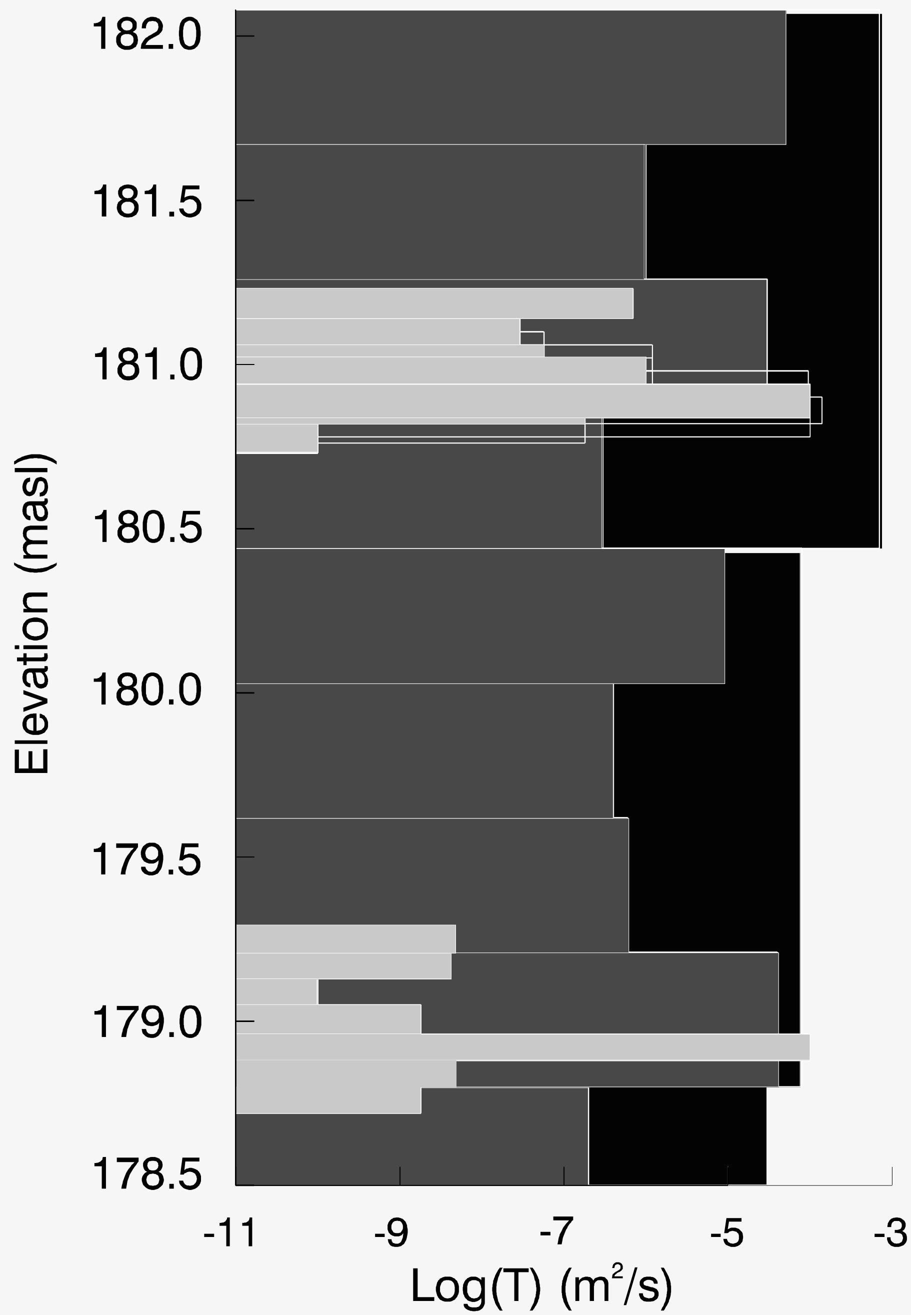
Discrete Fractures

- Very difficult to obtain hydraulic properties of specific fractures
- Geophysics is of limited use
- Measure hydraulics directly using an interval testing method
- Mean fracture spacing and scale play a significant role


