U.S. DEPARTMENT OF ENERGY
OFFICE OF CIVILIAN RADIOACTIVE WASTE MANAGEMENT

NUCLEAR WASTE TECHNICAL REVIEW BOARD
FULL BOARD MEETING

SUBJECT: MODELING FLOW IN UNSATURATED ZONE FRACTURED ROCKS

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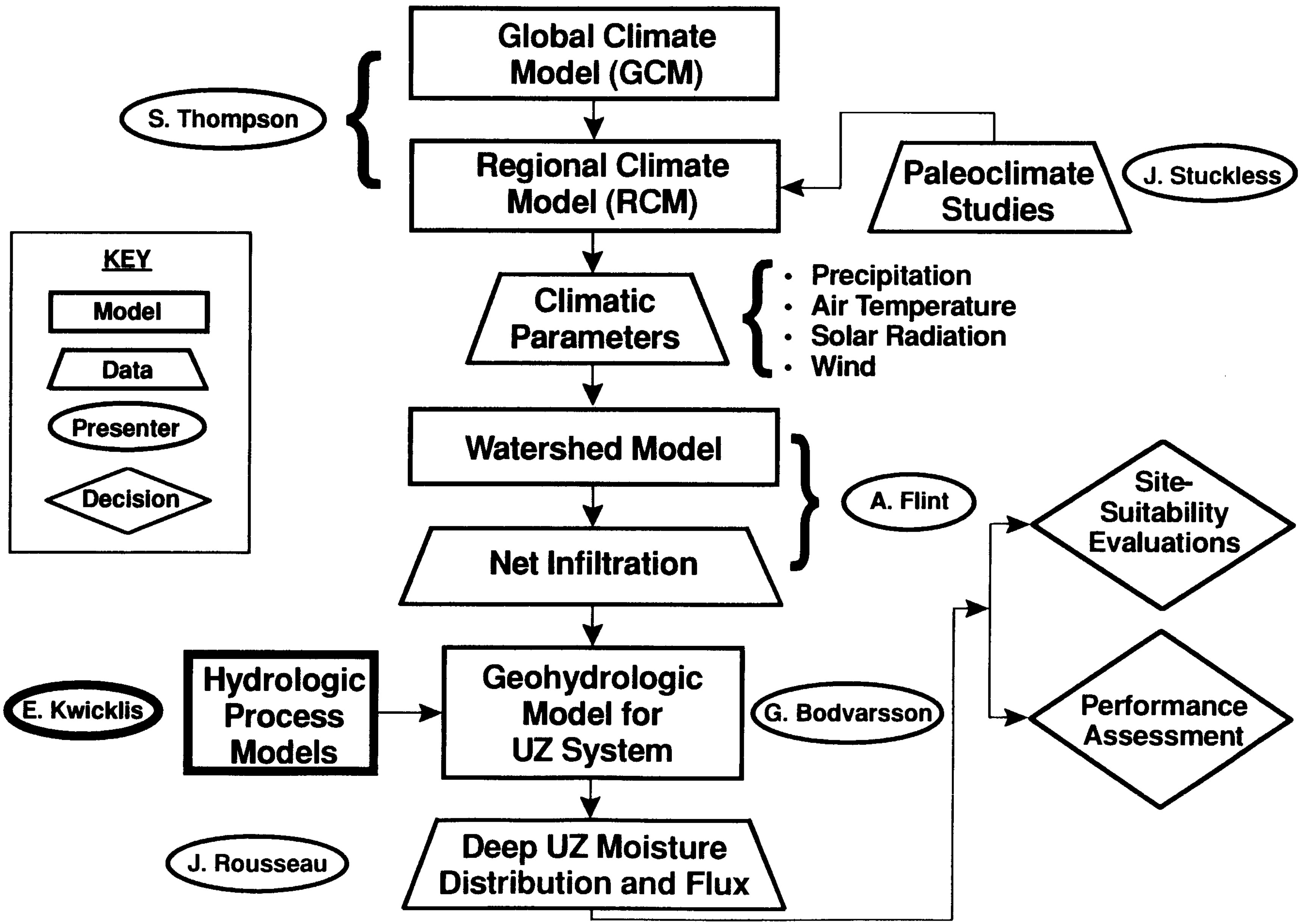
Example Model Hierarchy



4MFUZK5P1 125 NWTRB/4 21/22-93

Outline

Study Objectives

Site Processes

Possible Methods of Flux Estimation

Examples of Recent Work

Conclusions

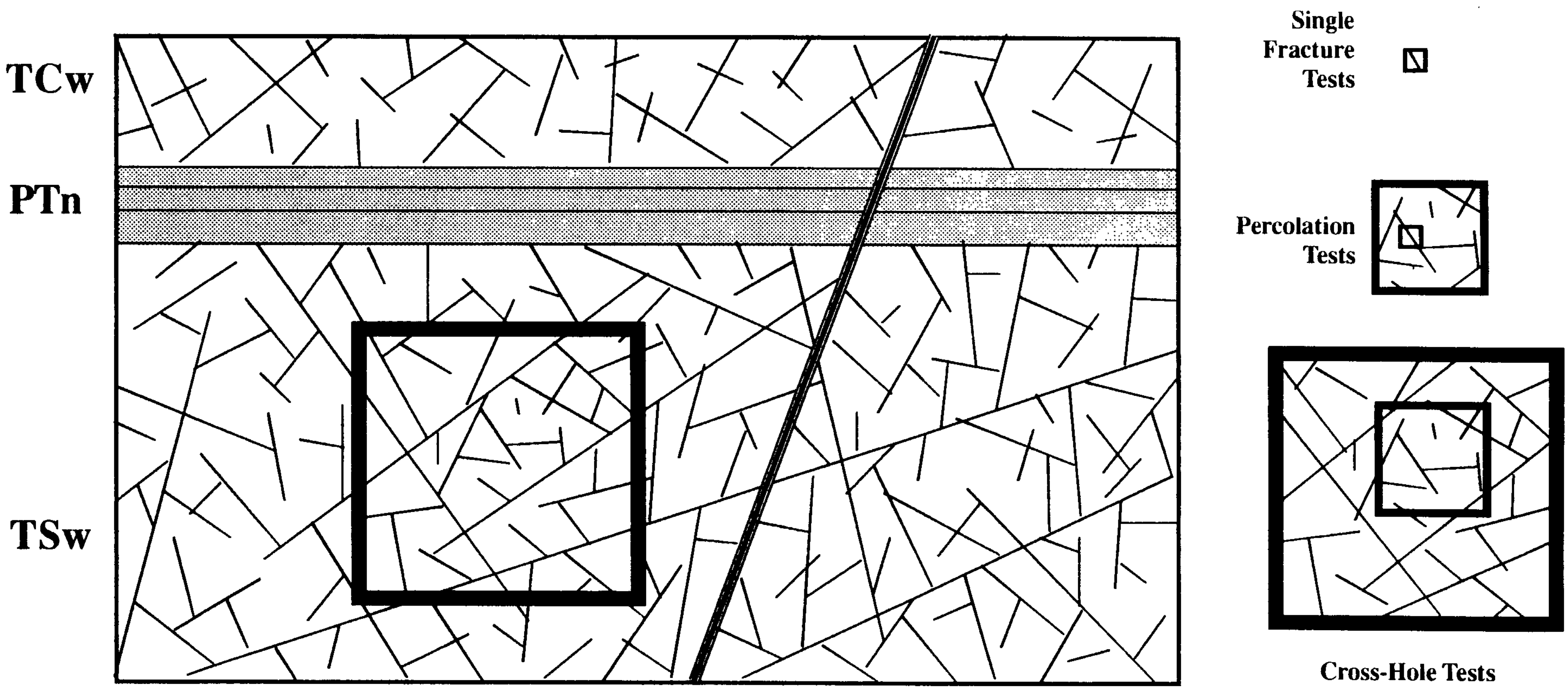
Study Objectives

- Construct conceptual and numerical representations of the physical processes that govern fluid flow and nonreactive tracer transport through partially saturated fractured rock
- Evaluate these through comparison with the results of controlled experiments

These Models Will be Used to

- Identify processes important to the hydrologic behavior of the unsaturated zone
- Design and analyze experiments and interpret field data
- Integrate data collected from a variety of scales
- Assess the conceptual representation of the physical system in large-scale models of the site

Test and Modeling Scales



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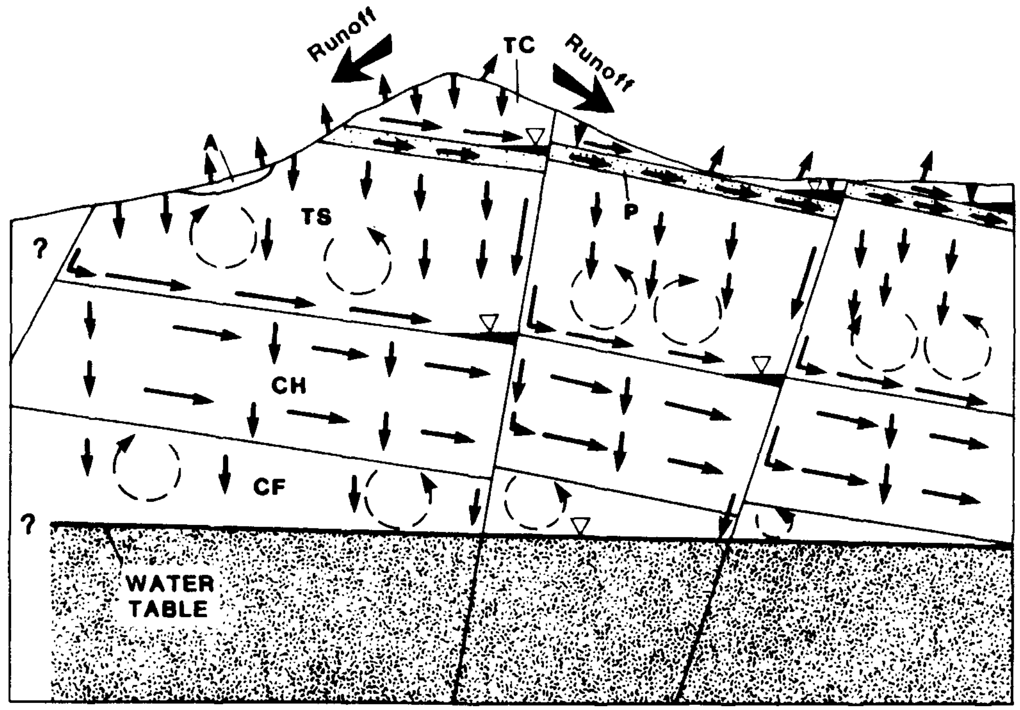
General Conceptual Model of Flow Regime at Yucca Mountain
(from Montazer and Wilson, 1984)



