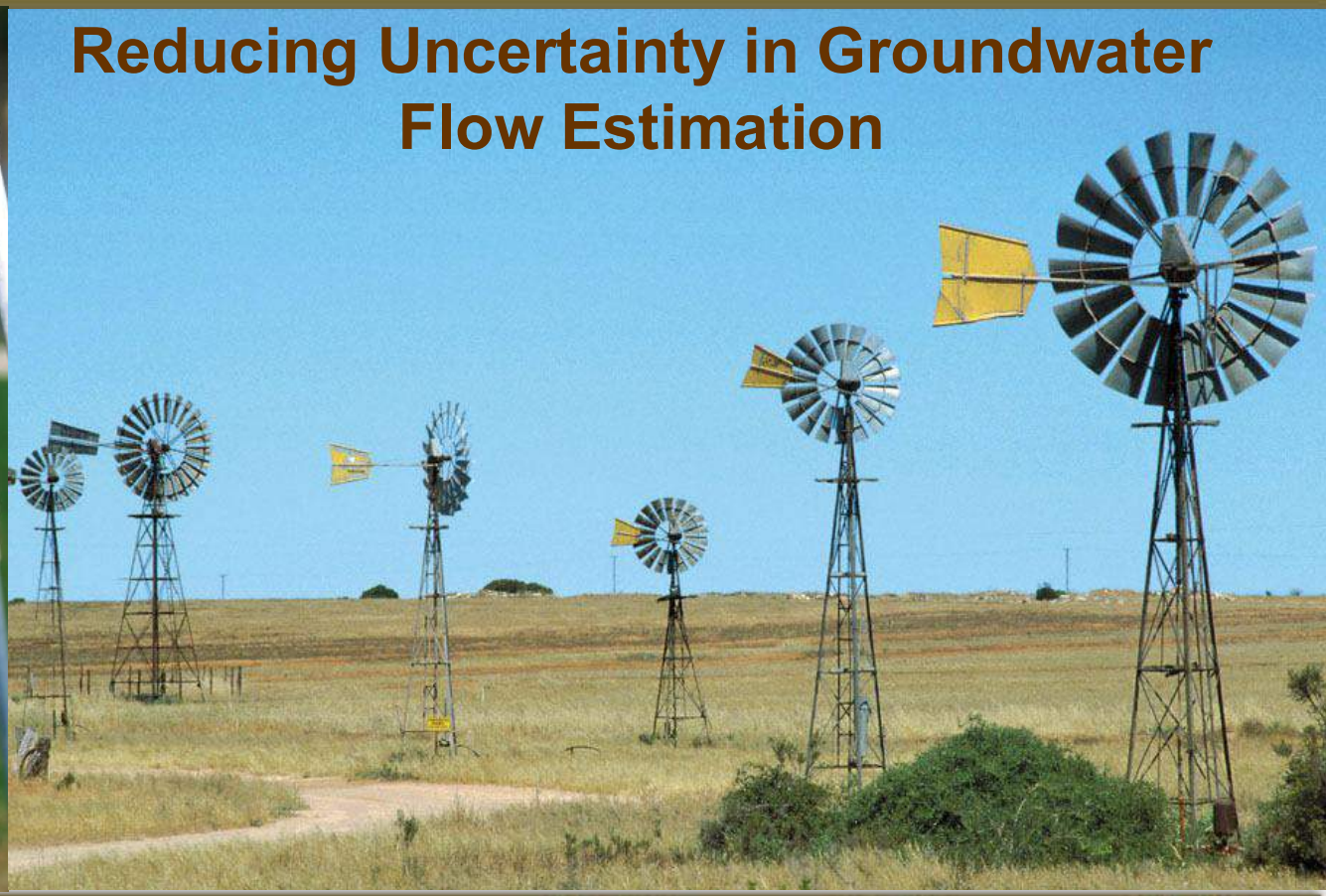
Henry Darcy Distinguished Lecture Series in Ground Water Science

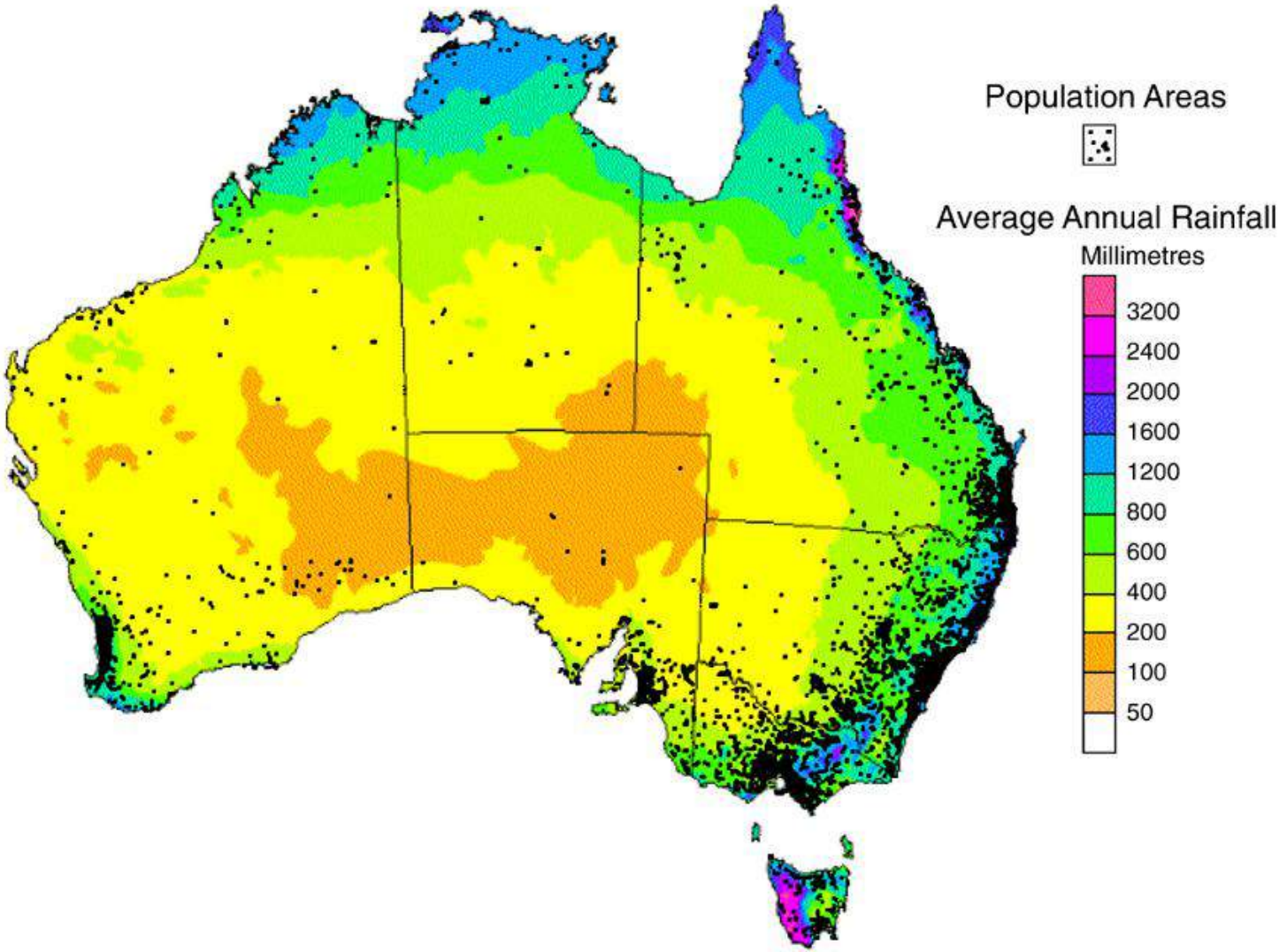
presented by the National Ground Water Research and Educational Foundation

ENVIRONMENTAL TRACERS IN MODERN HYDROGEOLOGY

Reducing Uncertainty in Groundwater Flow Estimation



Hydrogeology in Australia

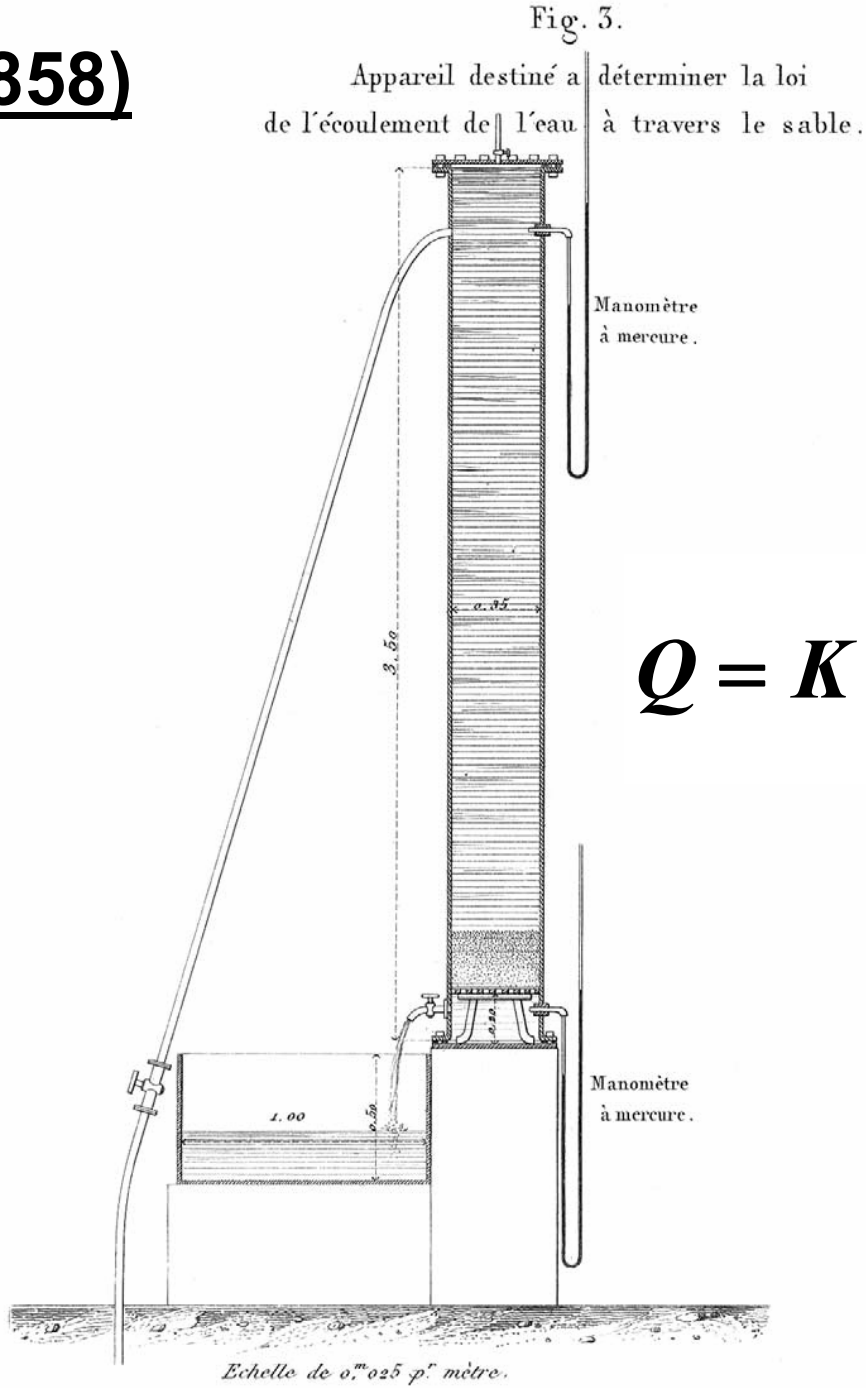


Would you drive across a bridge built by hydrogeologists?

Outline

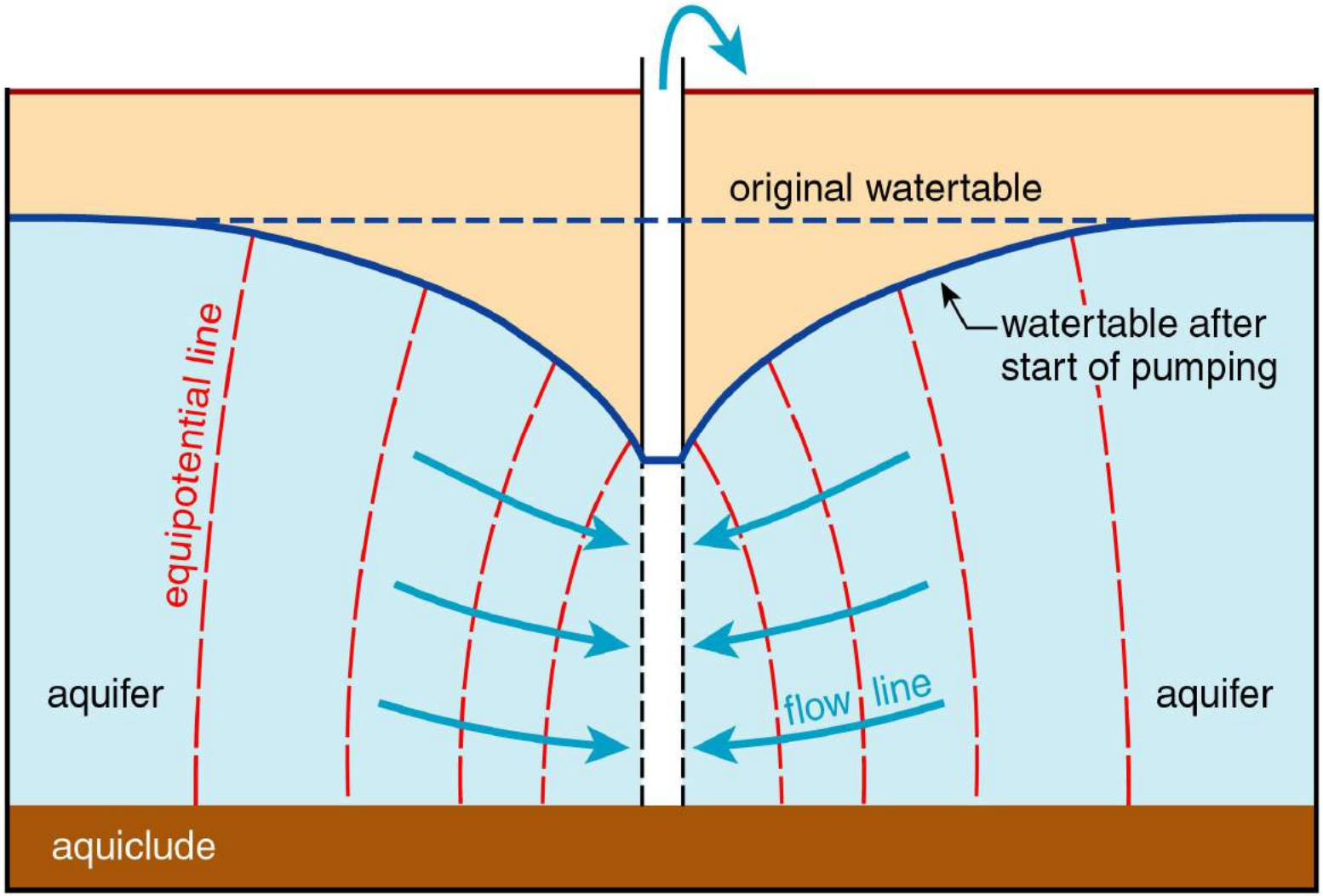
- Historical Background
- Heterogeneous Aquifers
- Fractured Rocks
- Future Directions

