

# Dating of Young Groundwater

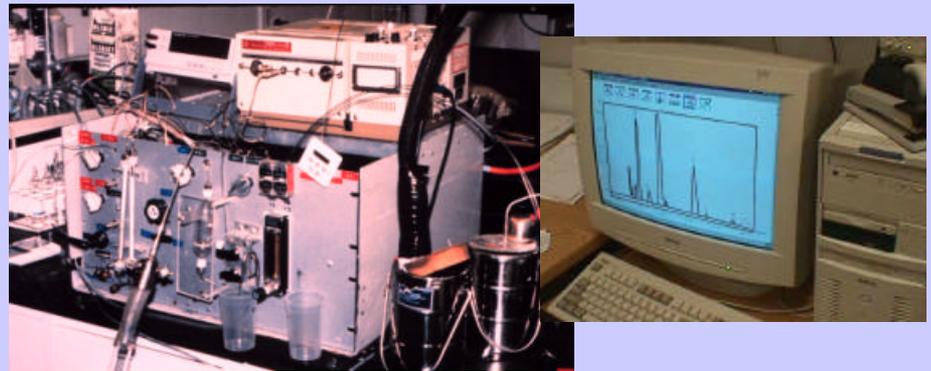
**L.N. Plummer  
USGS, Reston, VA**

**“Owing to dispersion, the “age” of a groundwater sample corresponds generally to a time distribution of many elementary flows. Thus, except in the theoretical case of a pure piston flow system, or of stationary waters entrapped in a geological formation, the concept of groundwater age has little significance”**

J.-Ch. Fontes (1983) *in* Guidebook on Nuclear Techniques in Hydrology, IAEA

# Approach to “Dating” Young GW

- Collect water samples without contacting air.
- Minimize mixing effects by sampling monitoring wells with narrow screens.
- Analyze with high precision for CFCs, SF<sub>6</sub>, <sup>3</sup>H, <sup>3</sup>H/<sup>3</sup>He, and others (multi-tracer approach).
- **Age interpretation.** Evaluate multiple tracer data in context of models of groundwater flow.
- **Age is model dependent.**

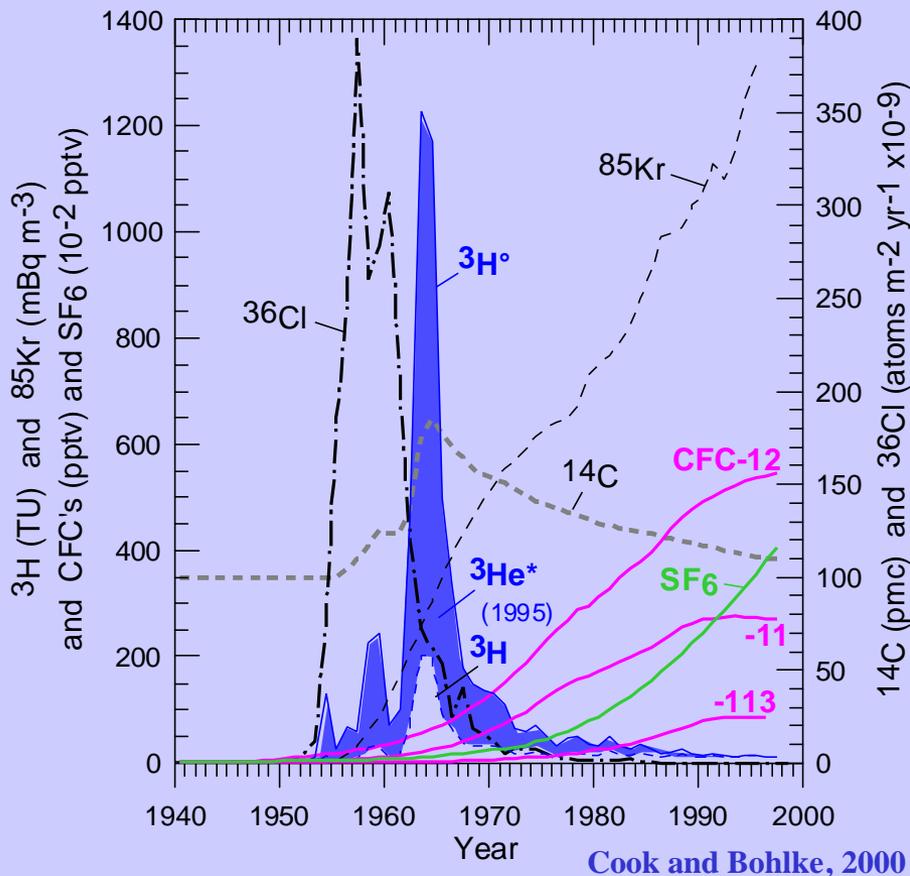


# Age Interpretation

- **Comparison of simulated and observed tracer concentrations. Lumped-parameter models. Helps to have multiple tracers from the source, or a time series from the source, or multiple tracers from multiple sources in the system.**
- **Tracer plots. Method of comparing simulated and observed multiple tracer data; recognizing cases of possible piston flow and binary mixing (dilution); elimination of some mixing models.**
- **Flow-model calibration and simulation of age.**
- **All “ages”, regardless of method, are model dependent.**

# Selected Environmental Tracers 0-50 Year Timescale

tracer1b.grf (JK Böhlke) 4/22/03



Cook and Böhlke, 2000

- $^3\text{H}$ ,  $^3\text{H}/^3\text{He}$
- $^{85}\text{Kr}$
- CFC-11, CFC-12, CFC-113
- SF<sub>6</sub>
- Event Markers:  $^3\text{H}$ ,  $^{36}\text{Cl}$ ,  $^{14}\text{C}$
- Age: time elapsed since recharge

# Tritium/Helium-3



- Half-life 12.3 years; decays to  $^3\text{He}$ .
- Atmospheric thermonuclear weapons testing from the 1950's, and especially in the period 1962-1963
- Initial  $^3\text{H}$  measured
- Terrigenous He sources
- Dispersion around bomb peak
- Confinement of  $^3\text{He}$

# Dating with $^3\text{H}/^3\text{He}$

Measured



$$^4\text{He}_m = ^4\text{He}_{eq} + ^4\text{He}_{atm} + ^4\text{He}_{ter}$$

$$\text{Ne}_m = \text{Ne}_{eq} + \text{Ne}_{atm}$$

$$d^3\text{He} = \left( \frac{R}{R_a} - 1 \right) \cdot 100$$

$$^3\text{He}_m = ^3\text{He}_{eq} + ^3\text{He}_{atm} + ^3\text{He}_{ter} + ^3\text{He}_{tri}$$

## Some Definitions

$$N_{\text{atm}} = (\text{He}/\text{Ne})_{\text{atm}} = 0.288 \text{ for air excess}$$

$$R_{\text{atm}} = ({}^3\text{He}/{}^4\text{He})_{\text{atm}} = 1.384 \times 10^{-6} \text{ for air excess } (R_a)$$

$$R_{\text{ter}} = ({}^3\text{He}/{}^4\text{He})_{\text{ter}} = 2 \times 10^{-8} \text{ for radiogenic helium } (R_{\text{rad}}) \\ = 1 \times 10^{-5} \text{ for mantle helium } (R_{\text{man}})$$

$$Ne_m = Ne_{eq} + Ne_{atm}$$

$${}^4\text{He}_m = {}^4\text{He}_{eq} + N_{atm} \cdot Ne_{atm} + {}^4\text{He}_{ter}$$

$${}^3\text{He}_m = R_{eq} \cdot {}^4\text{He}_{eq} + R_{atm} \cdot N_{atm} \cdot Ne_{atm} + R_{ter} \cdot {}^4\text{He}_{ter} + {}^3\text{He}_{tri}$$

$${}^3\text{He}_{tri} = {}^4\text{He}_m \cdot (R_m - R_{ter}) - {}^4\text{He}_{eq} \cdot (R_{eq} - R_{ter}) - N_{atm} \cdot (Ne_m - Ne_{eq}) \cdot (R_{atm} - R_{ter})$$

$$t = \frac{1}{\lambda} \cdot \ln \left( 1 + \frac{{}^3\text{He}_{tri}}{{}^3\text{H}_m} \right)$$

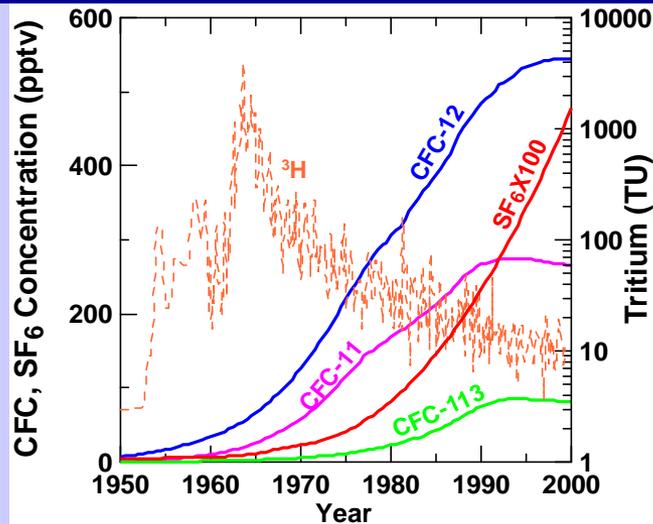
# Chlorofluorocarbons



New bottle method of collection.  
See <http://water.usgs.gov/lab/cfc>

- CFC-12 ( $\text{CF}_2\text{Cl}_2$ ), 1930
- CFC-11 ( $\text{CFCl}_3$ ), 1936
- CFC-113 ( $\text{C}_2\text{F}_3\text{Cl}_3$ ), 1944
- Input smooth, increasing until 1990s (dating range ~1950 to early 1990s).
- Stable in aerobic environments.
- In future- dual ages.
- Use of ratios.
- Can detect post 1940's water.
- Collection/analysis not overly labor intensive.
- Problems with contamination, degradation (anoxic), sorption?

# Sulfur Hexafluoride



- **Electrical insulator in high voltage switches**
- **First produced 1953**
- **Very low solubility in water.**
- **Does not degrade**
- **Terrigenous source**
- **Dating range: 1970-modern.**
- **Smooth input, increasing in air at 6%/yr; 5 pptv today.**



# Dating with CFCs and SF<sub>6</sub>

- Henry's law solubility  $C_i = K_H \times p_i$

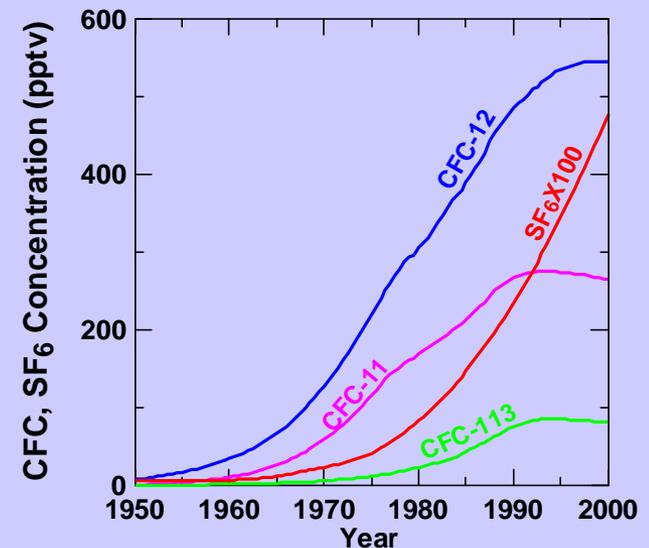
- Requirements:

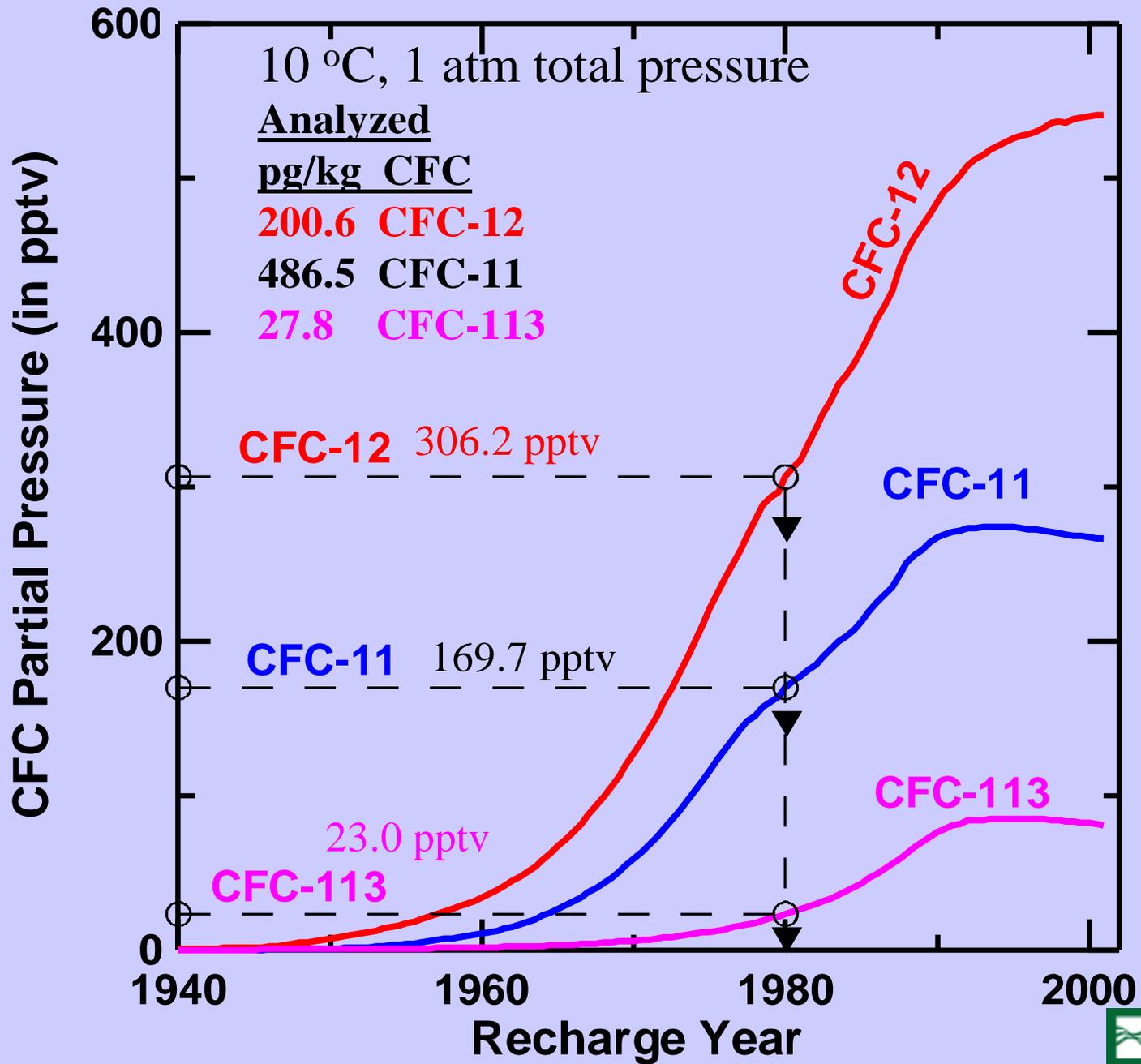
- Gas-water equilibrium at recharge

- Recharge temperature

- Barometric pressure at recharge

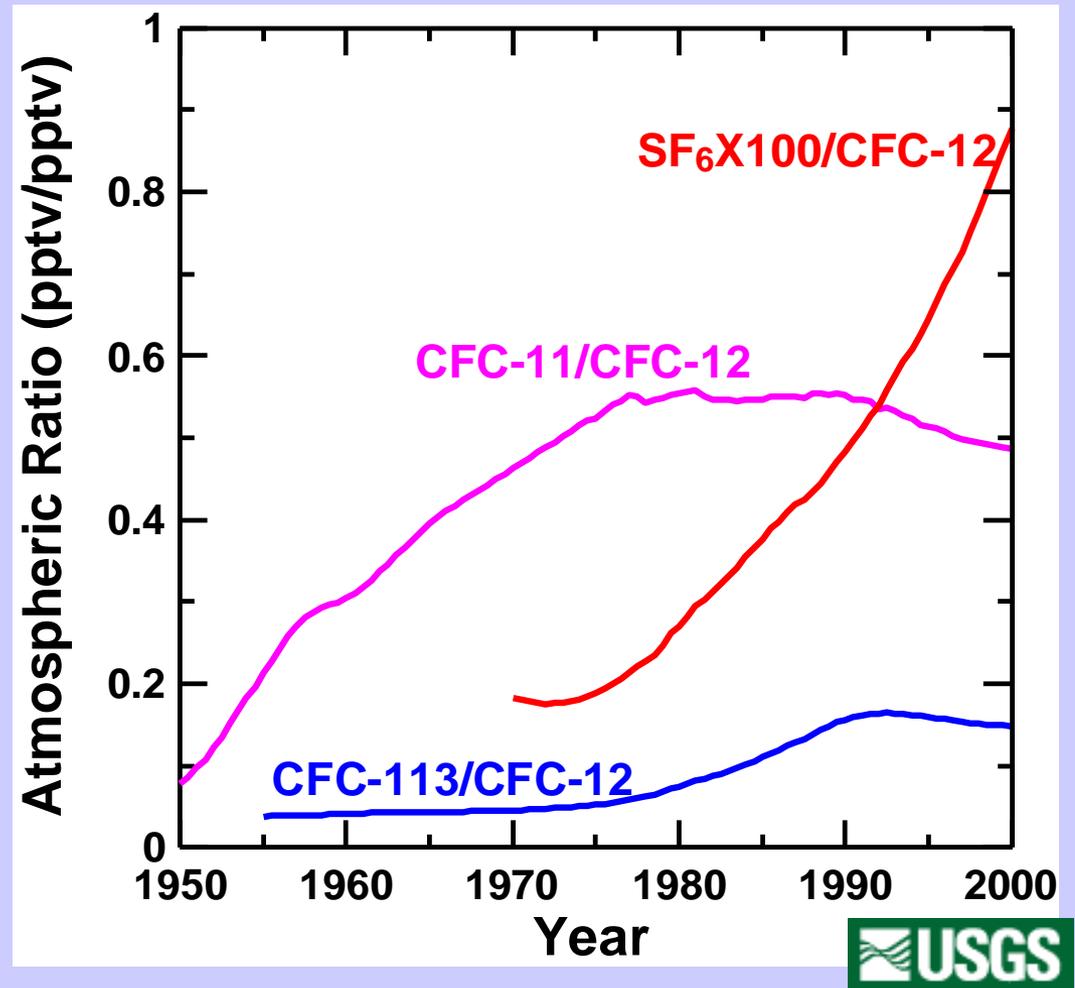
- Knowledge of atmospheric history of the gas



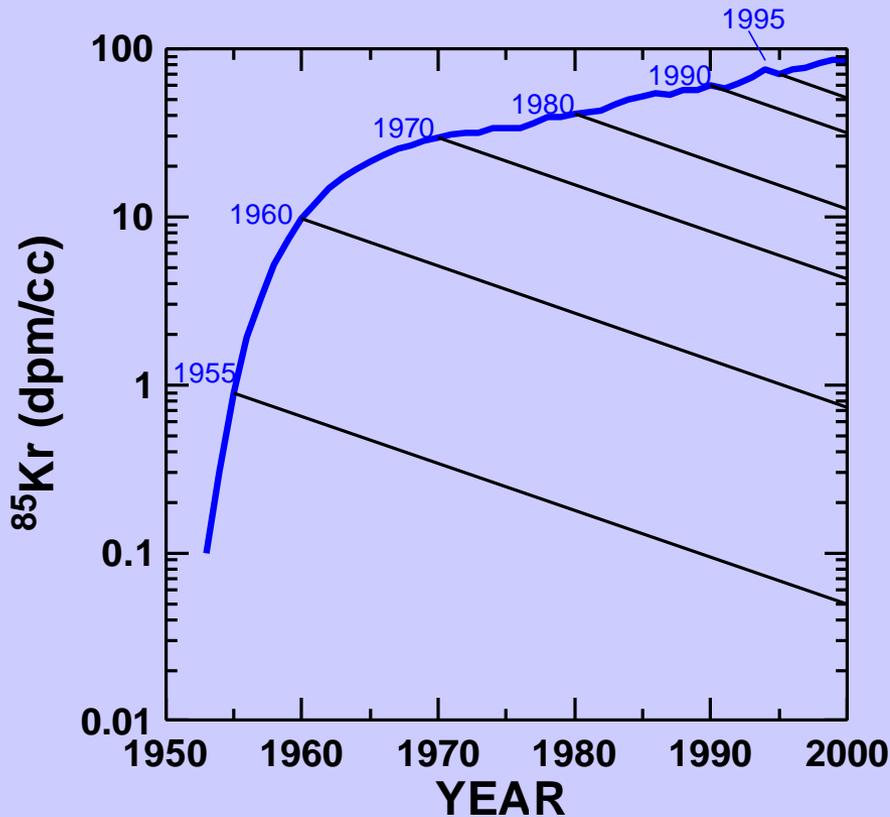


# Dating with Ratios

In binary mixtures of young and old (pre-tracer), the tracer ratio in the young fraction is preserved.



# Krypton-85



- Radioactive noble gas with a half-life of 10.76 years.
- $^{85}\text{Kr}$  in the atmosphere has steadily increased since the mid-1950s.
- Interpreted age insensitive to recharge temperature, altitude, etc.
- Does not degrade.
- Atmosphere is only significant source.
- Although difficult to collect and analyze, even a few  $^{85}\text{Kr}$  can often help resolve questions.

# Limitations

## $^3\text{H}/^3\text{He}$

- Cost
- Terrigenous He
- Bubbles, Gas-stripping, confinement
- Mixing

## $\text{SF}_6$

- Terrigenous  $\text{SF}_6$
- Mixing

## CFCs

- Contamination
- Degradation
- Mixing

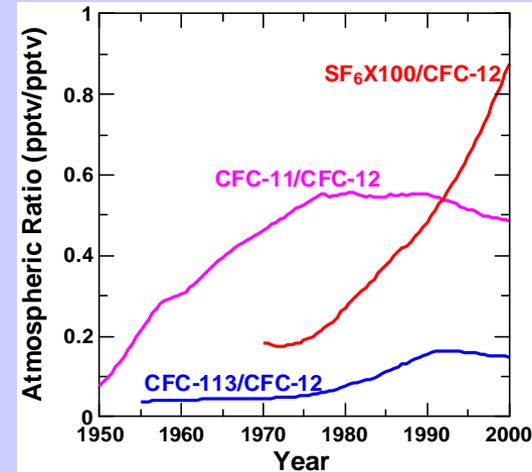
## $^{85}\text{Kr}$

- Very difficult collection and analysis
- No labs available to us

# Some Practical Applications (of interpreted age information)

- Estimate recharge rates.
- Calibrate models of groundwater flow.
- Estimate rates of geochemical and microbiological processes (natural remediation).
- Evaluate susceptibility to contamination.
- Retrieve historical records of contaminant loading to aquifers.
- Estimate remediation times.

# Tracer Method of dating the young fraction in binary mixtures of young and old



- CFC pptv ratio defines age of young fraction.
  - % young water  $(\text{pptv}_{(\text{measured})} / \text{pptv}_{(\text{ratio year})}) \times 100$
- 
- Cannot date outside range for ratio.
  - Cannot use if one of the CFCs in the selected ratio is “contaminated”, even if ratio is “in range”.
  - Ratio-based age must be less than (younger than) apparent (piston flow) model ages for both CFCs in the ratio.

# $^3\text{H}/^3\text{He}$ Age Applies to that of the Young Fraction in Simple Binary Mixtures

$^3\text{H}/^3\text{He}$  Age is based on an isotope ratio.

$$t = \frac{1}{\lambda} \cdot \ln \left( 1 + \frac{{}^3\text{He}_{tri}}{{}^3\text{H}_m} \right)$$

$\lambda = \text{decay constant} = \ln 2 / t_{1/2} = 0.05635 \text{ year}^{-1}$

$t_{1/2} = 12.3 \text{ years}$



## Chesapeake Bay Watershed

Region of 165,000 km<sup>2</sup> over parts of NY, PA, MD, DE, VA, and WV.

Evaluate residence times and nitrate transport in groundwater discharging to streams in the watershed.

Assess lag time between changes at the land surface and the response in the base-flow component of groundwater discharge to the bay.

