SOME OBSERVATIONS BASED ON UNSATURATED ZONE FLOW MODEL EXPERT ELICITATION PROJECT YUCCA MOUNTAIN, NEVADA

by

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PROJECT OBJECTIVE

Identify and assess ***model/parameter uncertainties*** associated with key aspects of unsaturated zone flow system at Yucca Mountain (YM) which affect

- ✓ ***ambient percolation flux*** through repository horizon (primary goal);
- ✓ ***seepage*** into open repository (secondary goal).

METHODOLOGY

Individual assessments by seven ***experts*** based on

- ***Workshops*** on
  - ✓ Significant issues and available data;
  - ✓ Alternative models and interpretations;
  - ✓ Preliminary expert assessments.
- YM ***Field Trip***.
- Supporting ***literature*** and copies of overheads.
- Elicitation ***interview***.
- ***Review/revision*** of written elicitation summary.

Opportunity for

- ✓ ***Interaction*** among experts and presenters;
- ✓ ***Revisions*** based on all expert opinions;

without attempt to generate ***consensus***.

INTRODUCTORY OBSERVATIONS

- ***No precedence*** for assessing unsaturated flow under comparable ***rock/climate conditions*** on comparable ***space-time scales***.
- Rich ***generic knowledge*** which, with proper ***site data***, should allow one to make ***intelligent inferences*** about subsurface flow at YM.
- To be ***credible***, such inferences should be based on ***theories/models*** supported by, and compatible with, ***experimental and site data***.

- Among the ***better understood*** processes of relevance to YM is ***heat flow***.
  - ✌ ***Enough/reliable data*** (temperature, heat flux, conductivity) could yield ***credible estimates*** of ***moisture flux*** on various spatial scales.
  - ☹ Available data may ***not*** be of ***sufficient quantity/quality*** for this purpose. More on this later.

- Among the ***least understood*** processes is the ***transformation of precipitation*** (rain/snow) ***into deep percolation*** below the root zone.
  - ☹ ***Assessments*** to date based on ***near-surface*** measurements/models seem ***unconvincing***. More on this later.
  - ☹ ***Nowhere*** have such assessments been ***verified*** on space-time scales comparable to YM.

CONCLUSION: The ***key*** to unraveling the nature and rates of ***subsurface flow*** at YM lies ***at depth***.

PROPOSED CONCEPTUAL FRAMEWORK

- Among the ***more reliable*** YM ***models/data*** are those concerning ***pneumatic monitoring/injection***. These suggest/reveal:
  - ✓ In ***welded units***, pneumatic data represent ***fractures/faults*** at ***low water saturation*** which are thus ***open to air flow***.
  - ✓ ***TCw/TSw*** are spanned by pneumatically ***interconnected networks of fractures/faults*** that ***conducts air with relative ease*** across considerable distances (more in some directions than others).
  - ✓ Pneumatic ***monitoring/injection*** data provide ***self-consistent*** (***high***) network ***permeabilities***.
  - ✓ Due to low saturation, these are probably ***close to*** the ***network intrinsic permeabilities***.
  - ✓ As matrix permeability of ***TCw/TSw*** is orders lower, ***flow*** in these units is ***dominated by fractures and faults***.
  - ☞ As at Apache Leap, pneumatic injection tests ***should*** yield ***air-filled porosity of fractures.***

☹ There is ***no information*** to evaluate directly the ***modes/rates/directions*** of ***water flow*** through ***fractures/faults*** in ***TCw/TSw***. Little is known about ***mechanisms/parameters*** that control flow

✎ in open vs filled fracture spaces;
✎ along fracture planes vs intersections;
✎ across wide areas vs channels/rivulets;
✎ in capillary films;
✎ between fractures and matrix blocks.

CONCLUSION: The ***key*** to assessing repository-level ***percolation flux*** lies within the overlying ***PTn*** where flow is ***matrix-dominated***, and within the ***ESF***.

- Evidence for ***matrix-dominated PTn flow***:
  - ✓ Relatively high matrix porosity/permeability;
  - ✓ Low enough saturation to cause imbibition from fractures/faults into matrix;
  - ✓ Relatively low fracture density;
  - ✓ Faults relatively narrow and difficult to identify;
  - ✓ Pronounced attenuation of pneumatic pressure signals across PTn.

- ***Bomb-pulse isotopes*** in waters ***within/below PTn*** imply some ***rapid flow paths*** through it.
  - ✓ ***Mean seepage*** velocity ***through PTn*** matrix is ***too slow*** to account ***for bomb signatures***;
  - ✓ Bomb-pulse isotopes in PTn matrix suggest ***fast paths in matrix***, not only fractures/faults;
- ***Fast flow in matrix*** (or fractures/faults) can take place through ***narrow channels*** of locally ***elevated hydraulic conductivity*** due to
  - ✎ ***Focused episodic infiltration*** causing
  - ✎ ***buildup of saturation*** (and thus ***conductivity***) along ***narrow paths***, without time to fully dissipate between events;
  - ✎ ***Spatial variations*** in matrix permeability;
  - ✎ ***Instability*** at layer interfaces and ***fingering***.
- Such ***preferential flow channels*** may ***persist*** or ***adjust dynamically*** to variable surface infiltration.
- Regardless of whether they develop within fractures, faults or the matrix, such flow channels ***occupy a minute proportion of the rock*** volume and are thus ***unlikely to be observed*** in the field.