Henry Darcy (1803 – 1858)

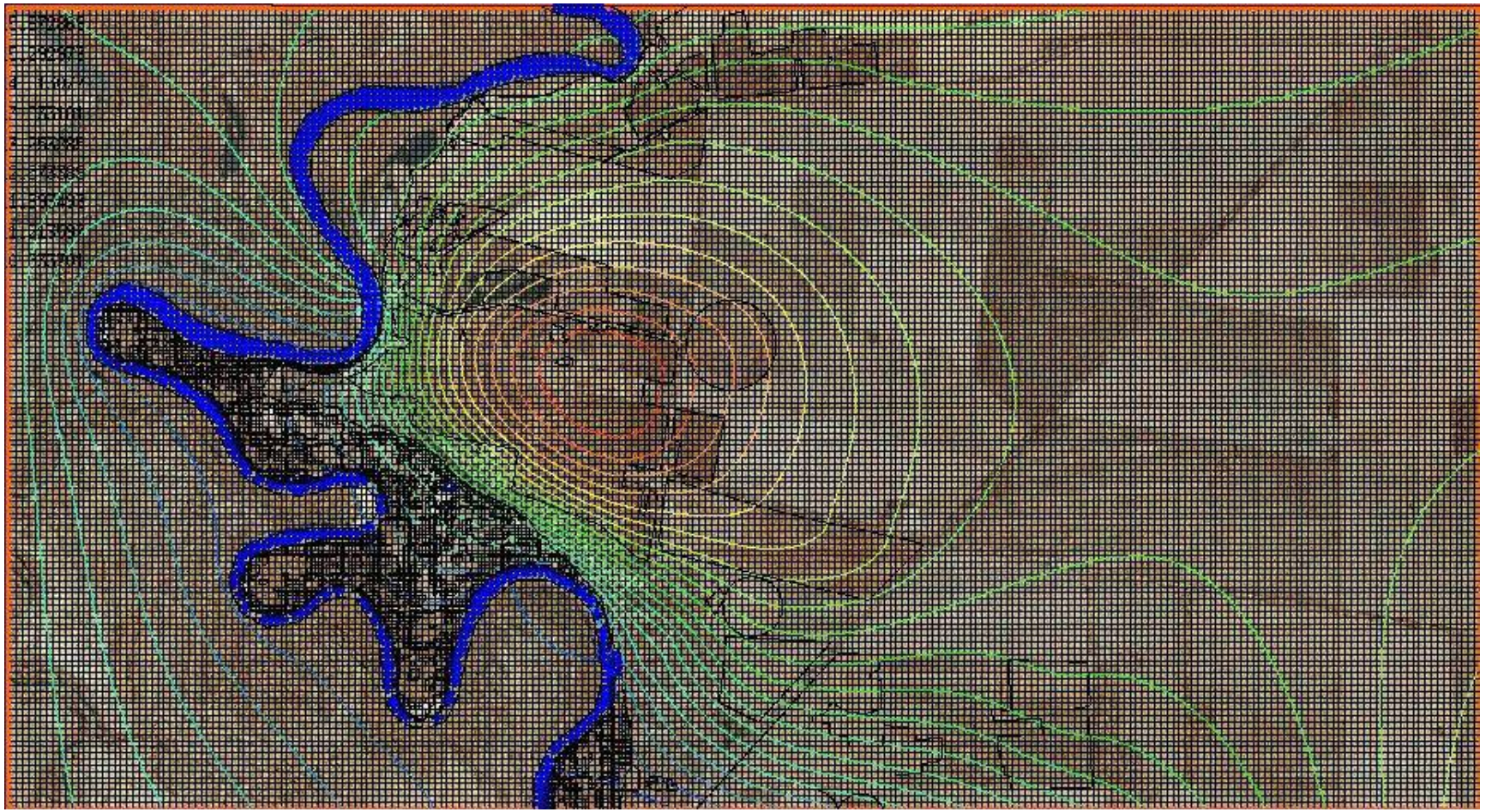


$$Q = K \frac{\partial h}{\partial x}$$

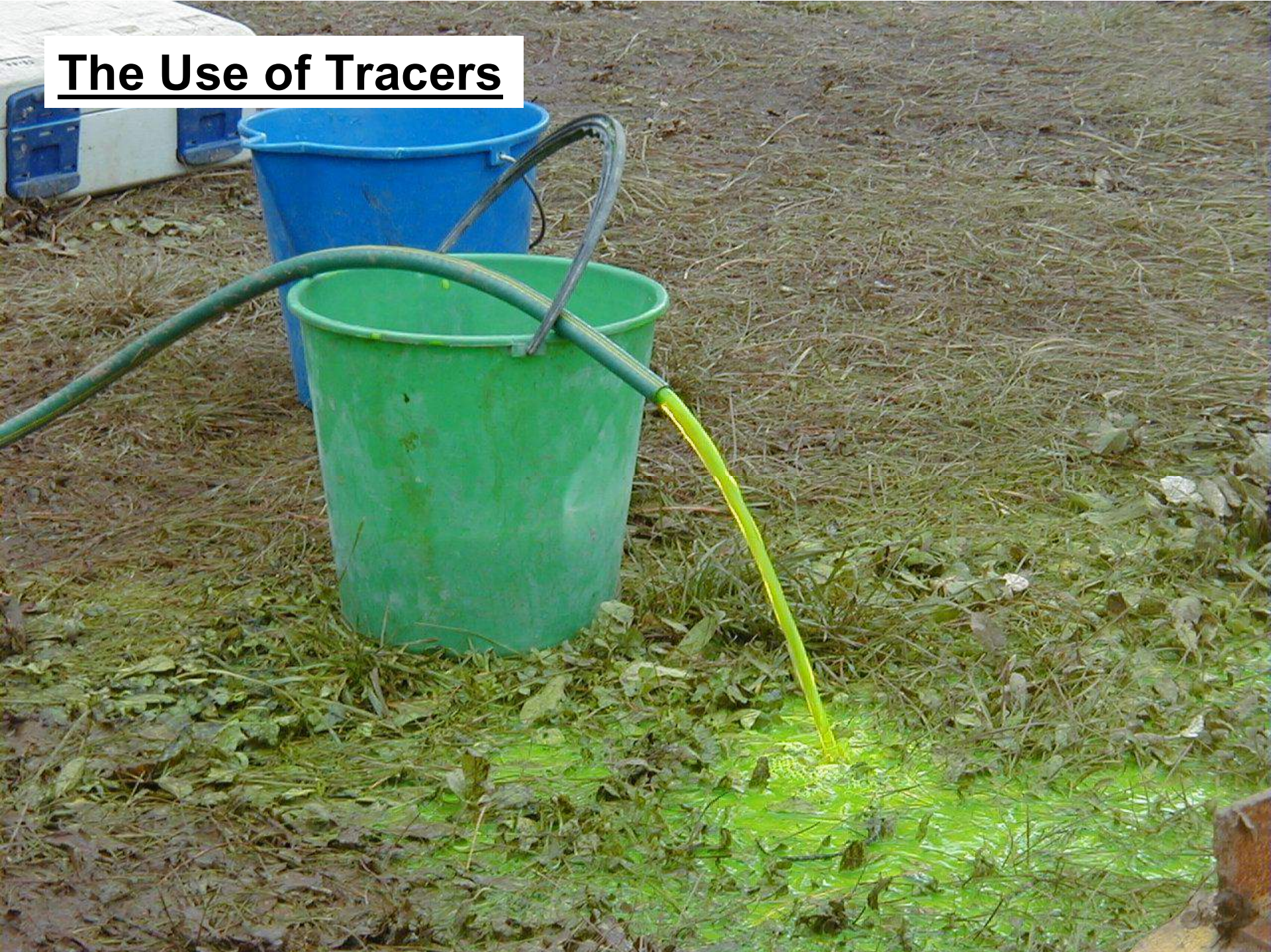
Pumping Tests



Groundwater Flow Modelling



The Use of Tracers

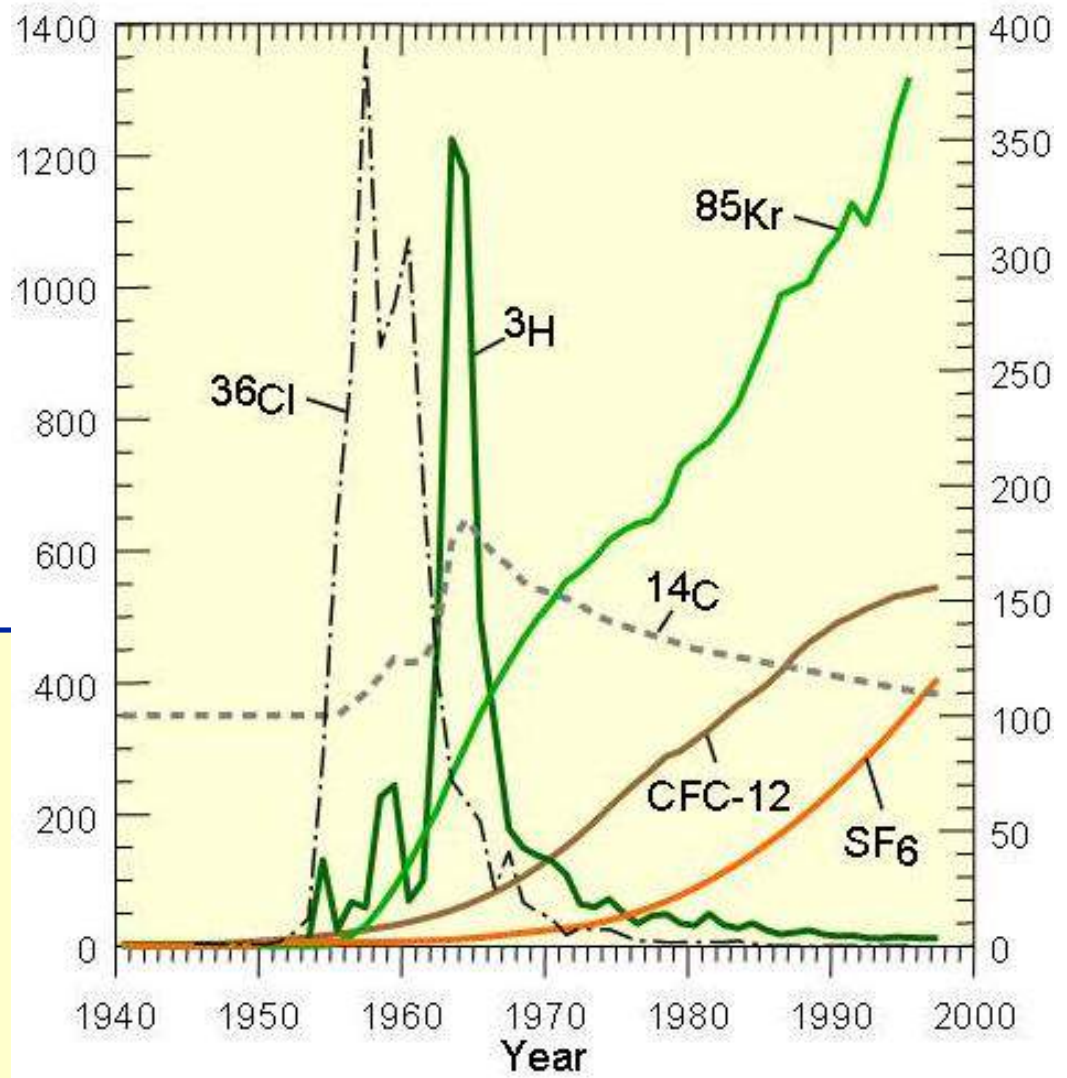


The Explosion of Environmental Tracer Studies

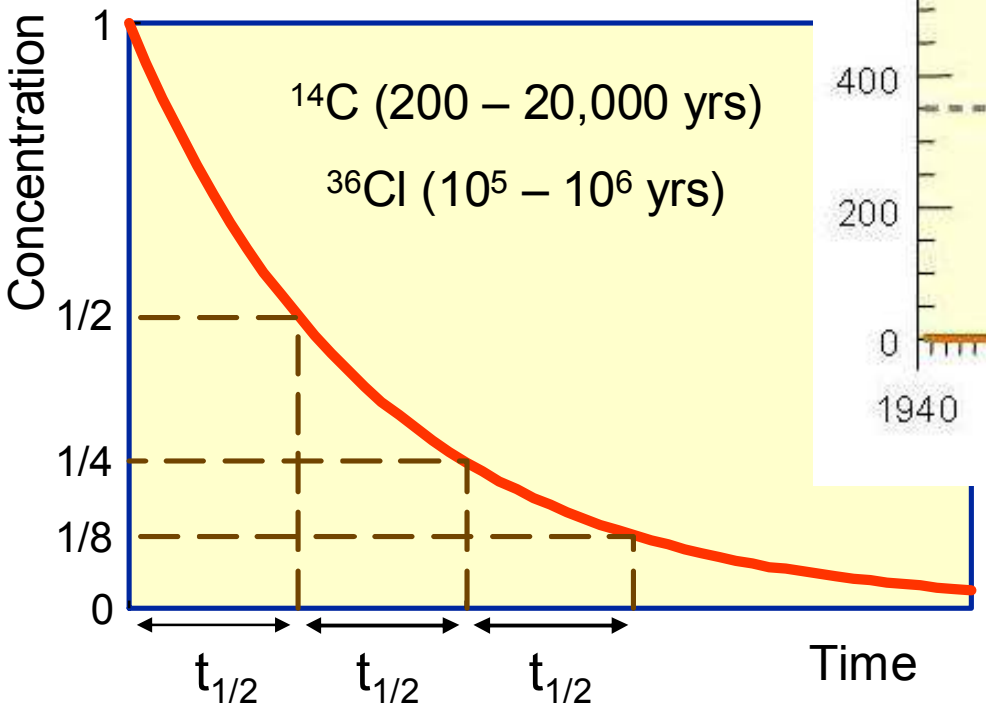
Willard Libby

Groundwater Dating Methods

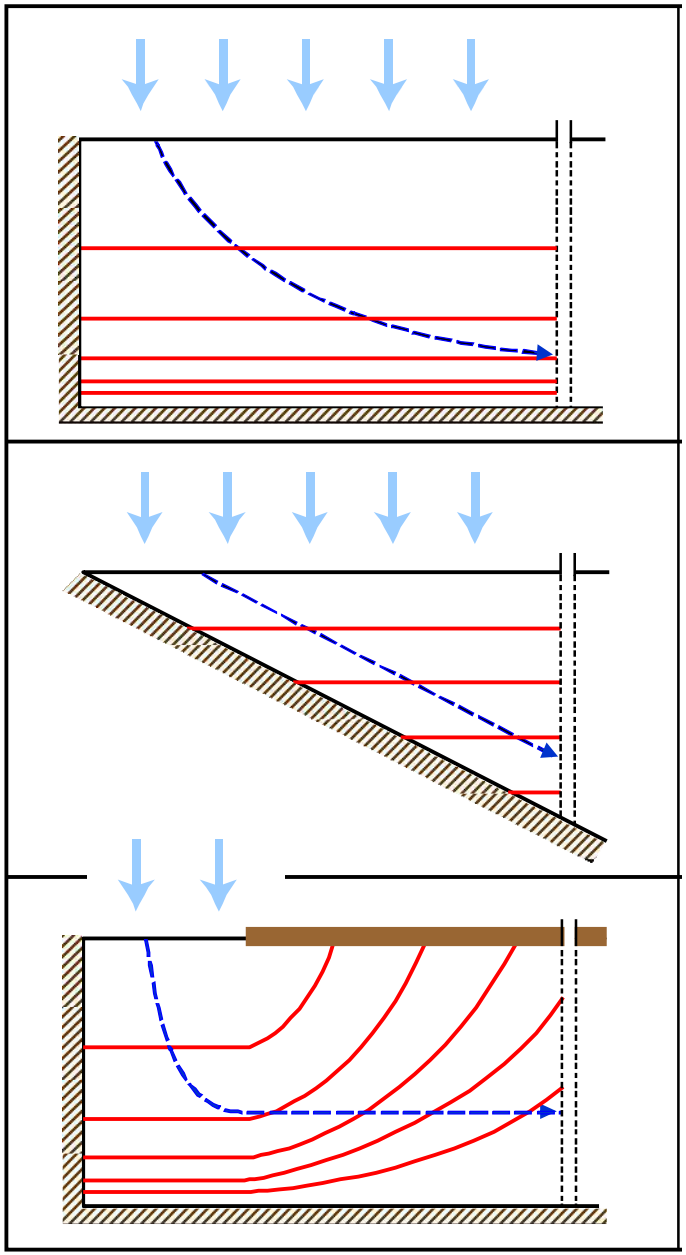
Event Marker – Based Methods



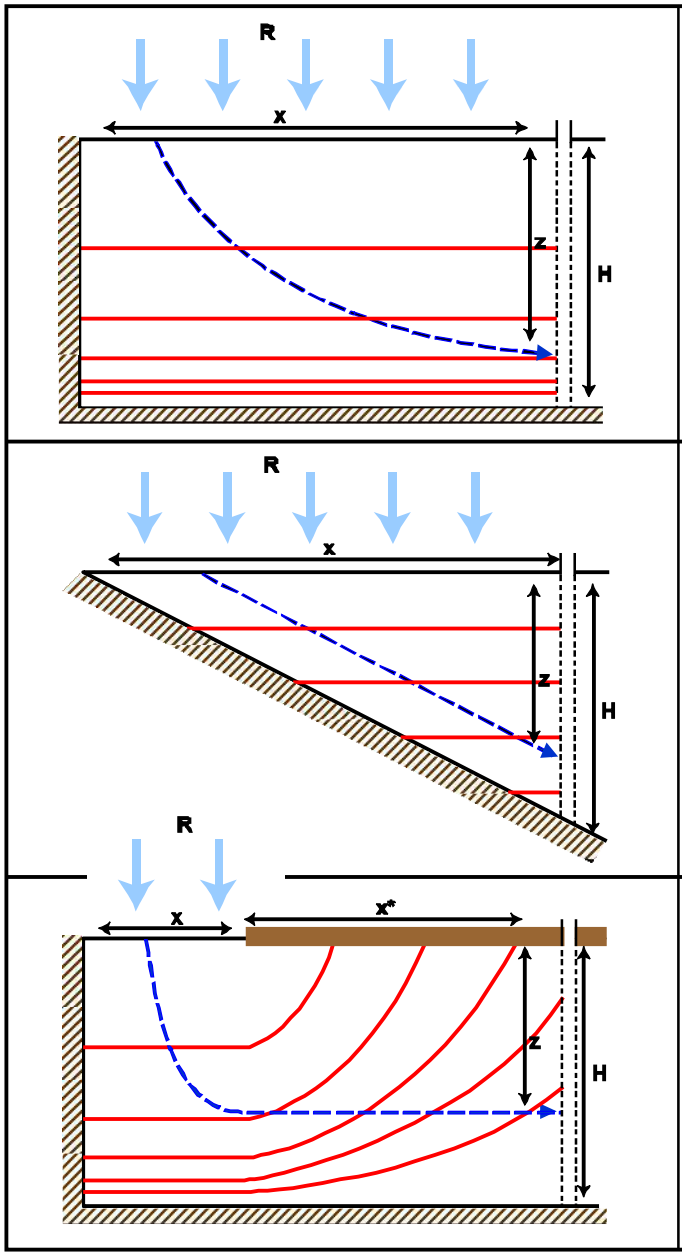
Radioactive Decay – Based Methods



Groundwater Ages in Simple Aquifers



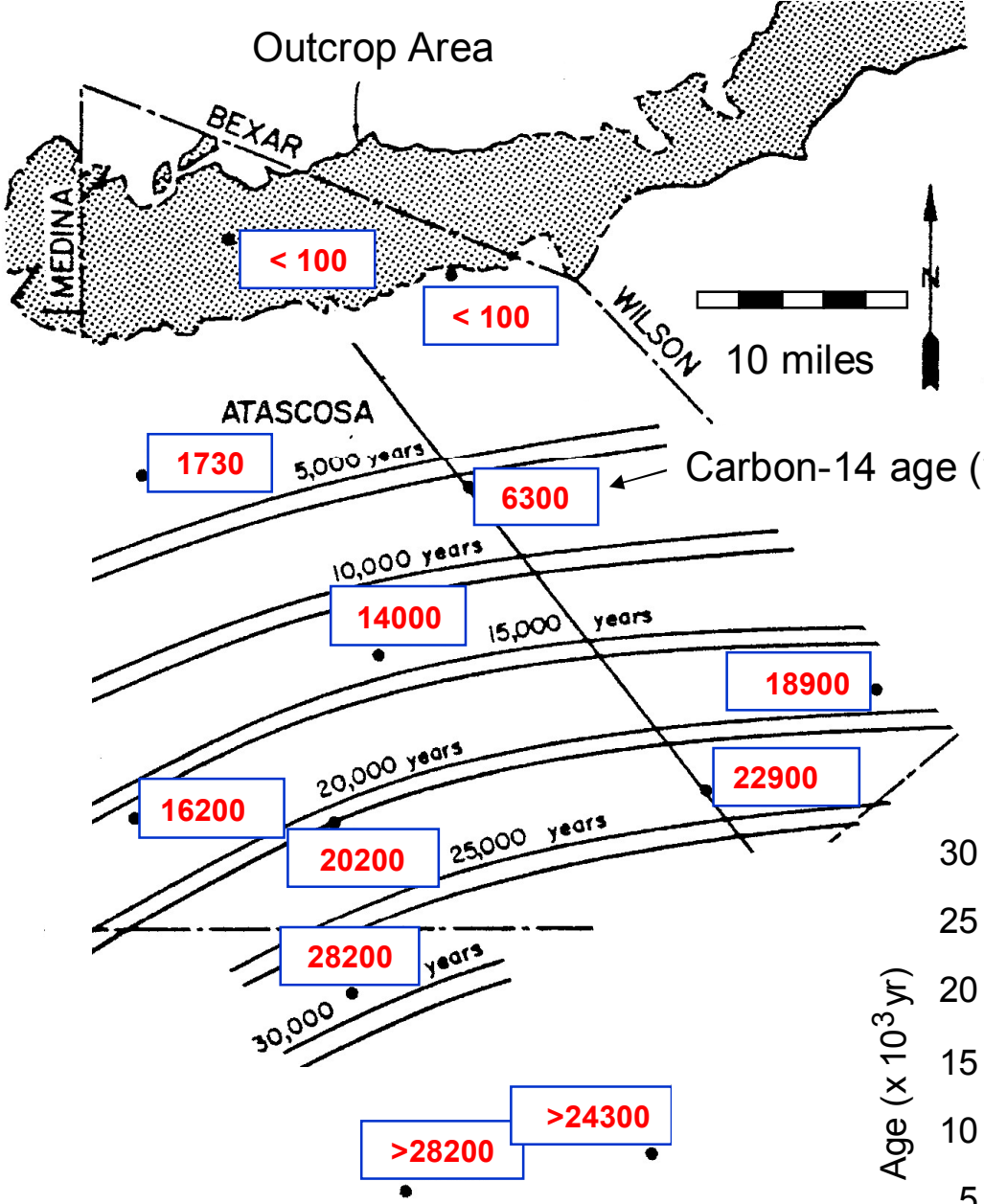
Groundwater Ages in Simple Aquifers

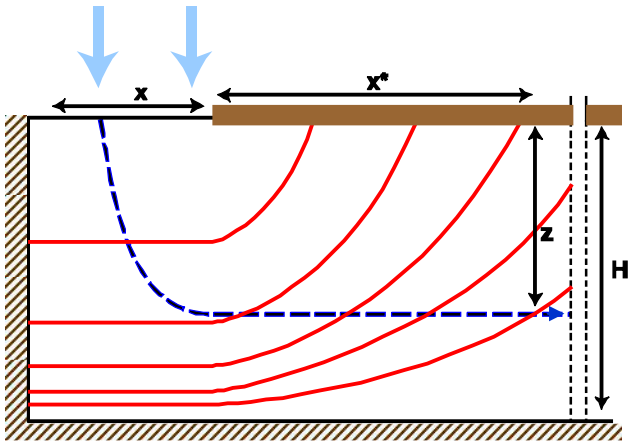


$$t = \frac{H\varepsilon}{R} ln\left(\frac{H}{H-z}\right)$$

$$t = \frac{z\varepsilon}{R}$$

$$t = \frac{H\varepsilon}{R} ln\left(\frac{H}{H-z}\right) + \frac{x^* H\varepsilon}{Rx}$$



