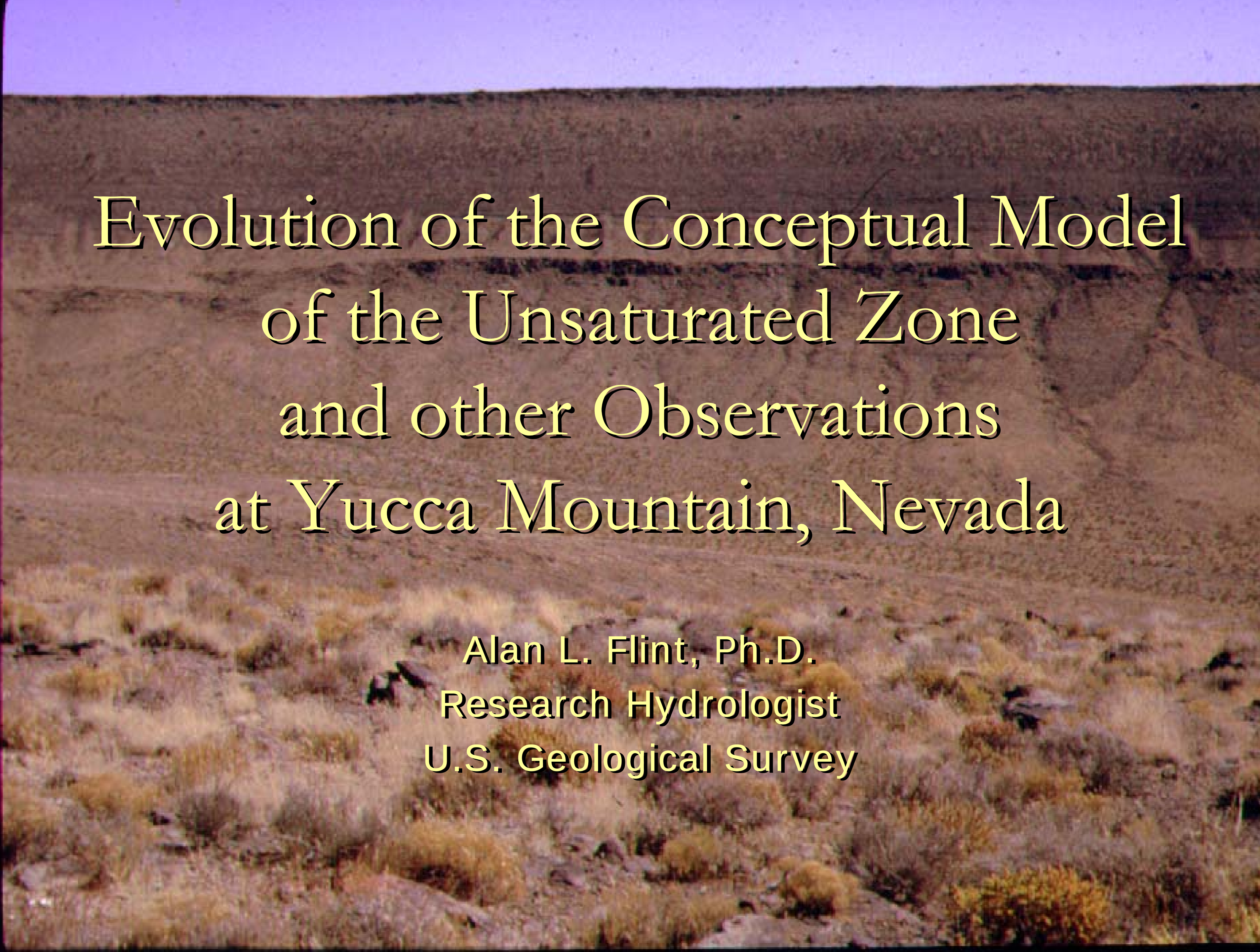


Evolution of the Conceptual Model of the Unsaturated Zone and other Observations at Yucca Mountain, Nevada

Alan L. Flint, Ph.D.
Research Hydrologist
U.S. Geological Survey

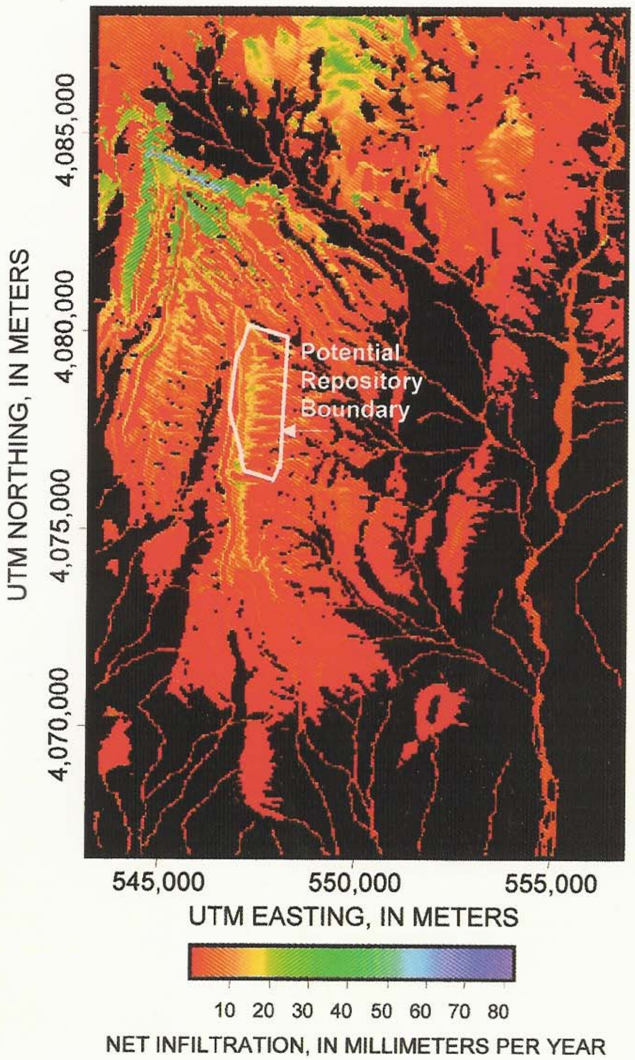
Documenting our current understanding and how we got here

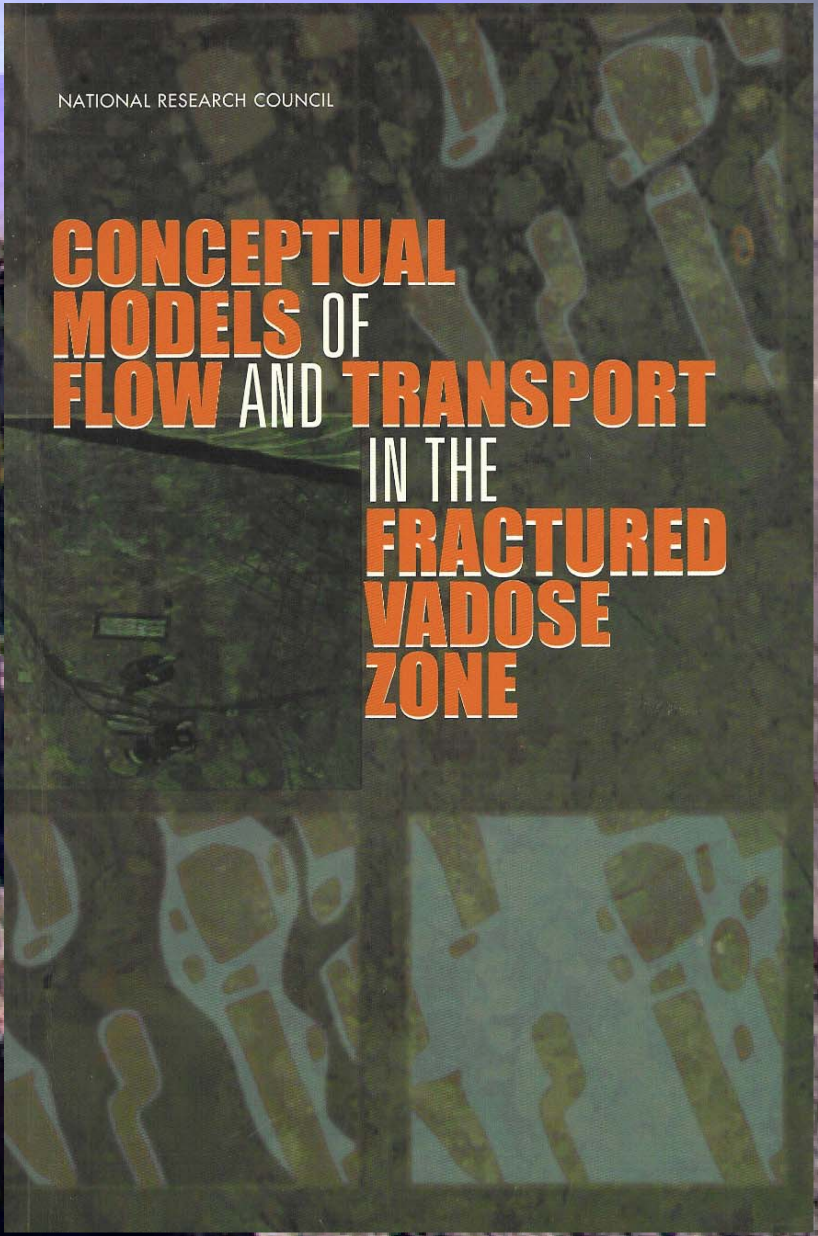
- National Research Council Panel (2001)
- Journal of Hydrology (2001)
- Reviews of Geophysics (2001)
- Hydrogeology Journal (2002)

Reviews of Geophysics

AMERICAN GEOPHYSICAL UNION

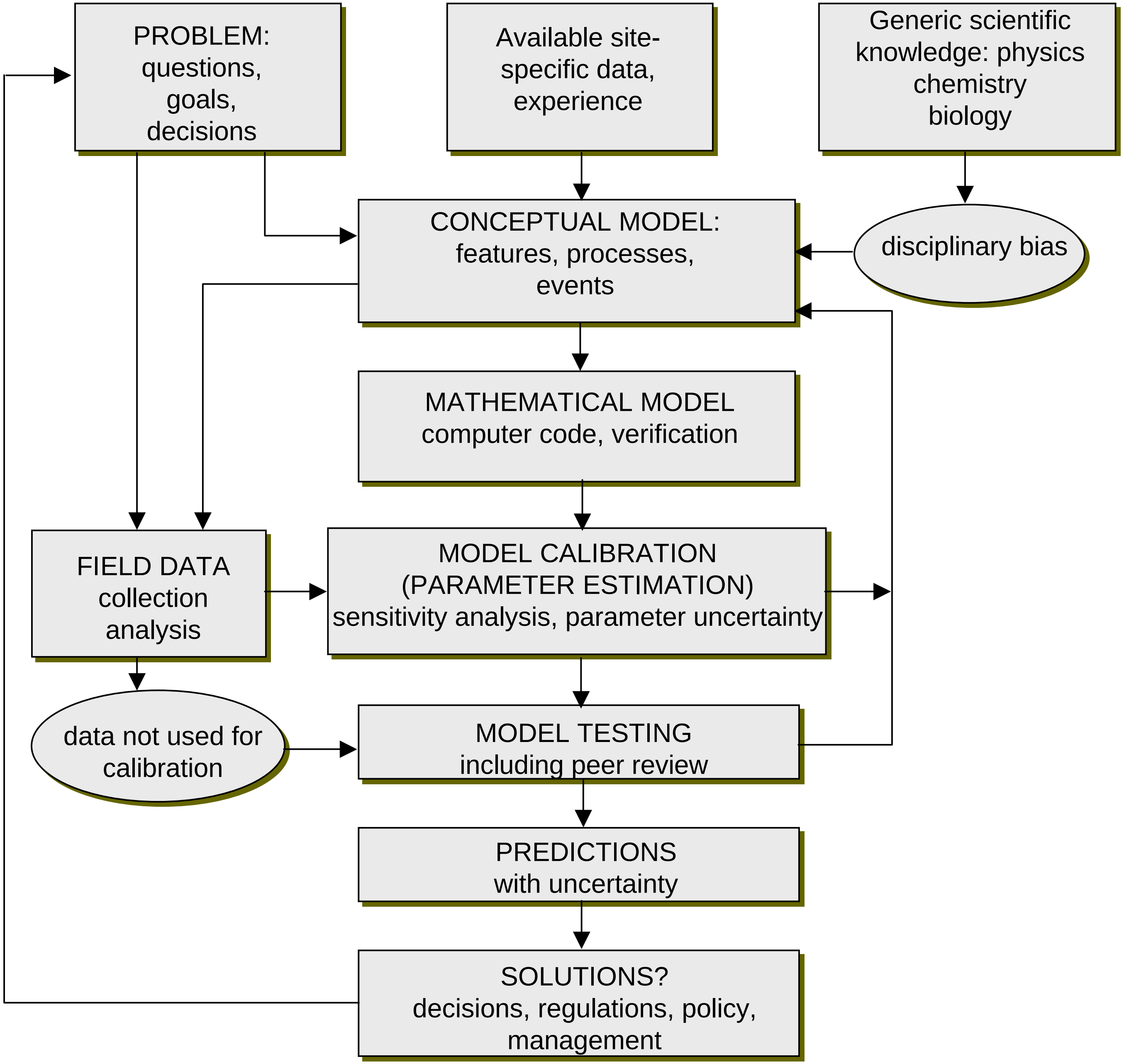
VOLUME 39 NUMBER 4 NOVEMBER 2001





NATIONAL RESEARCH COUNCIL

CONCEPTUAL MODELS OF FLOW AND TRANSPORT IN THE FRACTURED VADOSE ZONE



PROBLEM: questions, goals, decisions

Available site-specific data, experience

Generic scientific knowledge: physics chemistry biology

CONCEPTUAL MODEL: features, processes, events

disciplinary bias

MATHEMATICAL MODEL computer code, verification

FIELD DATA collection analysis

MODEL CALIBRATION (PARAMETER ESTIMATION) sensitivity analysis, parameter uncertainty

data not used for calibration

MODEL TESTING including peer review

PREDICTIONS with uncertainty

SOLUTIONS? decisions, regulations, policy, management

(from Hsieh et al., 2001)

Development of Early Conceptual and Numerical Models 1983-1990

- By 1990 TSPA estimated less than 1 percent chance that flux through the TSw was more than 3 mm/yr
- 80 percent chance the flux was less than 1 mm/yr

Early Data Collection

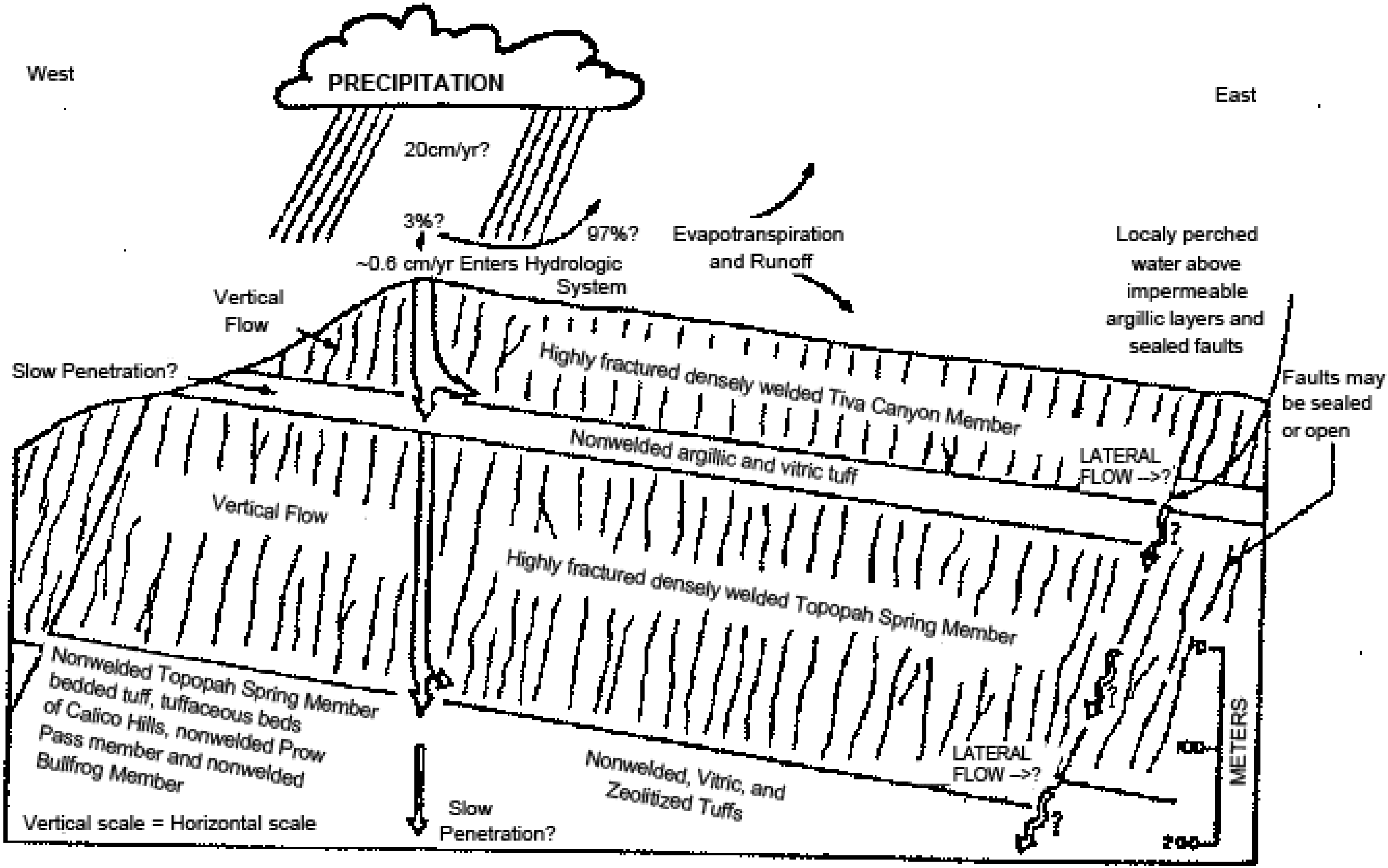
(by 1986 over 100 boreholes had been drilled)

- Deep boreholes
- Shallow neutron holes
- Surface geologic mapping
- Meteorology
- Geochemistry and hydrologic properties of rock core

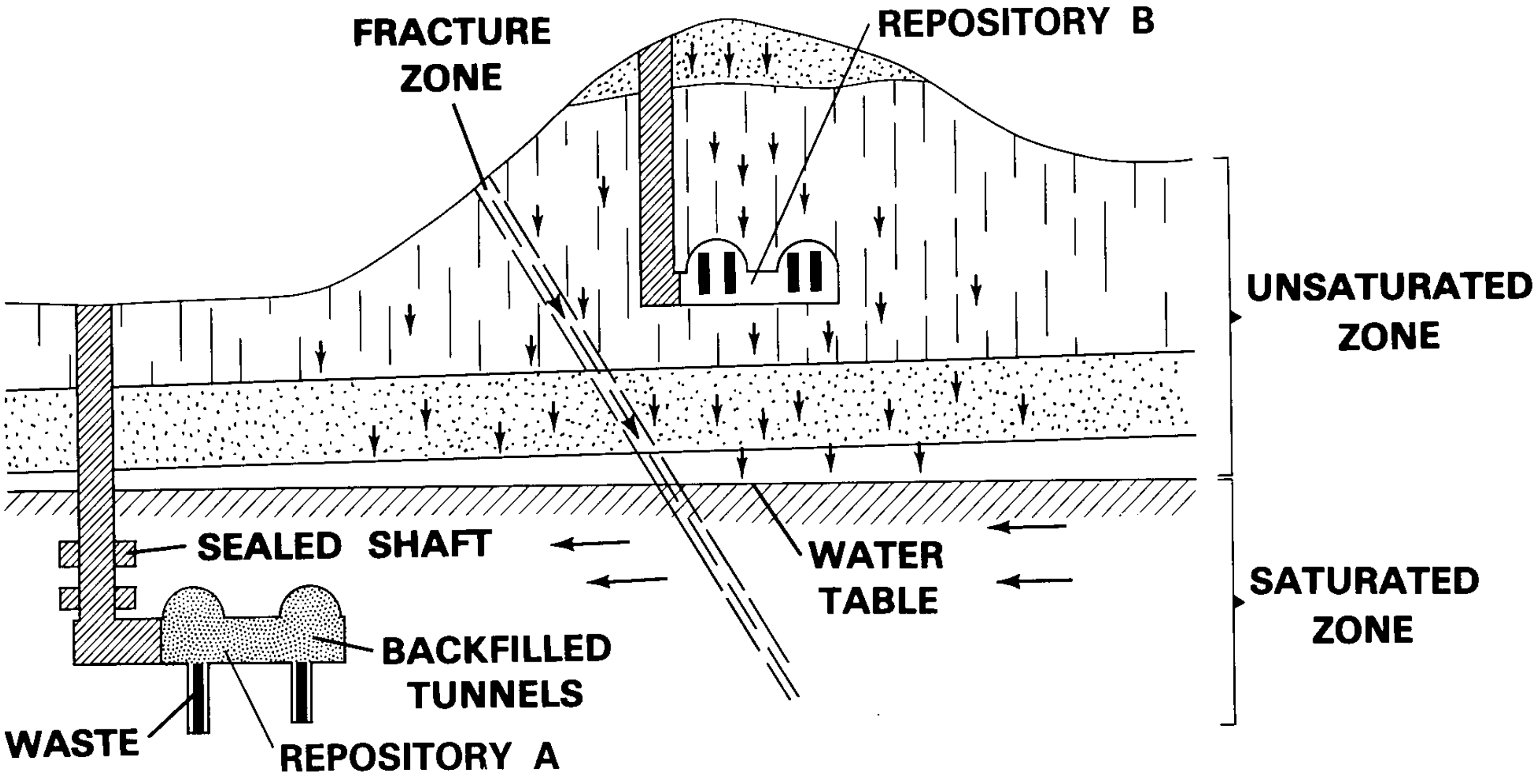
Early Conceptual Models of Hydrology

- Identified water as a critical parameter
- Described geologic/hydrologic framework
- Identified relevant hydrologic processes
- Described consequences of hydrologic flow

