Characterizing Flow and Transport in highly heterogeneous media - A theoretical study

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Talk Focus

- Strongly heterogeneous media -> spatial variability of point measurements
  - manifested in flow channeling and fast paths
- How uncertainties inherent in site characterization will influence performance predictions
- How site specific data should be assimilated into performance assessment process
  - reduce uncertainty of prediction
  - finite amount of data
- A site specific example

Outline

- Stochastic Continuum Model of a fracture medium
  - Site specific hydrological data from SKB's Aspo Hard Rock Laboratory
- Transport Predictions Sensitive to the Structures of Heterogeneity
  - Sensitivity depends on choice of predictive quantity/performance measure
- Calculations to Quantify Uncertainties in Transport from Single Canister Sources
- Fickian Limit Not Reached
  - implication to inference from small scale testing to large scale prediction
- Concluding Remarks

SKI SITE-94 Project

- **Part of Swedish Nuclear Power Inspectorate's strategy for developing integrated Performance Assessment as a licensing tool for nuclear waste repositories.**
  - Alternative geological, hydrological, transport, geochemical conceptual models
  - Dress rehearsal: from site characterization to performance assessment
- **Based on surface and borehole data (1986-1990) from SKB's Aspo Hard Rock Laboratory**
  - Geological
  - geophsical
  - hydrological
  - geochemical