**Lindsey and others, 2003, USGS WRIR 03-4035, <http://pa.water.usgs.gov/reports/wrir03-4035.pdf>**



The Chesapeake Bay Watershed

64,000 Square Miles of Land, Water, and People

"A Better Bay Through Better Science"

1997

Produced by the USGS from a mosaic of Landsat satellite imagery acquired from 1980-1984



<http://www.usgs.gov>  
1-800-4USGS



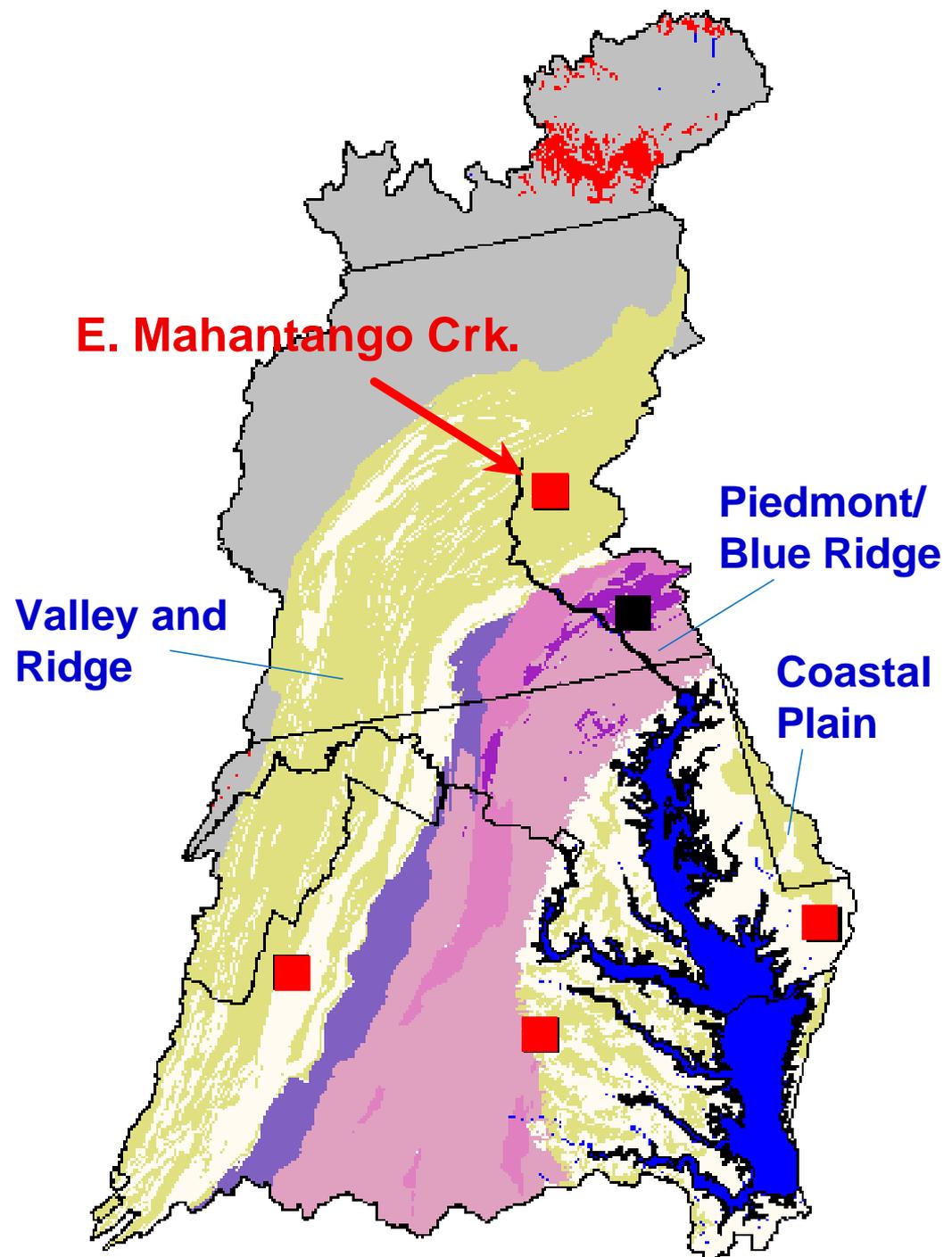
U.S. Geological Survey

<http://www.usgs.gov>

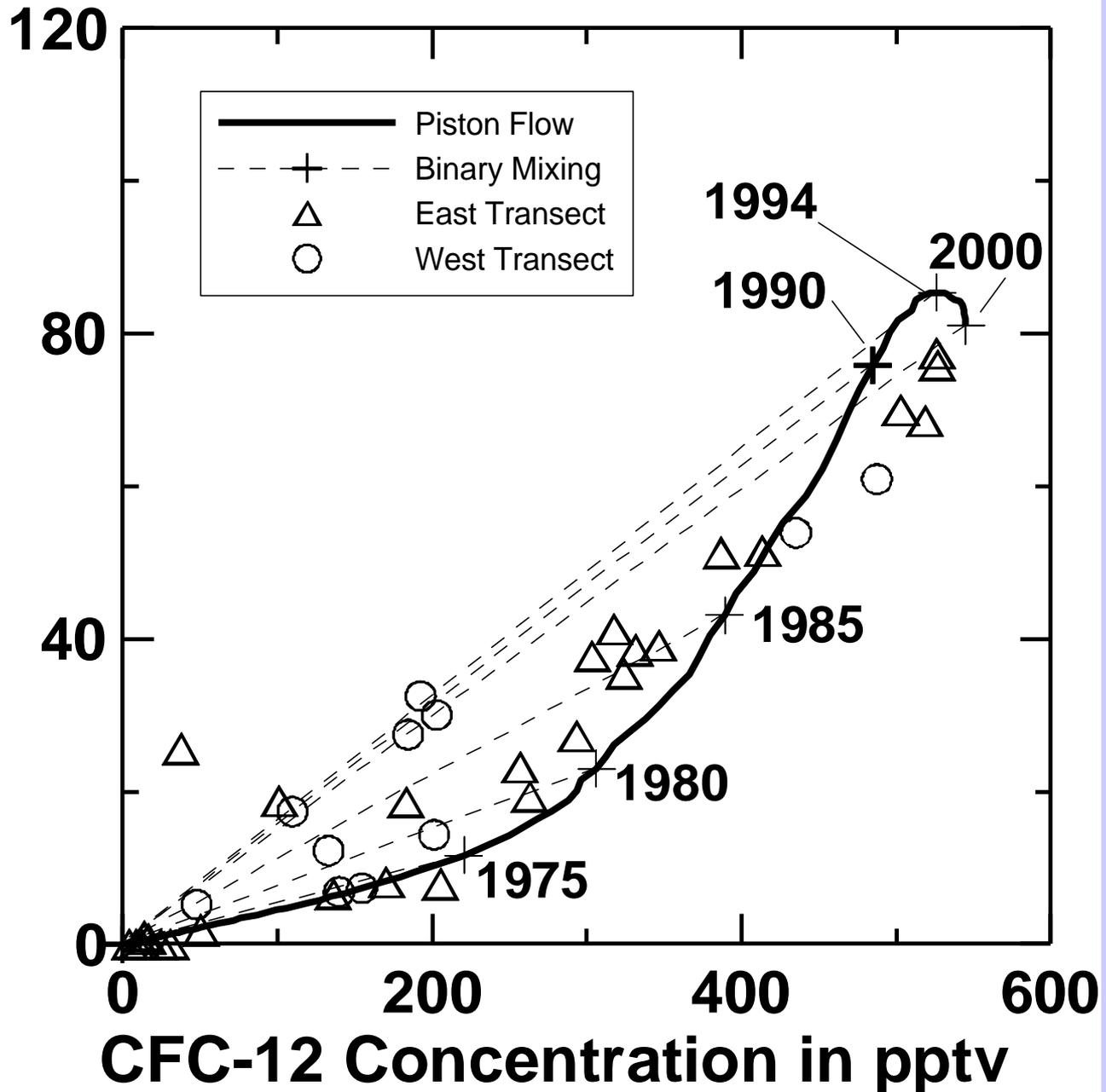


# USGS Chesapeake Bay watershed nutrient study

- Model influx of nitrogen into Bay
- “Targeted watersheds” in high-nitrate-source areas underlain by varied geology, including fractured bedrock
- What is effect of bedrock geology on base flow and groundwater travel times?

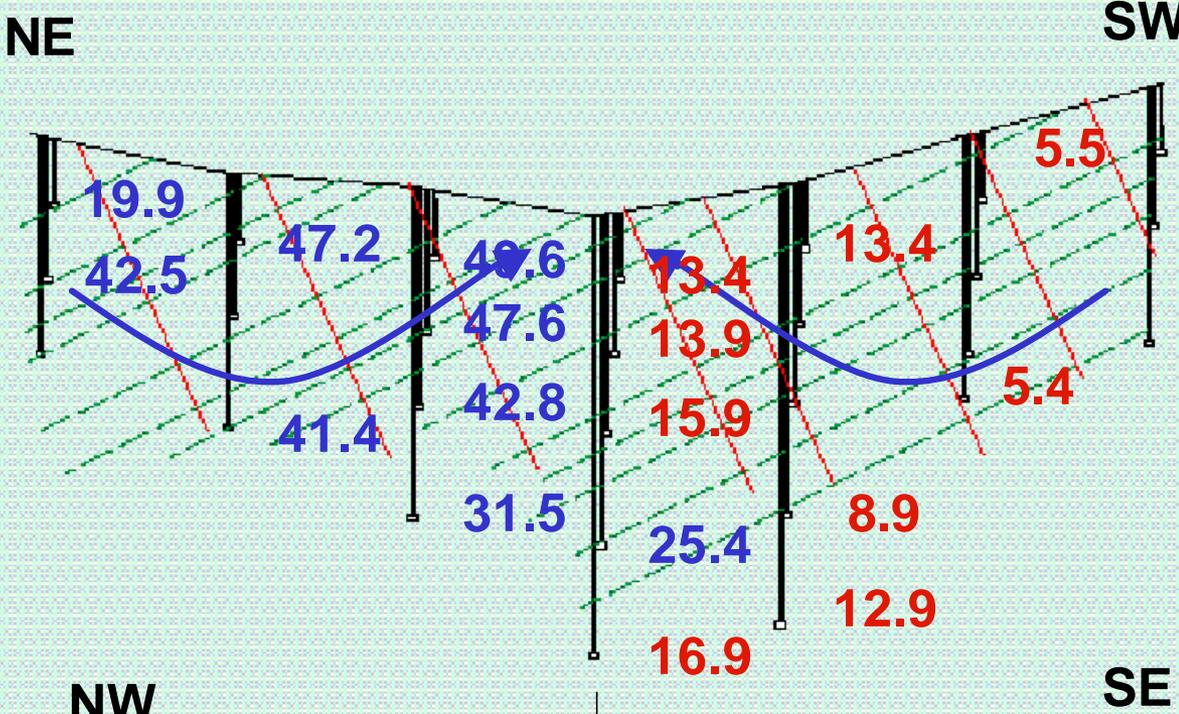


CFC-113 Concentration in pptv



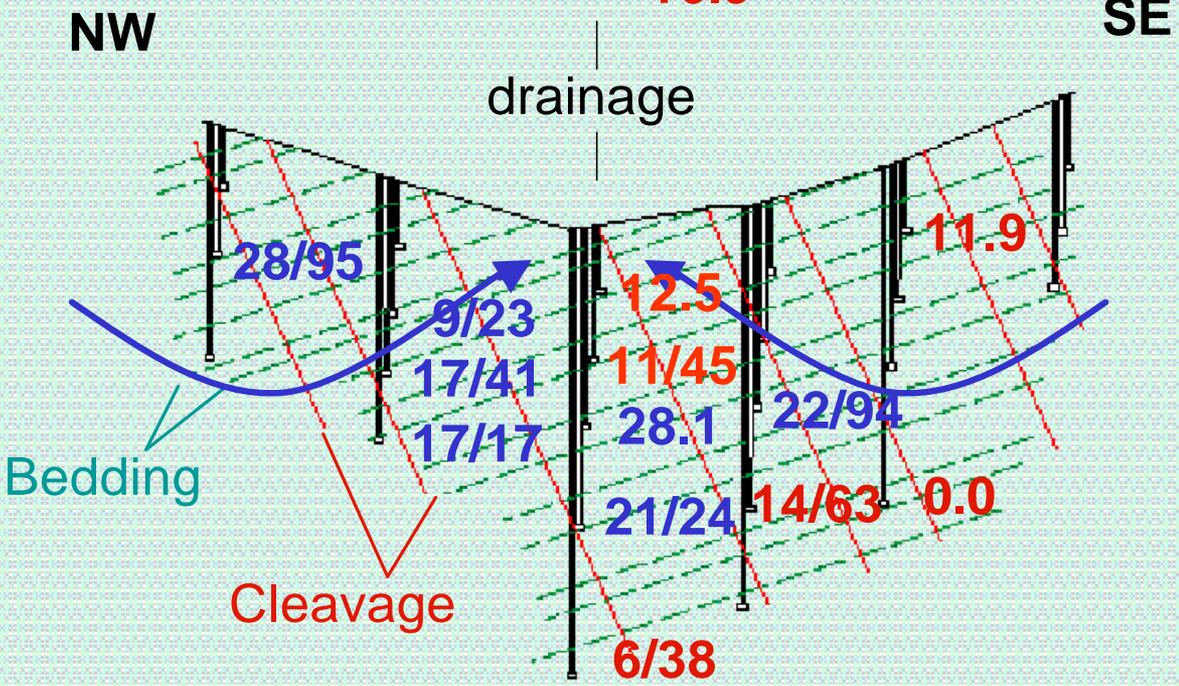
**East Piezometer Transect**

--Preferred CFC-12 ages NE of stream are older...  
 ..than those underneath and SW of stream  
 ..although these ages are really mixture ages!



**West Piezometer Transect**

--Ages are even more mixed, but % of young water (2<sup>nd</sup> #) shows older waters generally prevailing to NW  
 ...and younger to SE



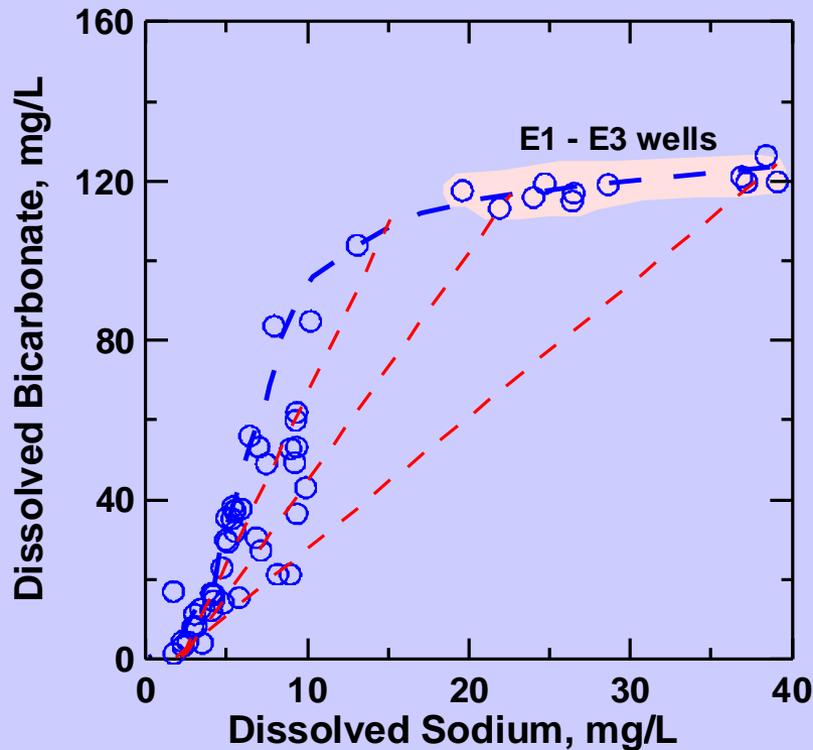
# Geochemical Reactions

Calcite dissolution

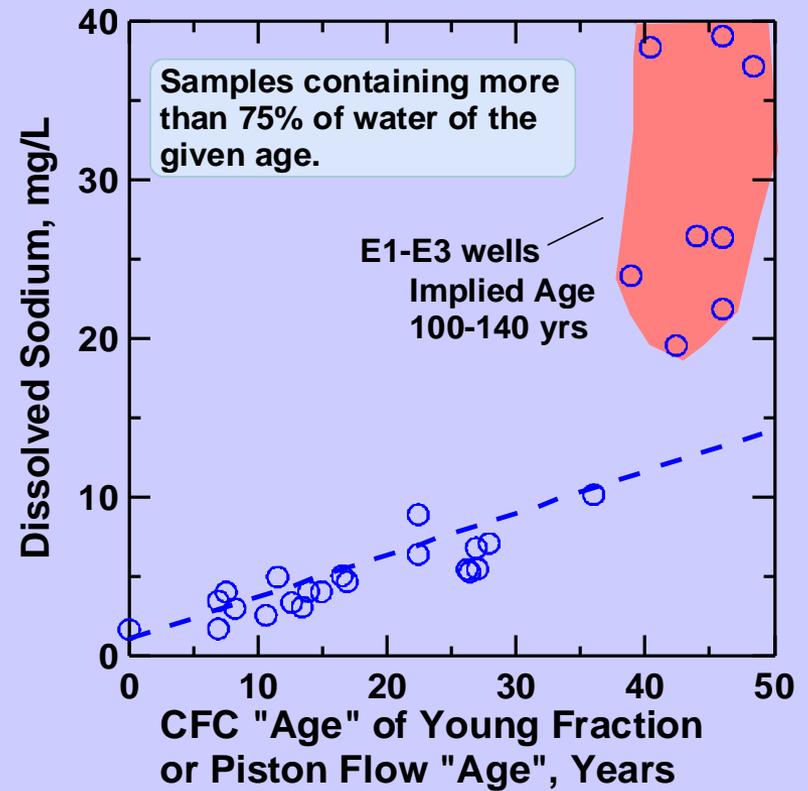
Ca/Na cation exchange

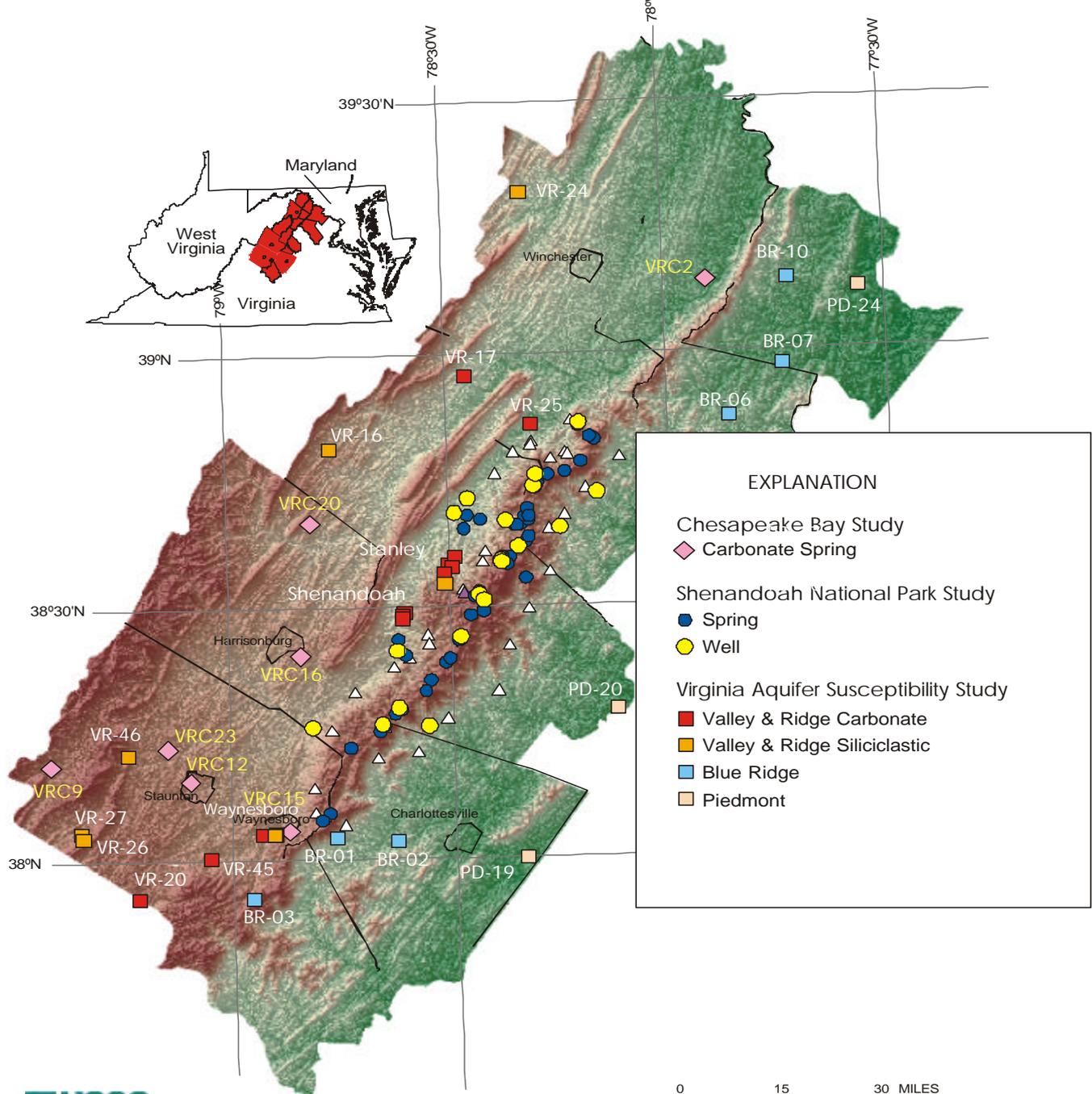
Plagioclase feldspar weathering

Evolve to Na-HCO<sub>3</sub> water



# Calibration of Local Reaction Rate, and “Dating” Beyond the CFC Range



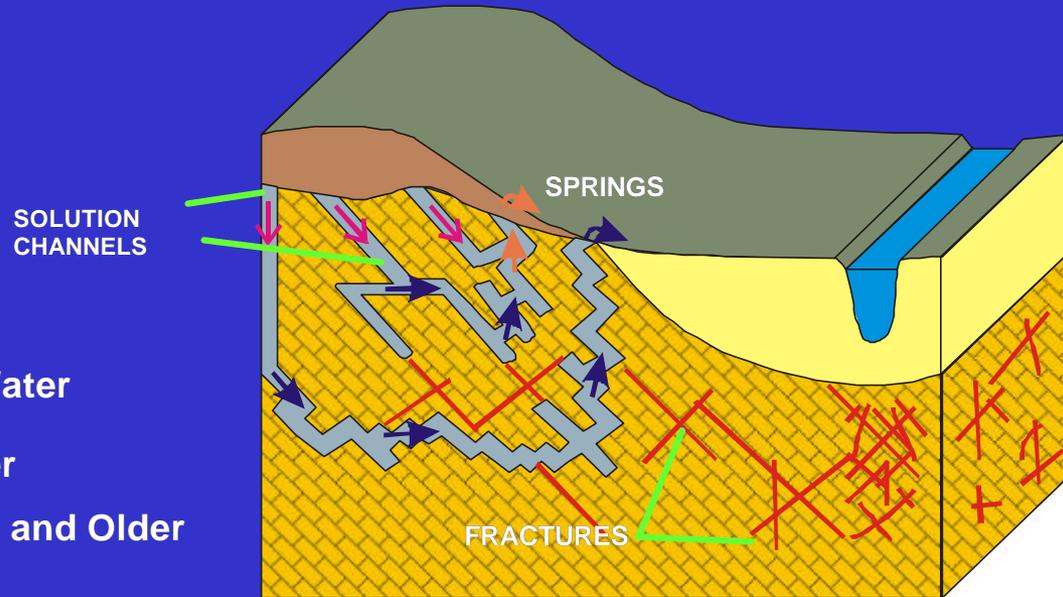


# Numbers of Samples from the Valley and Ridge Carbonates

Source	Chloro-fluoro-carbons	Tritium	Tritium/ Helium-3
Springs	69	25	18
Public Supply wells	11	11	9
Domestic wells	11	3	3
Monitoring wells	9	9	9
Total Samples	100	48	39

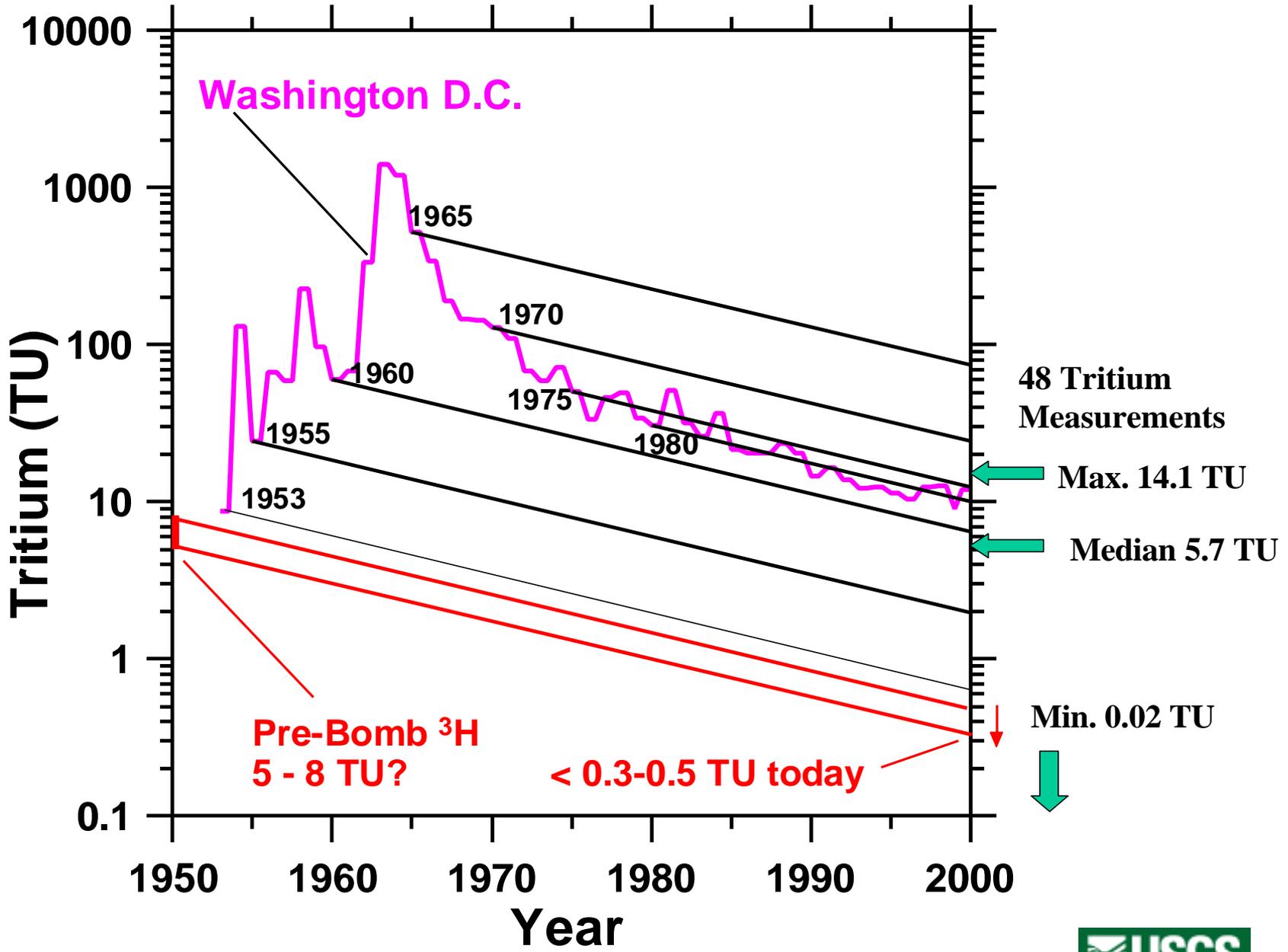
Although all samples are from Valley and Ridge carbonates, the extent of karst development is not well known.