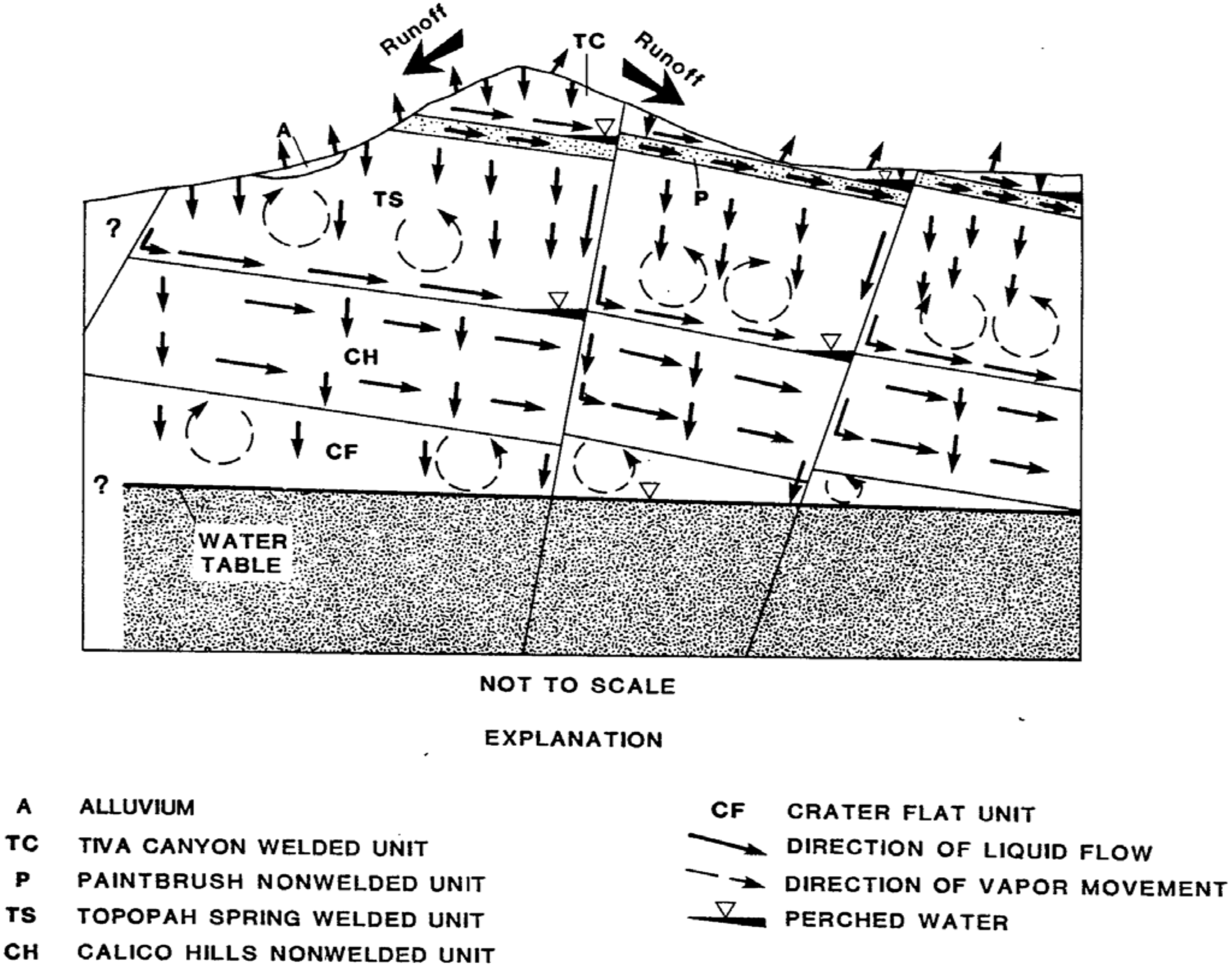
Early Conceptual Models (Scott et al., 1983)



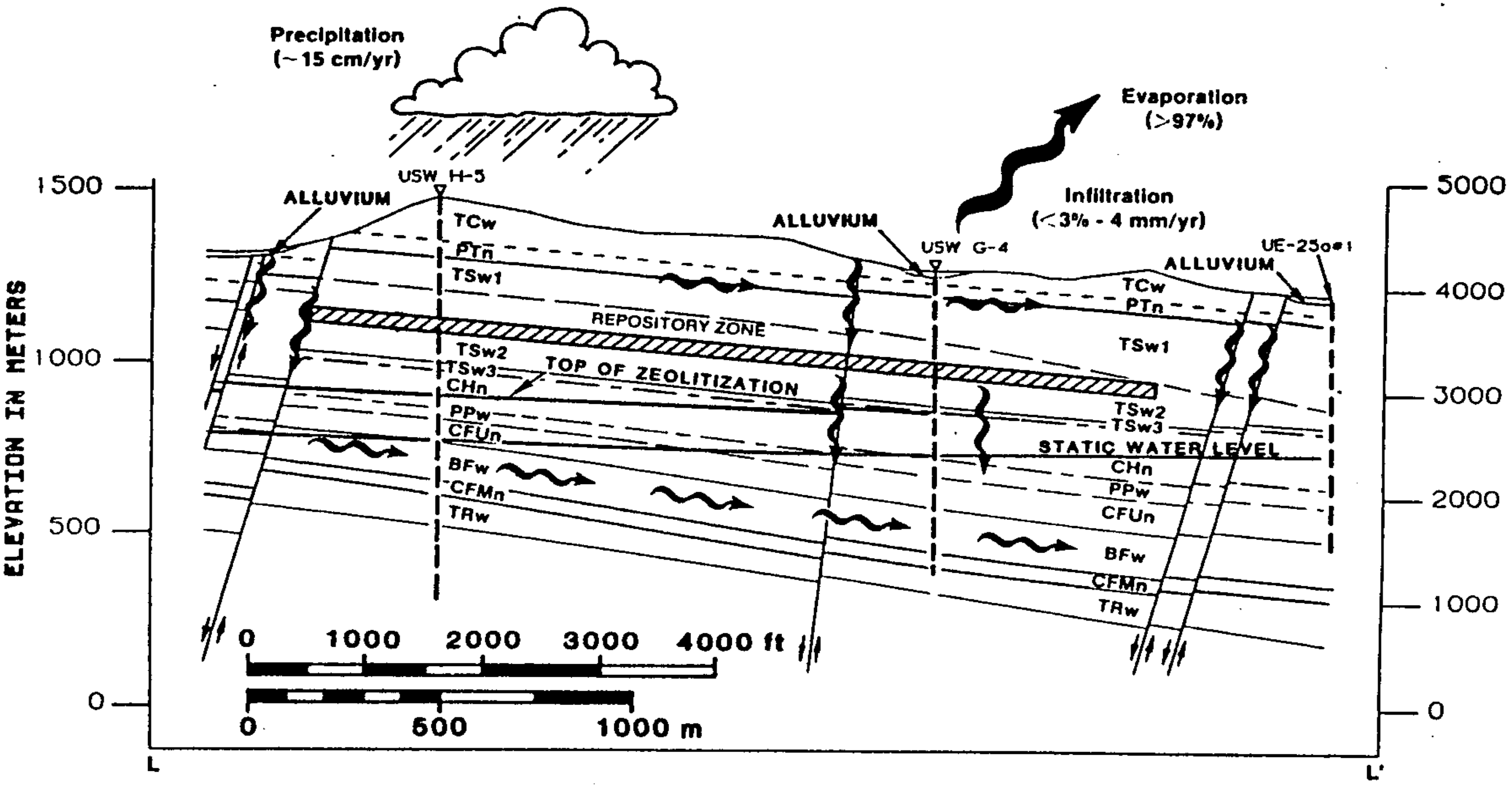
Early Conceptual Models (Roseboom, 1983)



Early Conceptual Models (Montazer and Wilson, 1984)

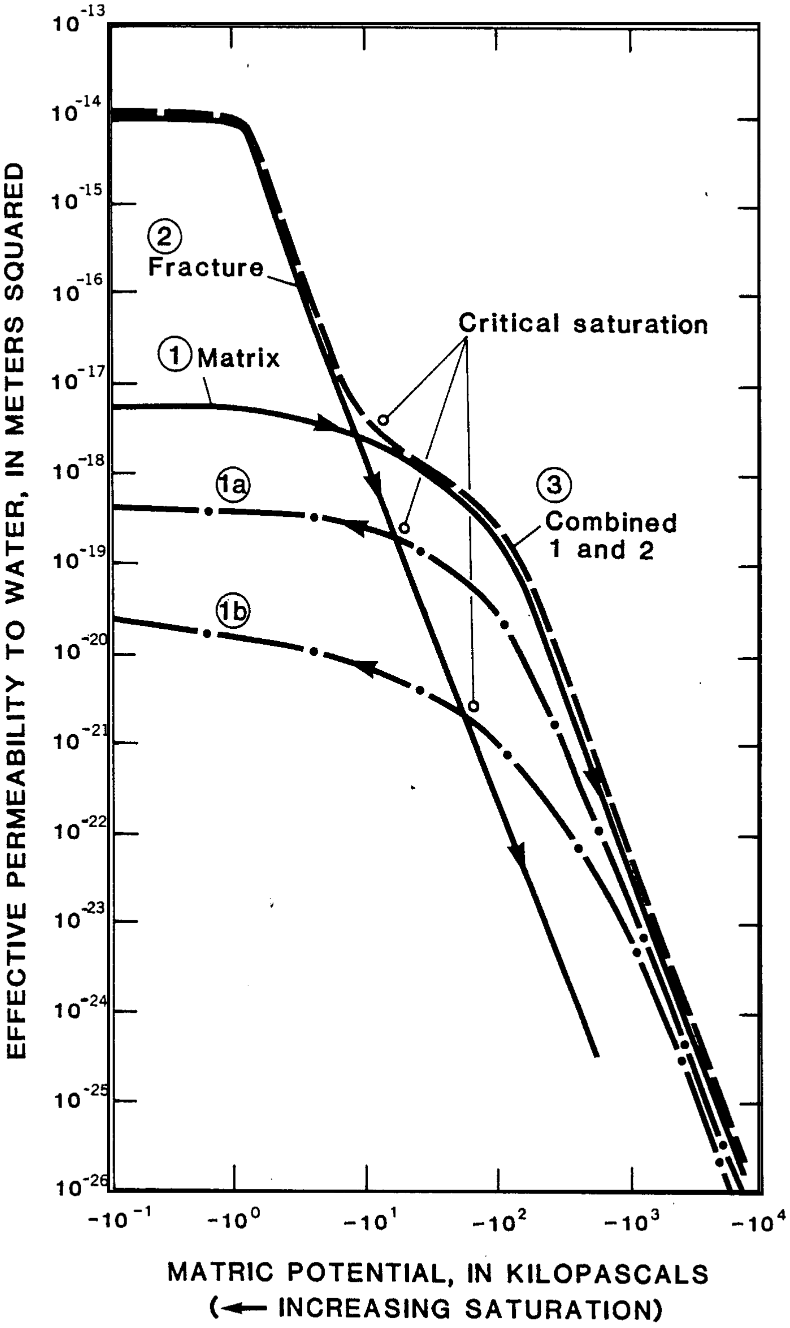


Early Conceptual Models (DOE, 1984)



Four major concepts that strongly influenced further development of the conceptual model

- Fully saturated matrix was required for fracture flow
- Overall flux was low
- Only matrix flow occurred in the TSw
- Most net infiltration was diverted laterally by the PTn

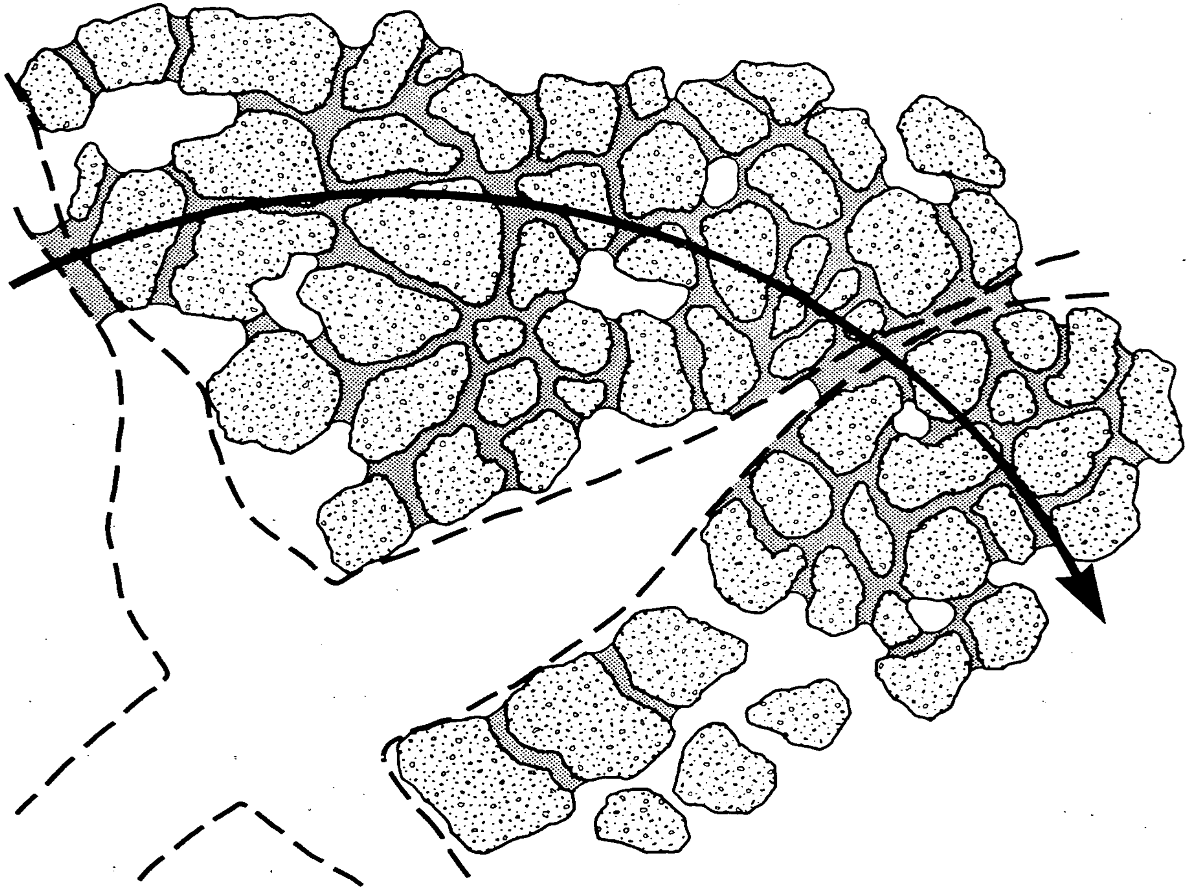


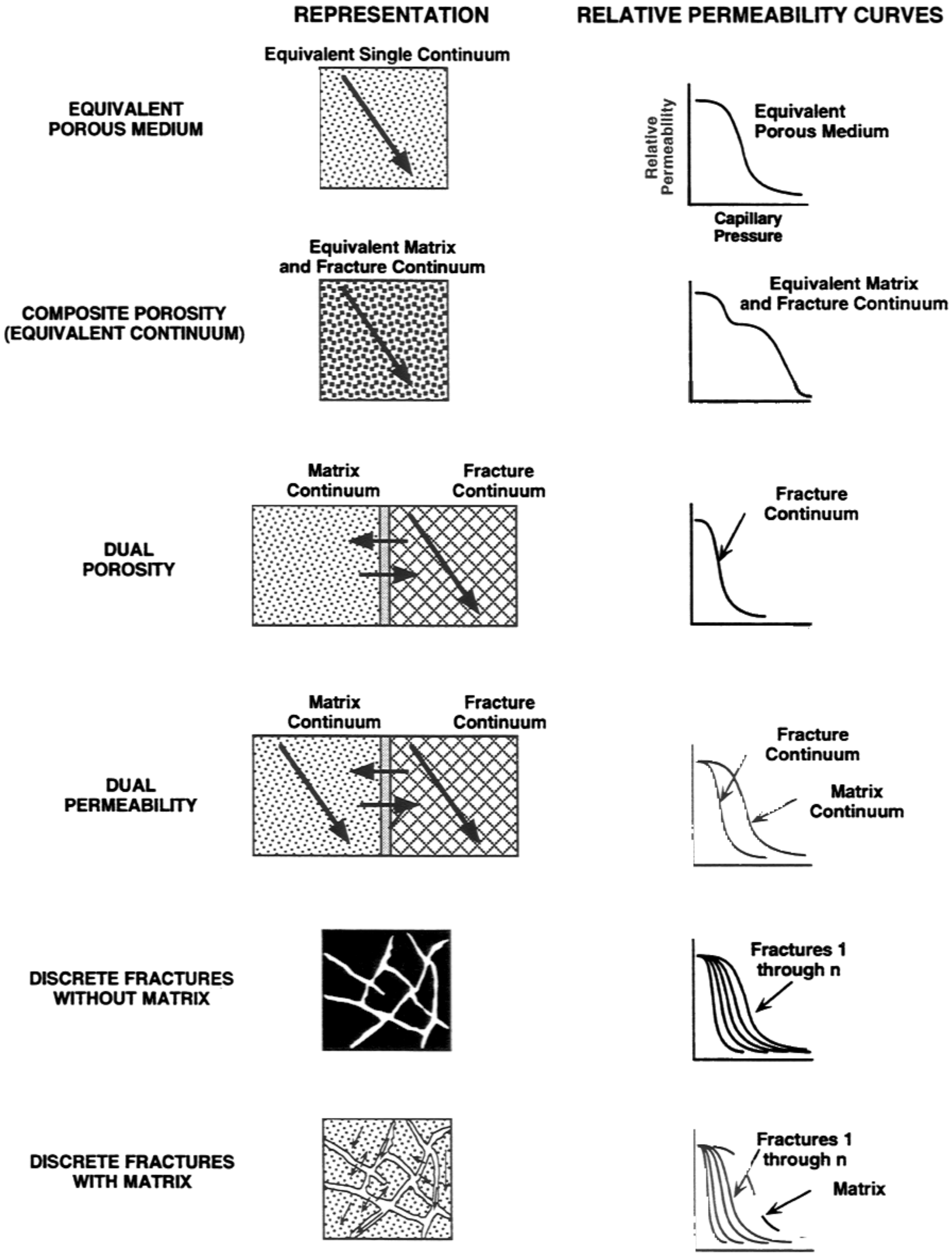
- Hypothetical relationship between effective permeability and matric potential for a double-porosity medium

(Montazer and Wilson, 1984)

Conceptual model of a partially saturated, fractured, porous medium

(Wang and Narasimhan, 1985)





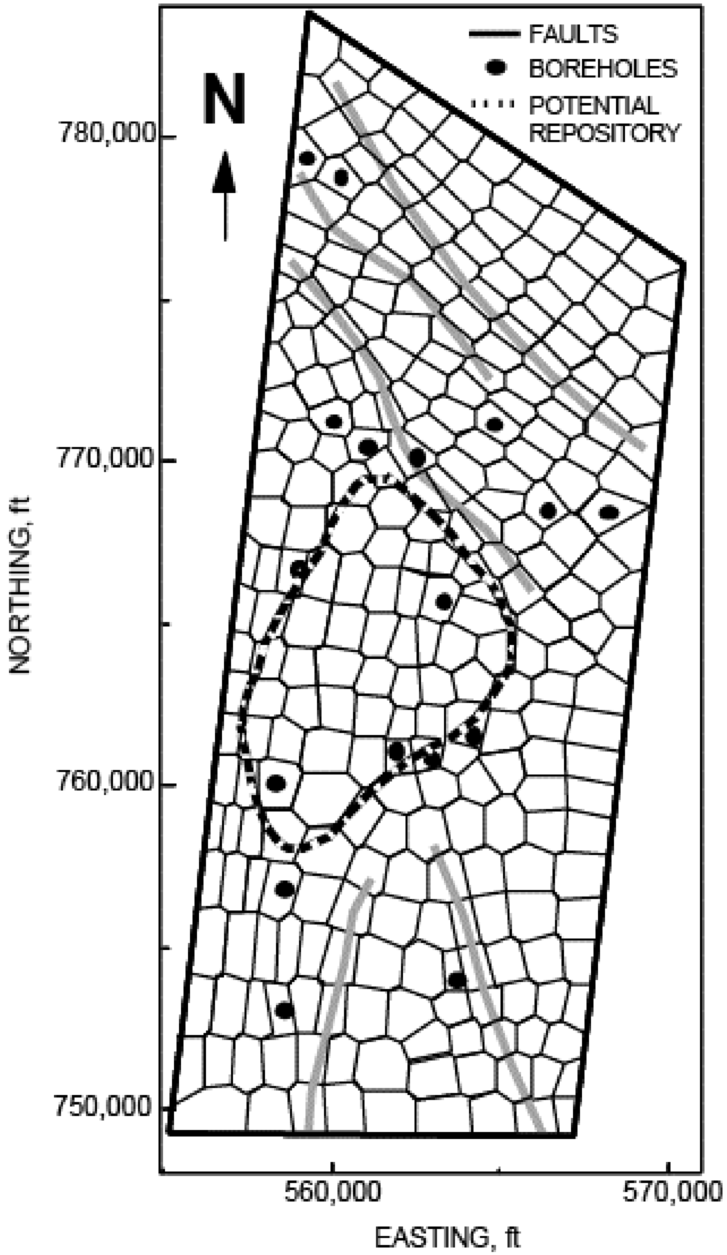
- Alternative conceptual models and their corresponding characteristic curves