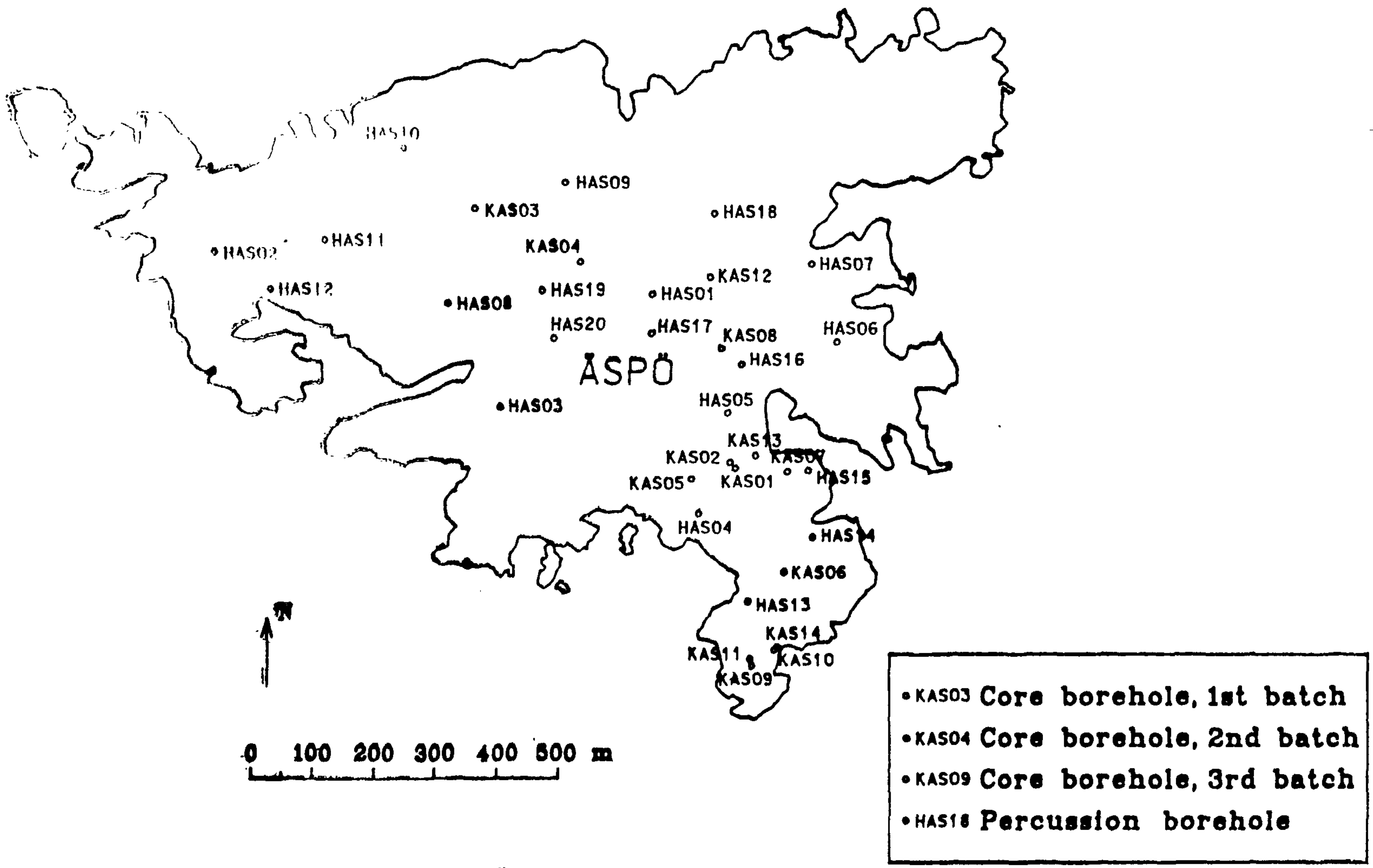


Figure 3.15 Location map of boreholes on Äspö

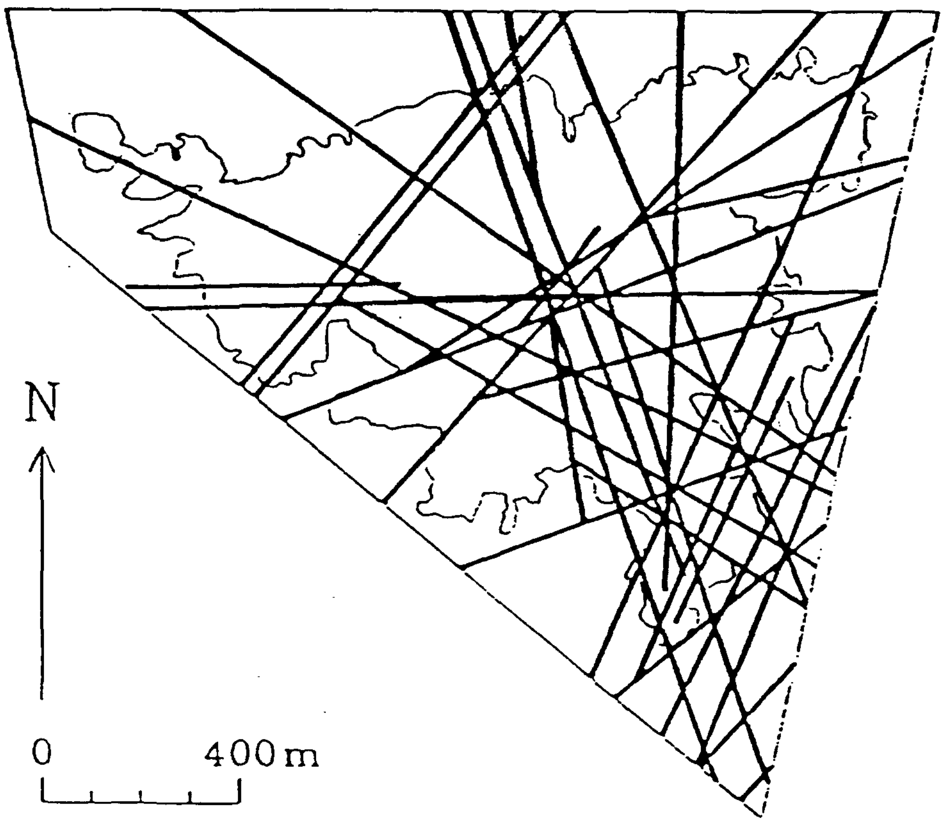
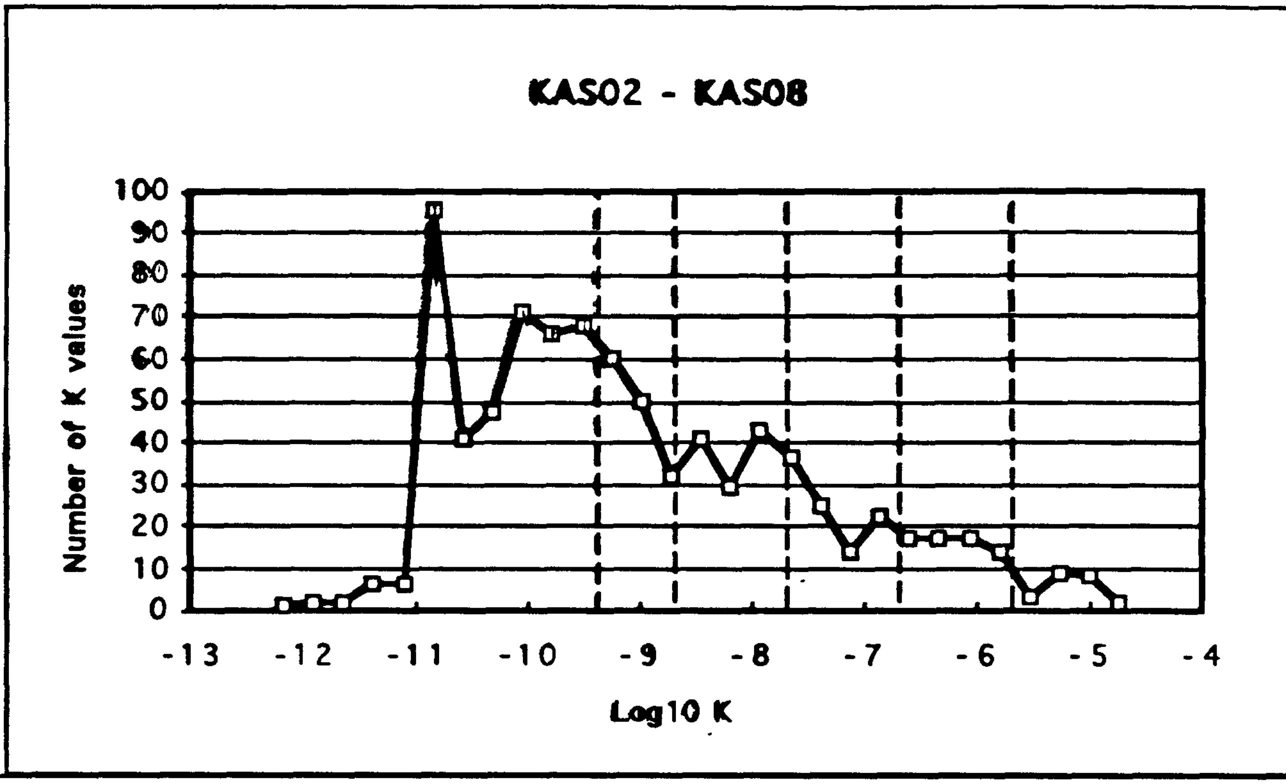
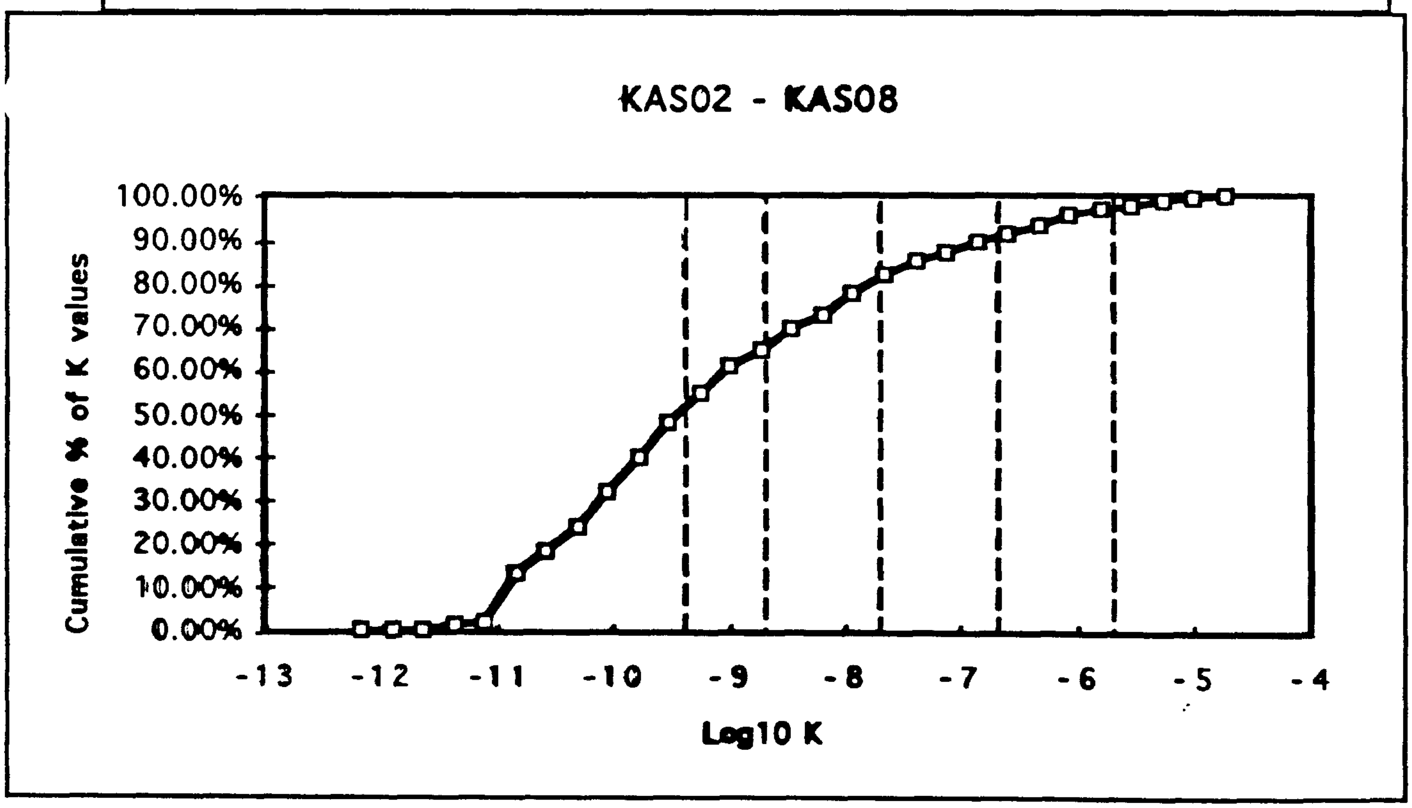
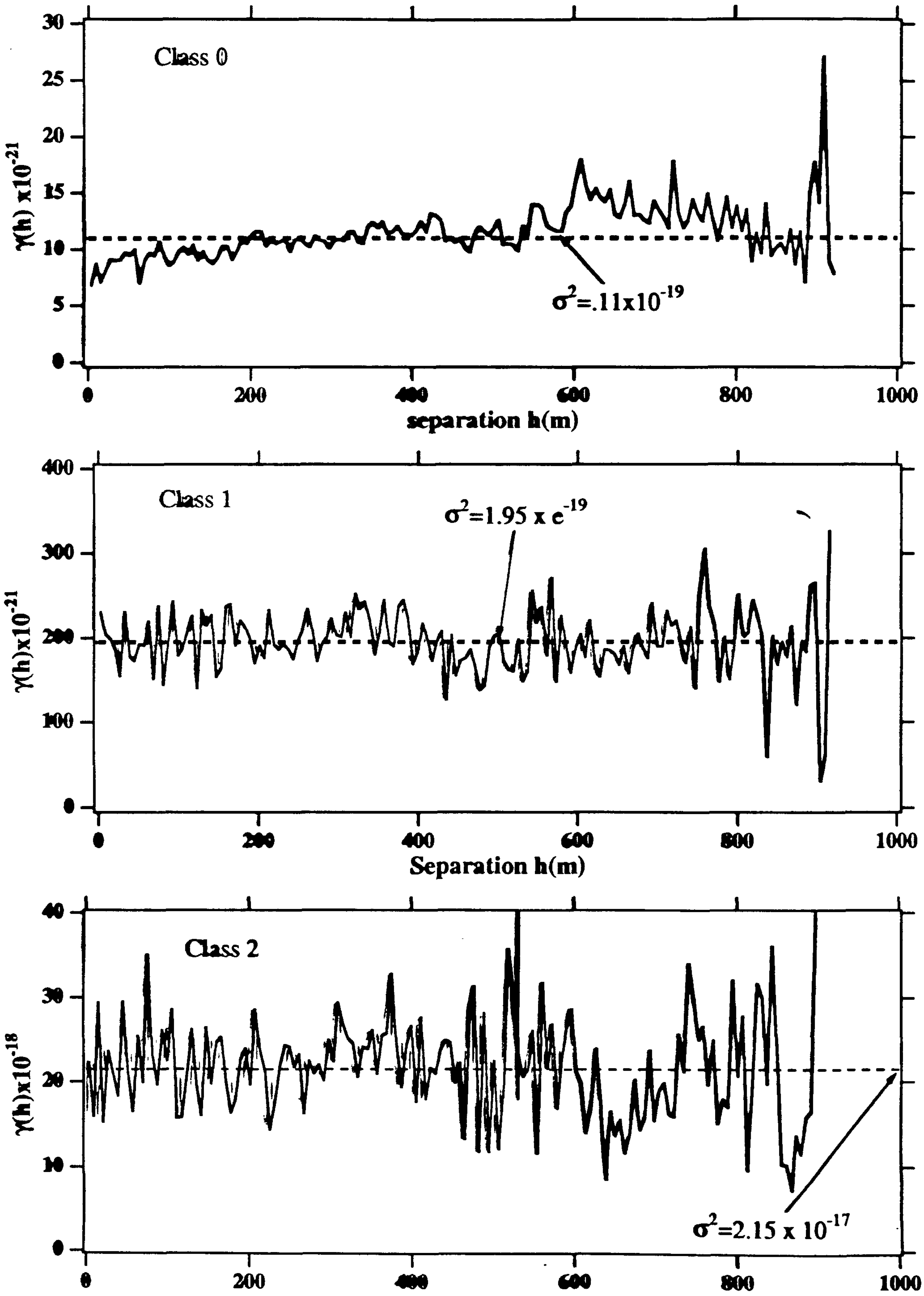


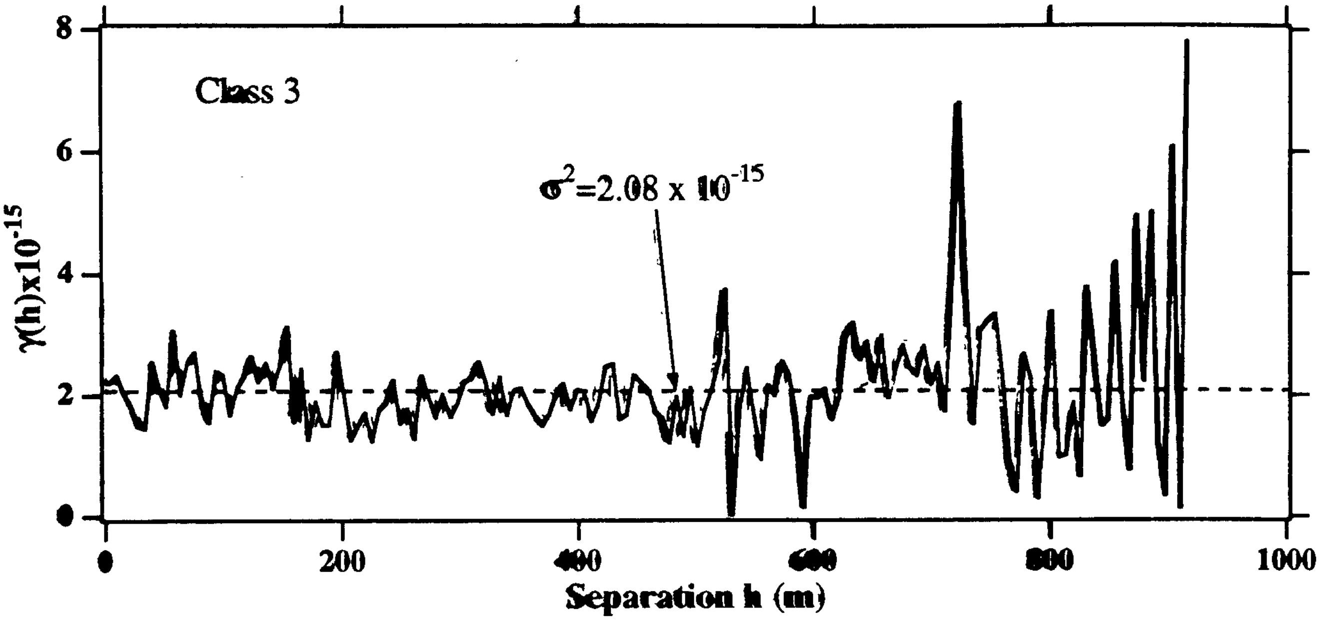
Figure 12. Map of extensive fractures which are identified in boreholes by means of fracture logs and borehole radar measurements. A 3D model is presented below in Figures 13–15.