NOT TO SCALE

EXPLANATION

A ALLUVIUM
TC TIVA CANYON WELDED UNIT
P PAINTBRUSH NONWELDED UNIT
TS TOPOPAH SPRING WELDED UNIT
CH CALICO HILLS NONWELDED UNIT
CF CRATER FLAT UNIT
DIRECTION OF LIQUID FLOW
DIRECTION OF VAPOR MOVEMENT
PERCHED WATER

Analyses of Percolation Flux will Consider

- Multiphase processes
- Fracture-matrix interactions
- Variable climate, and temporally and spatially variable net infiltration
- Stratigraphic discontinuities
- The possibility of focused percolation

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Possible Methods for Estimating Percolation Flux

- Direct calculation from Darcy's law
- Direct observation; for example, measurement of inflow in ramps and drifts
- Environmental tracers; for example, ^{14}C, tritium, ^{36}Cl
- Numerical modeling

Limitations and Constraints

- Flux estimates from each method subject to some uncertainty
- Complementary methods must yield internally consistent picture of the liquid flux and its spatial distribution
- Degree of accuracy and certainty required in estimates of percolation flux depend, in part, on performance assessment analyses and characteristics of the engineered barriers

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Examples of Modeling That Have Been Done to Understand Flow Behavior or to Estimate Liquid Flux

- Numerical investigation of steady liquid water flow in a variably saturated fracture network
- Estimation of unsaturated zone liquid water flux at boreholes UZ #4, UZ #5, UZ #7, and UZ #13

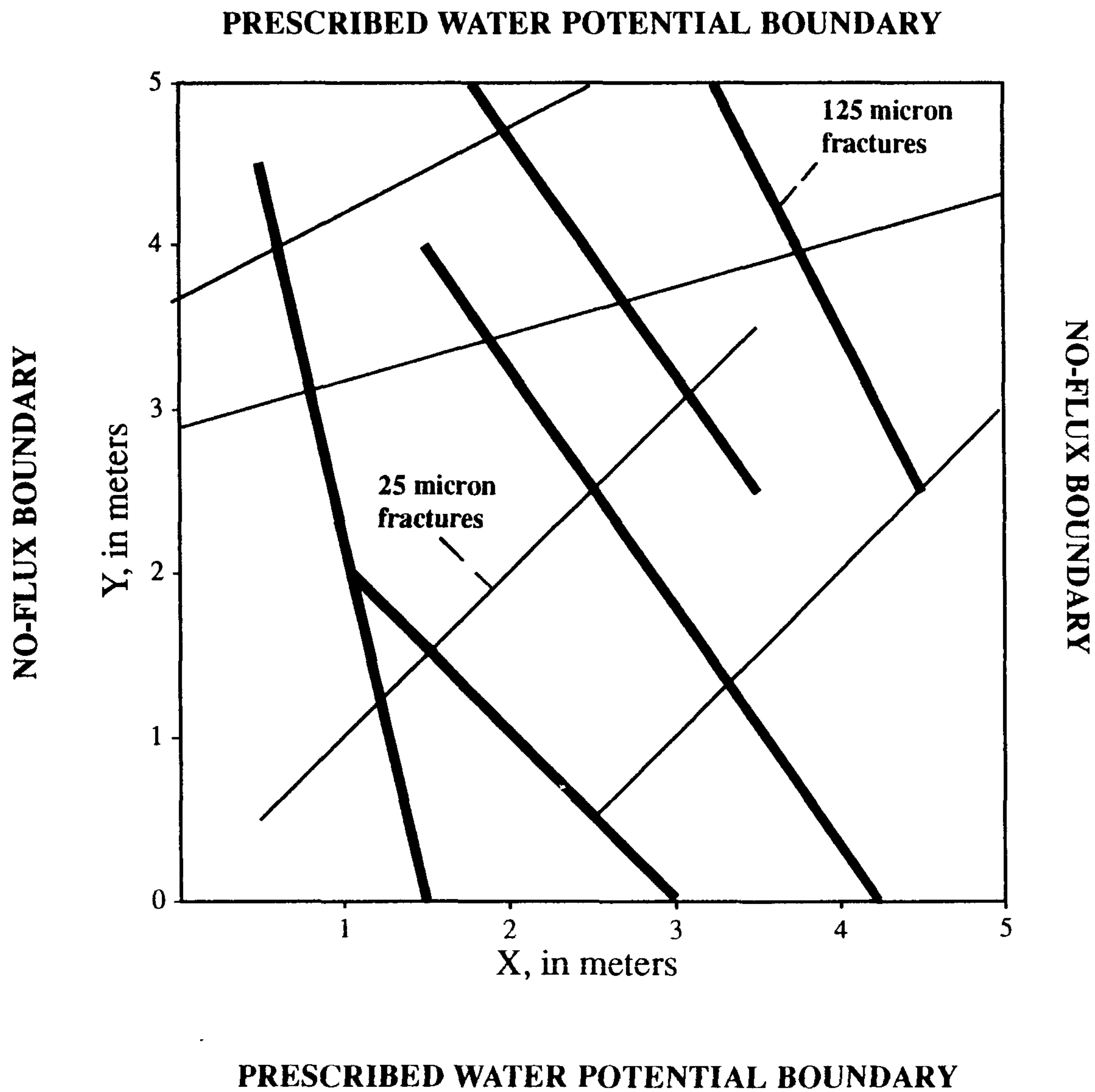
Numerical Investigation of Steady Liquid Water Flow in a Variably Saturated Fracture Network

(Kwicklis and Healy, 1993)

Objectives:

- To gain insight into the formation of preferential pathways within variably saturated fracture networks
- To assess the limitations and potential implications of point measurements of water potential in the field
- To evaluate the equivalent porous media representation of variably saturated fracture systems