OVERBURDEN
SHEET FRACTURES
FRACTURE ZONE

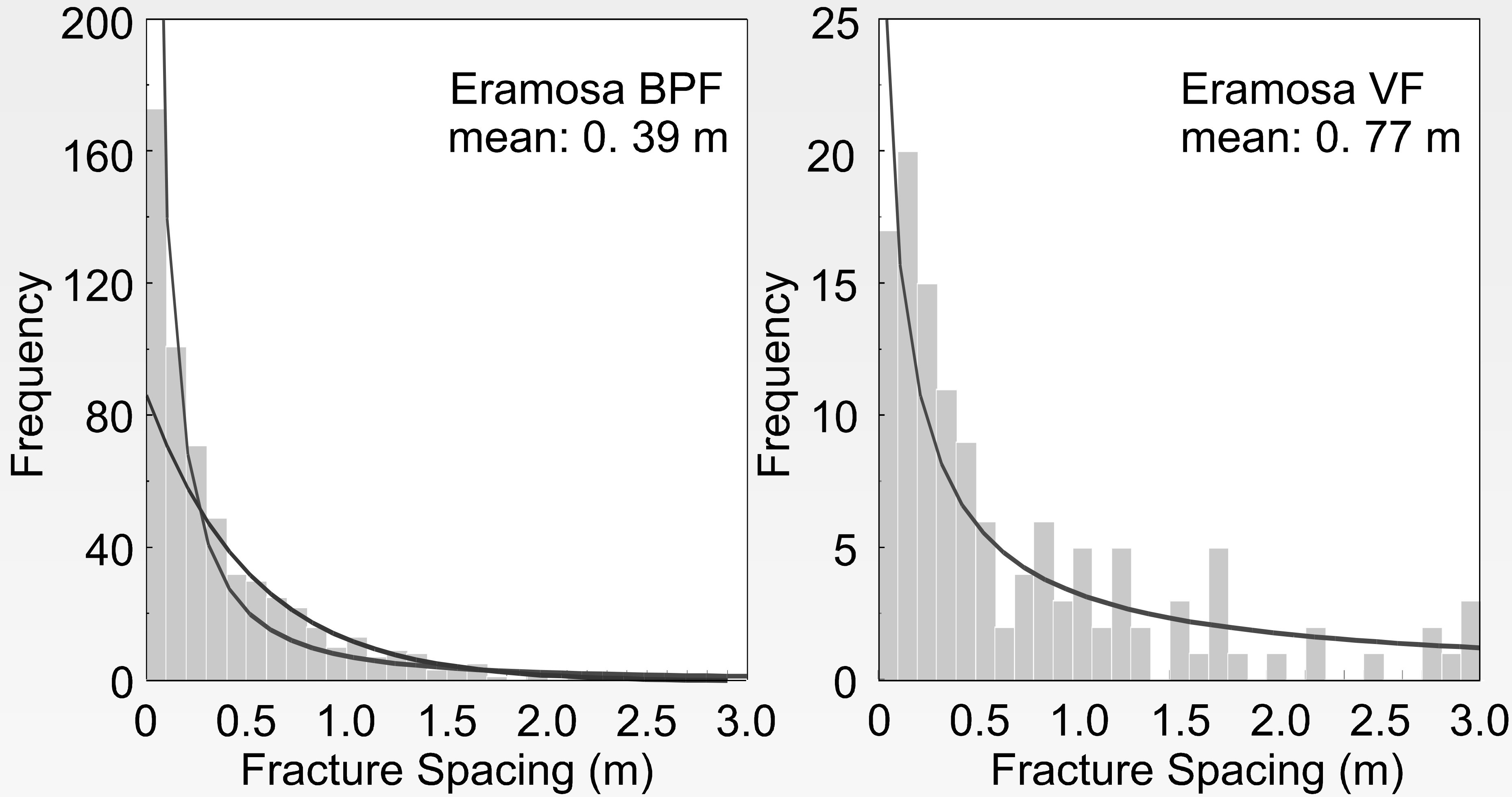

WATER INJECTION LINE
BOREHOLE
TRANSDUCER
TEST INTERVAL
PACKER
r_w
DATA AQUISITION SYSTEM
COMPRESSED NITROGEN
TANKS
CONTROL PANEL

