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Testing the Concept of Drift Shadow at Yucca Mountain, Nevada

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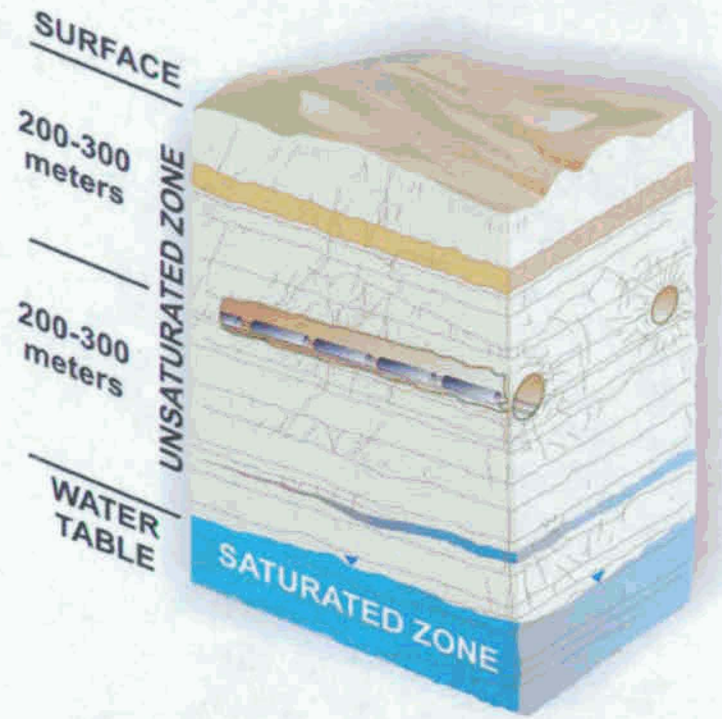
Yucca Mountain Background

- Designated site for long-term isolation of high-level radioactive waste
- Proposed geologic repository located in a >400-m-thick zone of unsaturated volcanic tuffs
- Repository performance relies on multiple barriers
  - Engineered barriers
  - Natural barriers



- Objectives of the OST&I Natural Barriers Thrust Area
  - Evaluate aspects of natural system that lead to enhanced repository performance

Drift Shadow Concept

- Capillary forces may prevent seepage of UZ water into rock openings at Yucca Mountain
  - "Seepage exclusion" occurs at rock/air interface or at fracture junctions within the rock mass
- Should result in uneven distribution of water in the rock mass surrounding openings
  - Zones of increased water saturation & flow rates
  - Zones of decreased water saturation & increased residence times (drift shadow)
- Benefits performance by increasing travel times beneath waste packages

Diffusion dominated

Advection dominated

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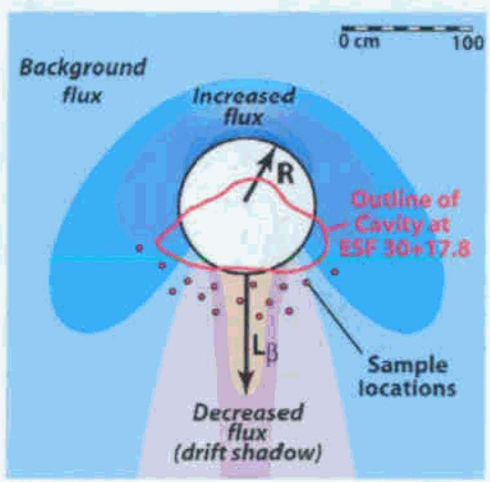
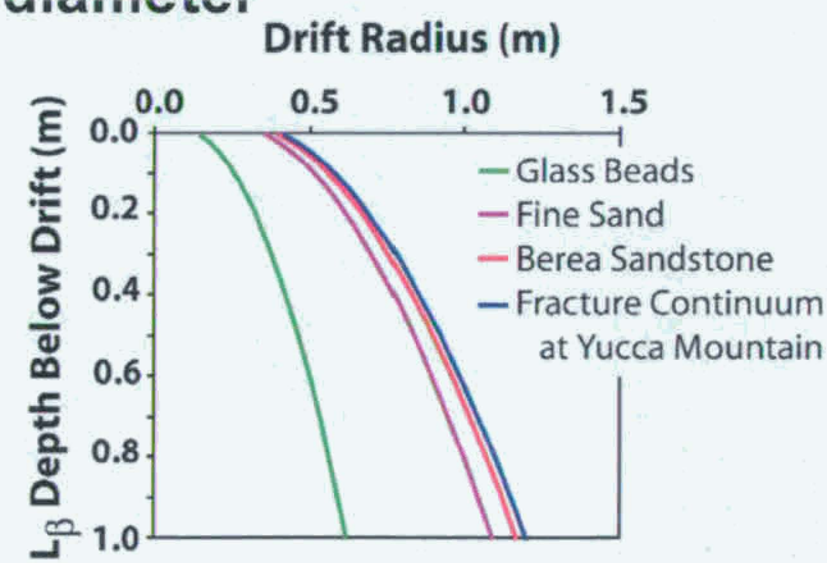
Testing the Drift Shadow Concept

- Multiple OST&I Drift Shadow investigations
  - Laboratory & field experiments require scaling to low-flow conditions at Yucca Mountain
  - Studies of small natural voids require scaling to emplacement drift dimensions
- Use isotopic and chemical variations around natural, meter-scale cavities (lithophysae) in welded tuffs
  - Whole-rock U-series compositions of tunnel-wall samples
  - Pore-water compositions of underground dry-drilled core

Numerical Modeling

- Numerical simulations used to predict drift-shadow scaling
  - Analytical solutions of Philip et al. (1989) used to simulate flow in a fracture-matrix continuum
  - Allows advective-diffusive exchange between flow regimes
  - Assumes no seepage into cavities
- Model results indicate that drift shadows should be present under cavities > ~70 cm in diameter