- ***No*** clear ***evidence to support/deny*** extensive ***lateral flow within PTn***. Probably dampened by heterogeneities, hence ***vertical flow dominates***.

"BACK-OF-THE-ENVELOPE" BOUNDING CALCULATIONS OF FLUX AND VELOCITY

- Water ***fluxes/velocities vary considerably*** in ***space-time*** and with ***direction/scale***.
- We ***consider*** only
  - ✓ space-time ***mean vertical flux/velocity***,
  - ✓ one for ***bulk rock (slow)***, one for ***preferential channels (fast)***.

Lower Bound on Percolation Flux

- Table 7 in Flint (1996) contains ***summary*** info about ***matrix properties*** and ***state variables*** of seven ***PTn*** units. We ***average*** these to obtain
  - ✎ Porosity $\phi \approx 0.4$
  - ✎ Saturation $S \approx 0.5$
  - ✎ Saturated conductivity $K_s \approx 3.25 \times 10^3$ mm/yr (geometric average).
- ☹ To date, ***no*** reliable ***experimental data*** on ***K(S)*** or ***$K(S_{ambient})$***, ***only*** indirectly ***calculated "data"*** from moisture retention curves.
  - ✌ L.E. Flint provided recent data on two rock samples. From these
  - ✎ $K(S=0.5) \approx 6$ mm/yr.

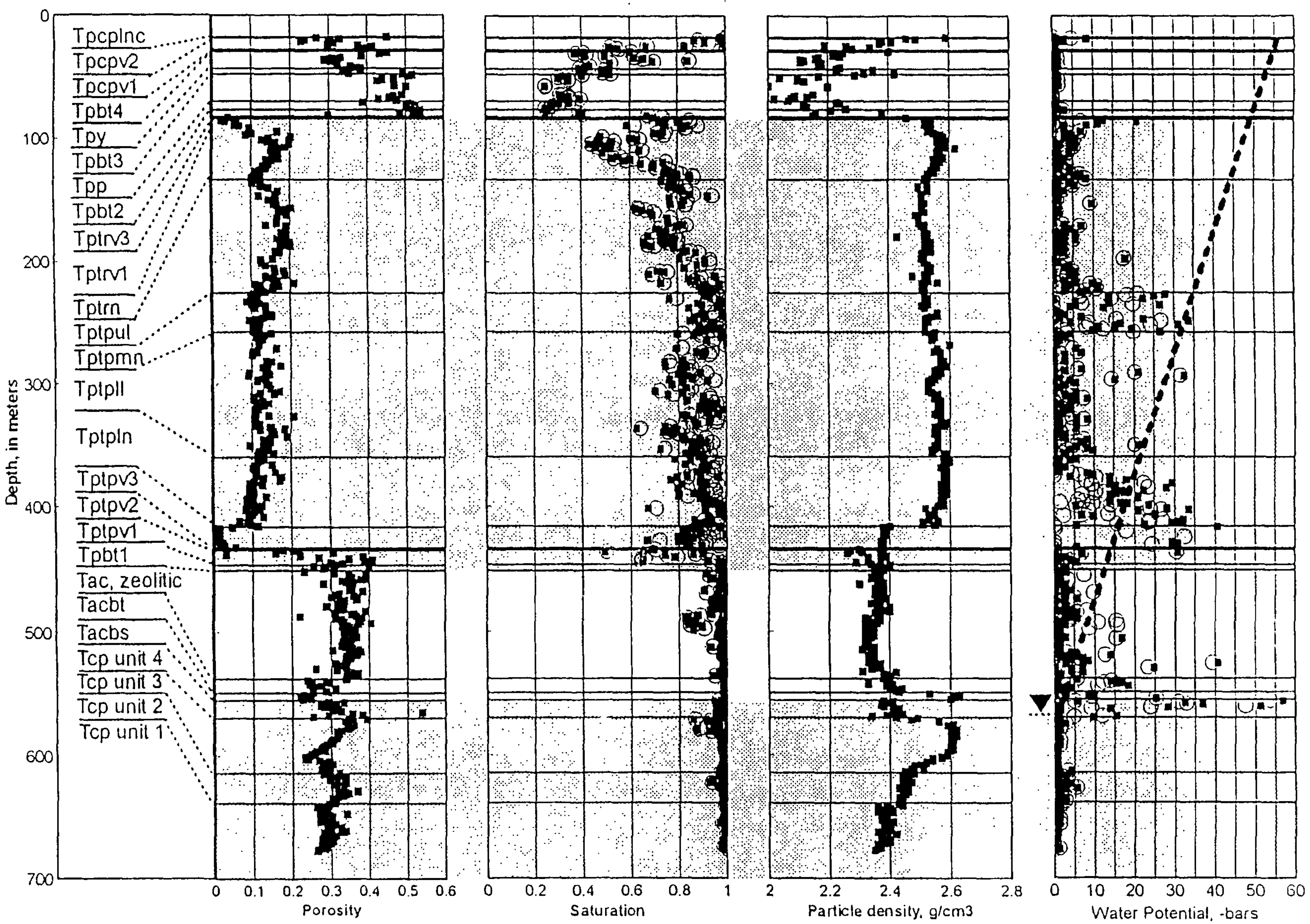

Figure 4. Porosity, saturation, particle density, and water potential with calculated no-flow conditions in equilibrium with the water table (dashed line), positioned with depth for borehole SD9. Open circles are saturation and water- potential values corrected for drilling and sample handling damage. Shading corresponds to formation, and lithostratigraphic unit assignment is from Engstrom and Rautman (1996).