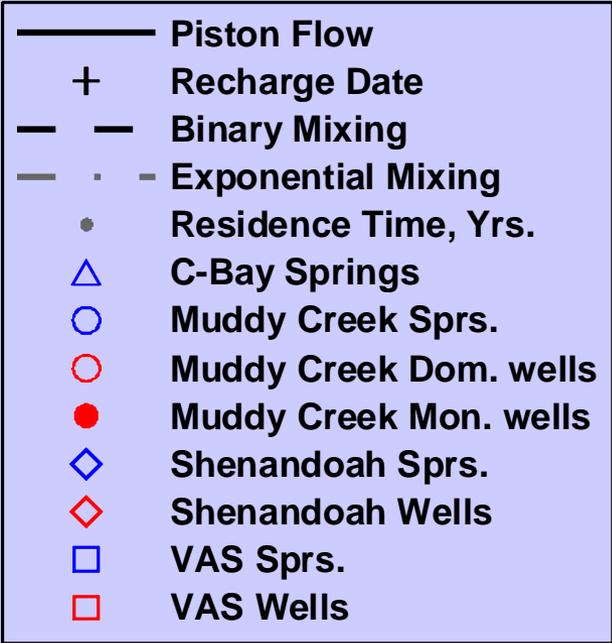
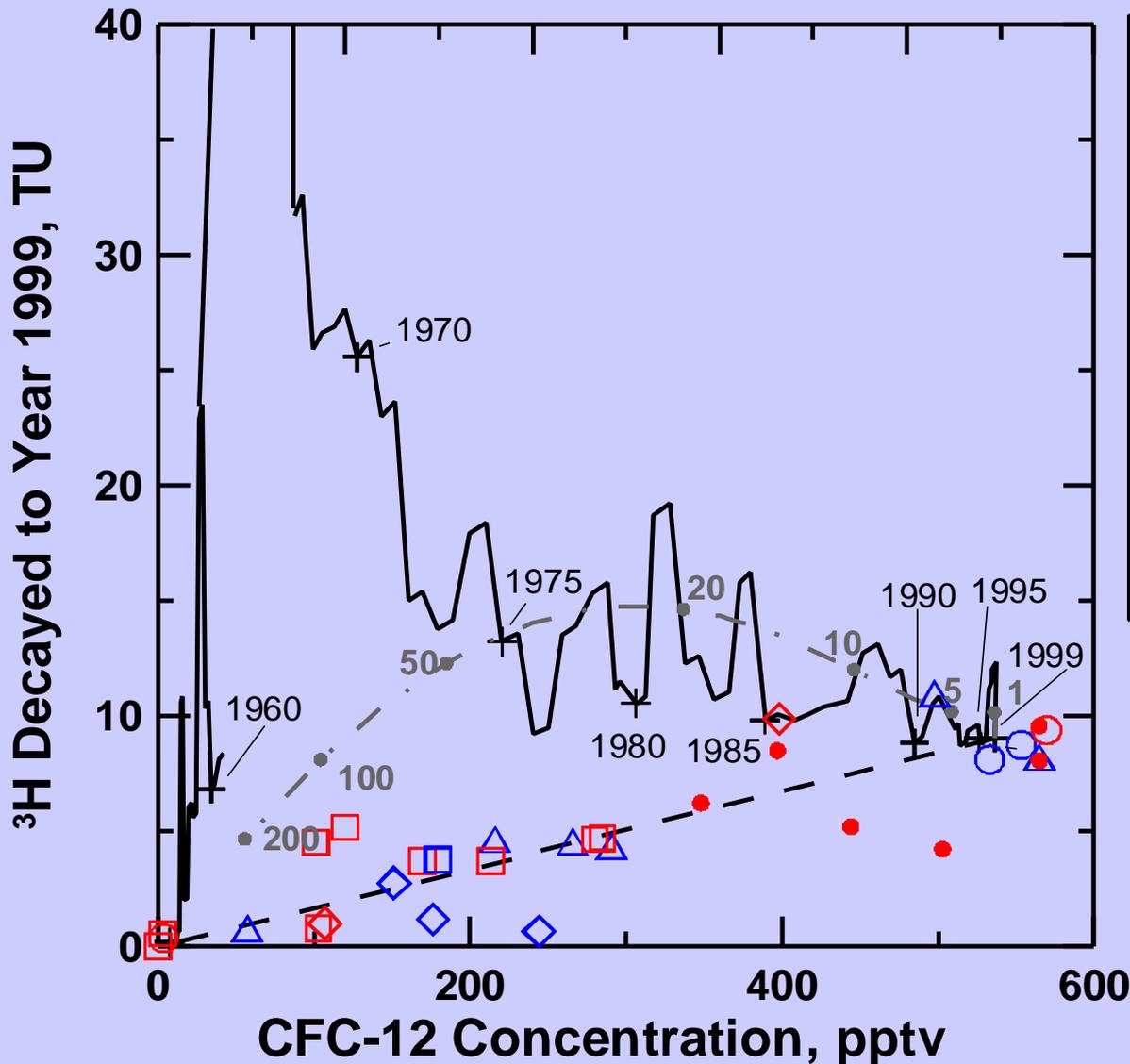
# Hydrogeology of Carbonate Terranes of the Valley & Ridge Province



Modified from Brahana and others, 1986

NOT TO SCALE

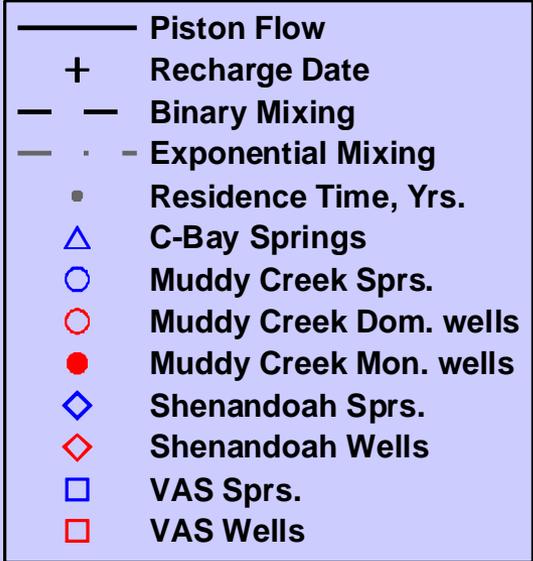
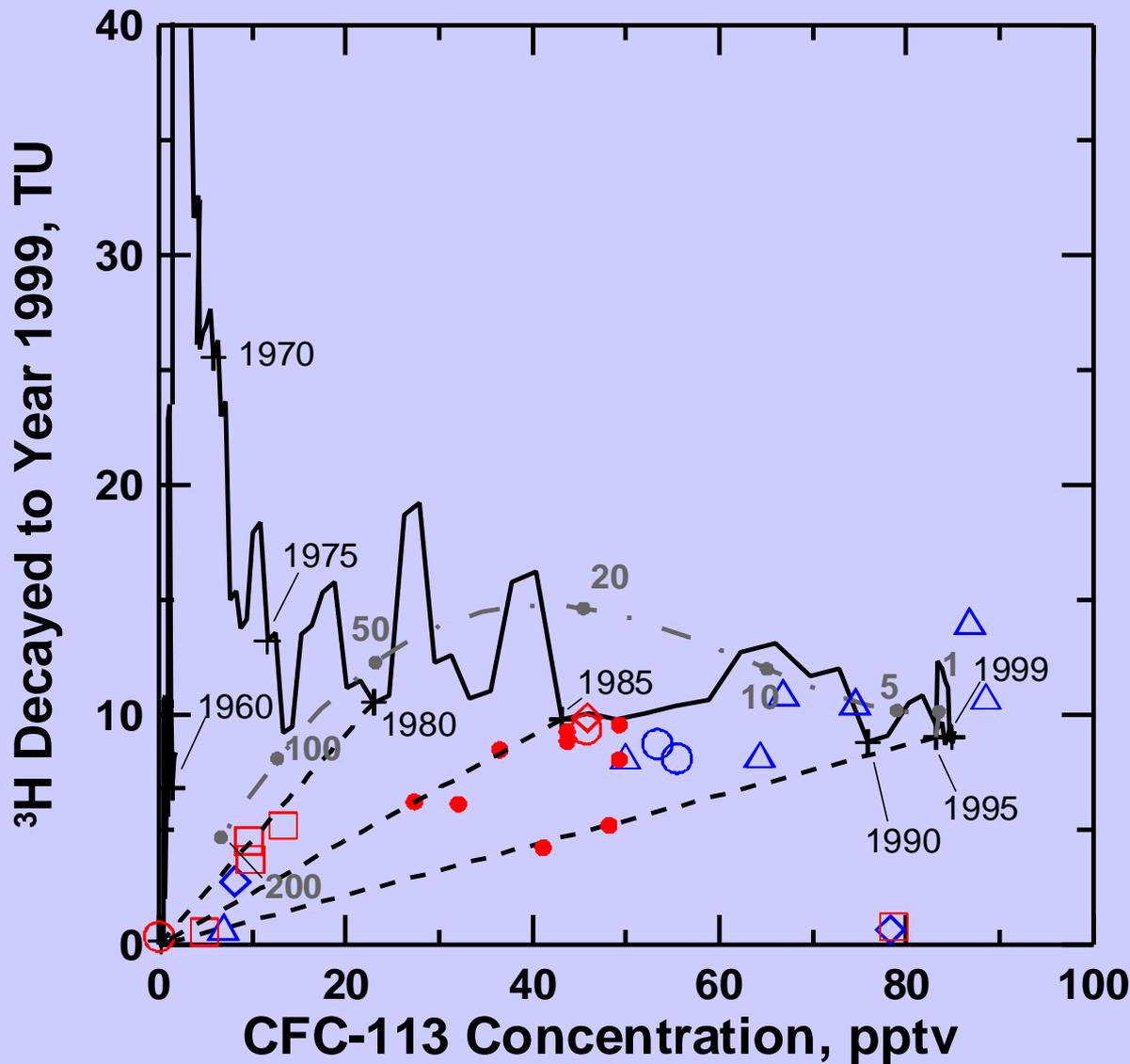




### Tritium vs CFC-12

- Young, piston flow
- Binary mixtures of young and old
- Few CFC-12 contamination

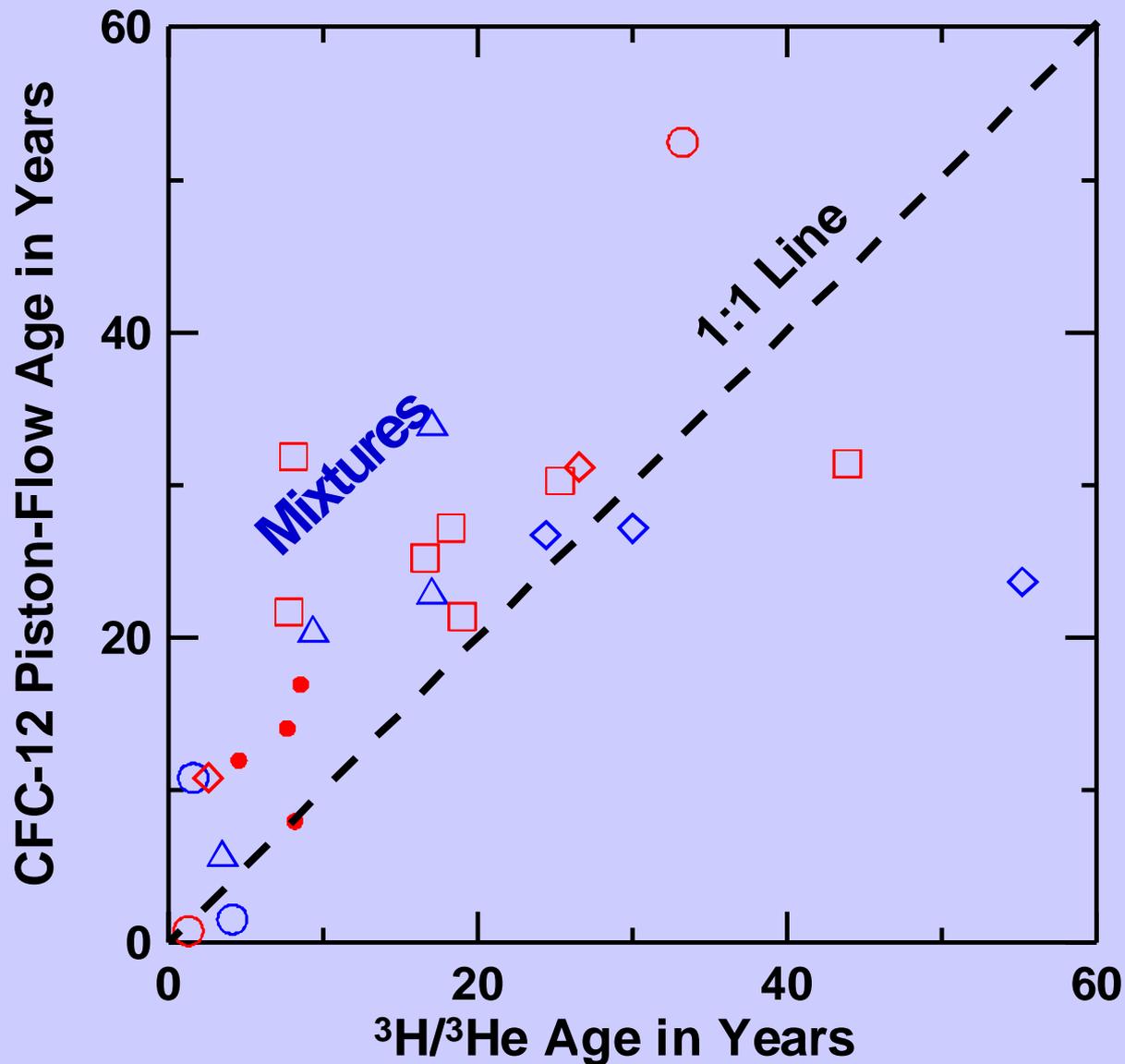




### Tritium vs CFC-113

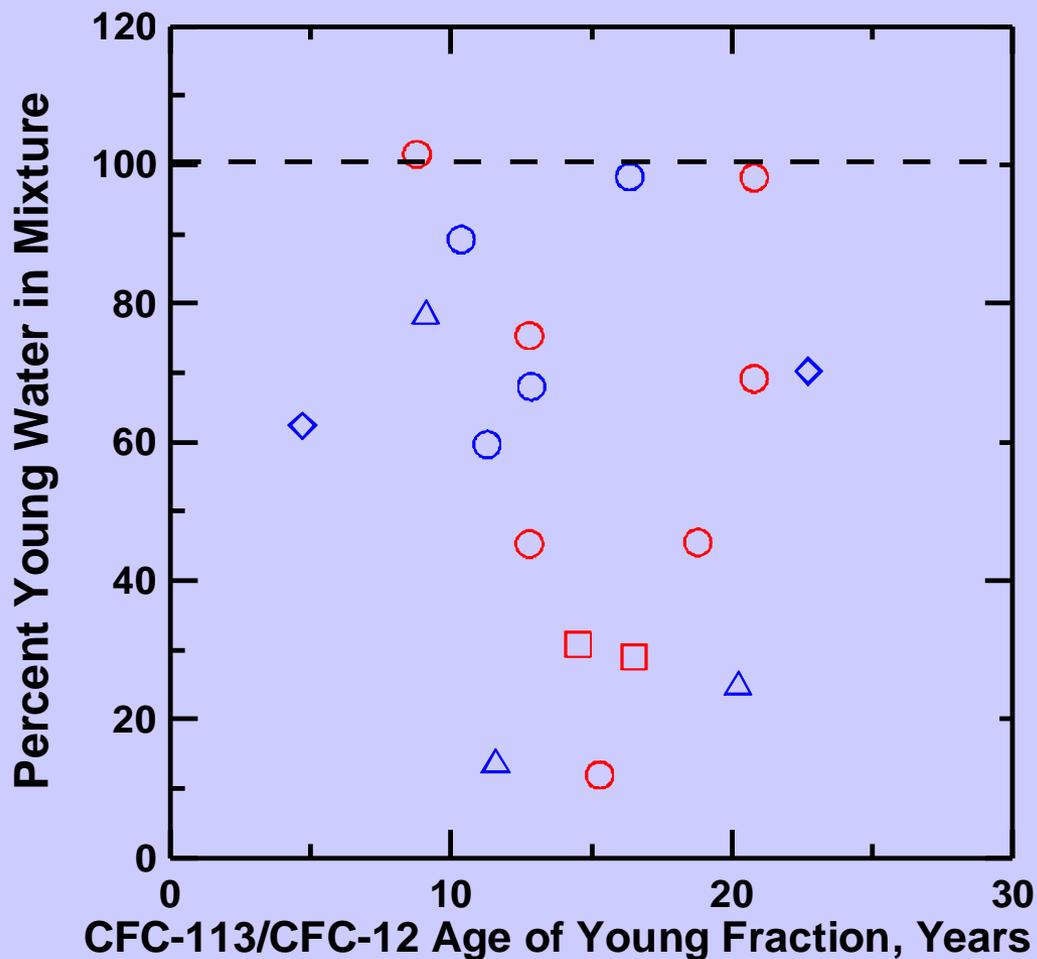
- Linear plot
- Binary mixtures; 1980 to modern with old





- Valley and Ridge Carbonates**
- △ C-Bay Sprs.
  - Muddy Creek Sprs.
  - Muddy Creek Dom. wells
  - Muddy Creek Mon. wells
  - ◇ Shenandoah Sprs.
  - ◇ Shenandoah wells
  - VAS Sprs.
  - VAS wells

- 2 samples beyond dating range of  $^3\text{H}/^3\text{He}$ .
- 9 samples may be unmixed.
- 13 samples look like mixtures.



- Valley and Ridge Carbonates**
- △ C-Bay Sprs.
  - Muddy Creek Sprs.
  - Muddy Creek Dom. wells
  - Muddy Creek Mon. wells
  - ◇ Shenandoah Sprs.
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  - VAS Sprs.
  - VAS wells

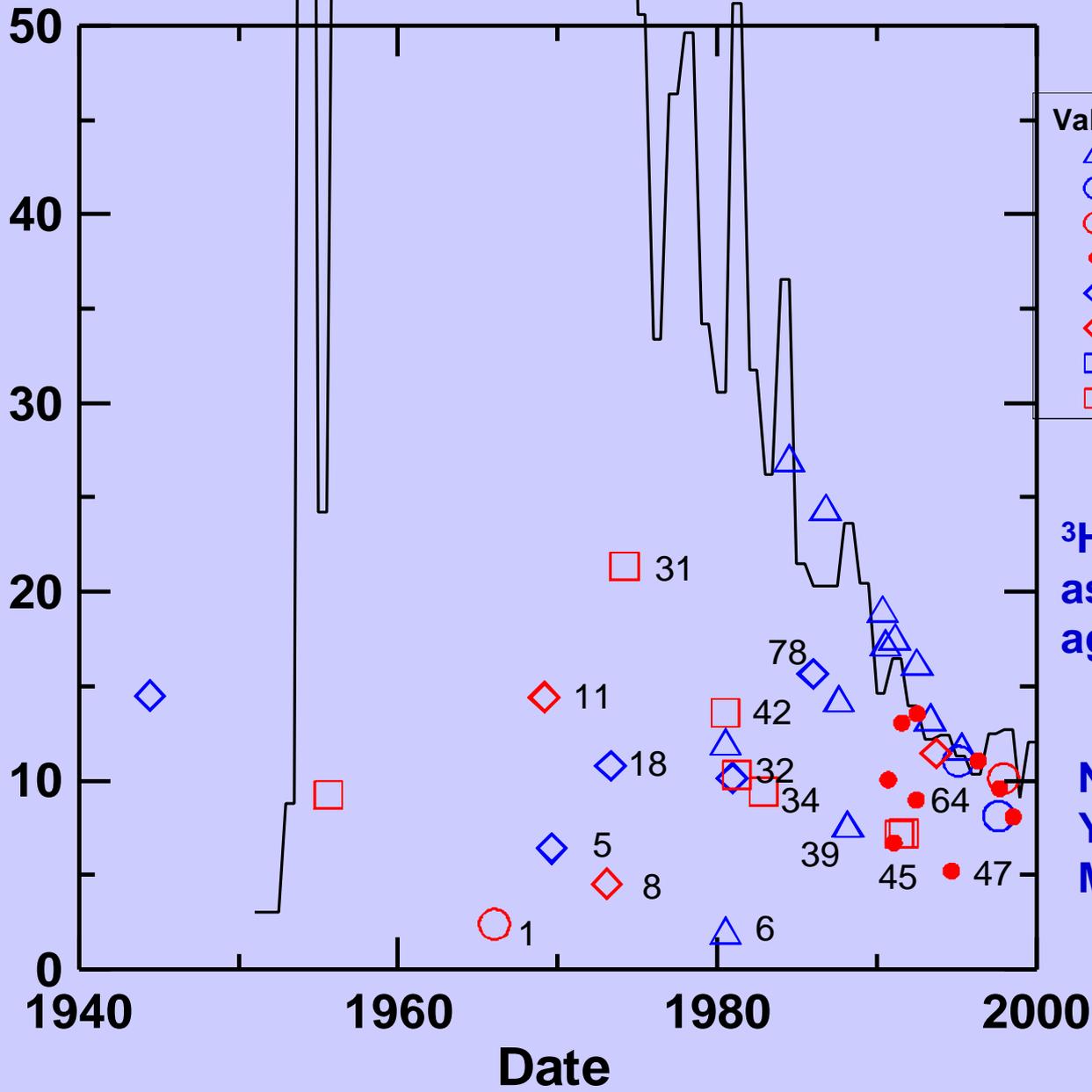
**Ages and mixing fractions determined from CFC-113/CFC-12**

**5-22 years and 10-100% young water in mixture.**

**Some are inconsistent with <sup>3</sup>H (CFC contam.)**



Tritium in Precipitation in TU



- Valley and Ridge Carbonates**
- △ C-Bay Sprs.
  - Muddy Creek Sprs.
  - Muddy Creek Dom. wells
  - Muddy Creek Mon. wells
  - ◇ Shenandoah Sprs.
  - ◇ Shenandoah wells
  - VAS Sprs.
  - VAS wells

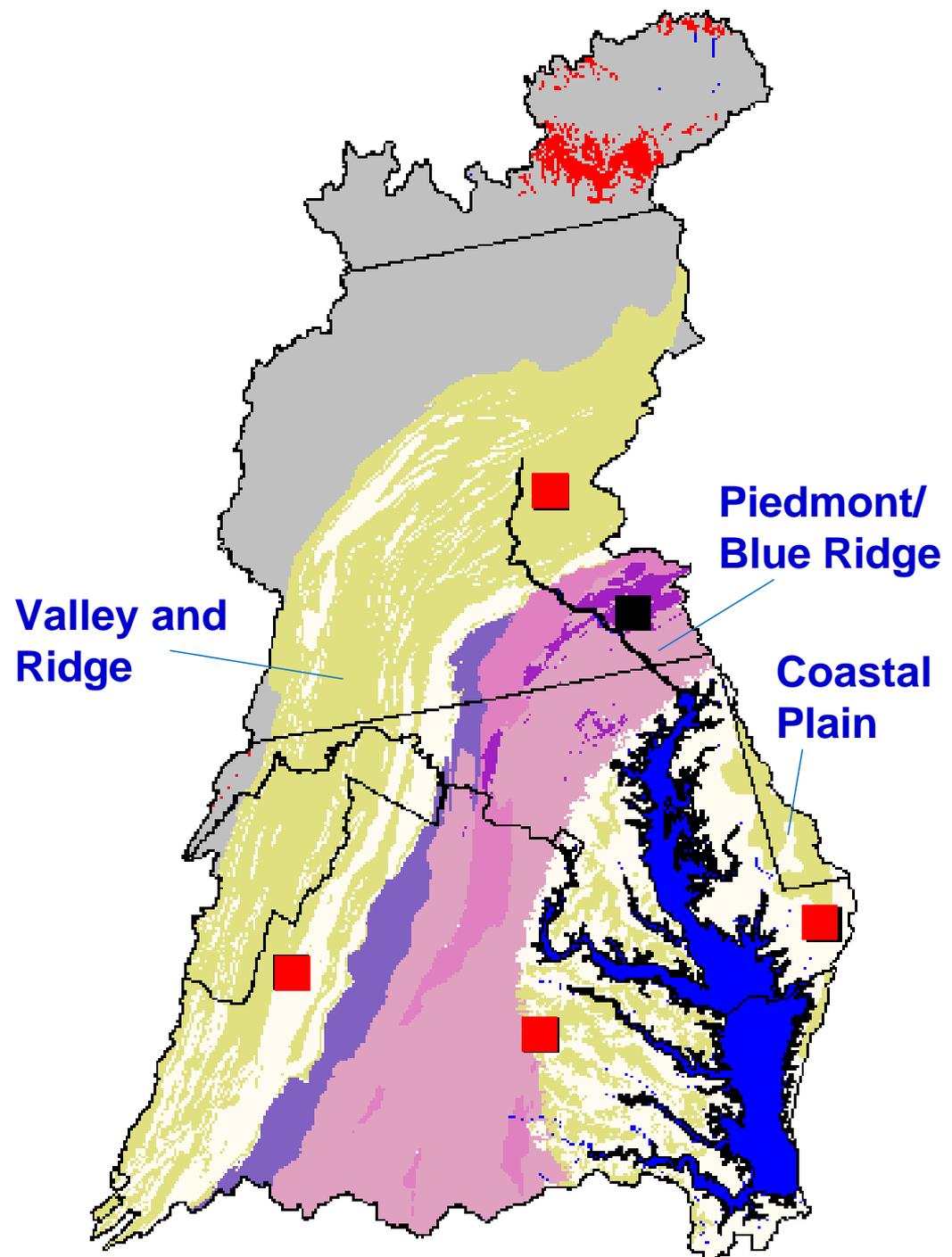
**$^3\text{H} + ^3\text{He}$ (tritogenic)  
as function of  $^3\text{H}/^3\text{He}$   
age.**