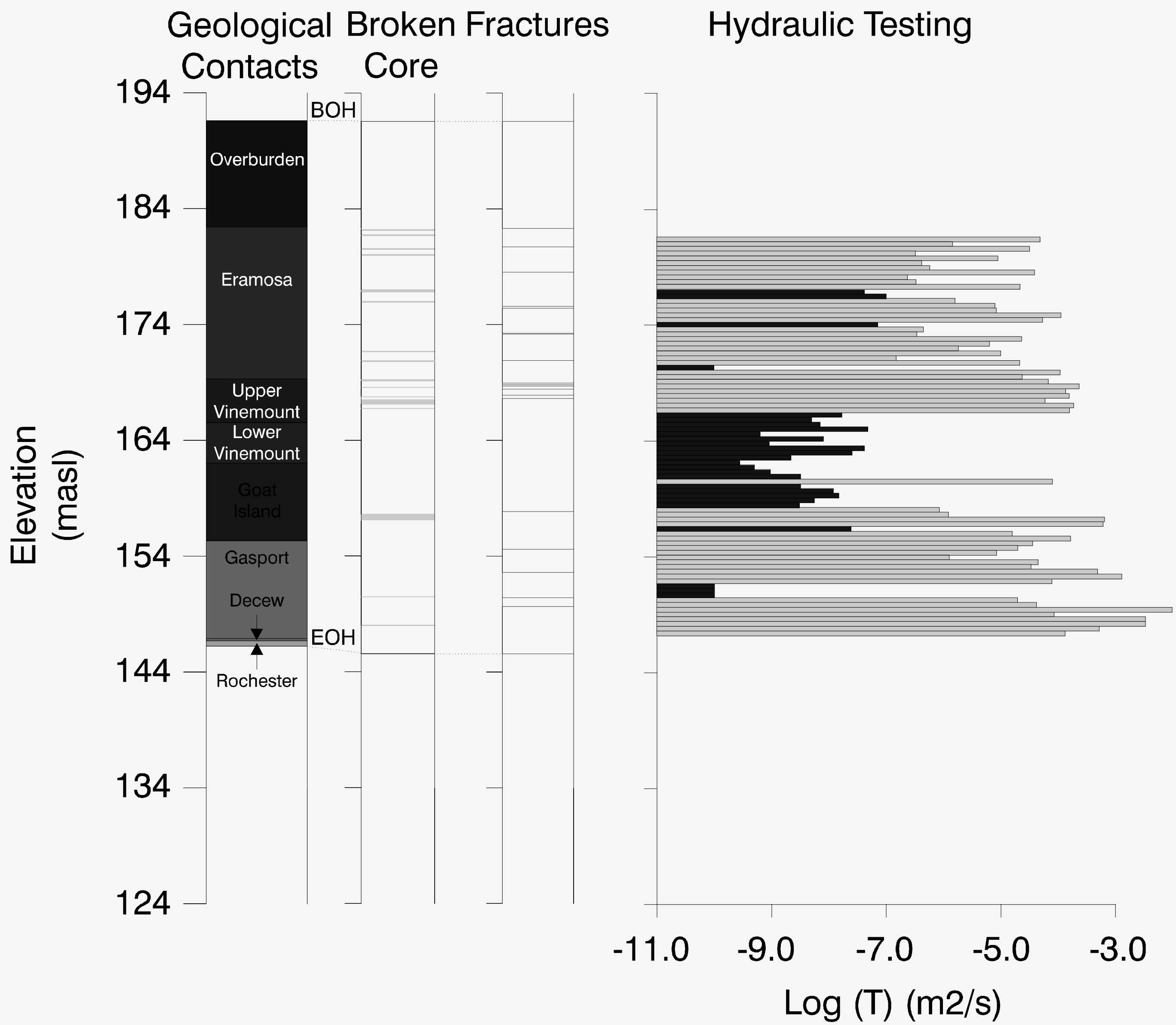
11/6/00


182.0
181.5
181.0
180.5
180.0
179.5
179.0
178.5
Elevation (masl)
-11
-9
-7
-5
-3
Log(T) (m2/s)

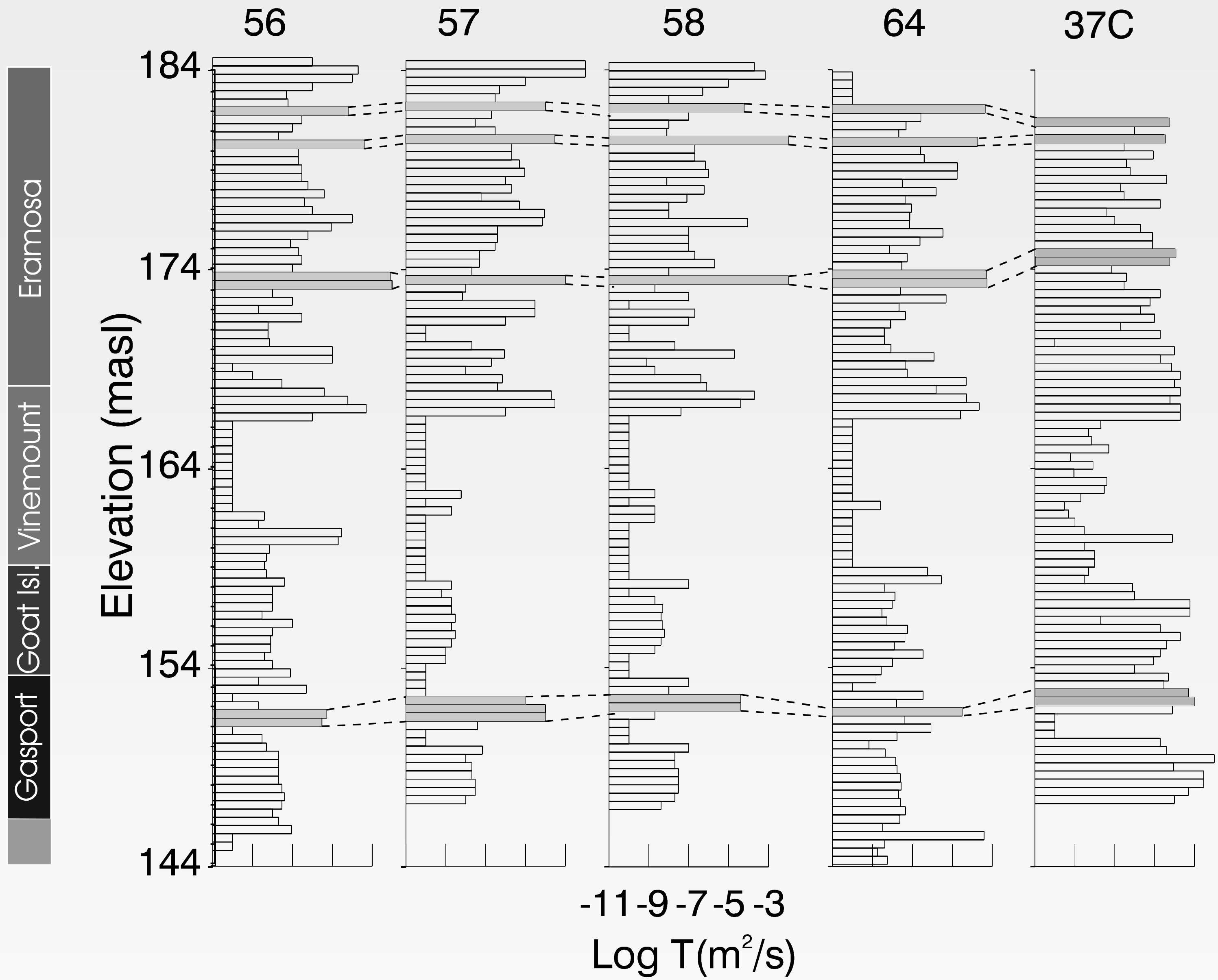
11/6/00

Fracture Spacings




Geological Contacts
Broken Core
Fractures
Hydraulic Testing
Elevation (masl)
194
184
174
164
154
144
134
124
BOH
EOH
Overburden
Eramosa
Upper Vinemount
Lower Vinemount
Goat Island
Gasport
Decew
Rochester
-11.0
-9.0
-7.0
-5.0
-3.0
Log (T) (m2/s)