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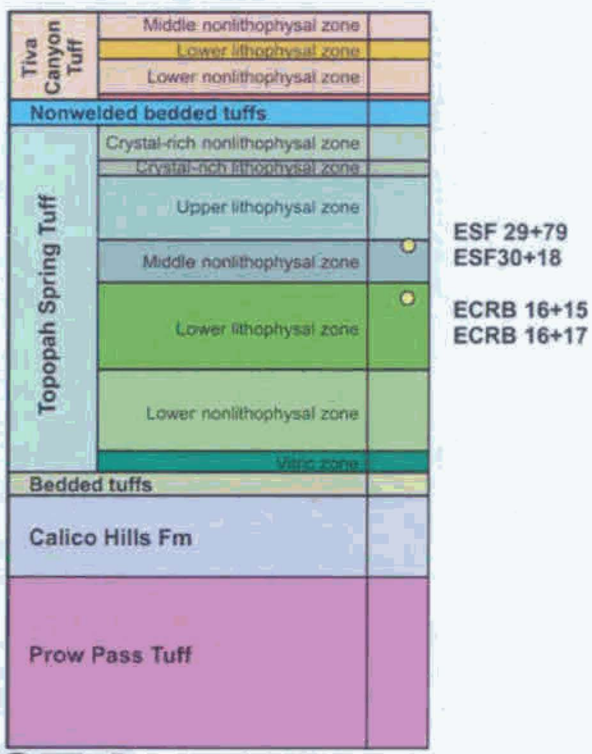
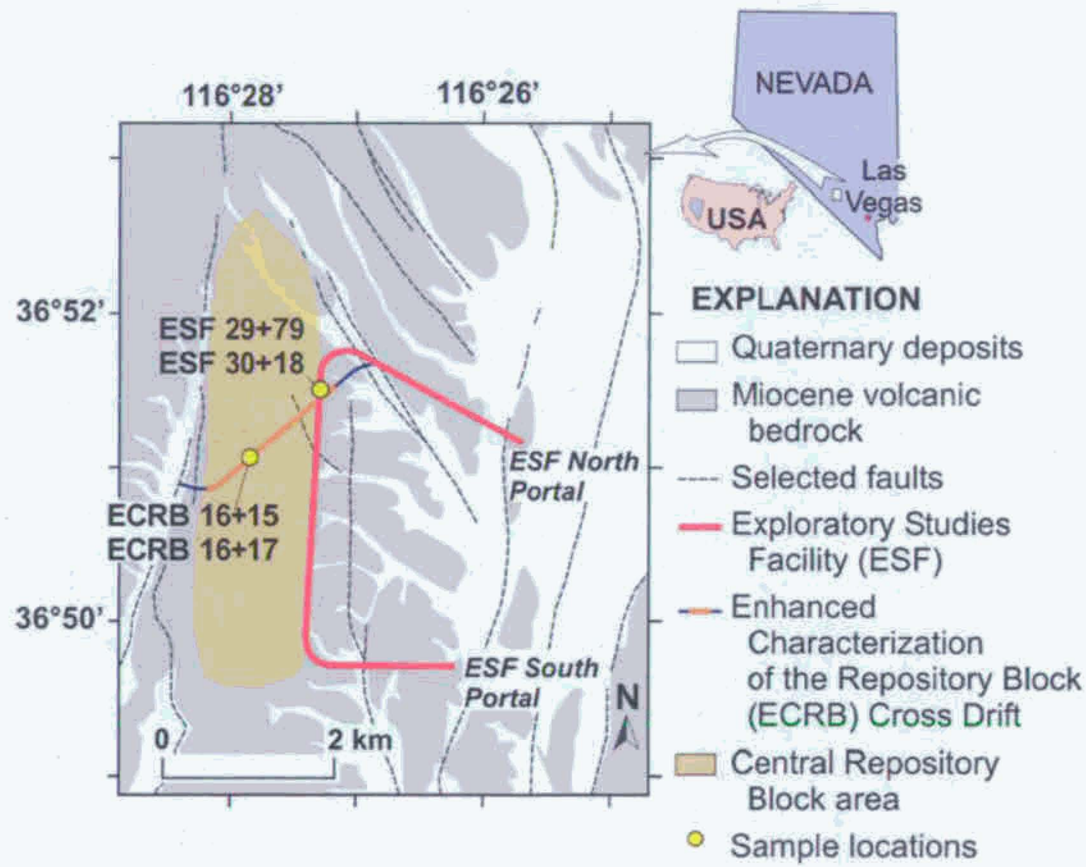
Tunnel-Wall Samples

- Two areas with large cavities sampled from tunnel walls of repository horizon (Topopah Spring Tuff)
  - ESF north bend
  - ECRB Cross Drift