- Uniformly low suction in ***PTn*** implies ***flow*** is ***gravity-dominated*** at near ***unit vertical gradient***.
  - ☞ ***Matrix flux*** $q_m \approx$ ***6 mm/yr***.
  - ☞ This is a ***lower bound*** because it
    - ✓ disregards fractures/faults;
    - ✓ disregards fast-flow channels in matrix;
    - ✓ cannot account for bomb-pulse signatures;
    - ✓ disregards increase of K with scale.
  - ✌ ***Independent calculations*** by Fabryka-Martin et al. (1996; Tables 8-3 to 8-6) suggest that a ***minimum flux of 1 - 5 mm/yr*** is needed to reproduce bomb-pulse ^{36}Cl signatures in ESF.
  - ✌ ***Agrees*** with ***Cl mass balance***.
- Average ***volumetric water content*** in ***PTn matrix*** is $\theta = S\phi \approx (0.5)(0.4) = 0.2$.
  - ☞ ***Velocity*** $v_m = q_m/\theta \approx$ ***30 mm/yr***.
  - ☞ At such velocity, it takes ***10,000 years*** to travel ***300 m***, over 13,000 years 400 m.
  - ✌ ***Agrees with*** elevated reconstructed atmospheric ***$^{36}Cl/Cl$ ratios*** (Fabryka-Martin et al., 1996, Figure 2-2) prior to about 10,000 years (at end of Pleistocene) and many corresponding ratios (Fig 5-1) in ESF .
  - ☞ Much ***too slow*** to account ***for bomb-pulse*** signatures; ***requires postulating fast paths***.

Table 8-3. Simulated transport of ^{36}Cl to the ESF using the original parameter set at Station 35

	CASE	PTn Fracture Properties (normalized to base-case value)				Infiltration Rate (mm/yr)				
		Assumed		Calculated		0.1	1	5	10	50
		Density	Aperture	Permeability	a_{frac} (m^{-1})					
Non Fault Zone Properties	Base	1	1	1	1	No 280814 281931	No 12067 22761	No 2500 4509	No 1221 2360	No 245 275
Modified PTn Fault Zone Fracture Properties	A Bomb Pulse? 1% 50%	2	1	2	1		No . .	No 2492 4503	No 1279 2357	No . .
	B Bomb Pulse? 1% 50%	1	2	8	2		No 12054 22437	Yes 2241 4631		
	C Bomb Pulse? 1% 50%	1	2.5	16	2.5	Not performed	Not performed	Not performed	Not performed	Not performed
	D Bomb Pulse? 1% 50%	2	2	16	2		No 12047 22447	No 2401 4547	Yes 1135 2334	
	E Bomb Pulse? 1% 50%	1	1	1	0.1		No 11518 22225	Yes 2336 4506		
	F Bomb Pulse? 1% 50%	2	2	16	0.1	No . .	Yes 10751 22626	Yes 1070 4597		

Bomb Pulse: Indicates the arrival of any solutes at ESF in less than 50 years.

1% : Indicates the breakthrough at the ESF of 1% of a pulse injected at the surface.

50% : Indicates the breakthrough at the ESF of 50% of a pulse injected at the surface.

1% and 50% also represent the maximum age of the first 1% and 50% of a simulated water sample at the ESF

Table 8-4. Simulated transport of ^{36}Cl to the ESF using the original parameter set at Station 59

	CASE breakthrough simution results	PTn Fracture Properties (normalized to base-case value)				Infiltration Rate (mm/yr)				
		Assumed		Calculated		0.1	1	5	10	50
		Density	Aperture	Permeability	a_{frac} (m^{-1})					
Non Fault Zone Properties	Base Bomb Pulse? 1% 50%	1	1	1	1	No 208520 209586	No 6671 15495	No 1246 3057	No 628 1492	No 130 142
Modified PTn Fault Zone Fracture Properties	A Bomb Pulse? 1% 50%	2	1	2	1		No 6660 15599	No 1347 3053	No 628 1490	No 130 141
	B Bomb Pulse? 1% 50%	1	2	8	2		No 6818 15019	Yes 1156 3109		
	C Bomb Pulse? 1% 50%	1	2.5	16	2.5		No 6819 14891	Yes 835 3024	Yes 304 1497	
	D Bomb Pulse? 1% 50%	2	2	16	2		No 6823 15039	No 1257 3072	No 577 1507	Yes 108 147
	E Bomb Pulse? 1% 50%	1	1	1	0.1		No 5841 15624	Yes 1205 2963	Yes 560 1494	
	F Bomb Pulse? 1% 50%	2	2	16	0.1	No 58431 213438	Yes 5051 15302	Yes 893 2902	Yes 390 1445	

Bomb Pulse: Indicates the arrival of any solutes at ESF in less than 50 years.
1% : Indicates the breakthrough at the ESF of 1% of a pulse injected at the surface.
50% : Indicates the breakthrough at the ESF of 50% of a pulse injected at the surface.

