Review of Unsaturated Zone Studies in Arid Sites and Implications for Contaminant Transport

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Review of Arid Zone Studies

Location	Authors	Ann. pptn. (mm)	Method	Water flux (mm/yr)	Notes
S. Australia	Allison et al., 1985	~ 300	chloride	0.1 to > 100	karst and dunes
S. Australia	Cook et al., 1994	260	chloride chlorine-36	0.1 0.9	native veg., sands
S. Australia	Cook et al., 1994	340	chloride chlorine-36 tritium	3.8 - 28 2 - 11 8 - 17	veg. cleared, sands
Saudi Arabia	Dincer, 1974	80	tritium	23	Dahna sand dune
N. Senegal	Aranyossy & Gaye, 1992	395	tritium	22 - 26	sand dune
Sudan, Africa	Edmunds et al., 1988	225	chloride	0.25 - 1.28	interfluve sandy clay
Cyprus	Edmunds et al., 1988	406	chloride tritium	10 - 94 22 - 75	sands
Israel	Nativ et al., 1995	200	tritium bromide	16 -66 30 - 110	fractured chalk
Texas, USA	Scanlon, 1991	280	chloride chlorine-36 tritium	0.01 - 0.7 1.4 7	silt loam ephemeral stream
New Mexico, USA	Phillips et al., 1988	200	chloride chlorine-36 tritium	1.5 - 2.5 2.5 - 3 6.4 - 9.5	sandy loam to sand
New Mexico, USA	Stephens and Knowlton, 1986	200	soil physics (unit gradient)	7 - 37	sand loam to sand
New Mexico, USA	Stone, 1984	385	chloride	0.8 4.4 ≥12.2	cover sand sand hills playas
Beatty, Nevada, USA	Prudic, 1994		chloride	2 (> 10 m depth)	
Nevada Test Site, USA	Sully et al., 1995	125	liquid flux vapor flux net flux	0.03 0.02 ~ 0	soil physics depth 75 - 180 m
Yucca Wash, USA	Norris et al., 1993	170	chlorine-36	1.8	
Ward Valley, California, USA	Prudic, 1994	117	chloride	0.03 - 0.05 (> 10 m depth)	alluvial fan

TERMINOLOGY

Infiltration: water movement from the surface into the subsurface (can be vertical or lateral.)

Percolation: deep penetration of water below the shallow subsurface.

Recharge: addition of water to the underlying aquifer.

Flux: direction not specified.

Basic Issues

Groundwater resource evaluation
Waste disposal/contaminant transport

Controls on subsurface flow: texture, vegetation, topography, preferred pathways, climate, paleoclimate

Direction of water movement: up down laterally

Rate of water movement: variable

Spatial variability: focused recharge beneath washes and playas, preferential flow

Temporal variability: seasonal annual paleorecharge

Mechanism of water movement: piston flow, preferential flow

Techniques to evaluate subsurface flow: soil physics, environmental tracers

Controls on Subsurface Water Movement

- soil texture
- vegetation
- topography
- preferred pathways
- climate and paleoclimate

Controls on Subsurface Water Movement

Soil Texture: Negative correlation between water flux and clay content in surficial sediments.
Water fluxes higher in coarse grained soils, e.g. sand dunes.

Vegetation: Water fluxes higher in bare soil than in vegetated soil.
Clearing of mallee vegetation in Australia resulted in increased water flux from 0.1 to 0.6 mm/yr to 4 to 28 mm/yr.
Different types of vegetation not equally effective in transpiring water.
Plant roots may act as preferred pathways.
Vegetation concentrates in areas of high subsurface water flux (fissured sediments and washes).

Topography: high water flux occurs in topographically low areas where water frequently ponds, i.e. washes, playas, sinkholes, and in fissured sediments.