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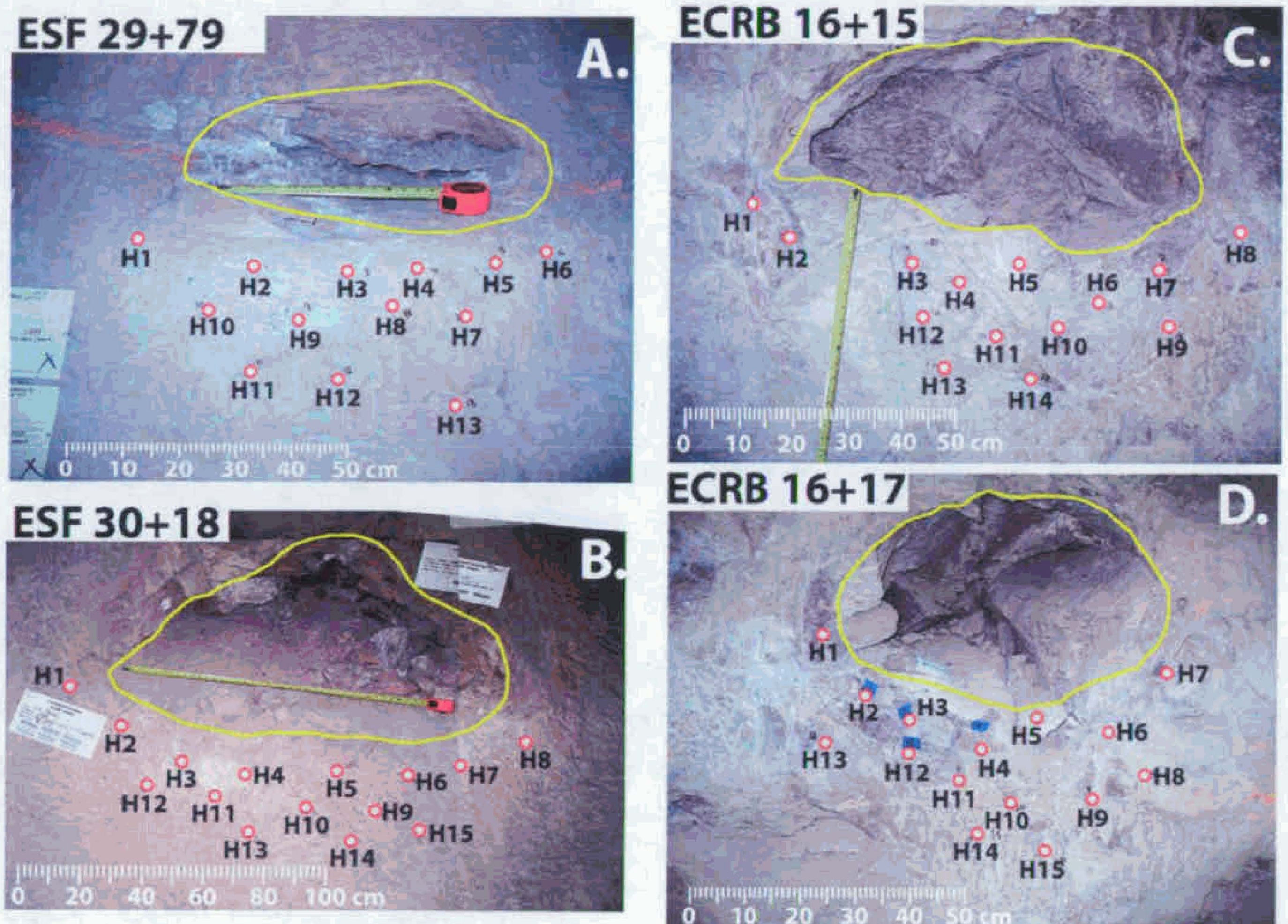
Spatial Distribution of Subsamples

- Subsamples obtained using hand-held rotary hammer



Uranium-Series Isotopes

- U concentrations in host tuffs range from 4 to 5 µg/g
- Chemical behavior of U
  - U in rock is present as insoluble tetravalent U^{+4}
  - In UZ, rock U can oxidize to hexavalent U^{+6}, which is highly soluble as uranyl complexes (UO_2CO_3 and UO_2OH^+)
  - Greater mobility of U relative to many other elements
- Natural radioactivity of U
  - Three isotopes: ^{238}U (99.27%), ^{235}U (0.72%), ^{234}U (~0.006%)
  - ^{234}U and daughter ^{230}Th form by alpha decay from ^{238}U

$$^{238}U \xrightarrow{-\alpha} {}^{234}Th \xrightarrow{-\beta} {}^{234}Pa \xrightarrow{-\beta} {}^{234}U \xrightarrow{-\alpha} {}^{230}Th$$

^{238}U	^{234}Th	^{234}Pa	^{234}U	^{230}Th
4.5E9y	24.1d	6.69h	2.45E5y	7.5E4y

  - In rocks closed to transfer of mass, $^{234}U/^{238}U$ activity ratios (AR) are equal to 1.0 (secular equilibrium)

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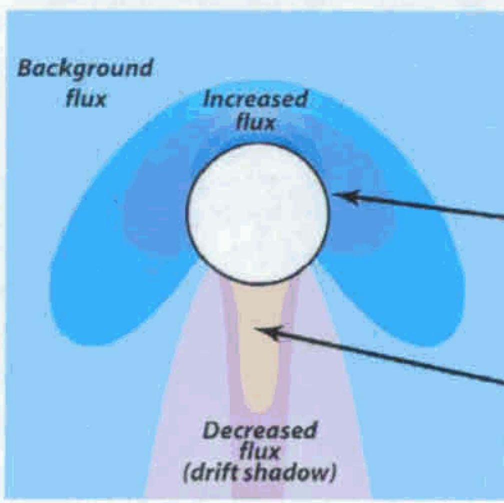
Effects of Water-Rock Interaction on U

- U is leached from rock mass over time leaving lower concentrations relative to other elements
- Alpha-recoil effects allow preferential leaching of ^{234}U relative to ^{238}U
  - $^{234}U/^{238}U$ activity ratios (AR) > 1.0 in water and < 1.0 in rock
- Degree of U and ^{234}U loss depends on water-to-rock mass ratio in rocks with uniform properties



$^{234}U/^{238}U$ AR results expected in rocks around individual cavities

Larger water-to-rock mass ratios; greater ^{234}U depletion, lower $^{234}U/^{238}U$ AR

Smaller water-to-rock mass ratios; less ^{234}U depletion, higher $^{234}U/^{238}U$ AR

