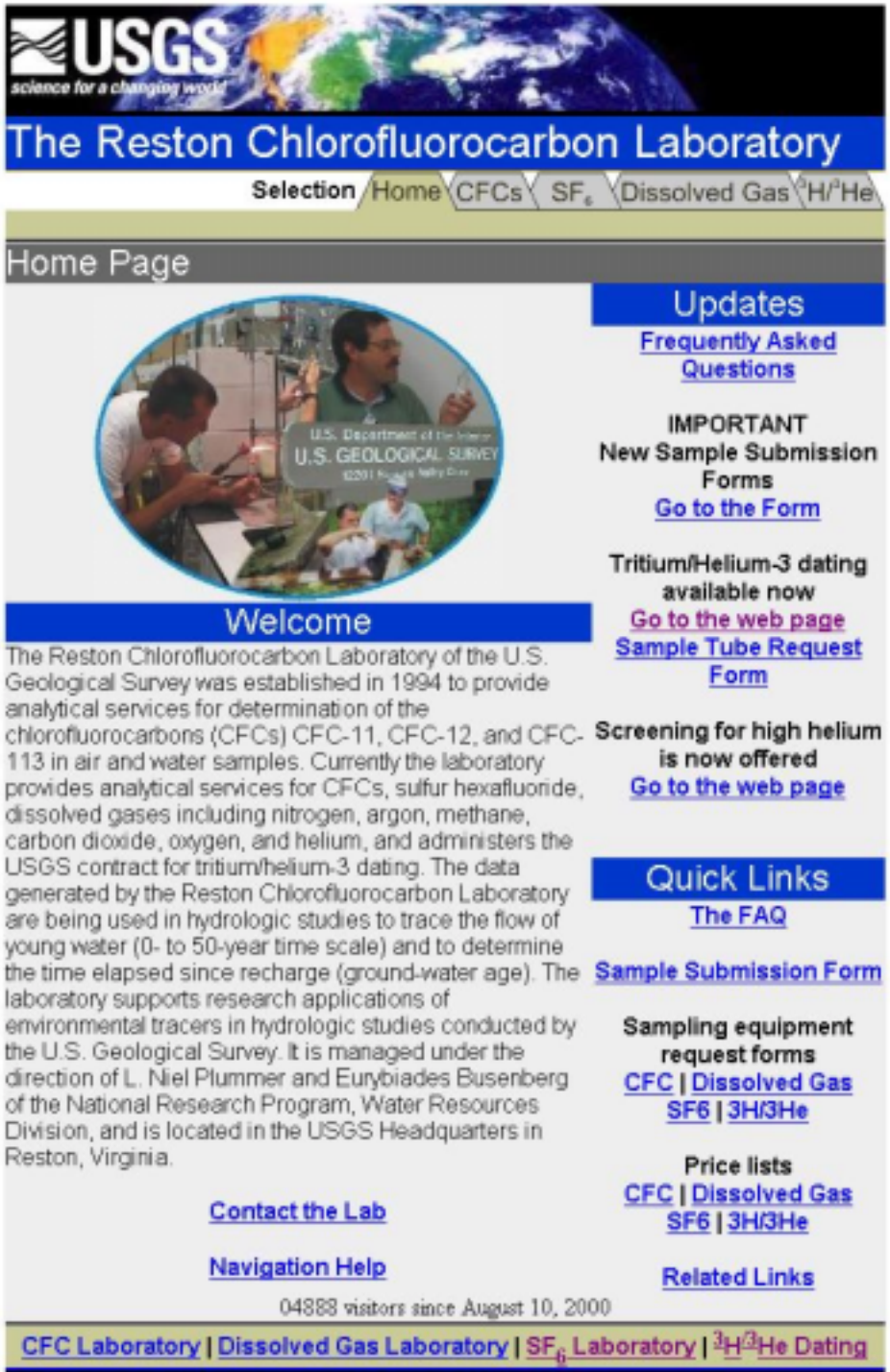
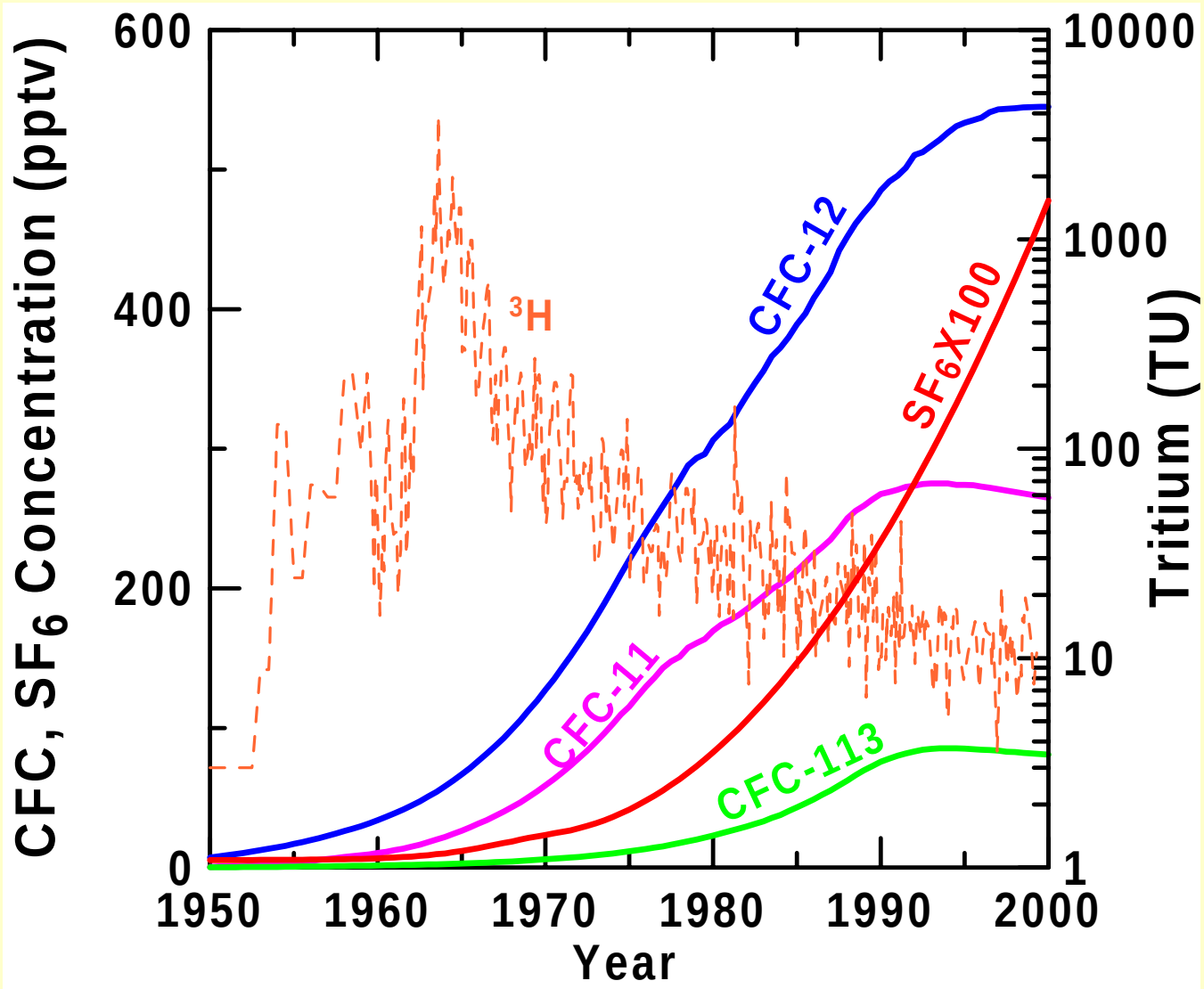
Some Uses of Environmental Tracers in Fractured Rock

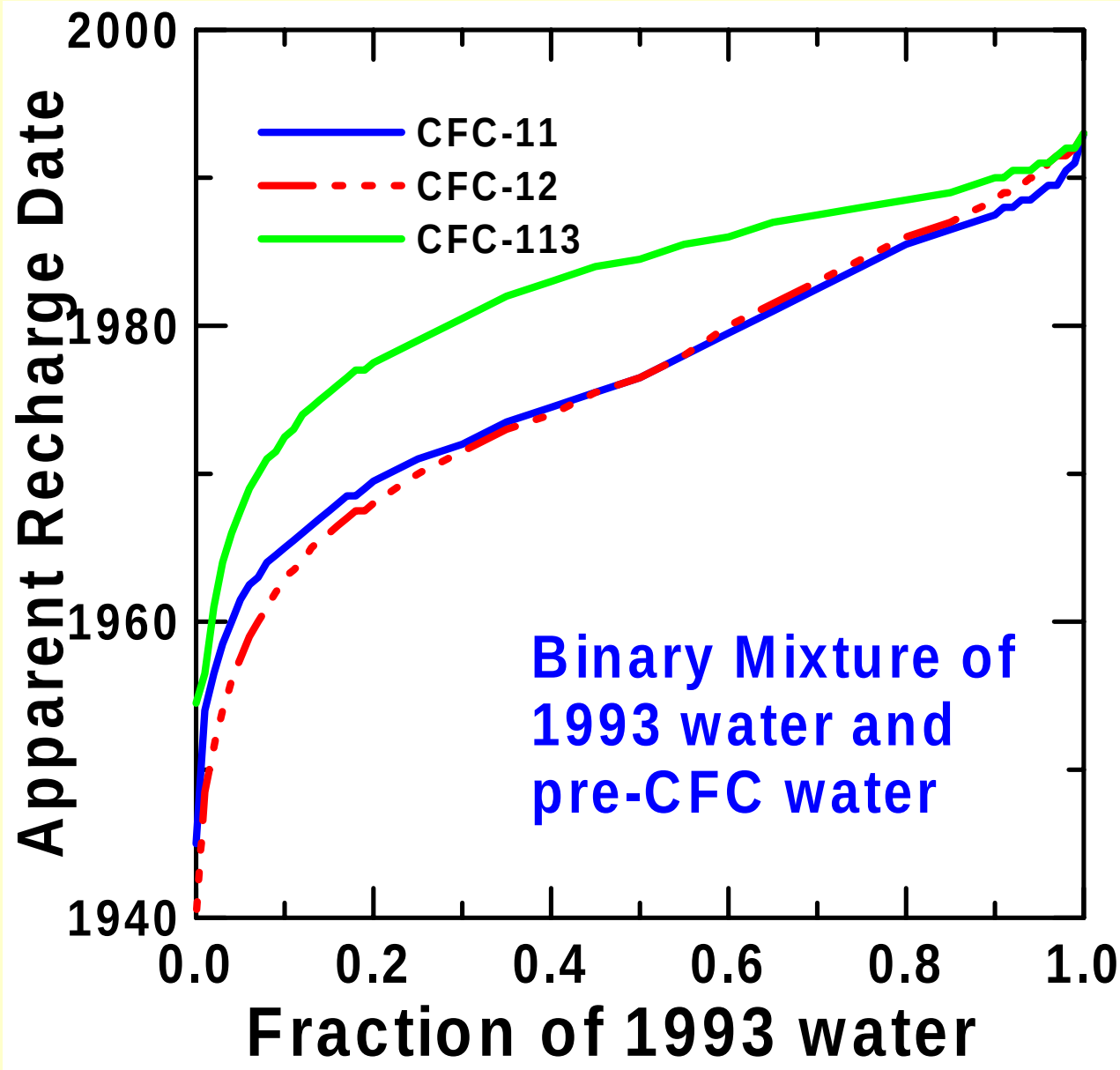
- Some important anthropogenic tracers on the 0 to 50 year timescale: ^{3}H, $^{3}H/^{3}He$, ^{14}C, ^{36}Cl, CFCs, SF_6, ^{85}Kr.
- Presence indicates post-1940s or mixture containing fraction of post-1940s water.
- Binary mixing of young (post-1940s) and old (pre-1940s) water seems common. Examples: Blue Ridge, VA; Valley and Ridge, PA, South Africa.
- Ground water in the Piedmont and Blue Ridge of VA can be highly susceptible to anthropogenic inputs.