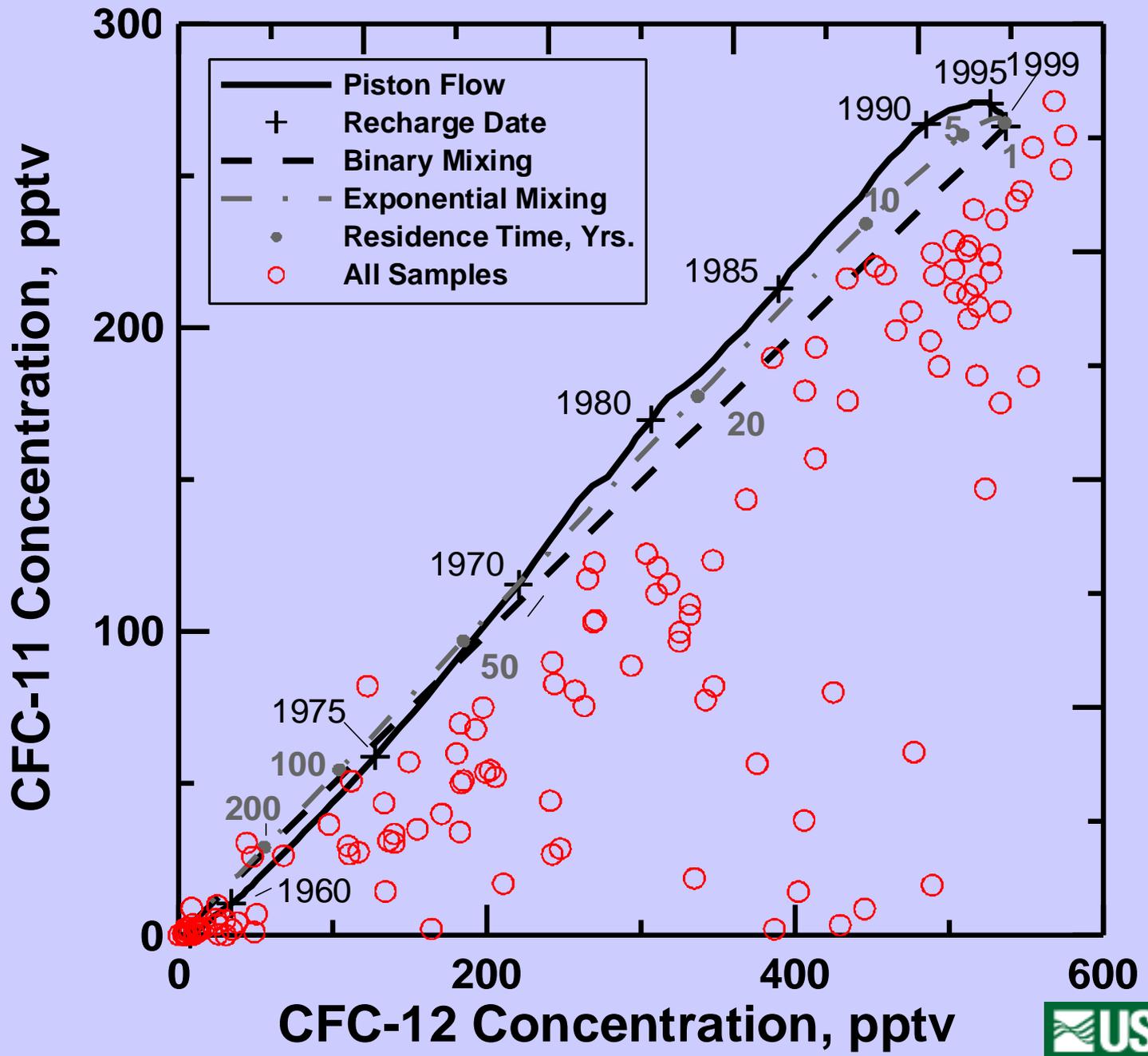
**Numbers are % of  
Young fraction in  
Mixture.**

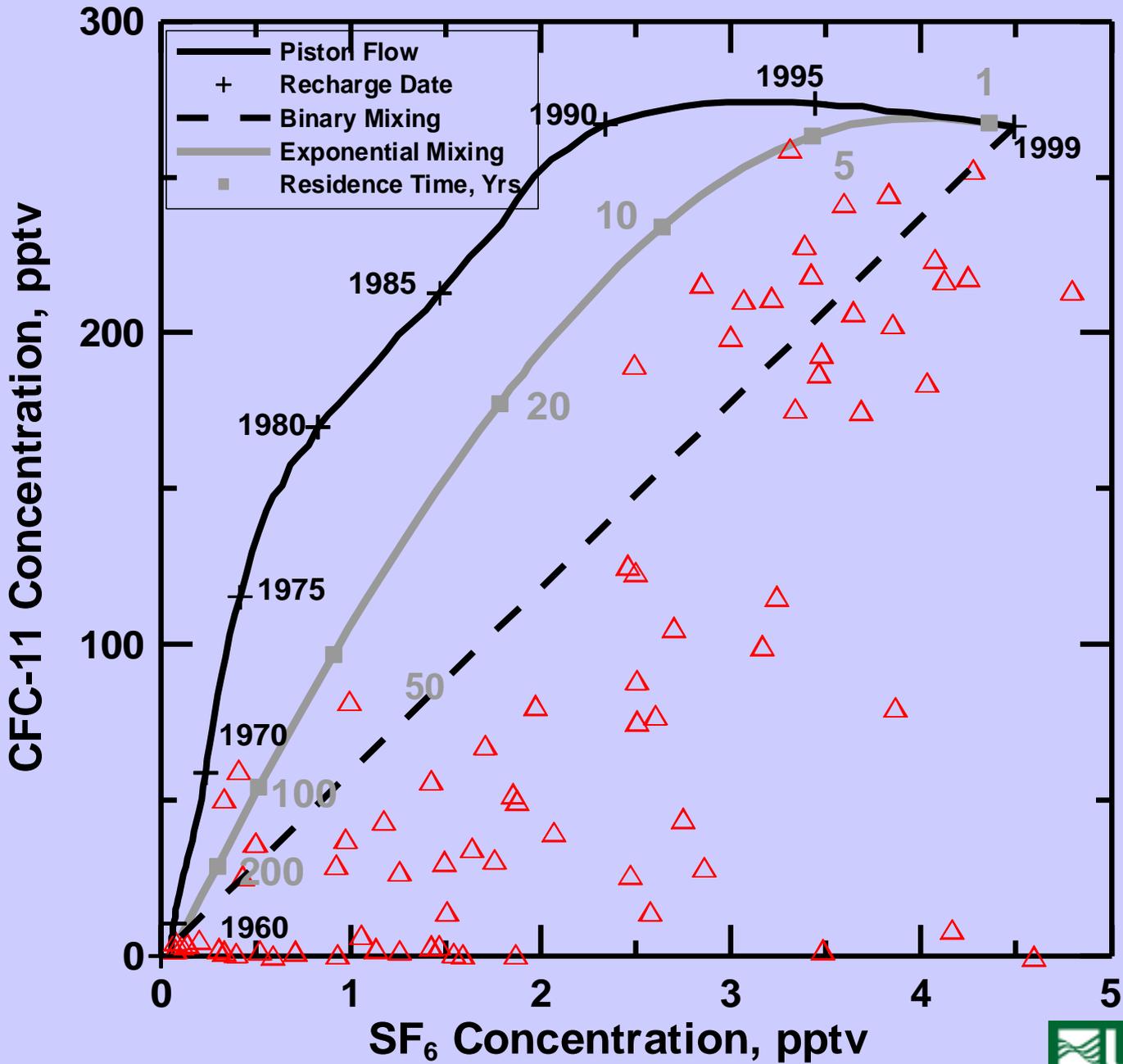


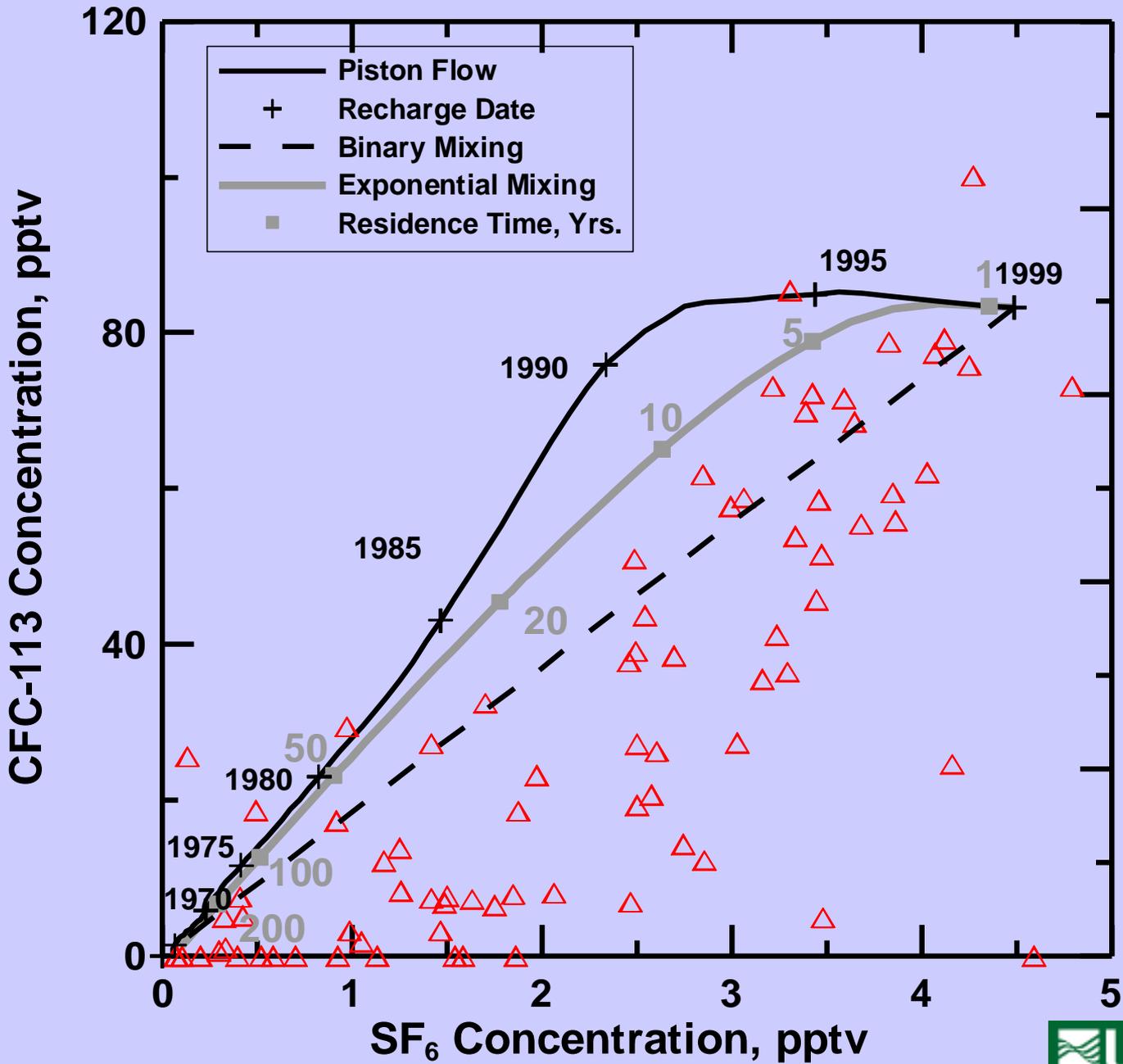
# USGS Chesapeake Bay watershed nutrient study

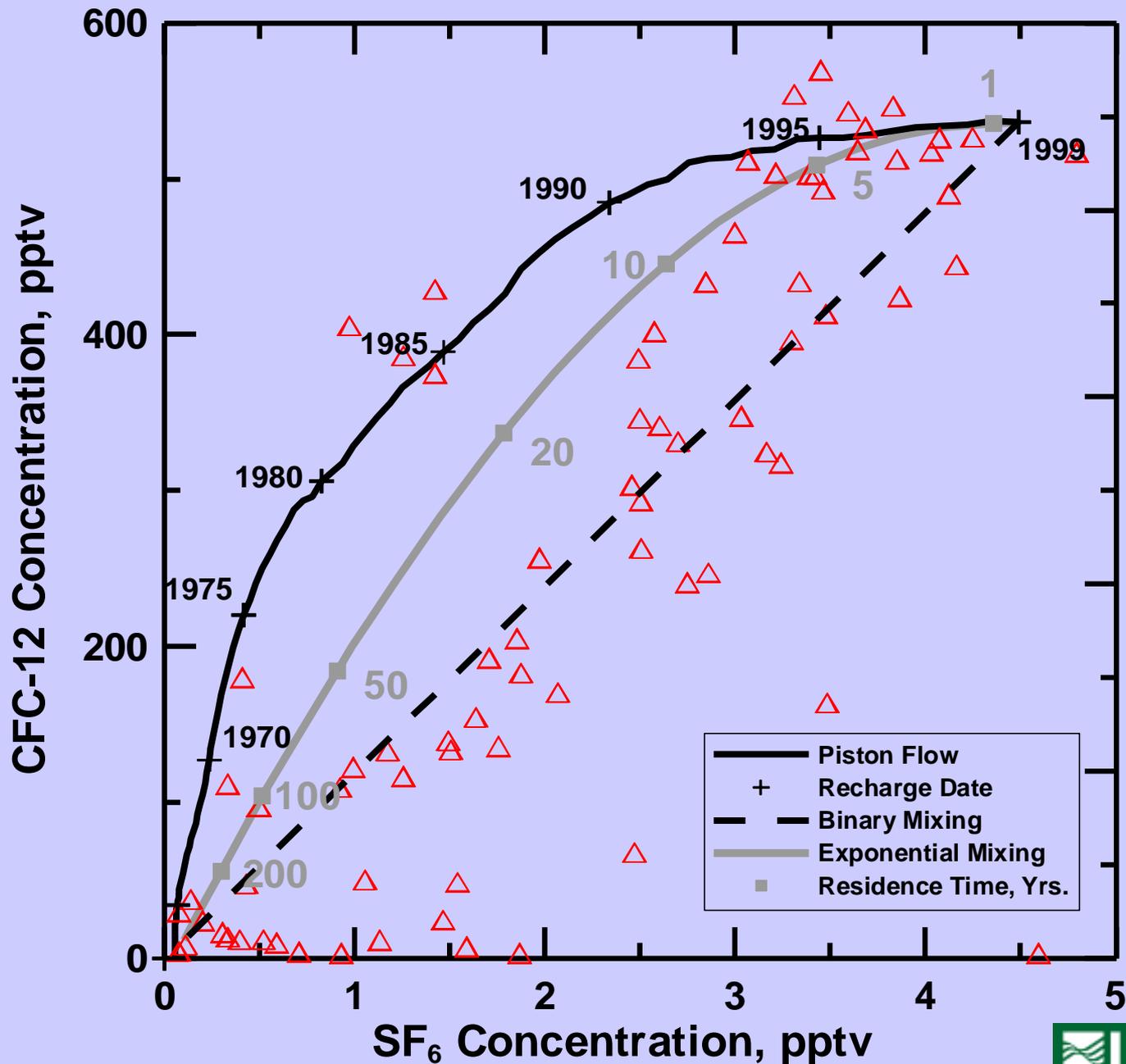
- Relations among  $^3\text{H}$ , CFCs, and  $\text{SF}_6$

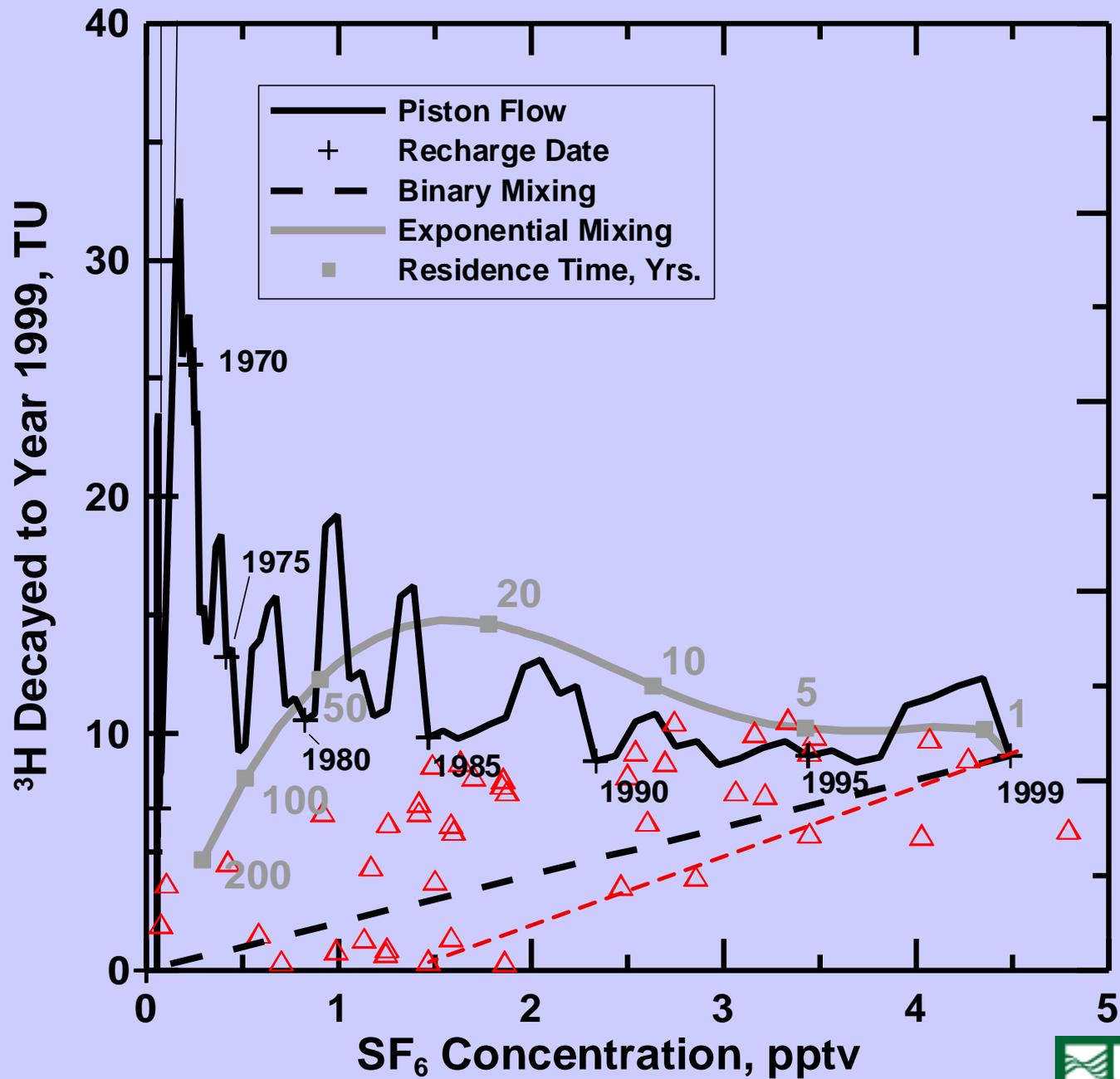


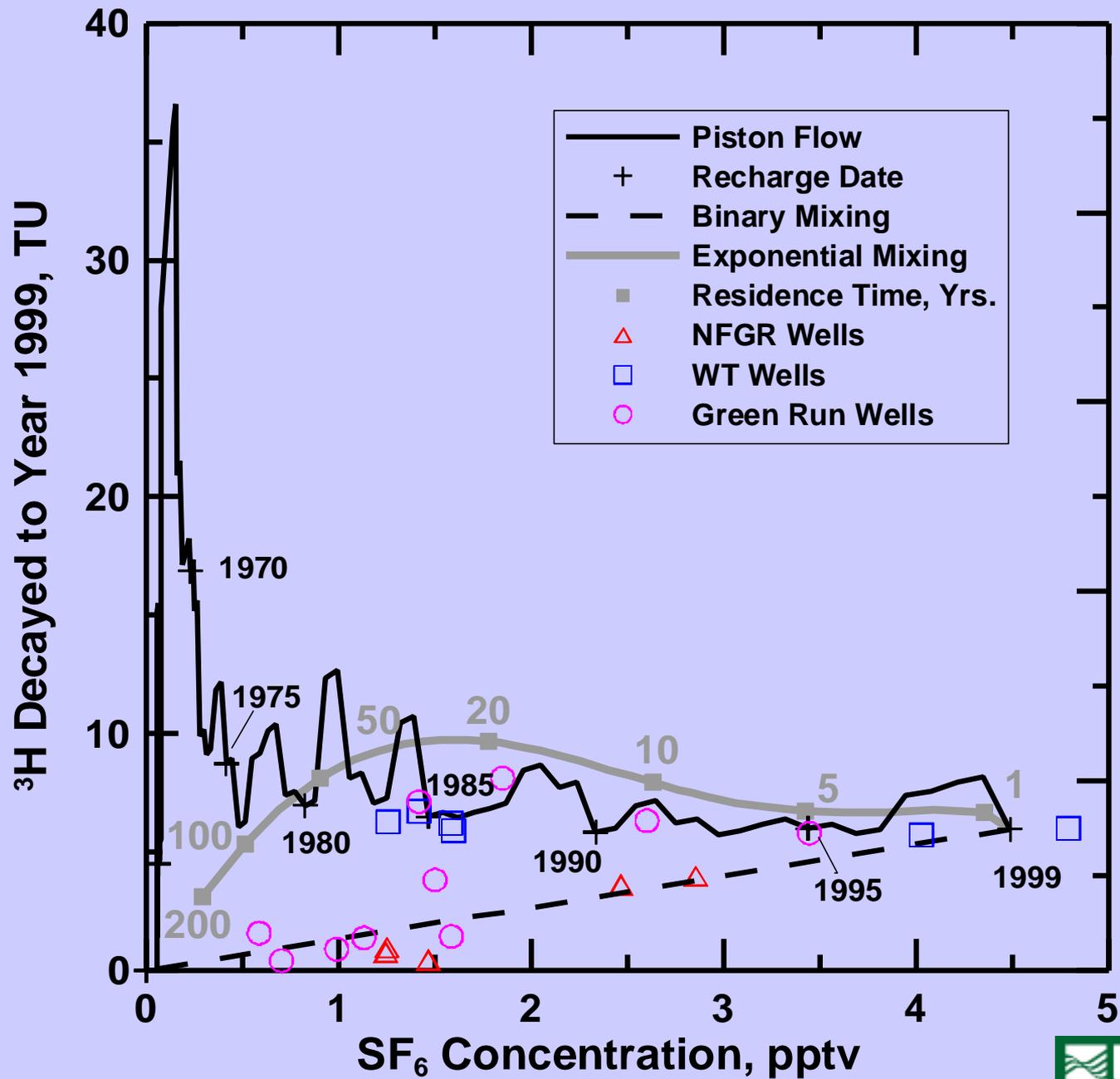












## Bear Lithia Spring (9/2/99)

### Piston-Flow Ages

CFC-11 27.2 yrs

CFC-12 27.2 yrs

CFC-113 >Modern (100 pptv)

$^3\text{H}/^3\text{He}$  30.0 yrs

Agreement in ages suggests  
Piston flow (30 yrs in pipe flow).

### Major Contradiction:

Tritium =  $1.2 \pm 0.2$  TU

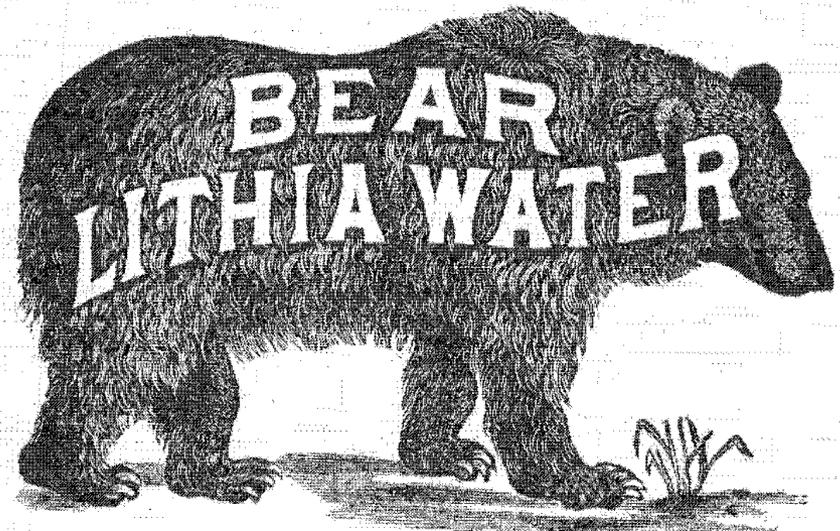
1969.6 water contained

about 130 TU; decays to 25 TU



A. B. C. Expectorant warranted purely vegetable—no narcotics.

**NATURE'S OWN REMEDY!**



Cures KIDNEY and BLADDER Troubles,  
URIC ACID, GOUT, and RHEUMATISM,  
PHOSPHORIC DEPOSITS,

INFLAMMATION OF THE BLADDER,  
DROPSICAL AFFECTIONS,  
BRICK-DUST DEPOSITS,

And all forms of DYSPEPSIA which  
Arise from a Non-Assimilation of Food,  
Such as INDIGESTION, HEARTBURN,

FLATULENCE, SICK HEADACHE  
And a Sense of Fullness After Eating.

For further particulars, address

BEAR LITHIA WATER COMPANY,  
ELKTON, VIRGINIA.

Price, \$3.50 per Case of one dozen half-gallon bottles, f. o. b., at  
Elkton Depot, S. V. R. R., Rockingham county, Va.

AGENTS.—Polk Müller & Co., Richmond; N. Wyatt & Bro.,  
Staunton; E. P. Mertz, Washington, D. C.; P. Schever & Co.,  
New York; W. H. Douglass, Brooklyn, N. Y.

Routt's Emulsion is used and prescribed by the best physicians.