Controls on Subsurface Water Movement

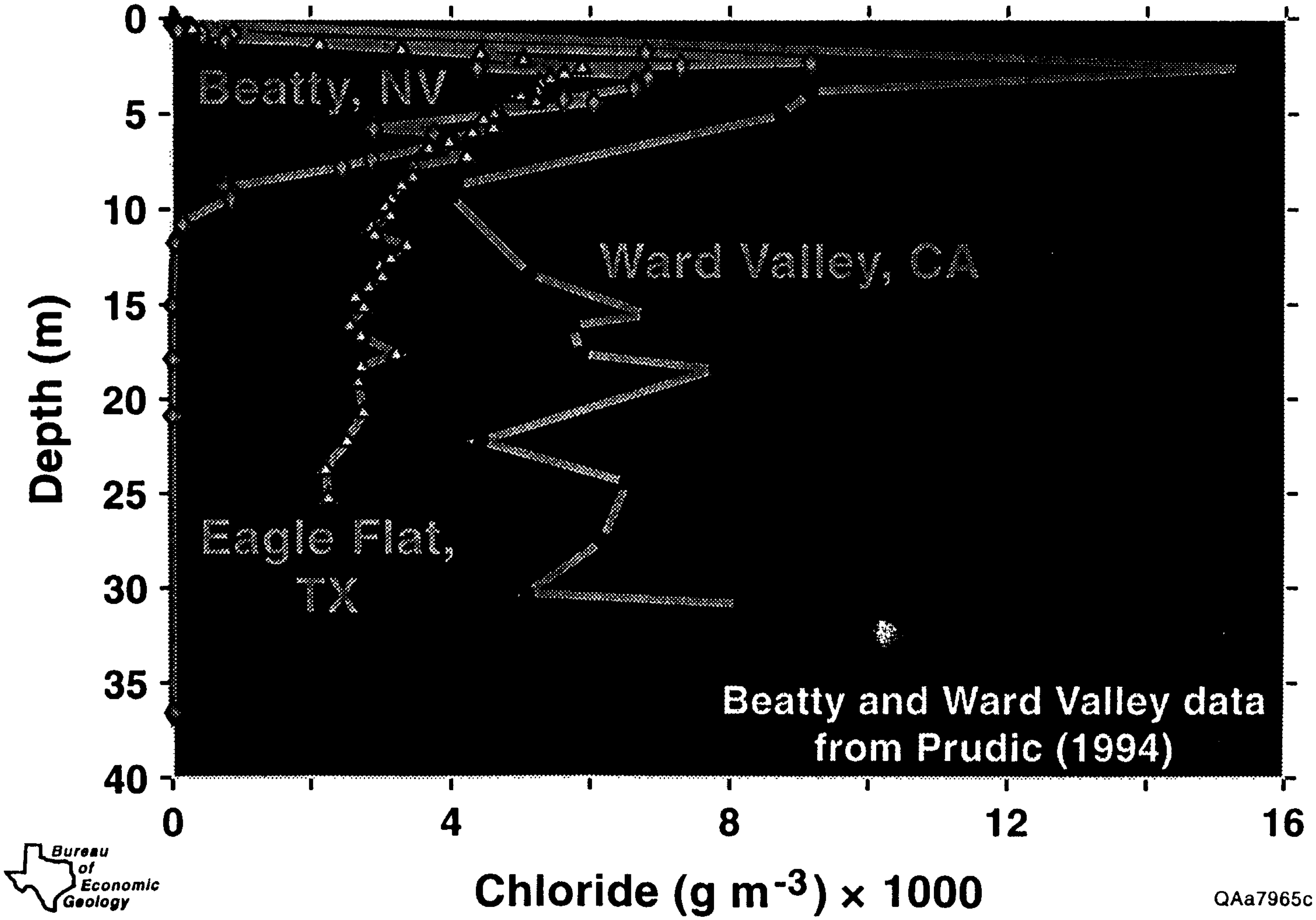
Climate:
Seasonal variation: winter precipitation much more effective in percolating through the soil because ET much lower in winter.

Interannual variation: large variations in subsurface flow related to interannual variability in rainfall.

Paleoclimate: Australia and Southwestern U.S. higher rates of subsurface flow in Pleistocene.