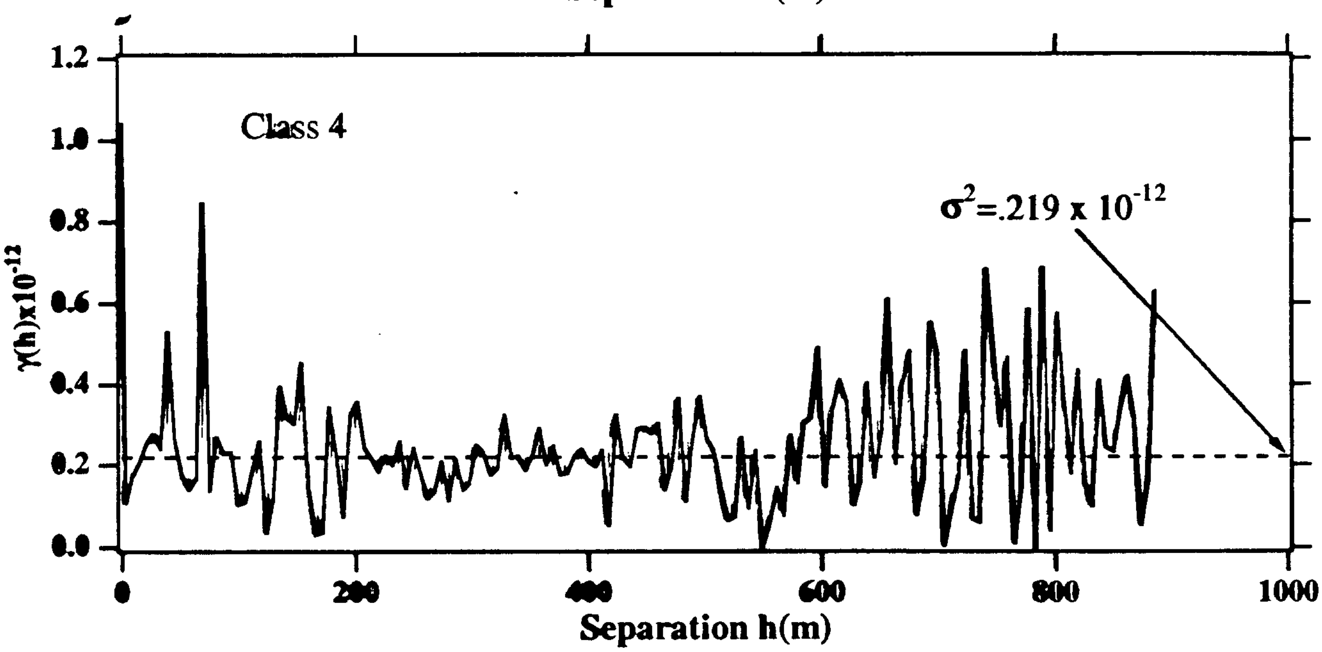

KAS02 - KAS08
Number of K values
100
90
80
70
60
50
40
30
20
10
0
-13
-12
-11
-10
-9
-8
-7
-6
-5
-4
Log10 K

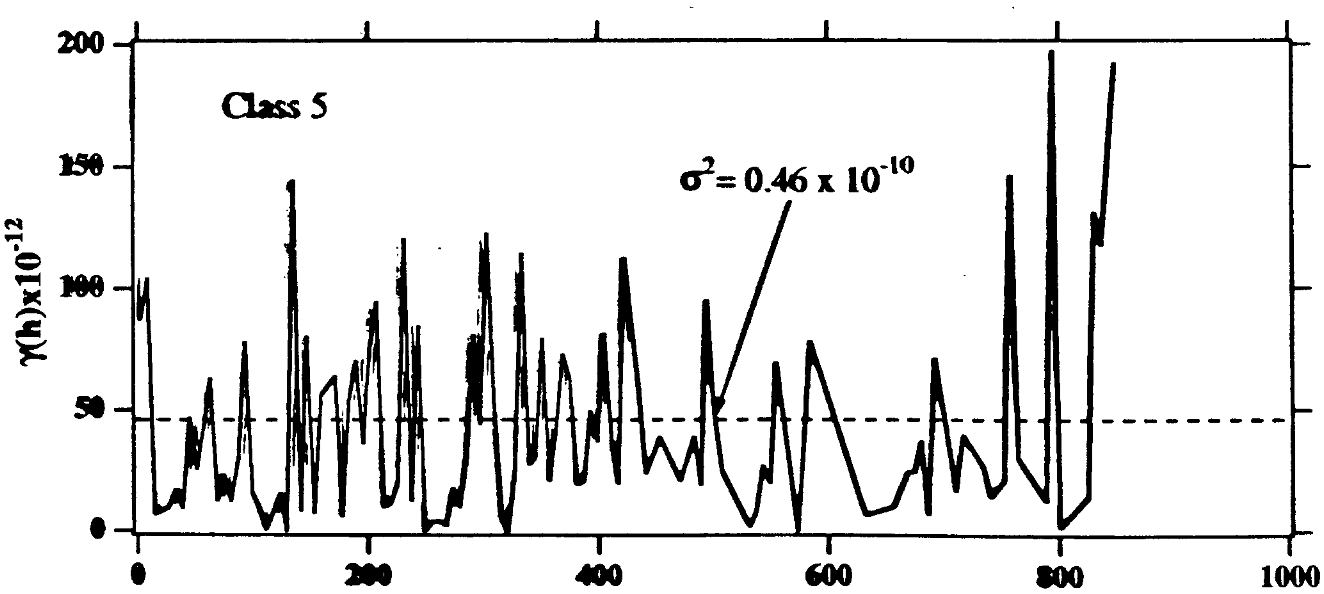

KAS02 - KAS08
Cumulative % of K values
100.00%
90.00%
80.00%
70.00%
60.00%
50.00%
40.00%
30.00%
20.00%
10.00%
0.00%
-13
-12
-11
-10
-9
-8
-7
-6
-5
-4
Log10 K



Class 0
σ^2=.11x10^{-19}
γ(h) x10^{-21}
separation h(m)
Class 1
σ^2=1.95 x e^{-19}
γ(h)x10^{-21}
Separation h(m)
Class 2
σ^2=2.15 x 10^{-17}
γ(h)x10^{-18}


Class 3
σ²=2.08 x 10⁻¹⁵
γ(h)x10⁻¹⁵
0
2
4
6
8
0
200
400
600
800
1000
Separation h (m)


Class 4
σ²=.219 x 10⁻¹²
γ(h)x10⁻¹²
0.0
0.2
0.4
0.6
0.8
1.0
1.2
0
200
400
600
800
1000
Separation h(m)