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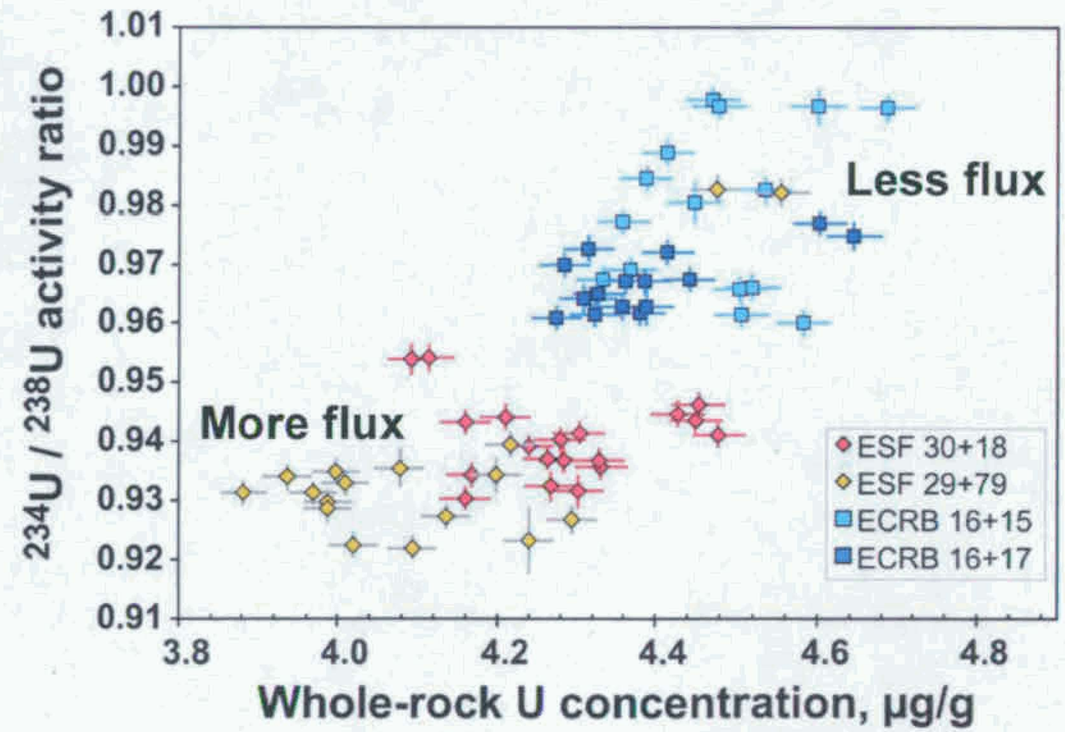
General Whole-Rock U Characteristics

- Rock has different U characteristics in different areas
  - Higher U and $^{234}U/^{238}U$ AR in ECRB Cross Drift samples
  - Lower U and $^{234}U/^{238}U$ AR in ESF samples

- Differences in both U concentration and $^{234}U/^{238}U$ AR are consistent with different water fluxes in different areas



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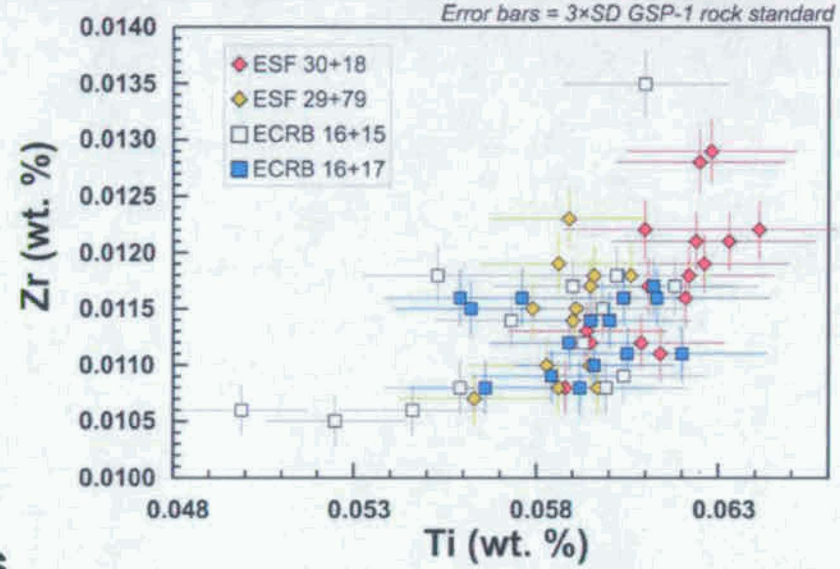
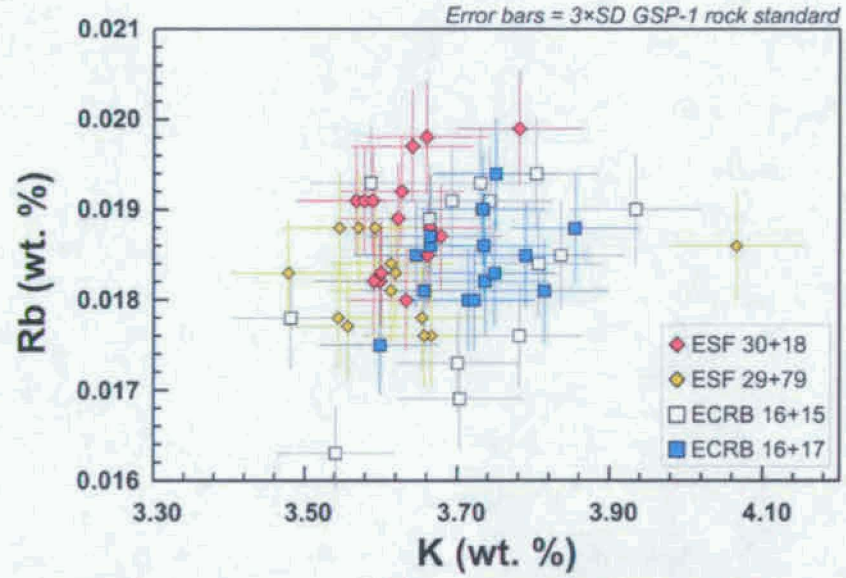
Whole-Rock Chemical Compositions

- Could U variations reflect differences in primary magmatic compositions?
- Same samples analyzed for major & trace elements by XRF
  - Concentrations overlap in both ECRB and ESF samples
- No significant primary compositional differences
- Observed U variations are caused by secondary processes