1% and 50% also represent the maximum age of the first 1% and 50% of a simulated sample of water at the ESF

Table 8-5. Simulated transport of ^{36}Cl to the ESF using the updated parameter set at Station 59

	CASE breakthrough simulation results	PTn Fracture Properties (normalized to base-case value): Assumed: Density	Assumed: Aperture	Calculated: Permeability	Calculated: a_{mf} (m^{-1})	Infiltration Rate (mm/yr): 0.1	1	5	10	50
Non Fault Zone Properties	Base	1	1	1	1	No 50005 104580	No 5579 10282	No 1204 2277	No 620 1191	No 132 270
Modified PTn Fault Zone Fracture Properties	A Bomb Pulse? 1% 50%	2	1	2	1		No 5577 10281	No 1203 2276	No 619 1190	No 132 270
	B Bomb Pulse? 1% 50%	1	2	8	2		No 5604 10307	No 1211 2284	No 624 1195	No 123 271
	C Bomb Pulse? 1% 50%	1	2.5	16	2.5		No 5634 10337	No 1221 2293	No 630 1201	Yes 124 273
	D Bomb Pulse? 1% 50%	2	2	16	2		No 5587 10290	No 1206 2279	No 621 1192	No 133 270
	E Bomb Pulse? 1% 50%	1	1	1	0.1		No 5464 10400	No 1137 2371	No 589 1258	No 94 269
	F Bomb Pulse? 1% 50%	2	2	16	0.1	No	No 5334 10535	Yes 870 2499		

Bomb Pulse: Indicates the arrival of any solutes at ESF in less than 50 years.

1% : Indicates the breakthrough at the ESF of 1% of a pulse injected at the surface.

50% : Indicates the breakthrough at the ESF of 50% of a pulse injected at the surface.

1% and 50% also represent the maximum age of the first 1% and 50% of a simulated sample of water at the ESF

Table 8-5. Simulated transport of ^{36}Cl to the ESF using the updated parameter set at Station 35 (continued)

	CASE	PTn Fracture Properties (normalized to base-case value)				Infiltration Rate (mm/yr)				
		Assumed		Calculated		0.1	1	5	10	50
		Density	Aperture	Permeability	a_{frac} (m^{-1})					
Non Fault Zone Properties	Base	1	1	1	1	No 50005 104580	No 5579 10282	No 1204 2277	No 5370 10280	No 132 270
Modified PTn Fault Zone Fracture Properties	G Bomb Pulse? 1% 50%	1	2.9	25	1			No 1233 2306	Yes 637 1208	
	H Bomb Pulse? 1% 50%	4	2	128	1			No 1242 2315	Yes 584 1214	
	I Bomb Pulse? 1% 50%	1	3.1	30	1		No 5693 10396	Yes 1240 1213		
	J Bomb Pulse? 1% 50%	1	4	64	1		No 5287 10555	Yes 971 2369		
	K Bomb Pulse? 1% 50%	1	4.6	100	1		No 2942 10770	Yes 15 2447		
	L Bomb Pulse? 1% 50%	1	5	125	1	No . .	No 79 10902	Yes 15 2495		
	M Bomb Pulse? 1% 50%	1	3.1	30	3.1	No . .	No 5681 10385	No 1237 2310		

Bomb Pulse: Indicates the arrival of any solutes at ESF in less than 50 years.

1% : Indicates the breakthrough at the ESF of 1% of a pulse injected at the surface.

50% : Indicates the breakthrough at the ESF of 50% of a pulse injected at the surface.

1% and 50% also represent the maximum age of the first 1% and 50% of a simulated sample of water at the ESF.