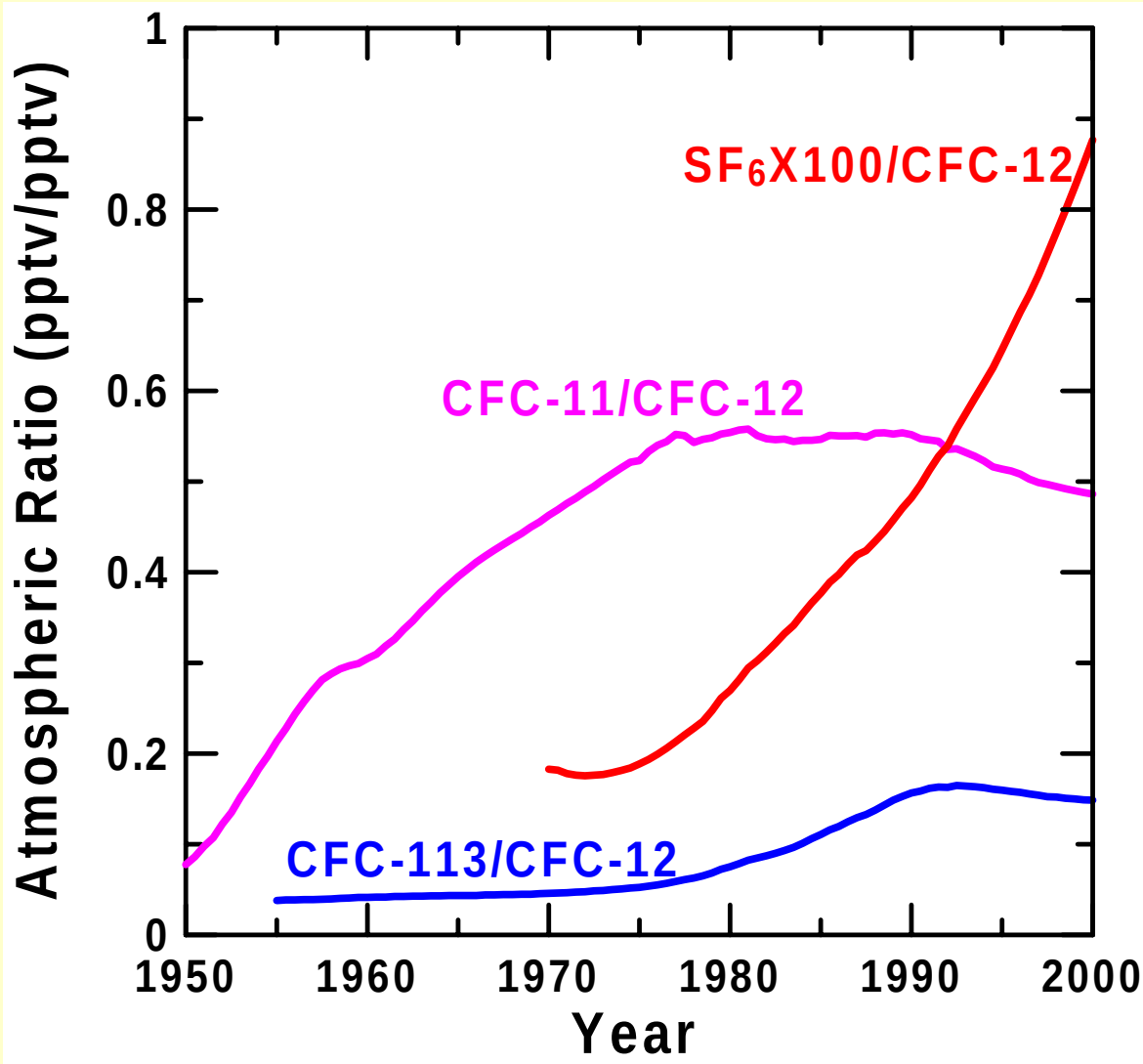


Reston Chlorofluorocarbon Laboratory

water.usgs.gov/lab/cfc


CFC, SF6 Concentration (pptv)
Tritium (TU)
Year
600
400
200
0
10000
1000
100
10
1
1950
1960
1970
1980
1990
2000
3H
CFC-12
SF6X100
CFC-11
CFC-113


2000
1980
1960
1940
Apparent Recharge Date
CFC-11
CFC-12
CFC-113
Binary Mixture of
1993 water and
pre-CFC water
0.0
0.2
0.4
0.6
0.8
1.0
Fraction of 1993 water

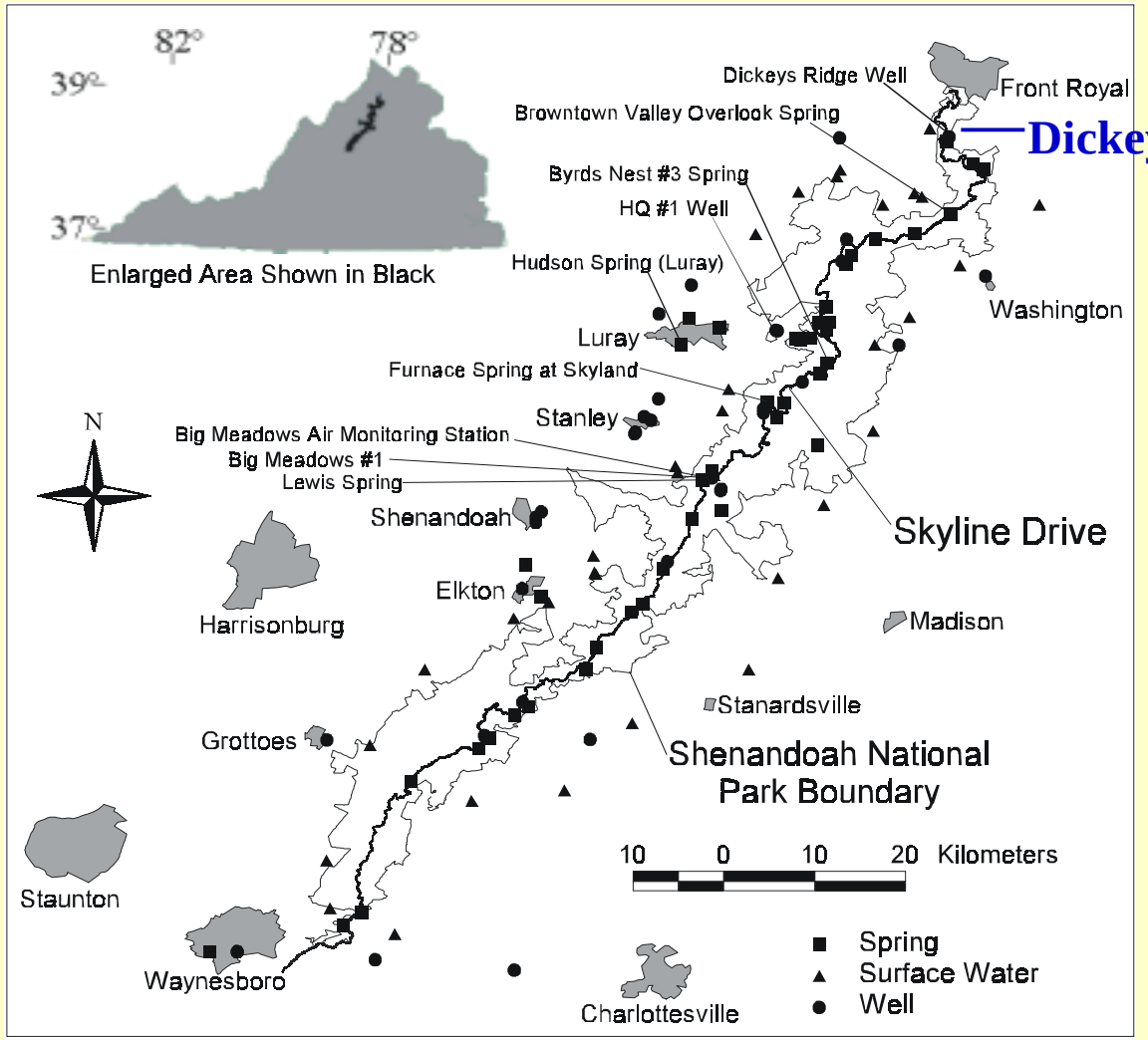

Atmospheric Ratio (pptv/pptv)
1
0.8
0.6
0.4
0.2
0
1950
1960
1970
1980
1990
2000
Year
SF6X100/CFC-12
CFC-11/CFC-12
CFC-113/CFC-12

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

- **CFC ratio defines age of young fraction.**
- **% young water = $(pptv_{(measured)} / pptv_{(ratio\ year)}) \times 100$**

- **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 model ages for both CFCs in the ratio.**

Blue Ridge
Shenandoah National Park



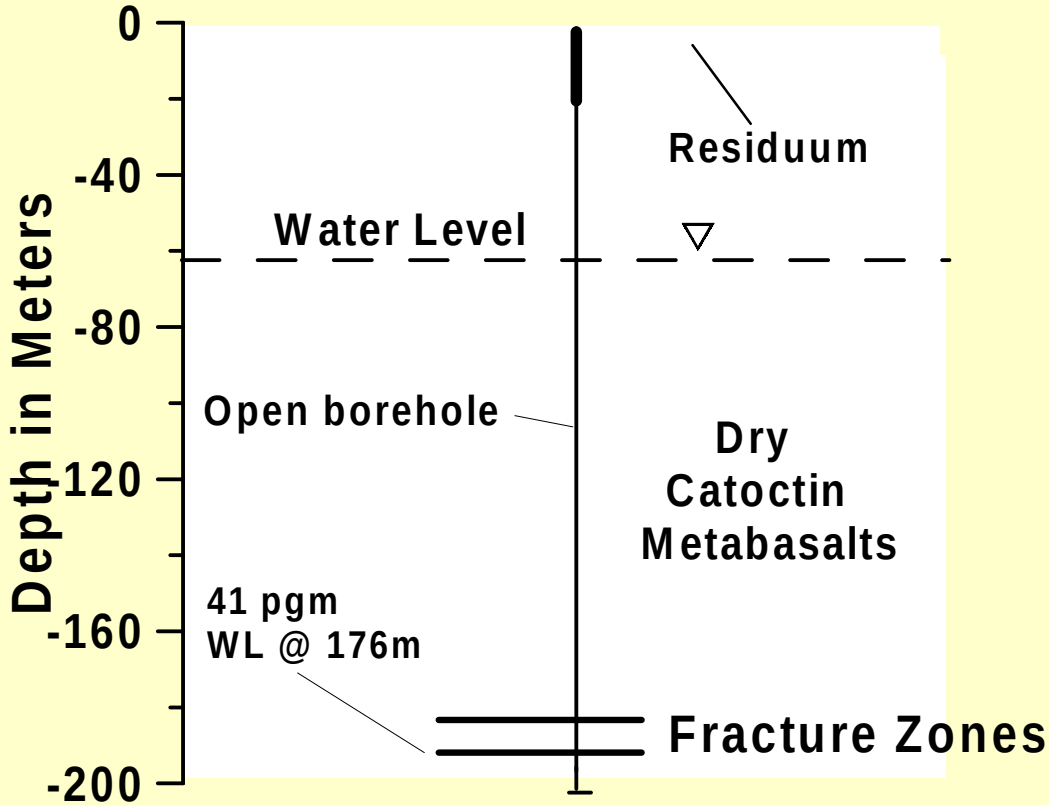
Dickeys Ridge Well

Dickey Ridge Well

Shenandoah National Park

As Binary Mixture of Young and Old Water
CFCs indicate Sample contains 46 percent
of water recharged in 1986.5
Young Fraction Age = 11.3 years

$^{3}H/^{3}He$ age (young fraction) = 9.7 years



Dickey Ridge well
Shenandoah National Park

CFC	pptv	Apparent Date of Recharge
CFC-11	104.9	1974.0
CFC-12	195.4	1973.5
CFC-113	24.1	1980.0