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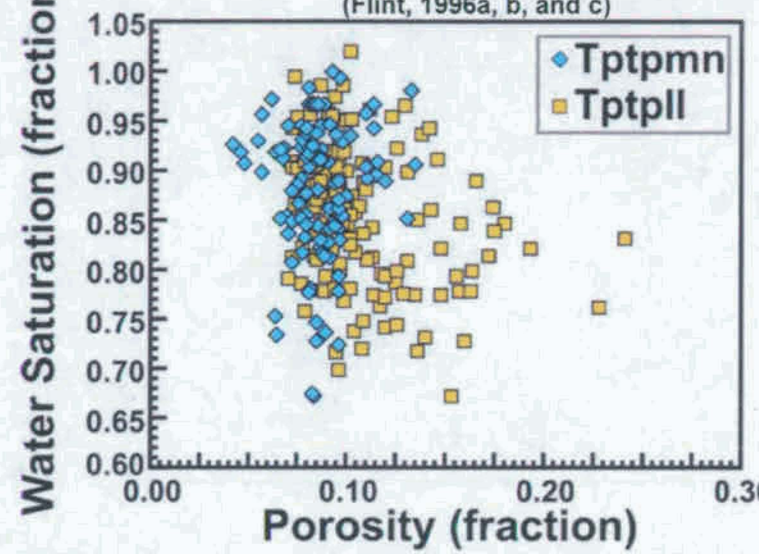
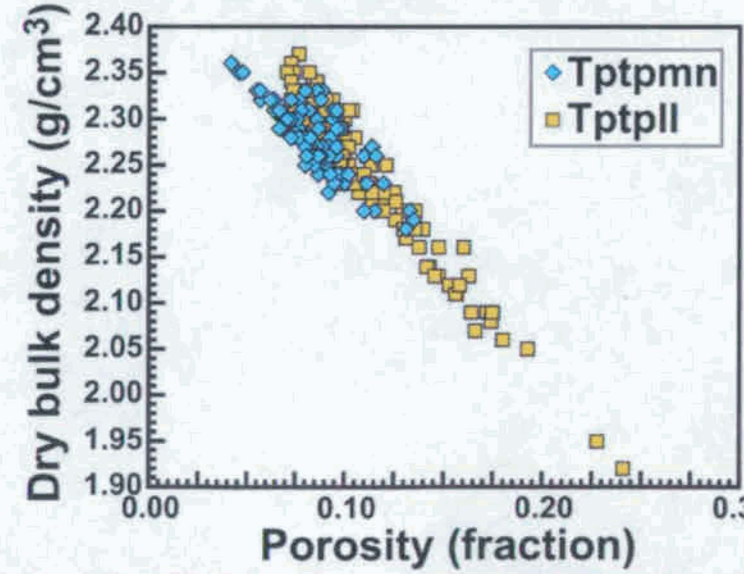
Differences in Physical Properties

- U leaching and ^{234}U loss by recoil processes depend on available surface area
- Physical properties measured from Tptpmn and Tptpll units in core from nearby boreholes
  - Relative water saturation
  - Dry bulk density
  - Porosity
- Substantial overlap in most properties
- Differences in porosity cannot explain U characteristics

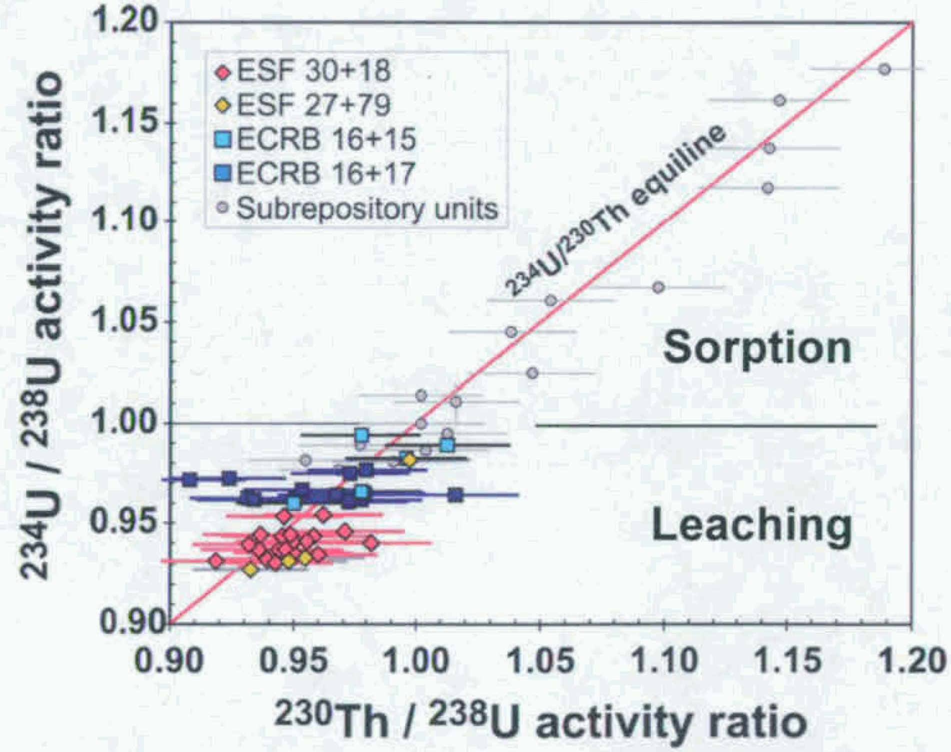
Data from USW SD-7, USW SD-9, and USW SD-12 (Flint, 1996a, b, and c)





Whole-Rock $^{230}Th/^{234}U$ Relations

- $^{234}U/^{238}U$ and $^{230}Th/^{238}U$ AR are similar: $^{234}U/^{230}Th$ AR ≈ 1.0
- Data indicate leach rates were slow enough to maintain radioactive equilibrium between ^{234}U and daughter ^{230}Th
  - Consistent with steady-state leach models and ^{238}U leach constants of $1\text{-}5\times10^{-8}\ yr^{-1}$
  - Similar value obtained from U concentrations
- Data imply both leaching and sorption processes are limited by similar rates of mass exchange