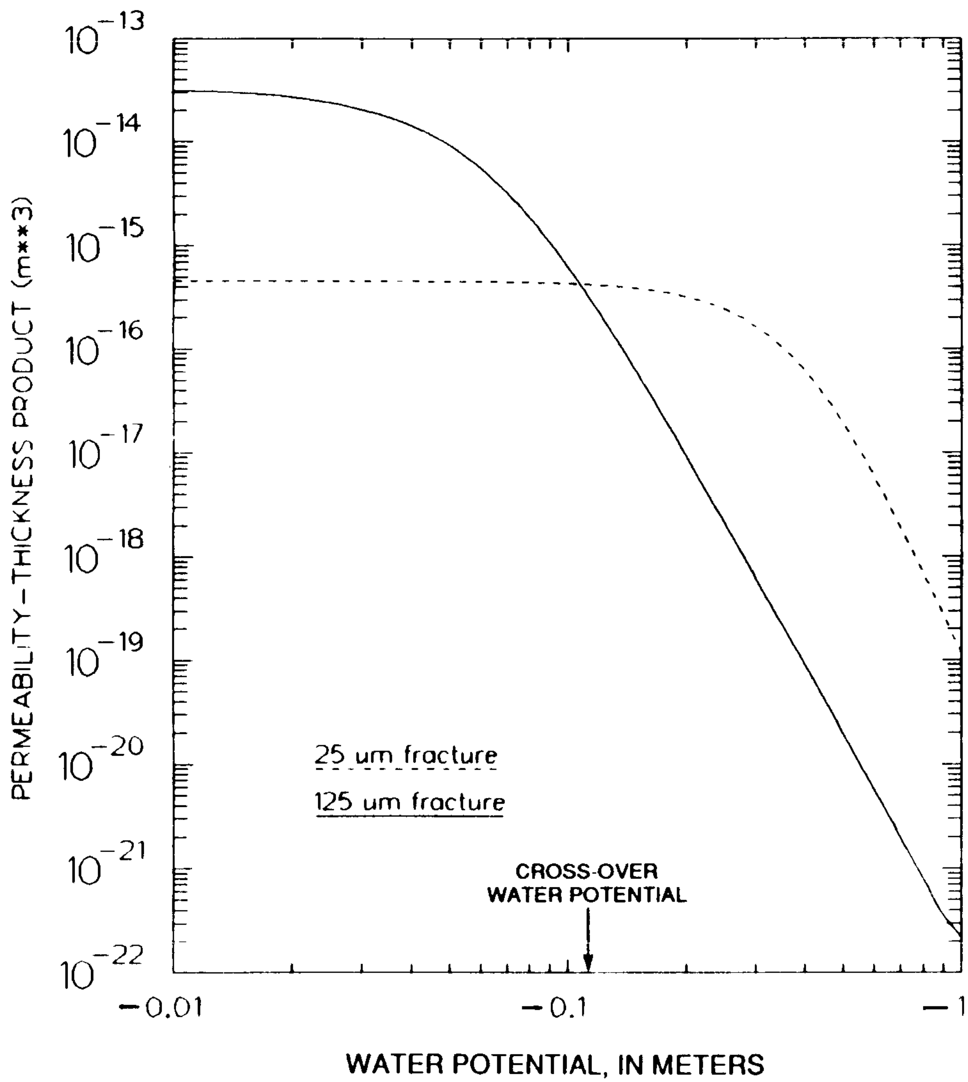
Fracture Network Assumed for Simulation



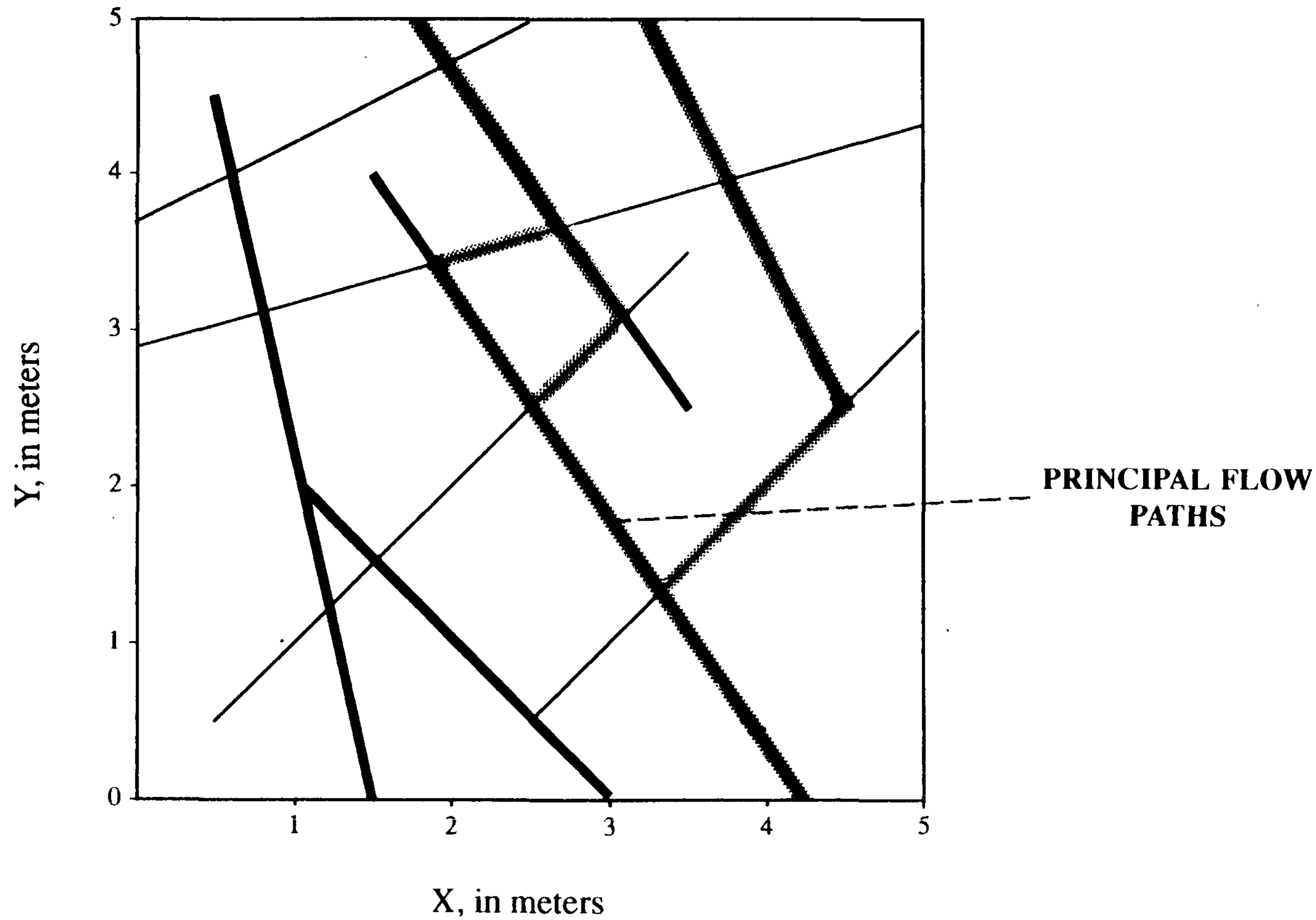
Simulation Assumptions

- Numerical simulation in vertical 5m-by-5m flow region
- Two fracture sets
  - Sub-vertical set with five 125 micron fractures
  - Sub-horizontal set with four 25 micron fractures
- Impermeable matrix
- Steady-flow
- Ignore hysteretic effects

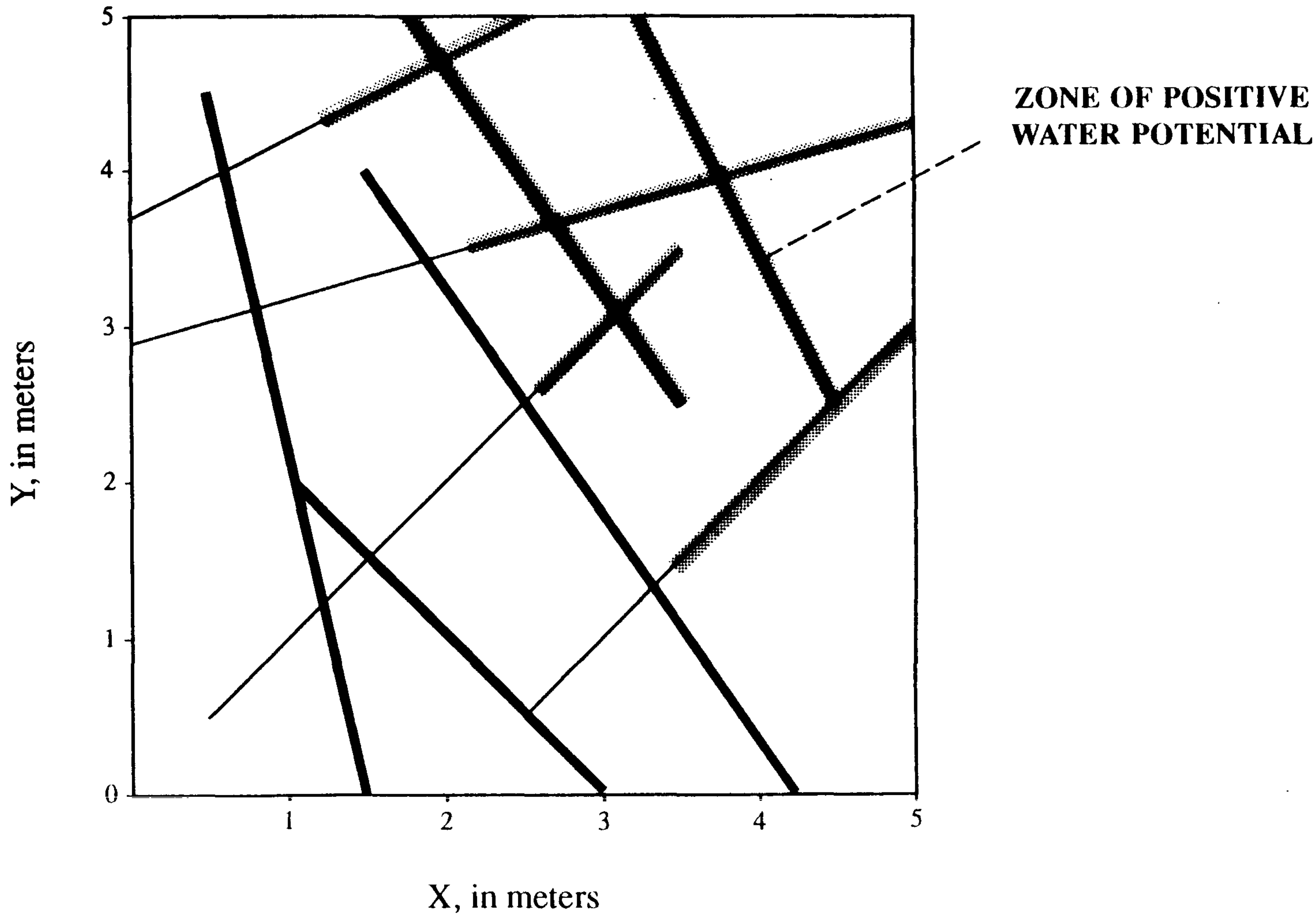
Permeability-Thickness Products as a Function of Water Potential



Location of Principal Flow Paths for Boundary Water Potentials of 0.0 Meters



Location of Positive Water Potentials for Boundary Water Potentials of 0.0 Meters



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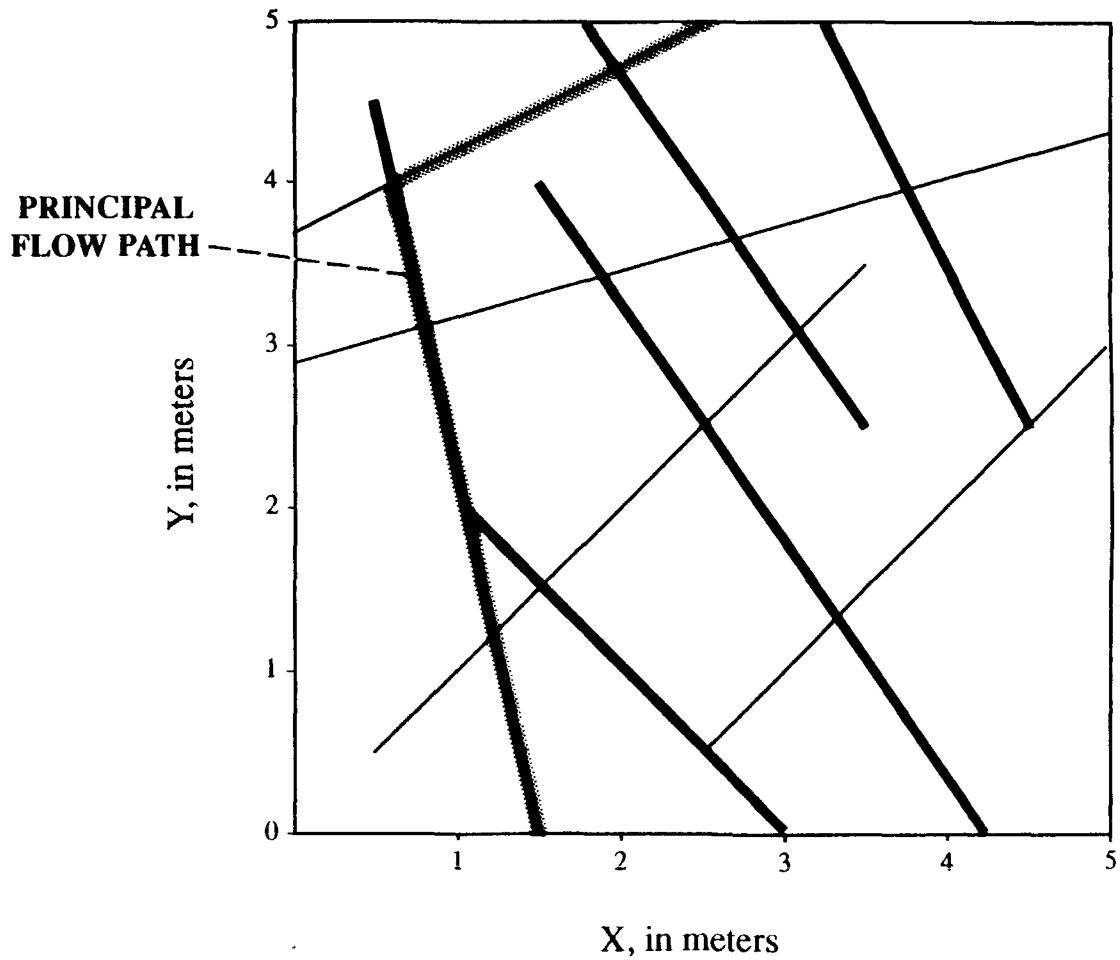
Location of Principal Flow Paths for Boundary Water Potentials of -0.25 Meters