September, 1997. pptv based on N_2-Ar recharge temperature

Mixing Calculations
Dickey Ridge well

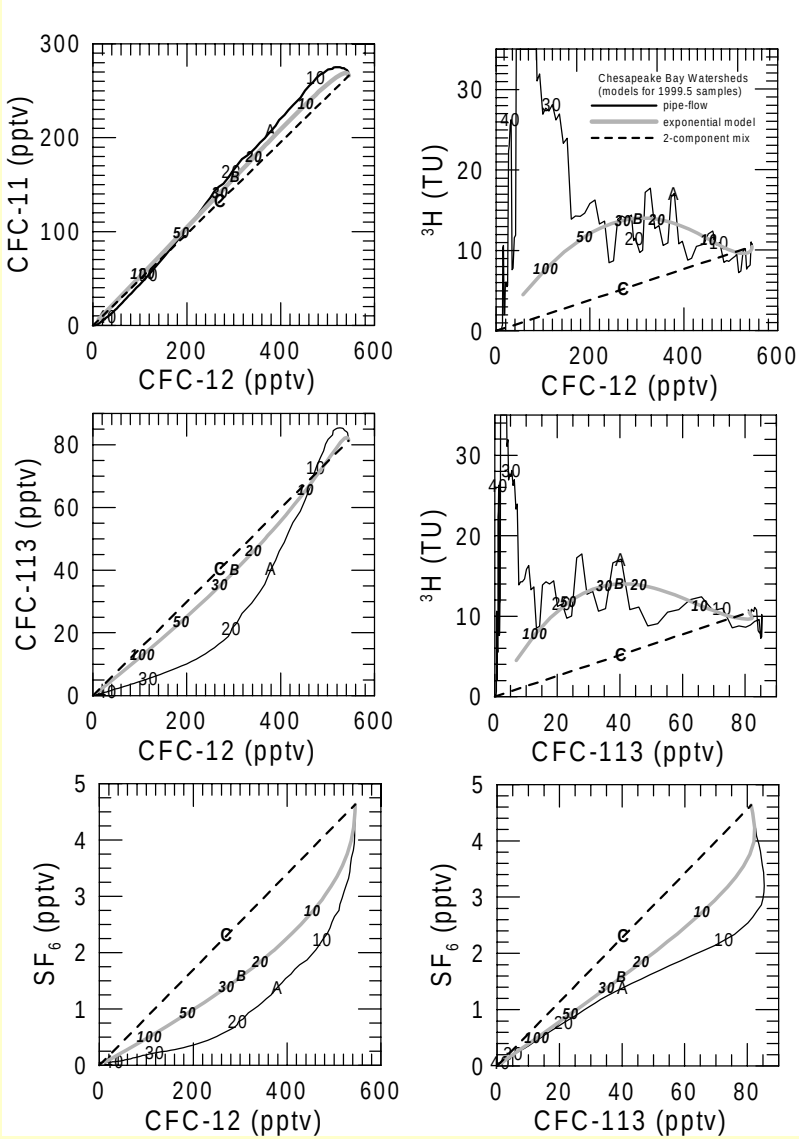
CFC ratio	Ratio	Date of young fraction	From CFC	pptv for Date	% young water
113/12	0.123	1986.5	12	416.6	46.9
113/11	0.230	1986.5	113	52.1	46.3
113/11	0.230	1986.5	11	229.4	45.7
11/12	0.537	Post-1976	-------	-------	-------

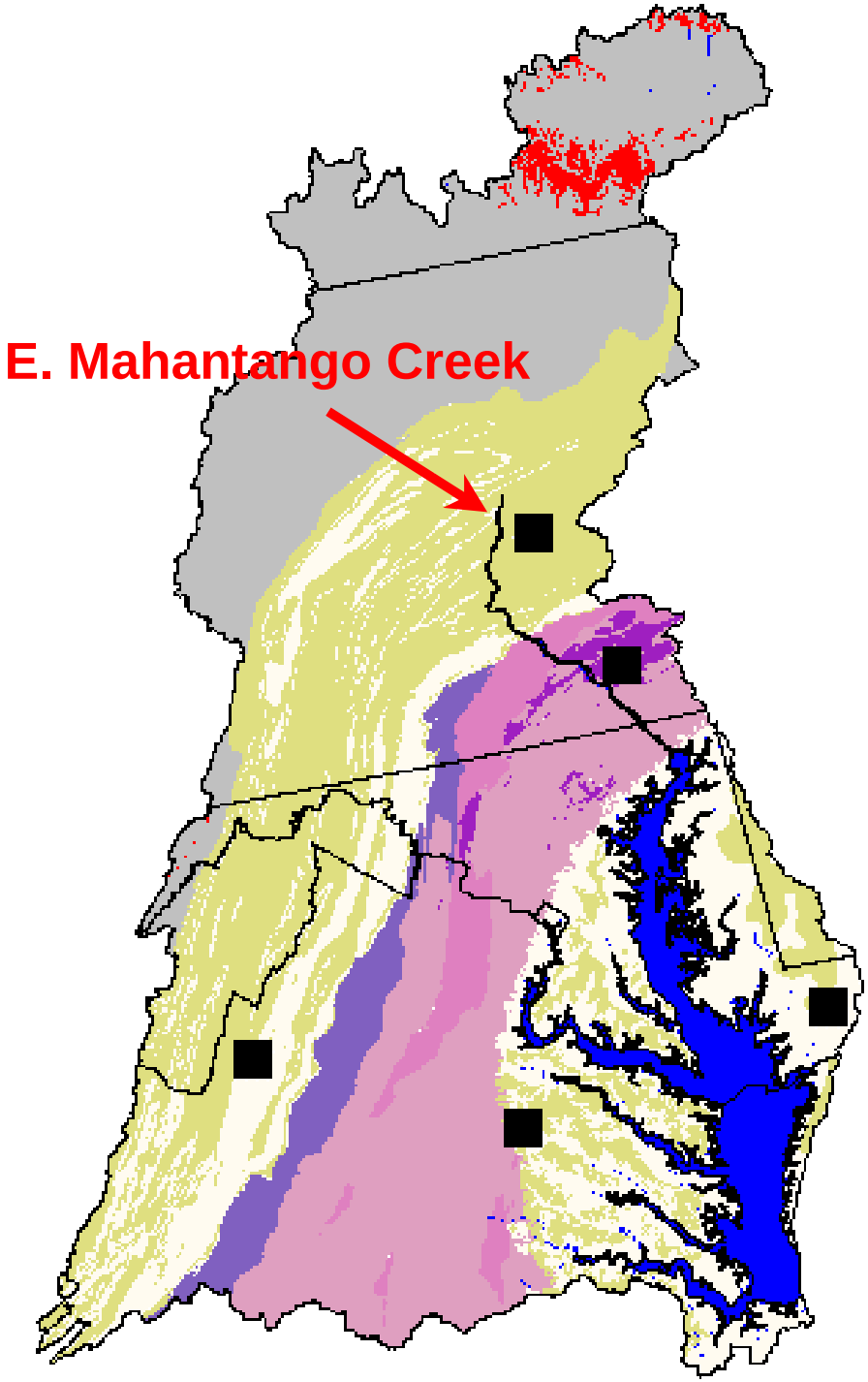
Tracer Plots

Many of the environmental tracers have differing temporal patterns to their input functions.

Plots of one tracer against another can be useful in distinguishing some mixing processes that may affect the samples.

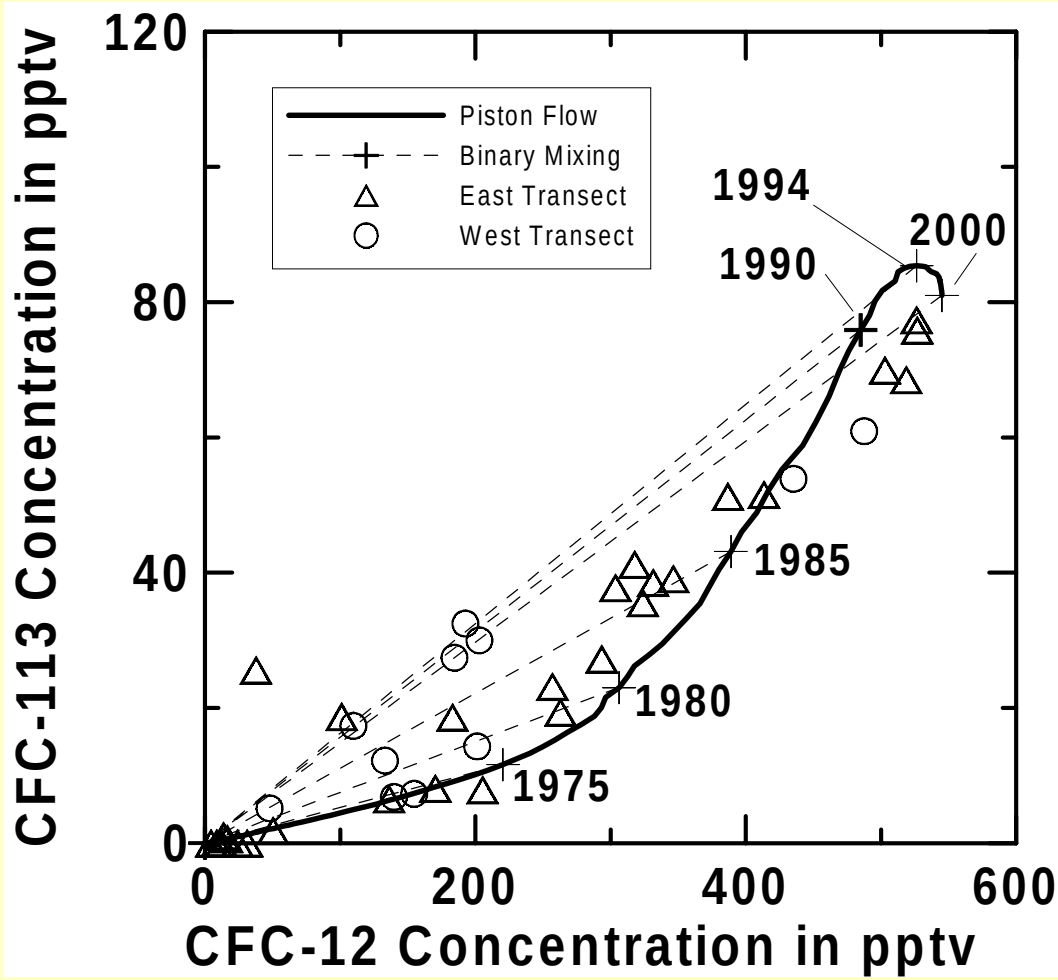
Examples


CFC-11 (pptv)
CFC-12 (pptv)
^{3}H (TU)
Chesapeake Bay Watersheds
(models for 1999.5 samples)
pipe-flow
exponential model
2-component mix
CFC-113 (pptv)
SF_6 (pptv)