## Bear Lithia Spring (9/2/99)

If we believe the  $^3\text{H}/^3\text{He}$  age:

$^3\text{H} = 1.2 \text{ TU}$

$^3\text{He}(\text{tritogenic}) = 5.2 \text{ TU}$

Initial  $^3\text{H} = 1.2 + 5.2 = 6.4 \text{ TU}$

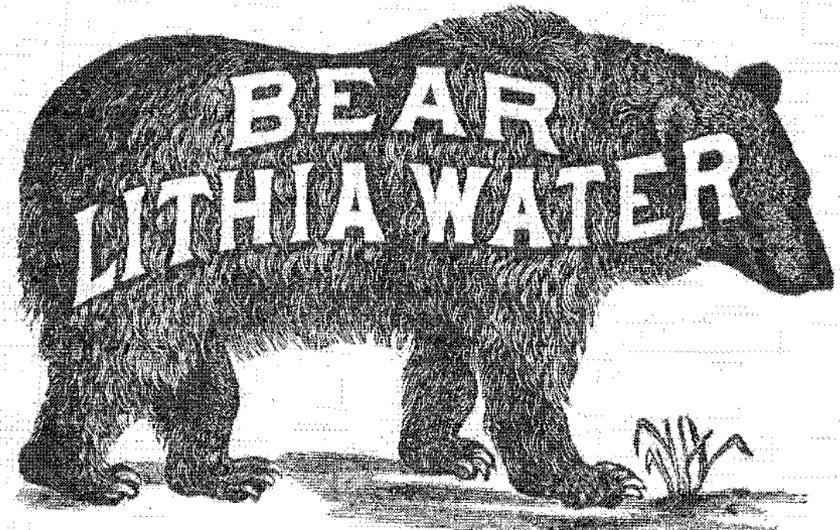
1969.6 precipitation = 130 TU

Samples contains only about  
5% 1969.6 water.



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## Bear Lithia Spring (9/2/99)

Implies CFC-11 and CFC-12 uniquely contaminated.

5% of 1970 air gives:

CFC-11 2.9 pptv

CFC-12 6.4 pptv

Measured:

CFC-11 87.9 pptv

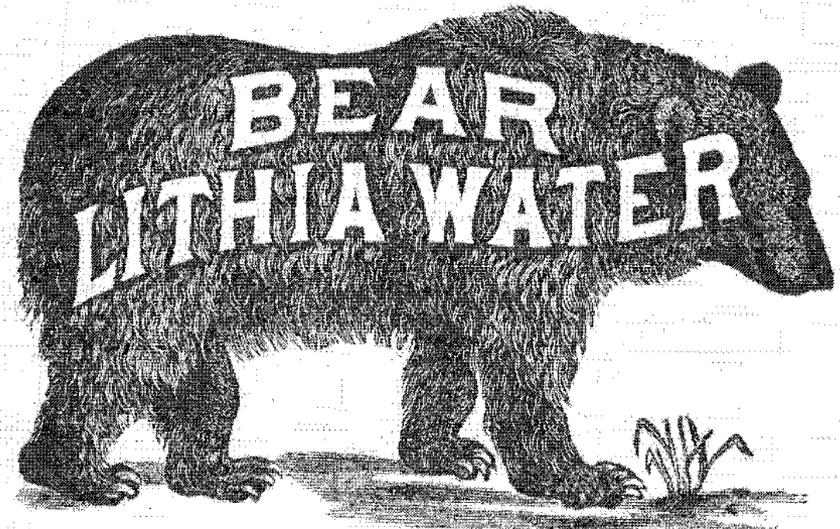
CFC-12 176.1 pptv

Very unusual to have CFC-11 and CFC-12 contaminated in such a way to give identical piston-flow ages.



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Is something wrong with the  $^3\text{H}/^3\text{He}$  age?

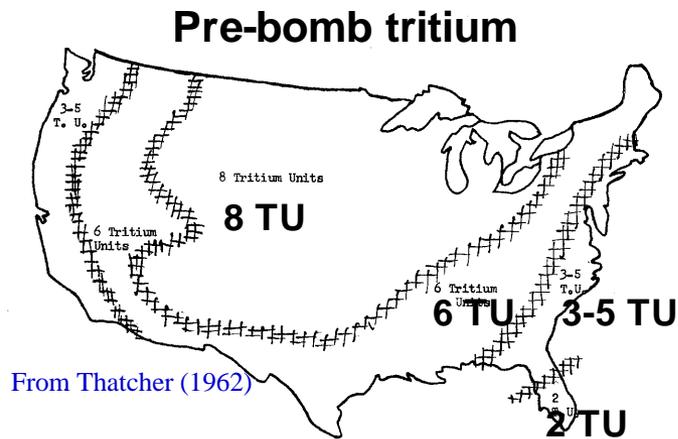


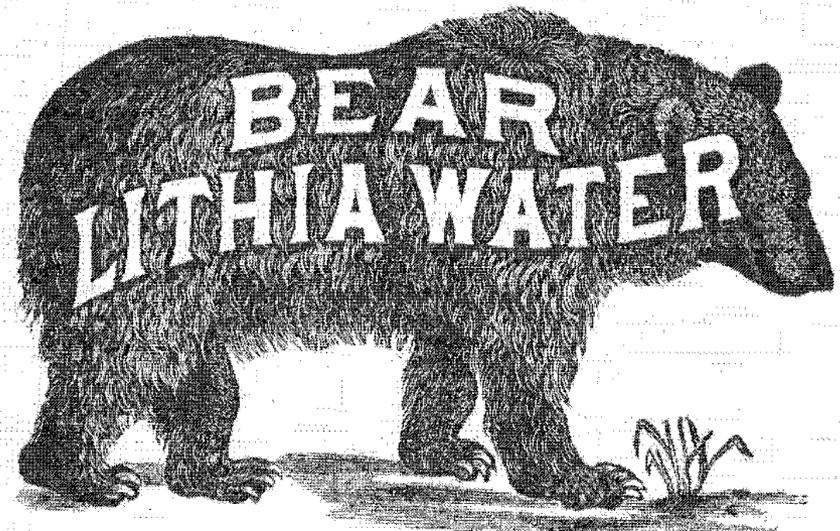
Fig. 2 — Suggested Variation of Natural Tritium Levels.

Sample contains > 90% pre-bomb water; Assumption that pre-bomb tritogenic  $^3\text{He}=0$  may not be valid



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Elkton Depot, S. V. R. R., Rockingham county, Va.

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Staunton; E. P. Mertz, Washington, D. C.; P. Schever & Co.,  
New York; W. H. Douglass, Brooklyn, N. Y.

Routt's Emulsion is used and prescribed by the best physicians.

## Bear Lithia Spring (9/2/99)

Correcting for assumed pre-bomb tritiogenic  $^3\text{He}$ , young fraction varies from 5% at 30 yrs to 12% at 0 yrs age.

From CFC-11: 33.0 % 0 yrs water.  
From CFC-12: 32.8 % 0 yrs water.

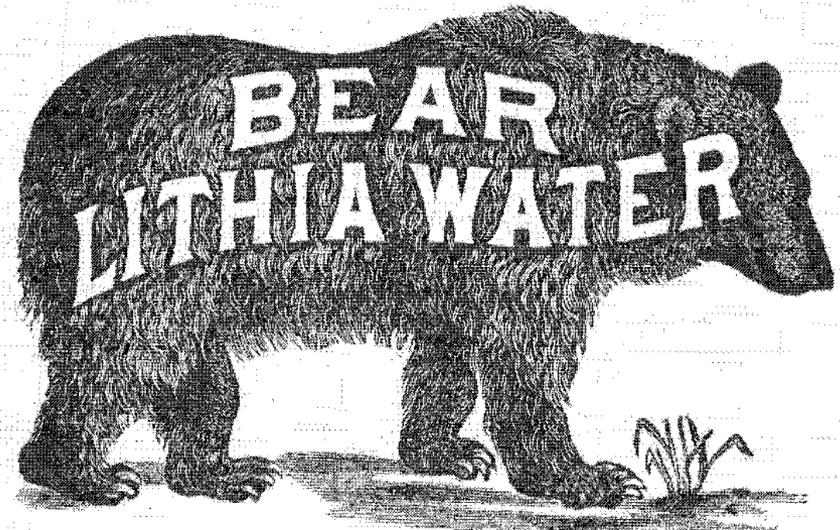
Implies  $^3\text{H}$  should have been around 3 TU instead of 1.2 TU.

**CONCLUSION:** Discharge 67-88 % pre-bomb water mixed with approx. 12-33% modern water.



A. B. C. Expectorant warranted purely vegetable—no narcotics.

**NATURE'S OWN REMEDY!**



**Cures KIDNEY and BLADDER Troubles,  
URIC ACID, GOUT, and RHEUMATISM,  
PHOSPHORIC DEPOSITS,  
INFLAMMATION OF THE BLADDER,  
DROPSICAL AFFECTIONS,  
BRICK-DUST DEPOSITS,**

**And all forms of DYSPEPSIA which  
Arise from a Non-Assimilation of Food,  
Such as INDIGESTION, HEARTBURN,  
FLATULENCE, SICK HEADACHE  
And a Sense of Fullness After Eating.**

For further particulars, address

**BEAR LITHIA WATER COMPANY,  
ELKTON, VIRGINIA.**

Price, \$3.50 per Case of one dozen half-gallon bottles, f. o. b., at  
Elkton Depot, S. V. R. R., Rockingham county, Va.

AGENTS.—Polk Müller & Co., Richmond; N. Wyatt & Bro.,  
Staunton; E. P. Mertz, Washington, D. C.; P. Schever & Co.,  
New York; W. H. Douglass, Brooklyn, N. Y.

Routt's Emulsion is used and prescribed by the best physicians.

# Susceptibility Determination

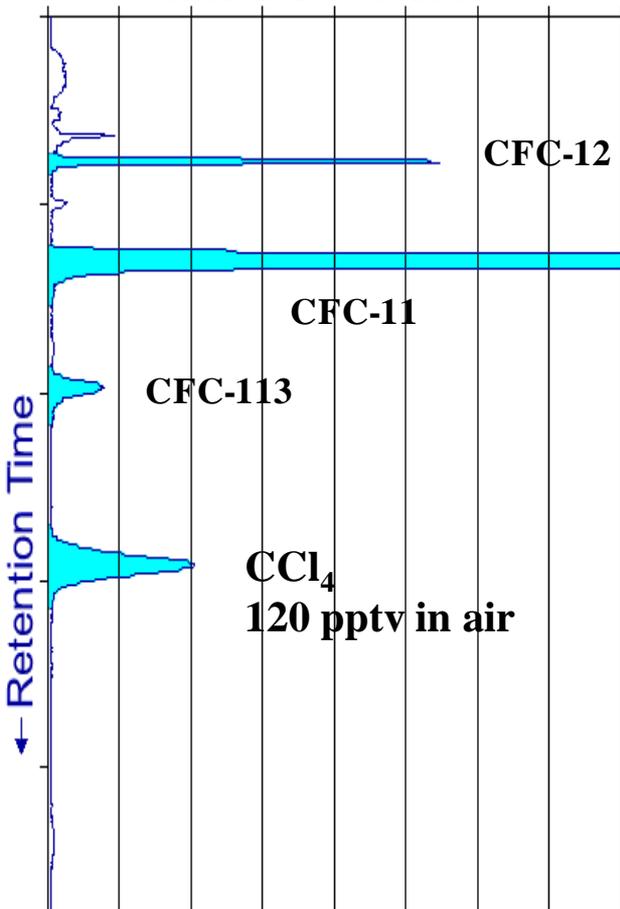
- **Tracer is Present:** Water discharged from the well is susceptible to contamination from anthropogenic inputs.
- **Tracer is “Absent”:** Water discharged from the well is less susceptible to contamination from anthropogenic inputs. (Can never prove that the source is not susceptible—lower and lower detection limits)

# GC-ECD Chromatograms

- Analysis by GC-ECD: Purge and trap gas chromatography with electron-capture detector.
- Detects halogenated VOCs (examples: CFCs,  $\text{CCl}_4$ , Halons, TCE, TCA, etc).
- Traditional analysis: GC-MS  $< 0.1 \text{ ug/L}$  (=  $100 \text{ ng/L} = 100,000 \text{ pg/L}$ )
- GC-ECD:  $< 1 \text{ pg/L}$  (= 5 orders of magnitude below normal reporting levels)

**Shenandoah National Park  
Spring  
Drinking Water  
Modern Clean Water**

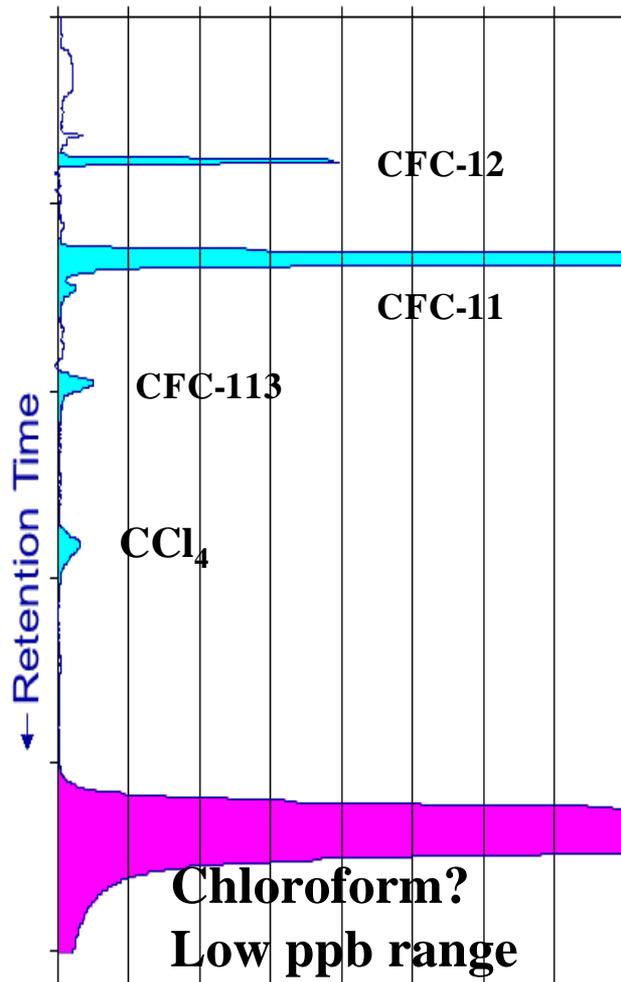
Relative Concentration



**Spring, Clean  
Modern Water**

**Spring  
Yorktown, VA  
Drinking Water**

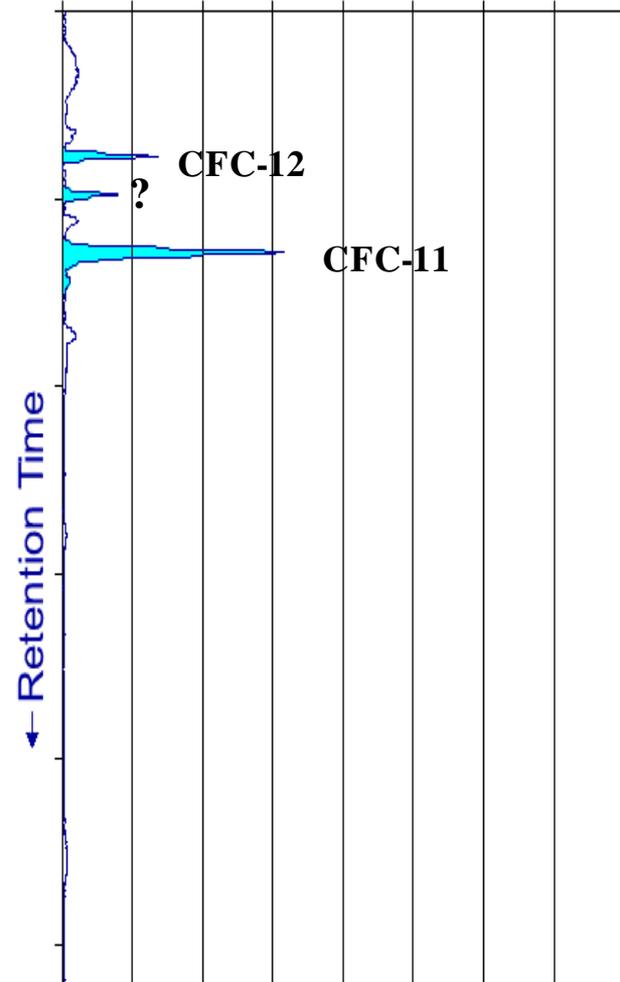
Relative Concentration



**10 Year Old Water**

**Fort Wainright  
Fairbanks, AK  
(Air Force Base)**

Relative Concentration



**25 Year Old Water**

A Town well in VA

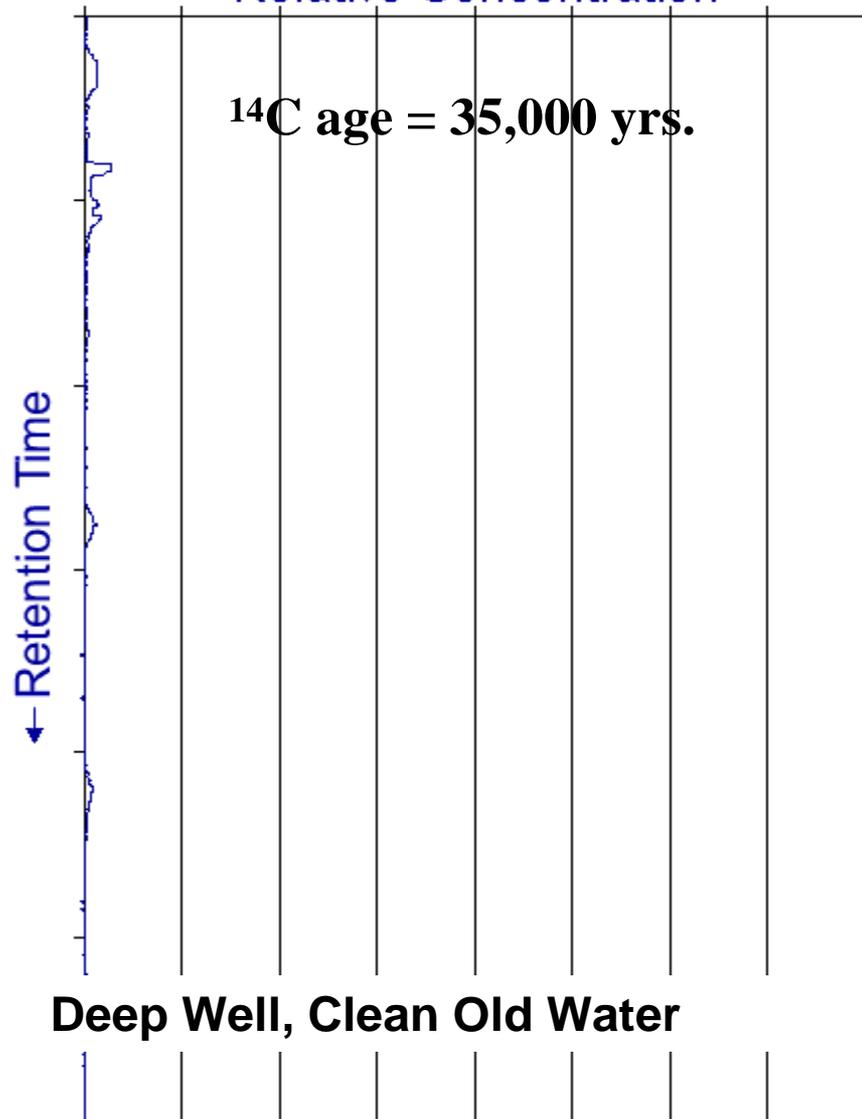
Depth: 135 (125-136) meters

Drinking Water Well

Atlantic Coastal Plain

Water Greater than 60 Years old

Relative Concentration



A Town well in VA

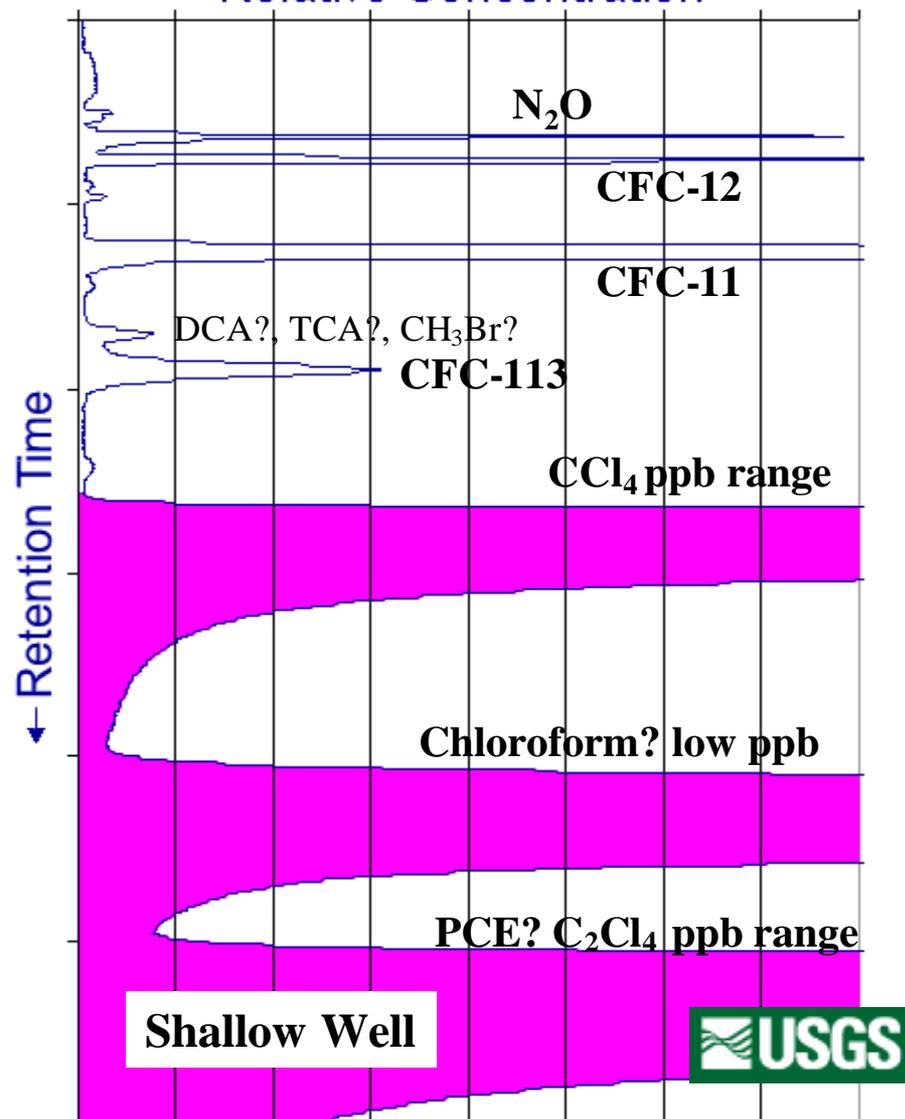
Depth: 18 (13-18) meters

Drinking Water Well

Atlantic Coastal Plain

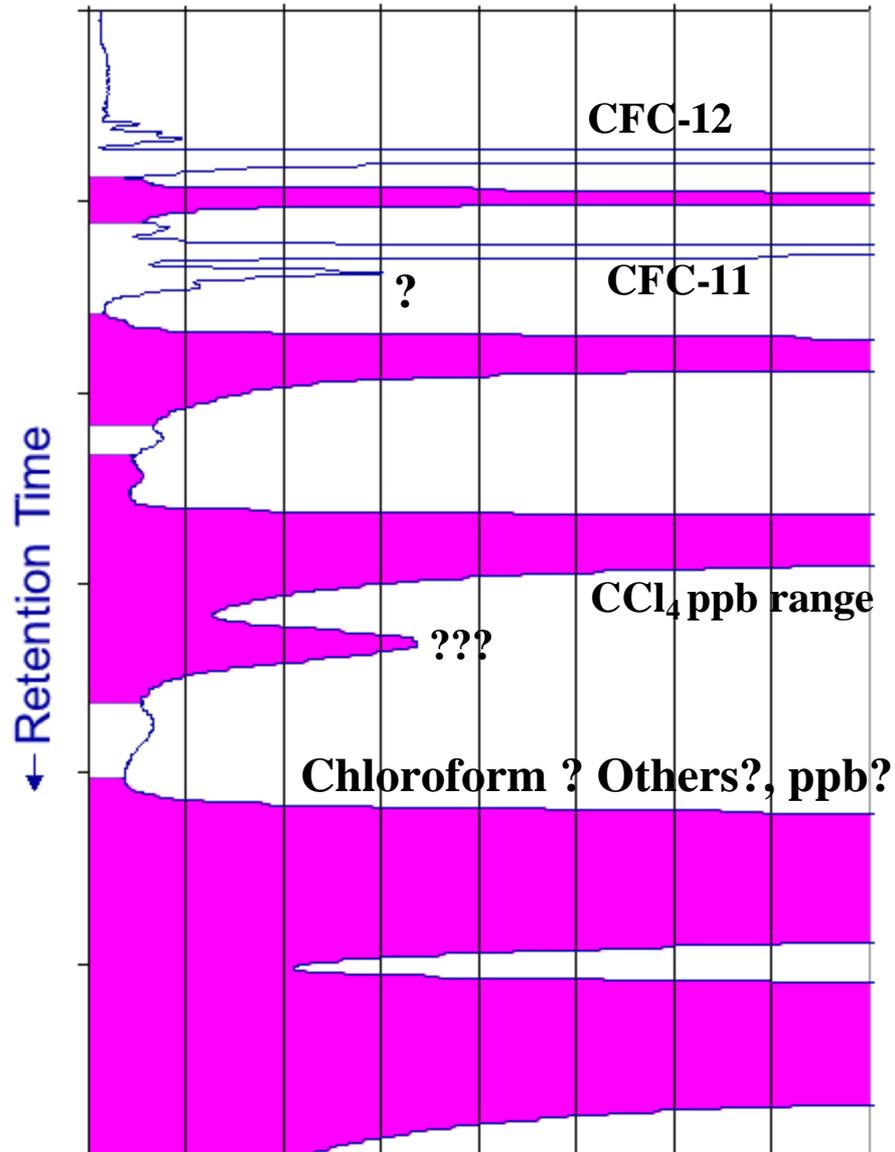
Apparent Age: 16-20 years

Relative Concentration



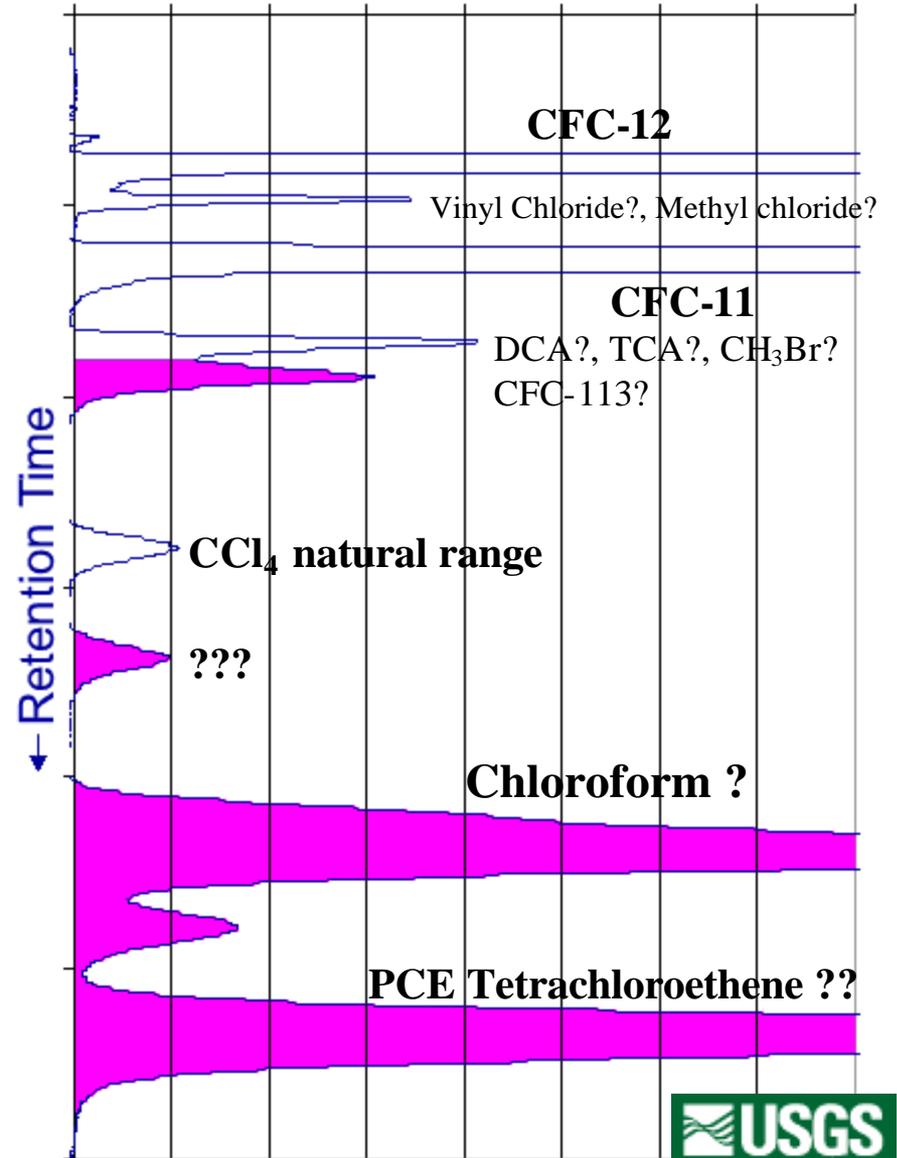
**A Town well in VA**  
Drinking Water Well  
Depth: 190 meters  
Valley and Ridge