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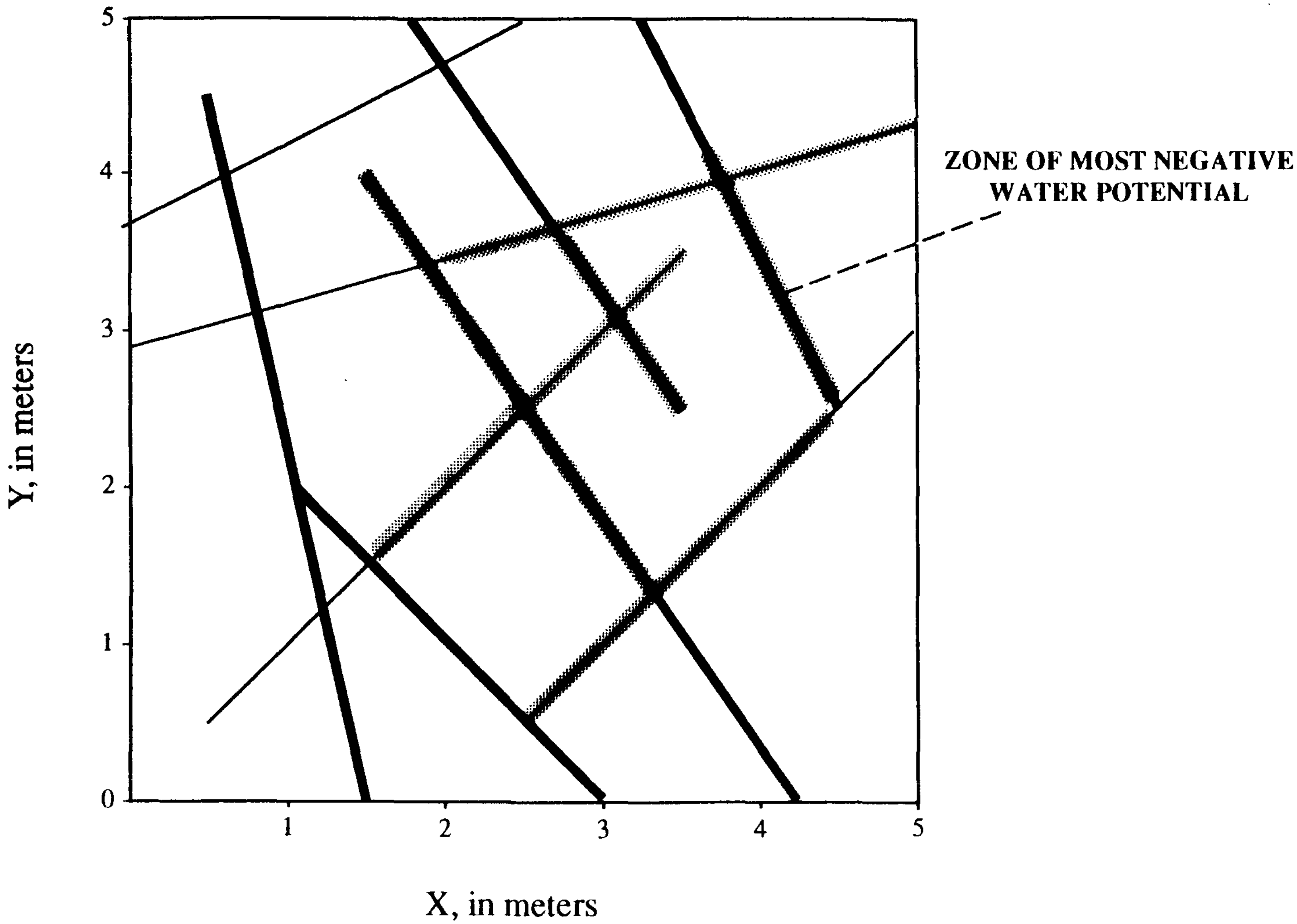
Location of Most Negative Water Potentials for Boundary Water Potentials of -0.25 Meters



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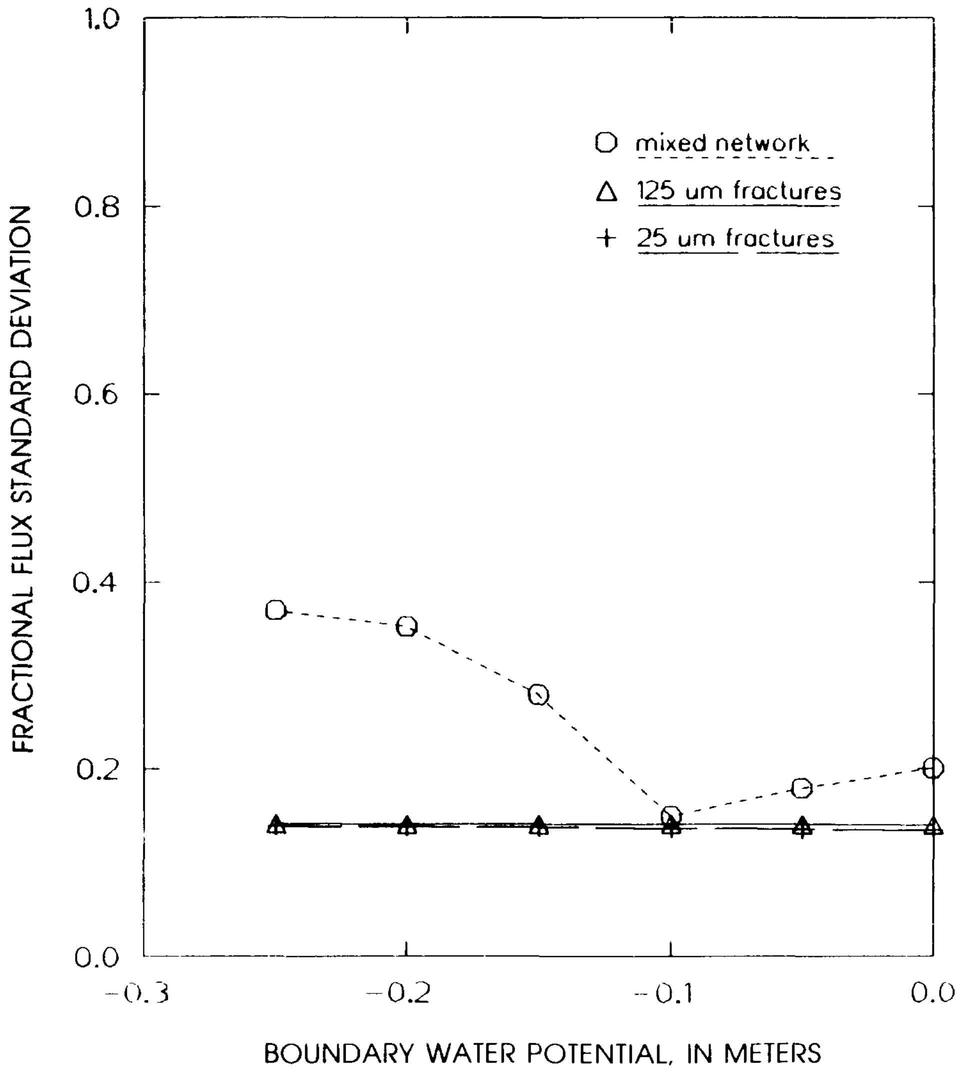
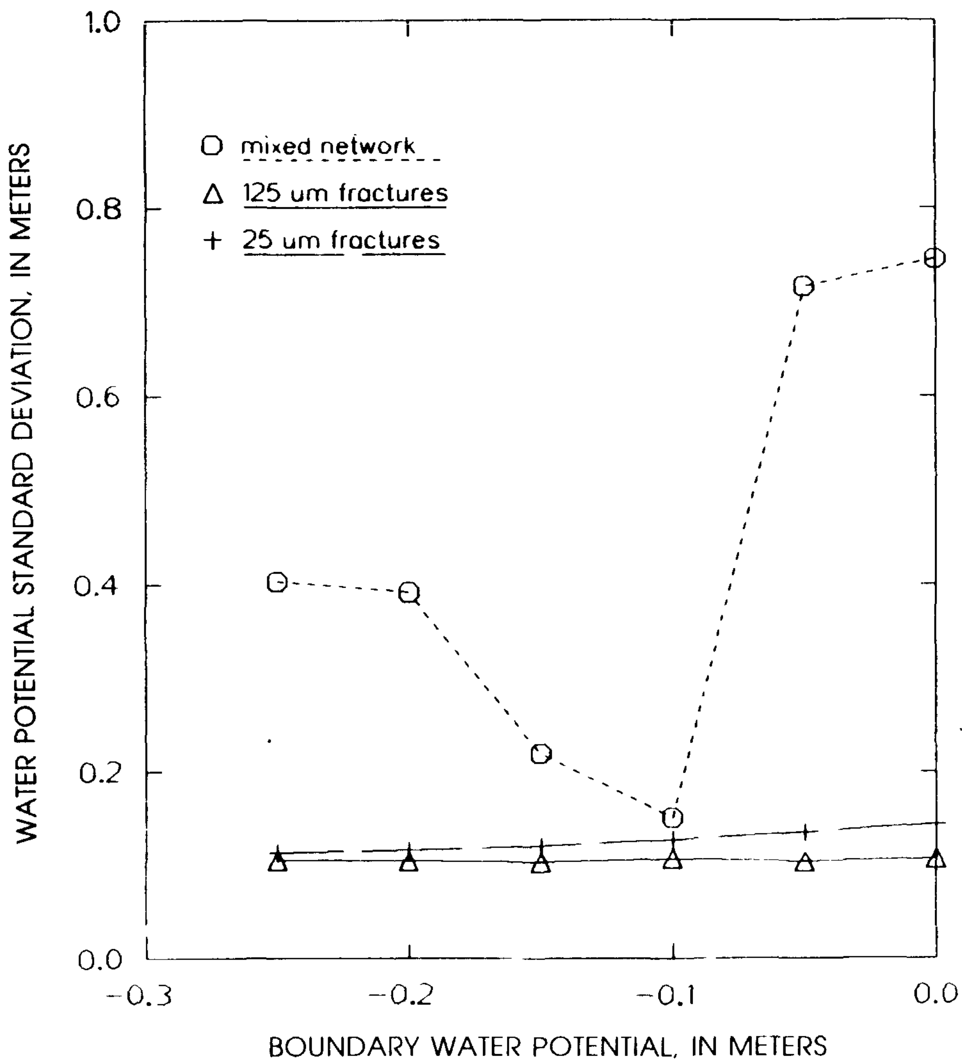
Standard Deviation of Fractional Flux as a Function of Boundary Water Potential