Targeted Watersheds In the Chesapeake Bay Study

Valley and Ridge, PA

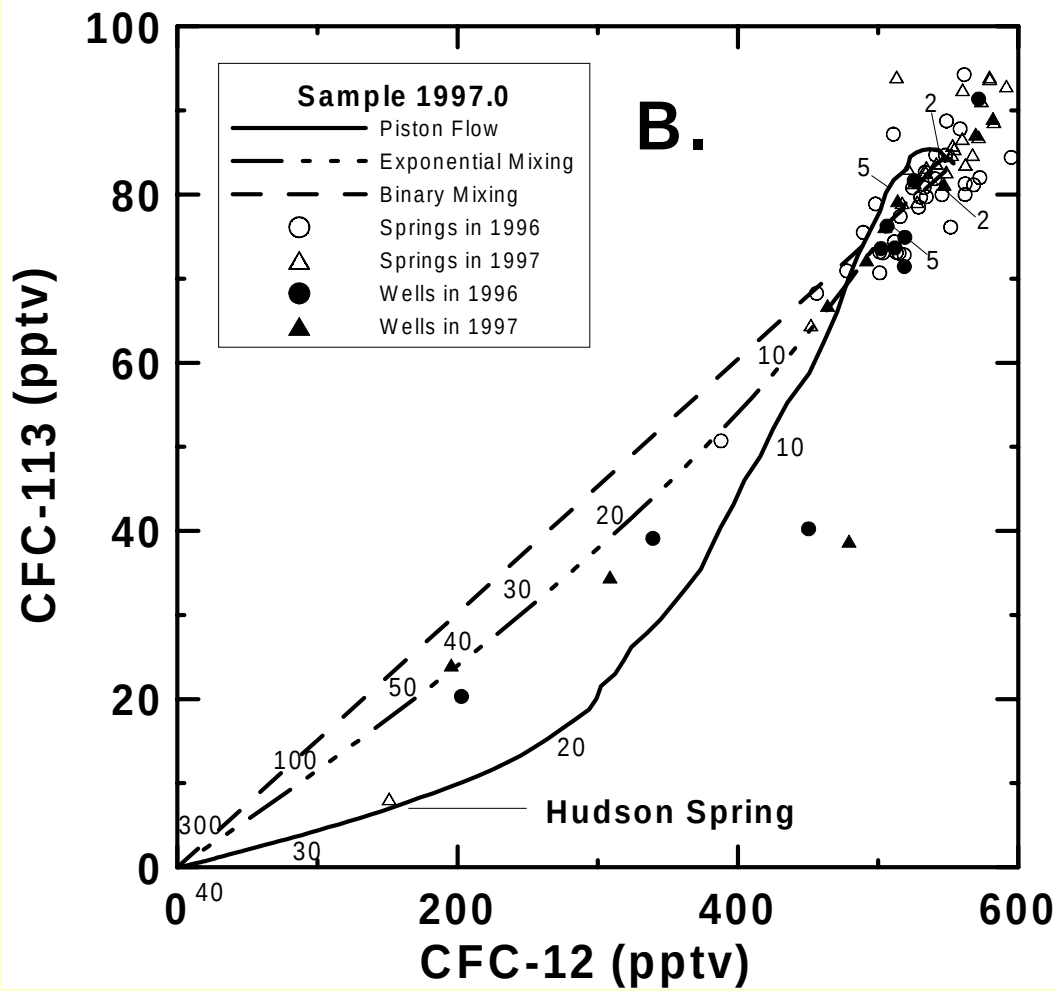


Burton et al., 2001

Valley and Ridge Mahantango, PA

Ground-water flow paths parallel to dip direction in well-developed bedding-plane partings in fractured bedrock resulted in a greater proportion of young water arriving at a given discharge point, and ground-water ages near the discharge point significantly younger, than for flow paths opposite the dip direction.

Blue Ridge, VA
Shenandoah National Park

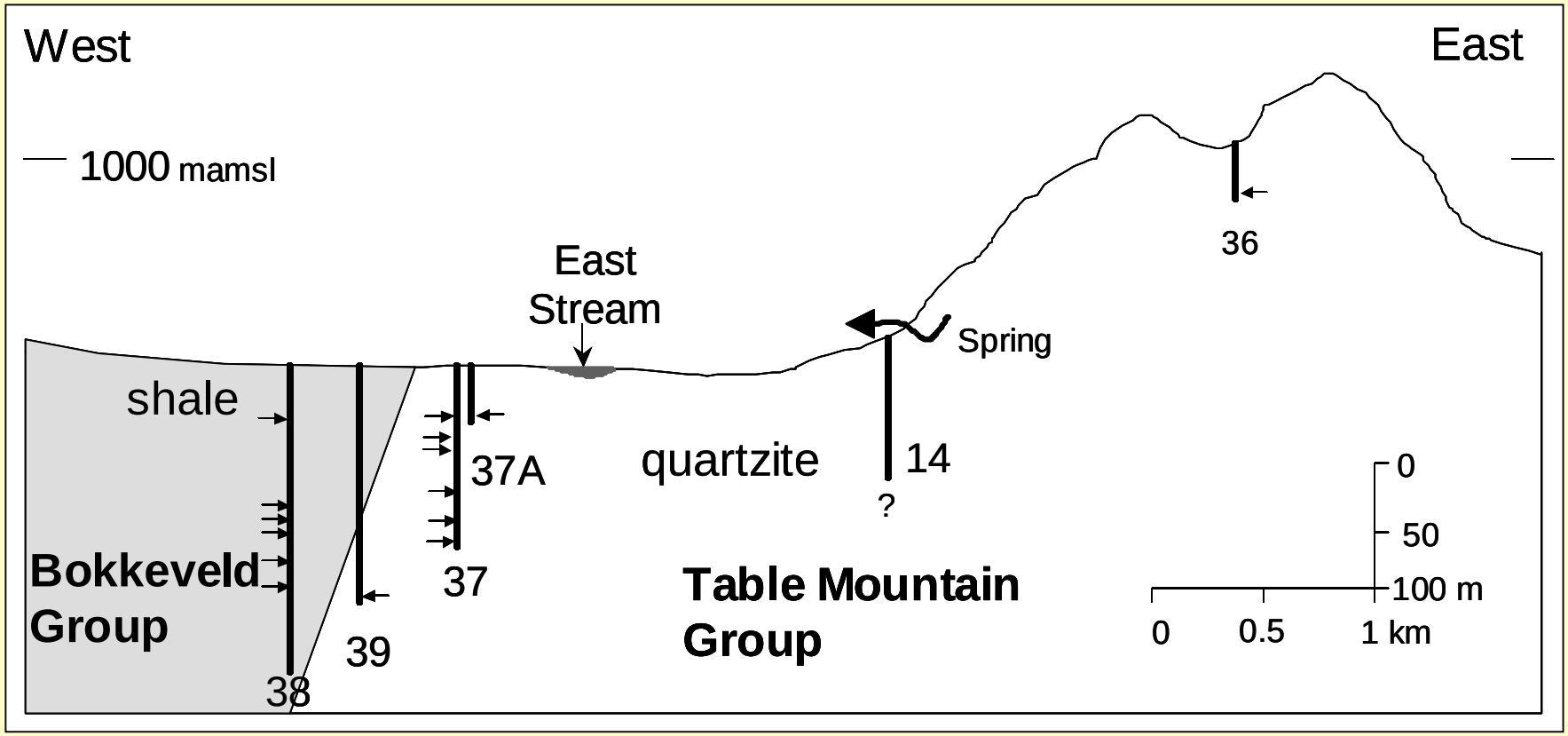


Plummer et al., 2001
(in press)