(Altman et al., 1996)

Development of current conceptual and numerical models

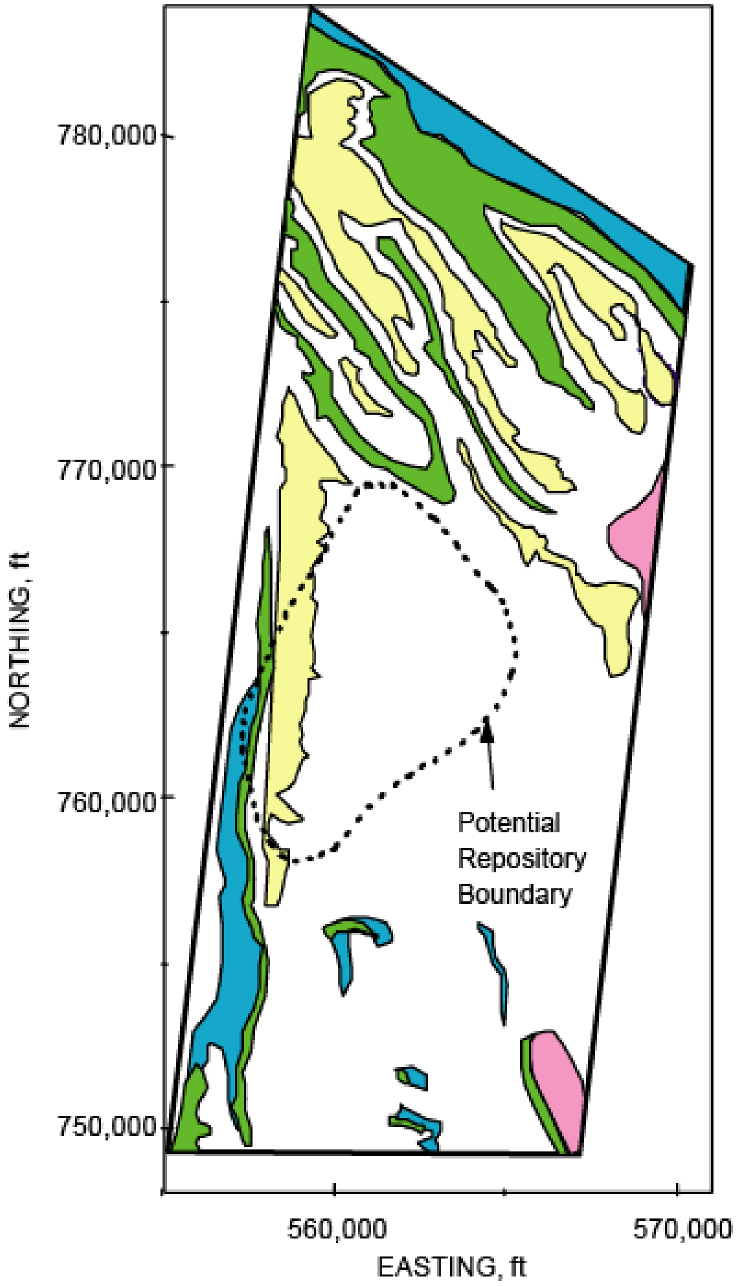
(mid 1990's paradigm shift)

- Three-dimensional site-scale numerical model
- Spatially distributed high infiltration
- Little lateral flow in PTn
- Evidence of fast fracture flow
- Decoupled fracture flow (important modeling breakthrough)



- Three-dimensional site scale model grid with early version of potential repository boundary

(Flint and Flint, 1994)

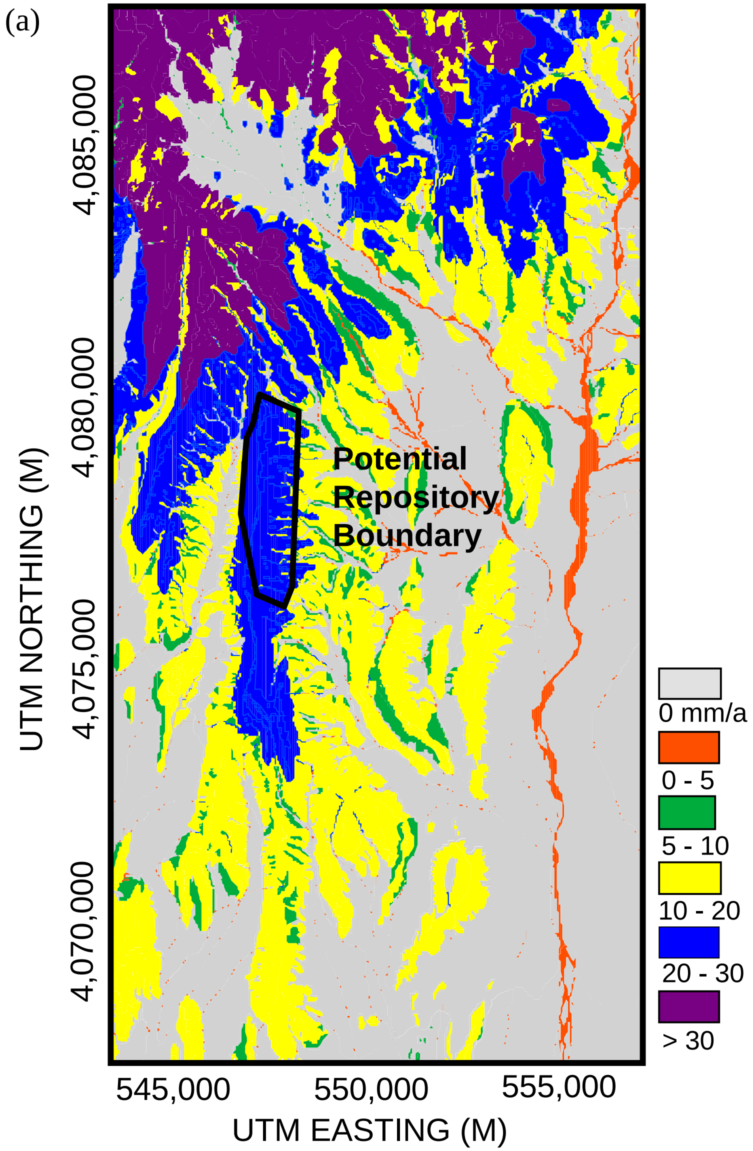


- Spatially distributed infiltration in bedrock units

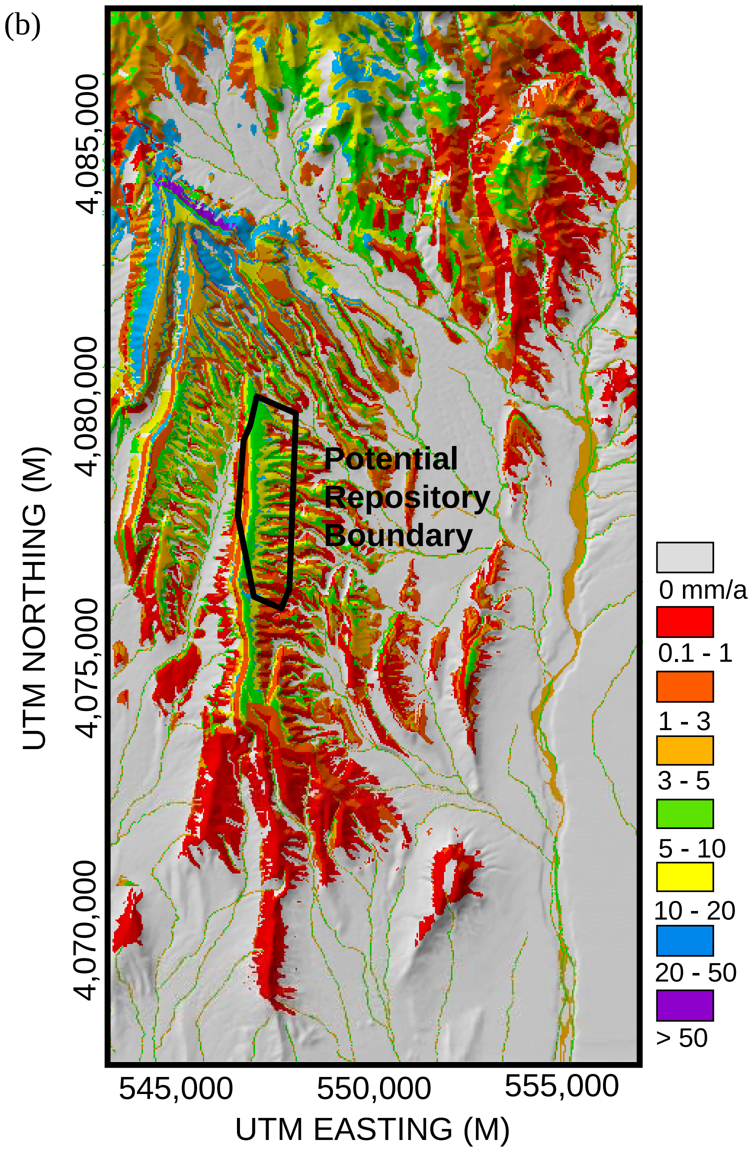
(Flint and Flint, 1994)

		Infiltration rate, in mm/year
🟨	Tiva Canyon Tuff moderately welded	0.22
⬜	Tiva Canyon Tuff welded	0.02
🟩	Paintbrush Group nonwelded tuff	13.40
🟦	Topopah Spring Tuff welded	0.08
🟪	Rainier Mesa Tuff	0.06

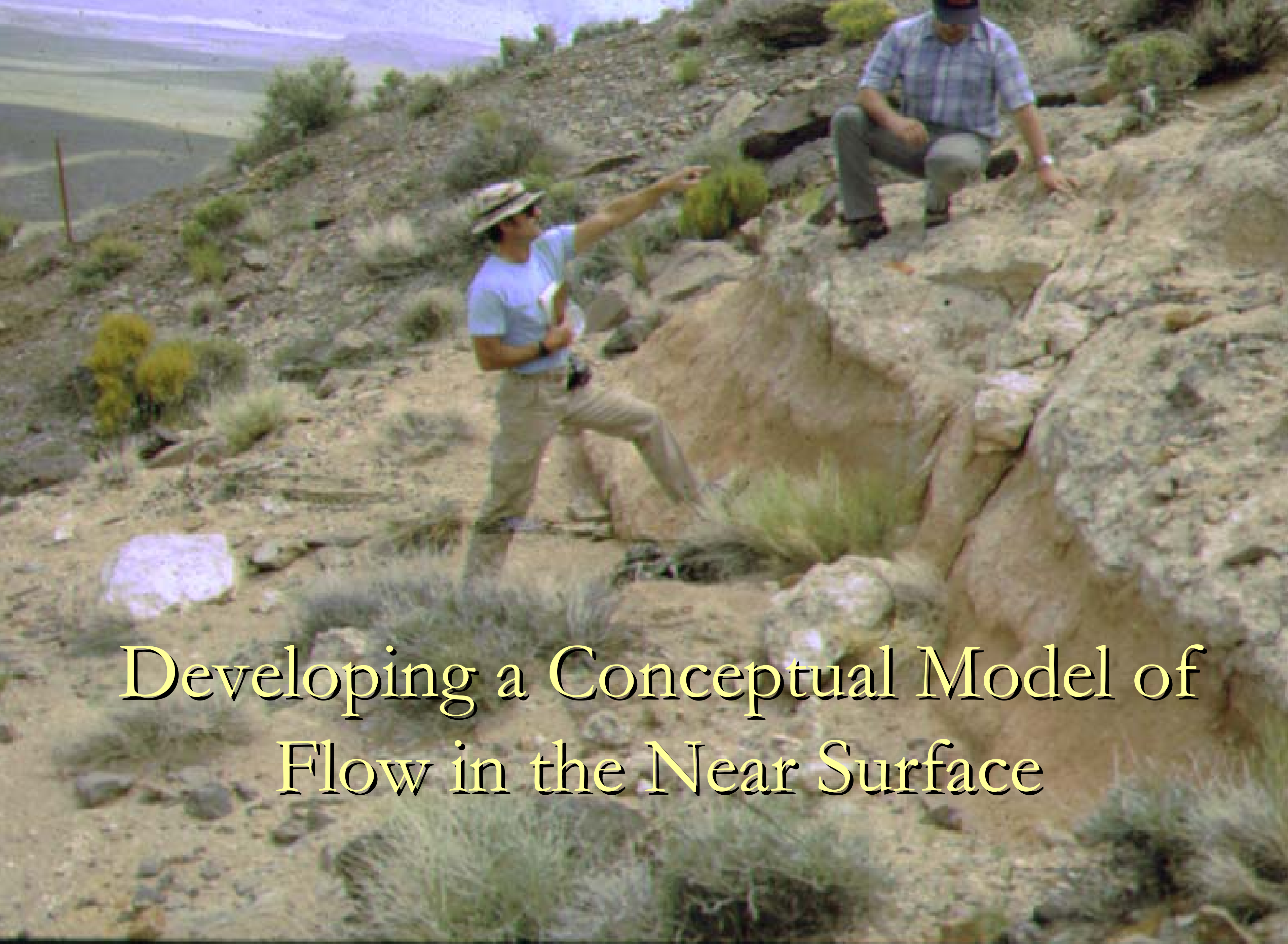
Spatially distributed net infiltration at Yucca Mountain using (a) statistical analyses and (b) numerical modeling



Hudson and Flint, 1995



Flint et al., 1996



Developing a Conceptual Model of Flow in the Near Surface

Net infiltration; a precursor to flux

- Infiltration is the process of water entering the soil surface
- Net infiltration is the quantity of water that has moved below the zone of evapotranspiration
- Knowing net infiltration is a critical precursor to knowing recharge
- Percolation or drainage is the process by which net infiltration moves through the unsaturated zone
- Recharge is quantity of net infiltration that reaches the regional water table (net infiltration today may be recharge 5,000 years from now)

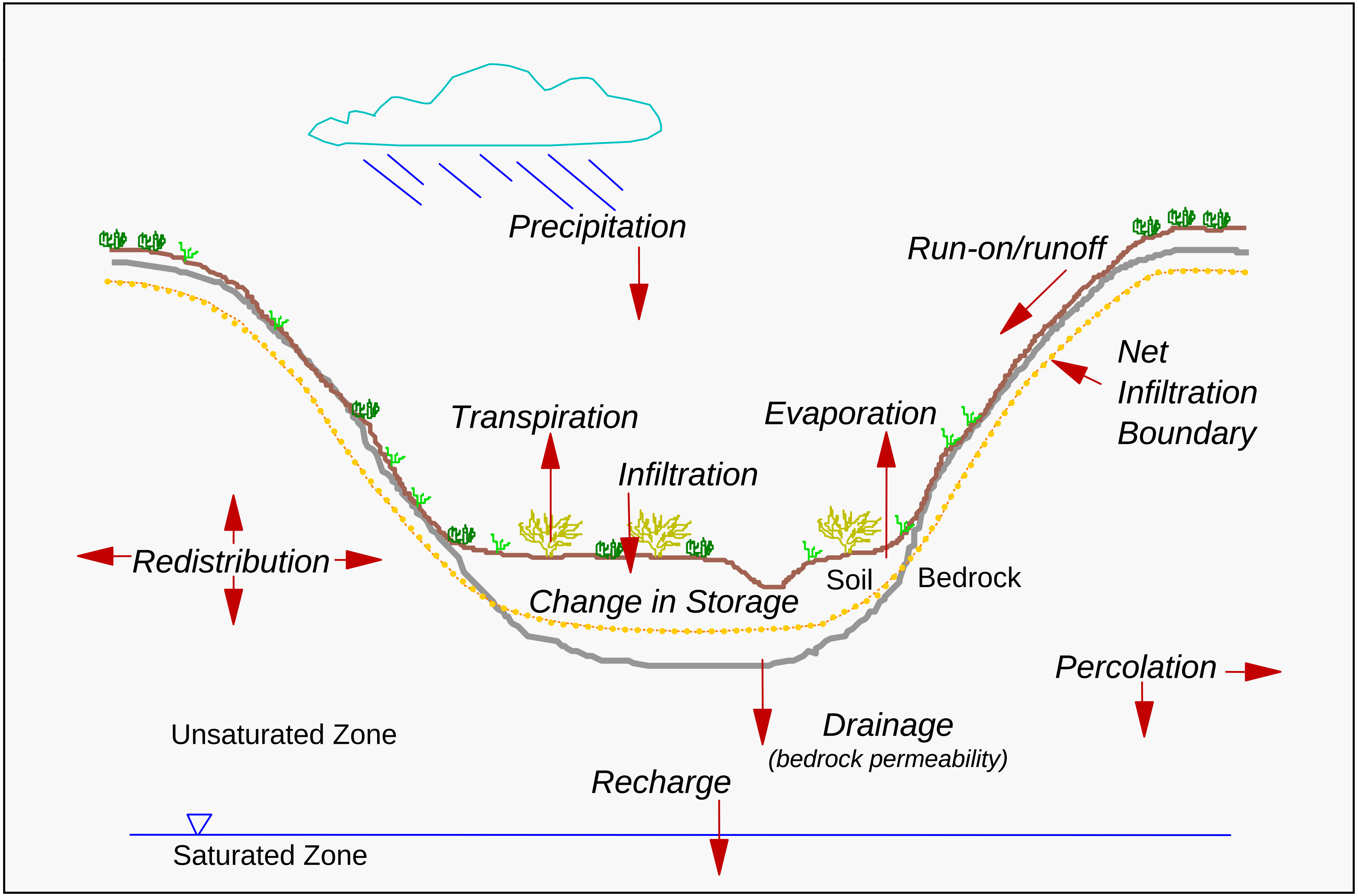
Net infiltration at Yucca Mountain

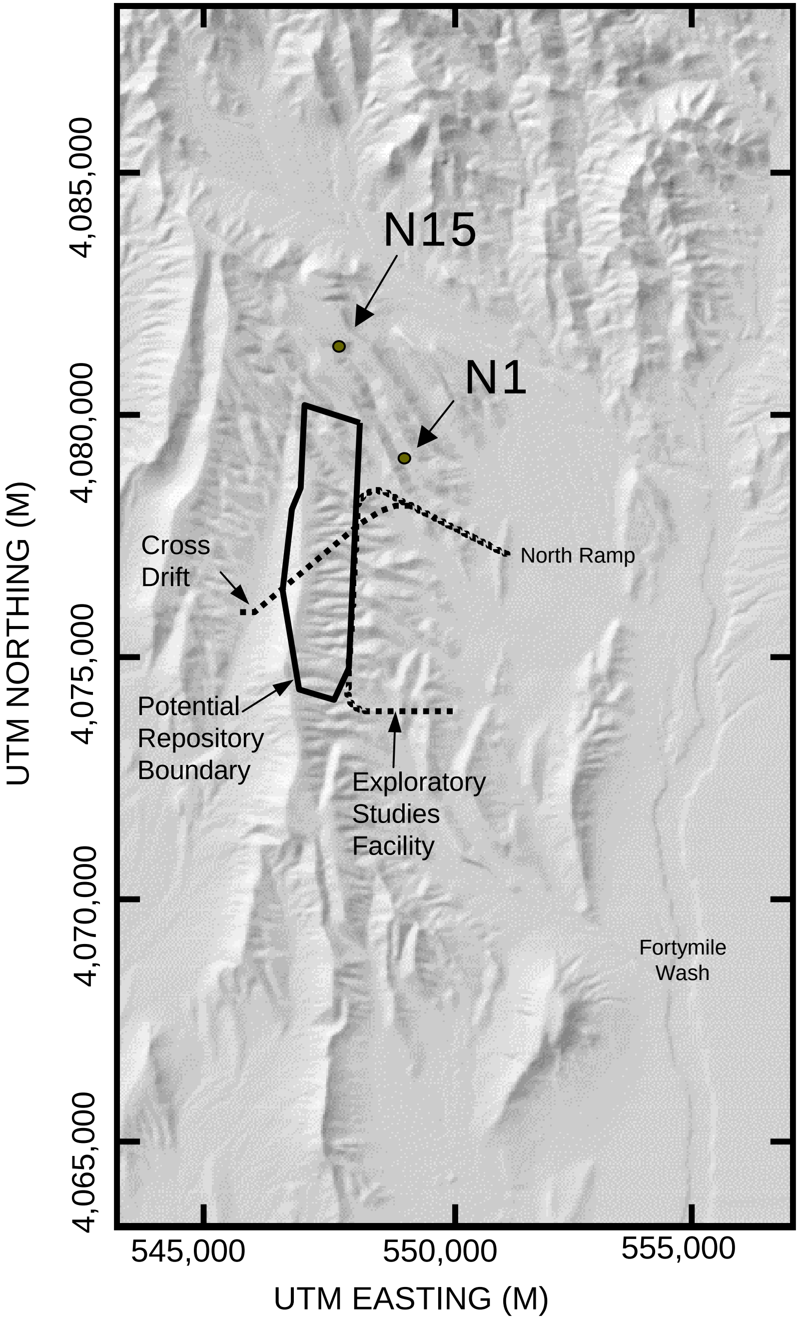
- Factors controlling infiltration
  - Precipitation
  - Soil thickness
    - Soil porosity
    - Drainage characteristics
  - Bedrock permeability
  - Evapotranspiration