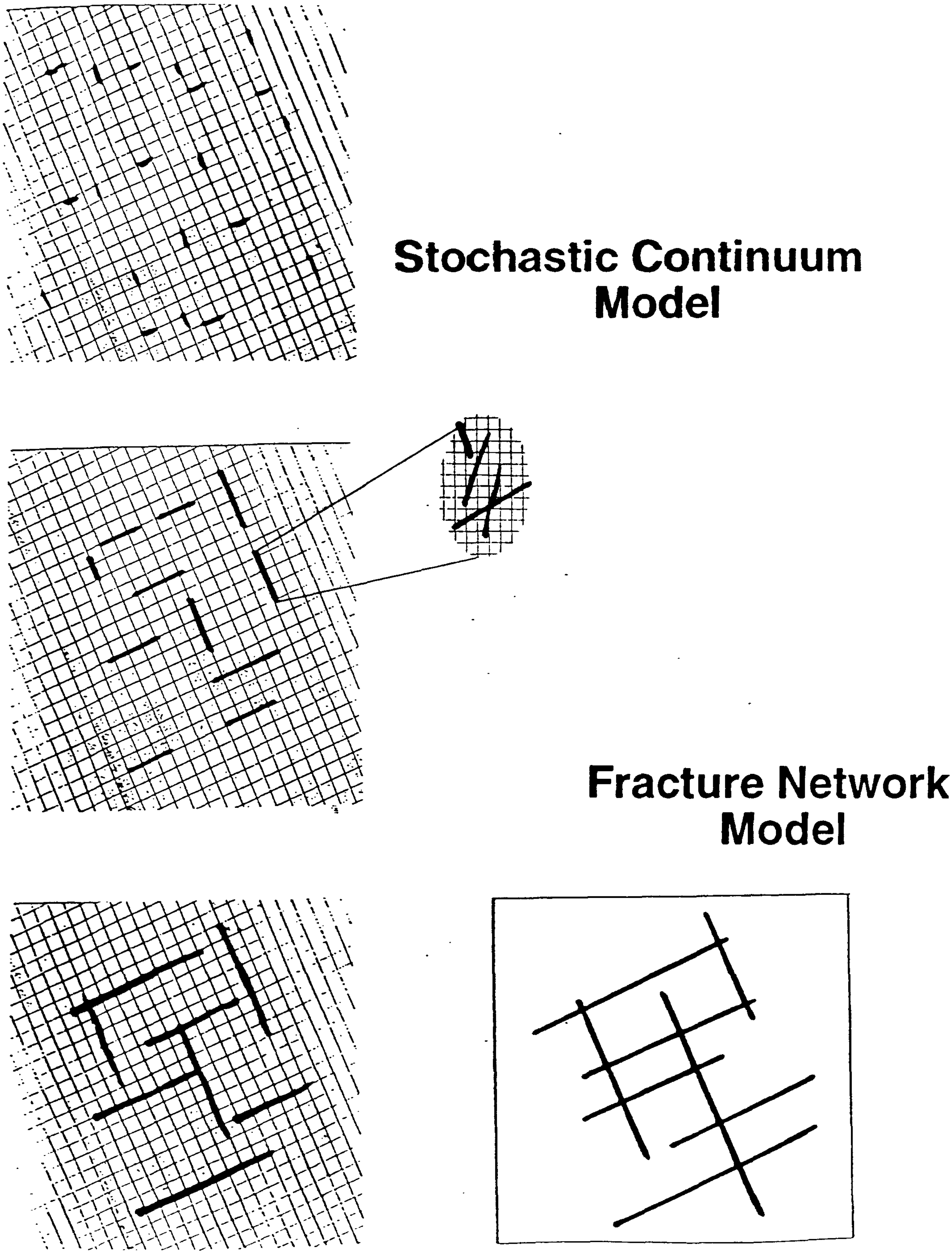

Class 5
σ²= 0.46 x 10⁻¹⁰
γ(h)x10⁻¹²
0
50
100
150
200
0
200
400
600
800
1000

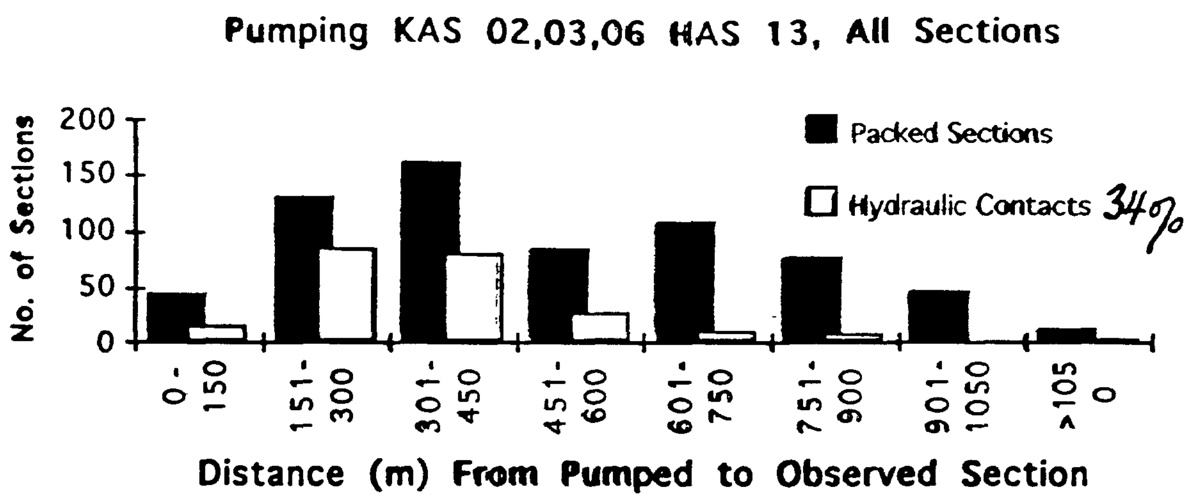
Stochastic Continuum Hydrological Model

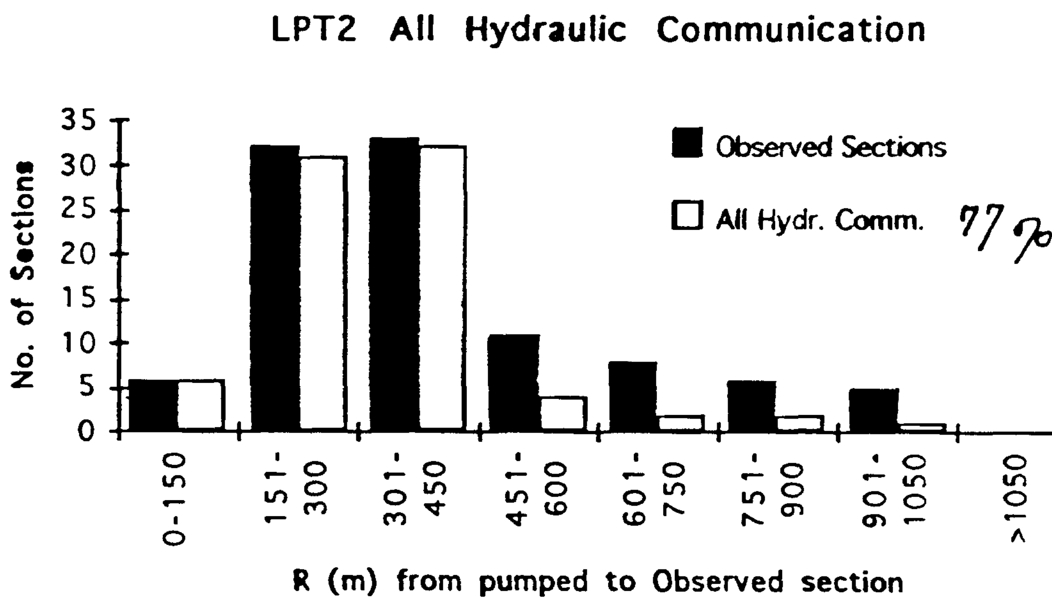
- Geostatistical generation of 3D hydraulic conductivity field conditioned on "point" data of injection test in 3m packed sections
  - Variograms of "point" data display only short range correlation
  - Clustered nature of data cannot discriminate presence or absence of long range correlation structure
- Option of incorporating geological information of major fracture zones
  - Very transmissive structures with long correlation lengths
  - Used as "soft" data
- Single continuum representation of both the fractures and the rock matrix
- Flow results calibrated by interference puming test
- Stochastic transport calculations by particle tracking

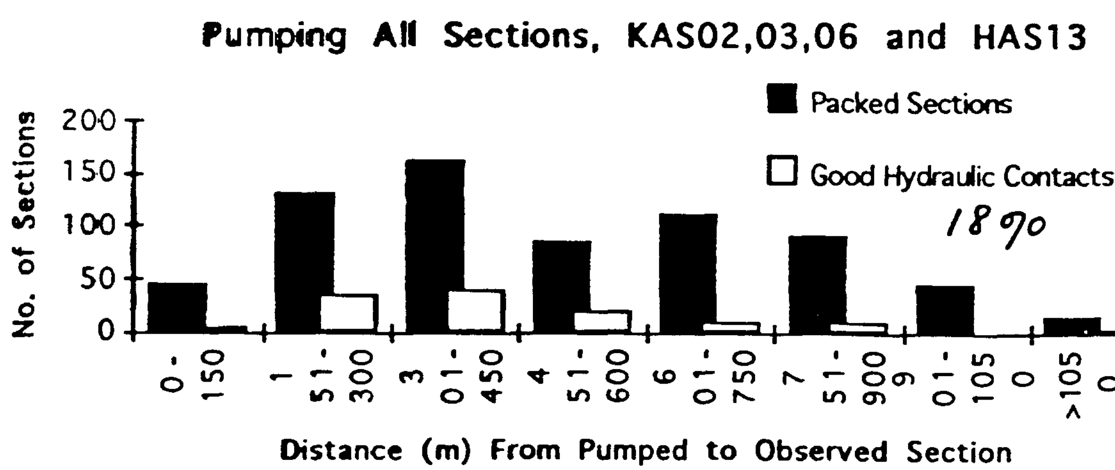
Conditioned Sequential Indicator Simulation

- Non-parametric technique (Gomez-Hernandez) - no particular distribution model is assumed; data are divided into classes bounded by indicators.
- Indicator covariance defined in terms of joint probability of two values in space.
- Classes of extreme values may have covariance different from the rest.
- If the extreme values of hydraulic conductivity are given a large correlation length, the generated field can have long range connectivity for only the extreme values.
- Allows concentration of large conductivities in specified planes of orientations - fractures in the stochastic continuum representation.


Stochastic Continuum Model
Fracture Network Model

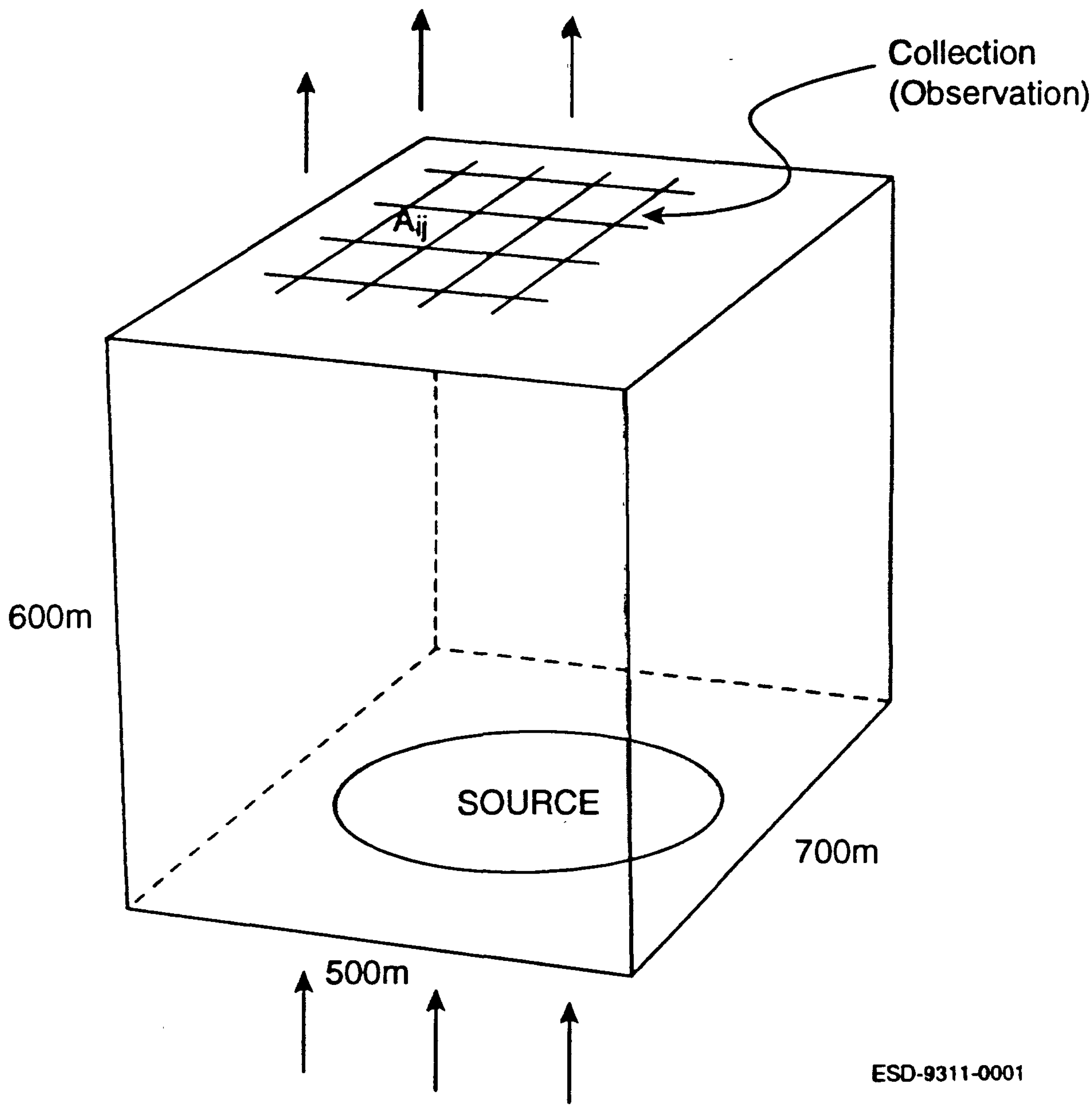

Pumping KAS 02,03,06 HAS 13, All Sections
No. of Sections
200
150
100
50
0
Packed Sections
Hydraulic Contacts
34%
0-150
151-300
301-450
451-600
601-750
751-900
901-1050
>1050
Distance (m) From Pumped to Observed Section


LPT2 All Hydraulic Communication
No. of Sections
35
30
25
20
15
10
5
0
Observed Sections
All Hydr. Comm.
77%
0-150
151-300
301-450
451-600
601-750
751-900
901-1050
>1050
R (m) from pumped to Observed section