Preferred Pathways:
Fractures, dessication cracks, root tubules

CHLORIDE PROFILES FROM CALIFORNIA, NEVADA, AND TEXAS



Beatty and Ward Valley data from Prudic (1994)

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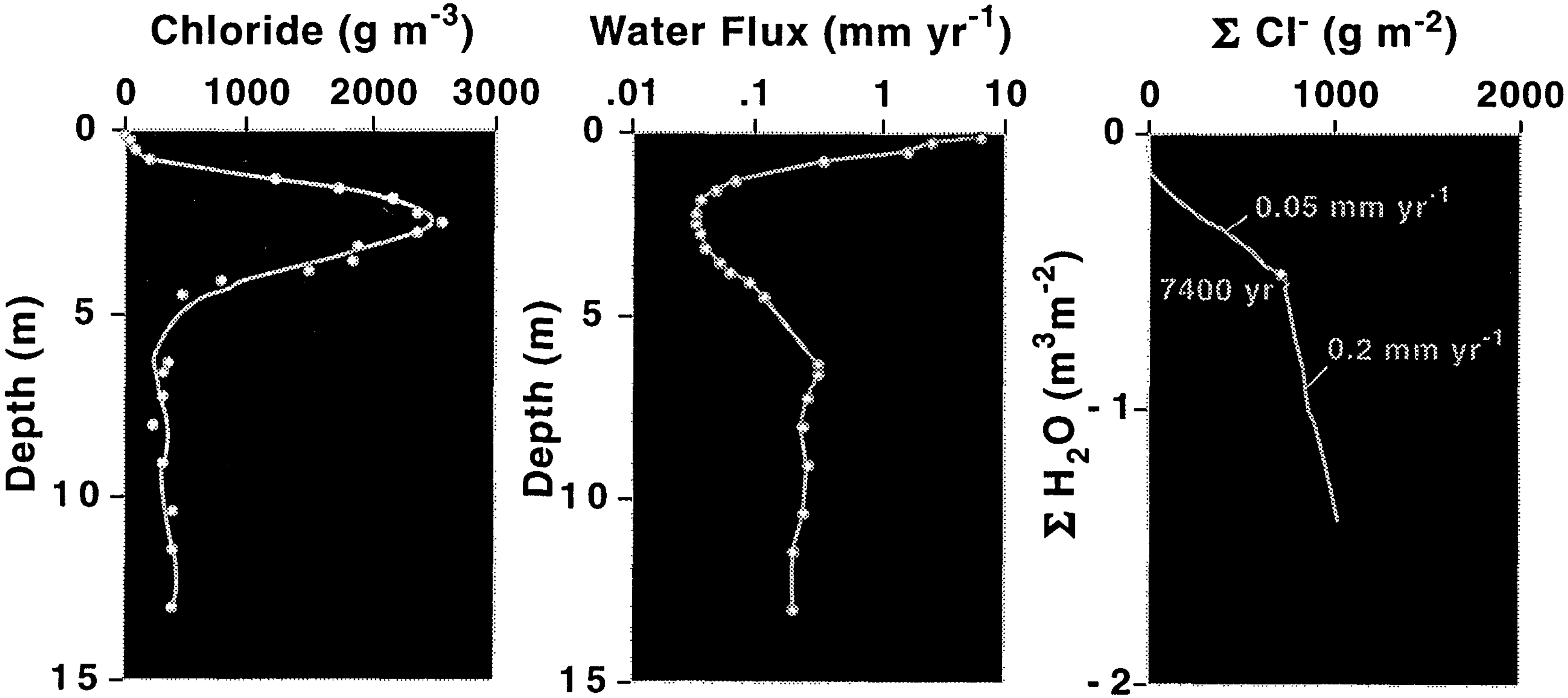

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Why is it difficult to evaluate the direction of water movement?

- Fluxes low in natural setting.
- Techniques for measuring flux have large uncertainties.
- Variety of driving forces: water potential, temperature, and osmotic potential.
- Flux direction may be spatially and temporally variable.

Driving Forces for Water Movement

Water flux: $q = q_L + q_v$

Liquid flux: $q_L = -K\nabla H$

Vapor flux: $q_v = q_{iv} + q_{Tv}$

$= -D_{\psi v}\nabla\psi - D_{Tv}\nabla T$

Isothermal System

Matric potential gradient positive ... upward water flux

negative ... downward water flux

Anisothermal System

seasonal T fluctuations .... downward thermal vapor flux

geothermal gradient .... upward thermal vapor flux

Net flux depends on balance between driving forces.