11/6/00


56
57
58
64
37C
184
174
164
154
144
Elevation (masl)
Eramosa
Vinemount
Goat Isl.
Gasport
-11 -9 -7 -5 -3
Log T(m²/s)

11/6/00

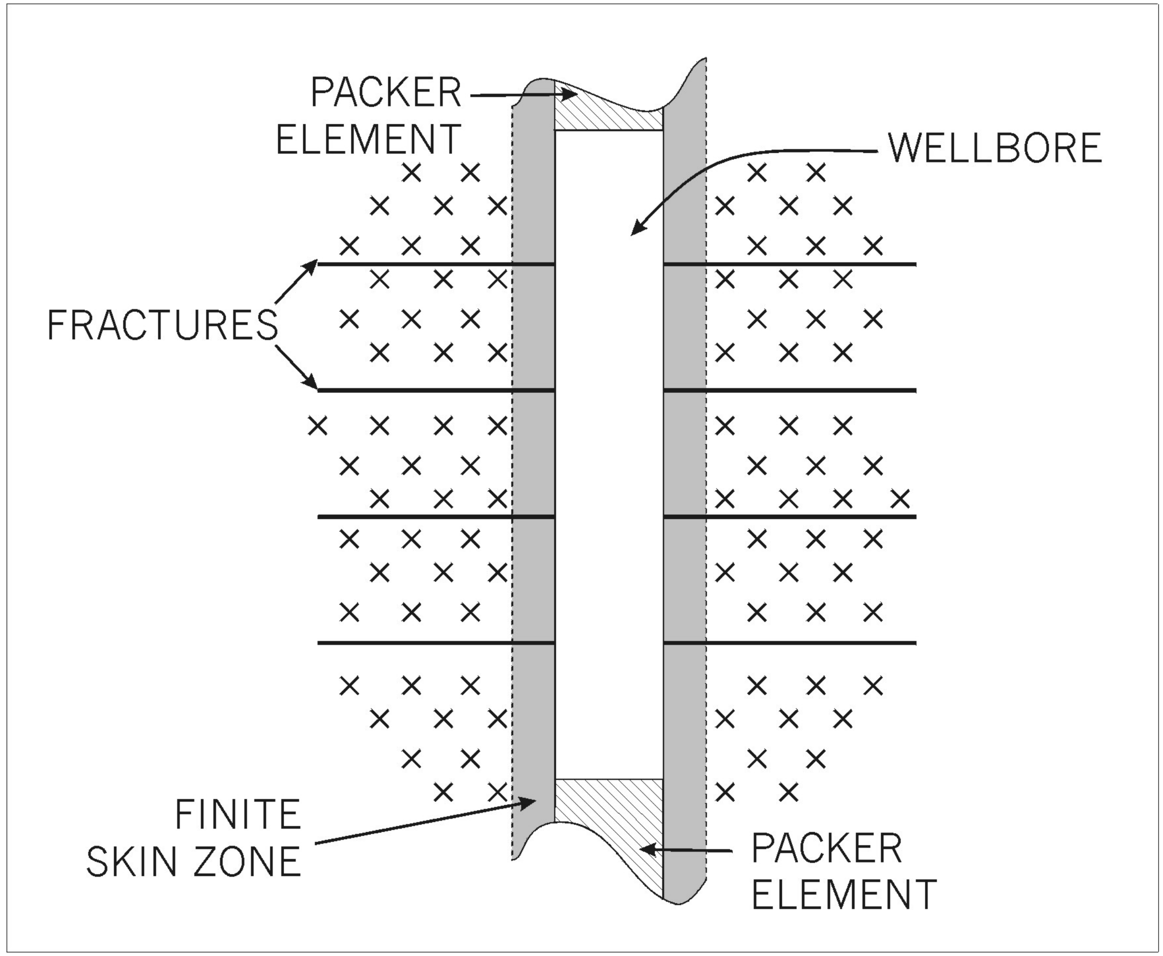
Groundwater Velocity

- Proportional to the square of the fracture aperture (cubic law)
- Darcy’s Law does not work
- Must know discrete fracture properties to predict velocity

Example

Four Fractures,
6-m interval

$T = 4x10^{-5}\ m^2/s$



Example

- Estimate velocity via Darcy's Law using T, i=0.001 and assuming a porosity of 1% = 0.06 m/day
- Equivalent single fracture aperture is 410 μm, thus velocity calculated using cubic law = 8.5 m/day

Example

- Assume fractures contribute evenly, aperture of each is then 257 μm
- Using the cubic law, the true velocity in each fracture is 3.4 m/day
- Detailed hydraulic testing results help this calculation immensely

Groundwater Velocity

- Measurement of hydraulic gradient another difficulty with velocity calculations
- Gradient often limited by “critical neck” at the network scale
- May be safest to use estimate of regional gradient and not direct measurement

Point Dilution Results from Smithville

Fracture	Depth (m.b.c.t.)	Aperture **(microns)**	N	v (m/day)	**dh/dx**
1	13.1	592	2	36-49	0.002-0.003
2	15.1	953	2	247-284	0.002-0.006
3	19.1	604	1	2	0.0001
4	19.9	638	1	4	0.0002
5	49.9	416	1	66	0.008