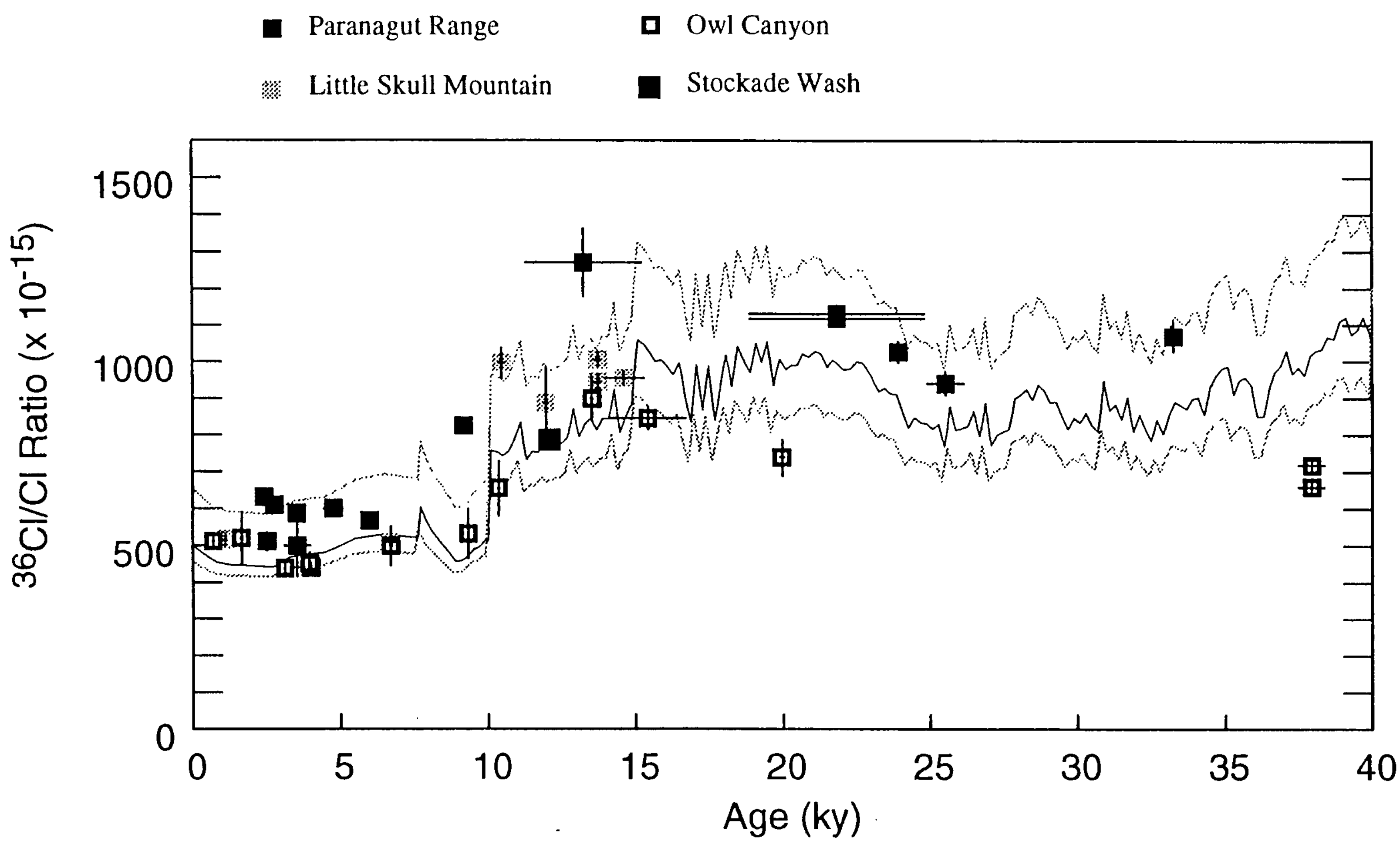

Figure 2-2. Reconstructed production rate of chlorine-36 in the atmosphere, compared against measured data for packrat middens from the vicinity of the Nevada Test Site. The reconstructed ^{36}Cl/Cl ratio shown by the solid line assumes that the deposition rate of stable chloride was constant at present day rates during the Holocene (i.e., ages less than 10 ky) but 33% lower throughout the Pleistocene. Lower and upper limits shown by the gray lines assume present-day ^{36}Cl/Cl ratios of 450 x 10^{-15} and 650 x 10^{-15}, respectively. See section 2.1 for a discussion of these reconstructions.