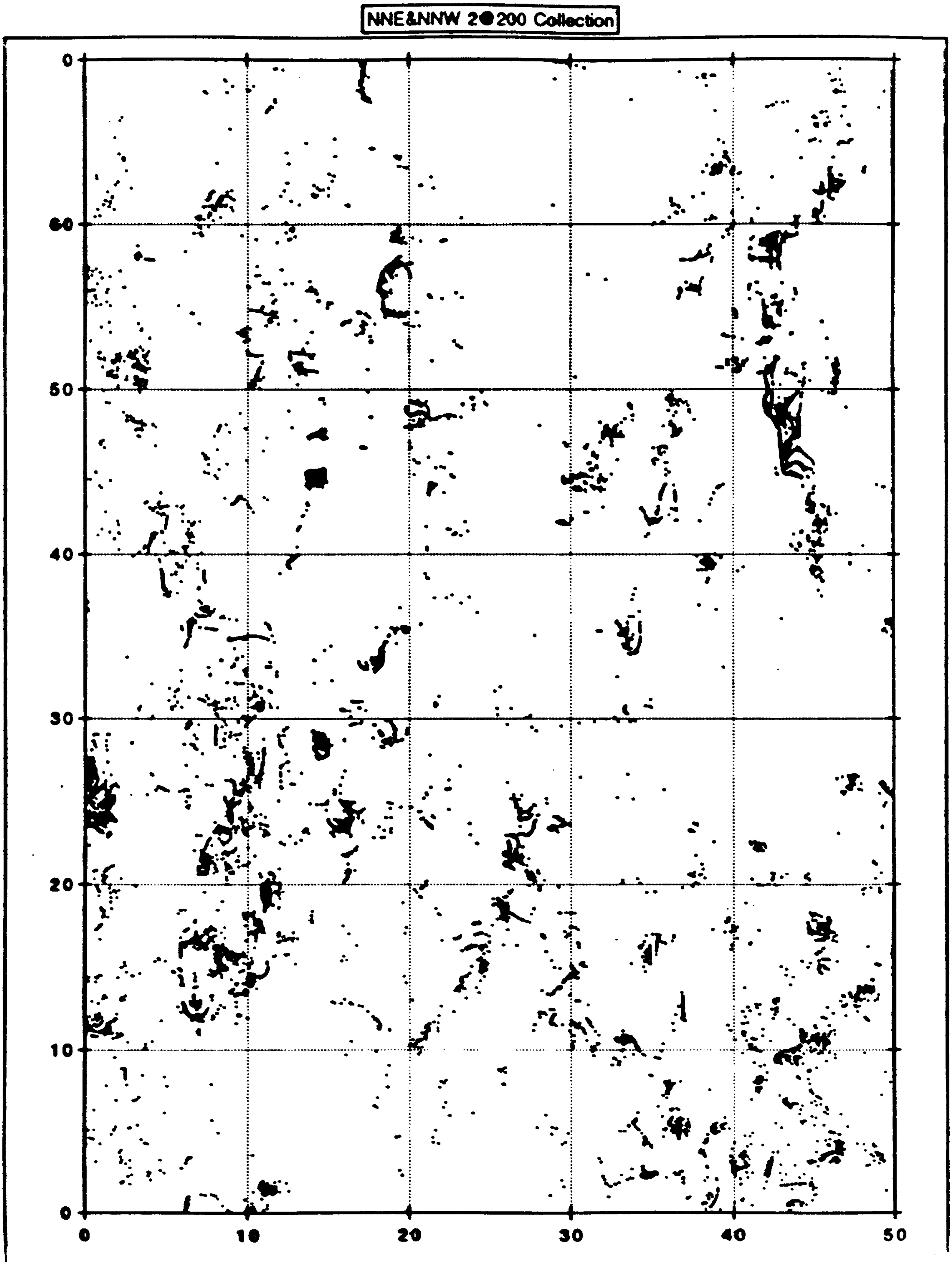

Pumping All Sections, KAS02,03,06 and HAS13
No. of Sections
200
150
100
50
0
Packed Sections
Good Hydraulic Contacts
18%
0-150
151-300
301-450
451-600
601-750
751-900
901-1050
>1050
Distance (m) From Pumped to Observed Section

Appropriate Performance Measure

(What are the feasible predictive quantities for management decisions?)

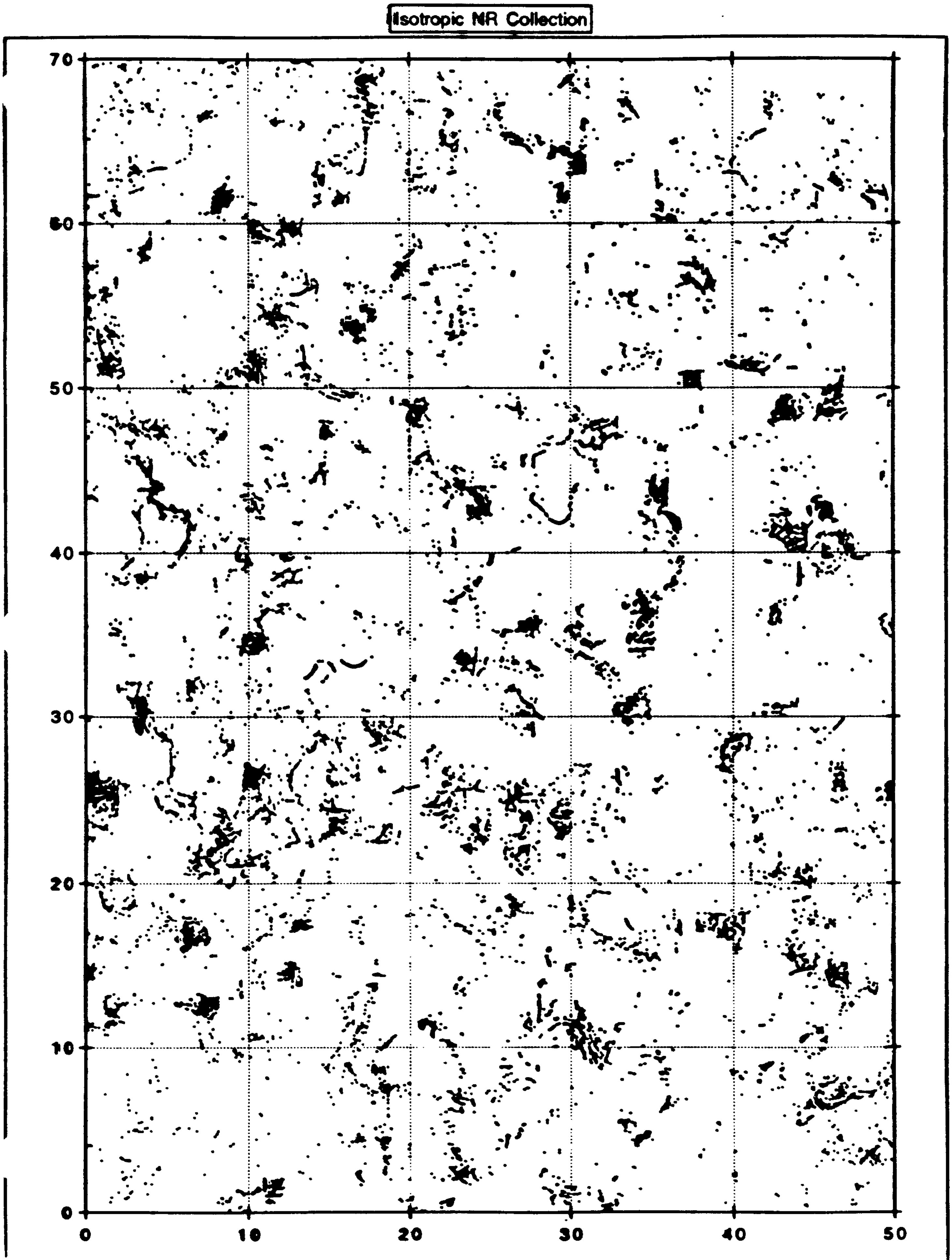


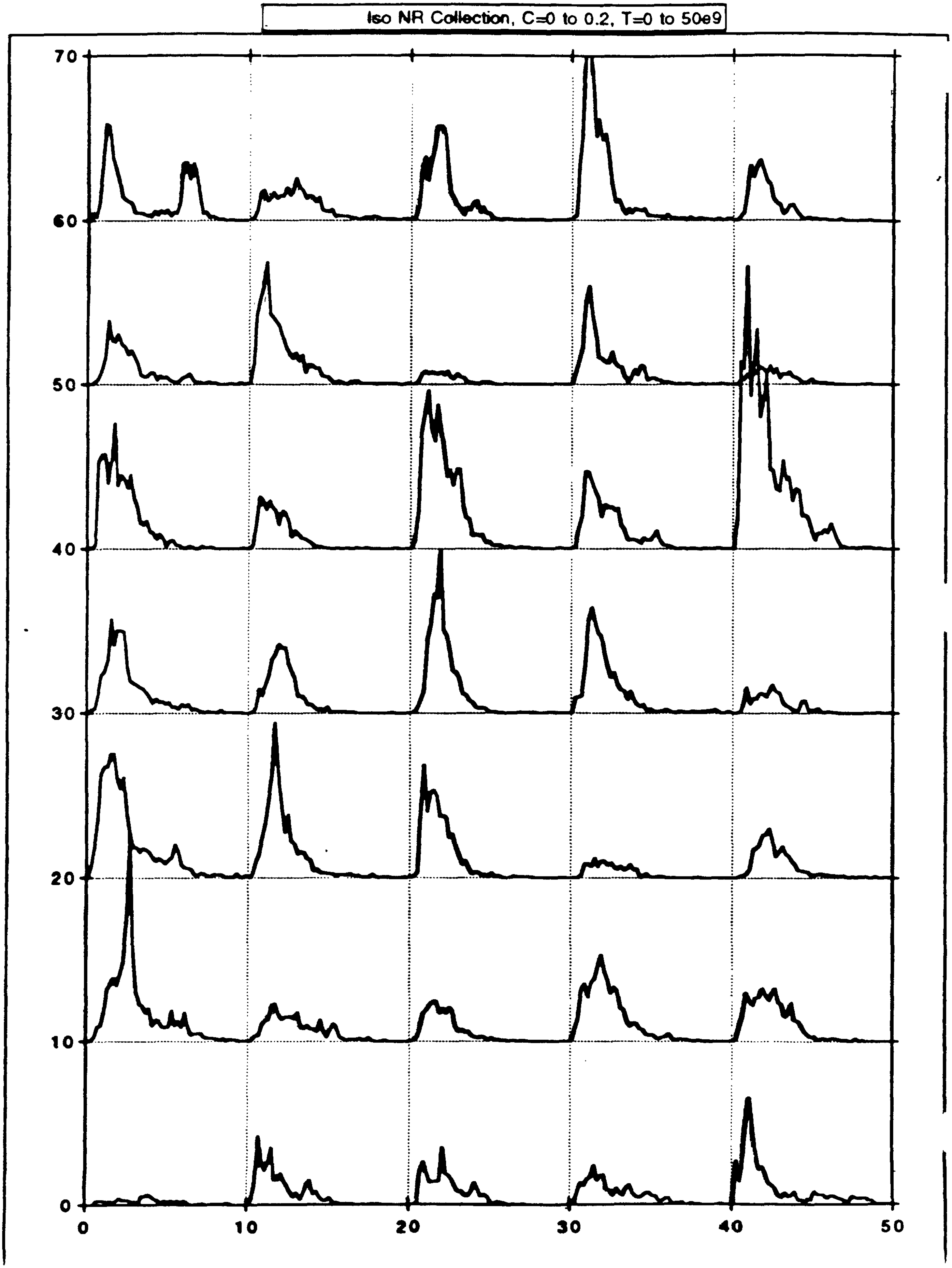
Solute breakthrough in small areas A_{ij} has strong spatial dependence (Flow Channeling)