Net infiltration at Yucca Mountain

- Conceptual understanding
  - Arid conditions make net infiltration an infrequent occurrence
  - Particularly wet winters allow for near saturated conditions at the soil-bedrock interface which allows fracture flow and deep penetration of infiltrated water below the zone of evapotranspiration
  - Deep soils (non stream channels) have sufficient soil water storage capacity to retain most precipitation in the root zone for eventual evapotranspiration
  - Runoff accumulates and infiltrates enough water to overcome the storage capacity of the root zone in deeper soils allowing for deep penetration of infiltrated water below the zone of evapotranspiration

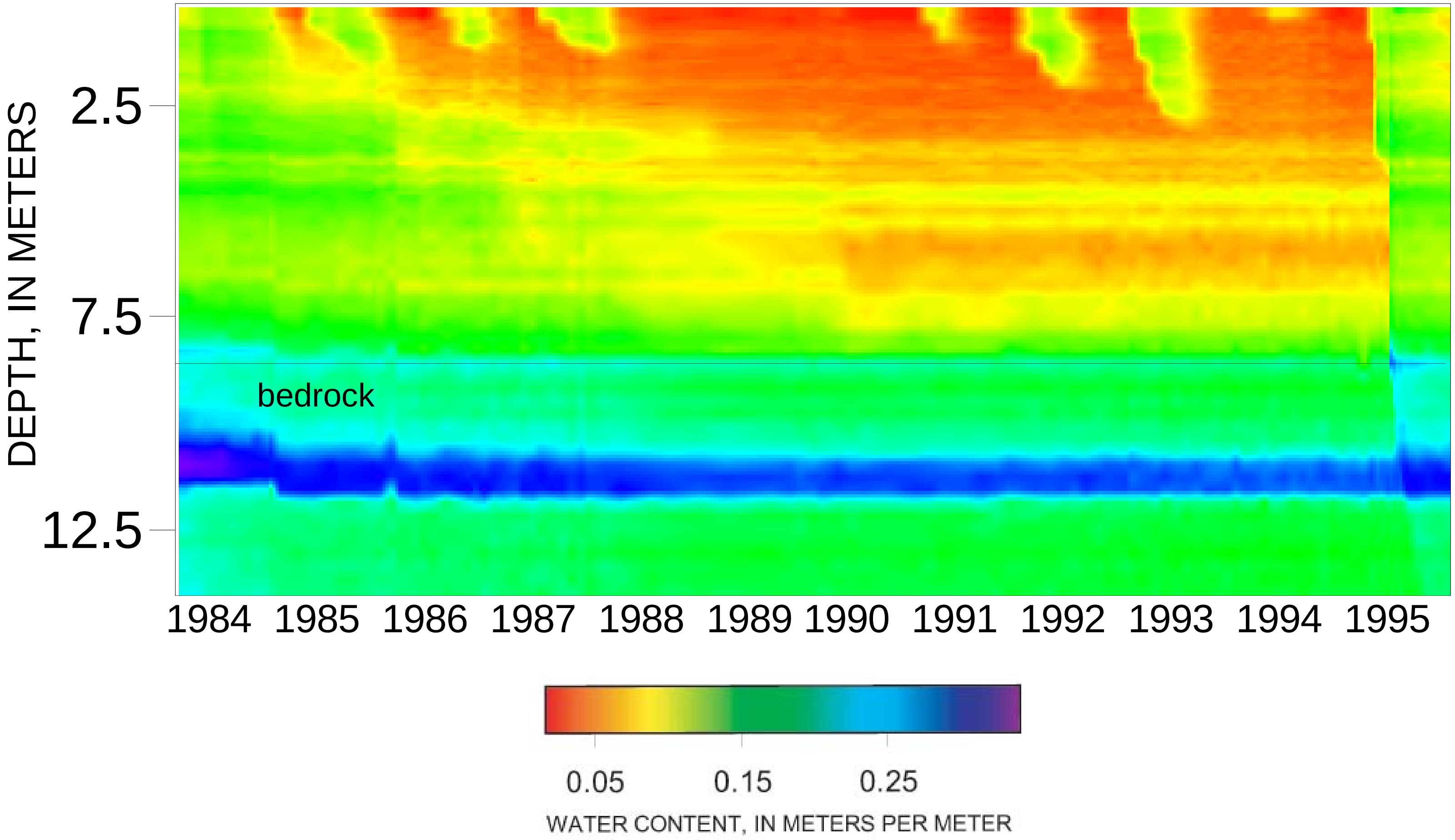
Mechanisms Controlling Net Infiltration (Recharge)
Precipitation + Change in Storage - Drainage - ET - Runoff = 0





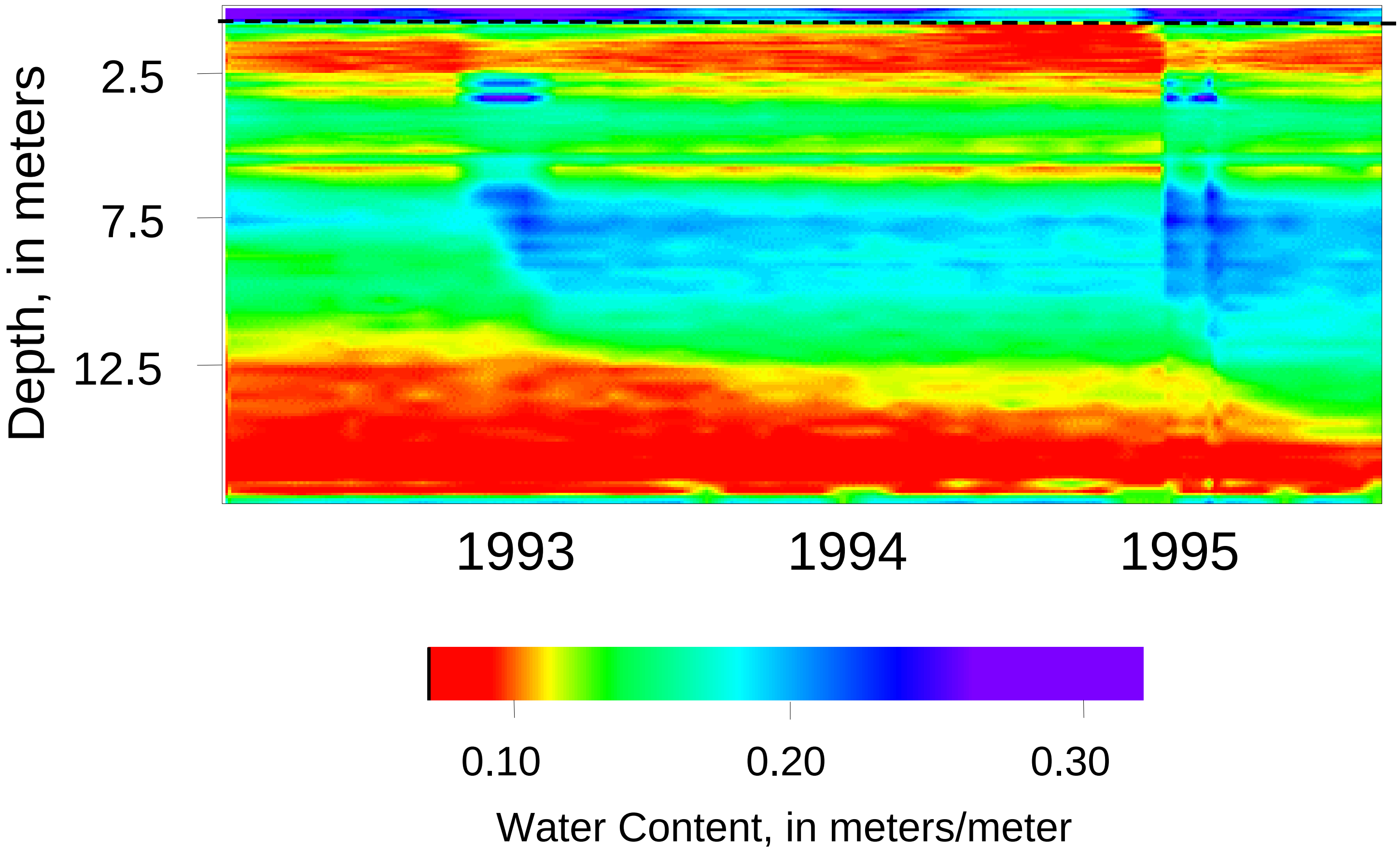
Moisture monitoring in 99 neutron-access boreholes monthly for over 10 years became one of the most useful tools for evaluating the spatial processes contributing to net infiltration and percolation

Infiltration at Borehole UZN #1

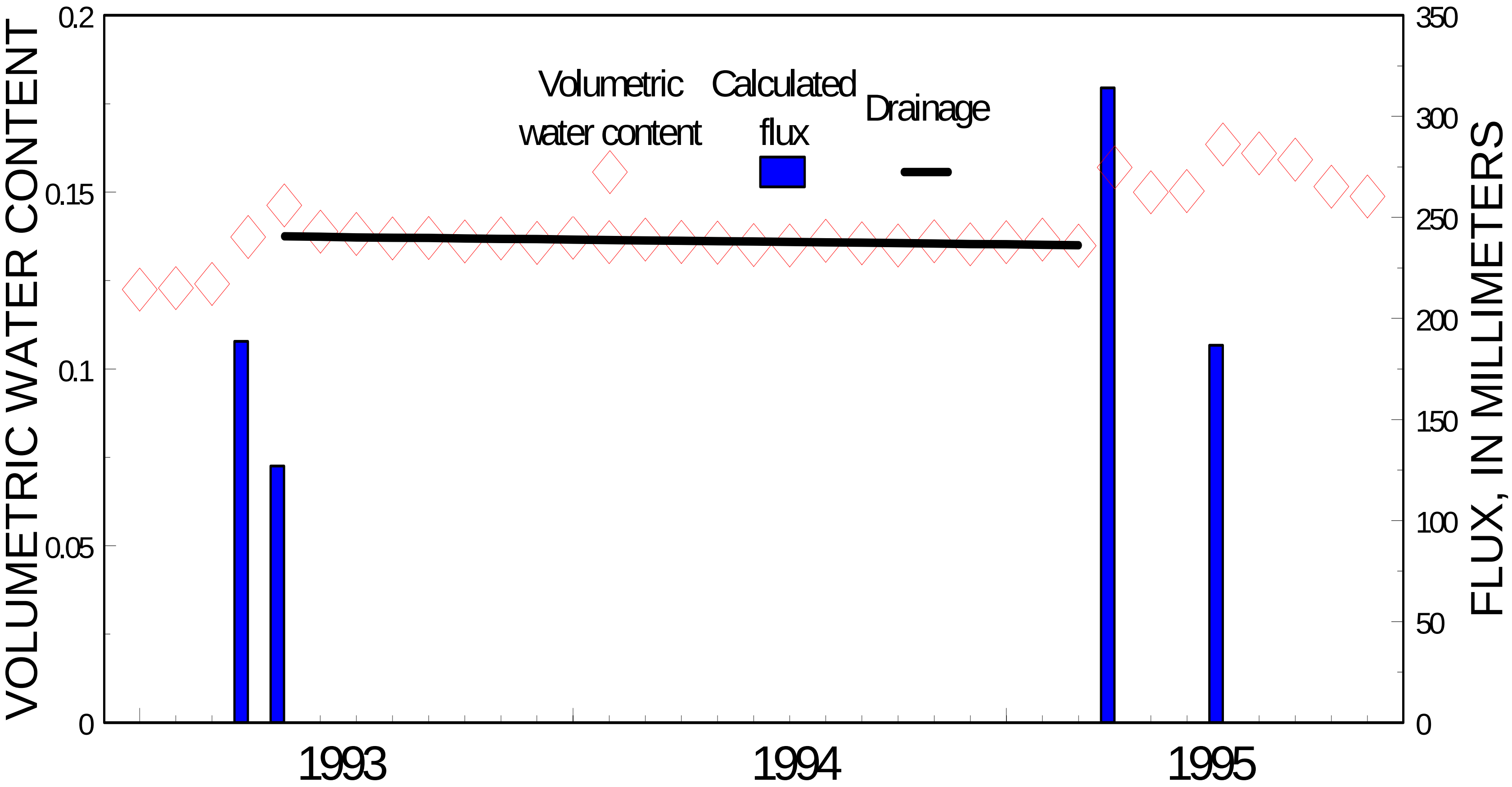


Infiltration at Borehole UZN-15

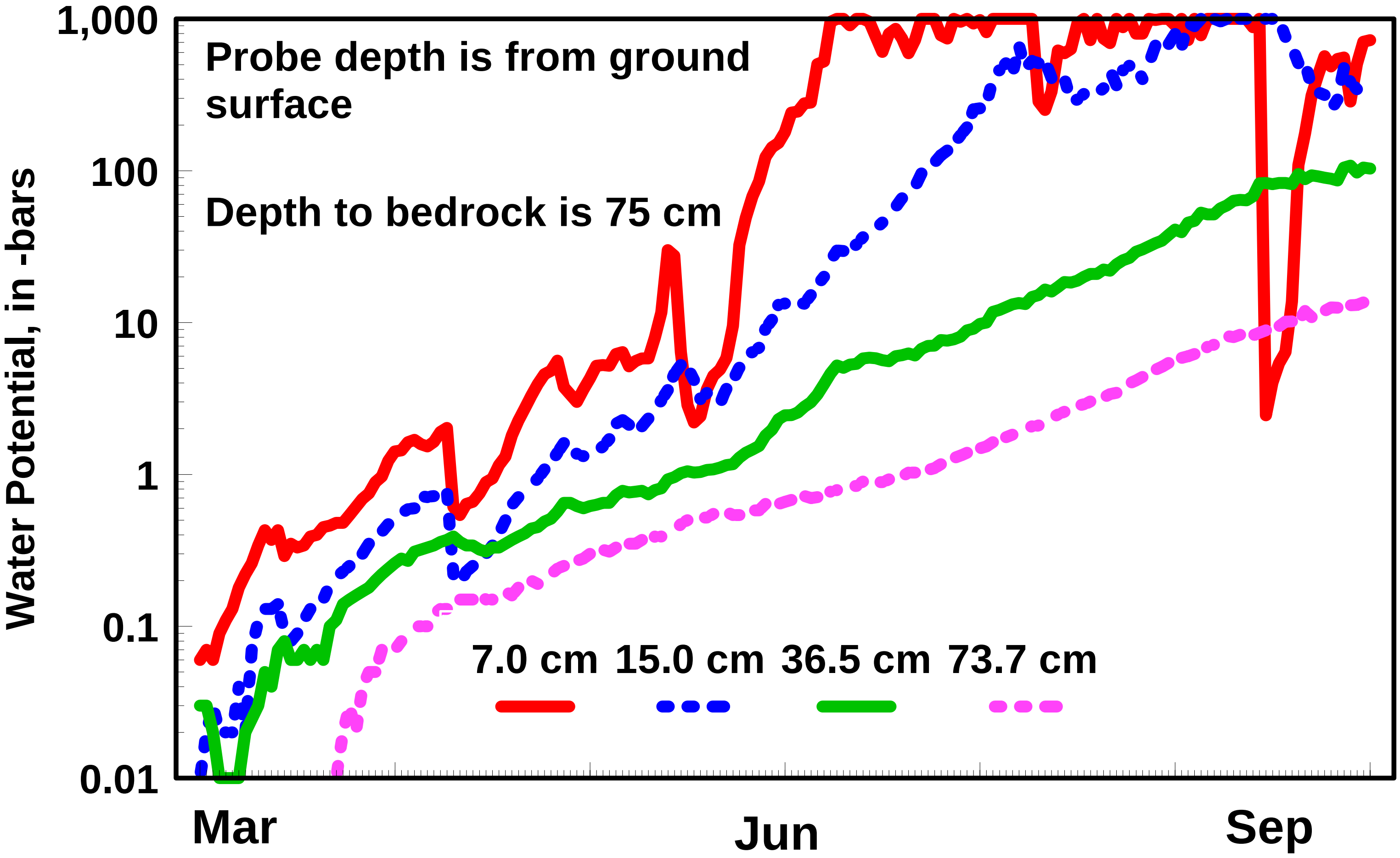
(75 cm soil over 2 m lower porosity fractured bedrock, underlain by 10 m high porosity fractured bedrock)