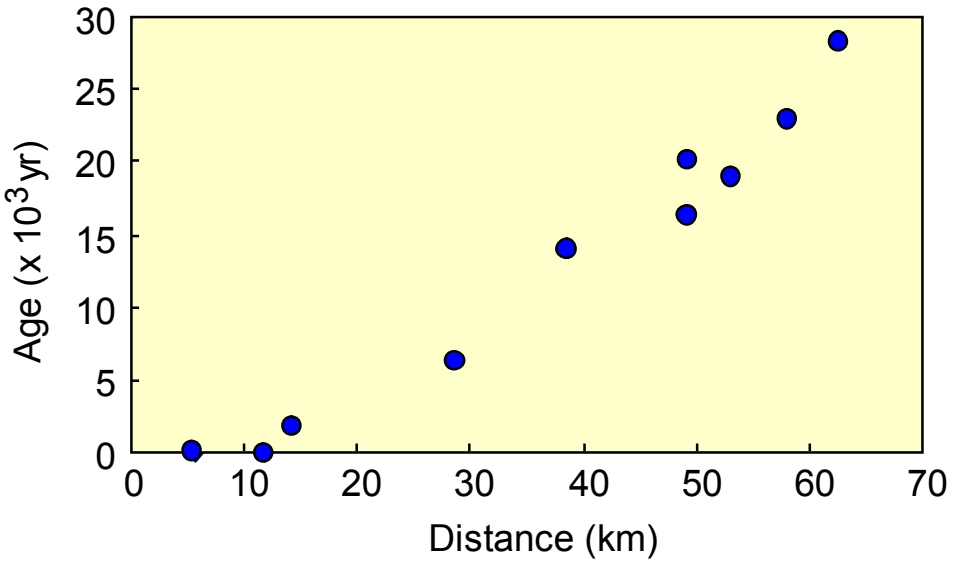


V_h = 2 m/y

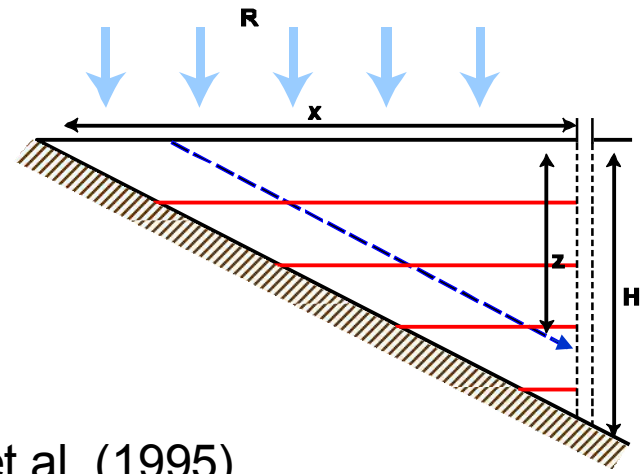
If H = 300 m, ε =0.4

then Rx = 240 m^2/y

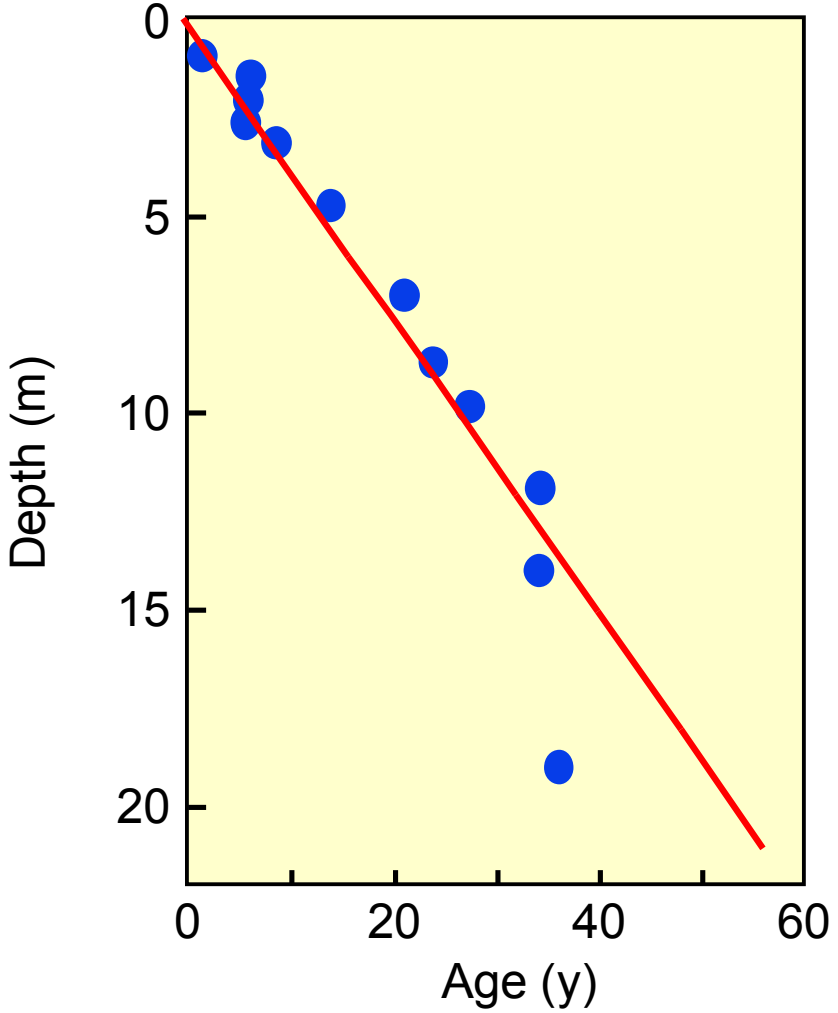
If x = 10 km, R = 24 mm/y



Pearson and White (1967)



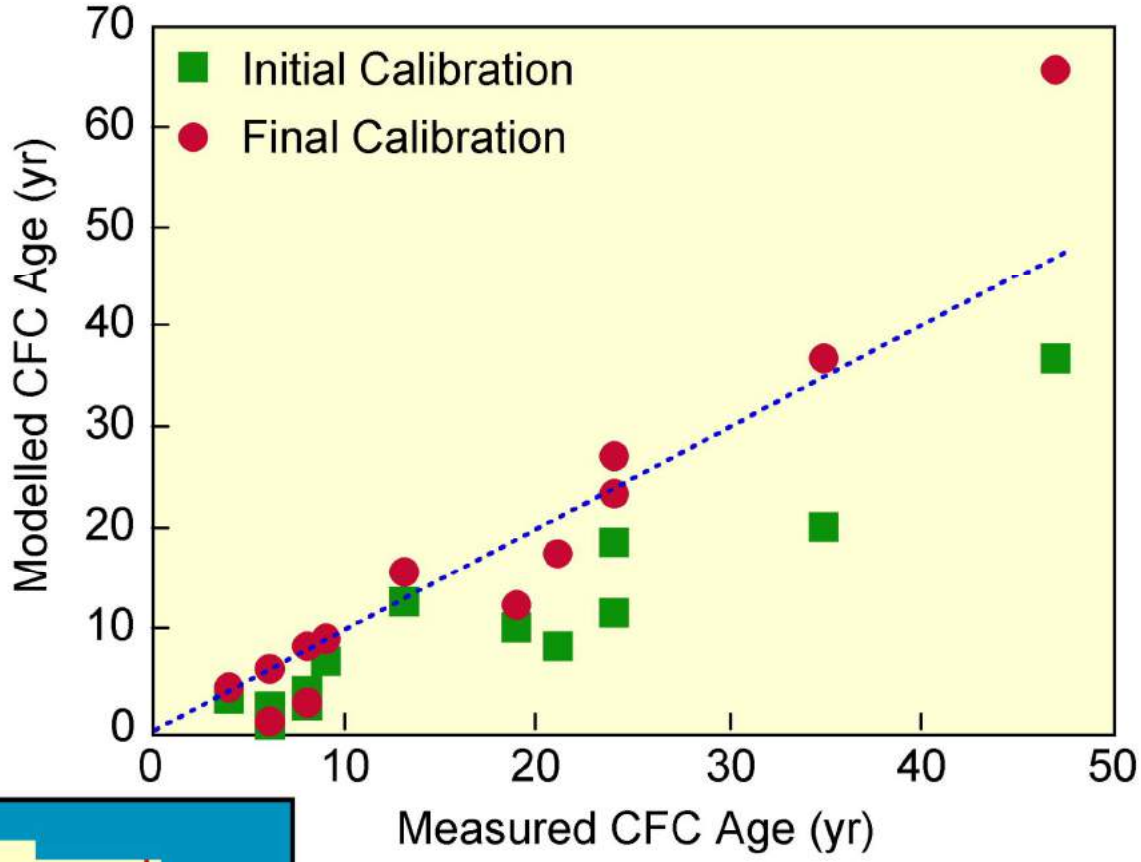
Cook et al. (1995)

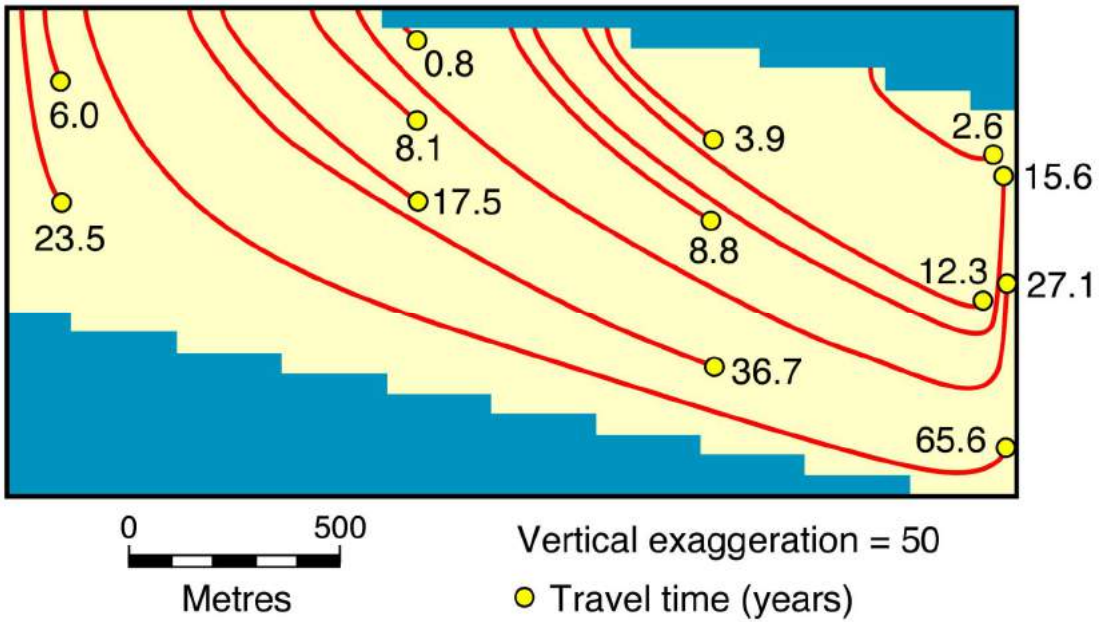


V_v = 0.375 m/y

If ε = 0.4 then R = 0.15 m/y

Groundwater Ages as Model Calibration Targets





Reilly et al. (1994)

Heterogeneity

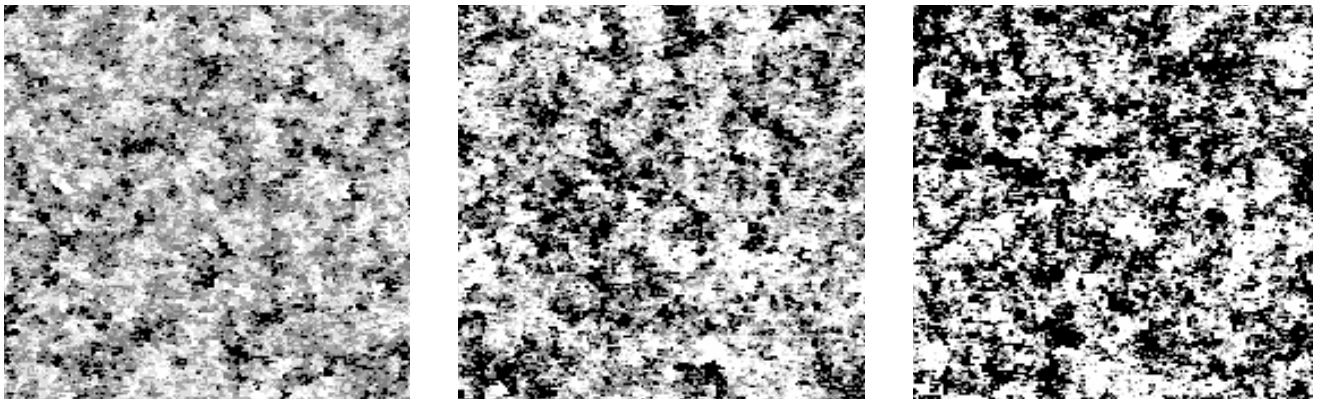
Variability of Hydraulic Conductivity

Aquifer	Lithology	No. of Wells	Range (Orders of Magnitude)
Fontainebleau	Sandy	28	1.2
Brie	Limestone	26	1.9
Champigny	Limestone	65	2.3
St Ouen	Limestone	13	2.4
Lutetian	Limestone	69	1.8
Cuisian	Sandy	13	2.1
Ypresian	Sandy	36	1.1
Nord	Chalk	144	2.4
C. De Nijar	Limestone	30	1.5
Kairouan	Alluvial	46	1.4
Aquitaine	Sandy	29	2.0
Normandy	Limestone	45	3.3
Durance	Alluvial	36	1.7

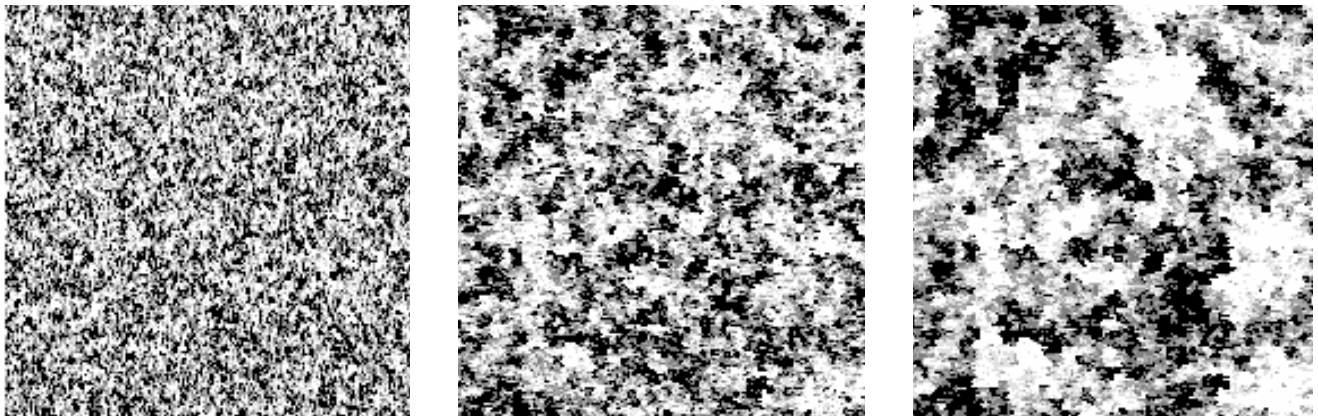
Delhomme (1979)