Relative Concentration

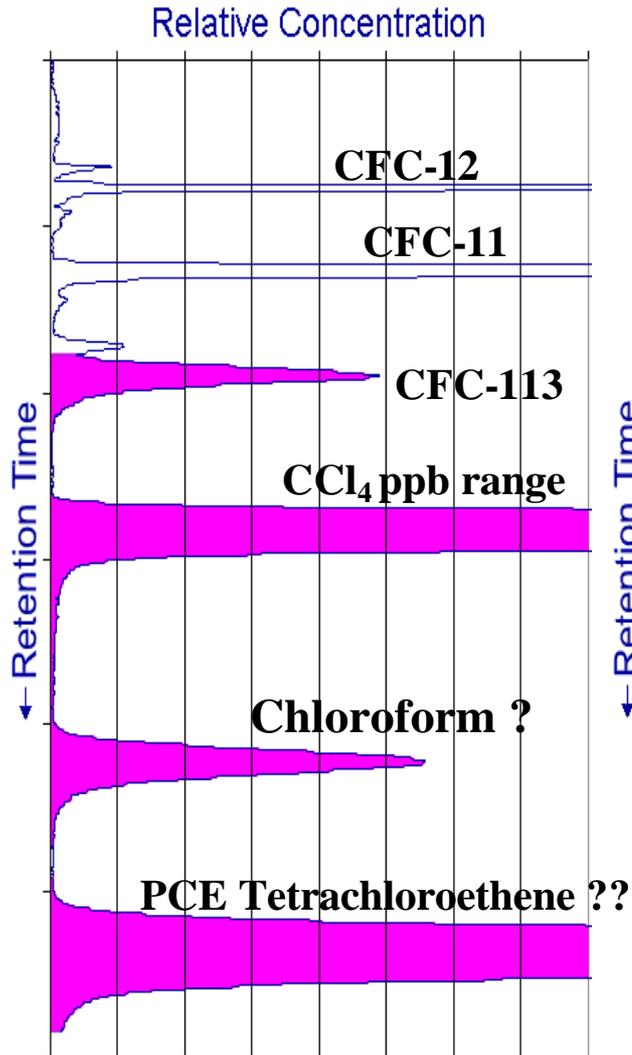


**A Town well in VA**  
Drinking Water Well  
Depth: 115 meters  
Blue Ridge

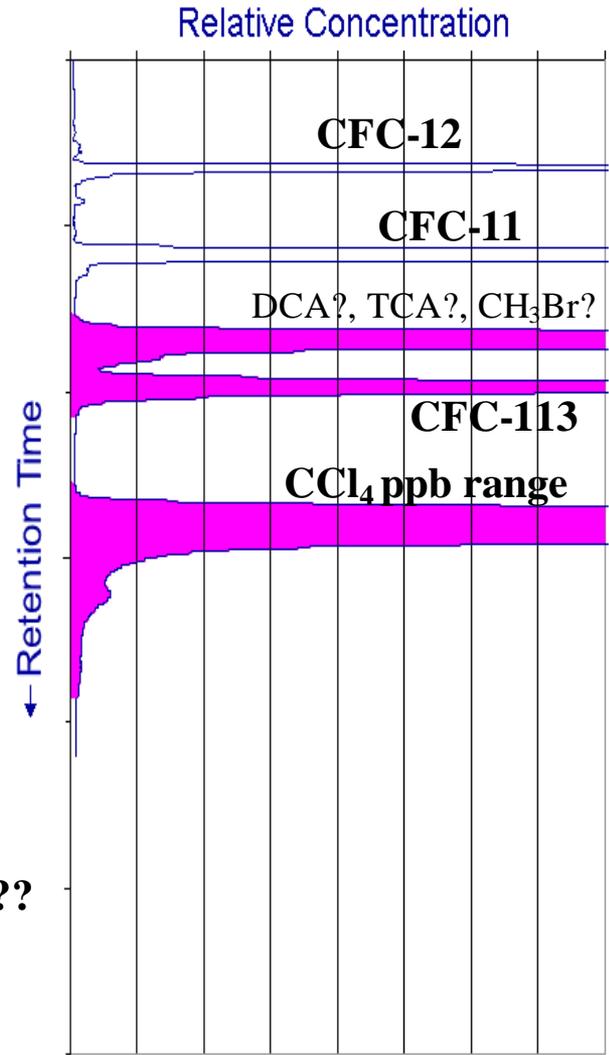
Relative Concentration



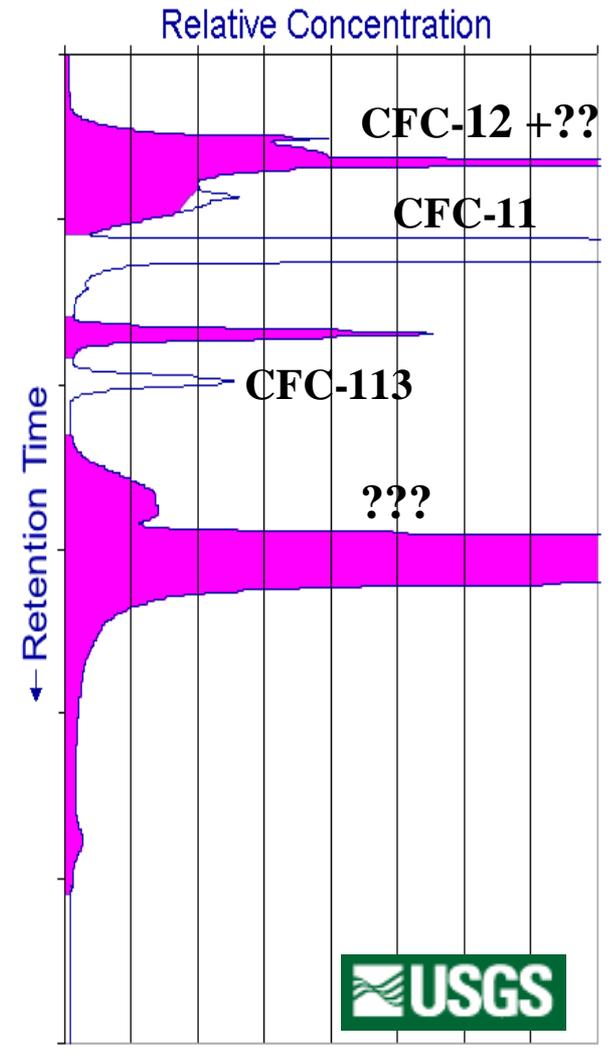
**A Town well in VA**  
Drinking Water Well  
Depth: 186m  
Blue Ridge



**A Town well in VA**  
Drinking Water Well  
Depth: 85m  
Blue Ridge

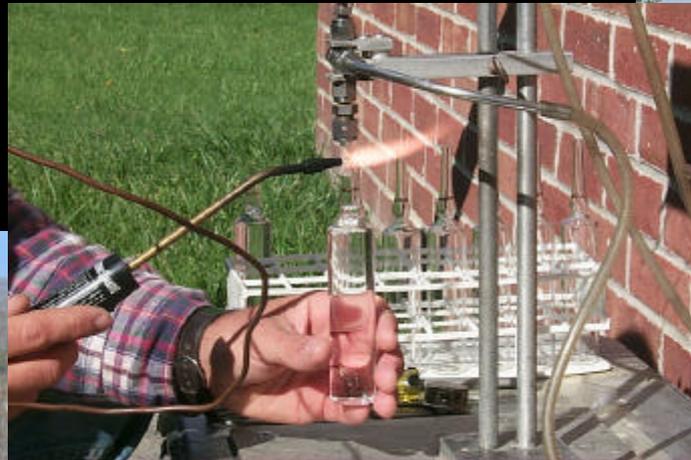


**A Town well in VA**  
Drinking Water Well  
Depth: 122m  
Piedmont



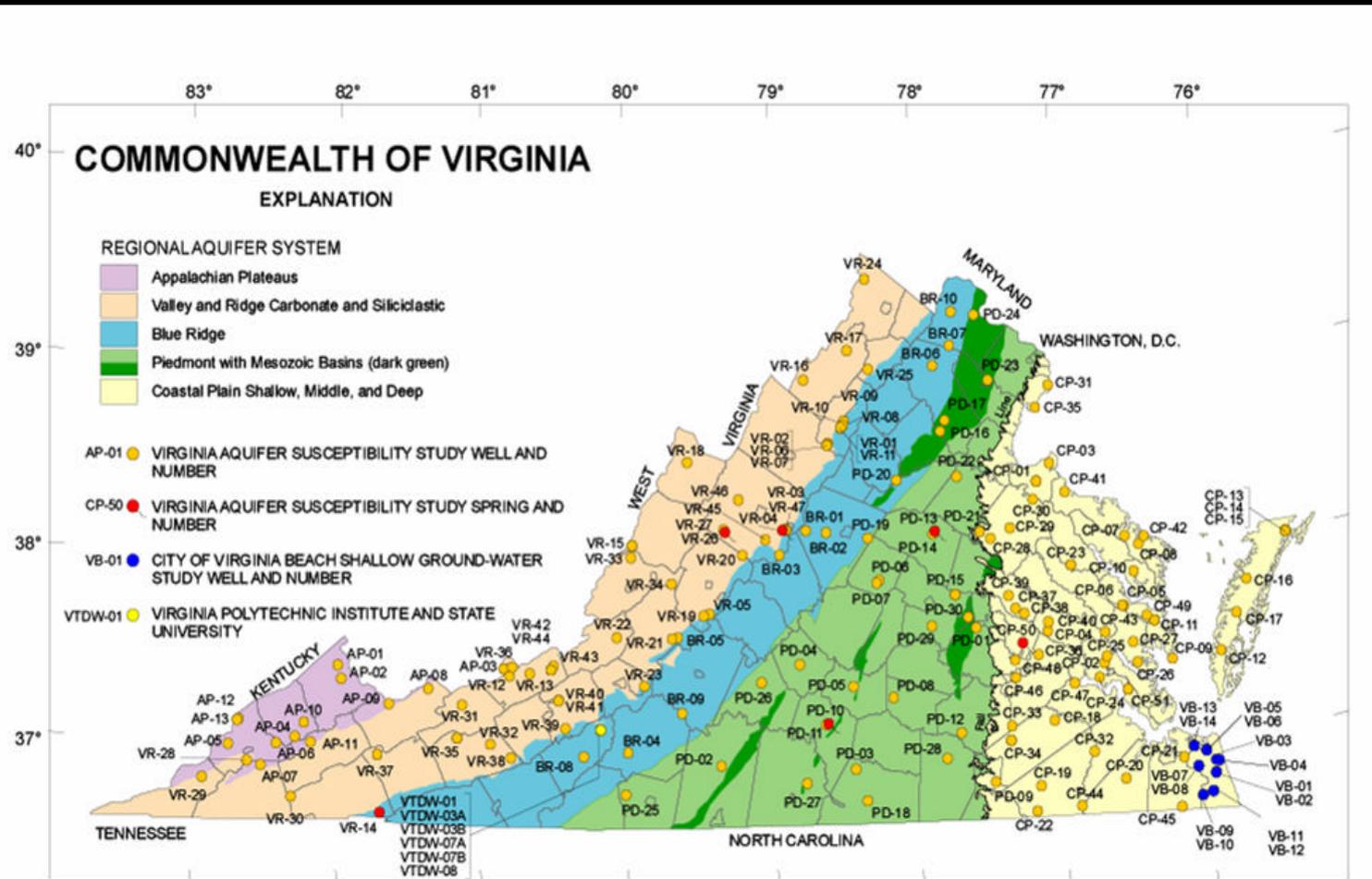
# Aquifer Susceptibility in Virginia, 1998-2000

Nelms, D.L. and others,  
2003, USGS  
WRIR 03-4278



<http://water.usgs.gov/pubs/of/2003/ofr03-246/ofr03-246.htm>

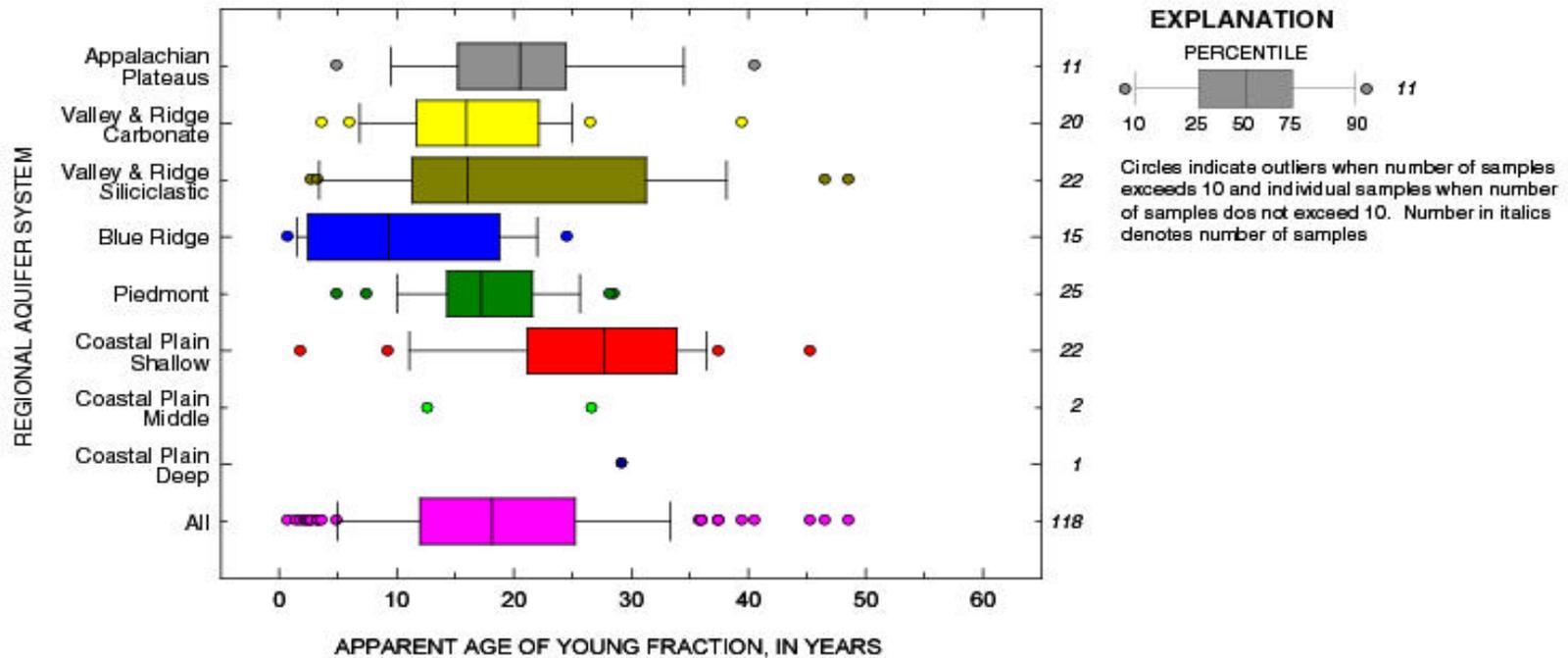
# Regional aquifer systems and sample locations



Province boundaries modified from Virginia Division of Mineral Resources (2003).

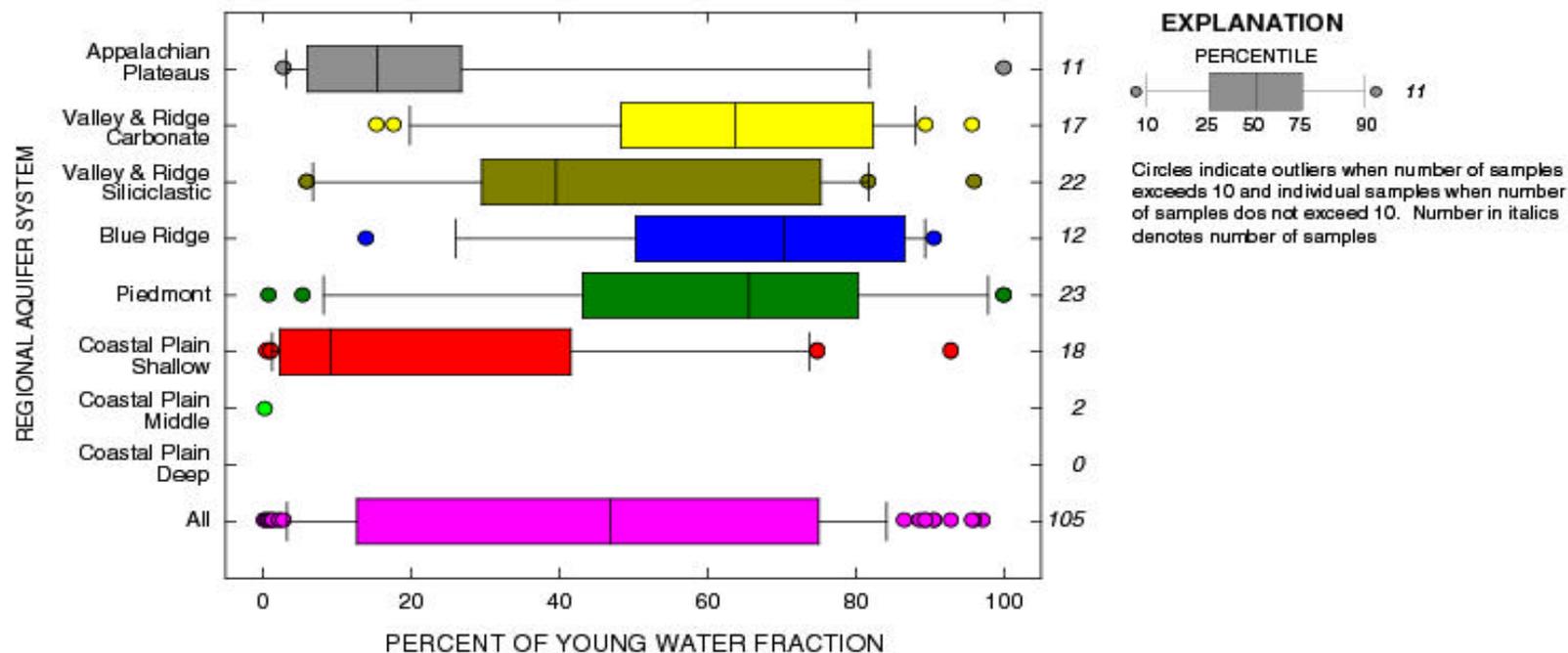
Figure 1. Location of wells and springs sampled in Virginia, 1998-2000.

# Apparent age of young water fraction



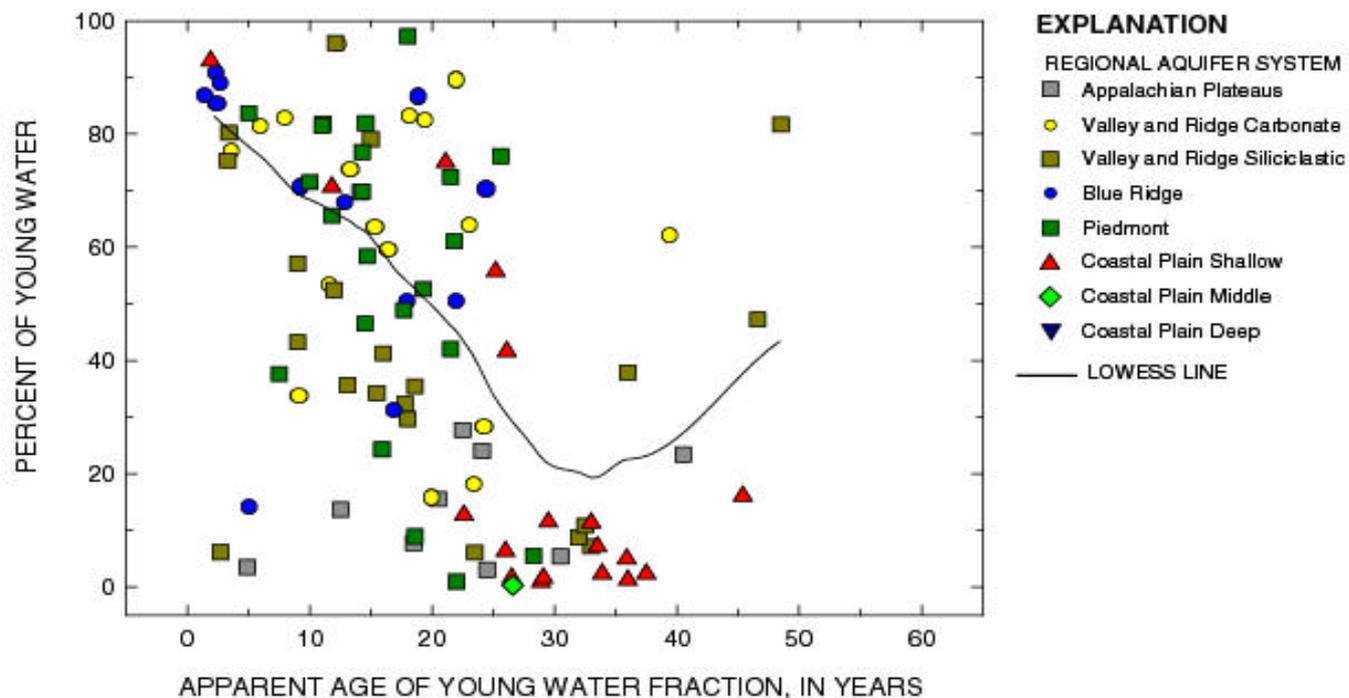
**Figure 6.** Distribution of apparent age of young fraction in binary mixtures with old (pre-chlorofluorocarbon) waters by regional aquifer system.