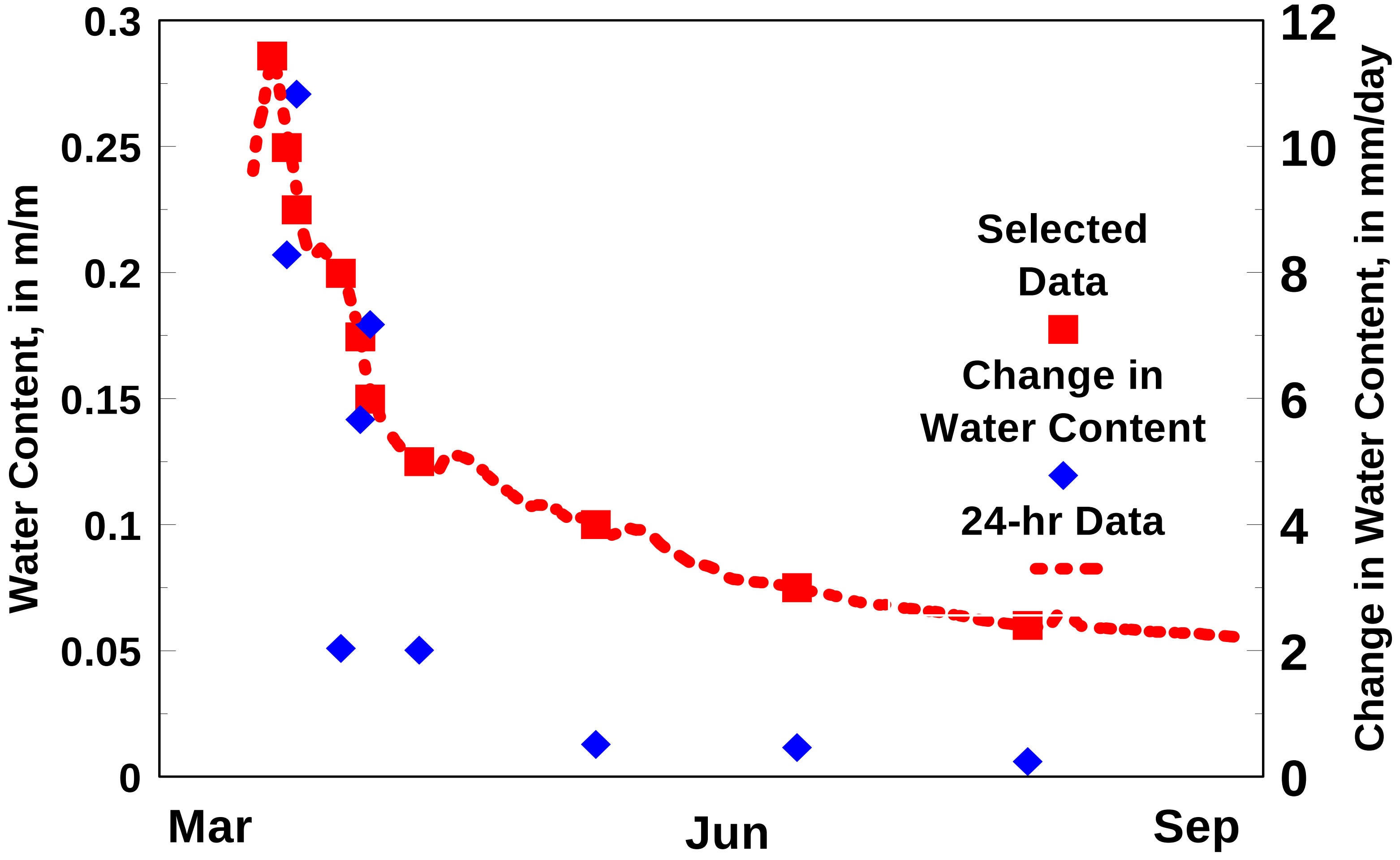
Calculation of Flux



Measuring Soil Water Potential Gradient using Heat Dissipation Probes

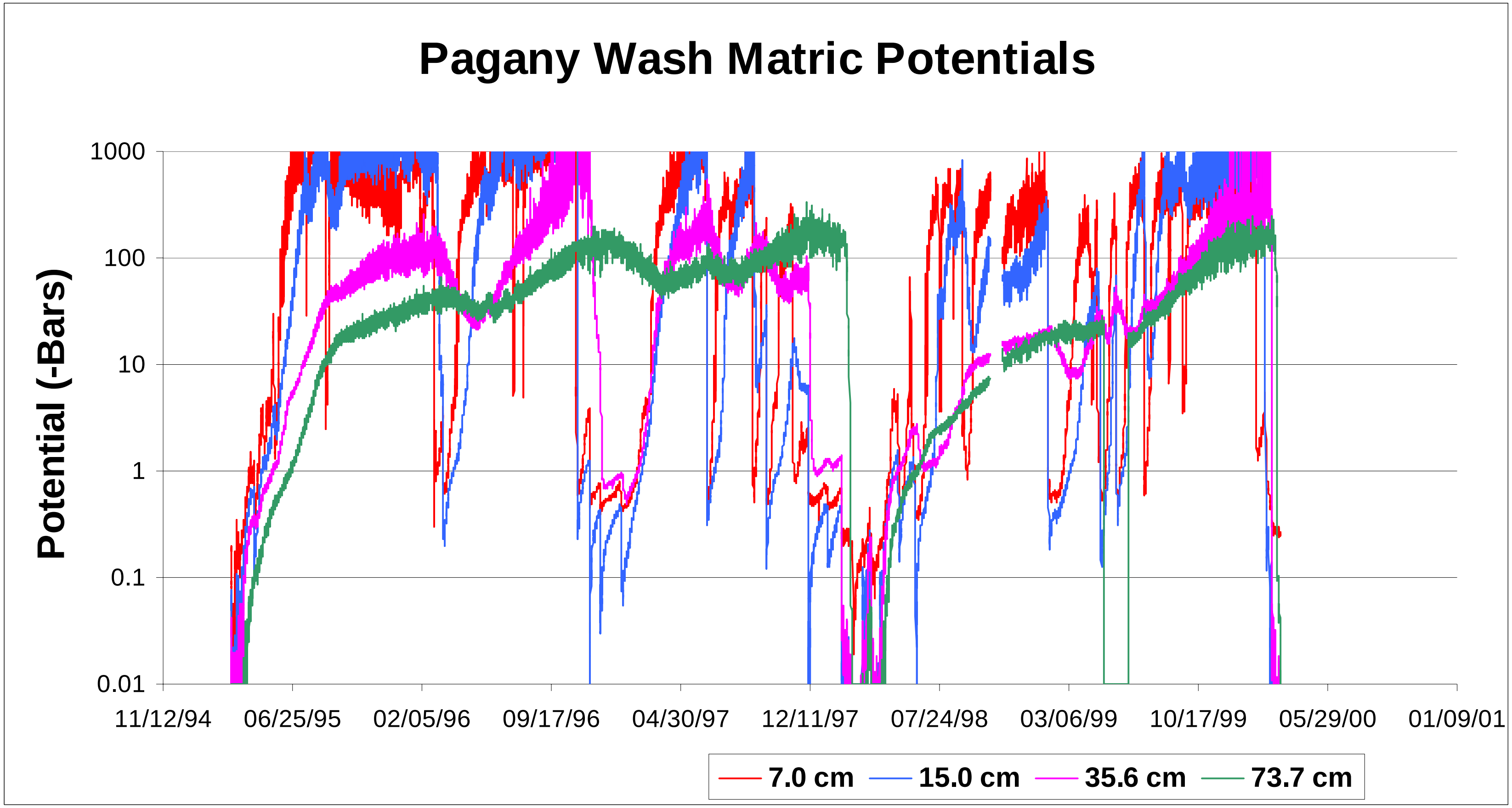


Calculation of Flux



Soil Water Potential

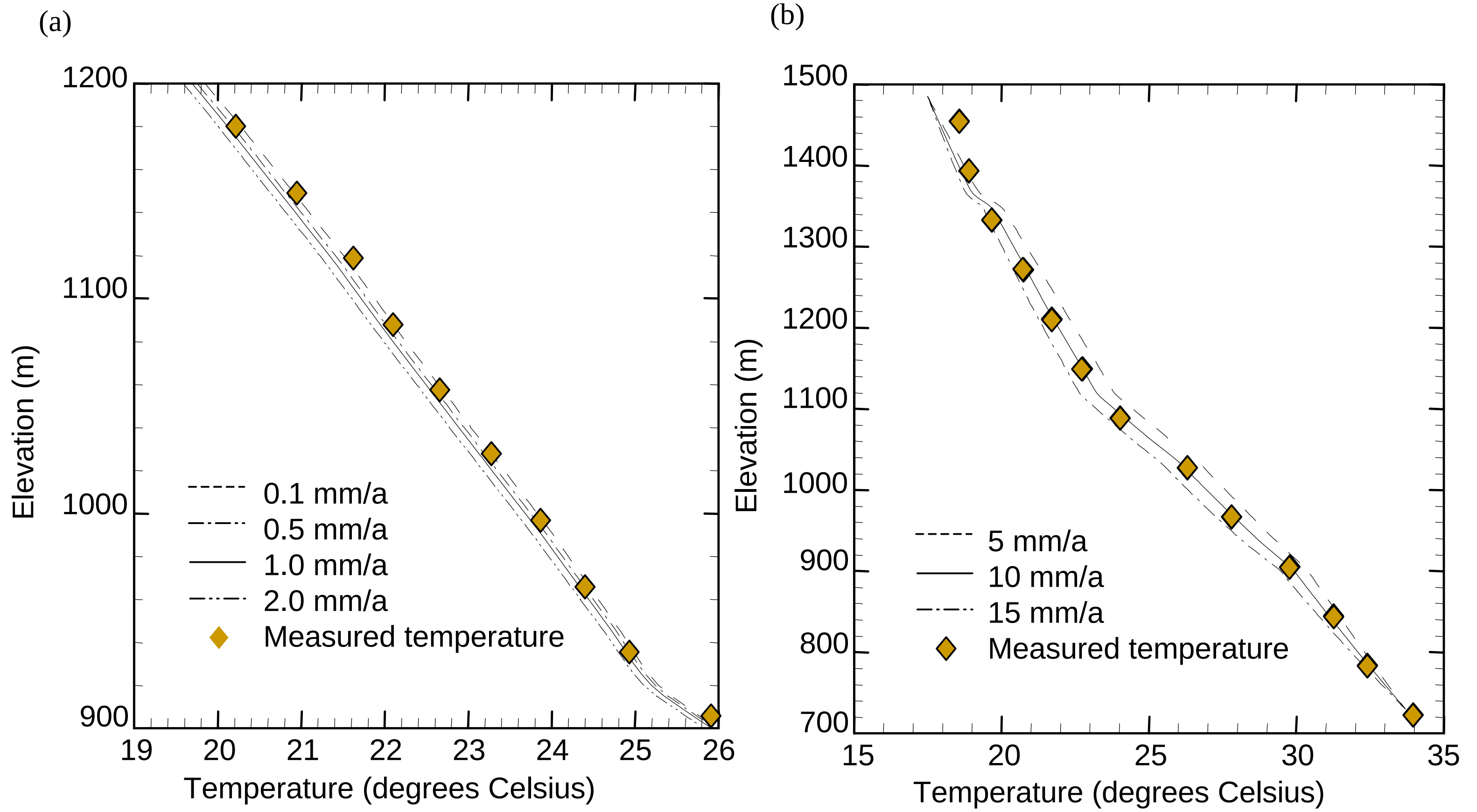
Heat Dissipation Probes at N-15



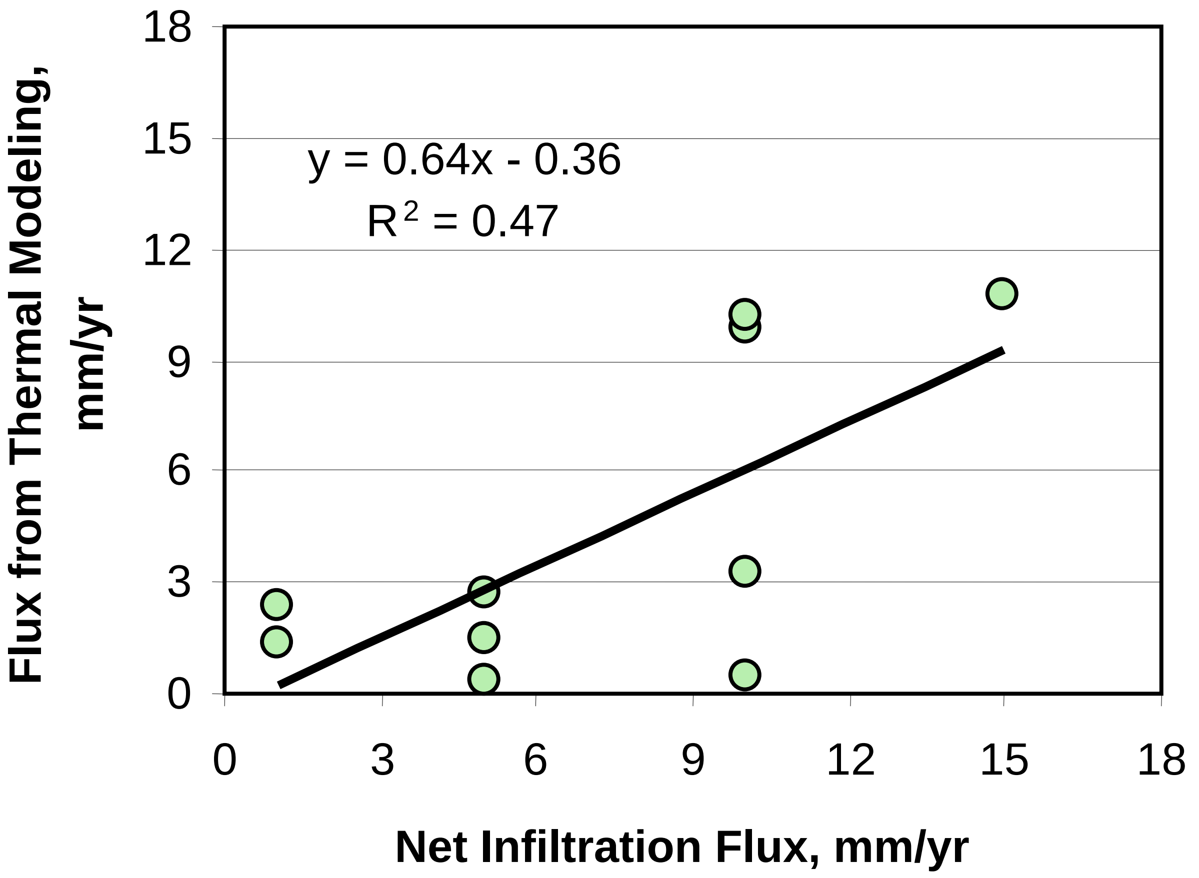
Observations on Data Supporting Higher Fluxes

- Neutron hole data
- Darcy flux calculations in the PTn
- Tritium
- C-14
- Thermal profiles
- Chloride mass balance
- Other chemistry techniques

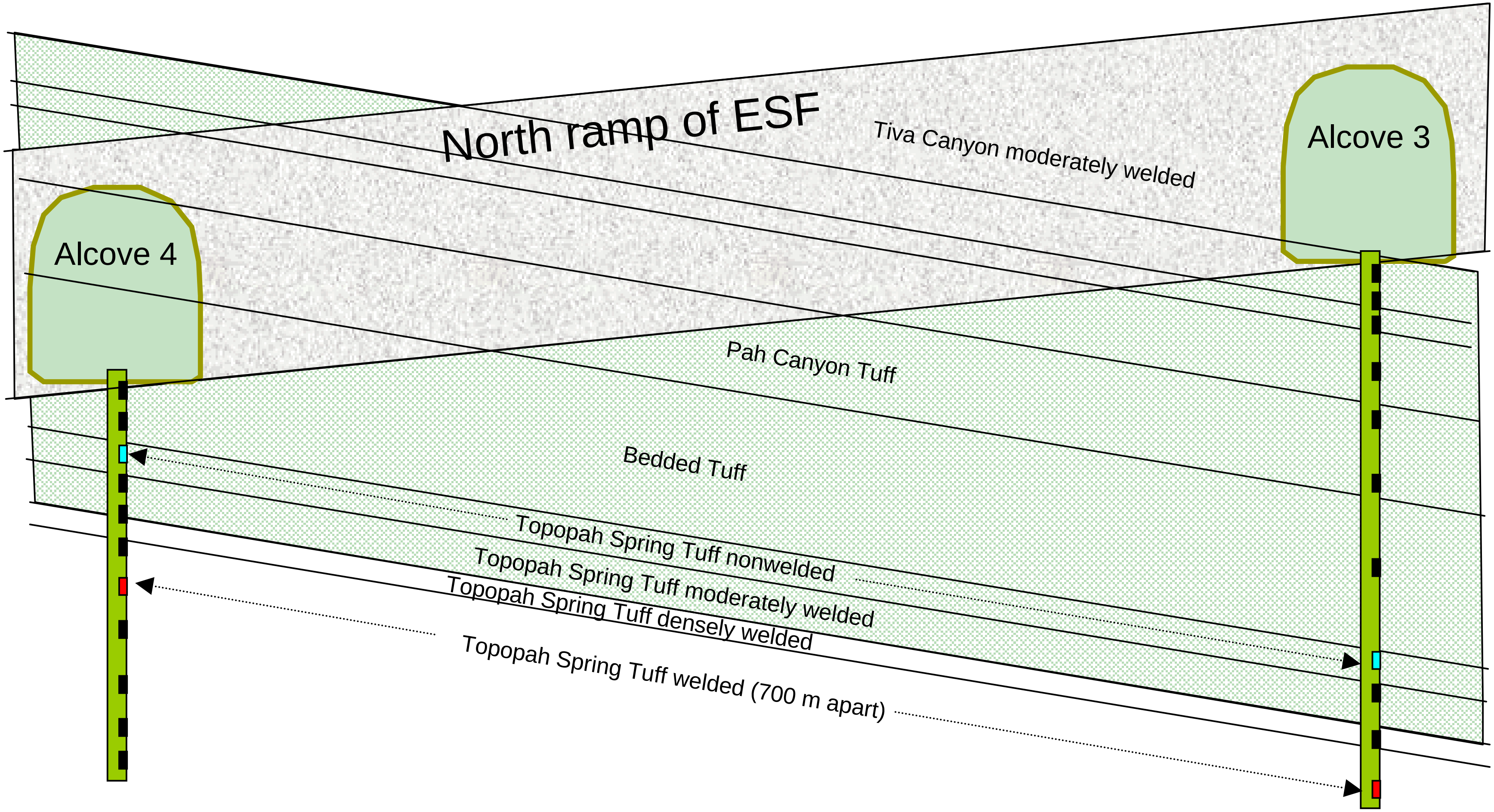
Temperature profiles: inverse modeling using various fluxes



Comparison of Flux from Thermal Modeling with Net Infiltration



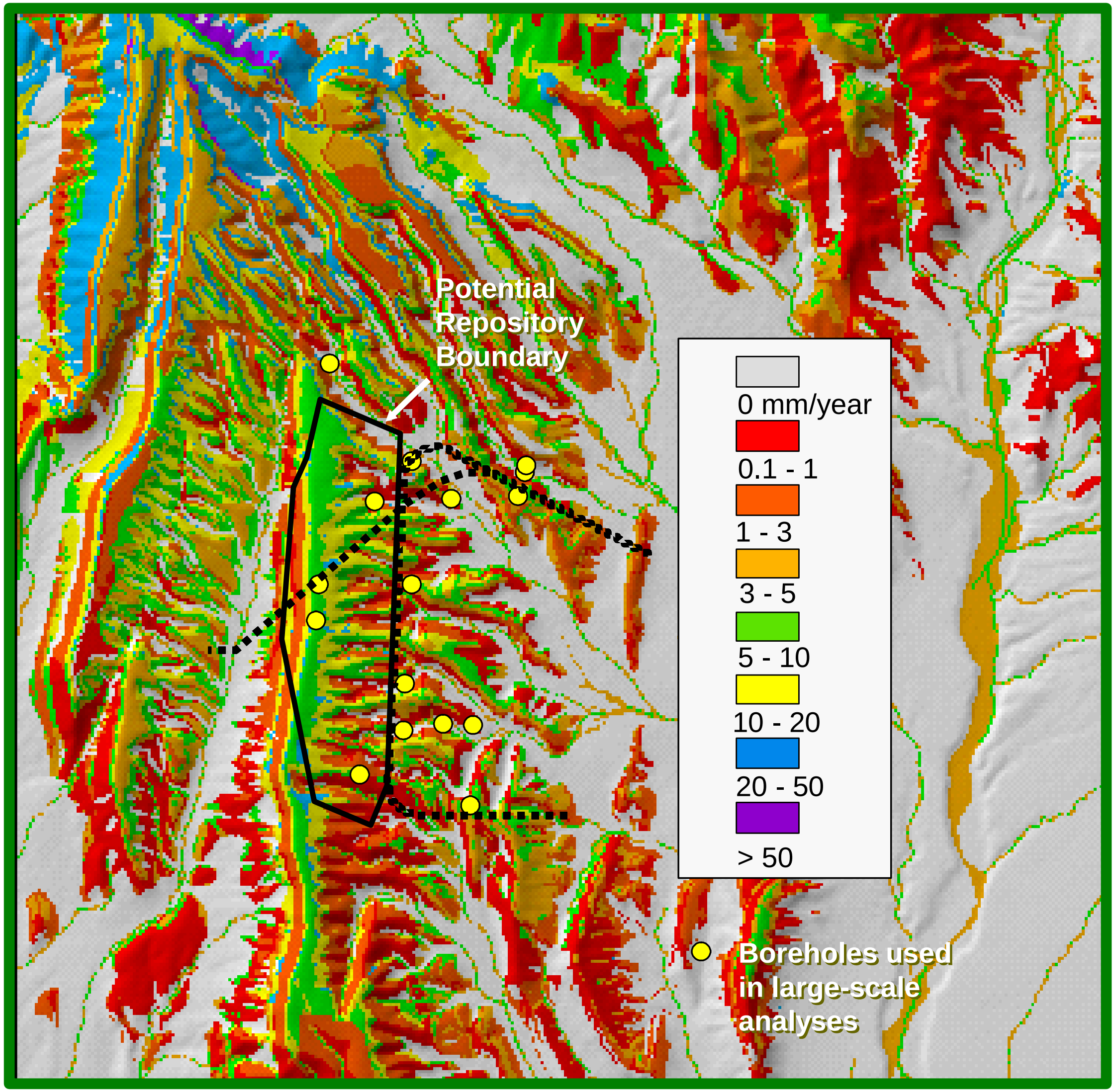
Schematic of North Ramp Alcoves used for Darcy flux calculations



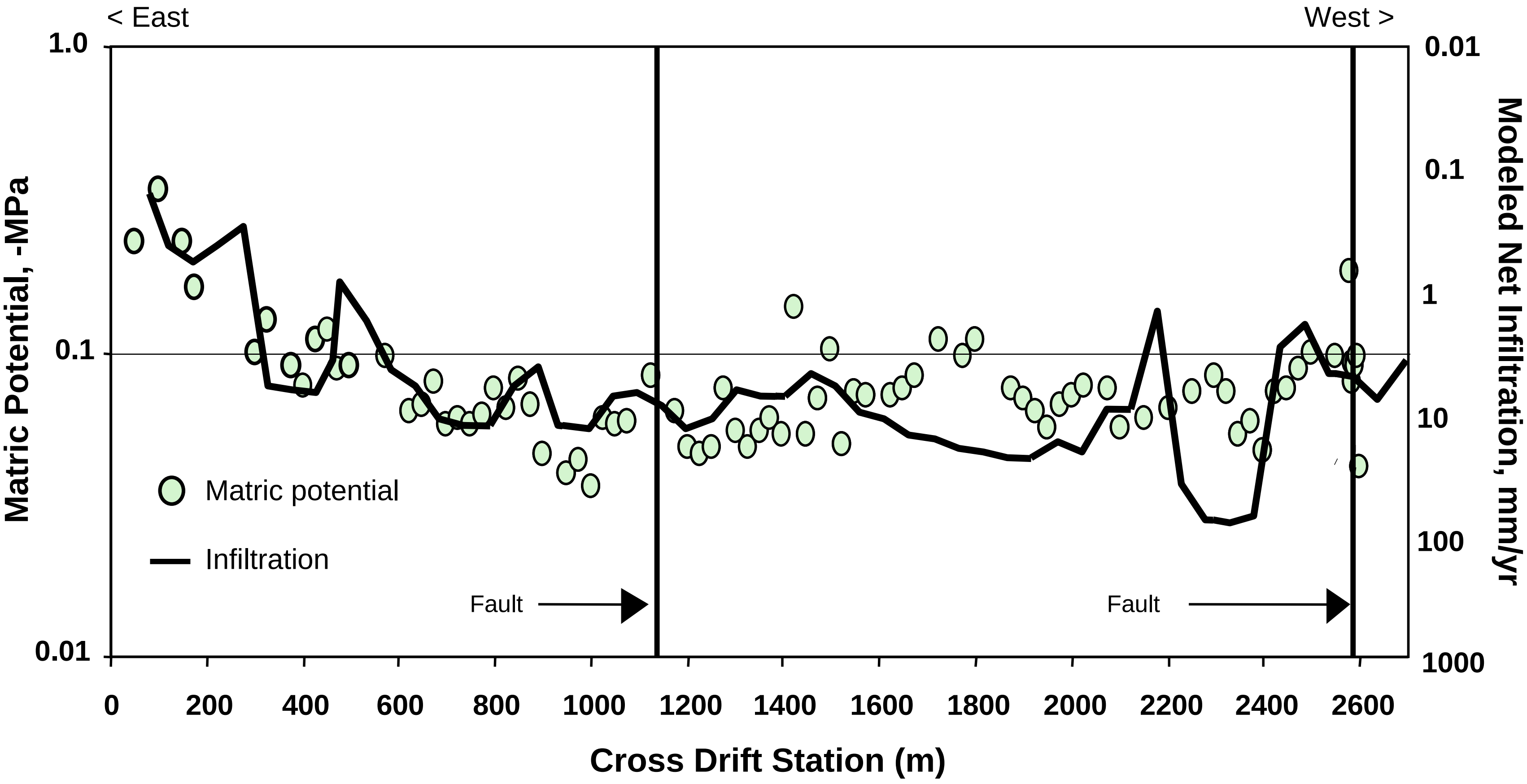
Darcian Flux Calculations

- Darcy's law, $q = K(\theta)\ (d\psi/dz)$
- Using *in situ* matric potential measurements from boreholes to estimate hydraulic gradient and core properties
  - 8-15 mm/yr vertical flux in 2 boreholes
  - < 1 mm/yr lateral flux in the PTn or the top of the welded Topopah Spring Tuff