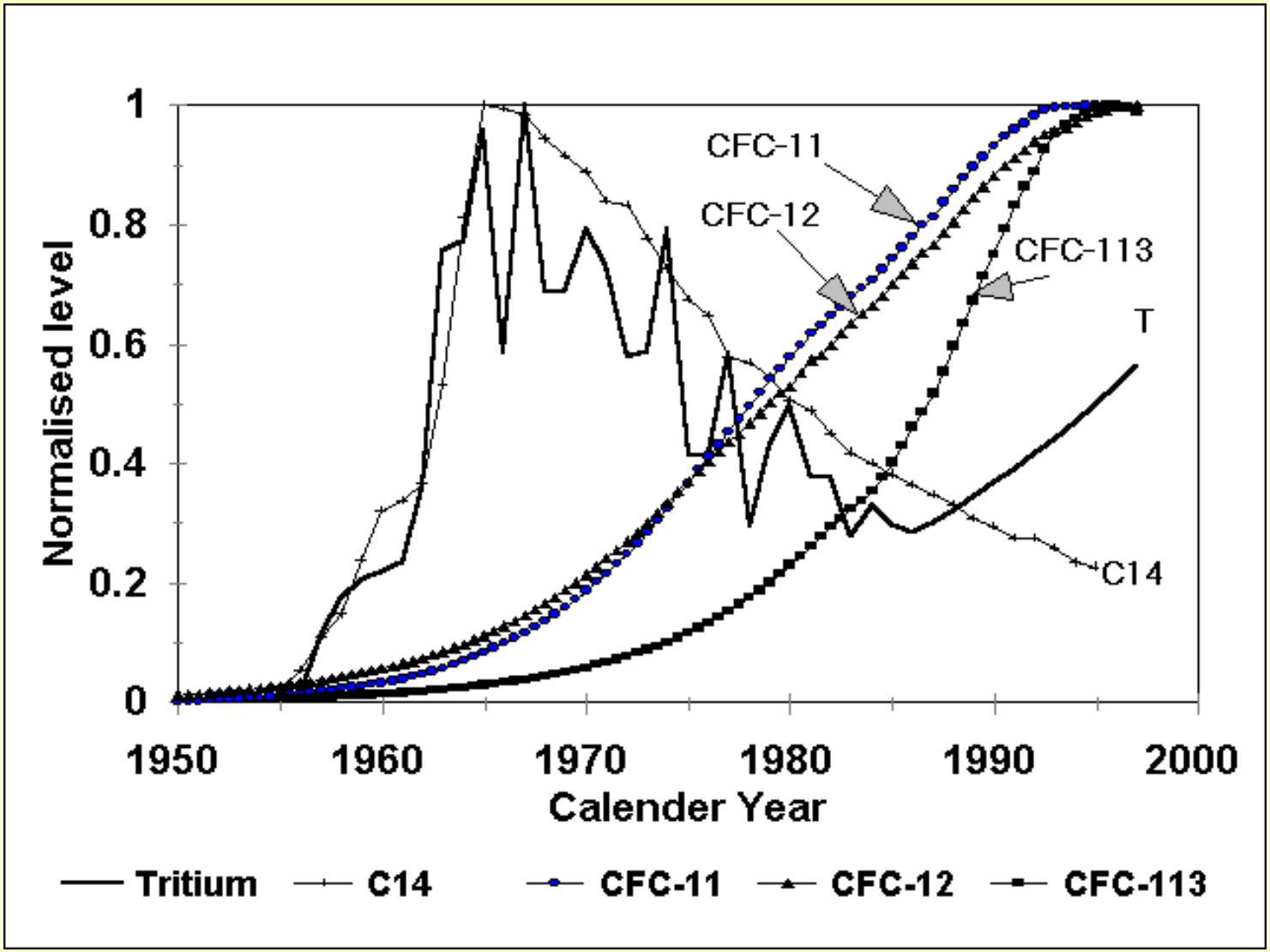
Blue Ridge, Virginia

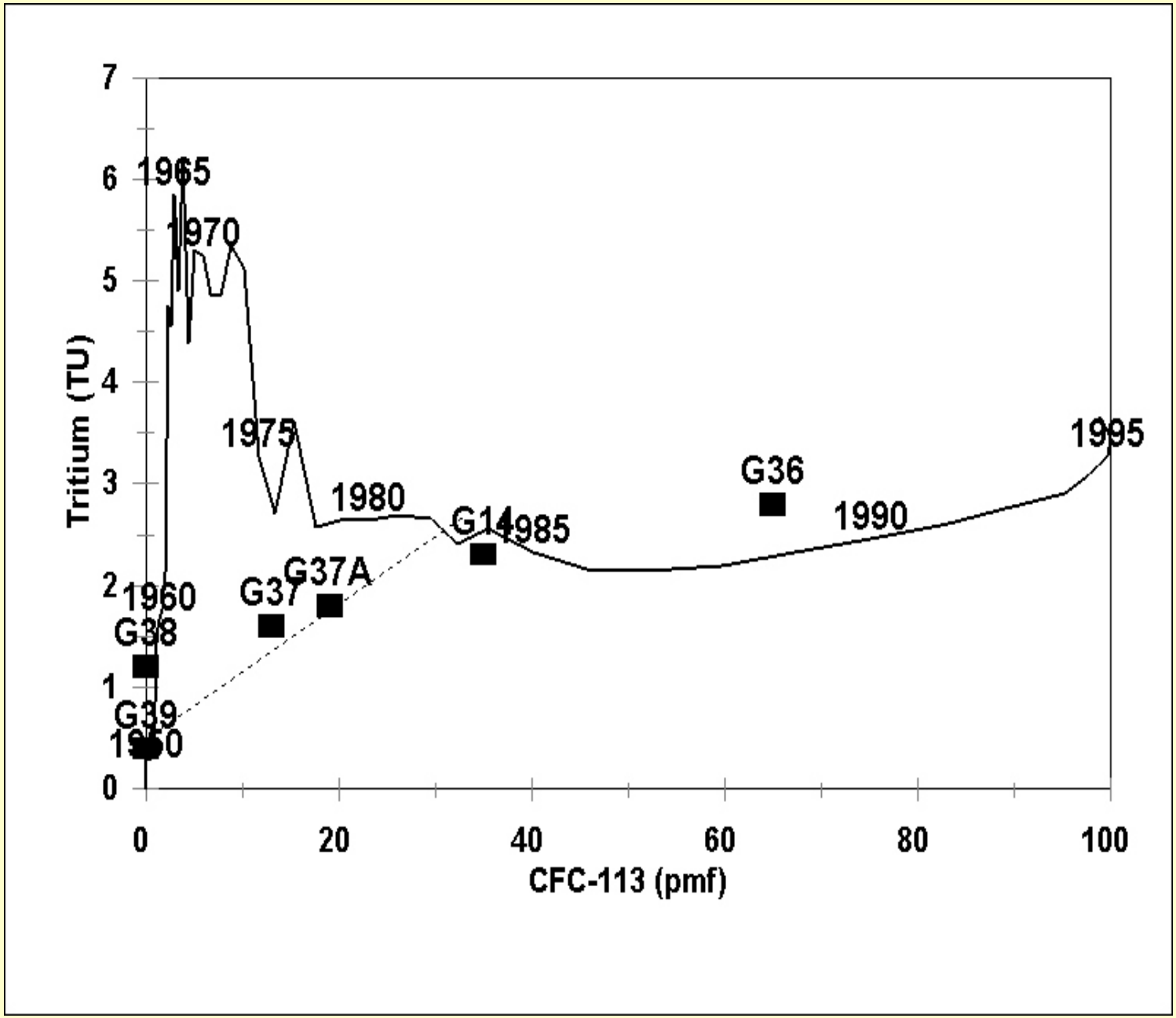
- Mean groundwater residence times of 0-3 years were determined for discharge from high elevation springs in Blue Ridge, SNP, based on SF_6 and $^3H/^3He$ data.
- Groundwater from wells and deep springs in the vicinity of SNP ranges in age from 0 to 25 years. The CFC and $^3H/^3He$ data indicate that some water samples from wells are mixtures of relatively young (0-10 year old) water with older, pre-CFC water.