# Percentage of young water fraction



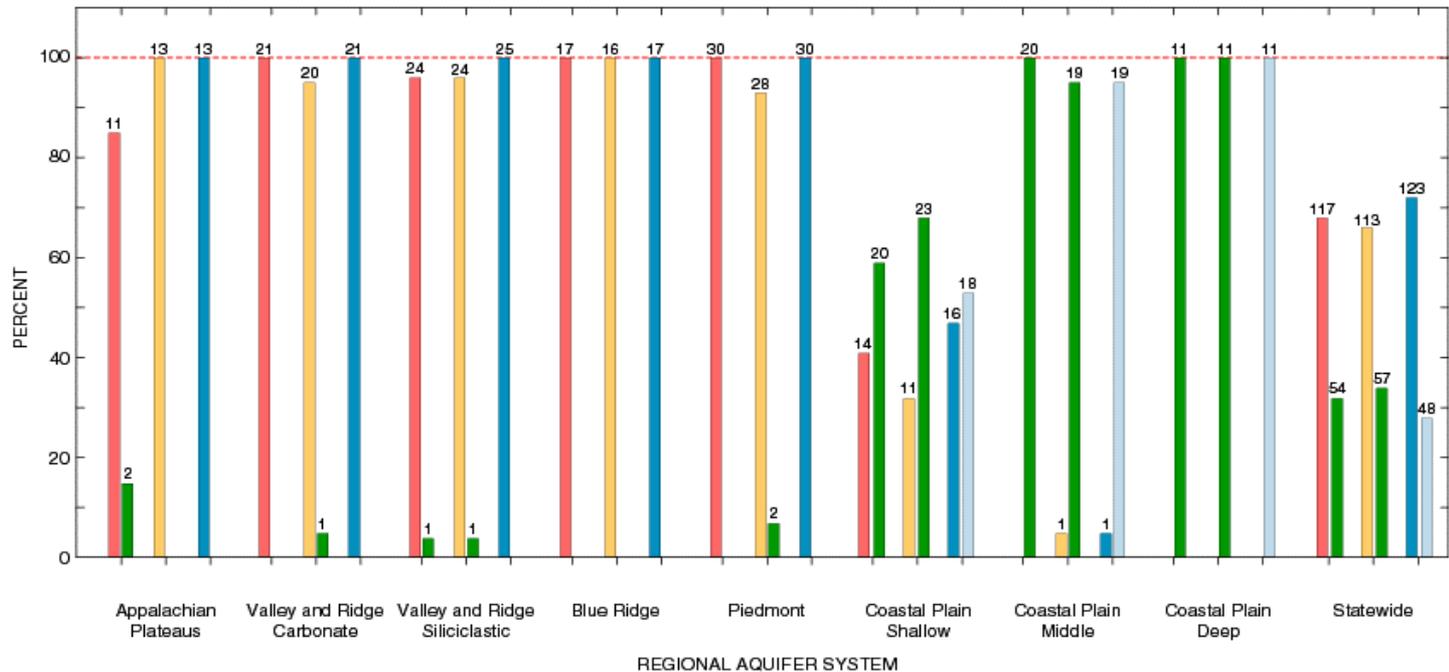
**Figure 7.** Distribution of young water fraction in binary mixtures with old (pre-chlorofluorocarbon) waters by regional aquifer system. Numbers in italics indicate number of samples.

## Percentage and apparent age of young water fraction



**Figure 8.** Comparison of percent and apparent age of young water fraction in binary mixtures with old (pre-chlorofluorocarbon) waters by regional aquifer system.

# Exceedance of threshold CFC and tritium concentrations



## Threshold Values

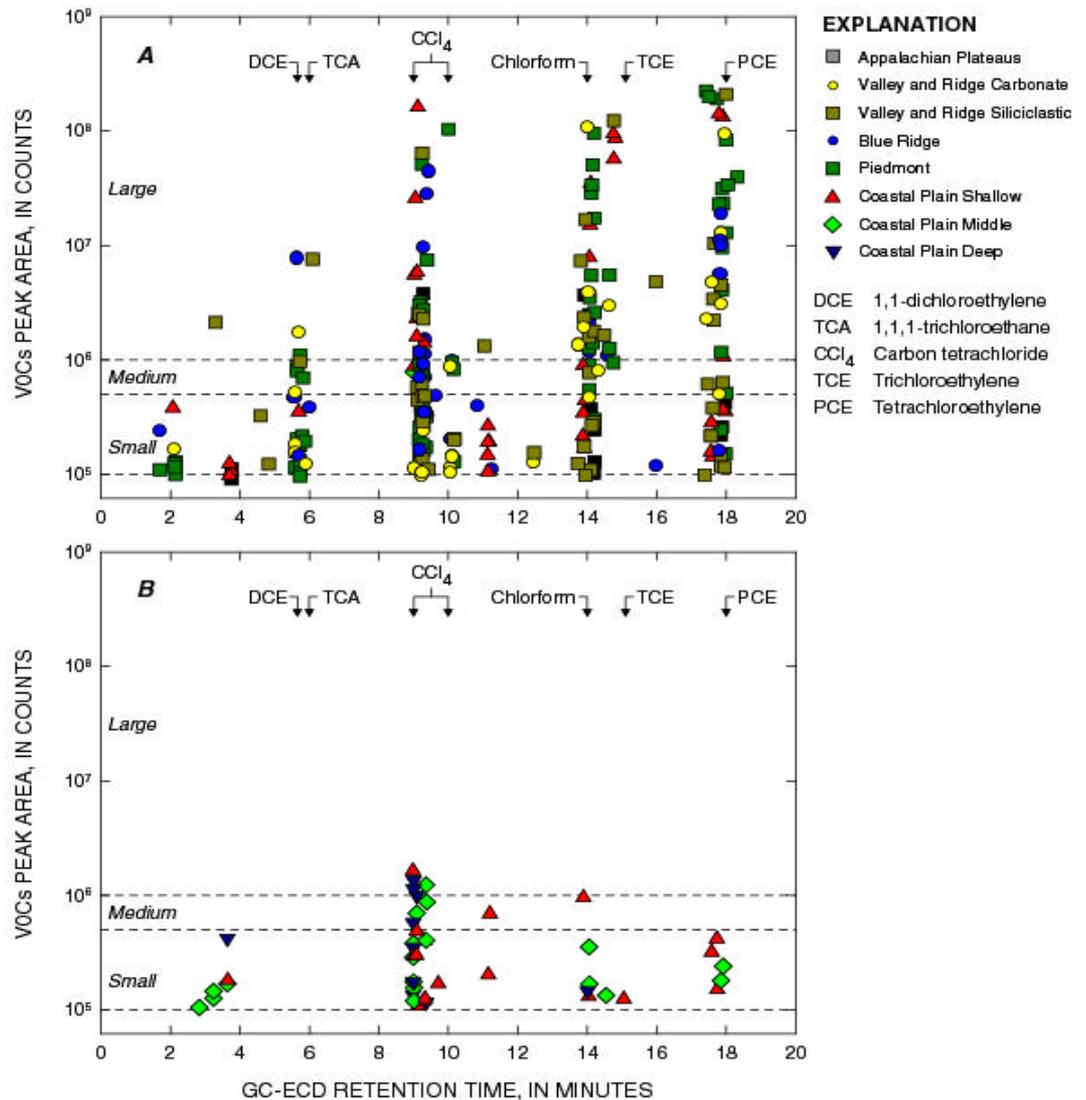
CFCs-- 5 pg/kg

Tritium-- 0.6 TU

- EXPLANATION**
- THRESHOLD CHLOROFLUOROCARBON CONCENTRATION EXCEEDED
  - THRESHOLD TRITIUM CONCENTRATION EXCEEDED
  - THRESHOLD CHLOROFLUOROCARBON OR TRITIUM CONCENTRATION NOT EXCEEDED
- SUSCEPTIBILITY DETERMINATION**
- SUSCEPTIBLE
  - NOT SUSCEPTIBLE

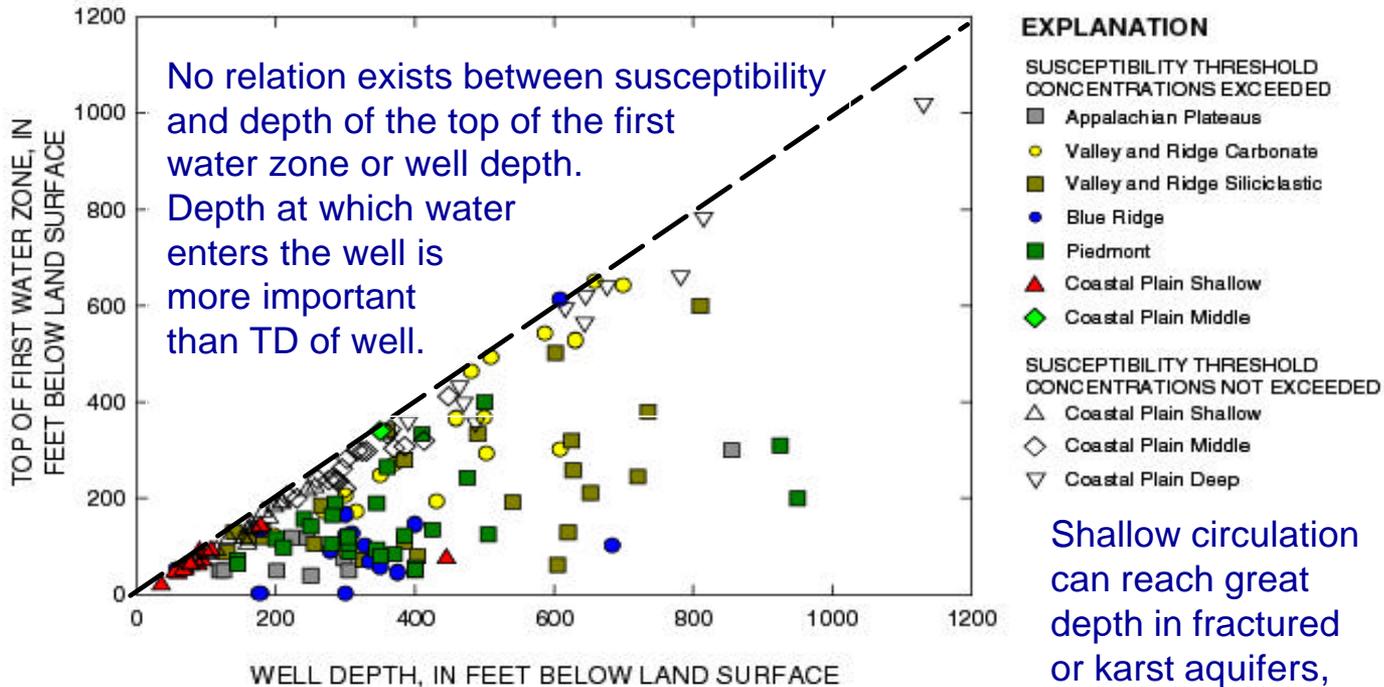
Figure 4. Exceedance of threshold chlorofluorocarbon and tritium concentrations and susceptibility determinations by regional aquifer system.

# VOCs detections and susceptibility thresholds



**Figure 17.** Comparison of peak areas and retention times for volatile organic compounds (VOCs) from gas chromatography with an electron capture detector (GC-ECD) analysis for samples that exceeded susceptibility threshold concentrations (A) and for samples that did not exceed susceptibility threshold concentrations (B). Data from Shapiro and others (2002).

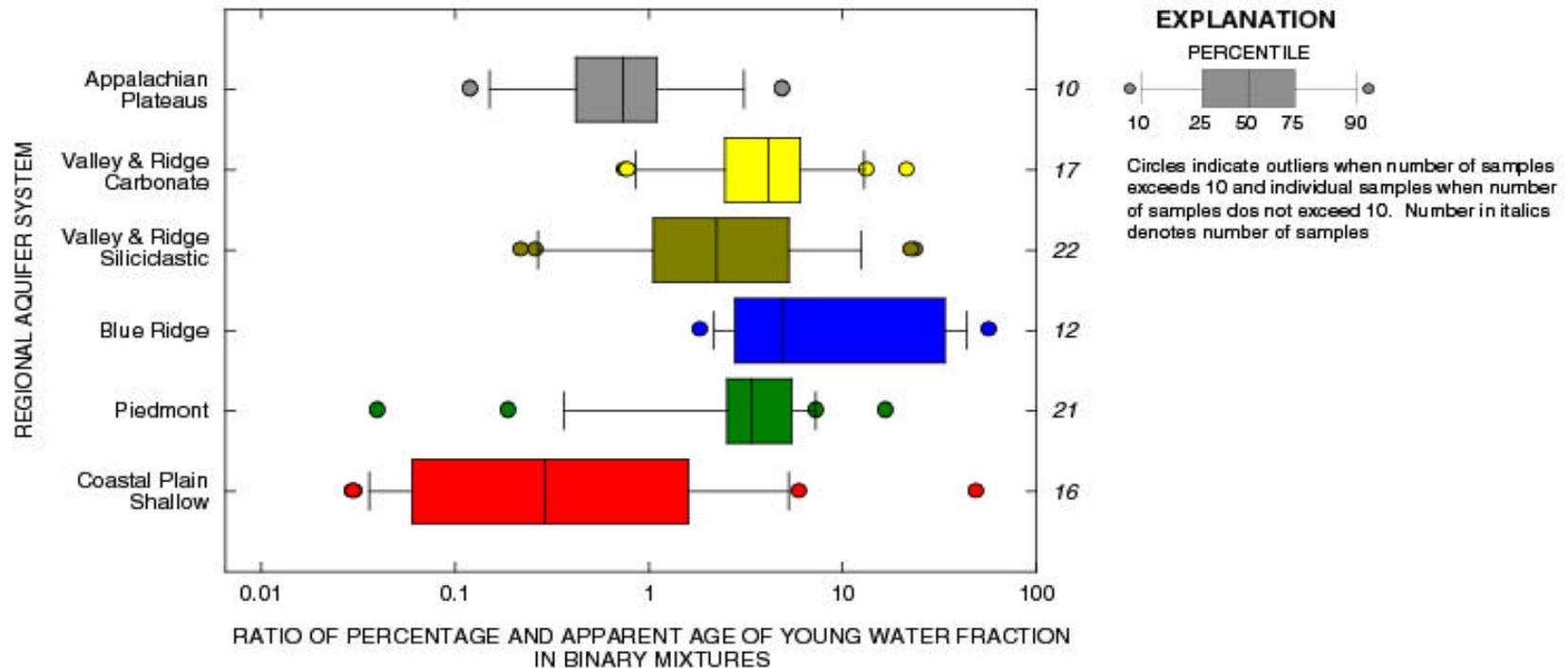
# Susceptibility thresholds and depths



Shallow circulation can reach great depth in fractured or karst aquifers, due in part to pumpage.

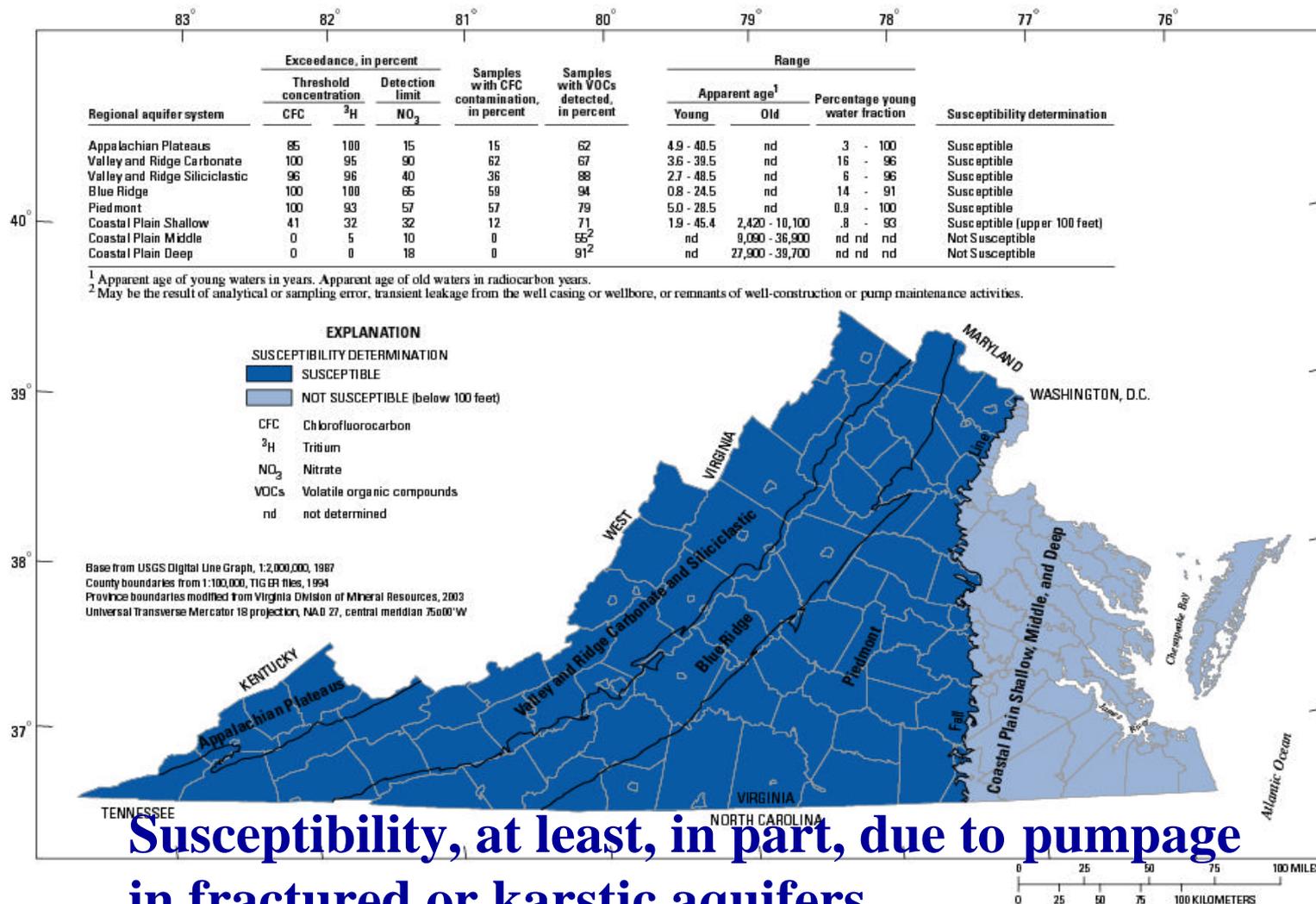
Figure 19. Comparison of depth to top of first water zone and well depth to exceedance of susceptibility threshold concentrations by regional aquifer system.

# Degree of aquifer susceptibility



**Figure 20.** Distribution of the ratio of the percentage and apparent age of the young water fraction in binary mixtures with old (pre-chlorofluorocarbon) waters by regional aquifer system.

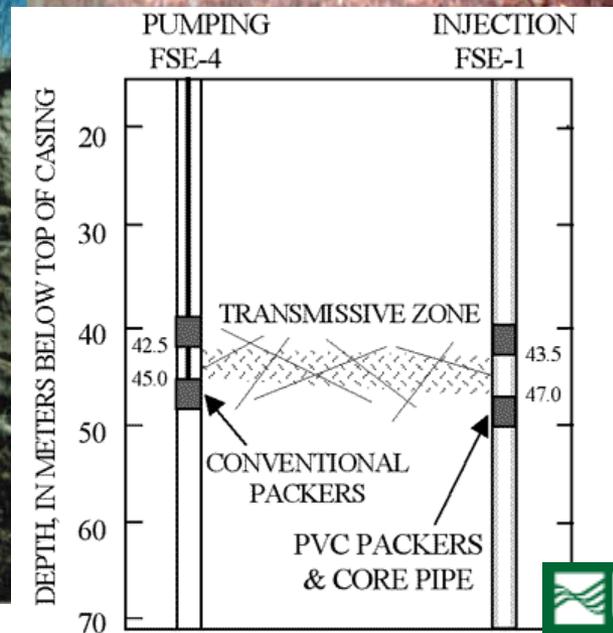
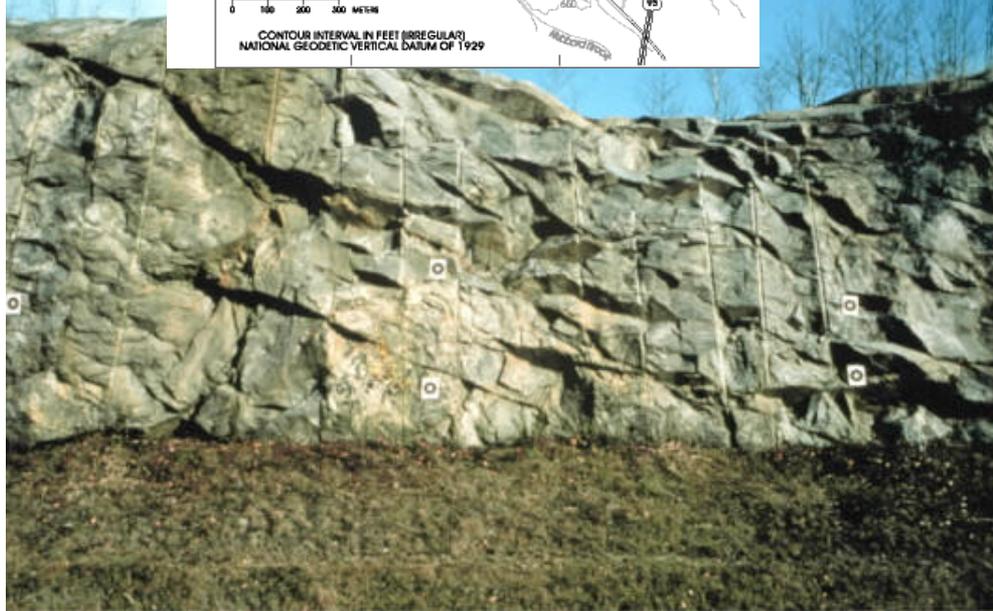
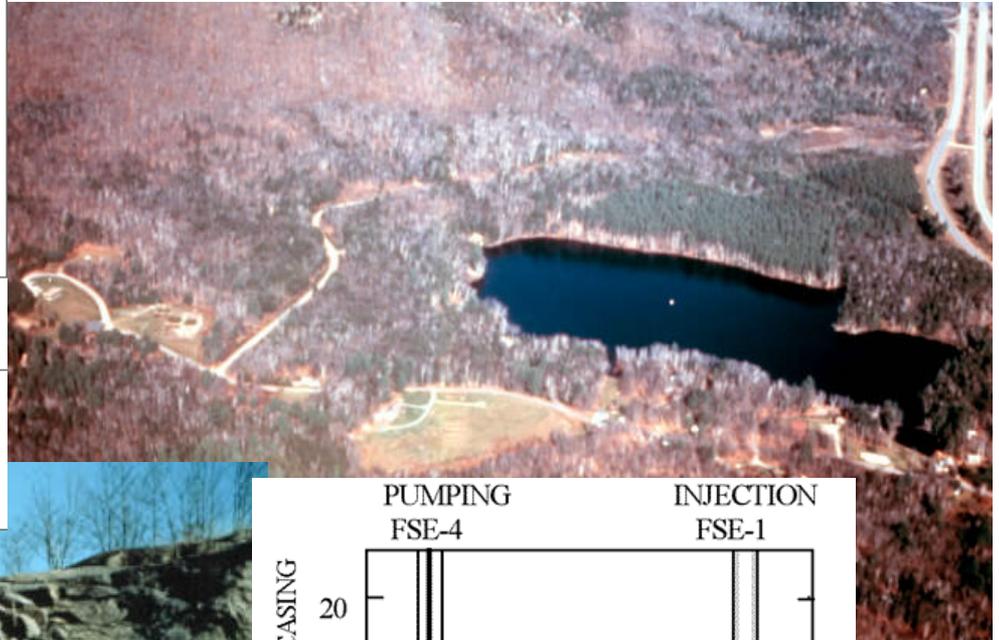
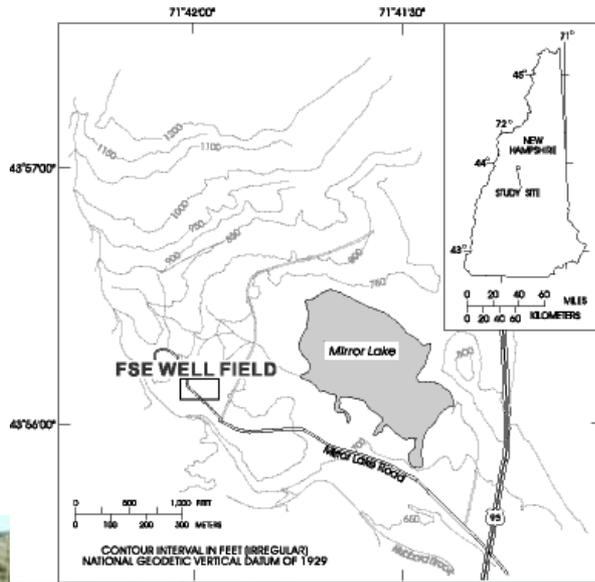
# Aquifer Susceptibility in Virginia



**Susceptibility, at least, in part, due to pumpage in fractured or karstic aquifers.**

Figure 19. Susceptibility to contamination from near-surface sources of the regional aquifer systems in Virginia, 1998-2000.