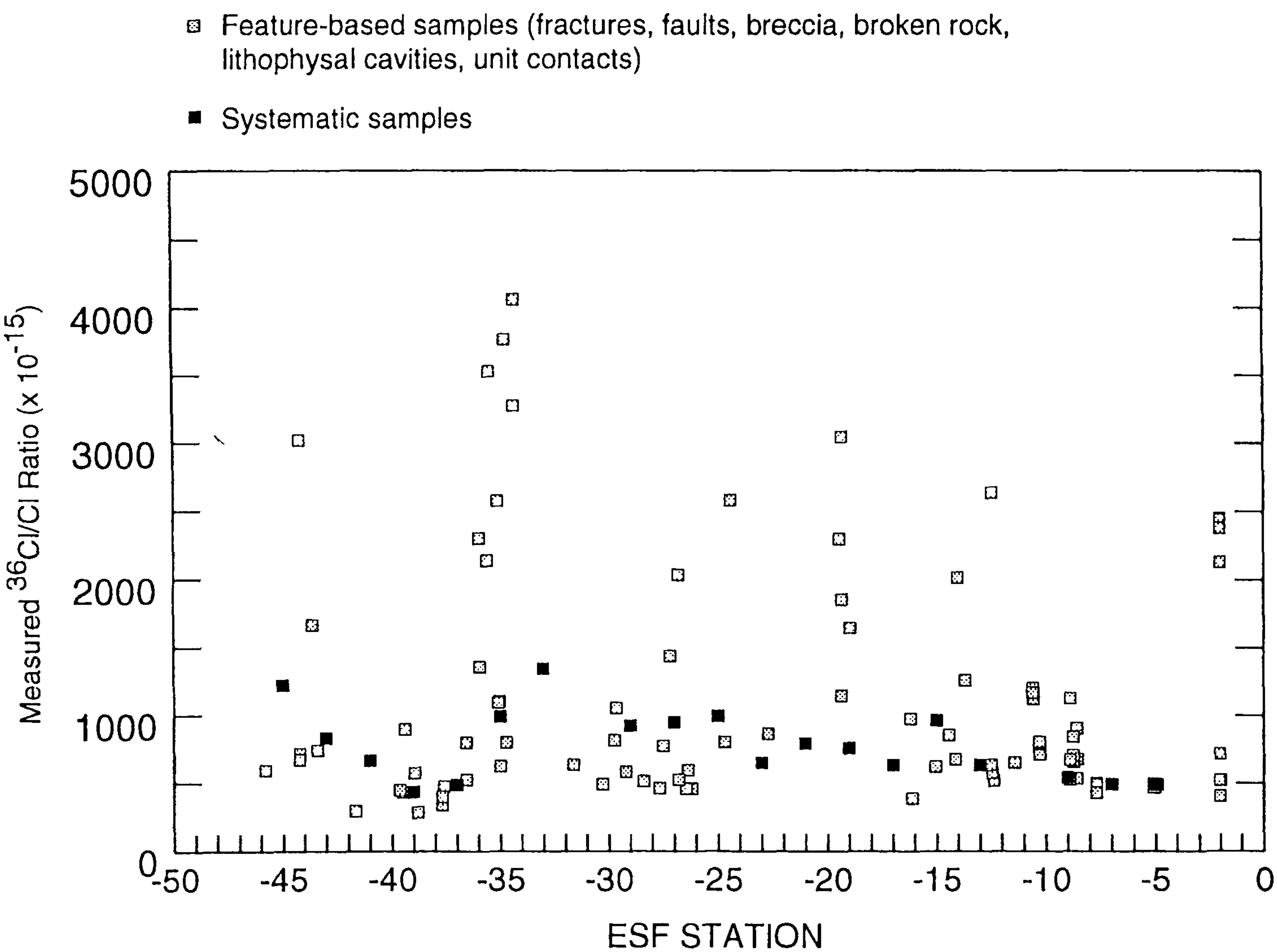

Figure 5-1. Distribution of $^{36}Cl/Cl$ ratios measured for rock samples, as a function of distance along the ESF North Ramp and Main Drift. ESF stations are marked in 100-m increments. Samples with ratios exceeding 1500 x 10^{-15} are considered to contain a component of bomb-pulse ^{36}Cl. Data from Table 5-3.

Upper Bound on Percolation Flux

- When ***ESF ventilation*** is ***shut off*** on weekends, moisture ***flux*** from rock averages about ***50 mm/yr*** (J.S.Y. Wang, personal communication).
  - ☞ This yields an ***upper bound*** on ***percolation flux*** across repository horizon.
  - ☞ Flux in ***excess of 6 mm/yr*** is associated with ***fast paths***.
  - ☞ Such paths ***can be unsaturated*** and ***need not form visible seeps*** in ESF or open repository.
  - ☞ There seem to be ***no*** other ***data to further constrain flux*** through fast paths ***from above***.

Matrix vs Fracture Flux in TSw

- TSw ***matrix permeability*** varies about a ***nominal*** value of $5 \times 10^{-18}\ m^2$ (Birkholzer et al. 1996).
  - ☞ As S ≈ 1, K ≈ 1.5 mm/yr.
  - ☞ Under unit gradient, ***matrix flux ≈ 1.5 mm/yr***.
  - ☞ ***Flux through fractures/faults*** varies between
    - ✓ nominal ***lower bound*** of ***4.5 mm/yr***,
    - ✓ nominal ***upper bound*** of ***48.5 mm/yr***.
  - ☞ ***Fractures/faults*** thus ***carry*** part of ***slow*** and all ***fast flow***.

Effective Porosity ϕ_f of Fast Paths

- ϕ_f = (rock volume occupied by fast paths)/ (bulk rock volume)
  = ***Probability of*** encountering a ***fast flow path***.
  = q_f/v_f = (fast flux)/(fast velocity).
- Atmospheric bomb-pulse released 1952 - 1963. Allow signatures within depth range 100 - 450 m.
  - ☞ $v_f \approx 2.5 \times 10^3 - 1.5 \times 10^4$ mm/yr.
  - ☞ In ***TSw*** $q_f \approx 4.5 - 48.5$ mm/yr implies ***$\phi_f \approx 3 \times 10^{-4} - 2 \times 10^{-2}$***.
  - ☹ ***No data*** to estimate ϕ_f in ***PTn***.
- $\phi_f = A_f N_f$ = (mean x-sectional ***area of fast path***)/ (***number of fast paths*** per unit x-area)
  - ☹ ***Cannot evaluate*** A_f or N_f without knowing one of them.

Probability Distribution of Percolation Flux

- Under a unit mean hydraulic gradient, flux is proportional to K.
  - ☞ Taking ***K log normal*** renders ***flux log normal***.
  - ☞ Taking ***lower/upper bounds*** to represent ***5/95 percentiles*** yields the ***shown pdf/cdf*** and a
  - ☞ <u>***Maximum likelihood flux $\approx$ 17 mm/yr***</u>.