Flow Mechanisms

Piston flow: uniform movement of water through the soil matrix

- Las Cruces Trench Experiments, New Mexico

- Chloride profiles, S. Australia after vegetation clearing

- Chlorine-36 profiles single peak

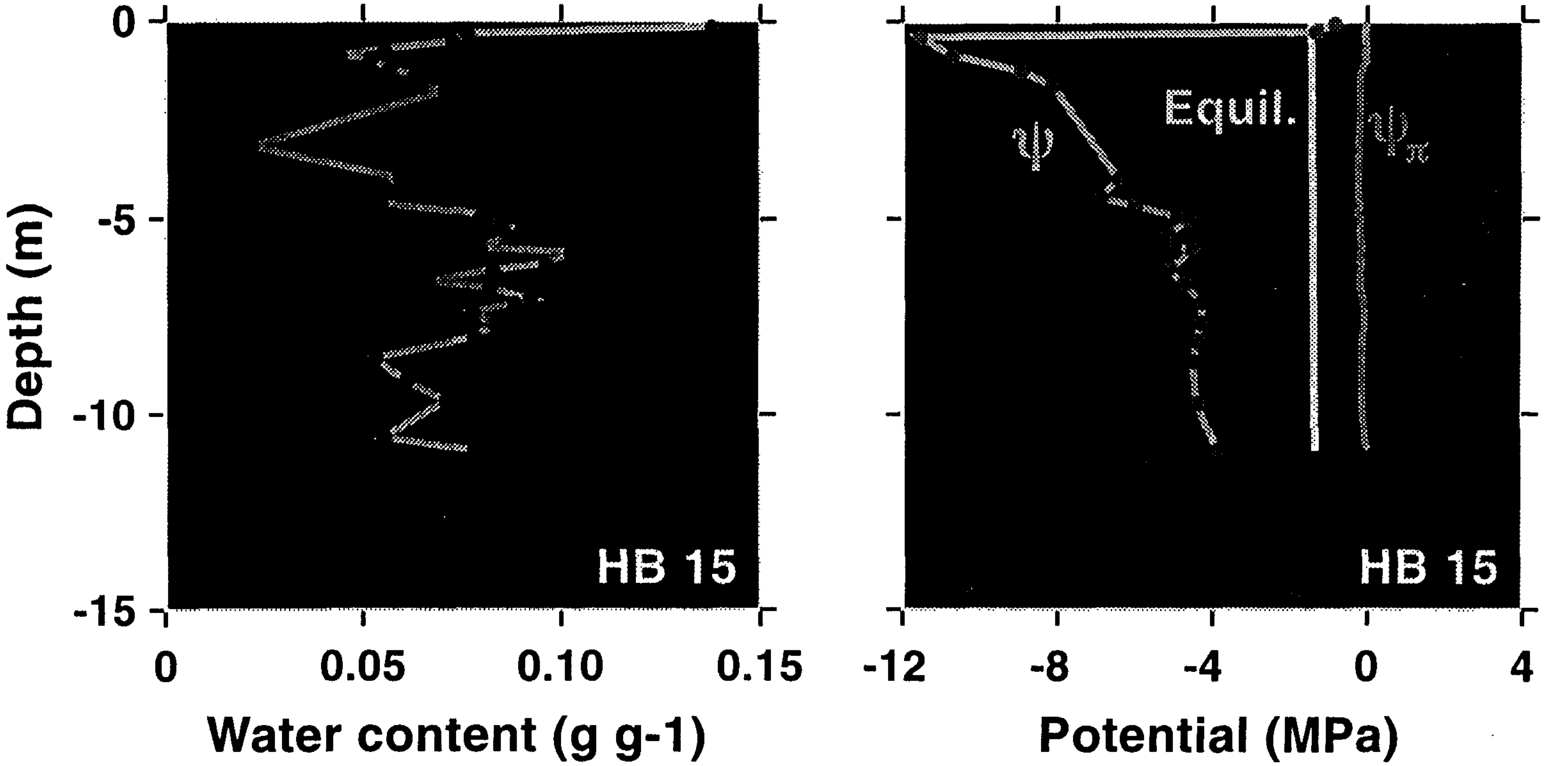
Preferential flow: water and solutes move along preferred pathways

macropore flow   unstable flow   funneled flow

Bomb pulse tracers at much greater depth than expected (Fabryka-Martin et al., 1992, Yucca Mtn; Nativ et al., 1994, Israel; Scanlon, 1992, Texas).