# Fractured-rock aquifers near Mirror Lake, New Hampshire, have highly varied and complex hydrologic characteristics.



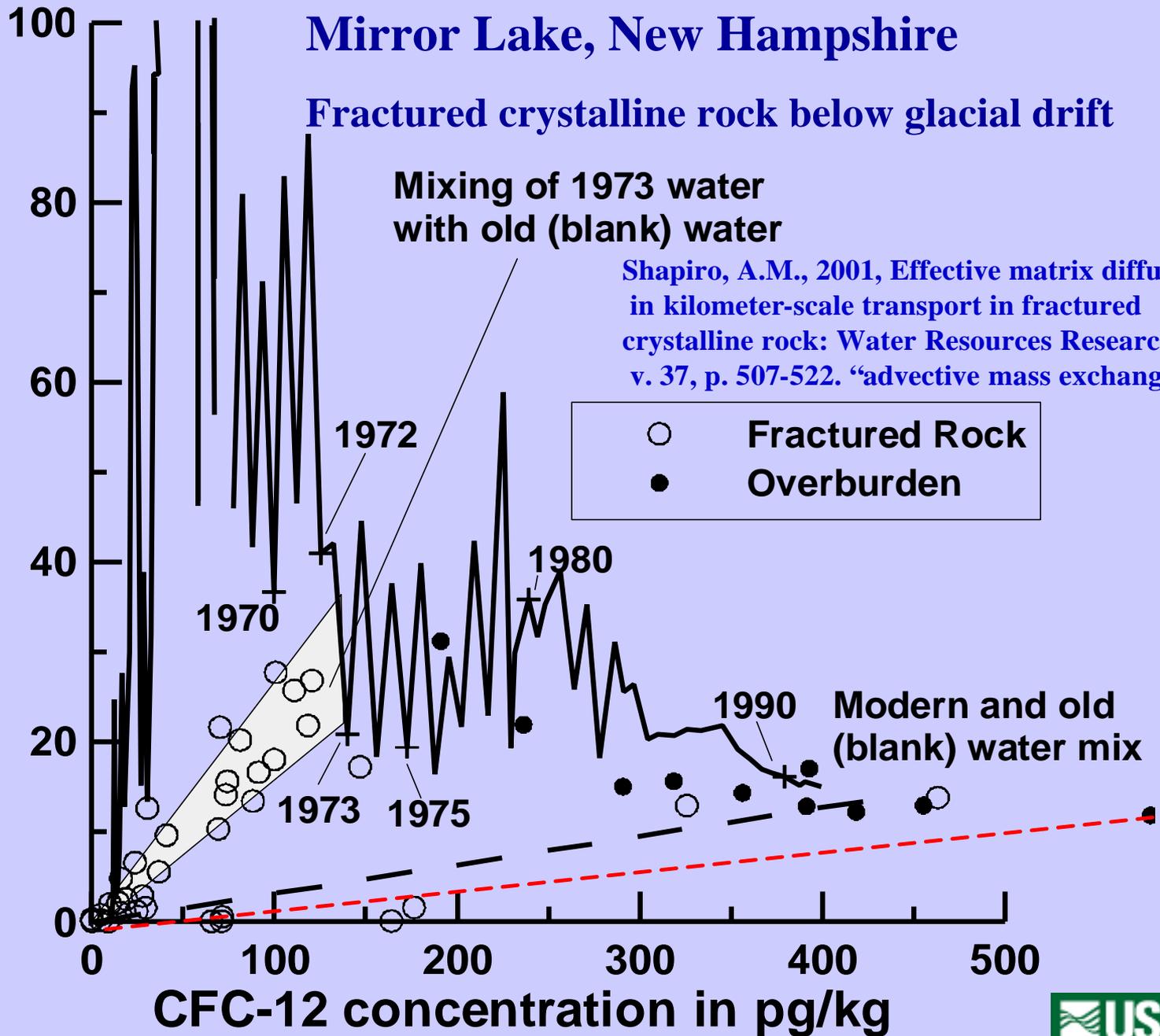
Tritium in precipitation decayed to 1992

# Mirror Lake, New Hampshire

Fractured crystalline rock below glacial drift

Mixing of 1973 water with old (blank) water

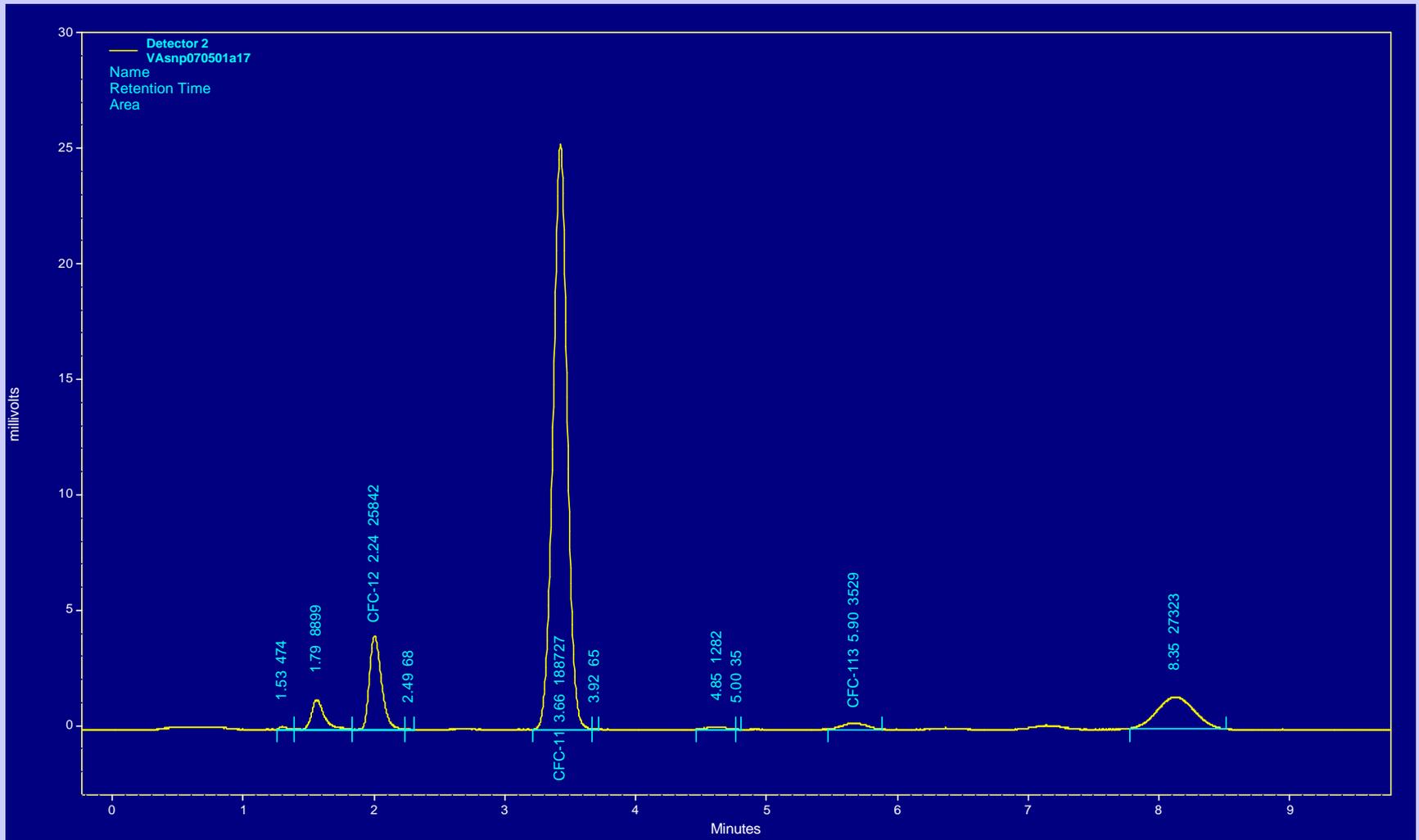
Shapiro, A.M., 2001, Effective matrix diffusion in kilometer-scale transport in fractured crystalline rock: *Water Resources Research*, v. 37, p. 507-522. "advective mass exchange"



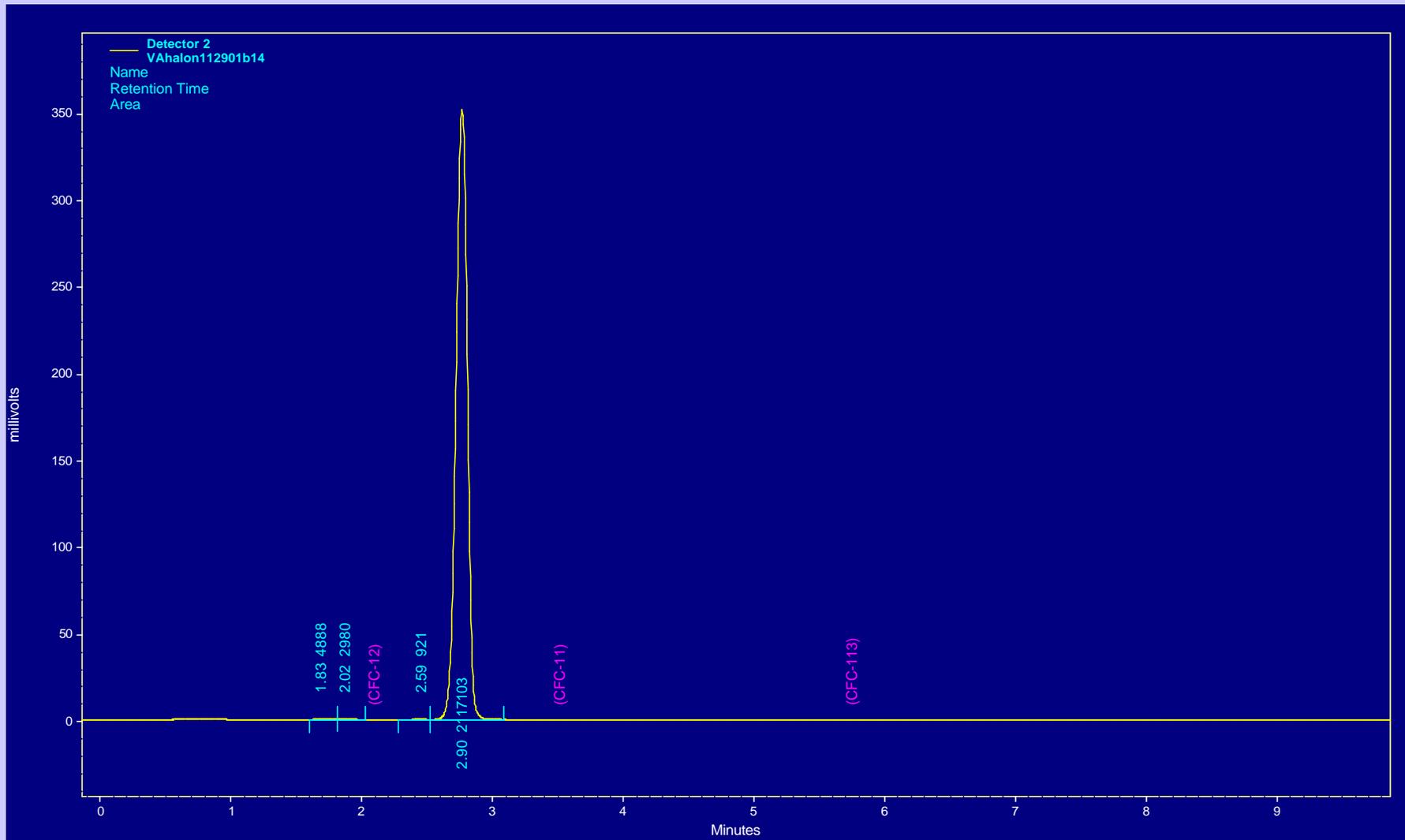


**Halon 1211  
Drilling Tracer**

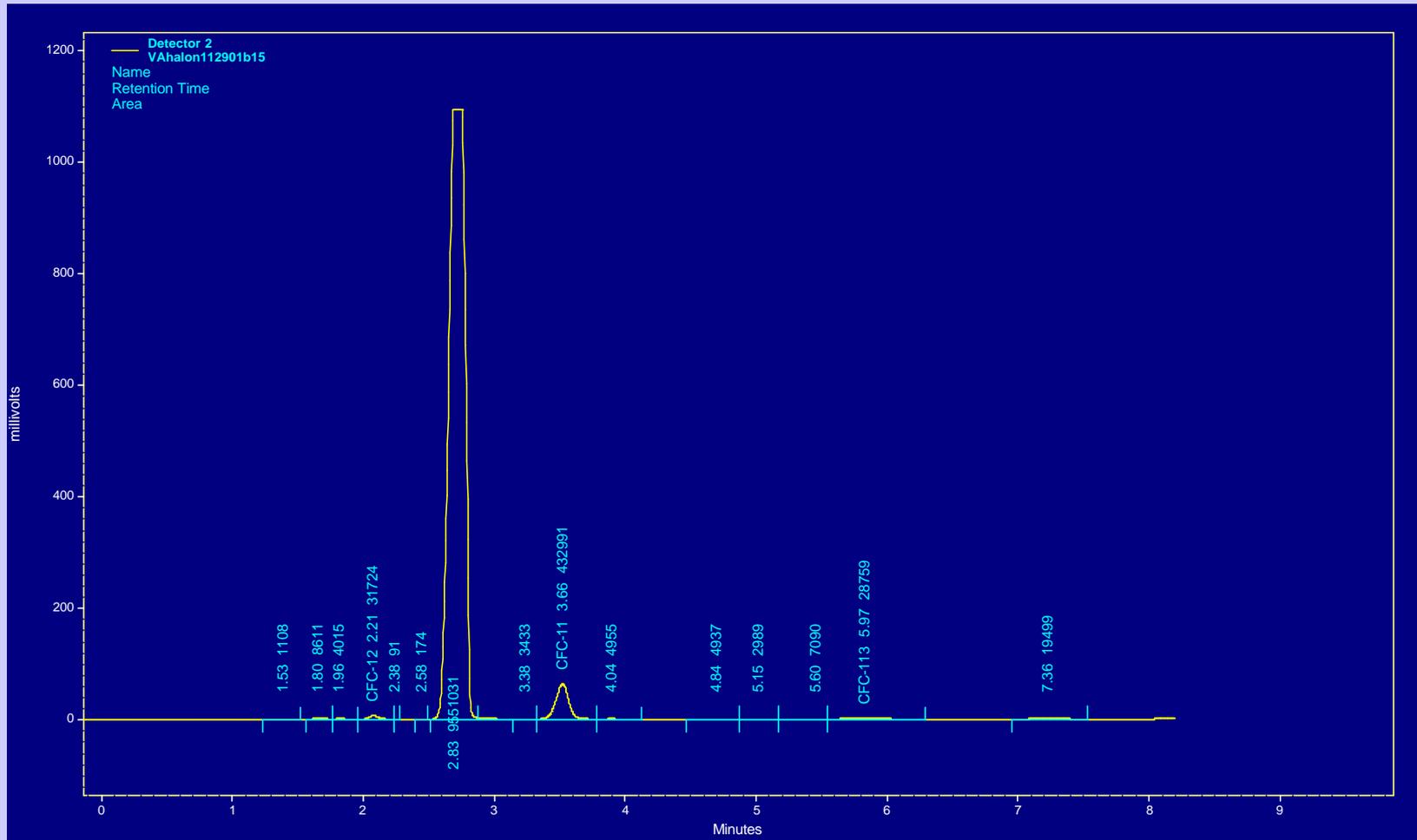




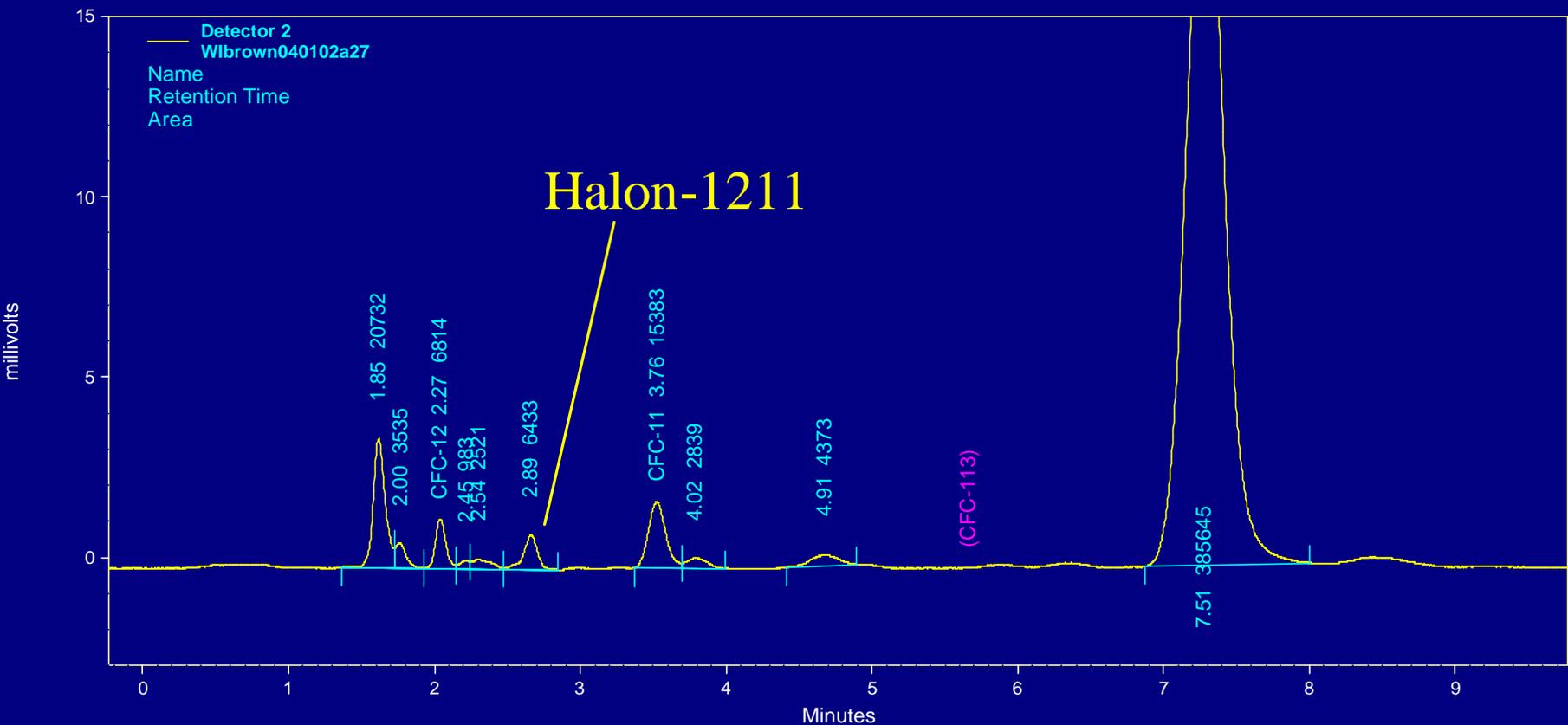
**Hudson spring, Luray, VA Approximately 1970 water**



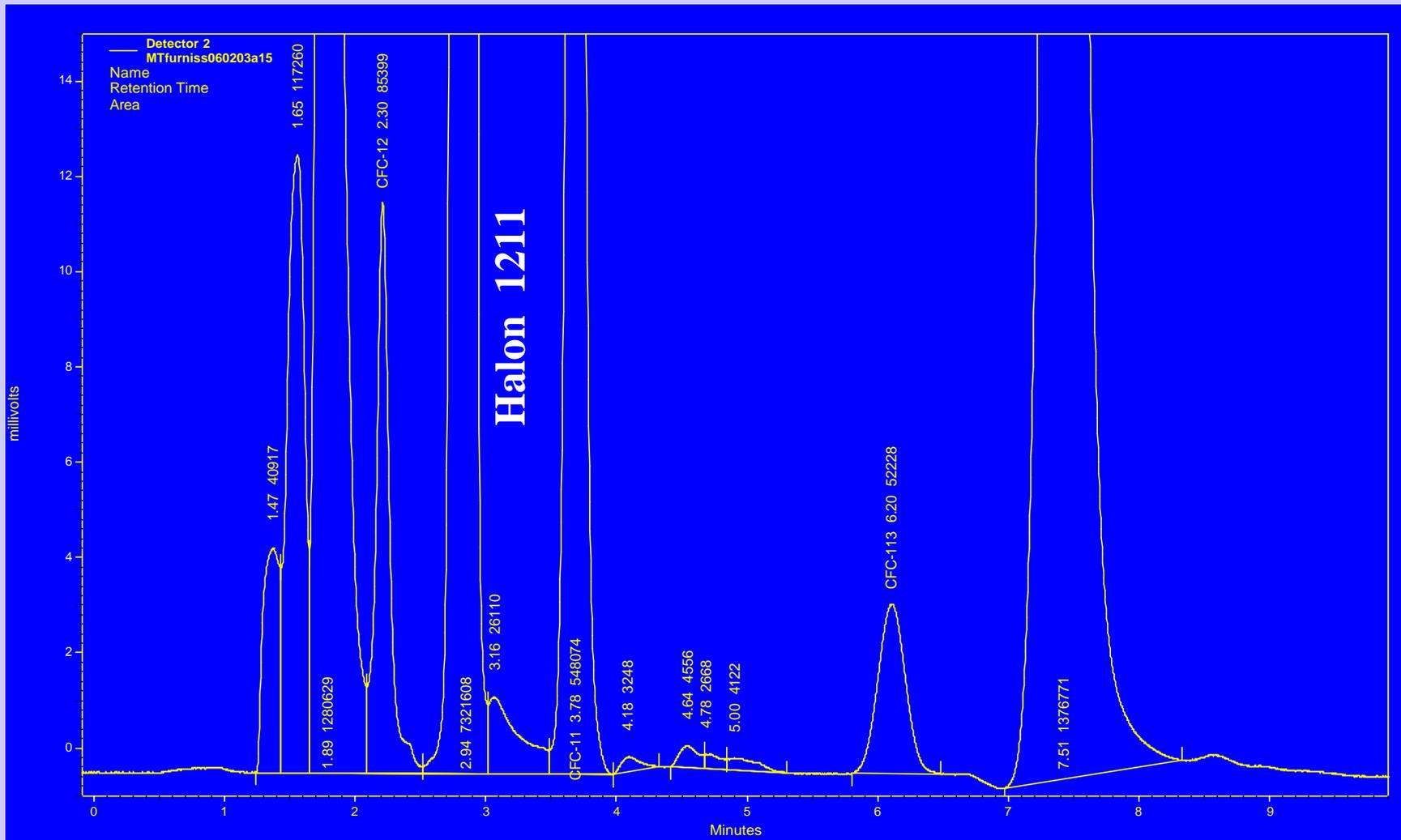
**Chromatogram of 1.16 cubic centimeter of nitrogen containing a concentration of 0.59 parts per billion Halon 1211.**



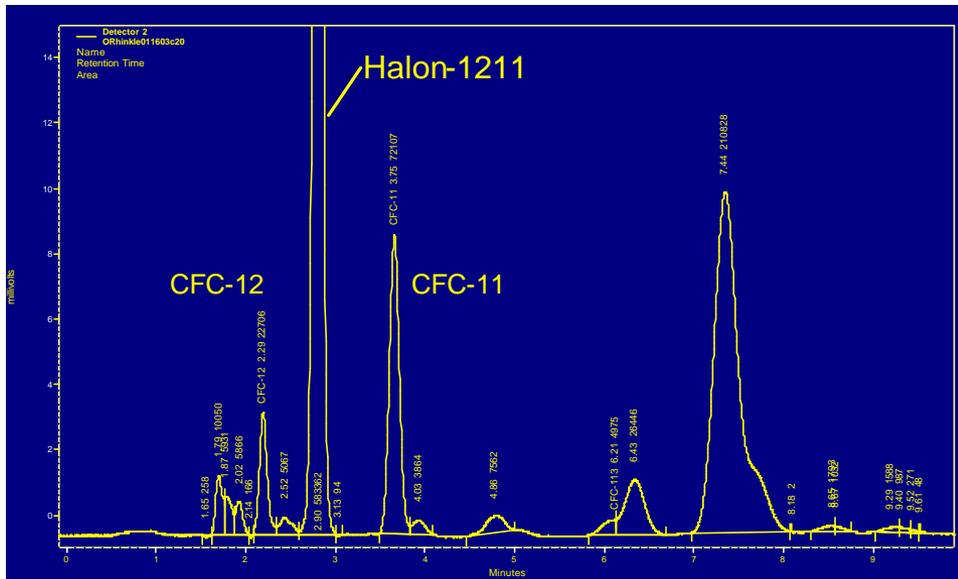
**Chromatogram of Halon 1211 stripped from 30 cubic centimeters of water equilibrated with nitrogen containing 0.59 parts per billion Halon 1211 at 54°F.**



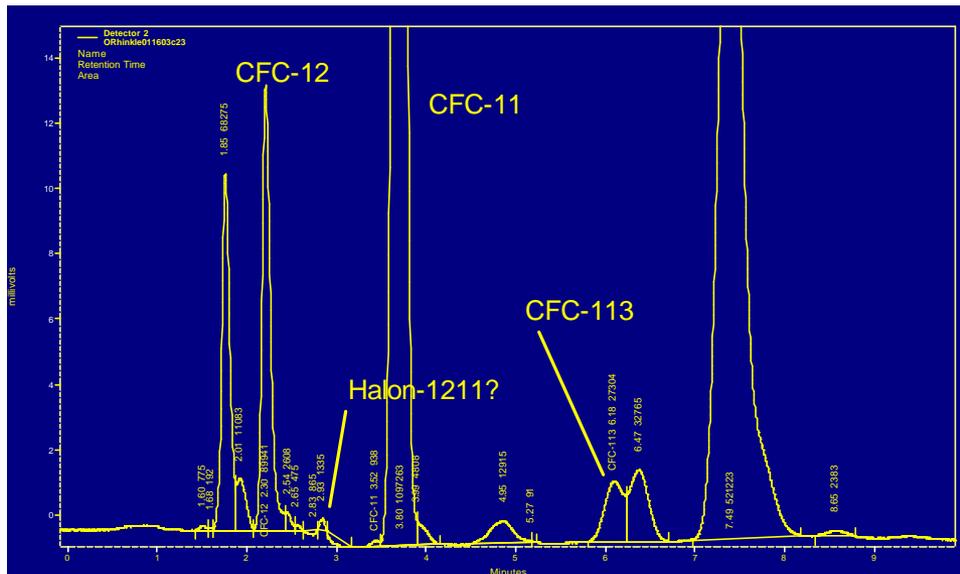
**Chromatogram of water from the Round Hill well taken after 6 hours of pumping (2 months after drilling) showing a small peak for Halon 1211 between the peaks for CFC-12 and CFC-11 (2.89). This peak is not detected in ambient air and indicates the presence of ground water affected by air from the drilling process.**



**Ground-water sample from June 2, 2003, after loss of drilling fluid during sidewall coring process.**



**Well MW-N3D.** Large Halon peak. CFC-11 and CFC-12 indicate mid- to late 1970s. Since CFCs came with Halon, water is older than 1970s, but cannot be dated further with CFCs because of contamination with drilling air. Possible mixture of old water and water contaminated with drilling air. Without the Halon data, we would have interpreted a CFC age that is too young.



**Well MW-N4D.** Trace or no Halon present. CFC data probably unaffected by drilling air. CFC data suggest a modern age for the water. Without the Halon data, we would not know that the CFCs are valid in this sample.

# CONCLUSIONS

- Use of multiple tracers and “tracer plots” can help to eliminate some mixing models and refine estimates of mean tracer age.
- To a first approximation, the ages and mixing fractions of many samples from karst or fractured rock can be interpreted using a simple binary mixing model. Is this the result of the sampling process?
- Most ground water from fractured rock or karstic aquifers is susceptible to contamination.
- Should include tracers in well drilling.

# CONCLUSIONS (cont.)

- “... the concept of groundwater age has little significance” (Fontes, 1983); yet investigation of multiple environmental tracers in groundwater systems can often help to refine the interpretation of age, refine hydrologic concepts, and identify susceptibility to contamination.

# Acknowledgements

- **Chesapeake Bay Study.** Scott Phillips, Bruce Lindsey, Gary Spieran, Mike Focazio, J.K. Bohlke, Bill Burton, Colleen Donnelly.
- **Virginia Aquifer Susceptibility Study.** Dave Nelms and George Harlow.
- **Shenandoah National Park Study.** Ed Busenberg, Dave Nelms, Jerry Casile, Julian Wayland, Wandee Kirkland, Stephanie Shapiro, Brian Norton.
- **Reston Chlorofluorocarbon Laboratory.**
- **Noble Gas Laboratory of Lamont-Doherty Earth Observatory, Columbia University.**