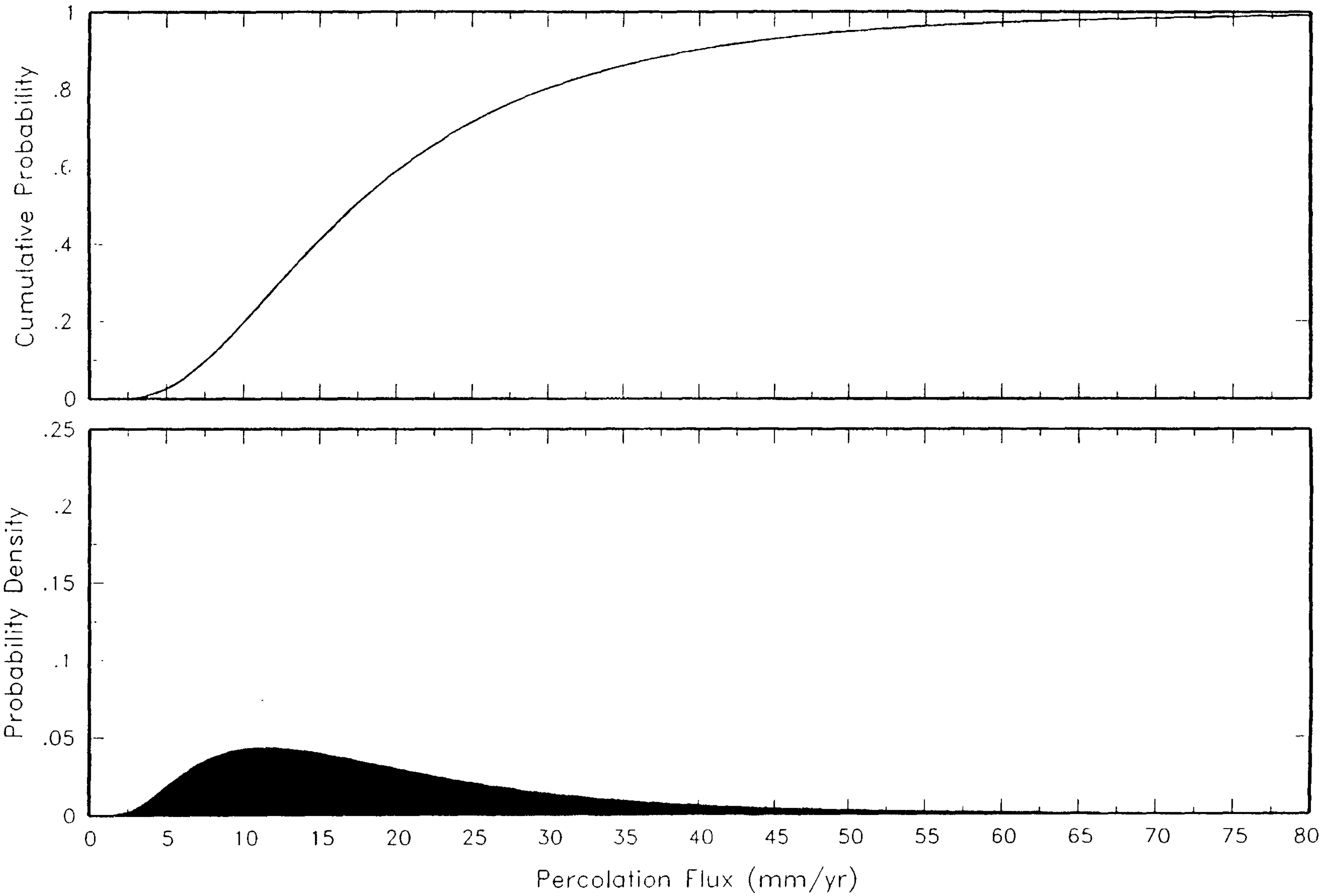

Figure SN-1 Assessed distribution for percolation flux at the repository level developed by Shlomo Neuman. The top plot shows the cumulative distribution function and the bottom plot the corresponding probability density function.

PROSPECTS FOR REFINED ANALYSES

- The above crude ***estimates*** could be ***refined*** by
  - ✓ Creating a ***more complete/reliable data*** base concerning ***PTn matrix*** properties/states;
  - ✓ Using it to estimate ***spatial variability*** of flow within ***PTn*** and to assess related ***uncertainty***.
- ***Existing*** UZ flow ***models***, though more ***detailed***, do ***not necessarily*** provide ***more reliable*** estimates of percolation flux ***at this time***. They
  - ✓ Suffer from same lack of K(S) data for PTn matrix as the above crude calculations;
  - ✓ Incorporate fractures/faults without adequate information about their flow properties and behavior across the site;
  - ✓ Are either driven by surface-based infiltration estimates of unknown reliability or
  - ✓ Show lack of sensitivity when fluxes are estimated by calibration against measured pressure heads and saturations;
  - ✓ Do not quantify uncertainties in model structure (conceptual framework), parameters (material properties), inputs (forcing terms), or outputs (predictions).