Characteristics of Heterogeneity

Increasing variance →

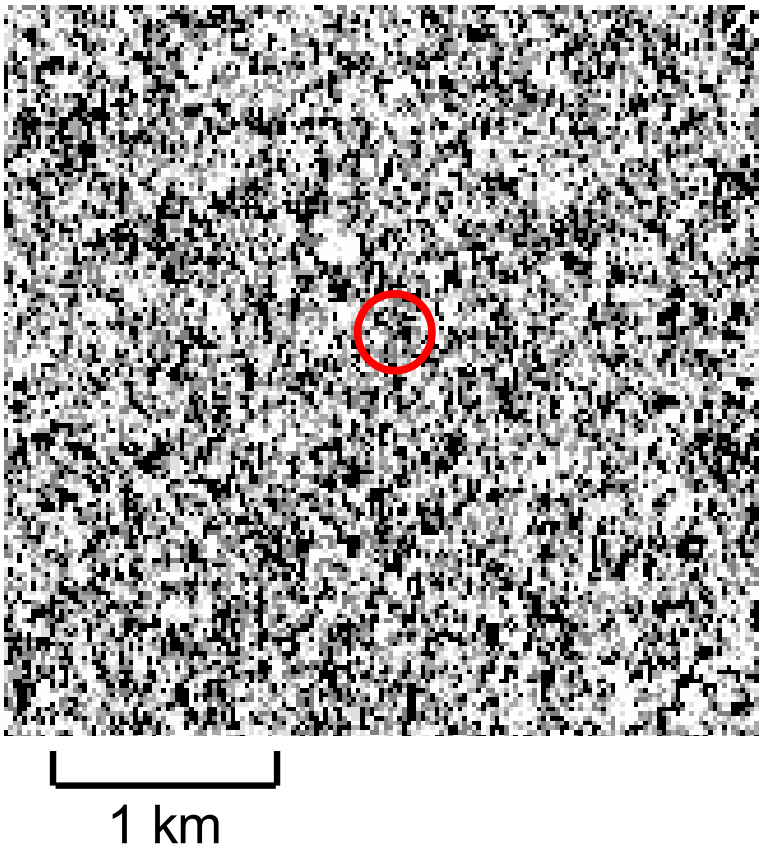


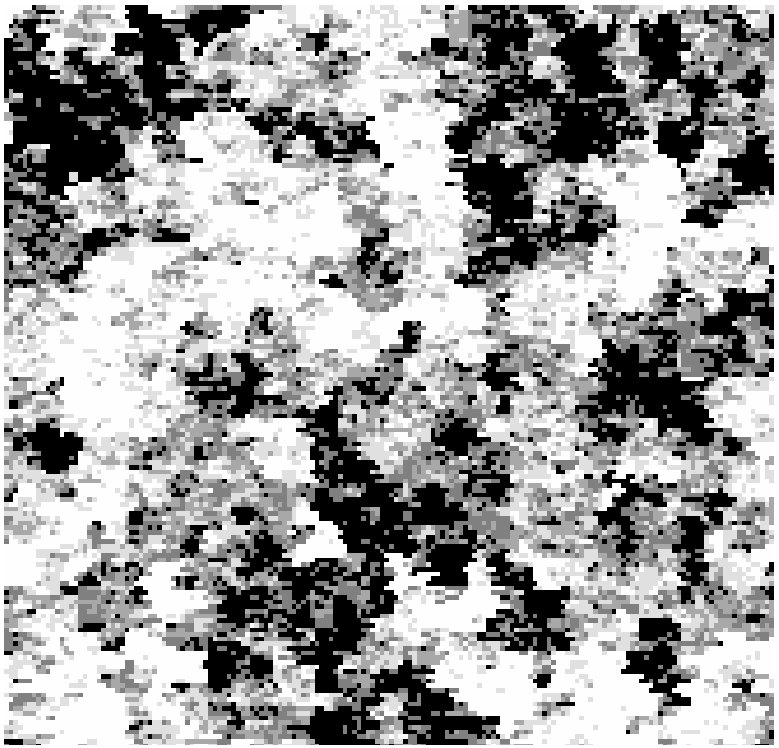
Increasing autocorrelation scale →



Measurement in Heterogeneous Systems

- Multiple measurements
- Large scale measurements





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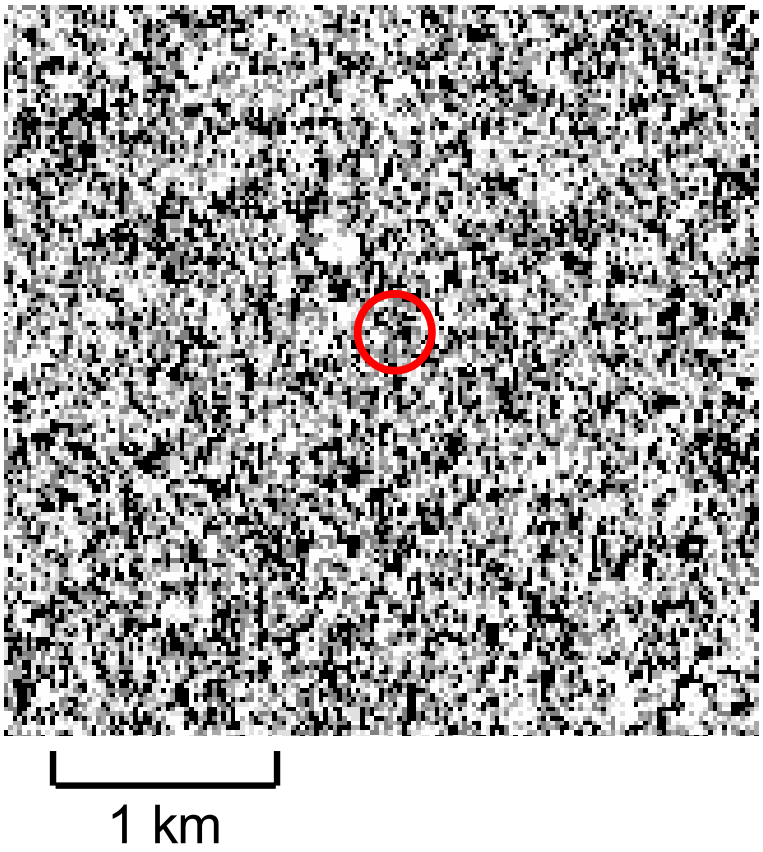

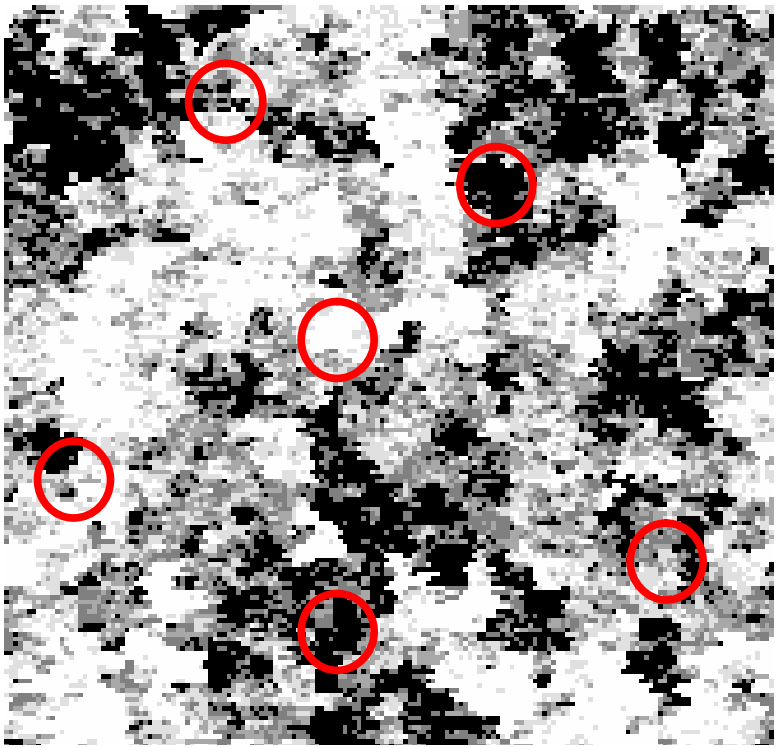

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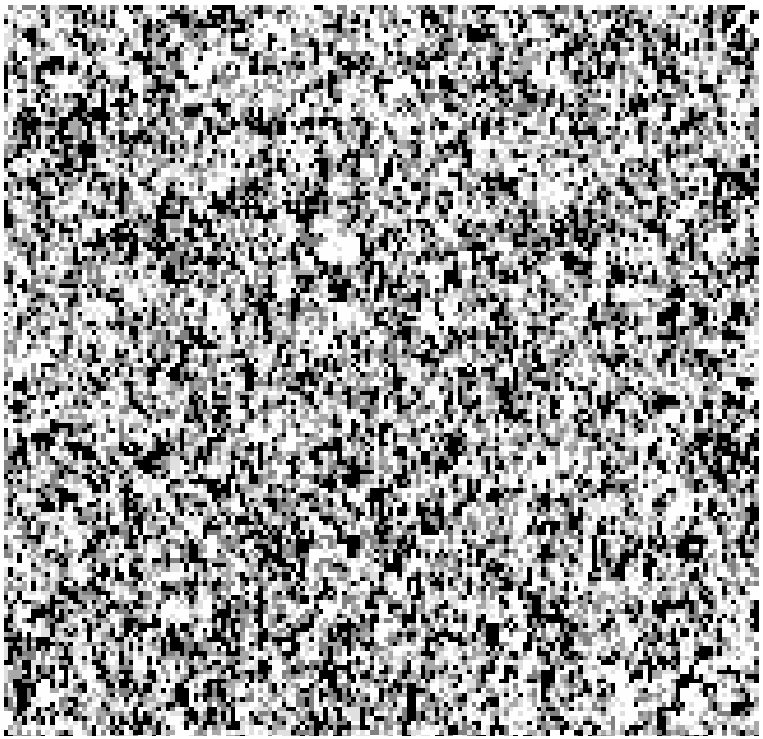
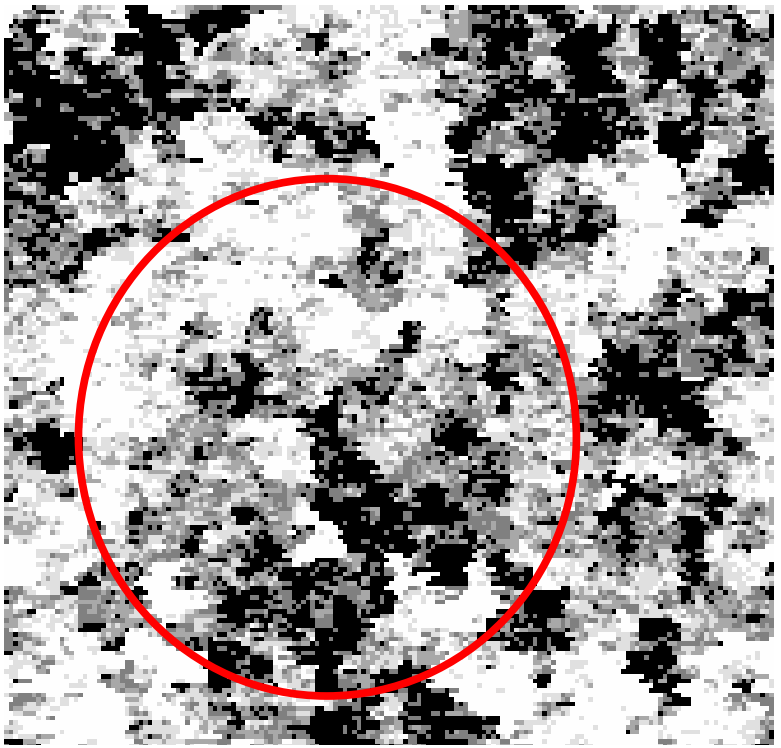
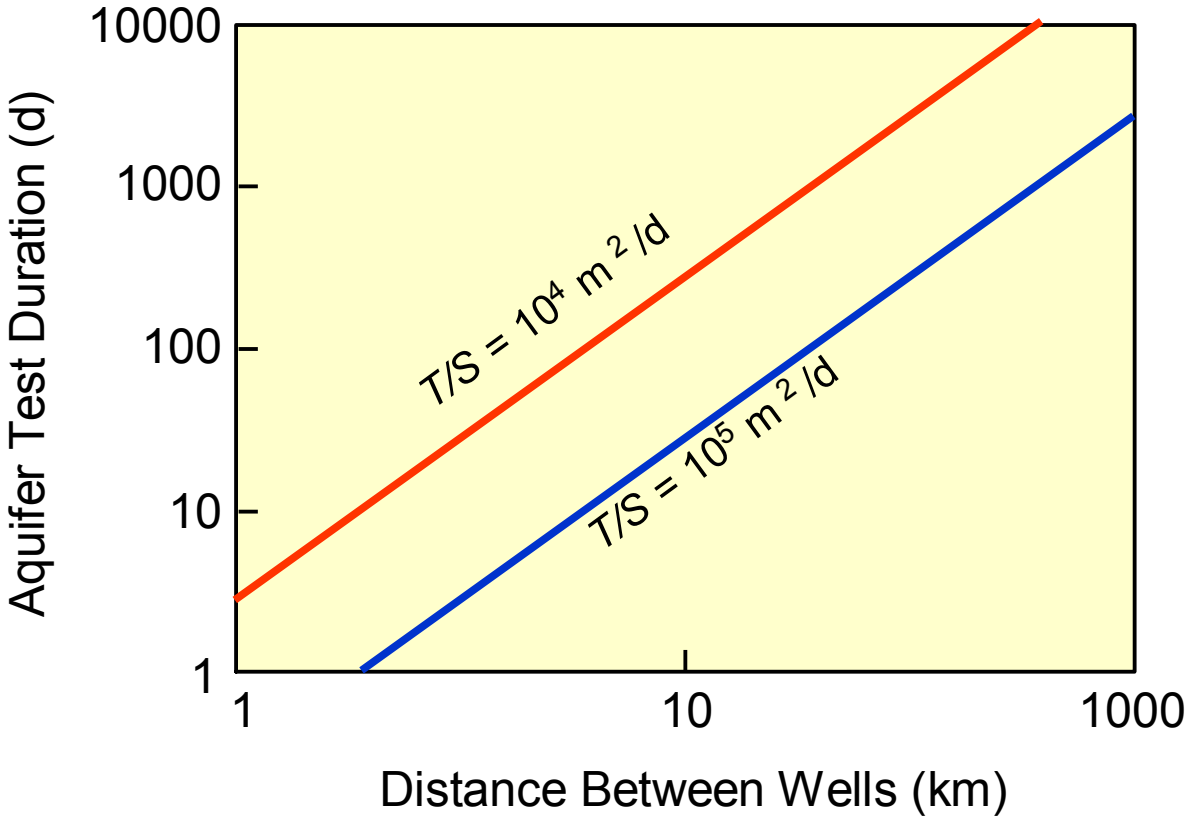




The important parameter is the ratio of the measurement scale to the autocorrelation scale

Tracers have a large spatial footprint



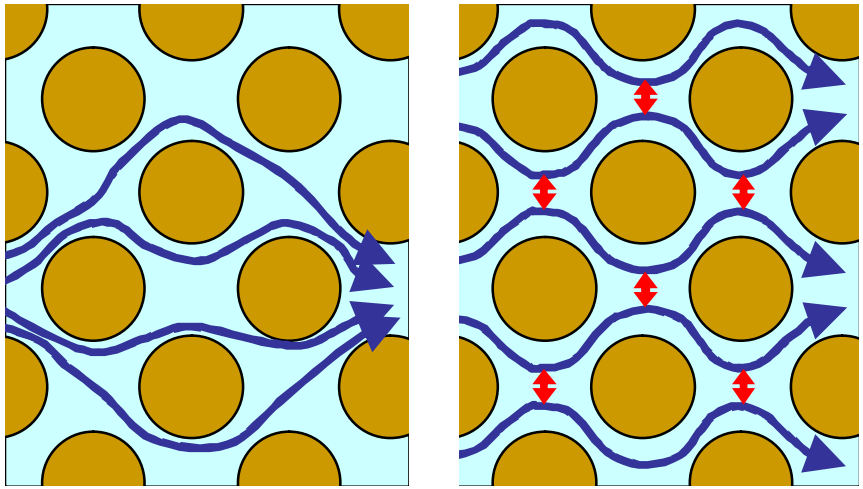
For $T/S = 10^5$ m^2/d …

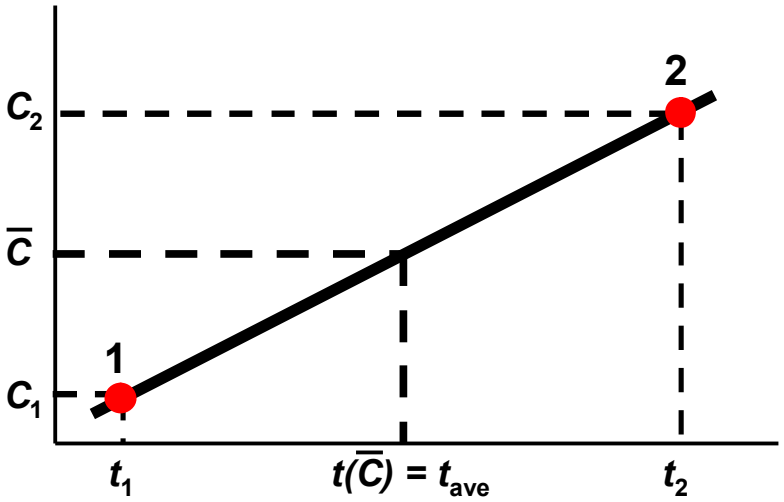
Tracer well separation of 10 km ≡ 1 month pumping test