Liquid vs. vapor flow: important for nonvolatile and volatile (^{3}H, ^{14}C, radon) contaminant movement.

WATER CONTENT AND POTENTIAL PROFILES



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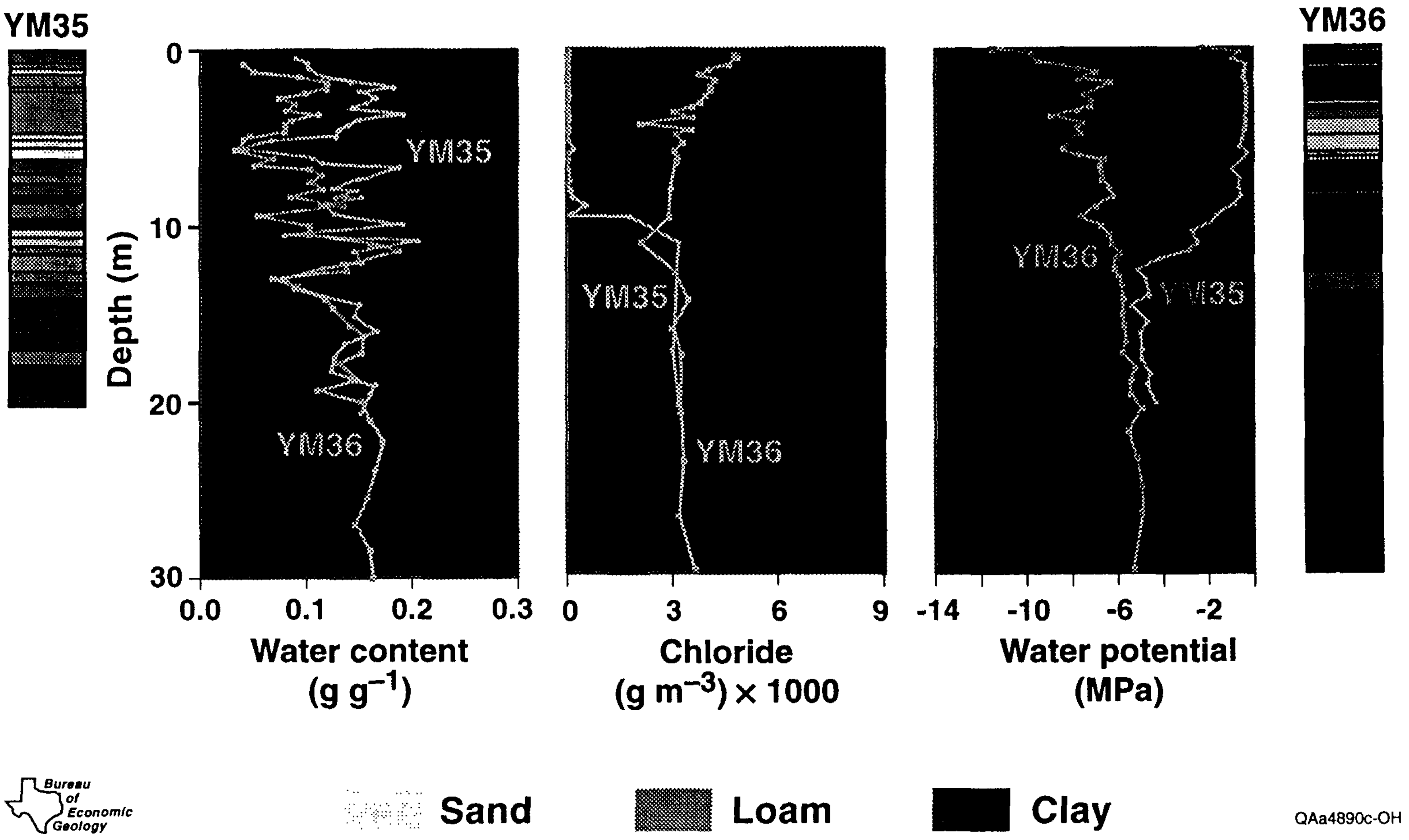