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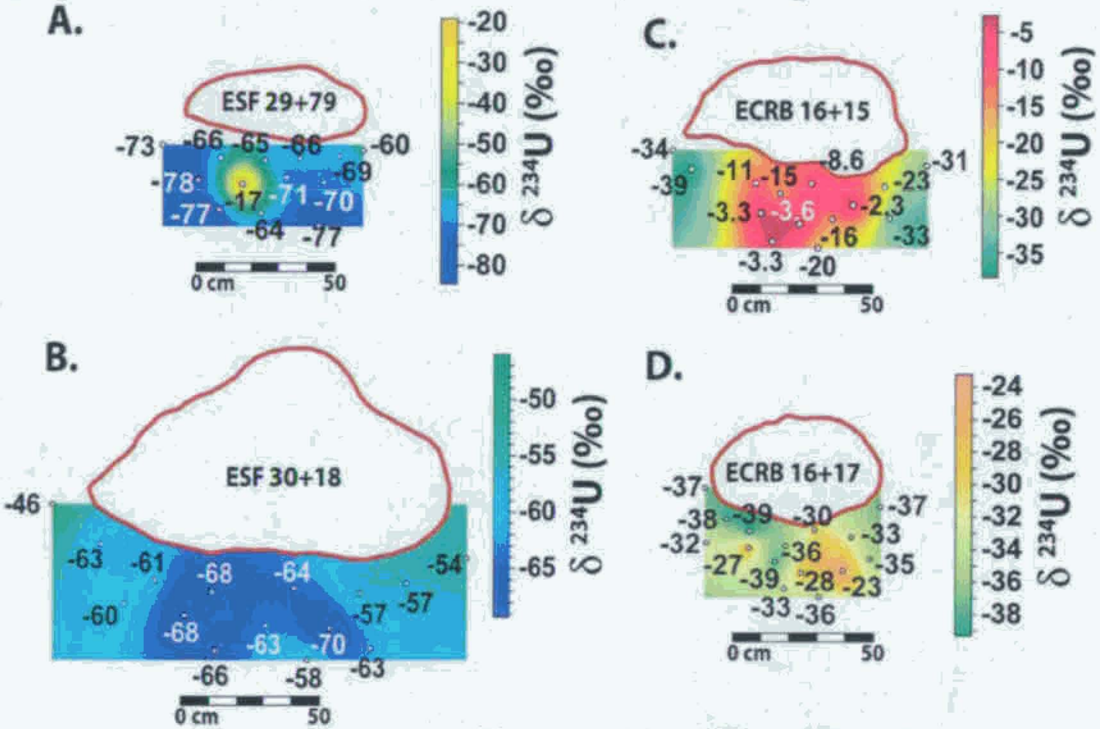
Distribution of $^{234}U/^{238}U$ in Tunnel-Wall Samples

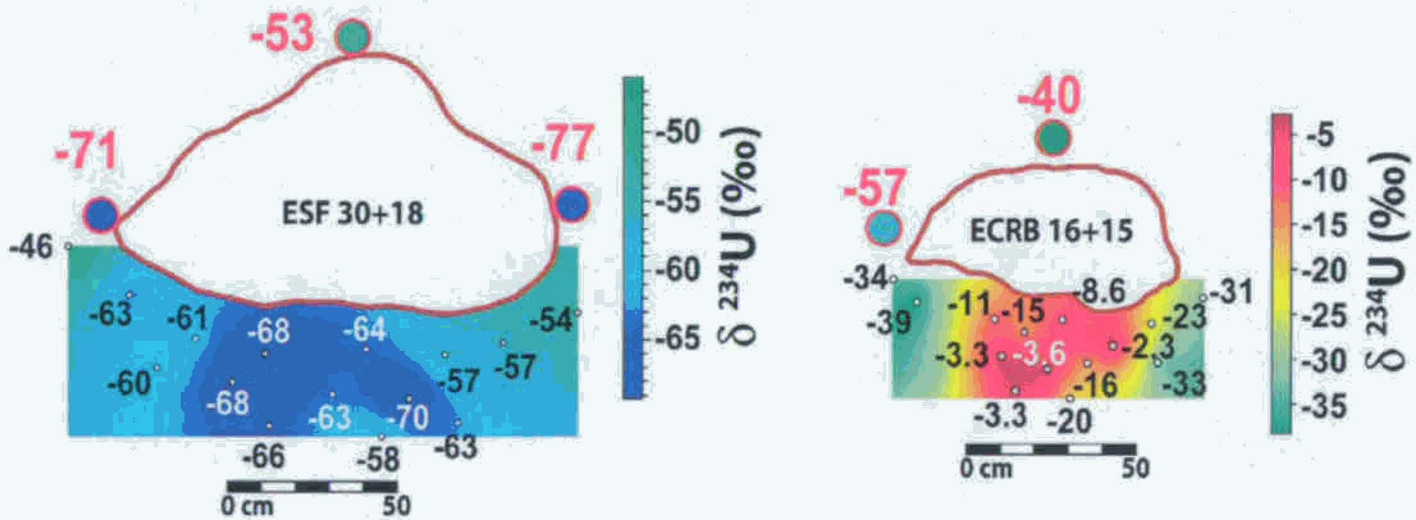
- All whole-rock samples have $^{234}U/^{238}U$ AR < 1.0
  - Indicates ubiquitous flow and preferential ^{234}U removal
  - $\delta^{234}U$ notation used to emphasize small variations
- Patterns of ^{234}U distribution beneath cavities vary
  - Decreased flow (drift shadow)
  - Increased flow
  - No systematic effect beneath smallest cavities (consistent with numerical model)



$\delta^{234}U = (^{234}U/^{238}U\ AR-1)\times1000$

$^{234}U/^{238}U$ in Walls & Ceilings

- Cavity walls and ceilings analyzed to evaluate leaching effects in areas of greater flow
  - Greatest ^{234}U depletion from cavity walls
  - Intermediate ^{234}U depletion from cavity ceilings
- Data support concept that more water flows through rock on sides of cavities