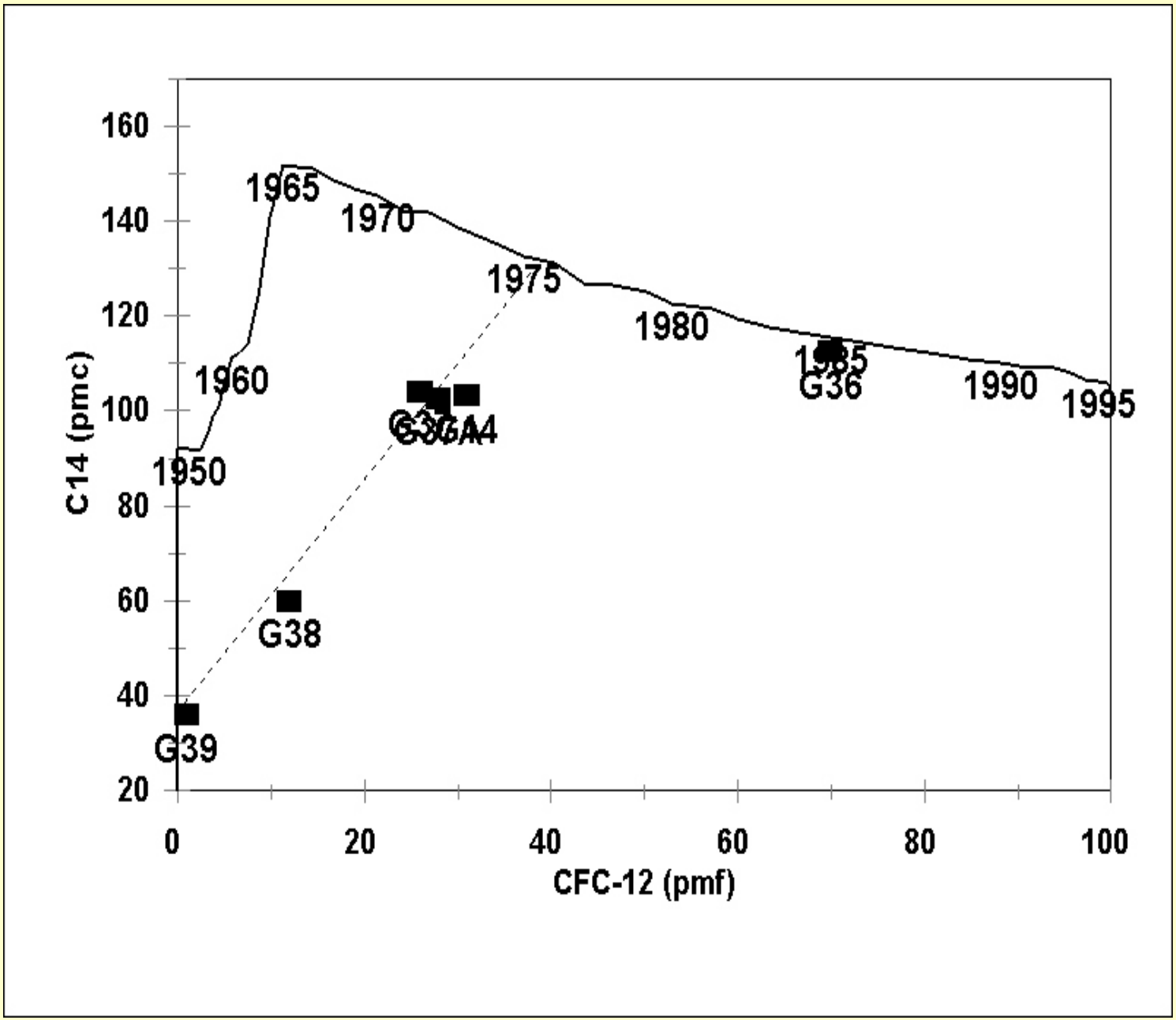
Agter-Witzenberg Valley South Africa

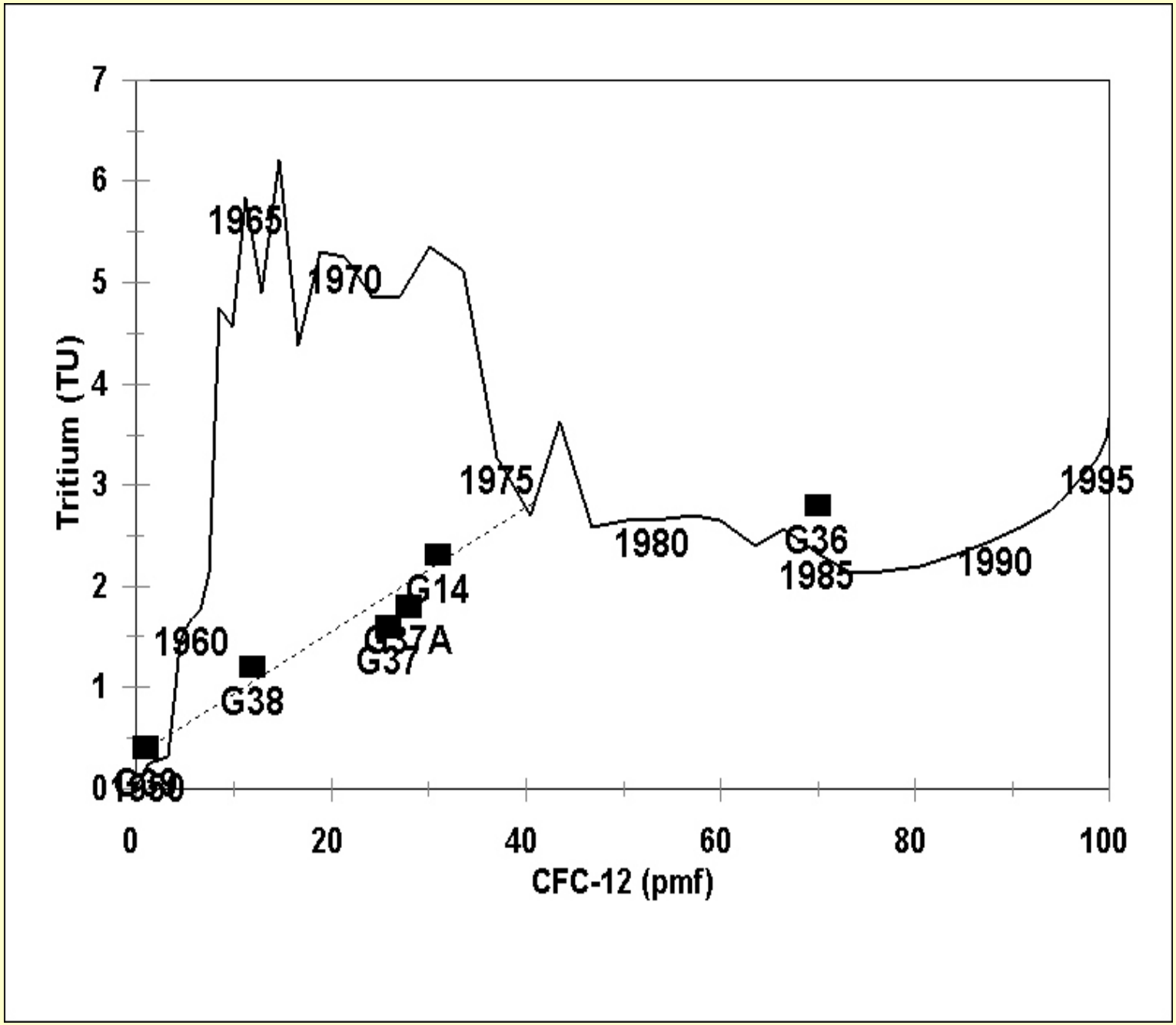


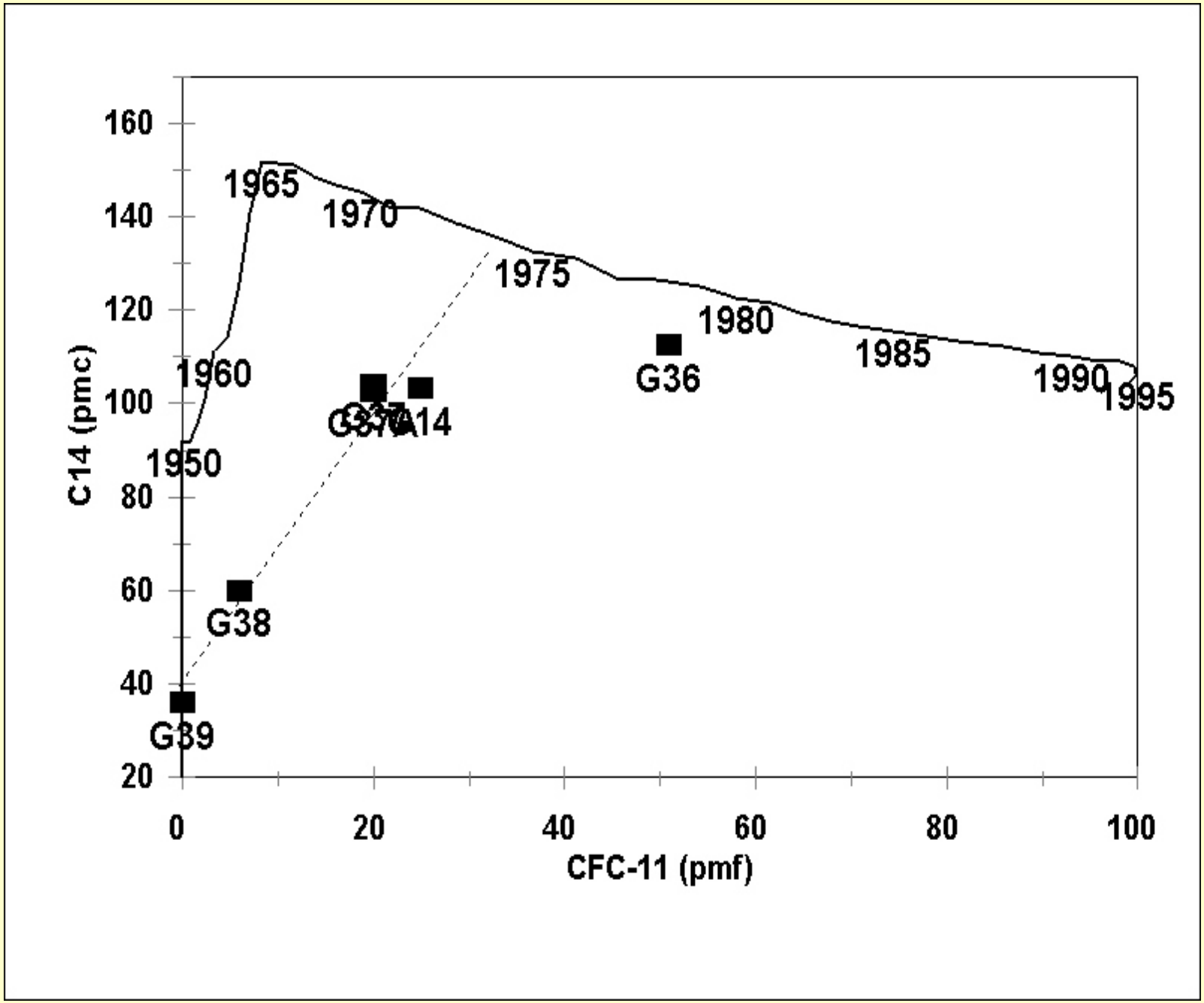
Talma et al., 2001

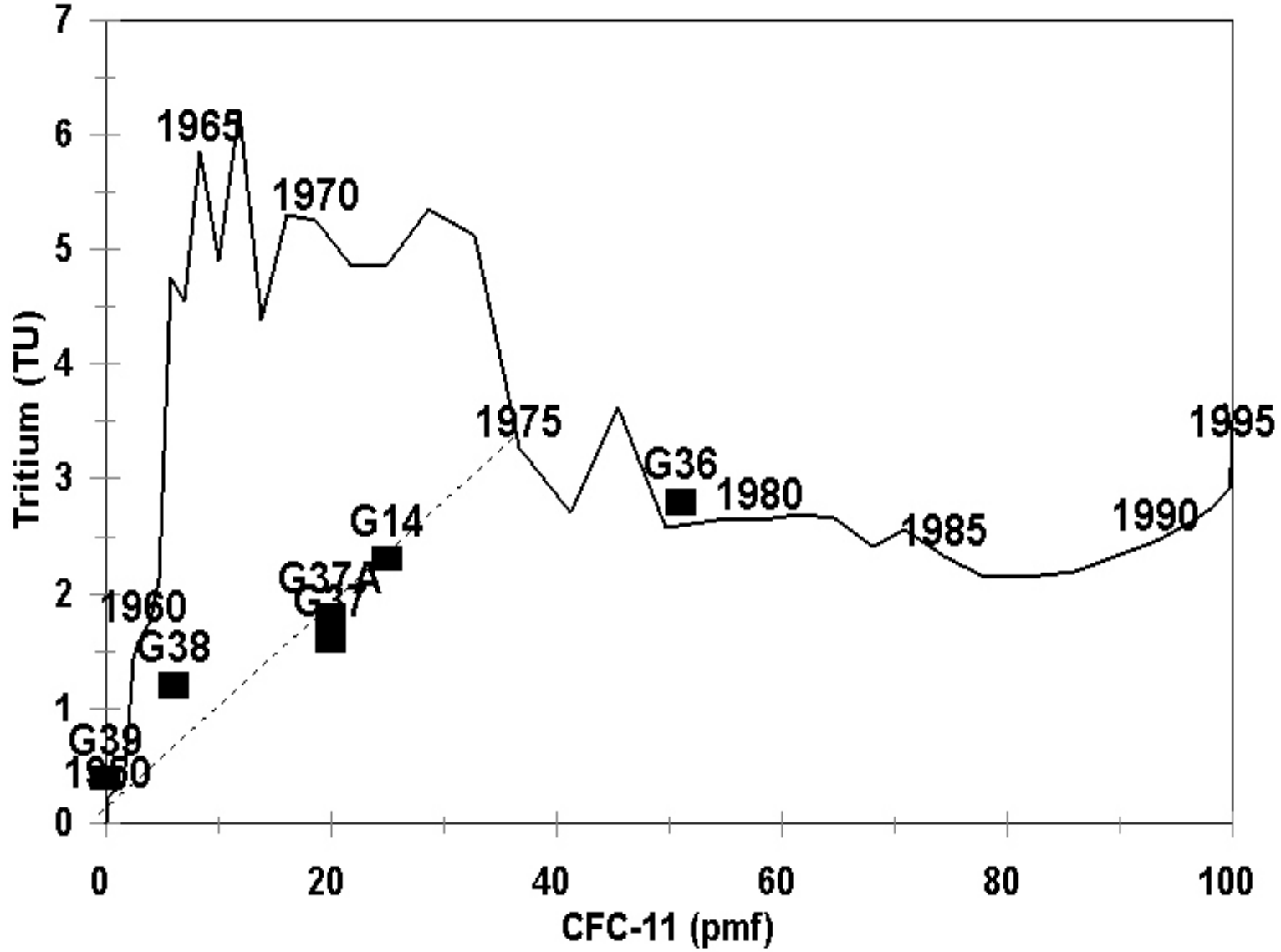

Normalised level
1
0.8
0.6
0.4
0.2
0
1950
1960
1970
1980
1990
2000
Calender Year
CFC-11
CFC-12
CFC-113
T
C14
Tritium
C14
CFC-11
CFC-12
CFC-113


Tritium (TU)
CFC-113 (pmf)
0
1
2
3
4
5
6
7
0
20
40
60
80
100
1965
1970
1975
1980
1985
1990
1995
1960
G38
G39
G37
G37A
G14
G36


160
140
120
100
80
60
40
20
C14 (pmc)
1950
1960
1965
1970
1975
1980
1985
1990
1995
G39
G38
G36
0
20
40
60
80
100
CFC-12 (pmf)


Tritium (TU)
CFC-12 (pmf)
0
1
2
3
4
5
6
7
0
20
40
60
80
100
1960
1965
1970
1975
1980
1985
1990
1995
G38
G37
G37A
G14
G36

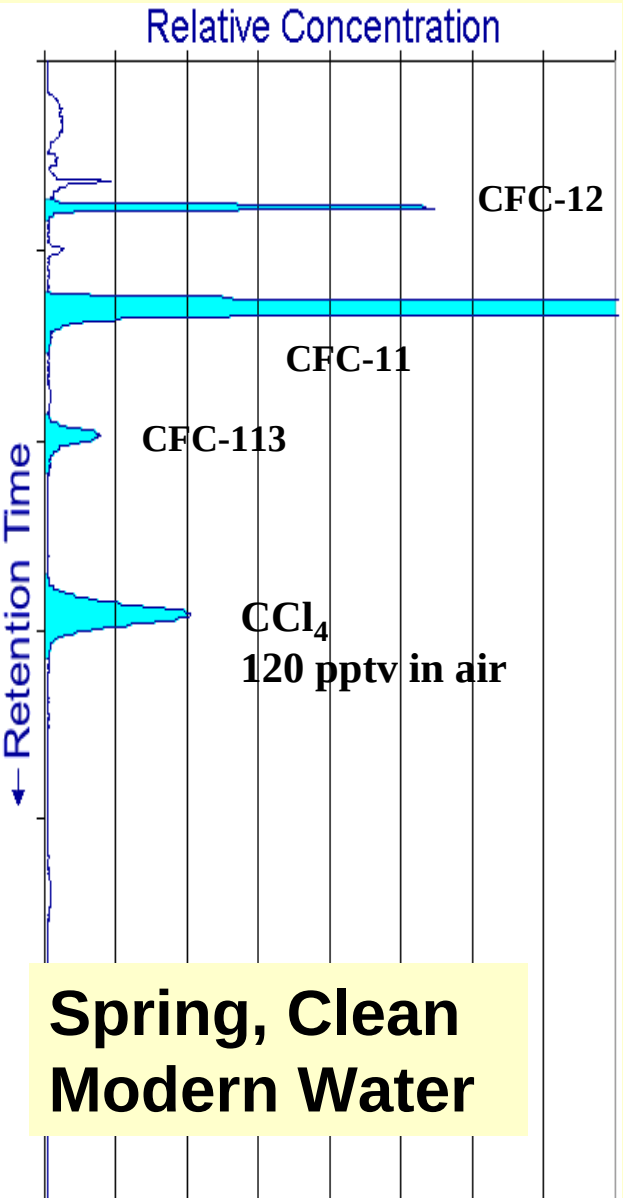

160
140
120
100
80
60
40
20
C14 (pmc)
0
20
40
60
80
100
CFC-11 (pmf)
1950
1960
1965
1970
1975
1980
1985
1990
1995
G36
G38
G39


Tritium (TU)
CFC-11 (pmf)
0
1
2
3
4
5
6
7
0
20
40
60
80
100
1965
1970
1975
1980
1985
1990
1995
1960
G36
G14
G37A
G37
G38
G39

South Africa (Talma et al., 2001)

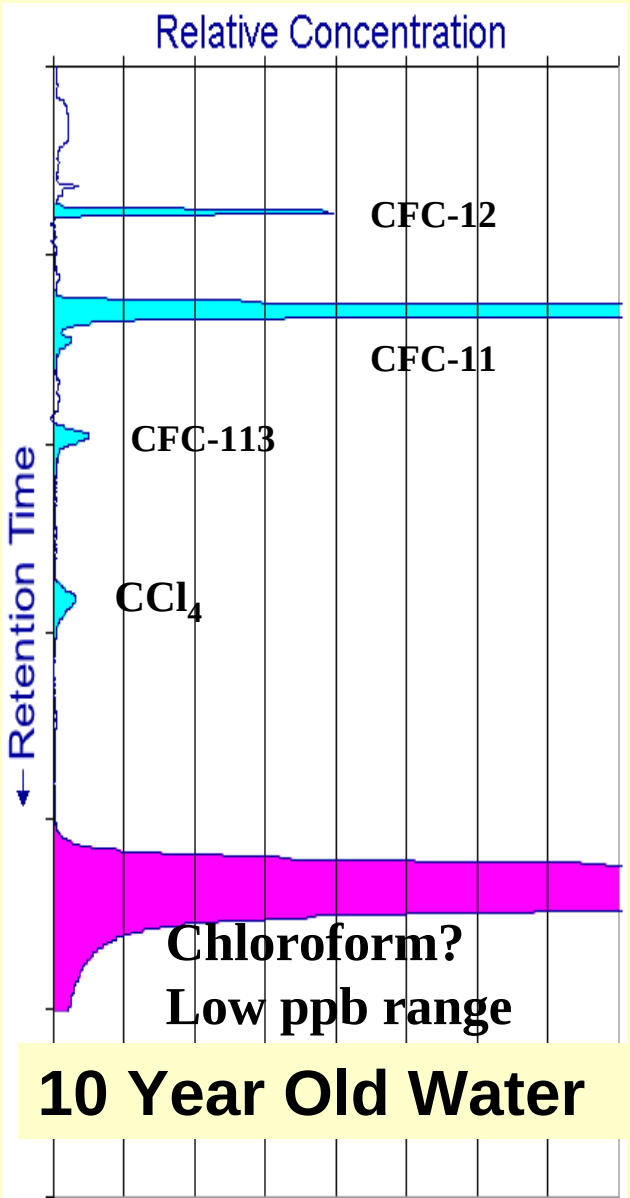
- **Mixing processes in groundwater can best be described by mixing lines with tracer concentrations plotted on linear scales.**
- **By using a normalized concentration (such as pmf) it is possible to view the three CFC gases collectively.**
- **In the South African study site it was possible to use CFCs for the young (post-1970 AD) component of the aquifer and ^{14}C for the older component.**
- **Tritium confirmed the mixture lines and enabled refinements to be made.**