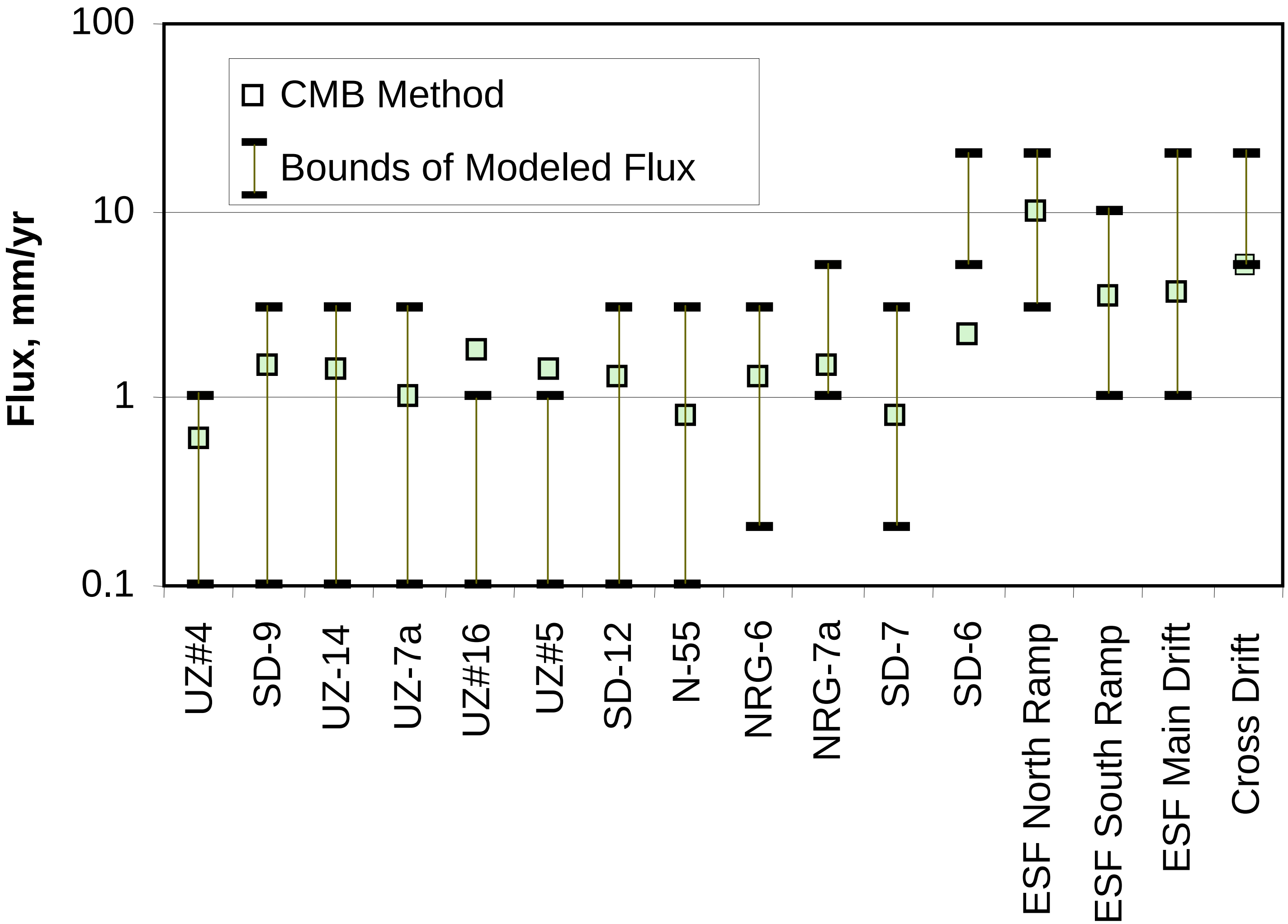
Surface Fluxes over Trace of ECRB



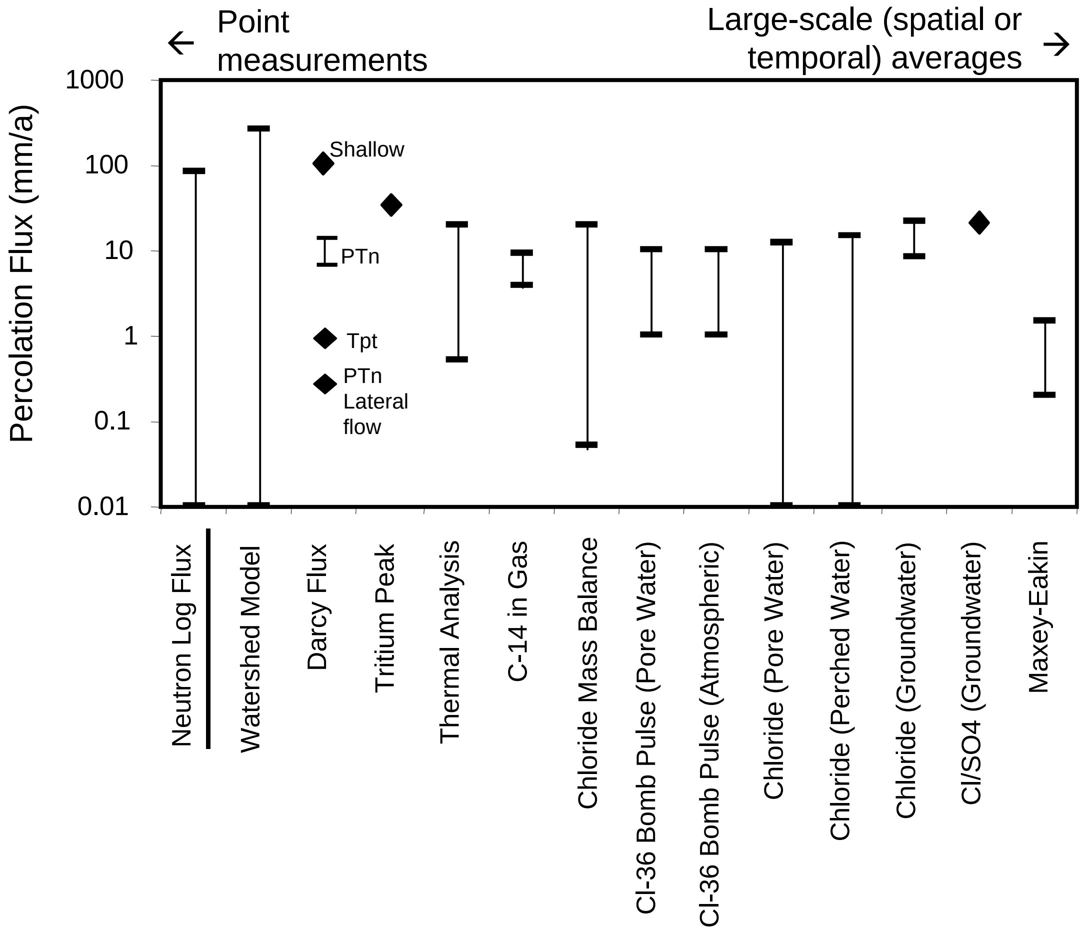
Cross Drift Moisture



Comparison of Flux from Chloride Mass Balance with Net Infiltration



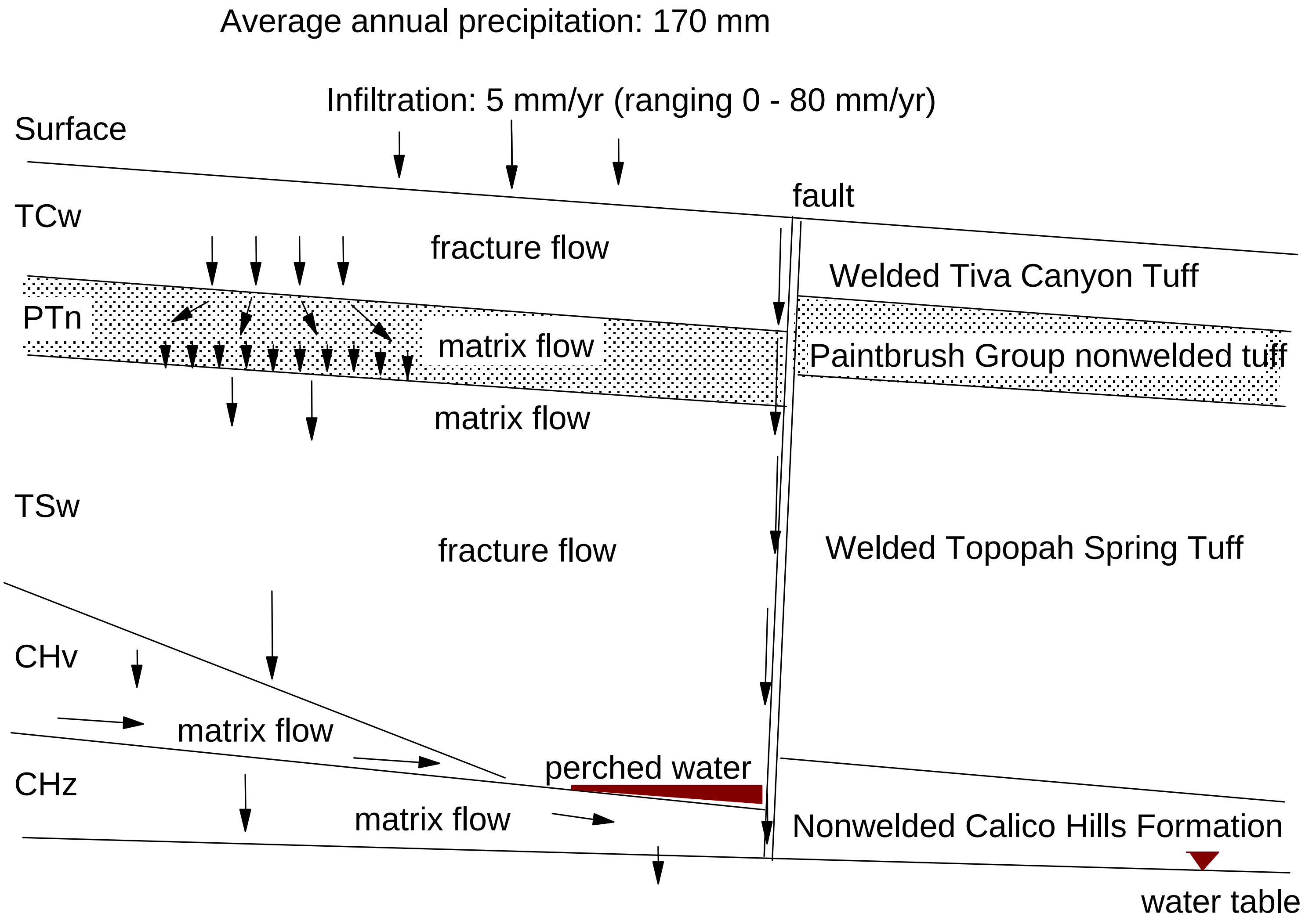
Comparison of percolation fluxes estimated by various methods



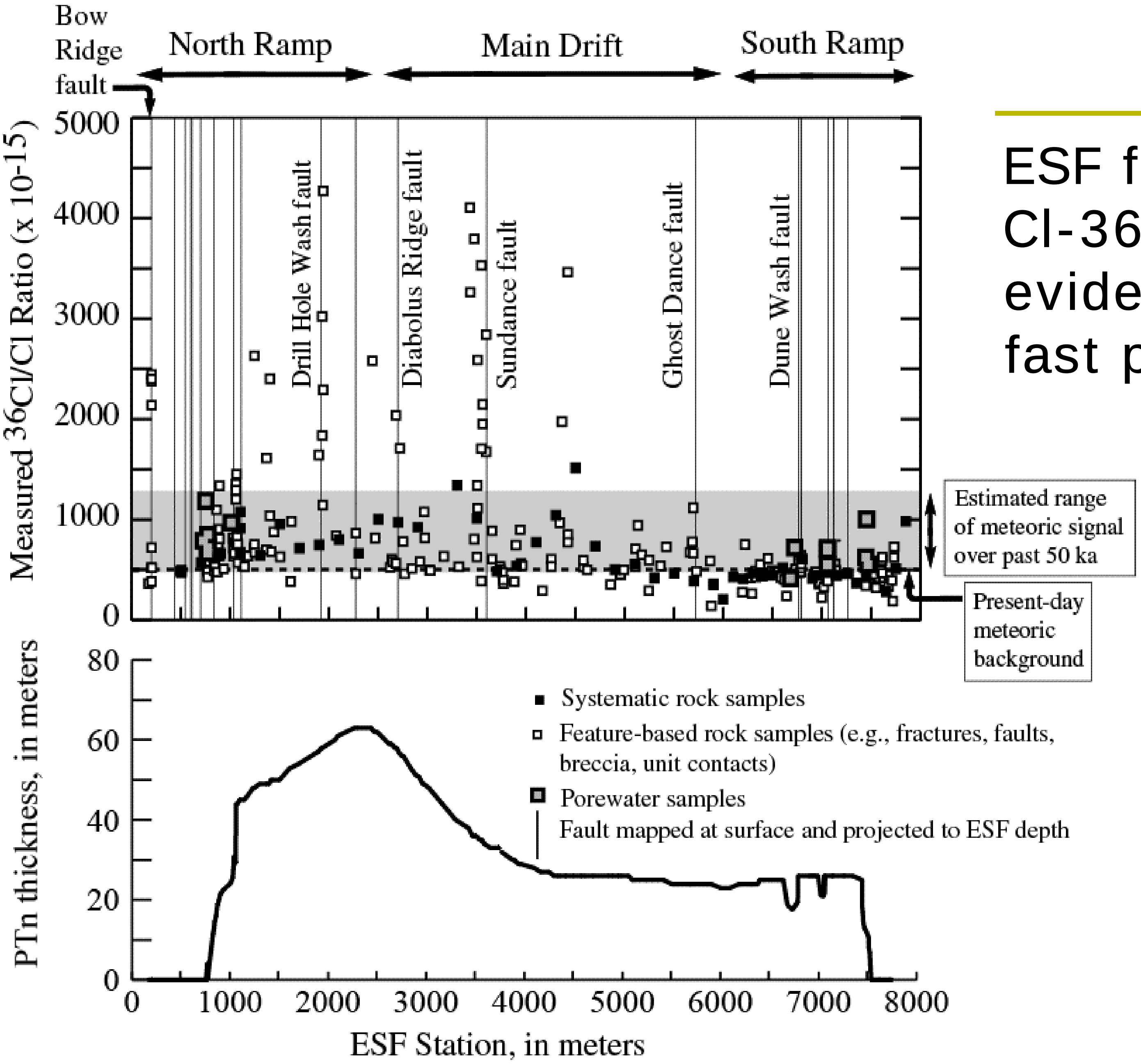
Beyond Net Infiltration

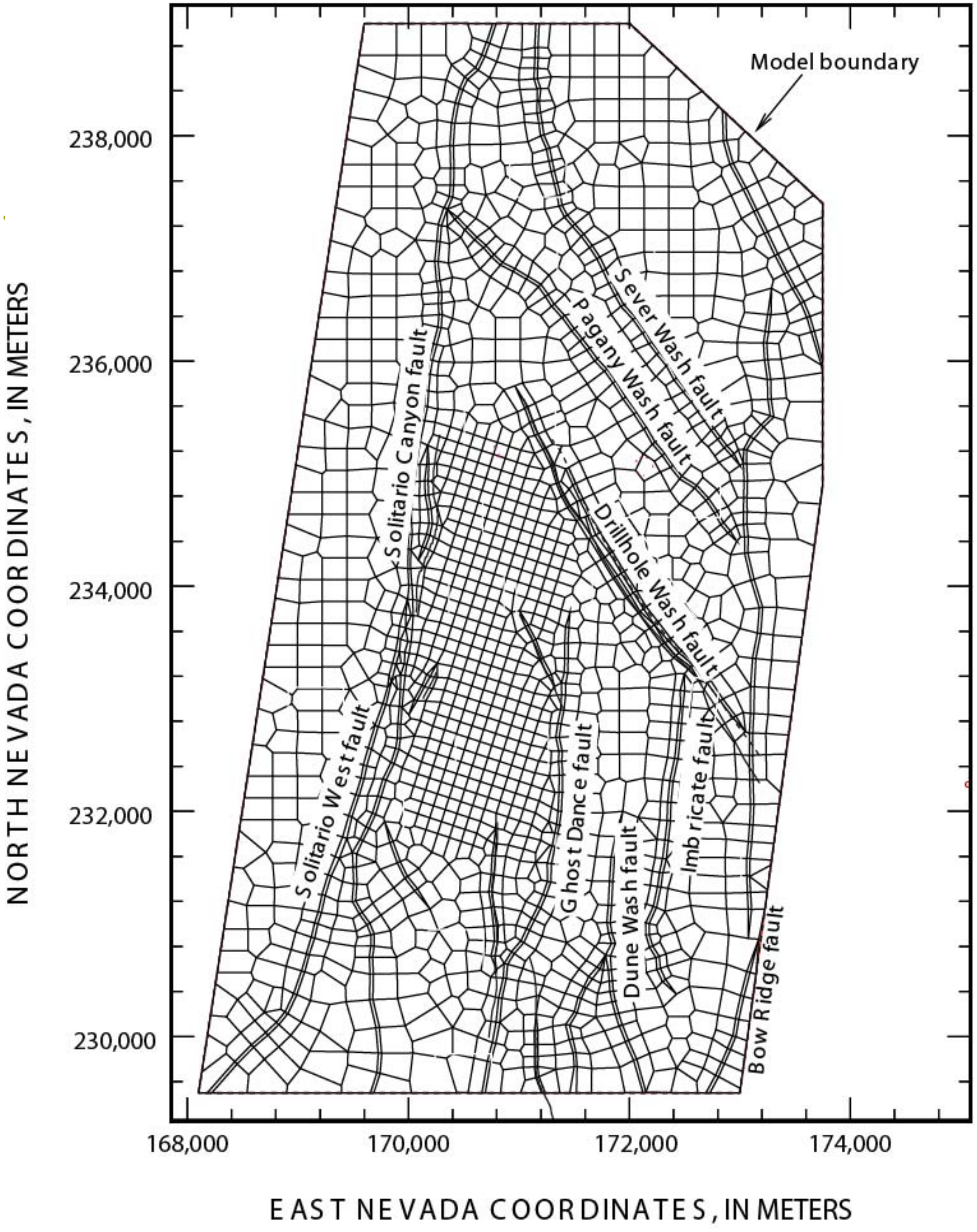
- Unsaturated flow in the UZ is vertical (gravitational gradients dominate)
- Lateral flow in the UZ generally occurs under locally saturated conditions
- Fracture flow initiated in the near surface can move quickly toward the PTn (<50 year travel time)
- Matrix flow in the PTn dampens seasonal and decadal pulses of water (except for faults) and greatly increases travel time
- Vertical fracture flow in TSw
- Lateral flow above the zeolitic CHz
- Recharge occurs through major faults