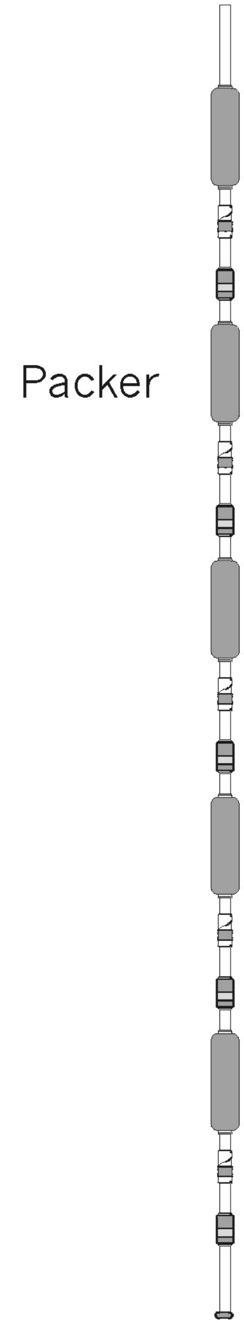
Hydraulic Head

- Very powerful information from which to infer connectivity
- Need hydraulic head over entire borehole (not just a discrete zone)
- Requires multi-level completions – the more discrete intervals the better

Example

Isolate intervals using packer elements

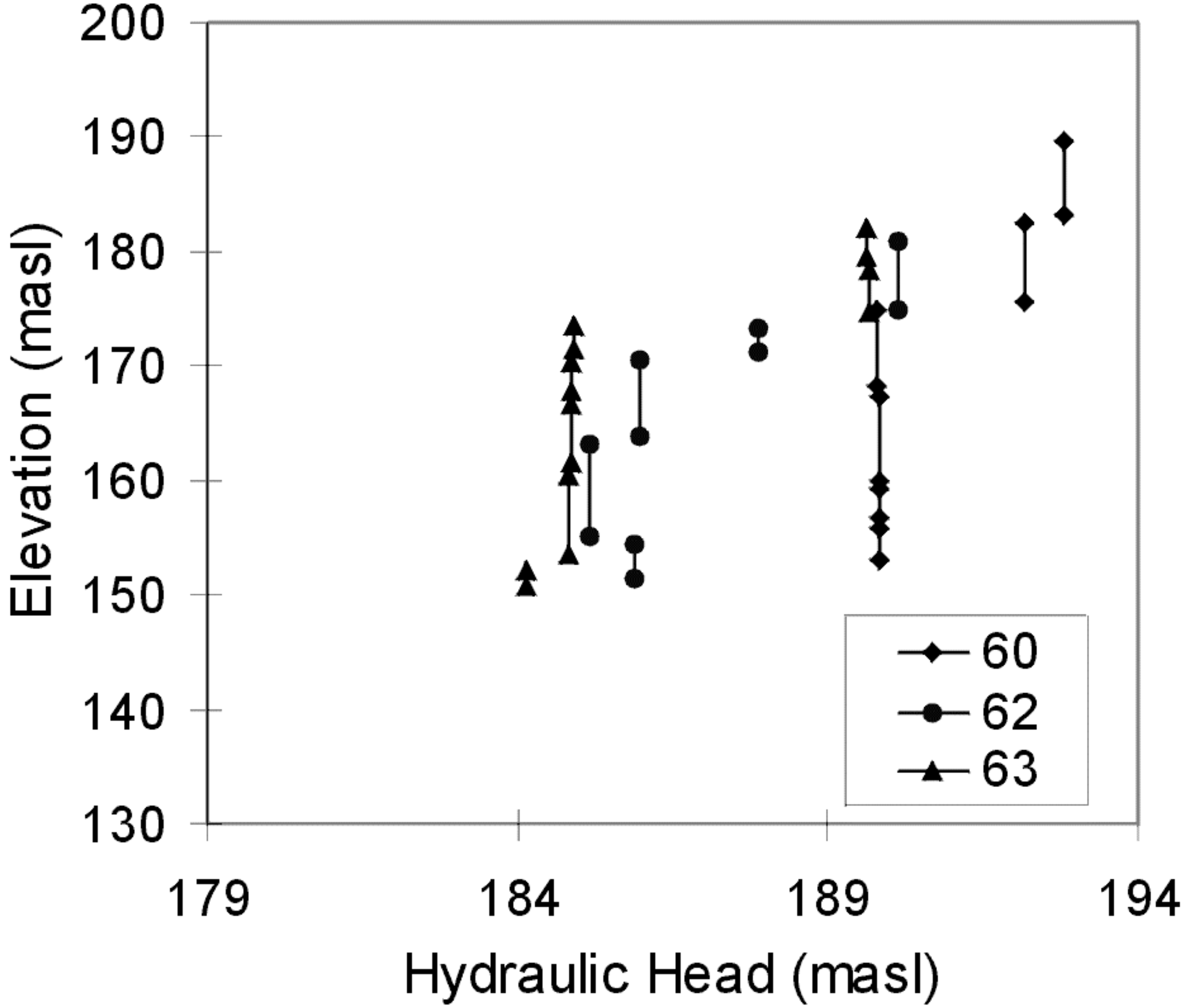