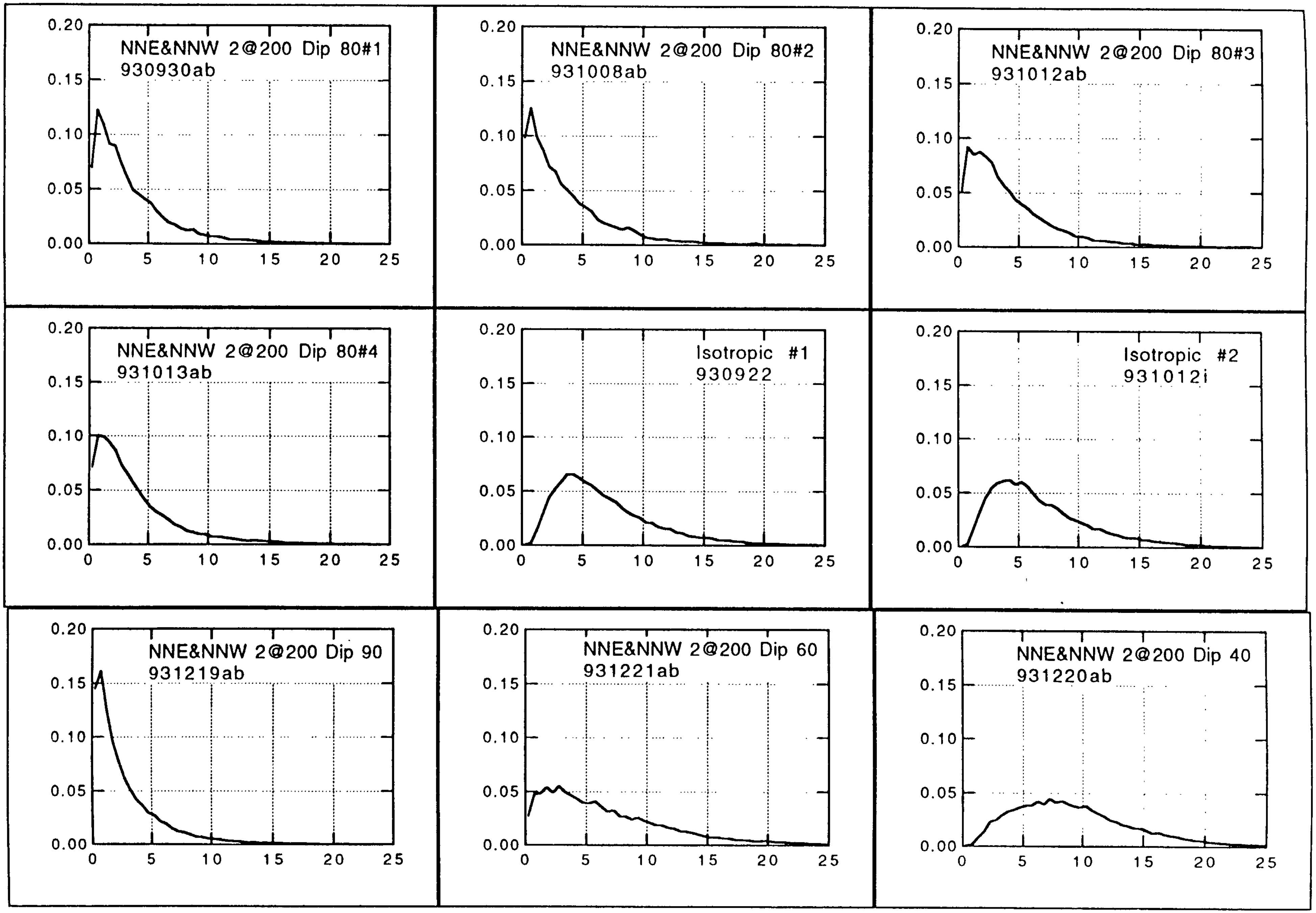
NNE&NNW 2●200 Collection
0
10
20
30
40
50
60
0
10
20
30
40
50

NNE&NNW 2●200 Collection, C=0 to 0.45, T=0 to 50e9


Isotropic NR Collection
70
60
50
40
30
20
10
0
0
10
20
30
40
50


Iso NR Collection, C=0 to 0.2, T=0 to 50e9
70
60
50
40
30
20
10
0
0
10
20
30
40
50

Revised Total Breakthrough Curves



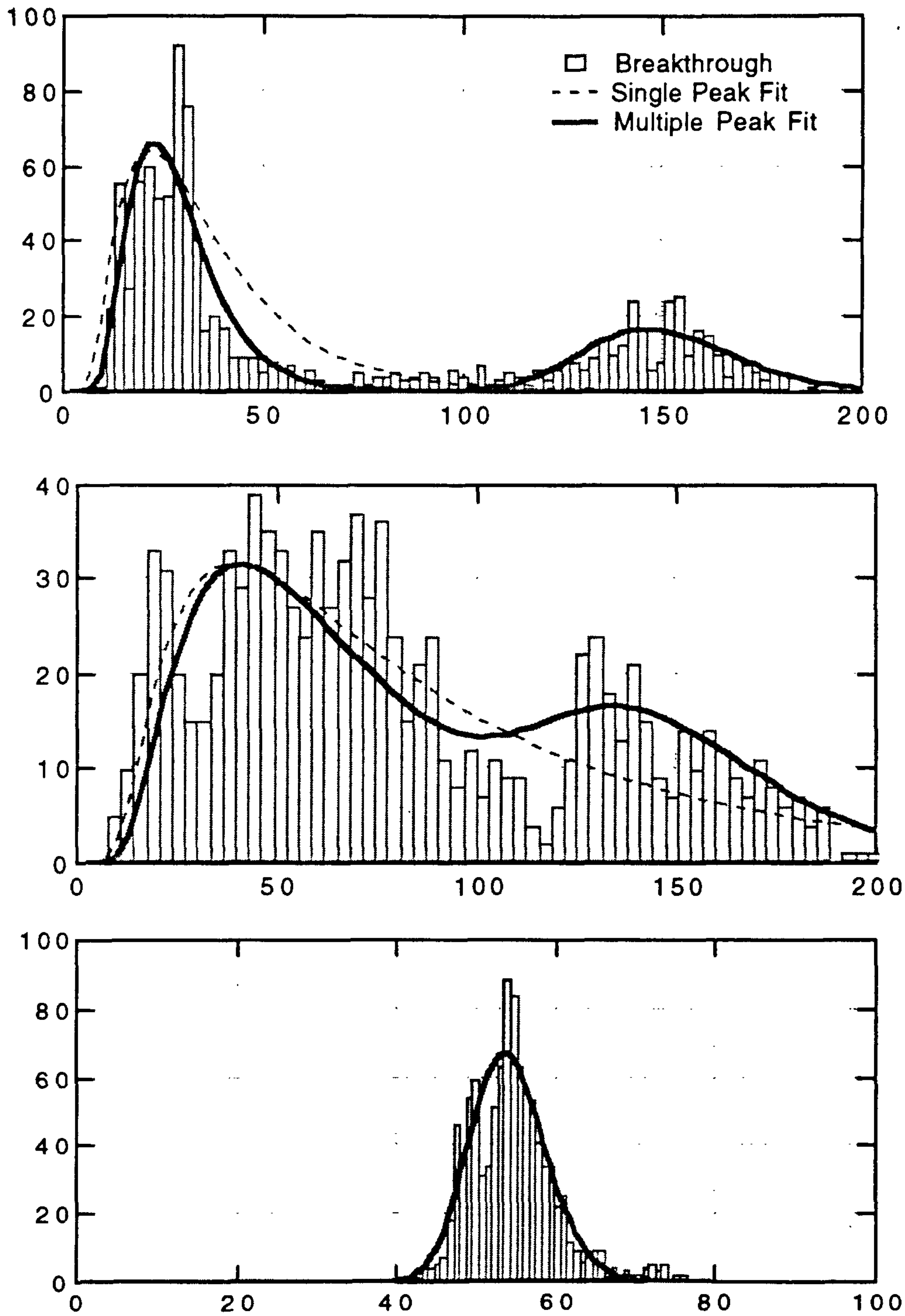
Remarks on Tracer Breakthrough Results

- Discrimination of fracture-dominated systems versus heterogeneous continuum requires extensive measurements
- Spatially integrated solute arrivals much less sensitive to alternative heterogenous systems - similar order of magnitude in solute arrival and concentration
- Implication on choice of performance measure - quantities to be predicted
  - "point quantities"- large variations
  - spatially integrated parameter, more stable, more commensurate with our ignorance of the heterogeneous medium

Tracer breakthrough from single canister sources

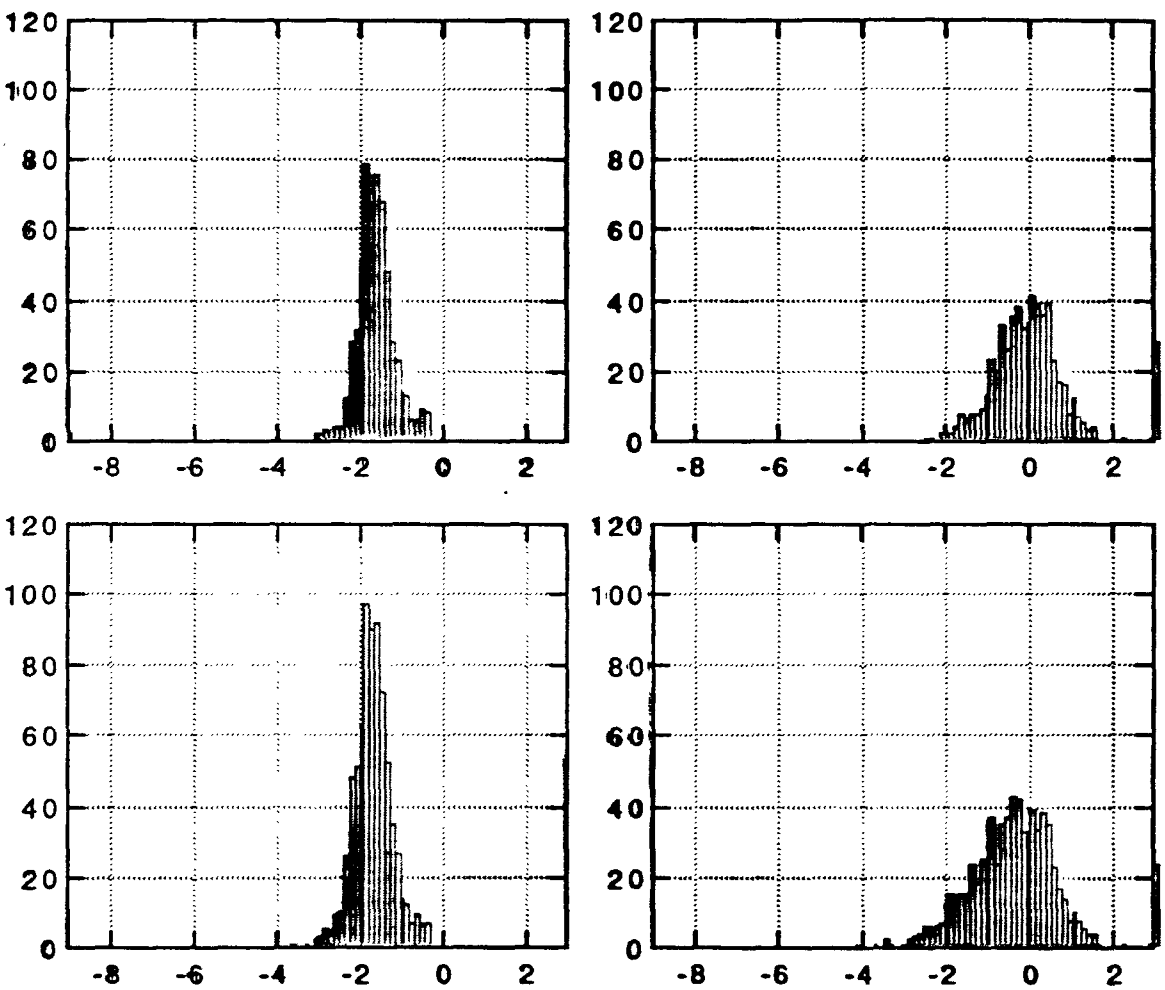
- Quantify uncertainties due to spatial variability
- Repeat calculations for hundreds of radomly selected sites of tracer source
- Obtain transport parameters for each breakthrough curve (v and D)
- Distributions of transport parameters are measures of the uncertainty