YM35
YM36
Depth (m)
0
10
20
30
0.0
0.1
0.2
0.3
Water content (g g⁻¹)
0
3
6
9
Chloride (g m⁻³) × 1000
-14
-10
-6
-2
Water potential (MPa)
YM35
YM36
YM35
YM36
YM36
YM35
Sand
Loam
Clay
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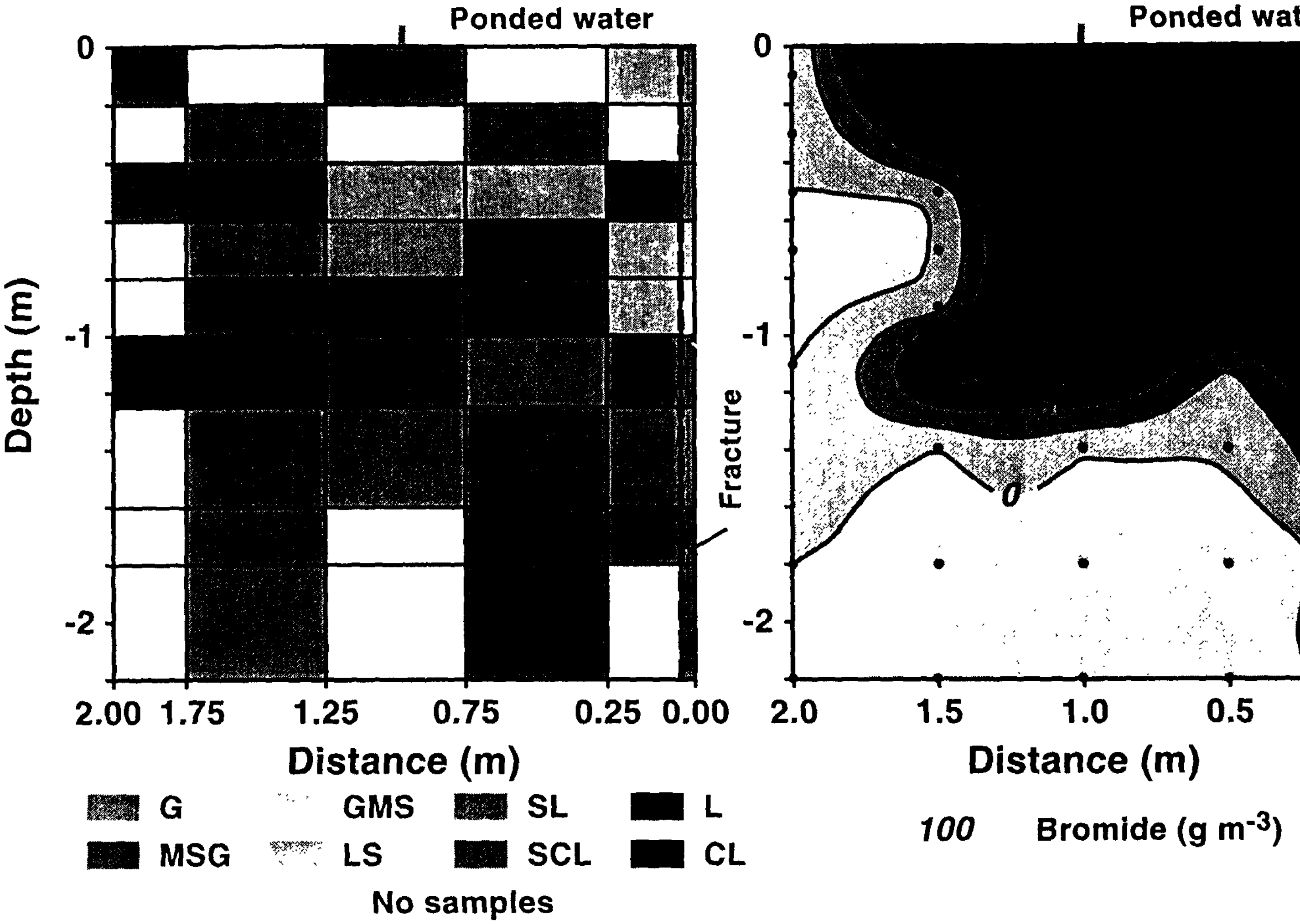

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Conclusions (Basic Issues)

Controls on subsurface flow: texture, vegetation, topography, preferred pathways, climate, paleoclimate

Direction of water movement: up down laterally

Rate of water movement: quite variable

Spatial variability: focused recharge beneath washes and playas, preferential flow.