Standard Deviation of Water Potential as a Function of Boundary Water Potential



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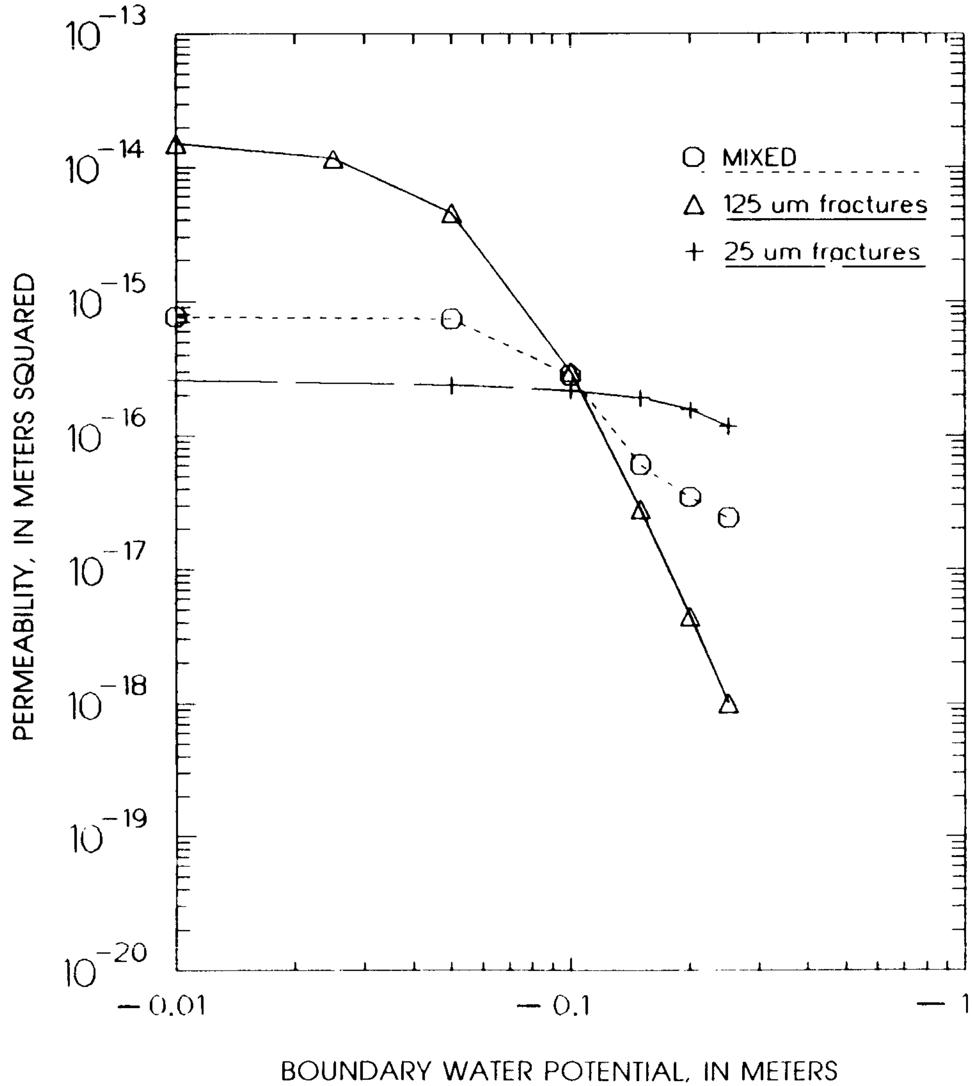
Equivalent Continuum Permeability as a Function of Boundary Water Potential



Conclusions from Fracture Network Modeling

- Water potential and flux are spatially variably within a network containing fractures of different aperture, even for steady-state flow

- The tendency for flow to become concentrated, as well as the location of the dominant flow pathways, varies as a function of the boundary water potential

- Variability in water potential within the flow domain is a function of the boundary water potential

Implications

- Measurements of water potential may reflect only the local environment for certain experimental conditions

- Some poorly connected fractures may be saturated and drain when intersected by boreholes or drifts

- Dominant flow pathways through fracture networks, if they occur, may change in response to changing climatic conditions

Estimation of Unsaturated Zone Liquid Water Flux at Boreholes UZ #4, UZ #5, UZ #7, and UZ #13 from Saturation and Water Potential Profiles

(Kwicklis, Flint, and Healy, 1993)

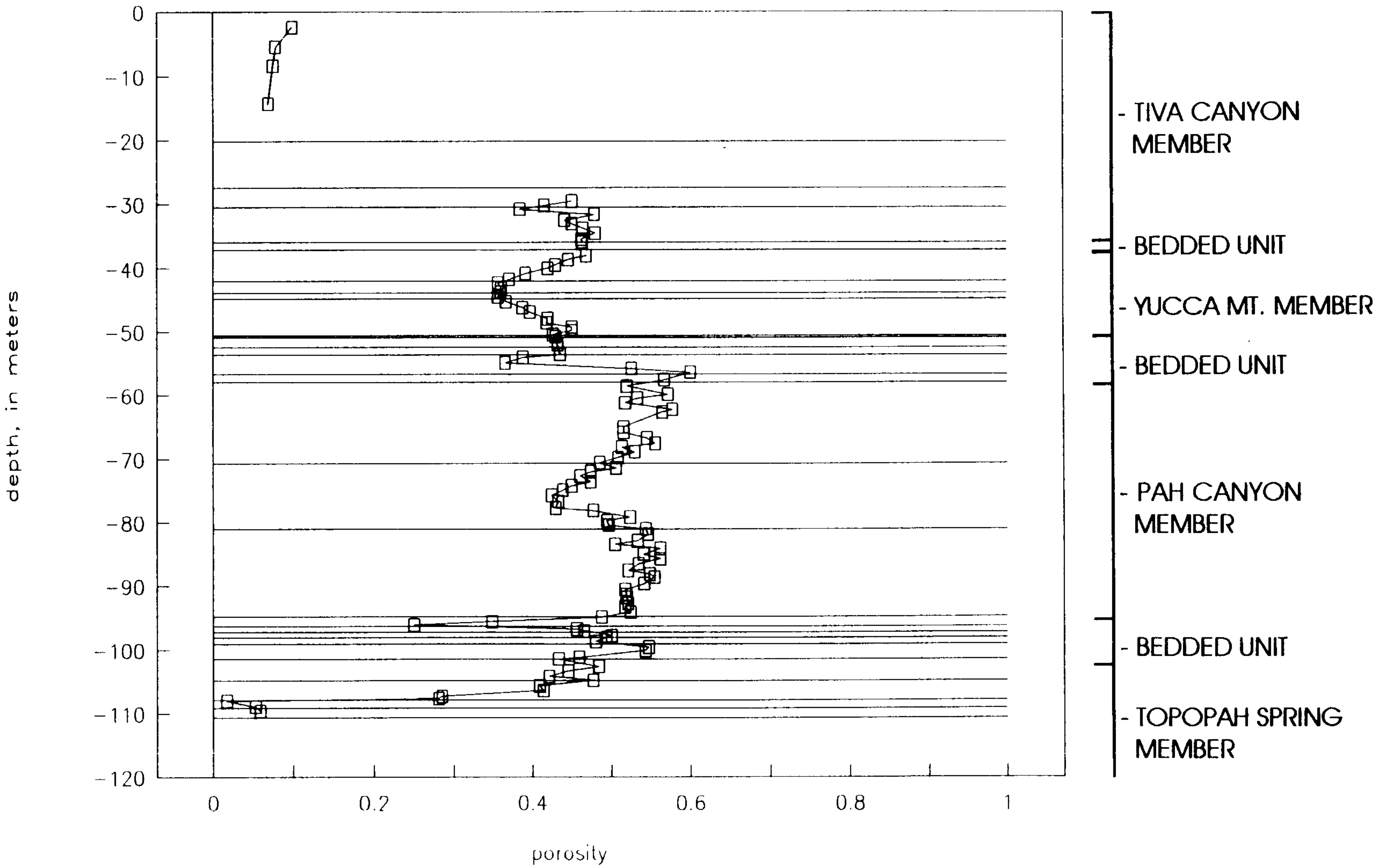
Objectives:

- To estimate liquid water fluxes through the nonwelded and bedded units
- To better understand recharge mechanisms and the role of the nonwelded units in redistributing infiltration
- To examine the internal consistency of hydrologic data collected to date
- To develop numerical models consistent with available data

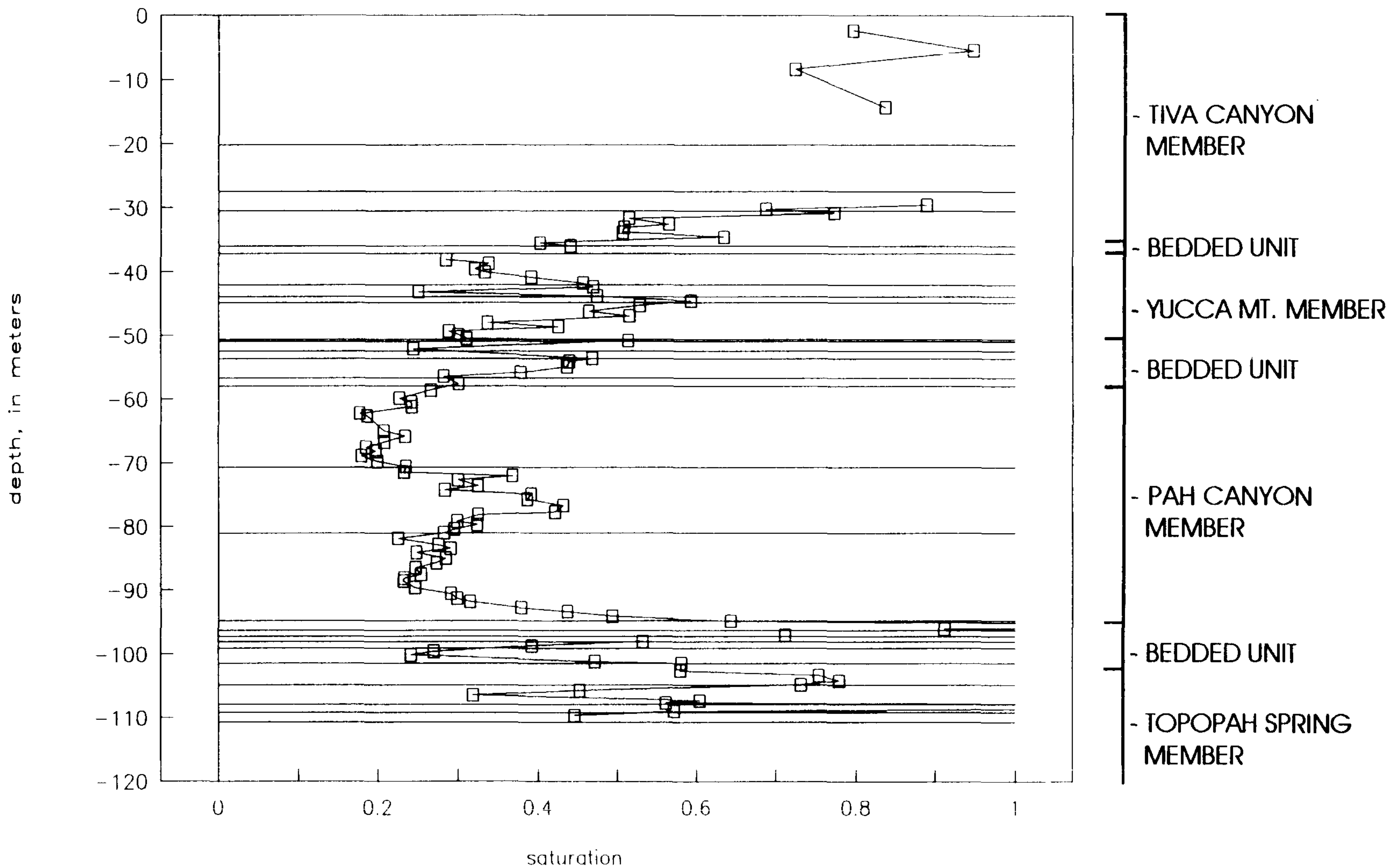
Methods

- Regression analyses using porosity (ϕ) as a predictor variable for K and van Genuchten parameters α and β
- Calculate saturation profiles for unsaturated zone boreholes from porosity, bulk-density, and gravimetric water-content information
- Estimate more or less continuous profiles of unsaturated K versus depth at unsaturated zone boreholes using regression relations between K, α, β and ϕ, and measured S_l
- Use measured and predicted water potentials, along with estimates of unsaturated K, to estimate liquid flux versus depth from Darcy's law