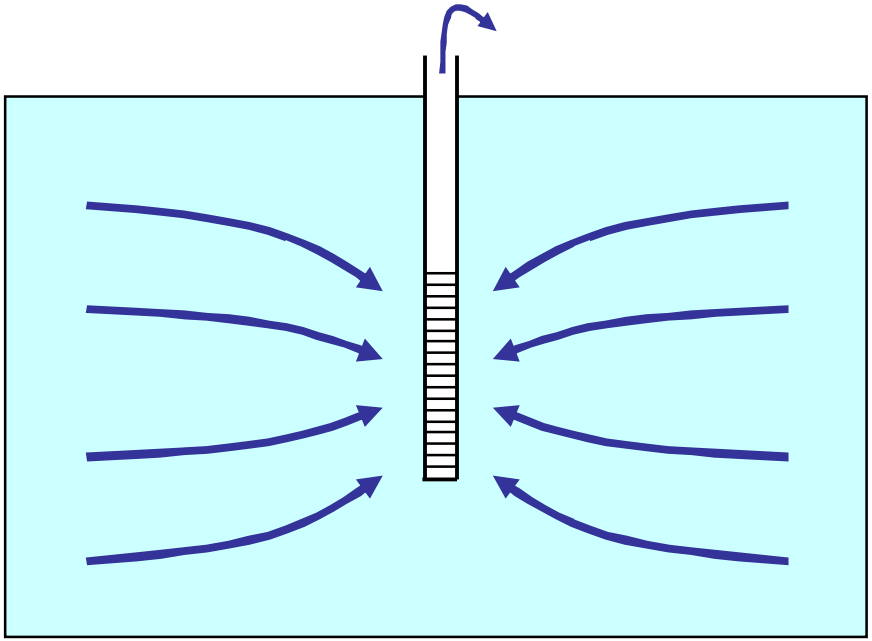
Tracer well separation of 100 km ≡ 1 year pumping test

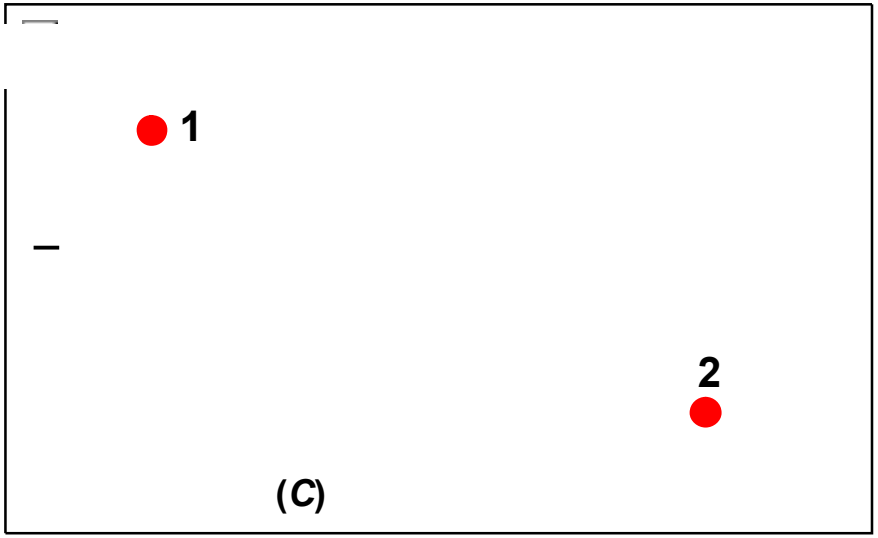
Larocque, Cook et al. (2009)