Measure hydraulic head in each interval

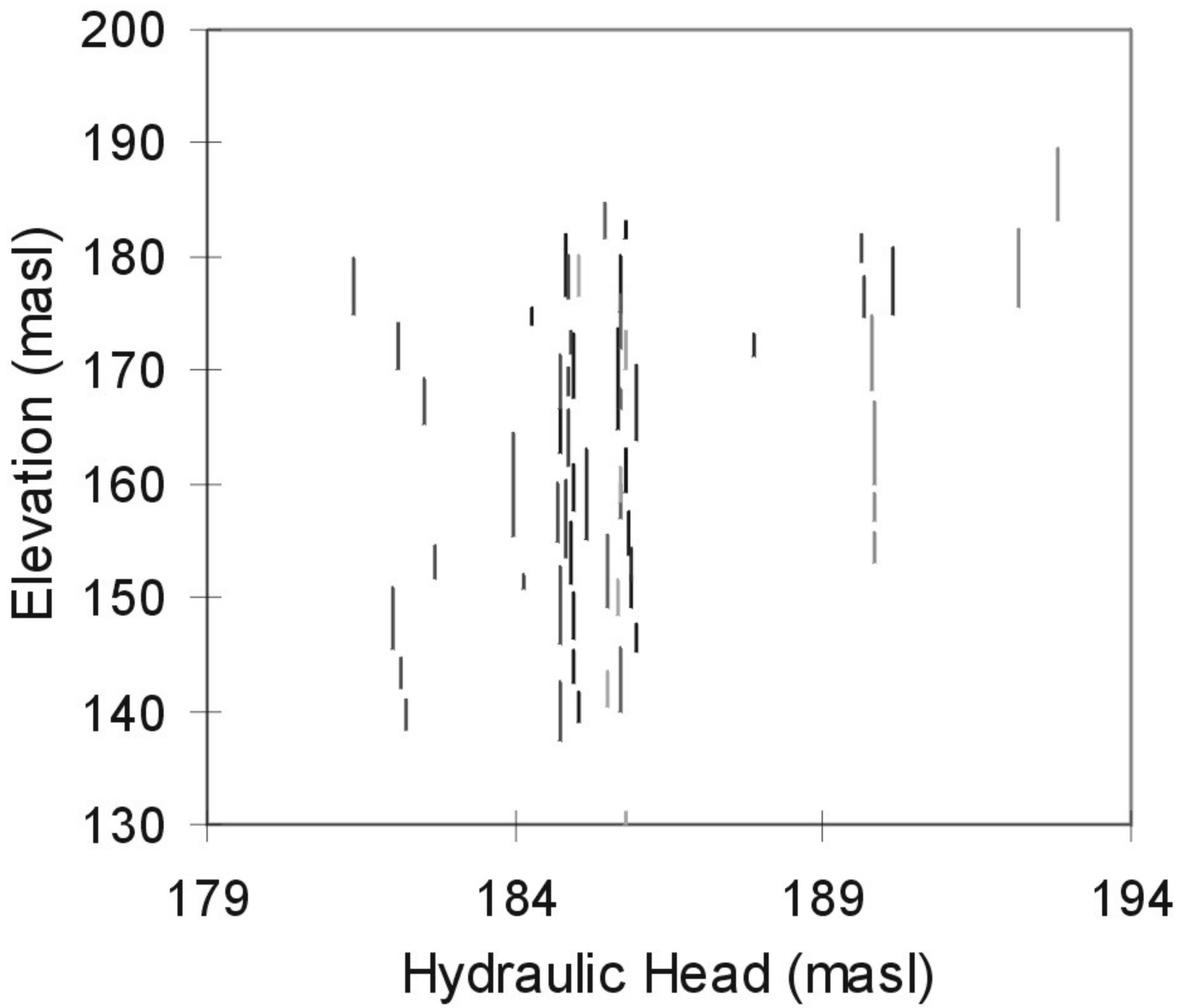


40 m borehole

8 isolated intervals

82% of borehole accessible


Elevation (masl)
200
190
180
170
160
150
140
130
179
184
189
194
Hydraulic Head (masl)
60
62
63


Elevation (masl)
200
190
180
170
160
150
140
130
179
184
189
194
Hydraulic Head (masl)