Porosity versus Depth, UZ #5

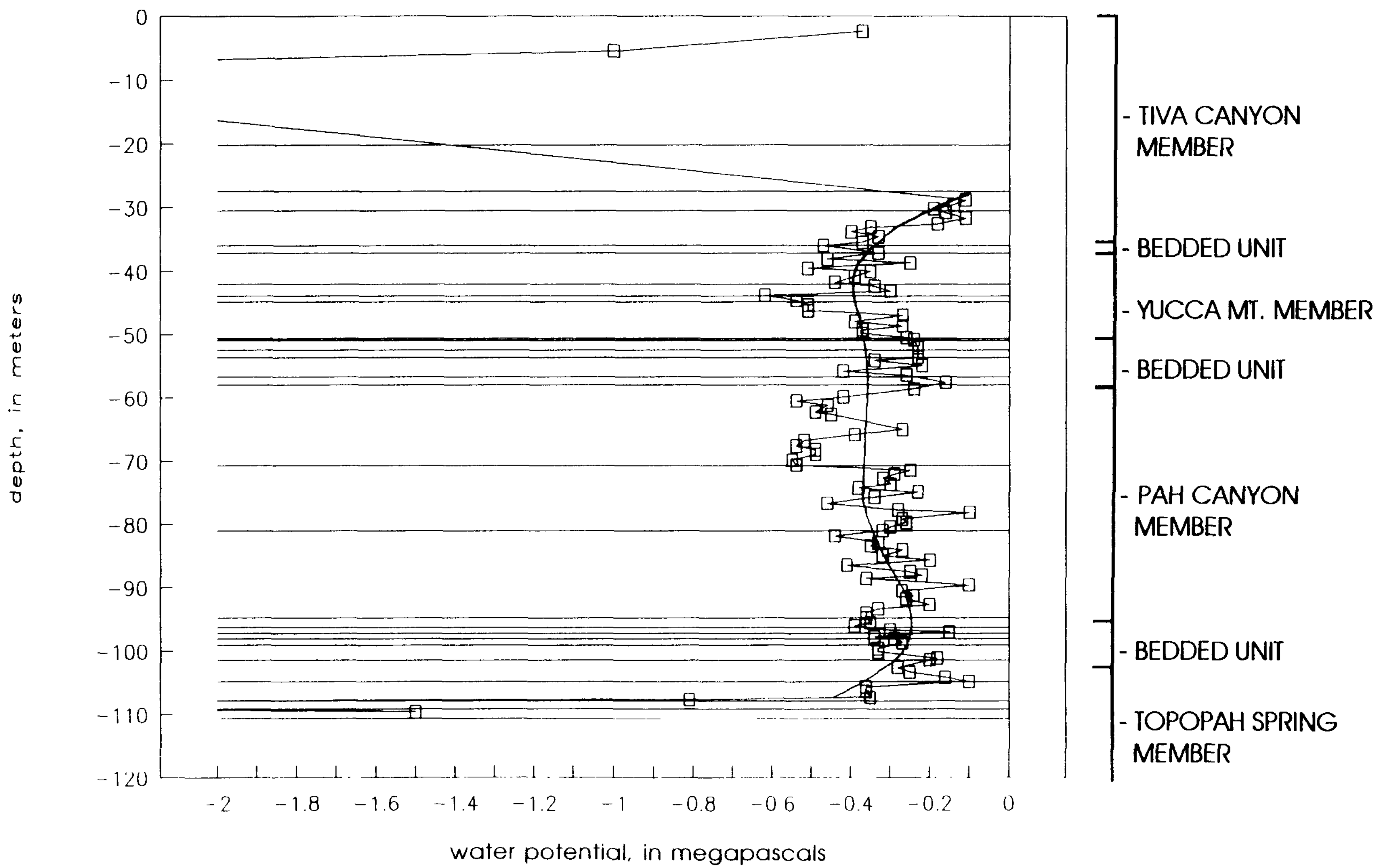


Saturation versus Depth, UZ #5



Measured Water Potentials versus Depth, UZ #5

(with 5th Order Polynomial Fit to Data From Nonwelded Horizons)



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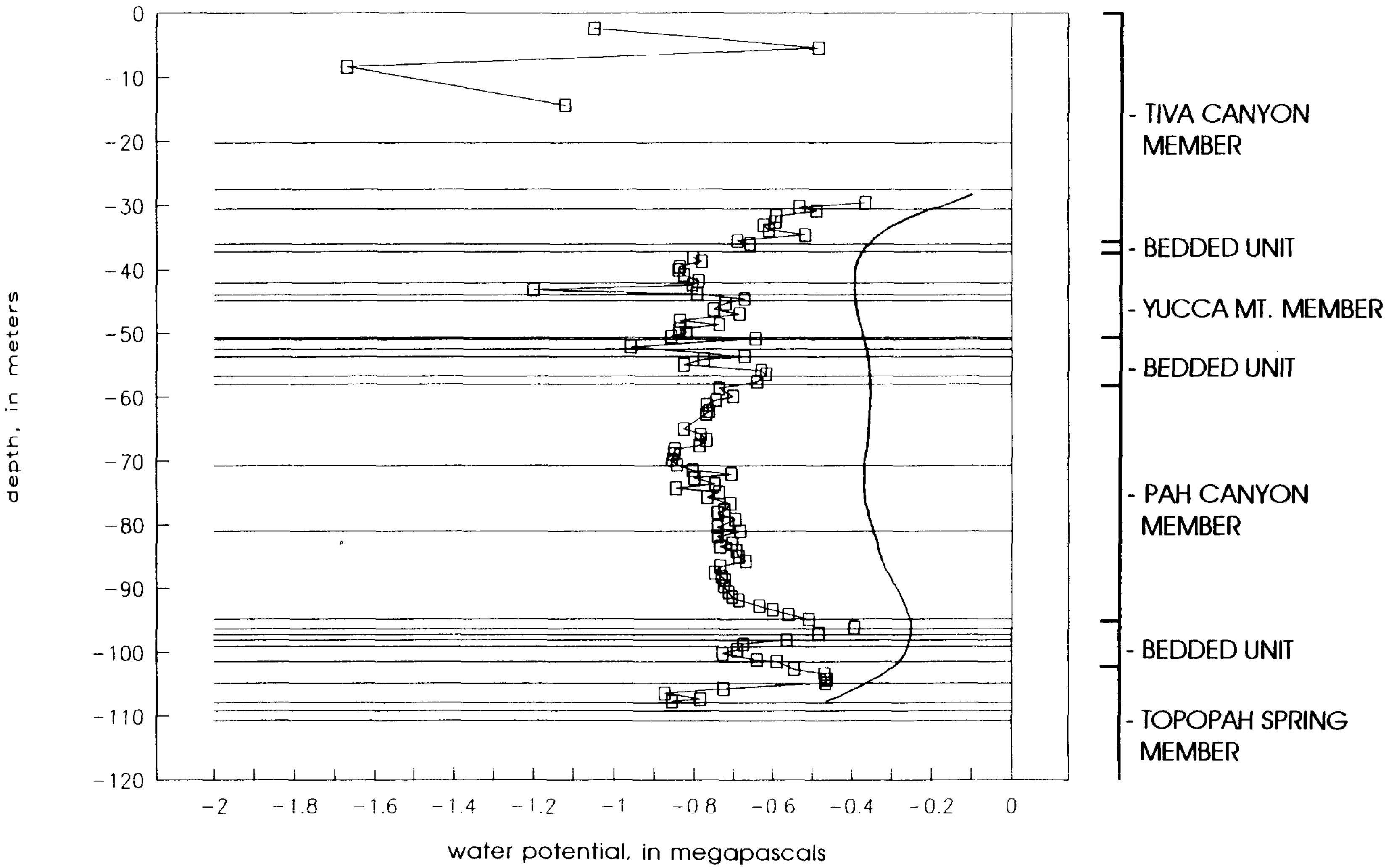
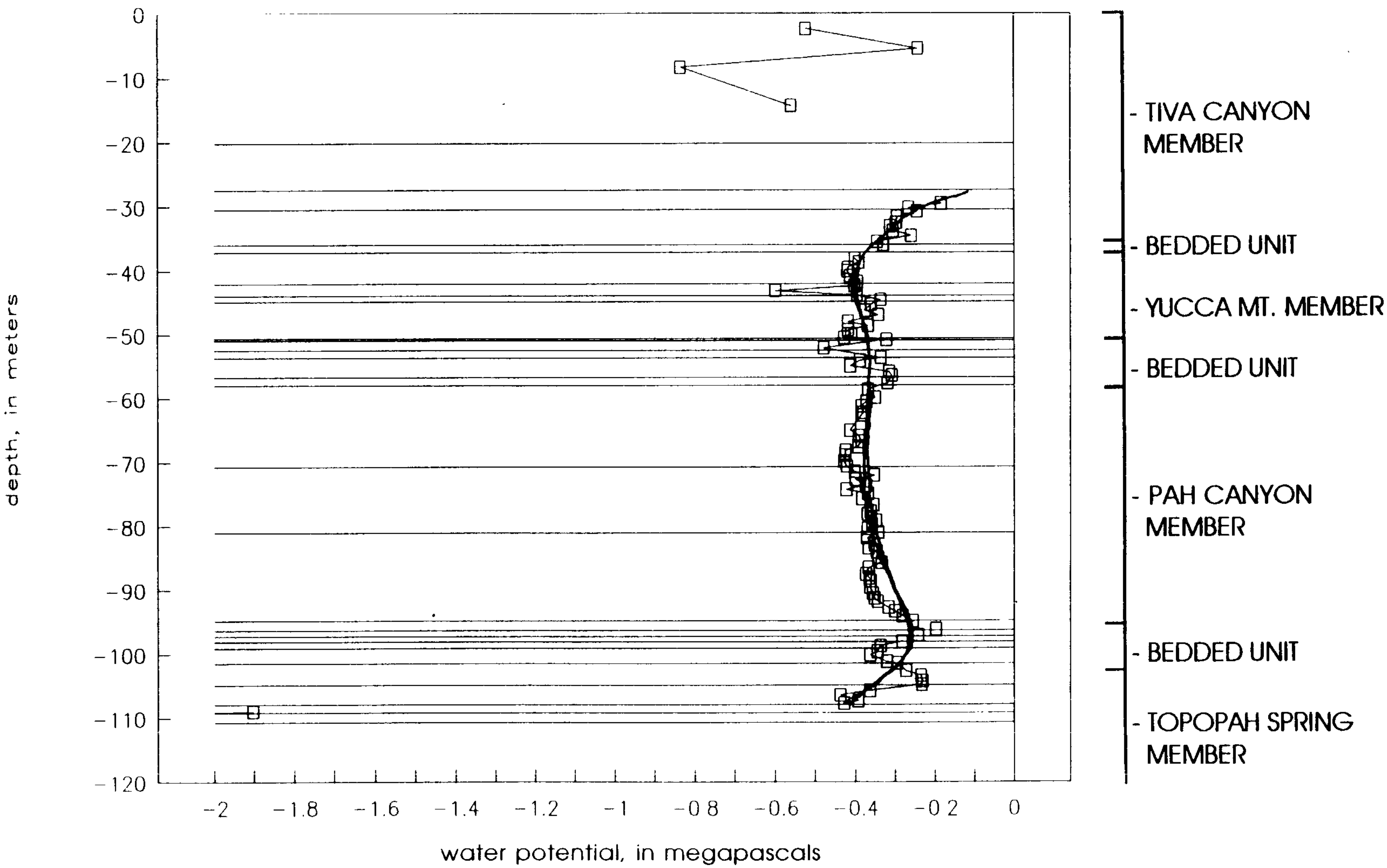
Predicted Water Potentials, UZ #5