Effect of Mixing on Groundwater Ages

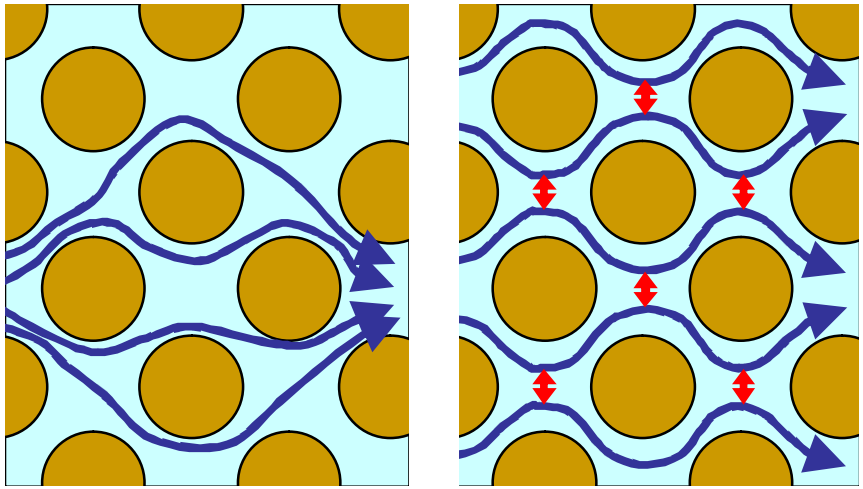


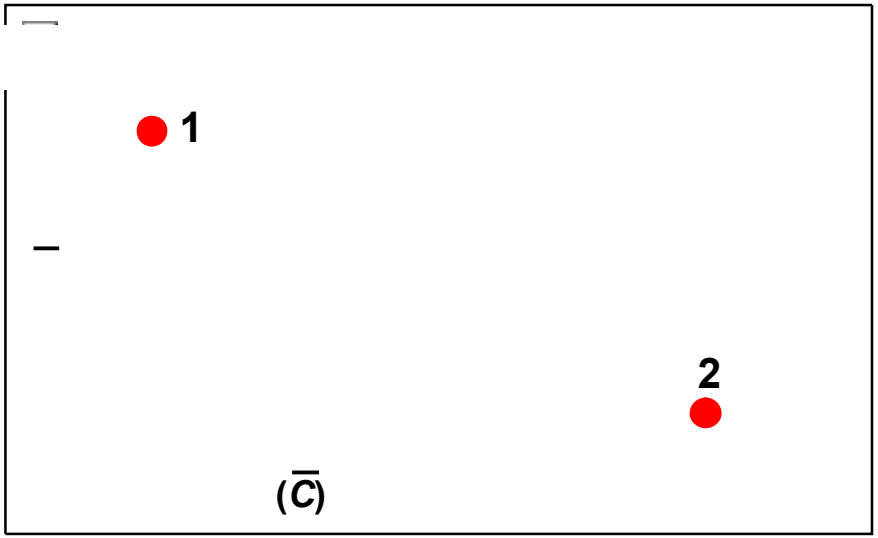


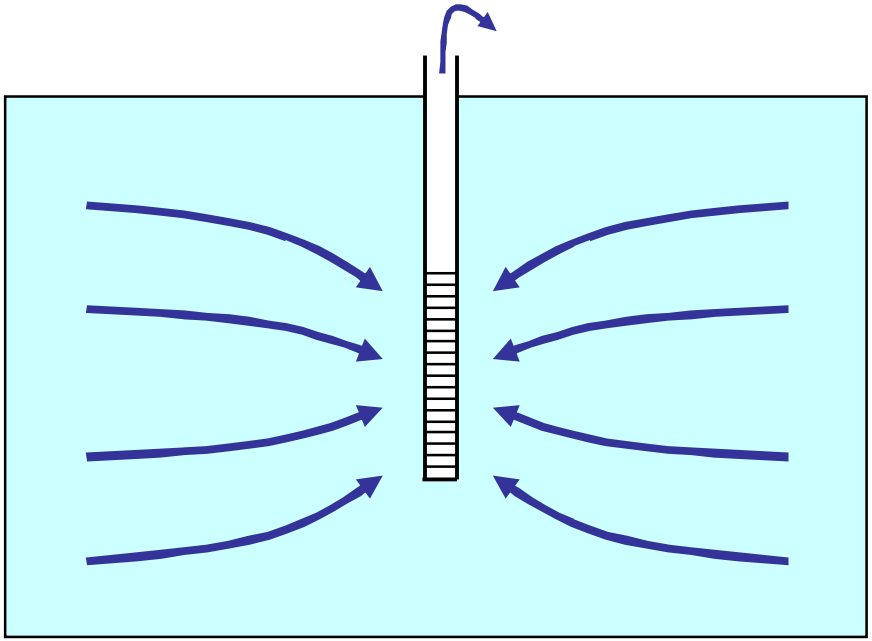


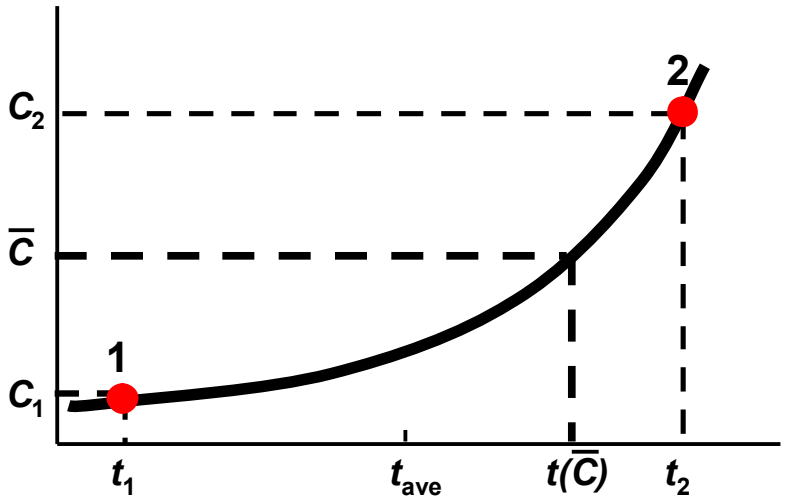


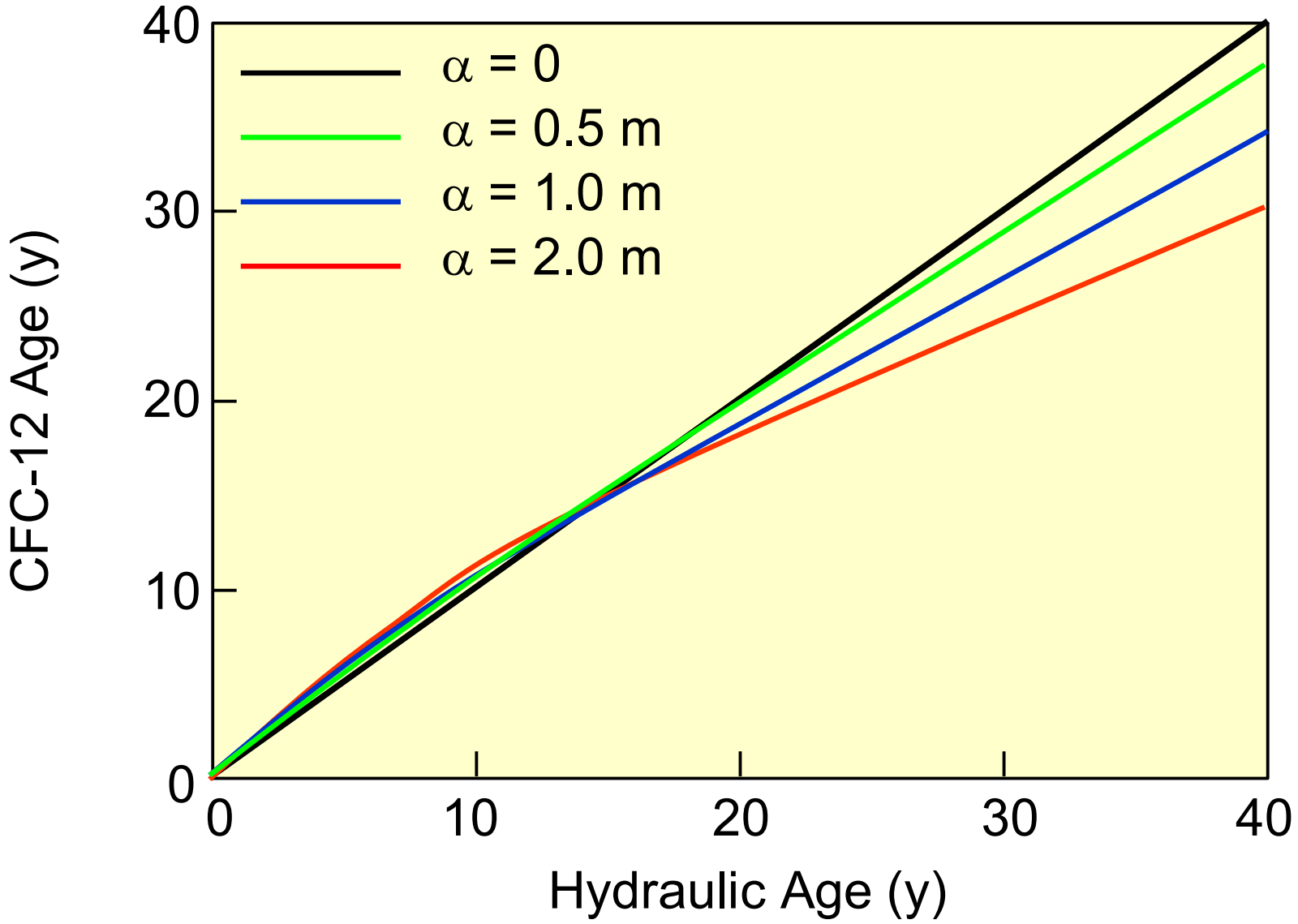
Effect of Mixing on Groundwater Ages



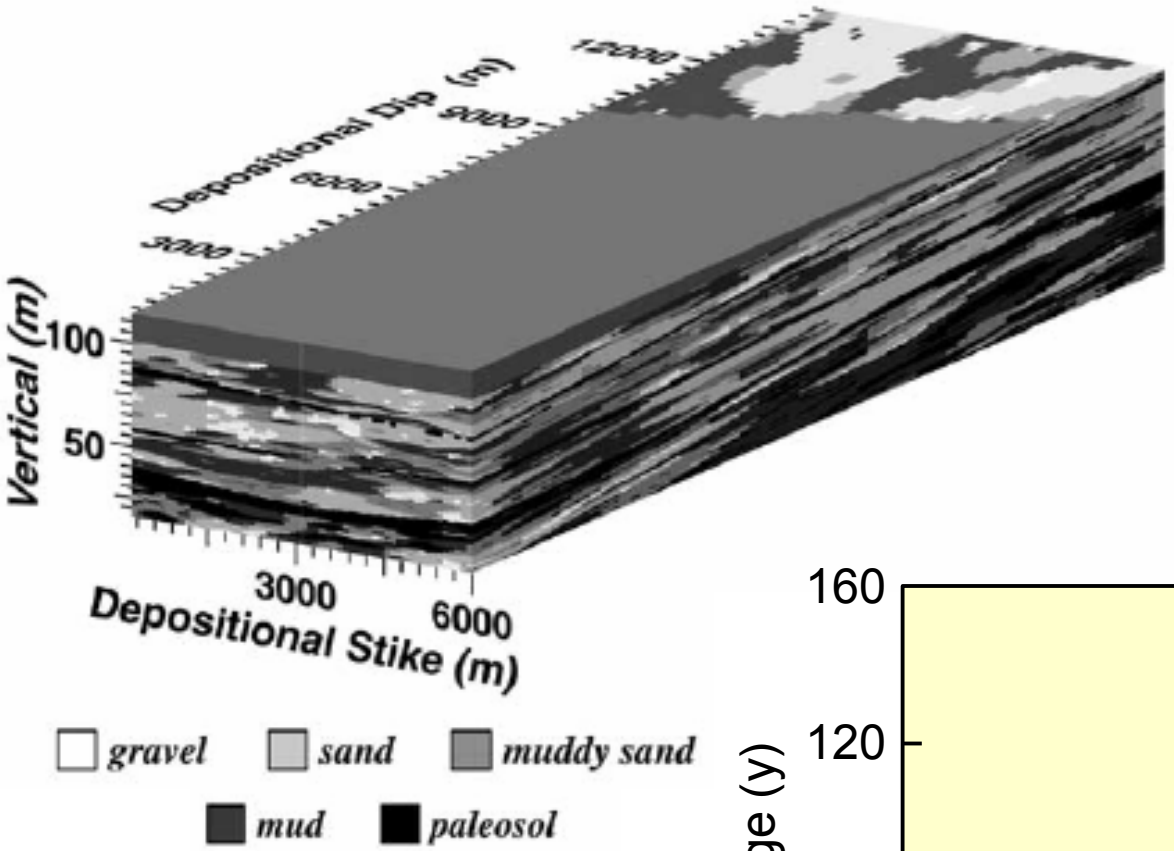


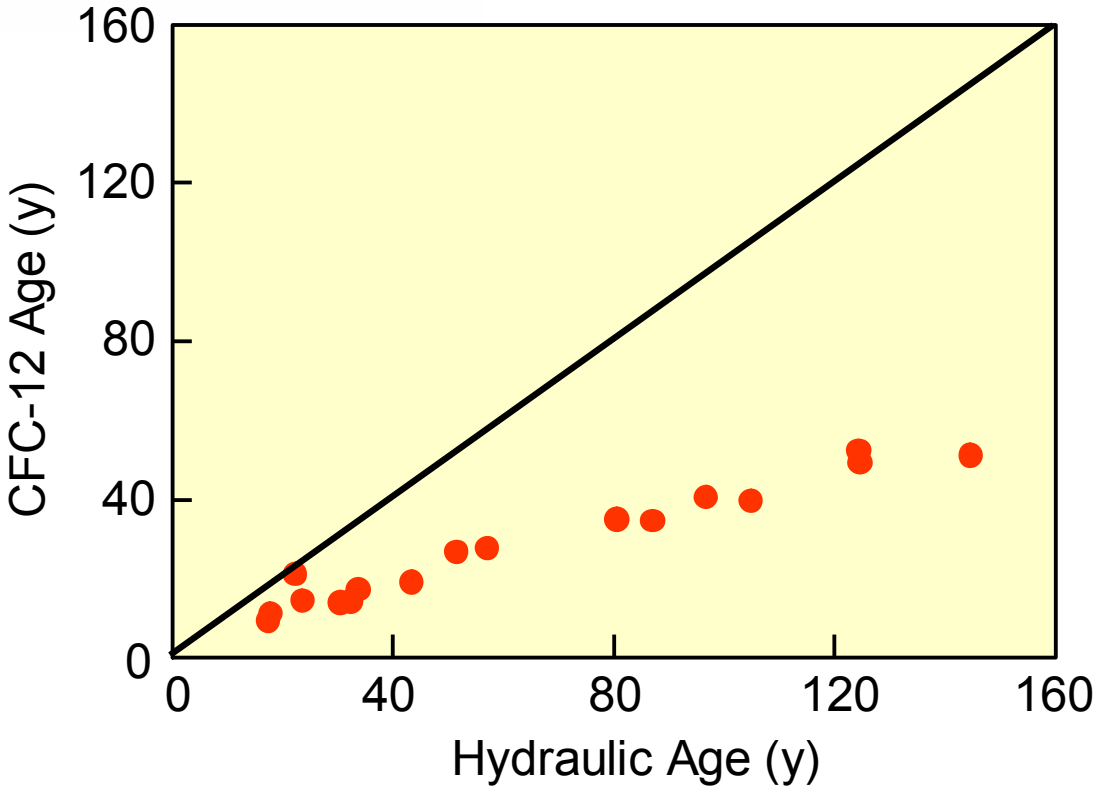