Analytical error = ±3‰

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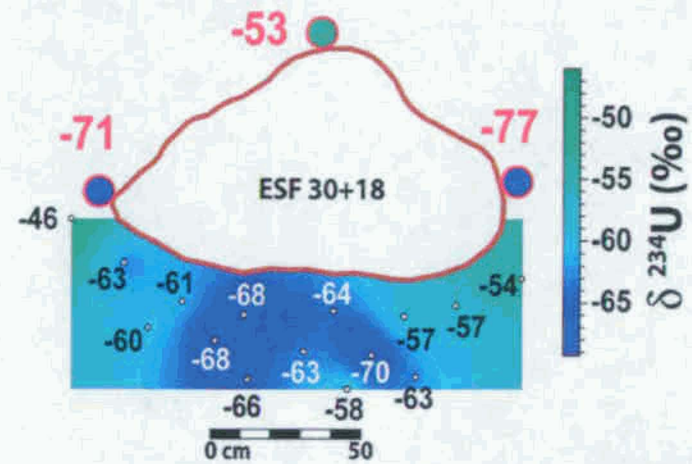
Differences in ^{234}U Depletion

- Greater long-term water fluxes around ESF 29+79 and ESF 30+18 relative to ECRB 16+15 and 16+17 based on:
  - Greater U loss and ^{234}U depletion in whole-rock samples
  - Thicker secondary mineral coatings on cavity floors
- Greater ^{234}U depletion beneath ESF 30+18 related to seepage
  - Thick calcite-silica coating reflects long-term seepage accumulation
  - Data imply that drift shadows are not likely where seepage is common
- Drift shadow effects are more prevalent in ECRB cavities with only minor mineral coatings

3- to 4-cm-thick mineral coating on floor of ESF 30+18



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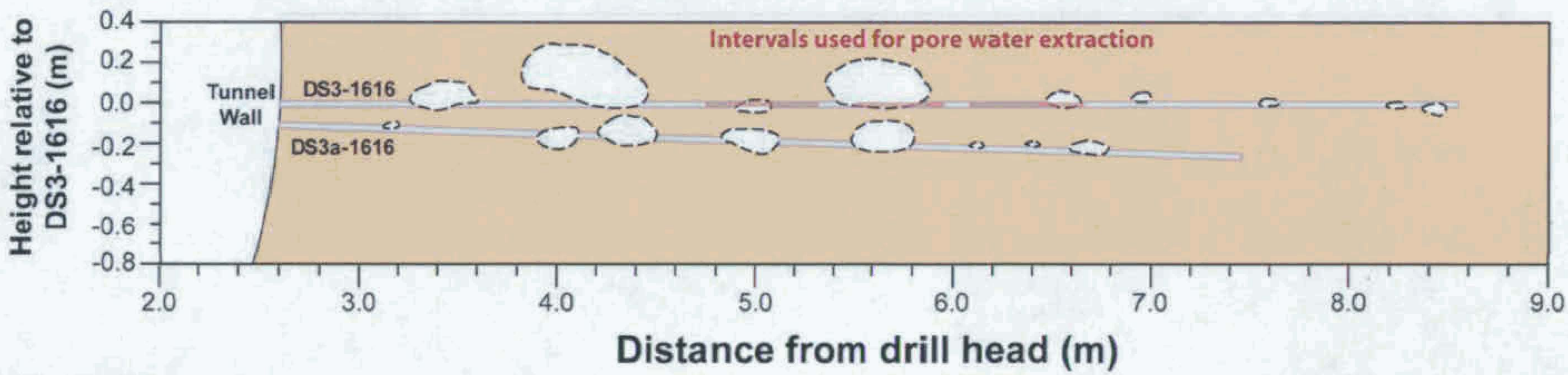
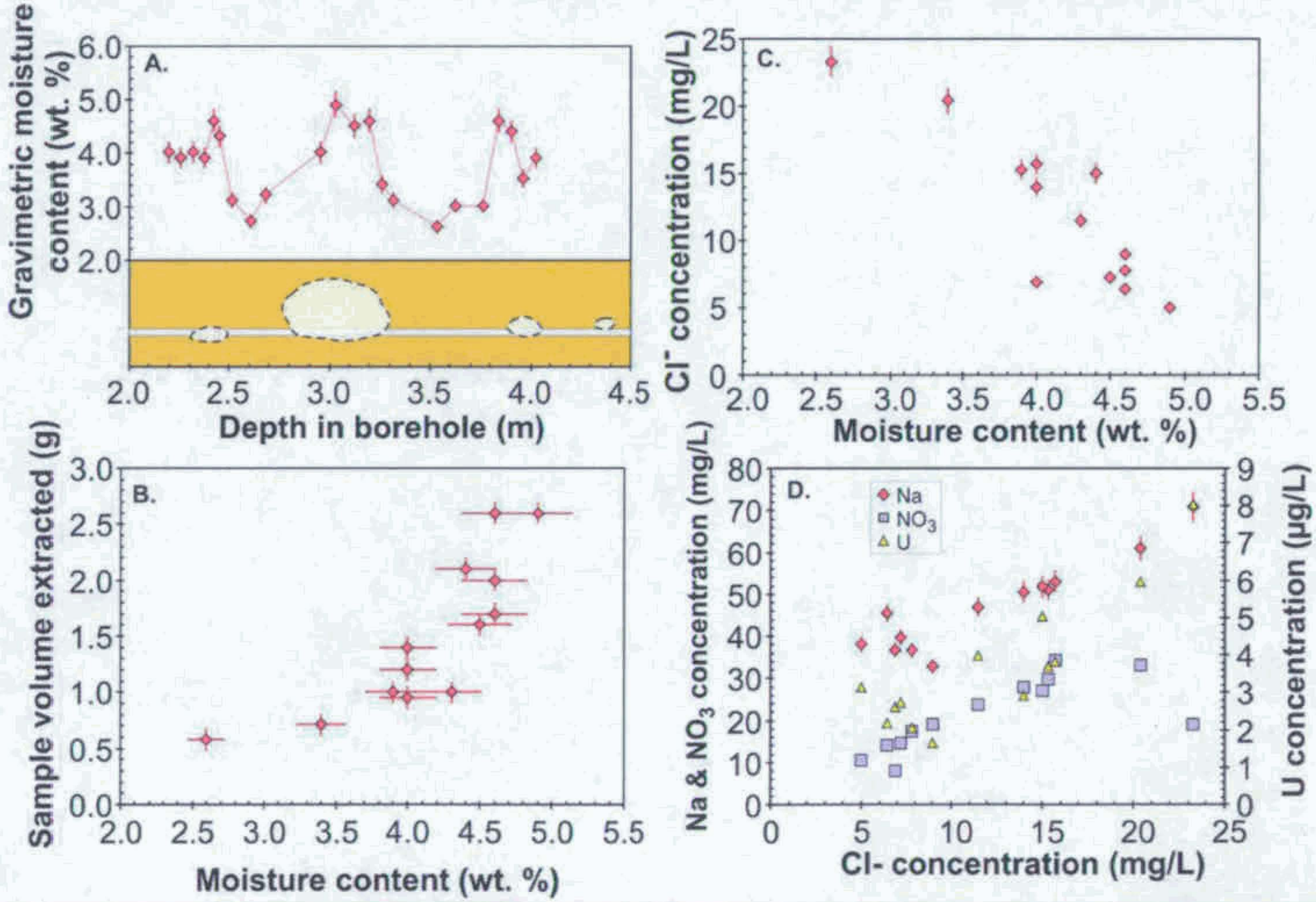
Pore-Water Samples