Fit of 3D Breakthrough Curves by 1D Advective-Dispersive Equation Solution



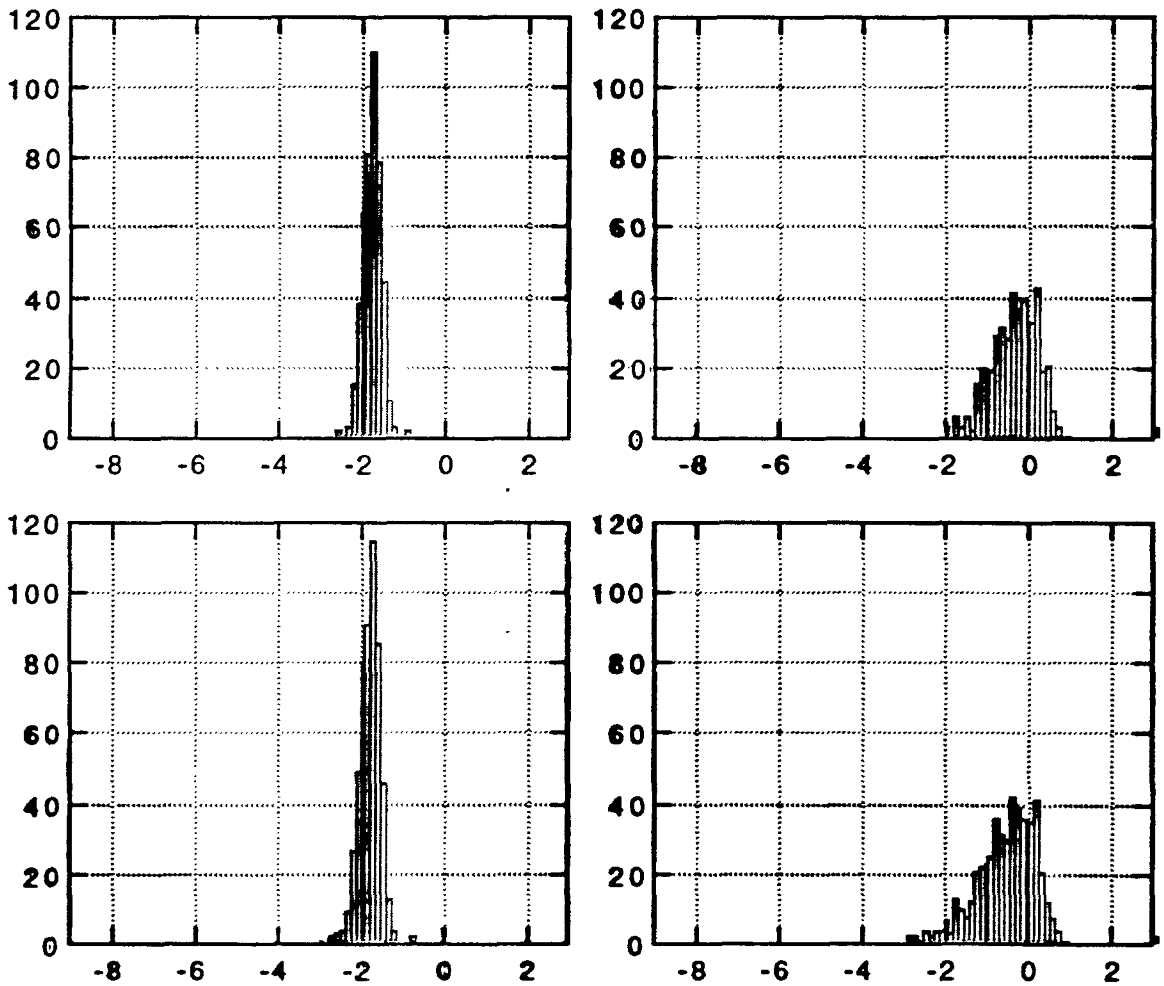
Distribution of Fitted U(m/yr, left graphs) and D (m²/yr, right graphs), in Logarithm Scale

- Reference Case, dip angle 80°



Distribution of Fitted U(m/yr, left graphs) and D (m²/yr, right graphs), in Logarithm Scale

- Isotropic case with only short correlation structure

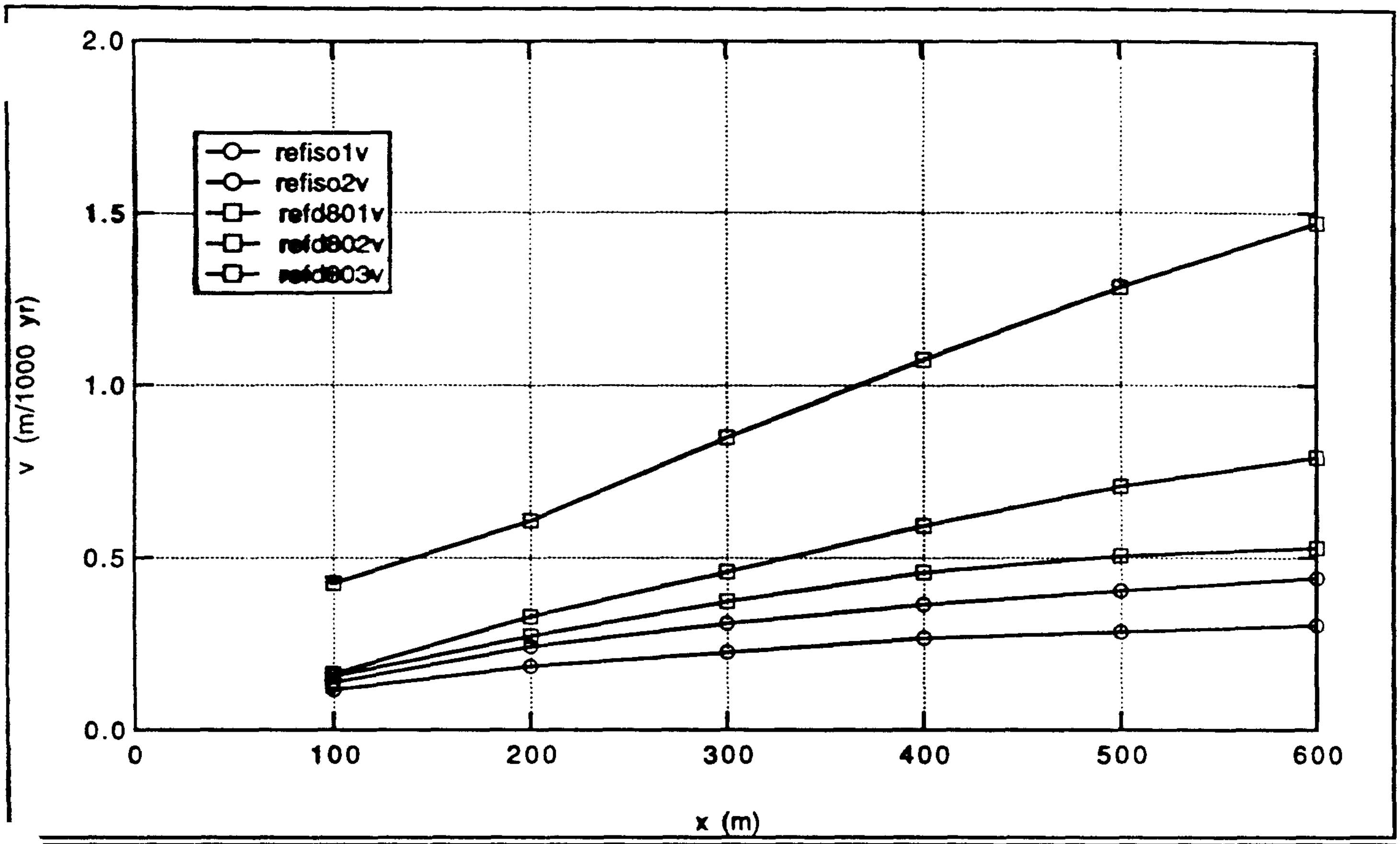


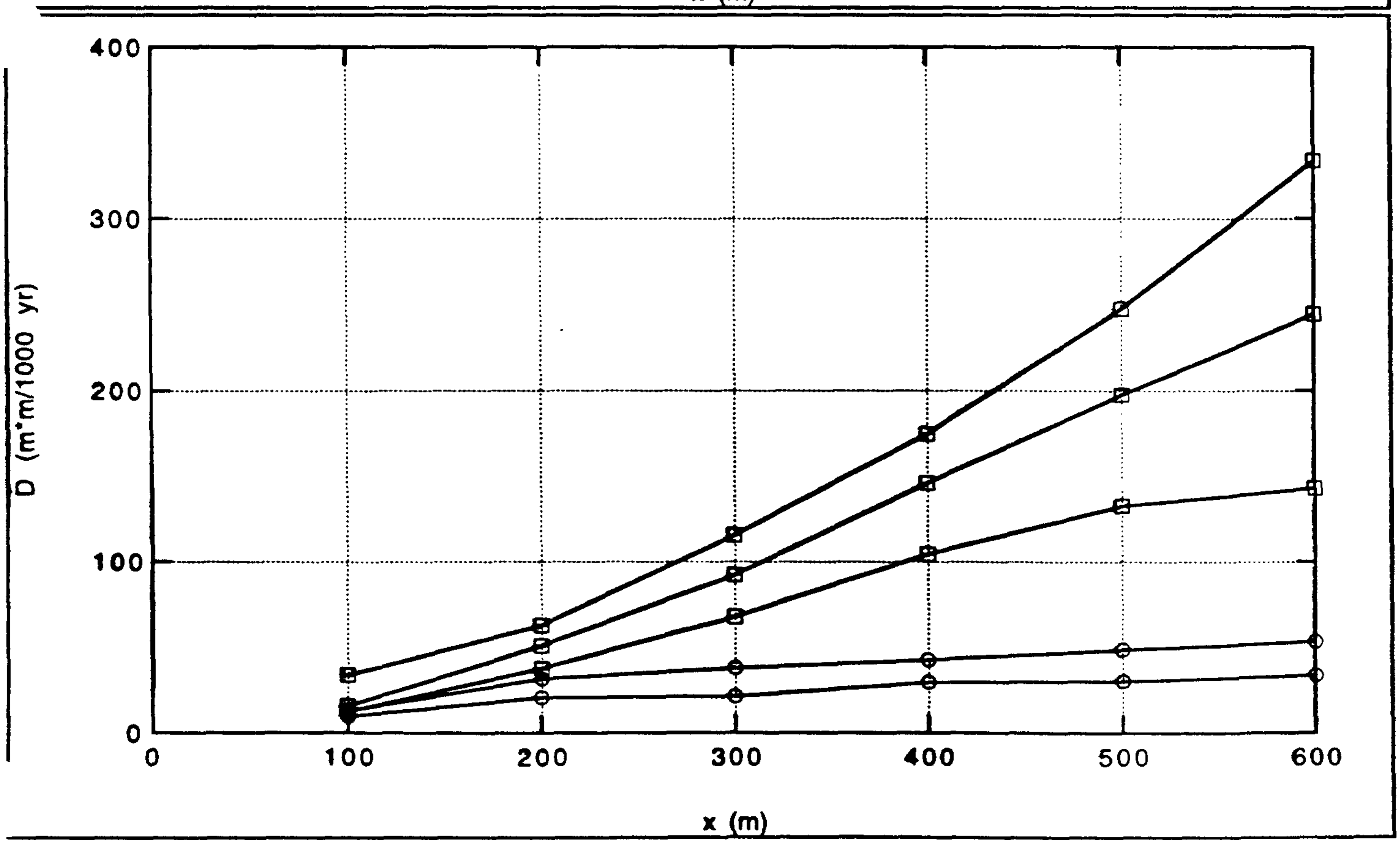
	Single Peak Fits			Multiple Peak Fits		
Nomenclature (*)	no. of peaks fitted	$\overline{V} \pm \sigma$ (m/yr)	$\overline{D} \pm \sigma$ (m*m/yr)	no. of peaks fitted	$\overline{V} \pm \sigma$ (m/yr)	$\overline{D} \pm \sigma$ (m*m/yr))
REF-DIP90	501	0.045±0.061	5.9±44.	680	0.041±0.058	5.0±43.
REF-DIP80-1	461	0.035±0.039	2.3±3.6	587	0.033±0.038	3.0±29.
REF-DIP80-2	556	0.035±0.041	4.7±35.	723	0.032±0.039	3.5±30.
REF-DIP80-3	465	0.036±0.036	4.4±33.	620	0.034±0.038	3.0±27.
REF-DIP80-4	458	0.040±0.036	4.4±22.	555	0.038±0.035	2.9±12.
REF-ISO-1	451	0.021±0.010	0.99±1.1	529	0.020±0.01	0.82±1.1
REF-ISO-2	519	0.024±0.013	1.4±16.	616	0.023±0.014	1.1±1.4
REF-DIP40-1	366	0.015±0.0058	0.55±0.66	427	0.014±0.0062	0.43±0.56