Ekwurzel et al. (1994)

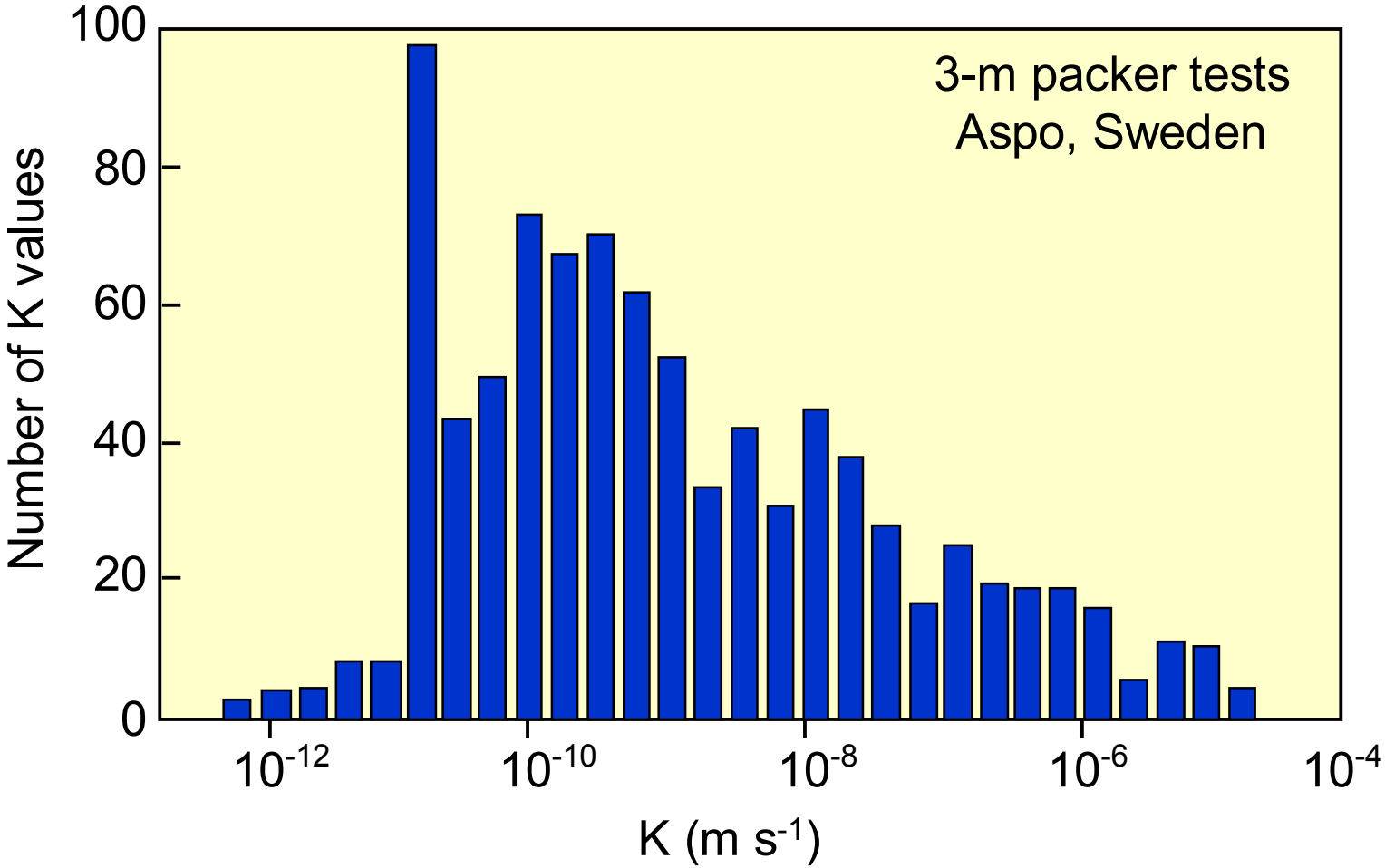




Weissmann et al. (2002)

Fractured Rock

Hydraulic Conductivity

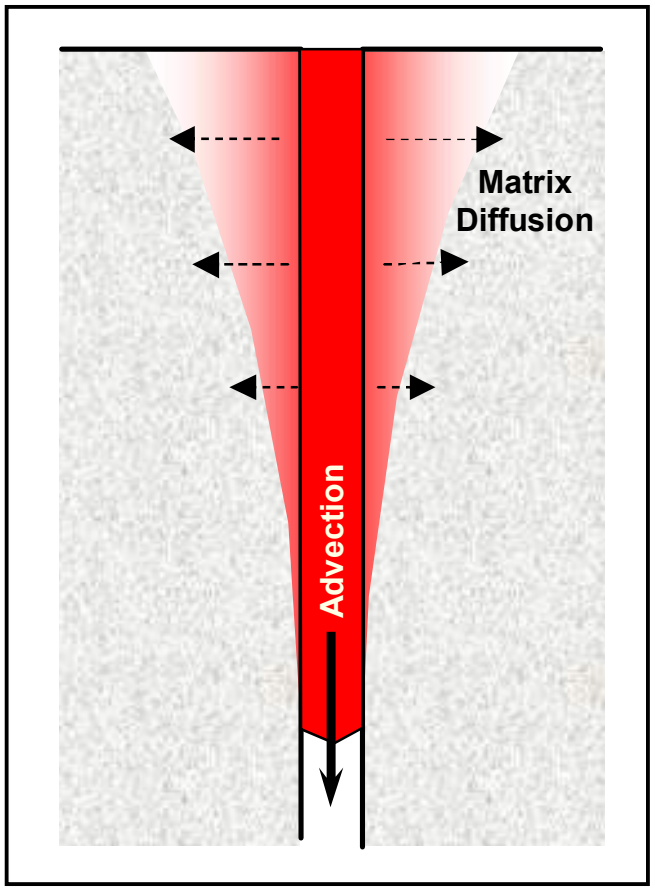


Tsang et al. (1996)

Solute Transport in Fractured Rock

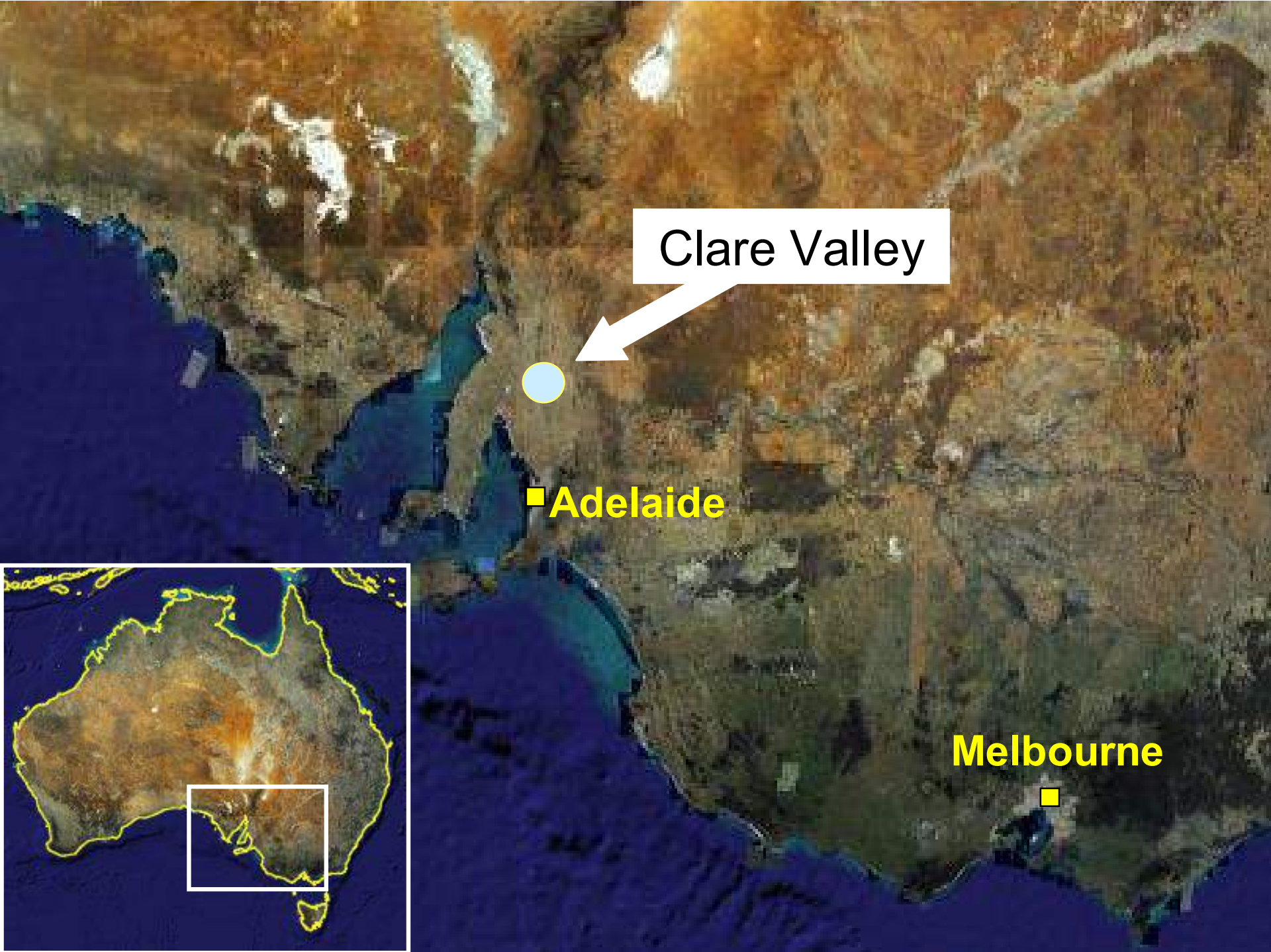
Matrix diffusion causes mixing between young water in fractures and old water within the rock matrix.