Temporal variability: seasonal annual paleorecharge

Conclusions (Basic Issues) (ctd.)

Mechanism of water movement:
Flow in sediments quite different from fractured rock.
Piston flow is the norm in interfluvial sediments not subjected to ponded conditions.
Preferential flow predominantly in fractured rock.

Techniques to evaluate subsurface flow:
soil physics... current processes
environmental tracers ... long term net water flux

Numerical modeling / performance assessment:
Need to consider spatial and temporal variability in water flux.

Flow processes can be quite complicated; therefore, need multiple independent lines of evidence.

Preferential Flow Issues

- Relative importance of piston vs. preferential flow for different types of contaminants.
- Continuity of preferred pathways.
- Local input conditions.
- Interaction between preferred pathway and surrounding matrix.
- Techniques for quantifying flow contribution from preferred pathways and from matrix.
- Differences between sediments and fractured rock.
- Information required for modeling these systems.

Methods of Quantifying Subsurface Flow

Soil Physics

Water content

Water potential

Temperature

Hydraulic conductivity

Water retention functions

Chemistry

Meteoric chloride

Bomb tritium

Chlorine-36

Stable isotopes of O and H

METHODS

Meteoric Chloride

Subsurface water flux: $q_w = \frac{D_{Cl}}{C_{Cl}}$ **Residence time:** $t = \frac{\int_0^z \theta C_{Cl} dz}{D_{Cl}}$

Assumptions:

- **1 dimensional, vertical, downward, piston flow.**
- **Rainfall and dry fallout only sources of chloride.**
- **Chloride deposition constant with time.**
- **Steady-state subsurface flow.**

Questions:

Is water flow downward? water potential data in sw U.S. indicates net upward flow in top 10 to 15 m.

Is subsurface flow steady? profiles in Australia and sw U.S. suggest higher recharge during Pleistocene.
Profiles in Australia transient in response to clearing of vegetation.

What is the contribution of dry fallout to Cl deposition rate? estimates of Cl deposition rate from prebomb ^{36}Cl/Cl ratios indicates not large variability in Cl deposition rate. (half-life 301 000 ± 4000 yr)

METHODS

Chlorine-36 (half-life 301 000 ± 4000 yr) liquid flow

- Bomb pulse chlorine-36: 3 orders of magnitude > background.
- Temporal variations in cosmogenic production of chlorine-36: only 2 x > background.
- Radioactive decay of cosmogenic chlorine-36

Advantages:
Sampling and analysis procedure straightforward.
Natural arid systems generally characterized by high Cl.

Limitations:
Bomb pulse within root zone at many sites.
In zones of high flux, Cl conc. may be too low.
Signature associated with variations in cosmogenic production in ^{36}Cl may not be preserved because of diffusion.
Temporal variations in cosmogenic production of ^{36}Cl will increase uncertainties associated with radioactive decay based ages.

METHODS

Tritium (half life 12.45 yr), liquid and vapor flow

Signature ≥ 2 orders of magnitude above bkgrd.

Limitations:

Bomb pulse within the root zone.

Natural arid systems have low water contents; difficult to collect water for tritium analysis.

Samples can be contaminated during collection.

Short half life.

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Methods of Evaluating Preferential Flow

Low probability of intersecting vertical preferred pathways with vertical boreholes. Tunnel should be much more effective.

Soil systems: shallow subsurface, visual observations with organic dyes, sampling tile drains and shallow groundwater.

Soil physics monitoring: provide information on current processes.
Monitor water content, water potential, pneumatic pressure.

Environmental tracers:
bomb pulse chlorine-36, prebomb chlorine-36 levels may actually be post bomb chlorine-36.
bomb pulse tritium.