- New 6-m-long boreholes drilled between ECRB stations 16+10 and 16+18 (lower lithophysal zone)
- Core beyond 2-m-deep dry-out zone was preserved for pore-water extraction by ultra-centrifugation
- Lithophysal cavities located by downhole video logging
- Drift shadows should have lower moisture contents and higher pore-water solute contents than adjacent rock



Moisture Content & Pore-Water Chemistry

- Preliminary results from a single 2-m-long core section
  - 22 moisture measurements, 13 pore-water extractions



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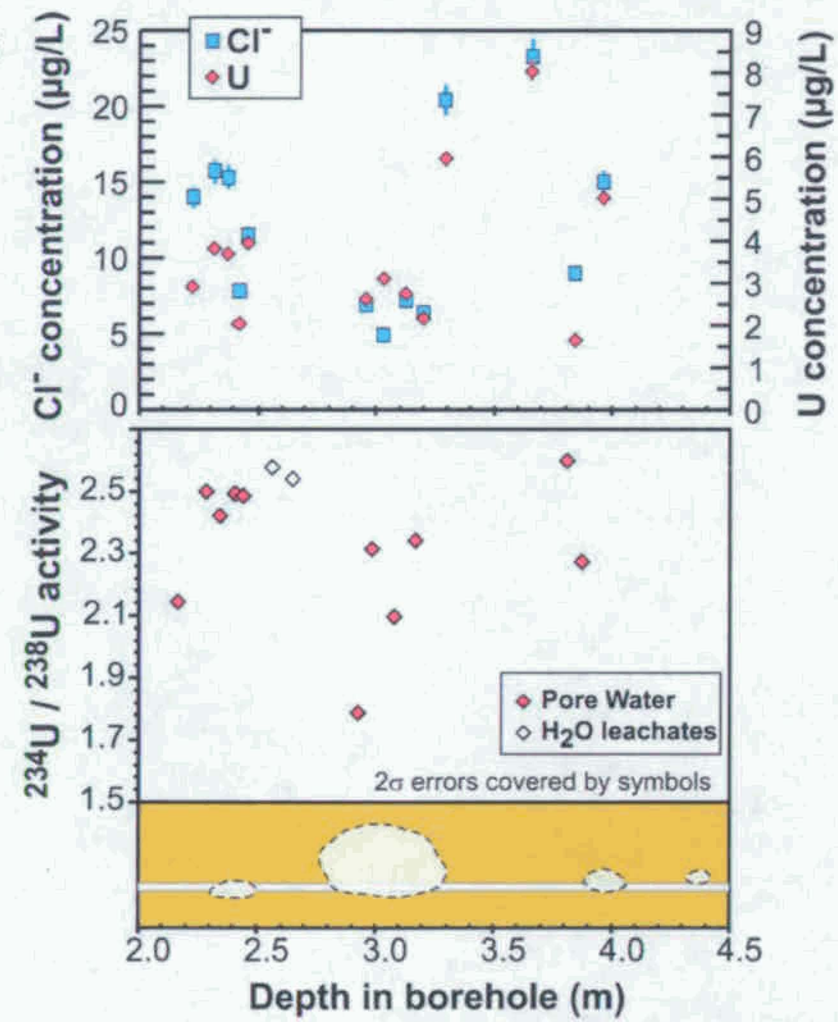
Pore-Water Profiles

- Solute concentrations correlate with moisture contents
  - Lowest solute concentrations in cavity-floor samples
  - Evaporative concentration in fragmented core (dry-drilled)
- $^{234}U/^{238}U$ AR results
  - Unaffected by drilling air
  - Lower values than in most other pore-water samples
  - Variations similar to Cl; consistent with higher water/rock mass ratios beneath cavity



Conclusions

- Numerical simulations predict small drift shadows beneath meter-scale lithophysal cavities
- Whole-rock U-series data document areas of greater and lesser UZ water flow through densely welded tuffs
  - Consistent with low rates of long-term, steady-state U loss
- Tunnel-wall samples show evidence for
  - Diversion of flow around natural cavities (drift shadow)
  - Flow focusing beneath cavities where seepage is common
- Drift shadows are likely to develop beneath cavities with low seepage fluxes
- Preliminary pore-water data show systematic differences around a lithophysal cavity
  - Moisture contents, chemistry, and $^{234}U/^{238}U$ AR values

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