Shenandoah National Park
Dean Mountain Spring
Drinking Water
Modern Clean Water



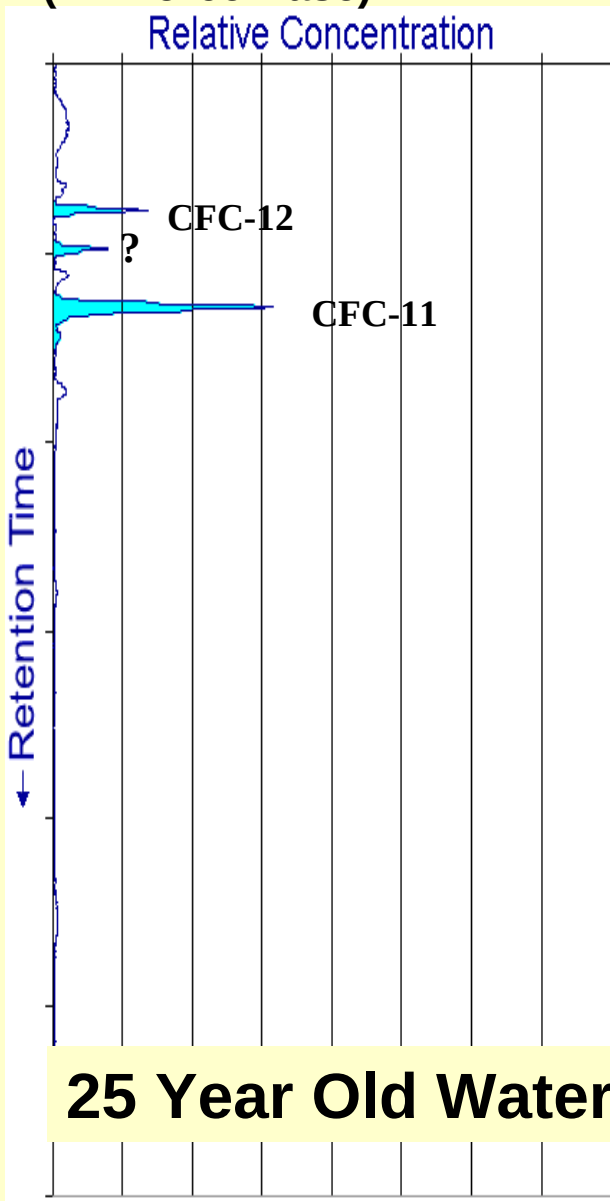
Spring, Clean Modern Water

George Washington
Spring #2
Yorktown, VA
Drinking Water



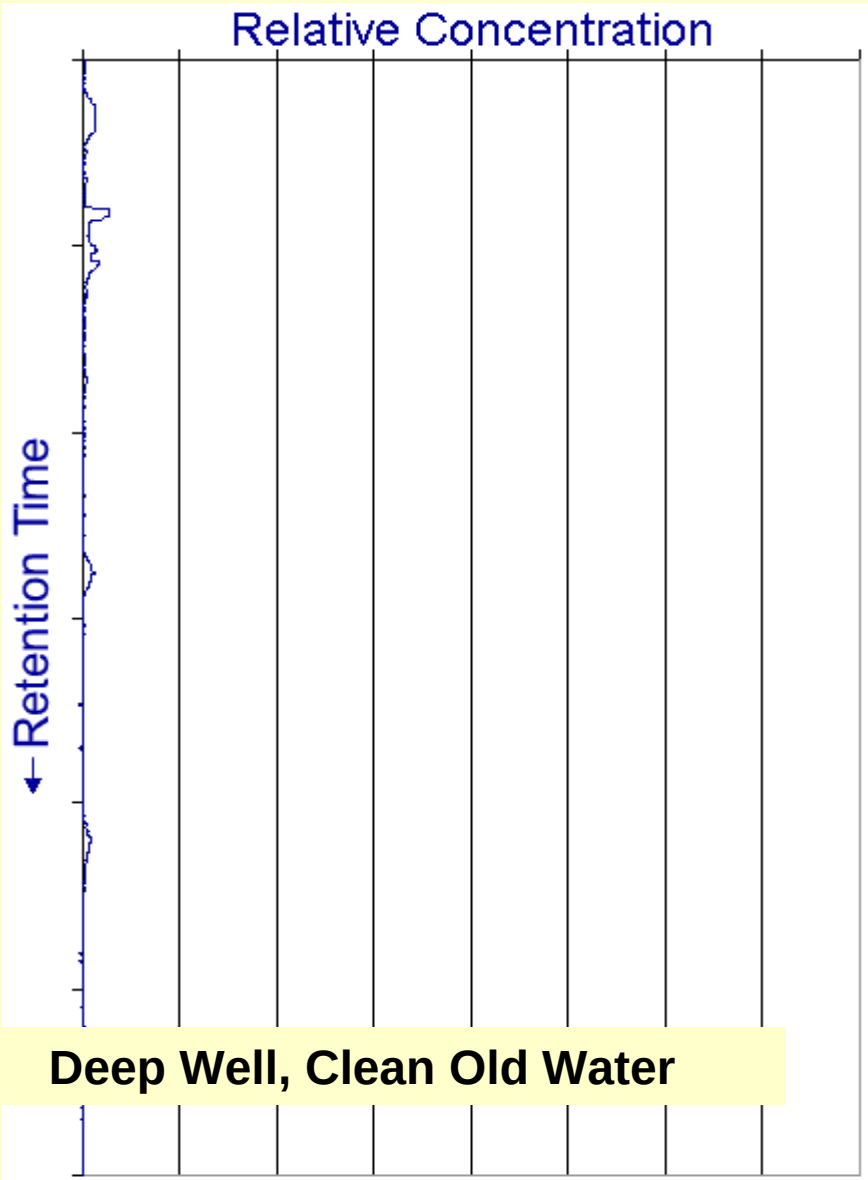
10 Year Old Water

Fort Wainright
Fairbanks, AK
(Air Force Base)



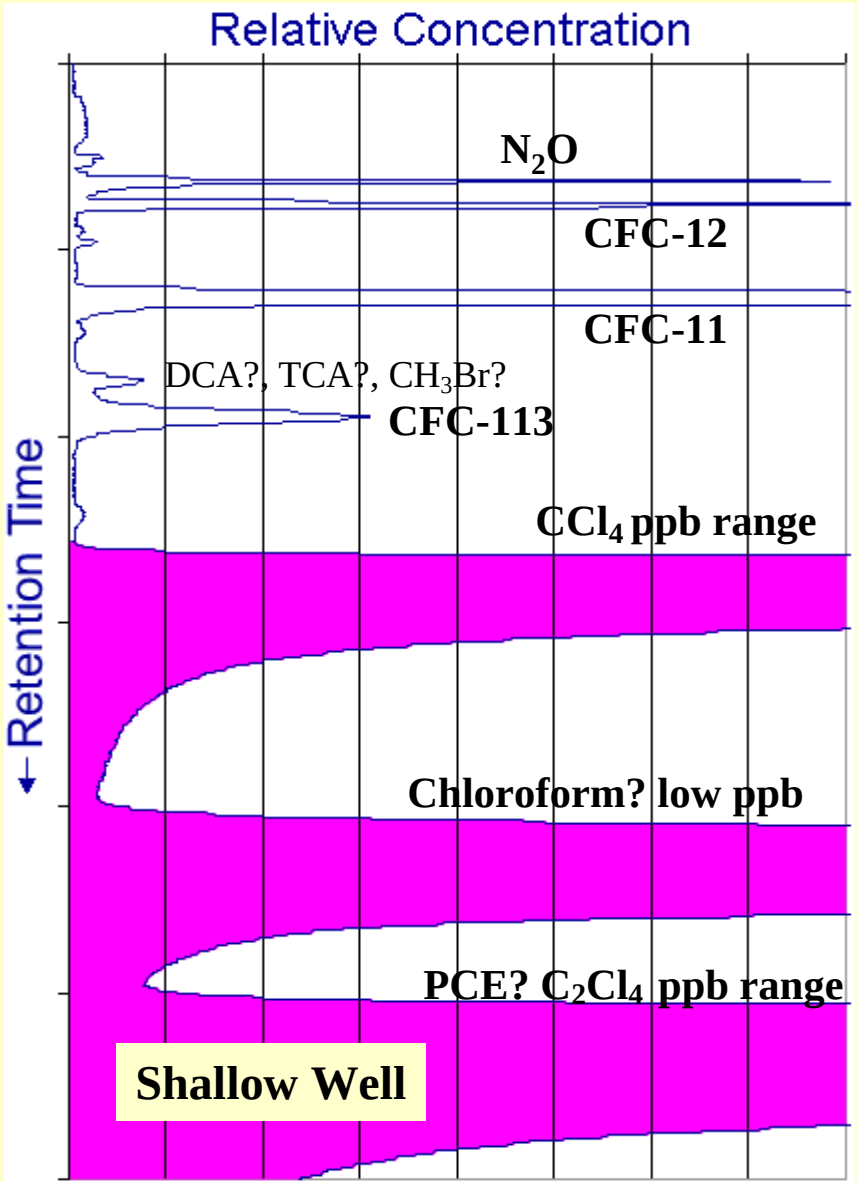
25 Year Old Water

Coastal Plain of Virginia
Depth: 448 feet
Drinking Water Well
Water Greater than 60 Years old