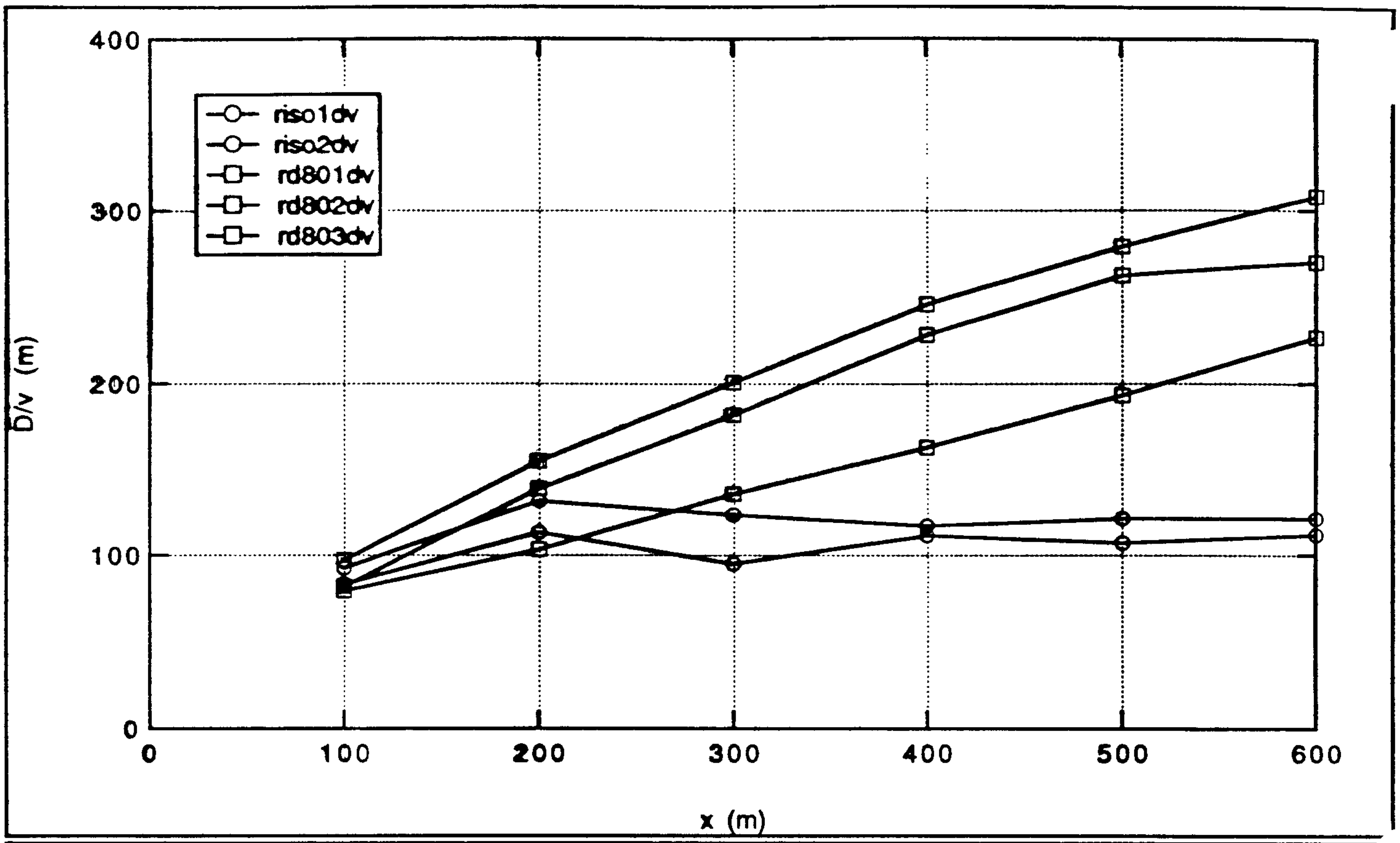
Inference from small scale measurement to large scale predictions

- Compute tracer breakthrough curves from single canister sources for transport distances of 100m, 200m..... up to 600m
- Fitted transport parameters v and D as function of transport distance

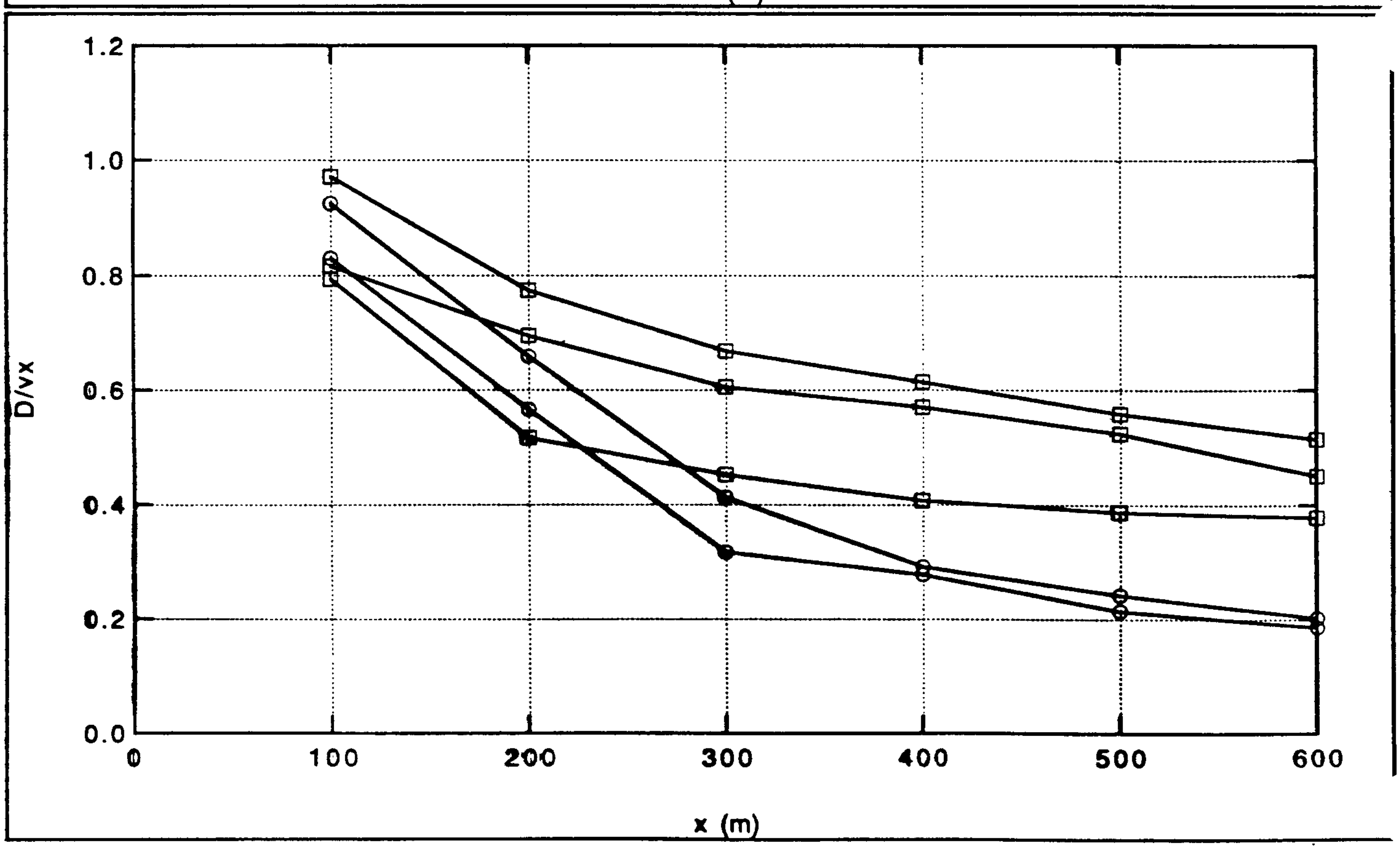
Combine full recorvery canisters into a single breakthrough curve; one fit at each distance







riso1dv
riso2dv
rd801dv
rd802dv
rd803dv
D/v (m)
x (m)
0
100
200
300
400
500
600



D/vx
x (m)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
0
100
200
300
400
500
600

Summary

- **Stochastic continuum model**
  - Non-parametric sequential indicator simulation conditioned to data
  - Long range correlation structures to account for fractures
  - Different heterogeneity structures, all consistent with data, to evaluate model uncertainty
- **Choice of Performance Measure**
  - Large uncertainty if "point" quantities are chosen as predictive quantity/performance measure - probably will never have enough data
  - Spatially integrated solute arrivals less sensitive to heterogeneity structures - more commensurate with our ignorance of the heterogeneous medium

Summary (cont.)

- **Transport from Single Canister Sources Releases**
  - Fit of 3D flow and transport results by 1D advective-dispersive equation
  - v and D for hundreds of calculations to quantify associated variability
- **Demonstrate an approach to go from site characterization data to performance assessment**
  - Fickian limit not reached - cannot infer from small scale measurement to large scale predictions
- **Caution in using the Predictions - inherent ignorance of a strongly heterogeneous system**
  - spatial variability
  - model uncertainty