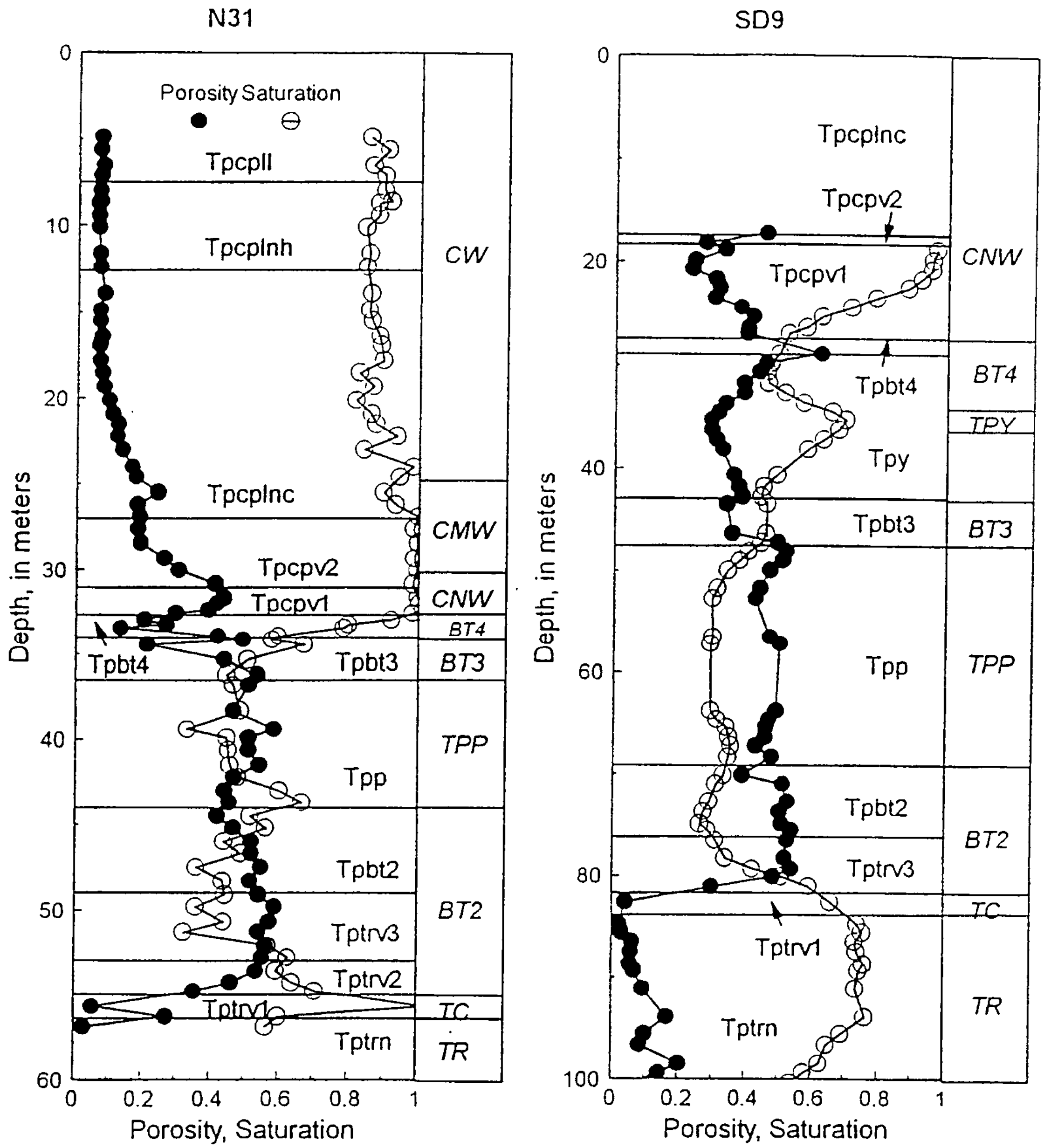

Figure 7. Oven-dry porosity and saturation of rocks from the Paintbrush Group between the lower Tiva Canyon Tuff and upper Topopah Spring Tuff in boreholes N31 and SD9. Lithostratigraphic unit assignment for N31 is from Geslin and others (1995) and SD9 is from Engstrom and Rautman (1996).

Calculations Based on Temperature Data

- ***Percolation fluxes*** were obtained by ***two methods***:
  - ❶ Estimating vertical conductive heat fluxes in UZ and SZ from vertical T° profiles, then setting conductive + convective flux in UZ equal to conductive flux in SZ;
  - ❷ Filtering out heat flux by considering variations along the vertical in UZ.
- A variant of Method 1 additionally considers lateral variations in heat flux and T° in UZ.

☹ ***Method 1*** is ***sensitive to*** errors and uncertainties in ***heat flux***, ***heat conductivity***, and ***1st-order variations in T°***.

☹ ***Method 2*** is ***sensitive to*** errors and uncertainties in ***1st-order variations in heat conductivity*** and ***1st- as well as 2nd-order variations in T°***.

☹ ***In no case have*** such ***errors and uncertainties been quantified*** through a transparent statistical analysis of available data.

Comments on Estimates of Net Infiltration

- Net infiltration ***varies strongly in space-time*** in a manner which is ***very difficult to assess***.
- ☹ ***Existing estimates*** are based in part on ***1-D*** interpretations of neutron-probe data in shallow boreholes at a few sites which ***disregard runoff and lateral subsurface flow***.
  - ☞ ***Lateral subsurface flow*** occurs when runoff from bedrock slopes seeps into alluvium along its margins, then propagates ***along a sloping bedrock-alluvium interface***;
  - ✌ The phenomenon is ***evidenced by bomb-pulse*** ^{36}Cl at the base of the alluvium in borehole UZ-16, without being found in the alluvium;
  - ☞ Shallow lateral subsurface flow may also take place ***along hillslopes in bedrock terrain*** (by virtue of the "thatched-roof" effect);
- ☹ ***Some estimates*** are based on a ***1-D "bucket model"*** whose ***reliability*** is ***open to debate***;
- ☹ ***Some estimates*** are based on ***bedrock permeabilities*** that are ***not measured but calculated*** on the basis of fracture densities and apertures, an approach known to be ***generally unreliable*** (Neuman, 1987);

- ☹ There has been ***no attempt to quantify*** the ***uncertainty*** associated with published YM ***infiltration maps***;
- ☹ The ***premise*** behind these maps that net ***infiltration*** rate is always ***higher along hilltops than along washes*** seems ***counter intuitive***;
- ☹ That net ***infiltration*** rates on these maps have been ***modified upward*** in recent years, ***by more than an order*** of magnitude, ***throws into question*** the methods used to develop ***these maps***.