Predicted Water Potentials, UZ #5
(Calibrated)



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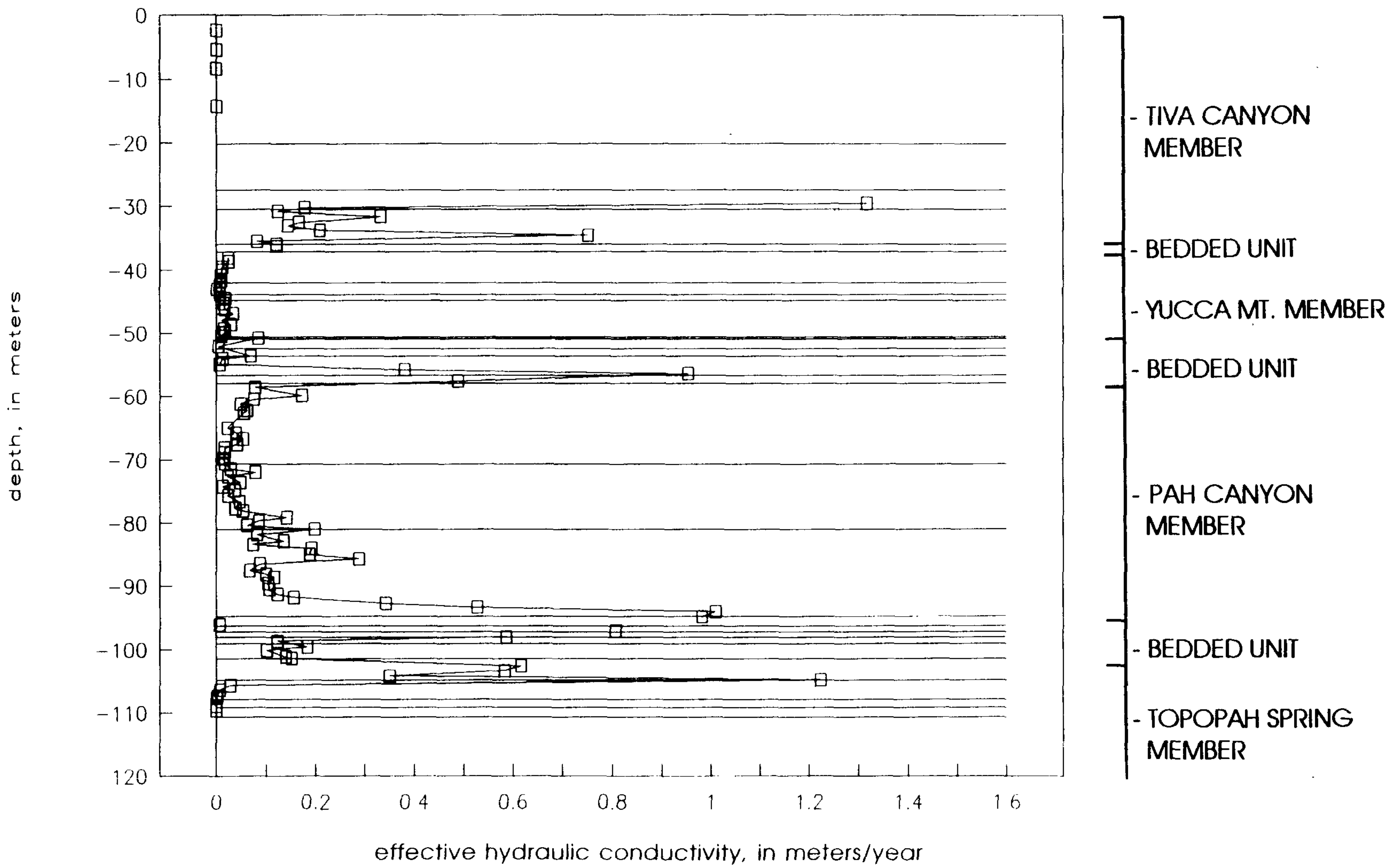
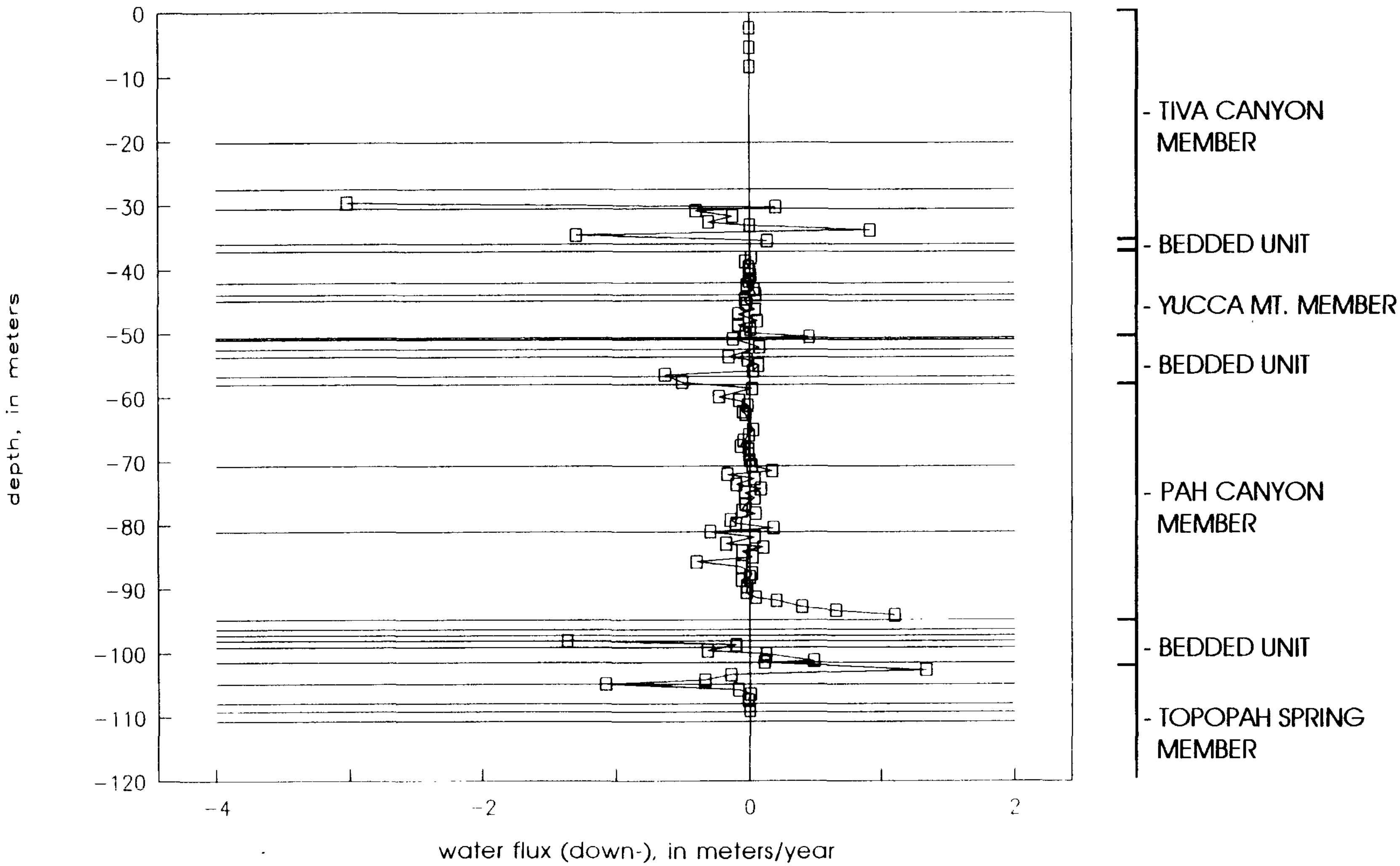
Estimated Effective Hydraulic Conductivity, UZ #5