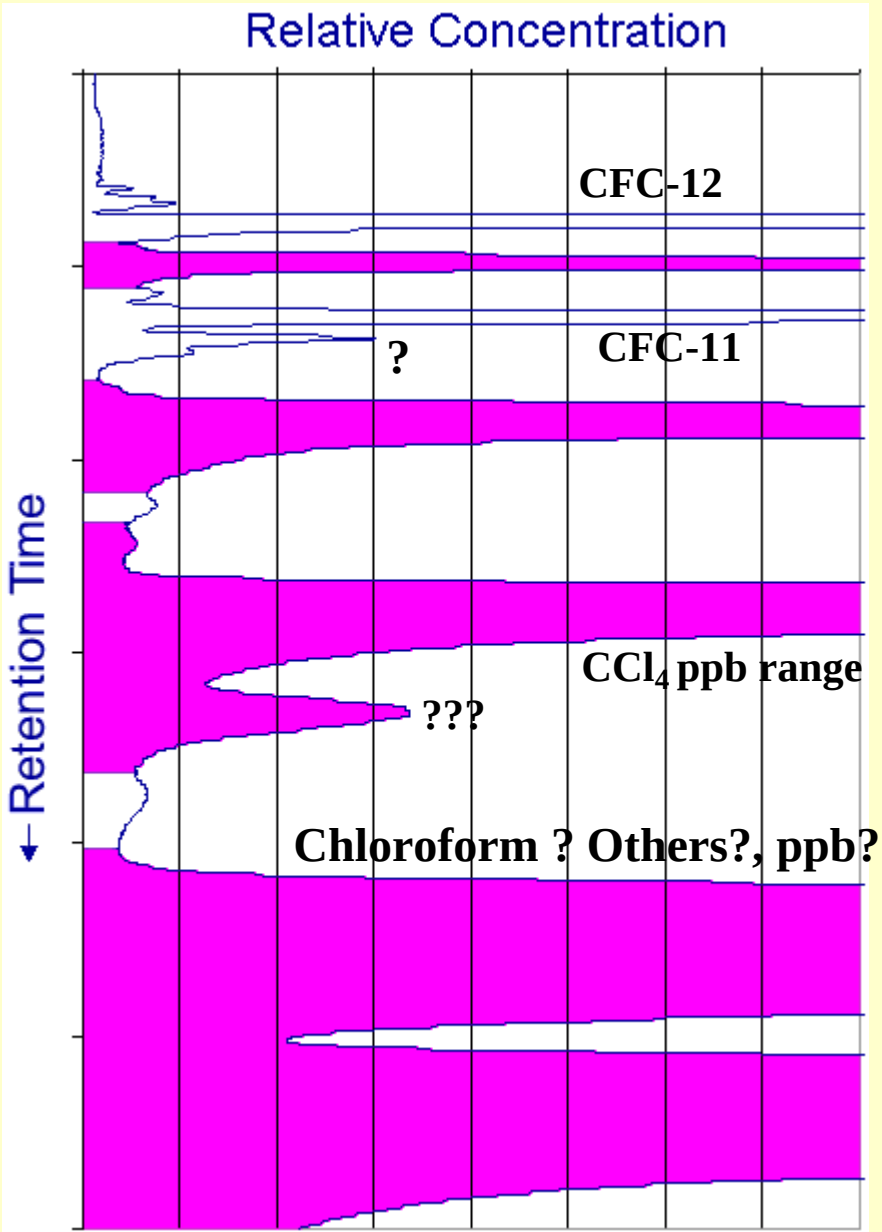


Deep Well, Clean Old Water

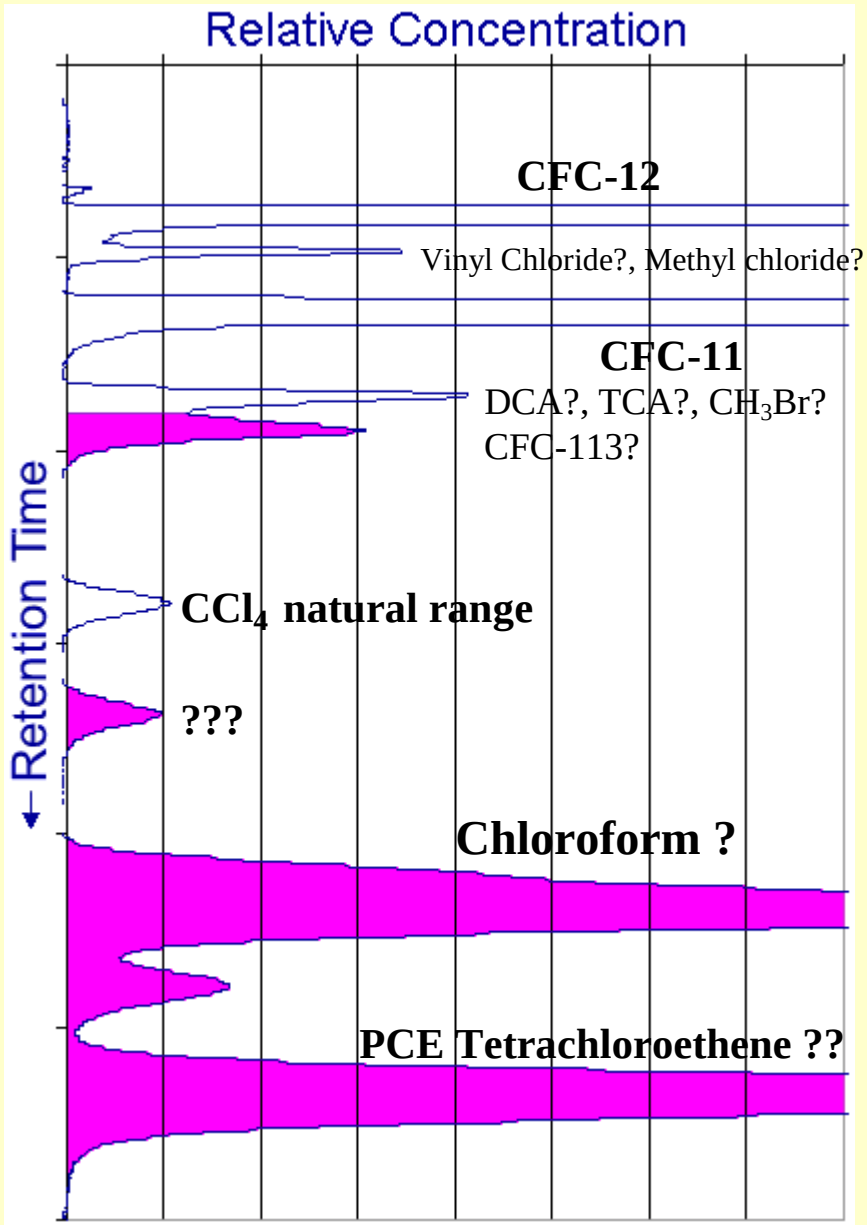
Coastal Plain of Virginia
Depth: 59 Feet
Drinking Water Well



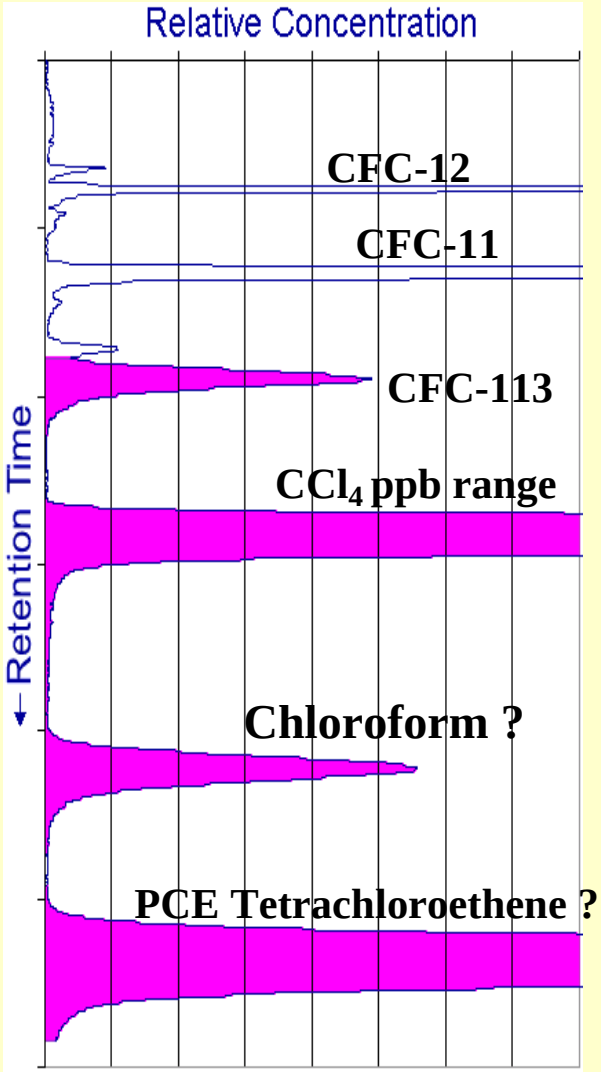
Valley Ridge of Virginia
Drinking Water Well
Depth: 625 feet



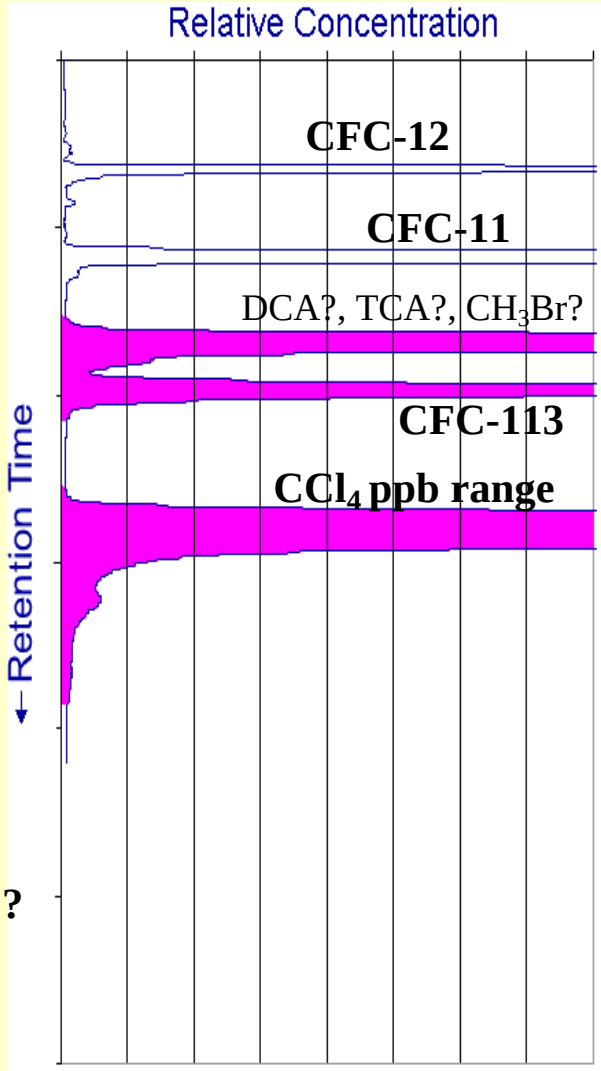
Blue Ridge of Virginia
Drinking Water Well
Depth: 376 feet



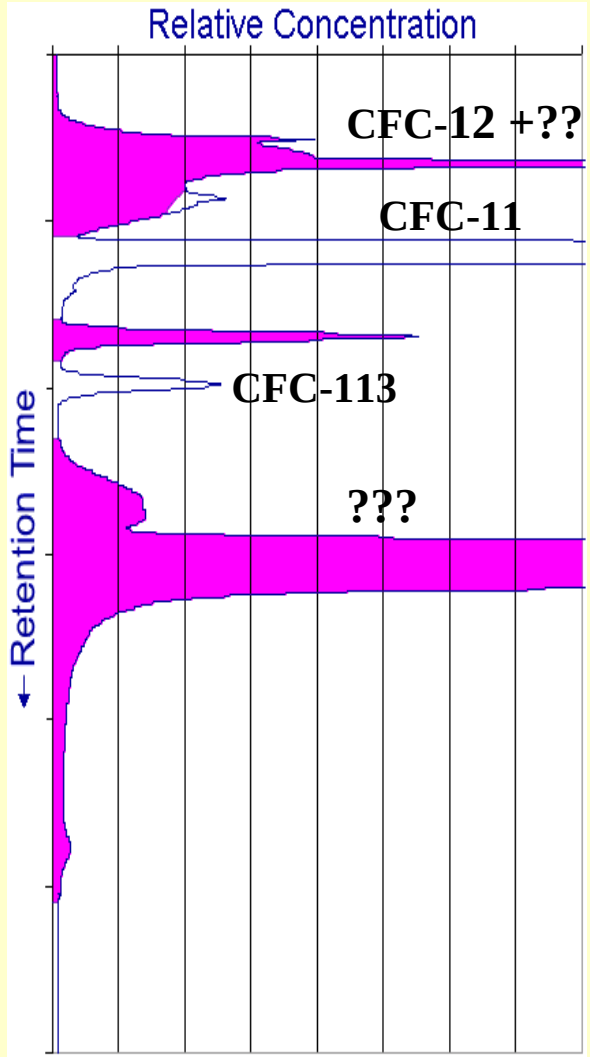
Blue Ridge of Virginia
Drinking Water Well
Depth: 610 feet



Blue Ridge of Virginia
Drinking Water Well
Depth: 280 feet



Piedmont of Virginia
Drinking Water Well
Depth: 400 feet



Concluding Remarks

- We commonly see tracer evidence of binary mixing of young and old in fractured rock.
- This mixing is also evident in dissolved helium, and in some cases other dissolved solutes.
- Exponential mixing, or more complex mixtures seem uncommon in fractured rock.
- Ground-water supplies in the Blue Ridge, Piedmont, and other fractured-rock environments can be highly susceptible to anthropogenic inputs.