Current (2000) conceptual model of flow in the unsaturated zone



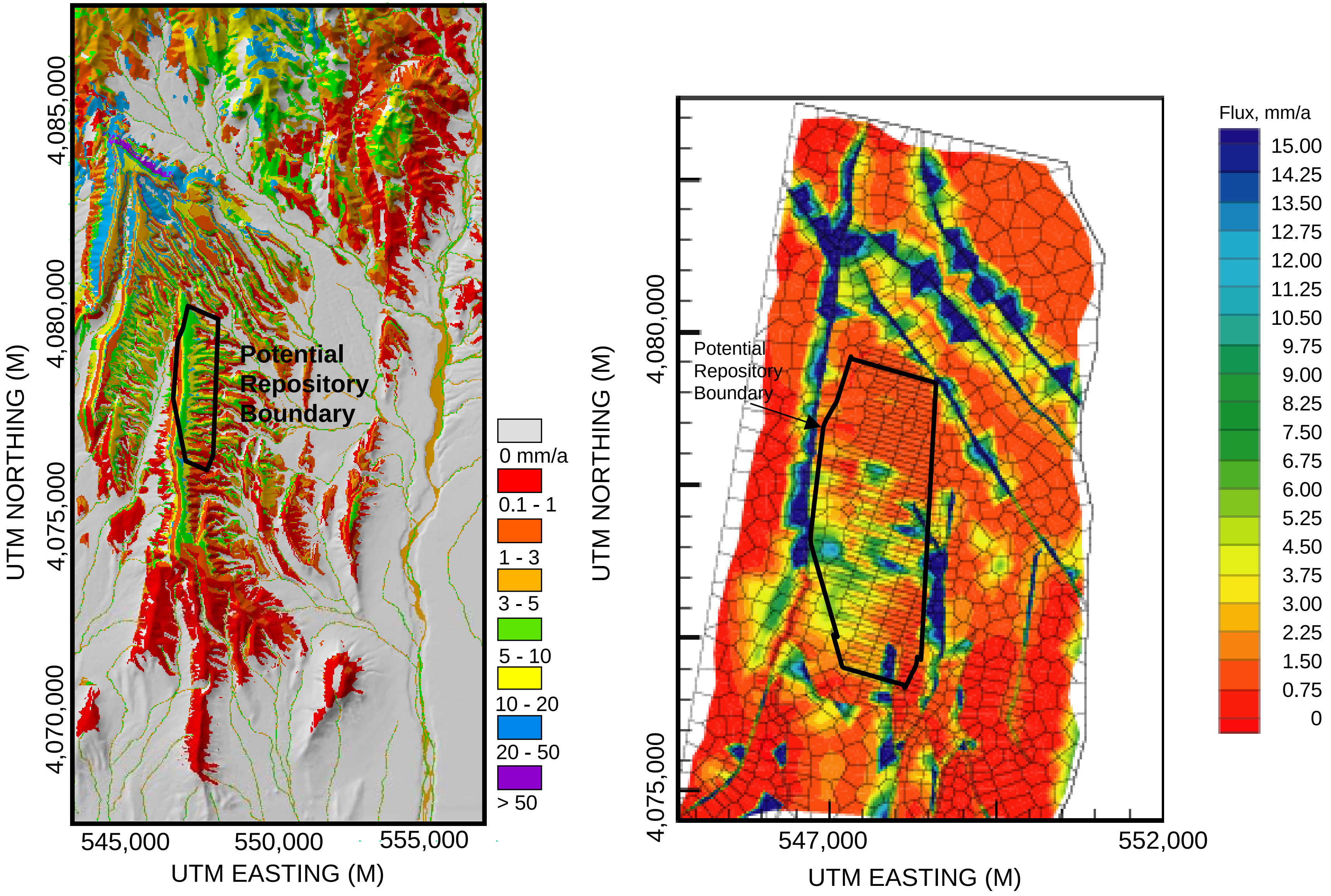
ESF faults and Cl-36/Cl: evidence for fast pathways





Current (2001) site-scale unsaturated zone numerical model grid

Spatially distributed net infiltration at Yucca Mountain compared to flux estimates at the water table using a 3-D hydrologic model

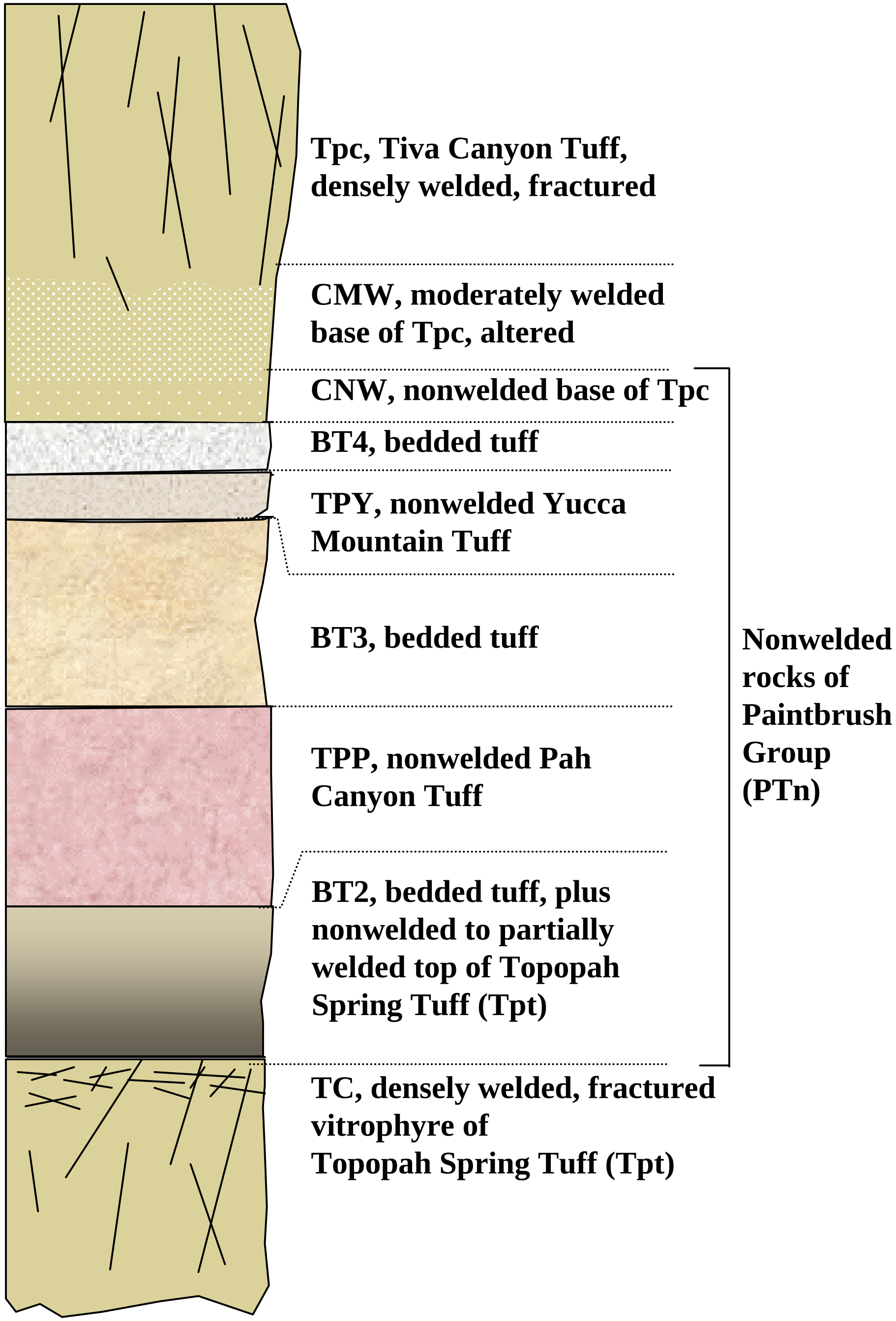


Observations on Lateral Diversion

- New analyses since the "Evolution" paper regarding the PTn

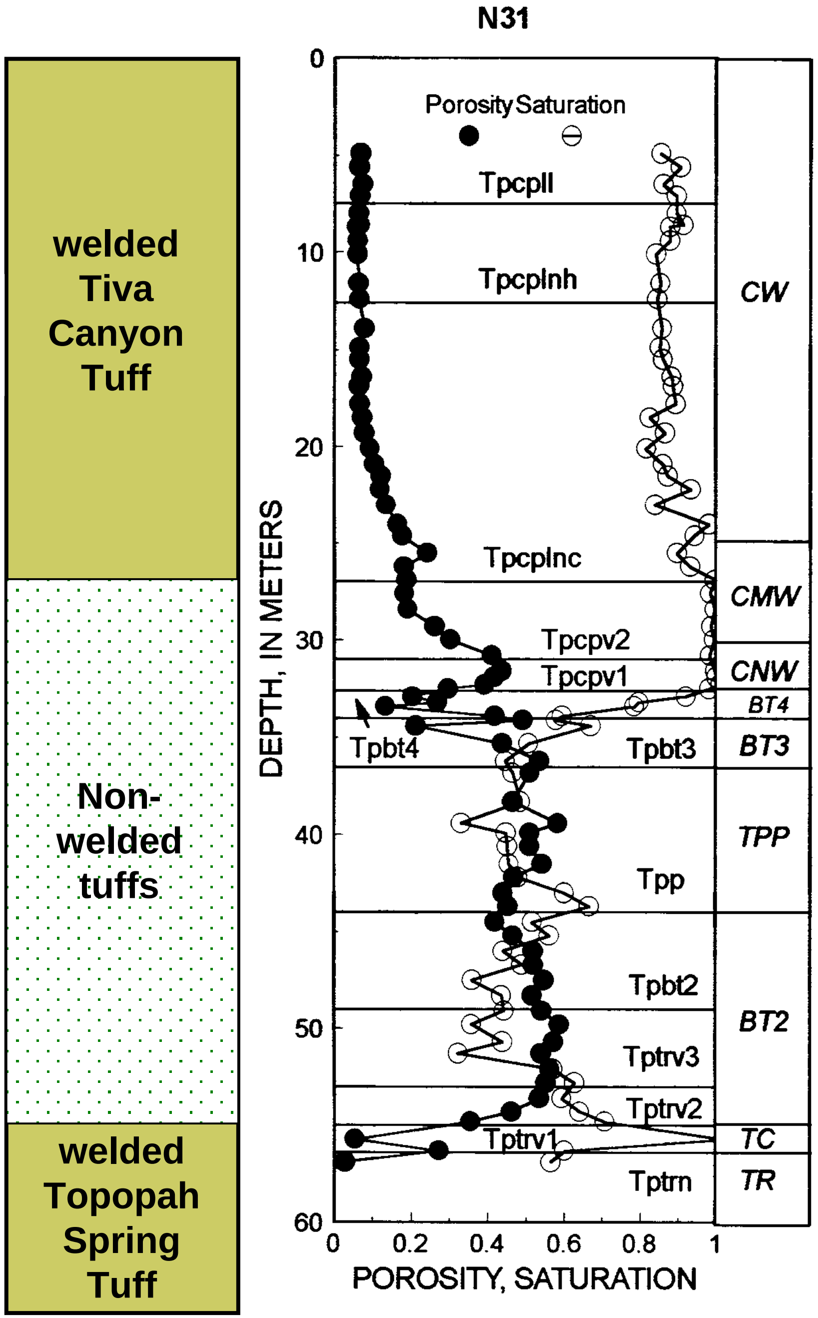
Paintbrush Tuff nonwelded unit (PTn)

- This unit has been targeted as the location of a capillary barrier mechanism for diverting downward percolation laterally
- modeling exercises have repeatedly supported this concept
- models have typically used idealistic geometry and large contrasts in properties



Diversion due to PTn

- Early observations of high saturation above the PTn suggested the potential for lateral diversion
- Core data, however showed the lack of strong property contrasts, except at the bottom of the PTn
- Analytical solution to the flow equation, using detailed measured properties, showed insignificant diversion



PTn Diversion: analytical estimates of Capillary Barrier Effects

$$Q_{\max} = \frac{K_s \tan\phi}{\alpha}\left[\left(\frac{q}{K_s^{\,*}}\right)^{\frac{\alpha}{\alpha^*}} - \left(\frac{q}{K_s}\right)\right]$$

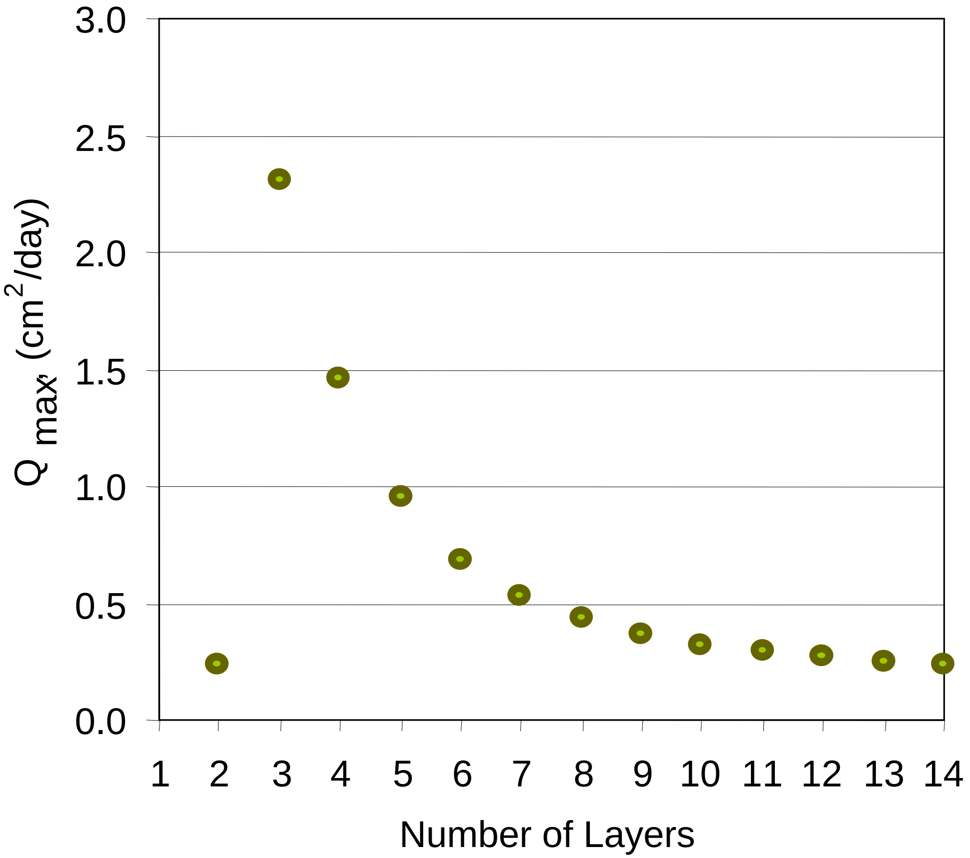
$$L = \frac{Q\max}{q}$$

(Ross, 1990)

- Equations are based on Darcy’s law and applied to sloping interfaces between 2 media
- Includes contrast in pore sizes with upper layer having smaller pores
- Downward flux rate, degree of slope, and permeability of the 2 media influence diversion due to capillary barrier effects

Diversion above PTn:

Influence of number of layers representing the real properties of transitional units



Diversion within PTn:

Analytical estimates using mean properties for each layer

Hydrogeologic unit	Porosity (v/v)	Saturated Hydraulic Conductivity (m/s)	α	Qmax (cm^2/d)	Fracture Density (F/m)
	Mean	Geometric mean			
CNW	0.39	1.2E-08	0.009	0	0.5
BT4	0.44	5.8E-07	0.005	4.7	0.5
TPY	0.27	1.6E-07	0.016	0	1.0
BT3	0.41	5.4E-07	0.009	0	0.5
TPP	0.50	9.3E-07	0.004	0.0001	1.0
BT2	0.49	2.2E-06	0.005		0.5

Diversion at the Base of the PTn:

Representing transition of vitric tuff properties overlying vitrophyre fractures

	Matrix porosity (v/v)	Fracture aperture* (microns)	α (1/cm)	K_s (cm/day)	Air entry of matrix (cm)	Total Q_{max} (cm^2/day)	L (m)
vitric tuff	0.2		0.0007	1.9E-02	1423	2.8	207
fractures		25	0.0248	1.8E-02	40		
vitric tuff	0.2		0.0007	1.9E-02	1423	3.2	230
fractures		125	0.1482	2.7E-01	7		
vitric tuff	0.1		0.0004	1.2E-04	2465	0	0
fractures		25	0.0248	1.8E-02	40		
vitric tuff	0.1		0.0004	1.2E-04	2465	0	0
fractures		125	0.1482	2.7E-01	7		
vitric tuff	0.05		0.0004	7.2E-07	2499	0	0
fractures		25	0.0248	1.8E-02	40		
vitric tuff	0.05		0.0004	7.2E-07	2499	0	0
fractures		125	0.1482	2.7E-01	7		

*Fracture properties from Kwicklis and Healy (1993)

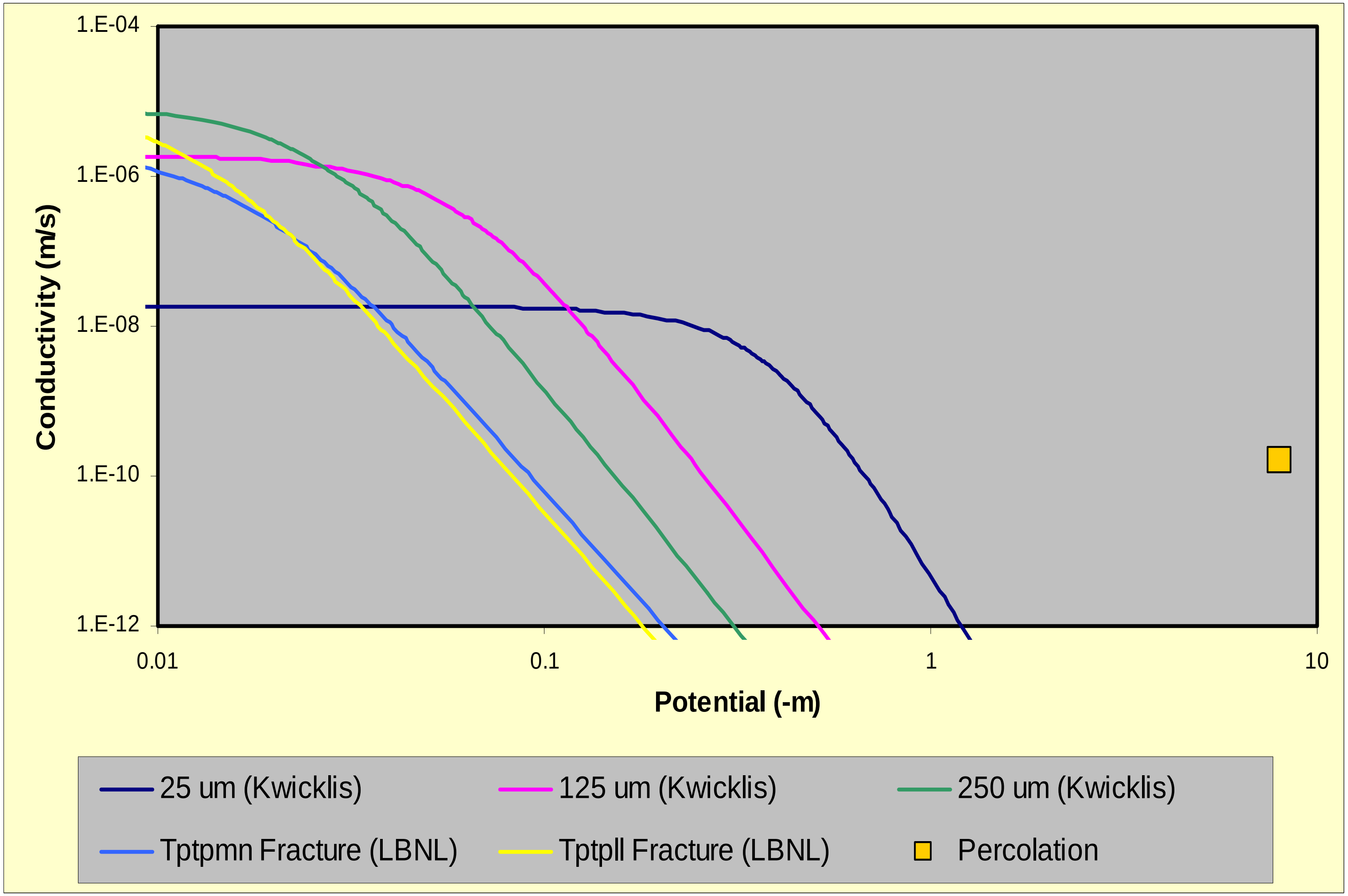
Potential for Lateral Diversion?