Interpretation of Hydraulic Head

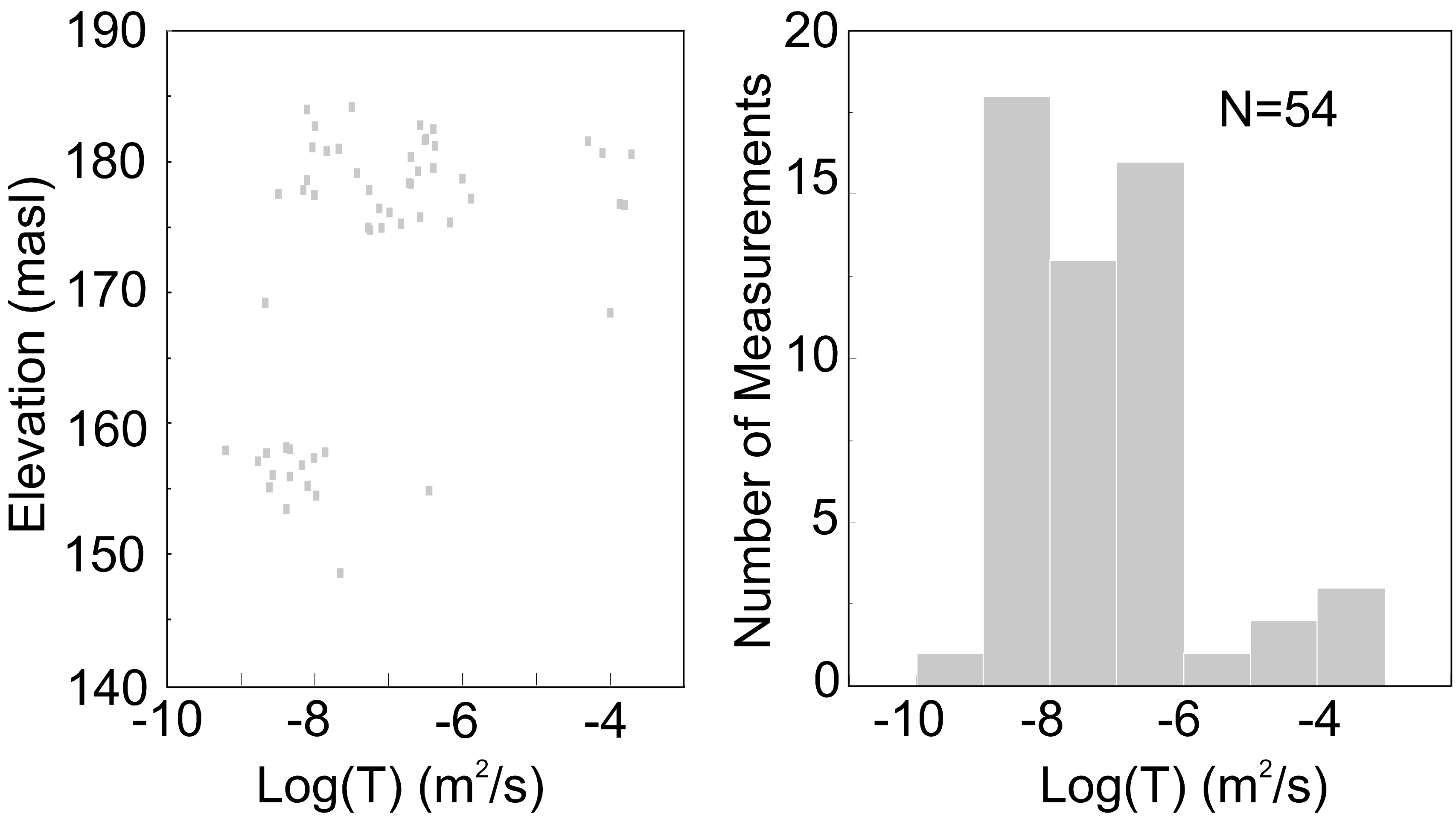
- Two laterally-continuous flat lying fractures separated by 0.8 m vertically
- Difference in hydraulic head between the two fractures of 2.0 m
- Two boreholes 15 m apart

	APERTURE (μm)	
Borehole	Upper Fracture	Lower Fracture
1	135	<10
2	<10	210

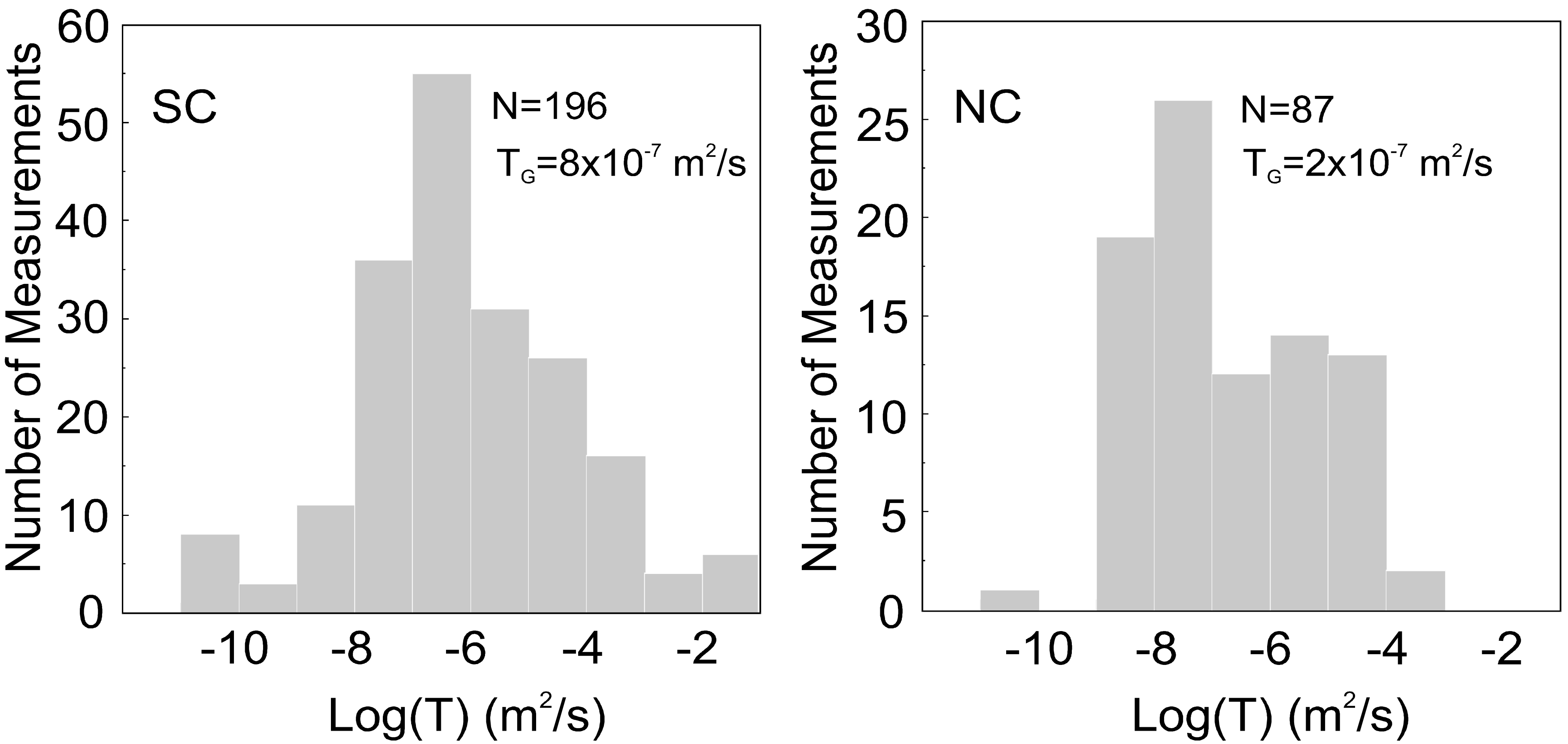
- Presumed hydraulic gradient = 0.13
- Real hydraulic gradient = 0.0015