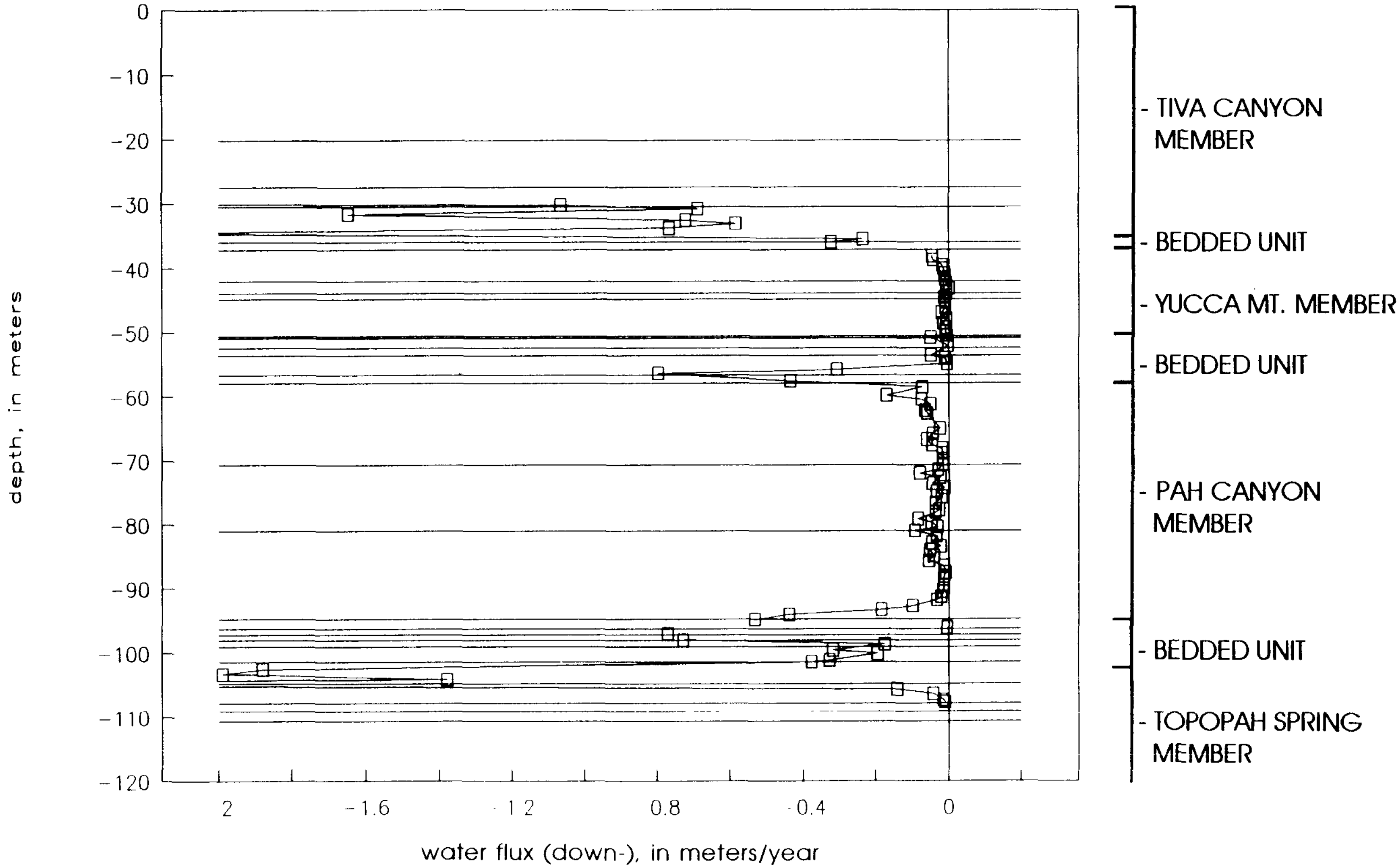
Estimated Liquid Flux, UZ #5

Calculated Using Predicted Water Potentials



Estimated Liquid Flux, UZ #5

Calculated Using Polynomial Fit to Measured Water Potential Profile



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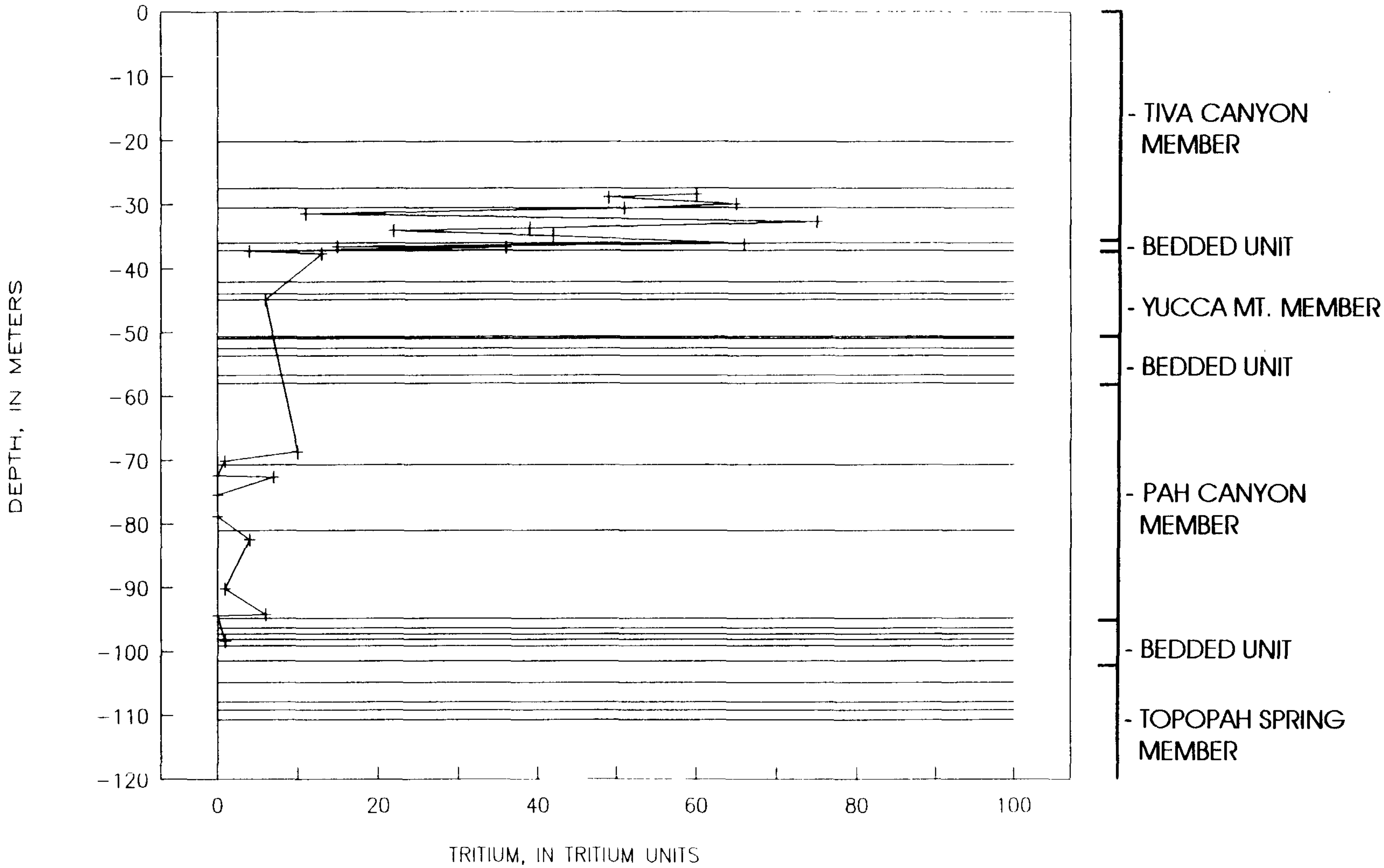
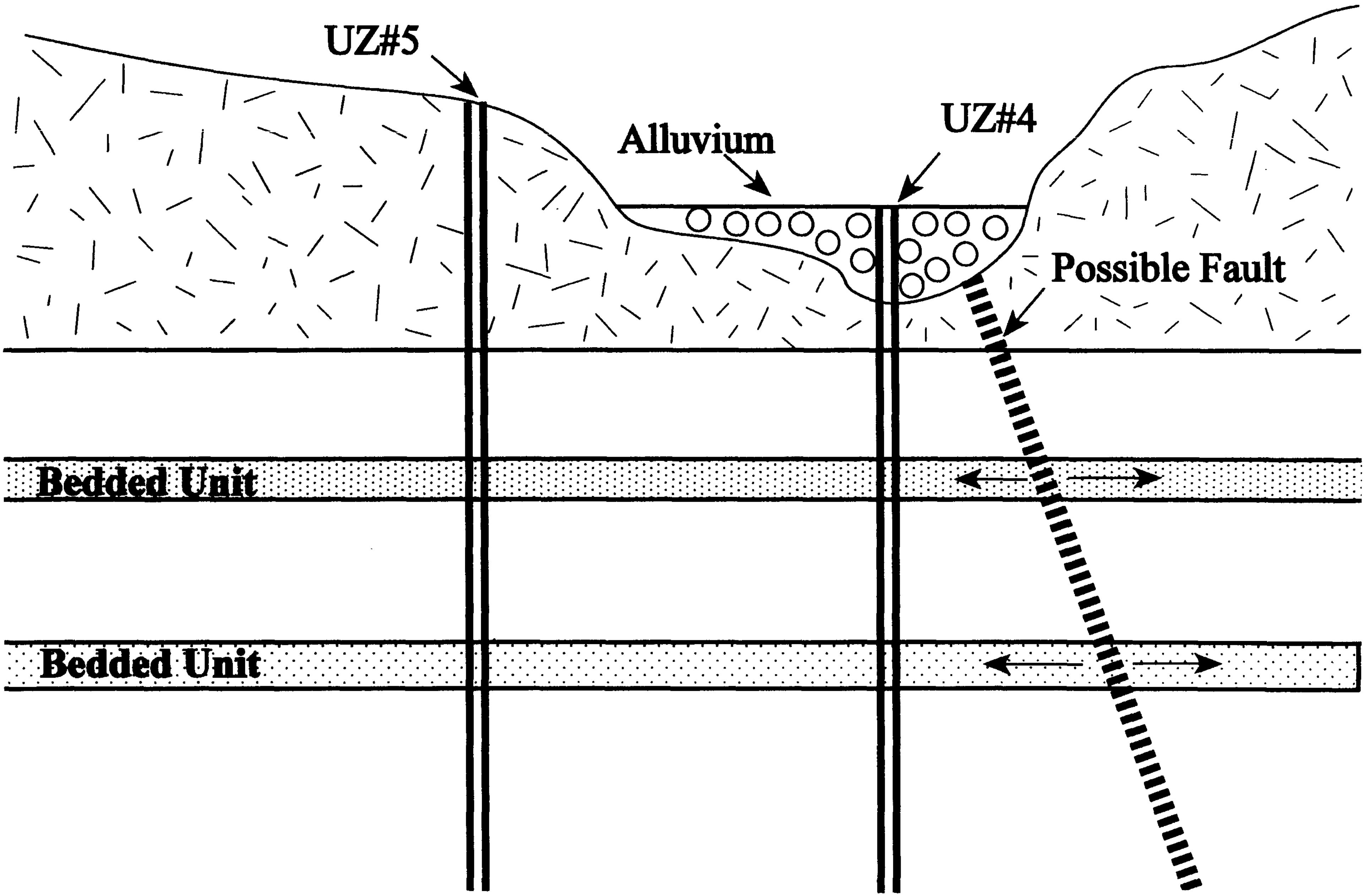
Tritium Distribution, UZ #5



Schematic Cross-Section Through Pagany Wash



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Conclusions

- Important statistical correlations were established that allow augmentation of existing hydrologic data and constrain parameter space in numerical models

- At present, flux estimates are imprecise because K versus S_l relations have been measured for only a few stratigraphic horizons, and unsaturated K estimates are subject to large uncertainty and potential error

Conclusions

(continued)

- The calculated flux profiles for boreholes located within and adjacent to the alluvial channels indicate that past recharge has been high relative to previous estimates made for the average flux over the site (generally less than 1 mm/yr)
- The calculated flux profiles display systemmatic trends, including large-scale reversals in flow direction within and near the bedded air-fall units, that suggest the occurrence of lateral flow

Implications

- An understanding of the microstratigraphy is essential to understanding the observed saturation profiles

- Flow within the upper part of the unsaturated zone is neither one-dimensional nor steady state. Numerical models that do not allow for transient behavior and multi-dimensional flow will not be able to reproduce the observed water potential or saturation data in the upper part of unsaturated zone

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Conclusions of Study

- Process-oriented models, particularly fracture network models, can play an important role in developing conceptual models of percolation through variably saturated fractured rock, and reveal potential limitations of both porous media equivalent models and field data

- Uncertainty exists in all approaches to characterizing percolation. Multiple approaches involving numerical modeling at different scales, hydrologic testing, geologic characterization, geochemistry, and in situ monitoring are necessary to provide constraints on possible percolation fluxes