- On the basis of analyses and interpretations, it seems clear that the early conceptual models of lateral diversion did not take into consideration the scale at which the mechanisms responsible for diversion operate in a natural system
- Neither data nor field observations corroborate the existence of lateral diversion caused by a barrier effect due to the PTn
- Calculations and field data support the conceptual model of small-scale localized lateral diversion, and generally large-scale vertical fluxes through the PTn

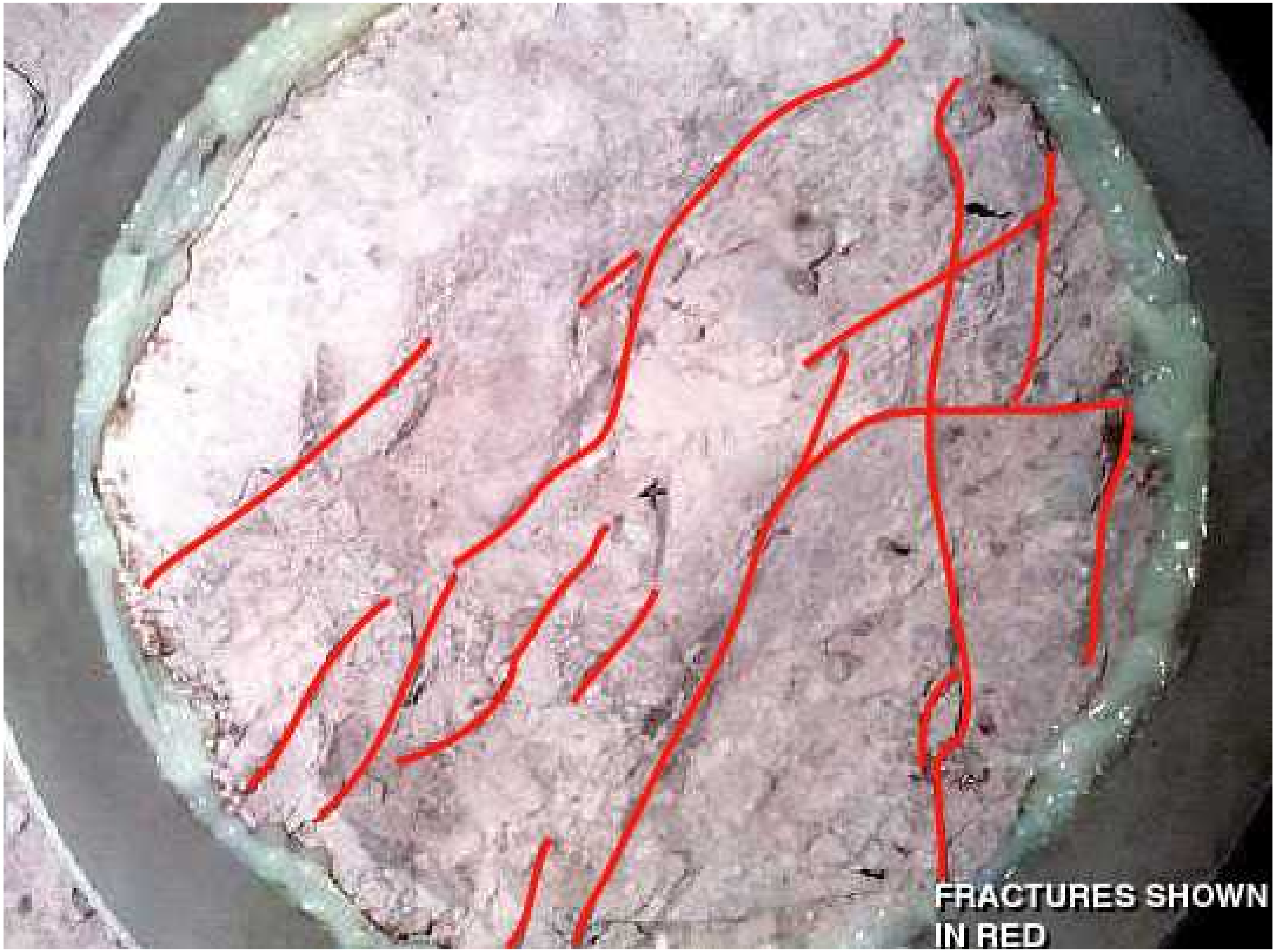
Observations on Fracture Characteristics

- Detailed measurements in ESF benches provide unsaturated properties of fractures
- Fractures may exhibit multi-hump curves
- Small fractures may carry high fluxes and be in potential equilibrium with matrix

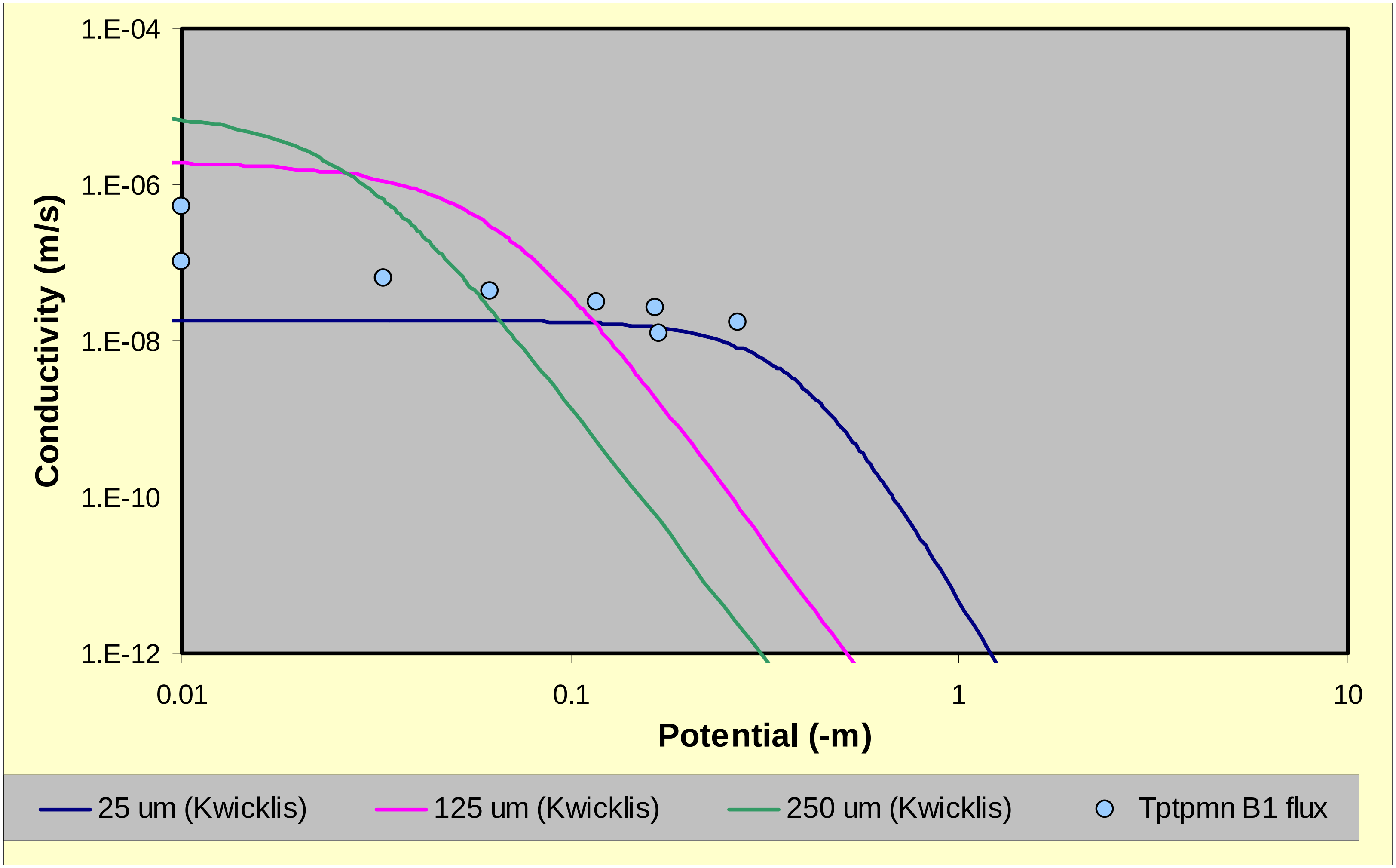
Fracture Permeability



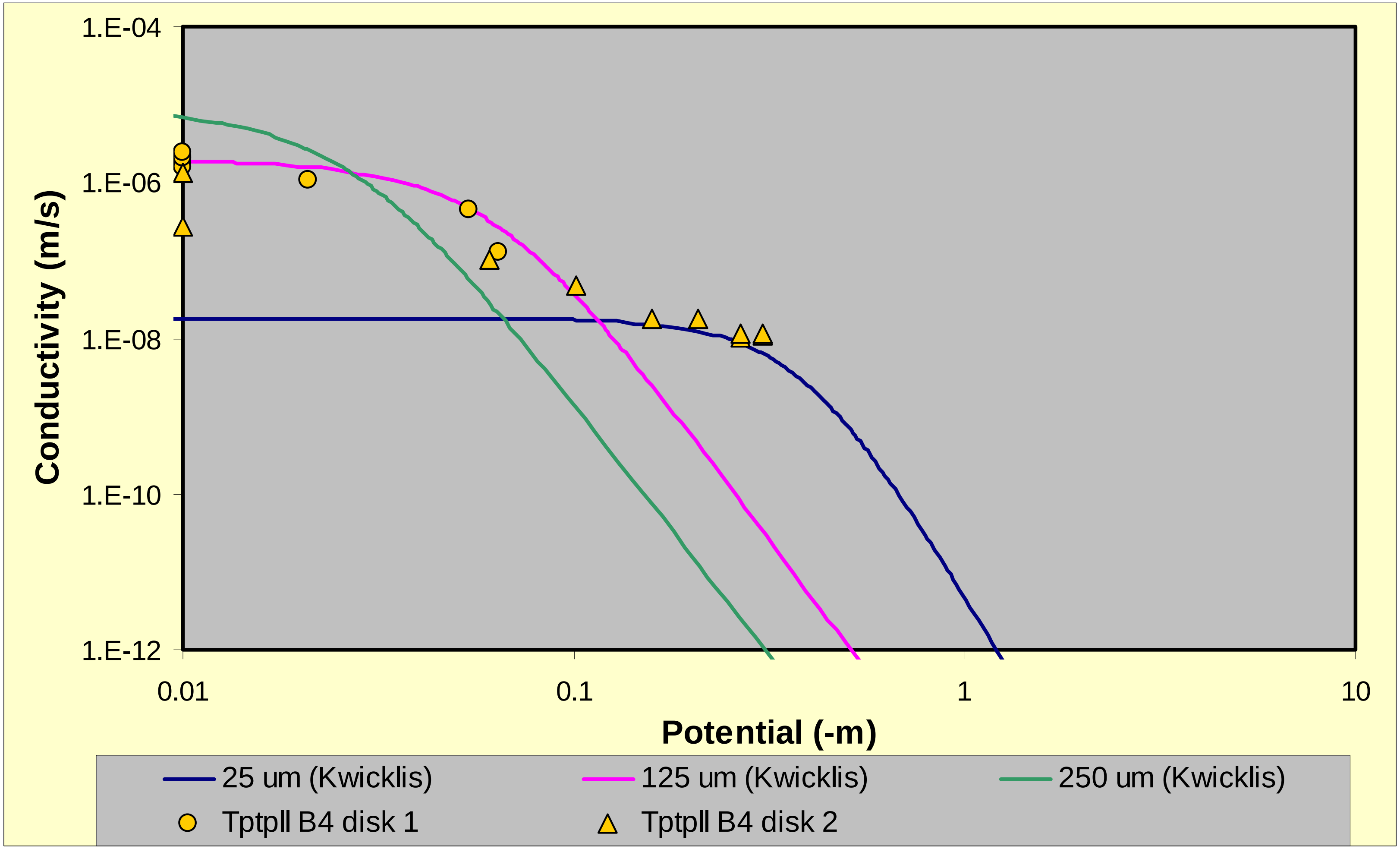
ECRB Bench #4, 17+35, Tptpll



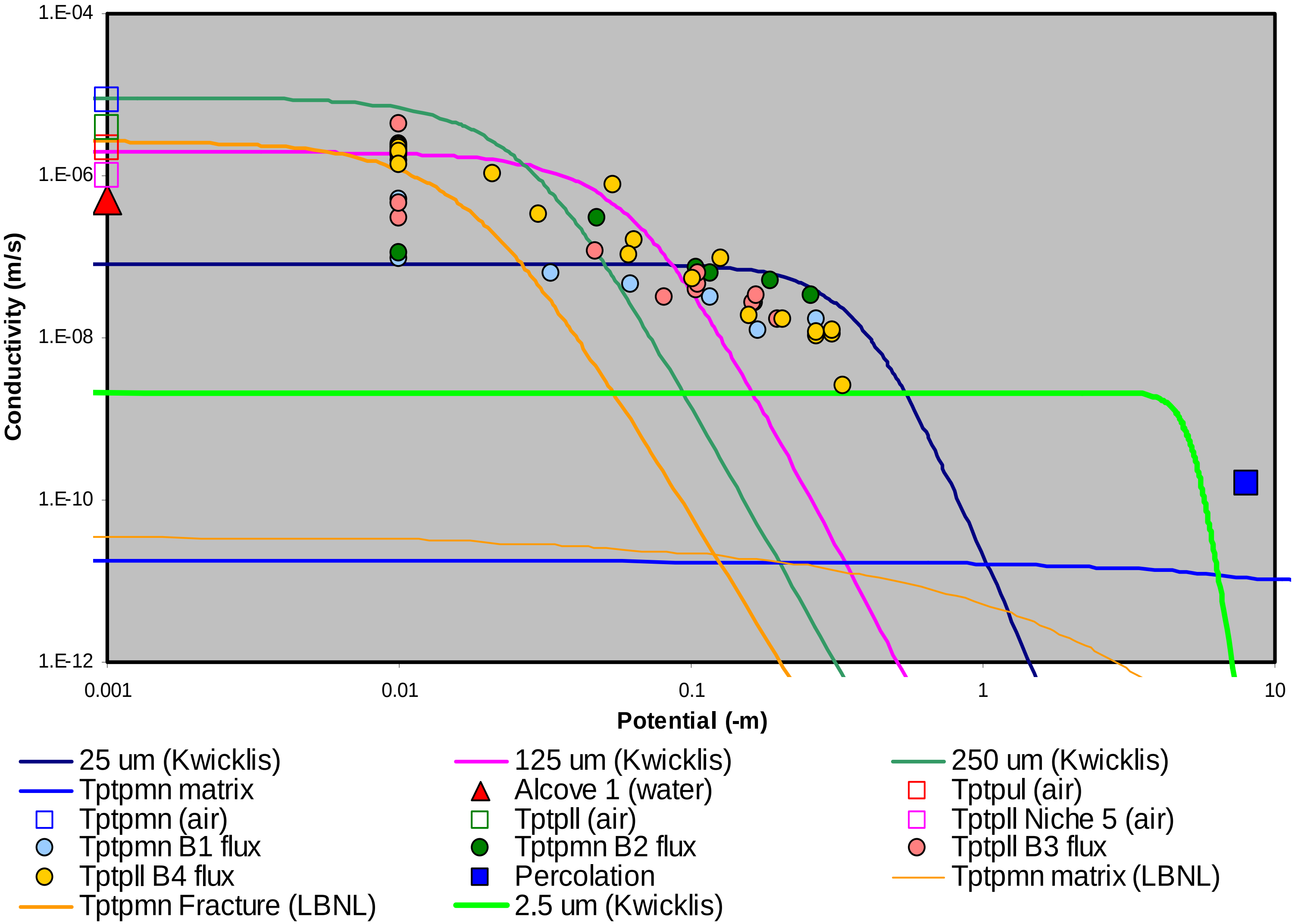
ECRB Bench #1, Fracture Permeability



ECRB Bench #4, Fracture Permeability



Measured and Modeled Fracture Permeability



Final Thoughts and Lessons Learned

- Model development must start with a clear statement of the problem and identify technical objectives
- A variety of alternative conceptual models should be formulated early on in project
- Numerical models should be developed concurrently with conceptual models
- Evaluation of conceptual models should rely on consistency with independent lines of evidence
- Robust model development depends on an extensive high-quality dataset at different spatial and temporal scales

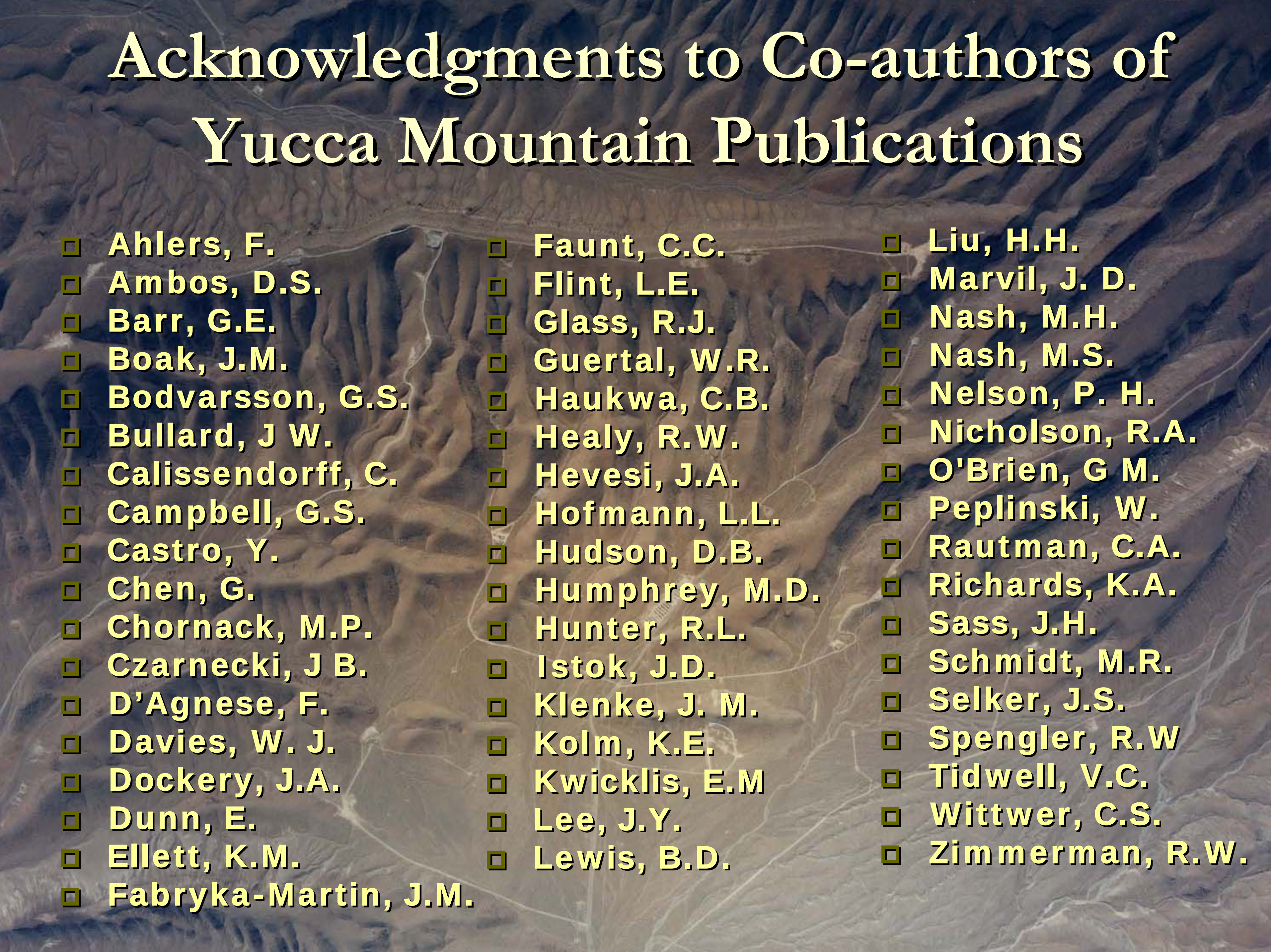
Summary

- The early models had low flux, extensive lateral flow in the PTn, and no fracture flow through the TSw.
- The current model has high flux (5 to 10 mm/yr) with over 80 mm/yr in some locations, vertical matrix-dominated flow in the PTn, fracture-dominated flow in the TSw, vertical matrix-dominated flow in the vitric rocks of the Calico Hills and Prow Pass, and extensive lateral flow above the zeolitic boundary in those units.

Summary

- Within these few concepts we have made significant strides in addressing the major issues regarding the behavior of Yucca Mountain as a potential nuclear waste repository.
- The conceptual model we have today has evolved over 20 years through an integrated scientific approach with highly motivated and creative scientists from a variety of disciplines and organizations that were provided a work environment that fostered quality technical interaction.

Acknowledgments to Co-authors of Yucca Mountain Publications



- Ahlers, F.
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- Boak, J.M.
- Bodvarsson, G.S.
- Bullard, J W.
- Calissendorff, C.
- Campbell, G.S.
- Castro, Y.
- Chen, G.
- Chornack, M.P.
- Czarnecki, J B.
- D’Agnese, F.
- Davies, W. J.
- Dockery, J.A.
- Dunn, E.
- Ellett, K.M.
- Fabryka-Martin, J.M.
- Faunt, C.C.
- Flint, L.E.
- Glass, R.J.
- Guertal, W.R.
- Haukwa, C.B.
- Healy, R.W.
- Hevesi, J.A.
- Hofmann, L.L.
- Hudson, D.B.
- Humphrey, M.D.
- Hunter, R.L.
- Istok, J.D.
- Klenke, J. M.
- Kolm, K.E.
- Kwicklis, E.M
- Lee, J.Y.
- Lewis, B.D.
- Liu, H.H.
- Marvil, J. D.
- Nash, M.H.
- Nash, M.S.
- Nelson, P. H.
- Nicholson, R.A.
- O'Brien, G M.
- Peplinski, W.
- Rautman, C.A.
- Richards, K.A.
- Sass, J.H.
- Schmidt, M.R.
- Selker, J.S.
- Spengler, R.W
- Tidwell, V.C.
- Wittwer, C.S.
- Zimmerman, R.W.