Vertical Fractures

Vertical Fracture Transmissivity



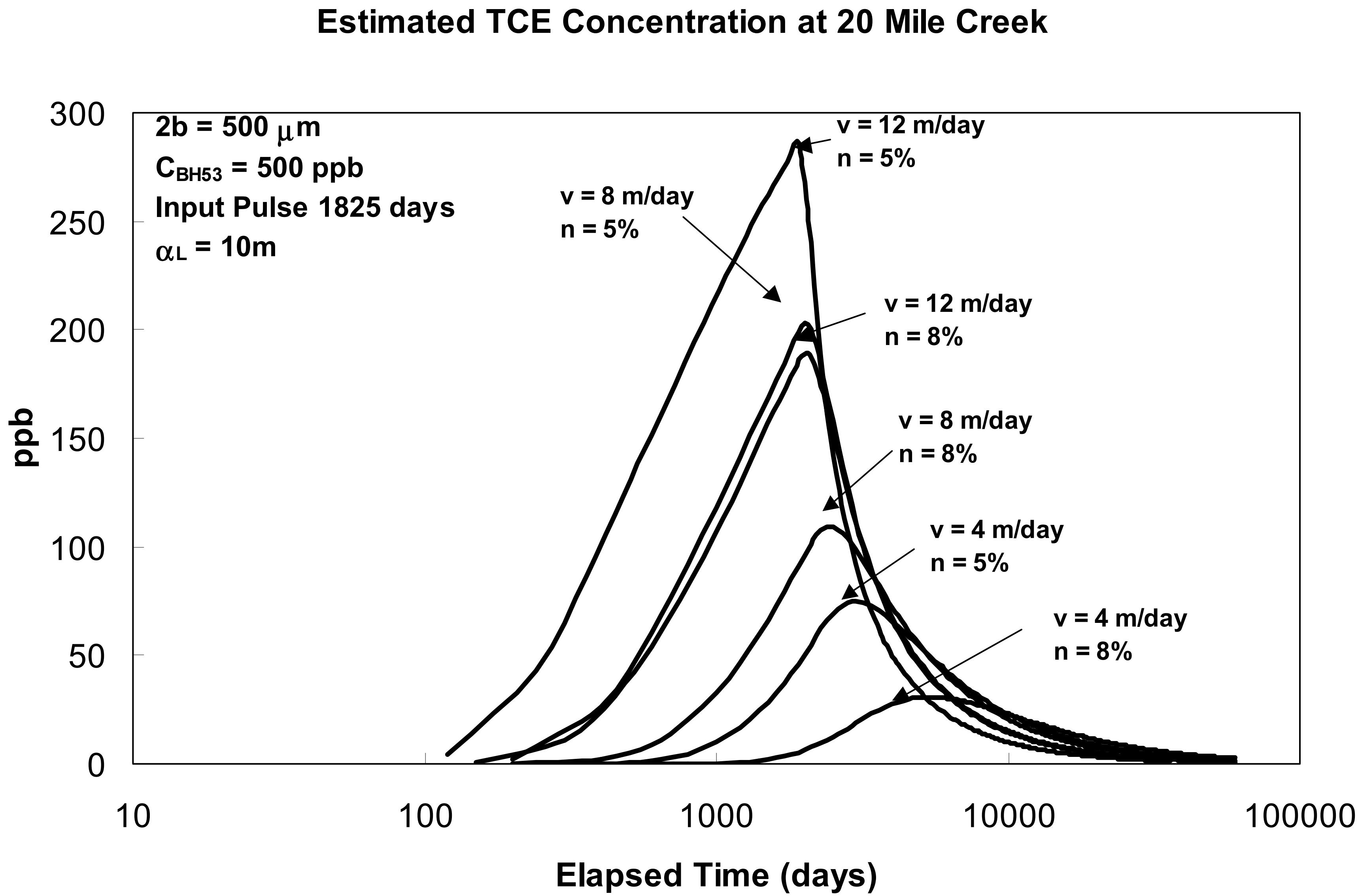
Eramosa Transmissivity



Modeling

- Once the discrete pathways are discovered, use a pathway model that accurately simulates the transport processes

- Analytical models can be easily used for this
  - Choose an appropriate aperture and fracture spacing


Estimated TCE Concentration at 20 Mile Creek
2b = 500 μm
C_{BH53} = 500 ppb
Input Pulse 1825 days
α_L = 10m
v = 12 m/day
n = 5%
v = 8 m/day
n = 5%
v = 12 m/day
n = 8%
v = 8 m/day
n = 8%
v = 4 m/day
n = 5%
v = 4 m/day
n = 8%
ppb
300
250
200
150
100
50
0
10
100
1000
10000
100000
Elapsed Time (days)

Conclusions

- Major discrete fracture pathways must be identified
- Use hydraulic head to determine inter-connectivity
- Estimate groundwater velocity using cubic law
- Use angle drilling to identify vertical fractures
- Simple pathway modeling (including matrix diffusion) very powerful tool