This mixing means that apparent groundwater ages derived from environmental tracers do not represent water ages.

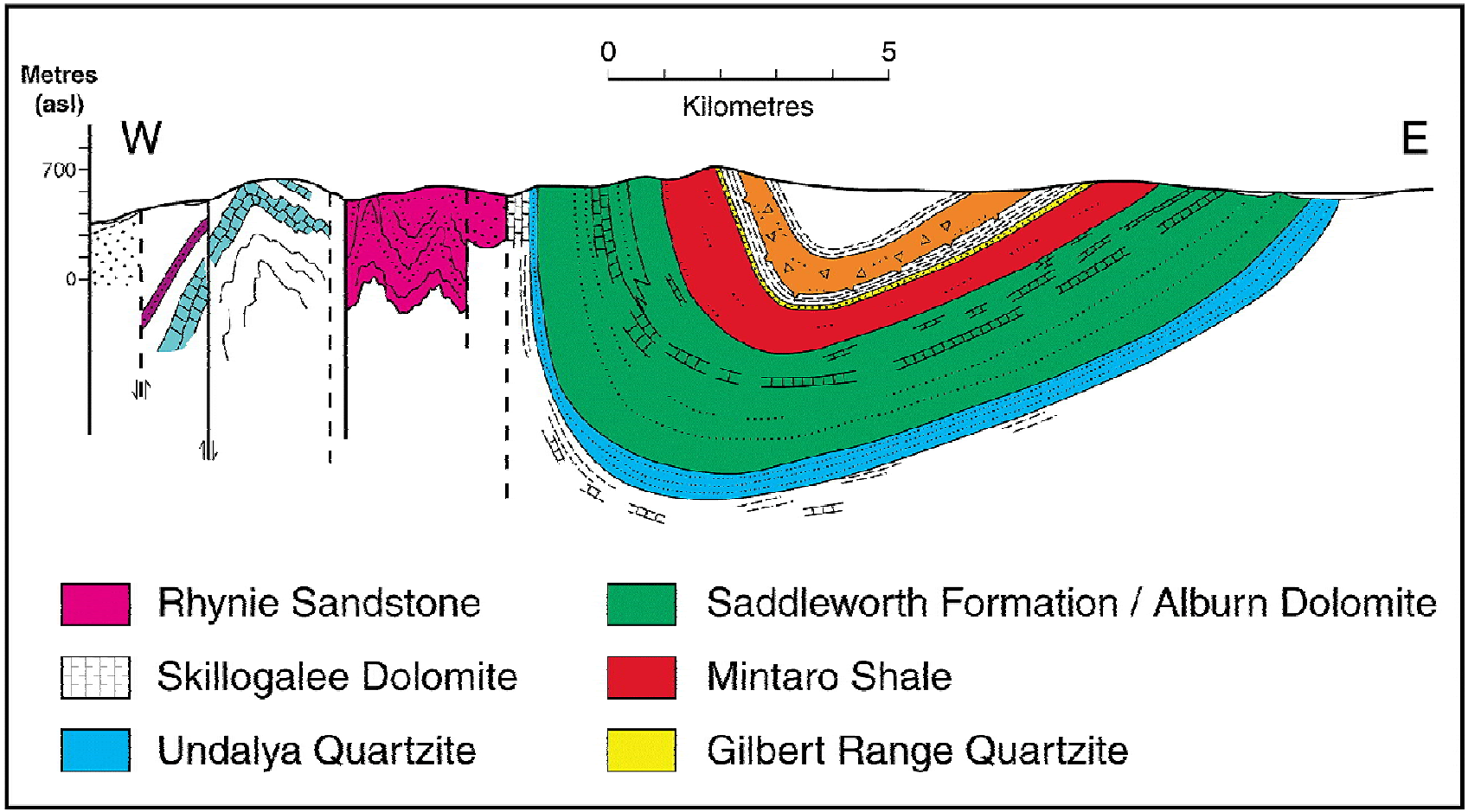


Previous Studies

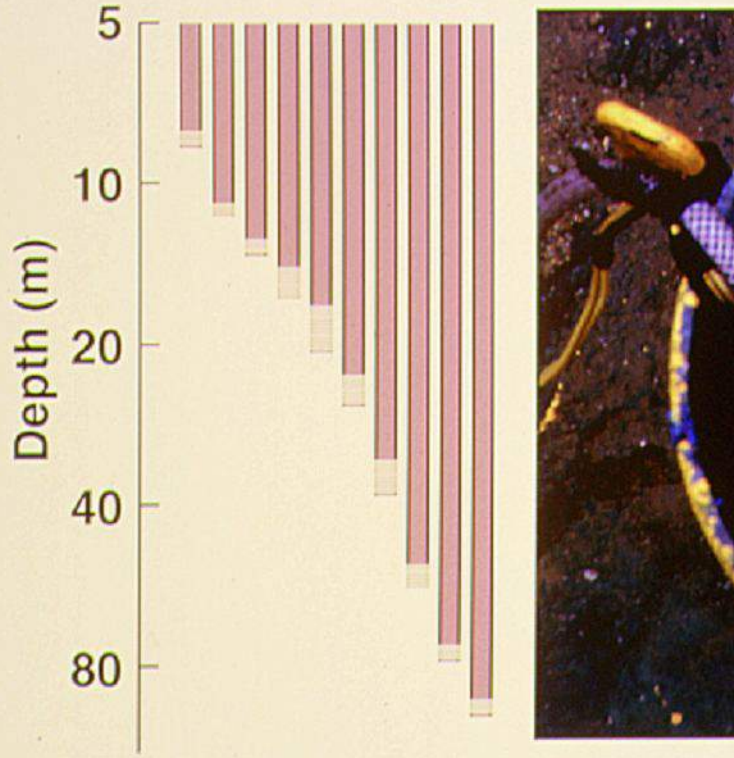
Observation	Geology	Location	Reference
^{3}H > 70 m	fractured dolomite	Wisconsin	Bradbury and Muldoon, 1992
CFC, ^{3}H > 60 m	fractured dolostone,	Smithville	Sheldon and Solomon, 2001
CFC, ^{3}H > 100 m	schists	New Hampshire	Busenberg and Plummer, 1996
^{3}H present, ^{14}C > 1000 years	Table Mountain Group	South Africa	Weaver et al., 1999
CFC-113 < CFC-12	fractured rocks	Virginia	Plummer et al., 2001
CFC-113 < CFC-12	fractured rocks	Pennsylvania	Burton et al., 2002

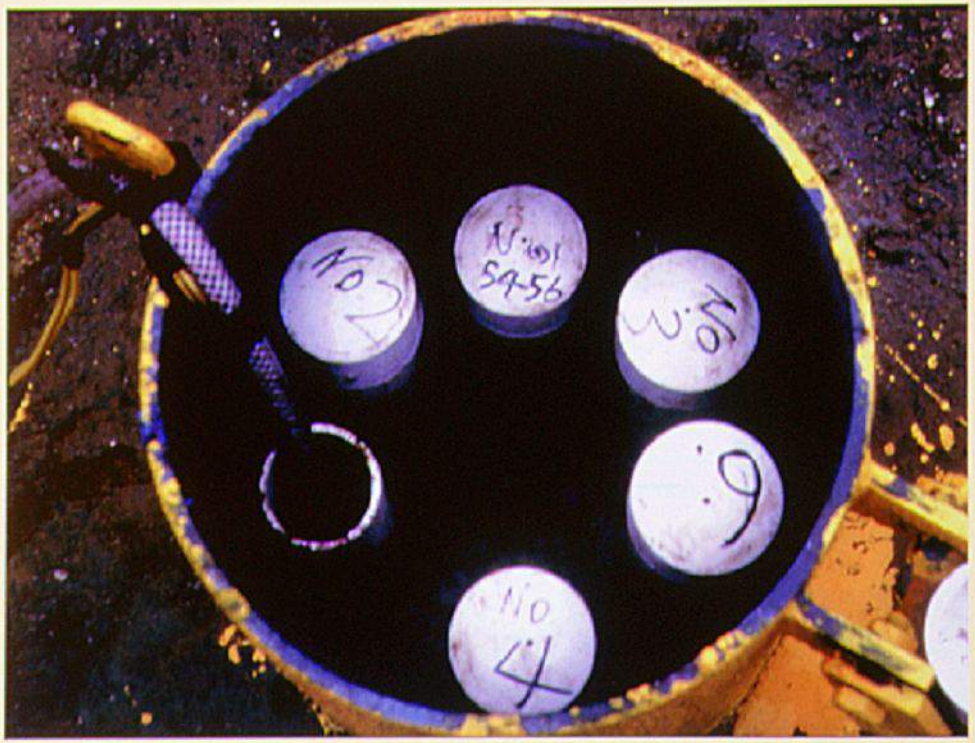

Clare Valley
Adelaide
Melbourne

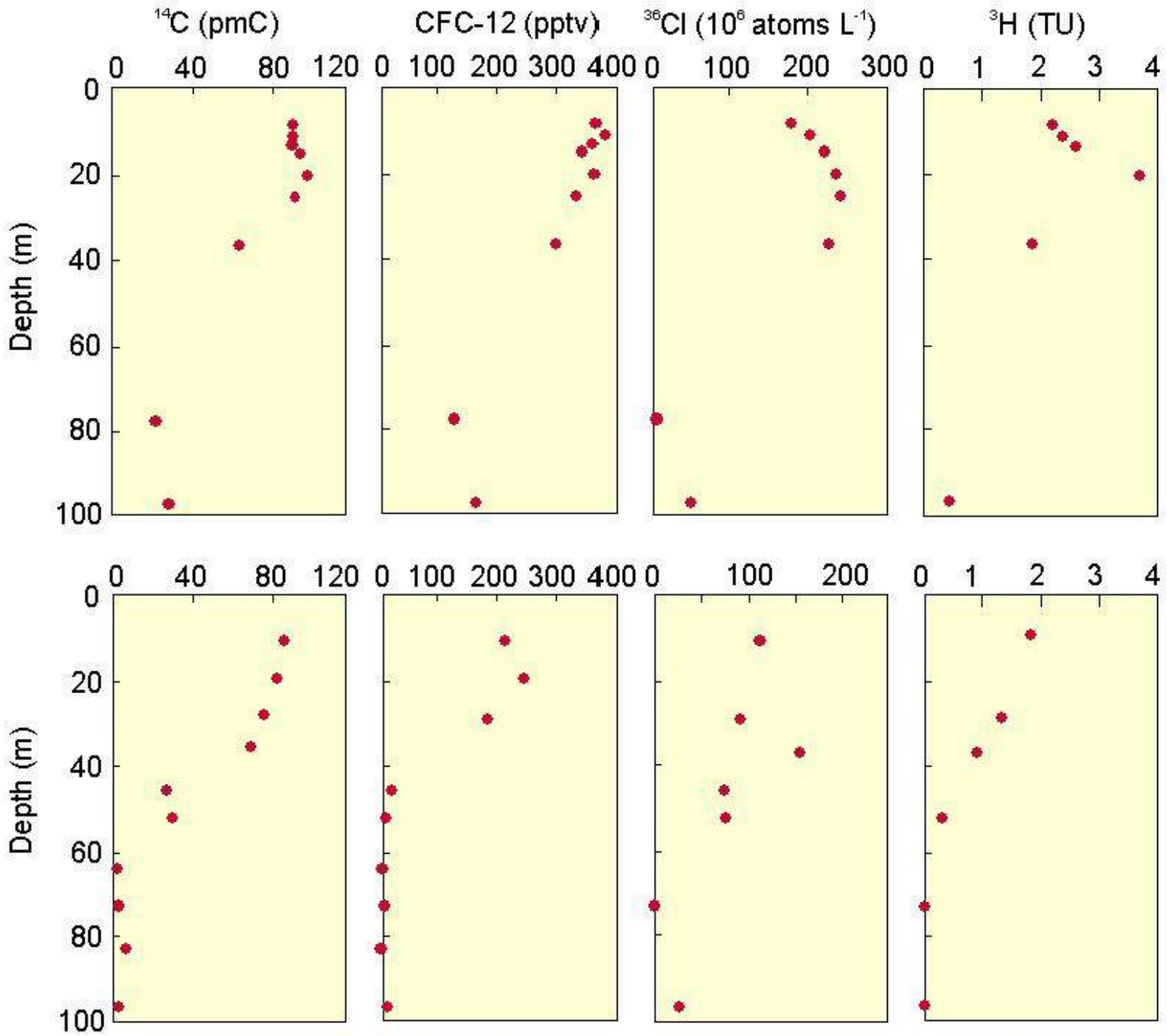
Clare Valley


Metres
(asl)
W
700
0
0
5
Kilometres
E
Rhynie Sandstone
Skillogalee Dolomite
Undalya Quartzite
Saddleworth Formation / Alburn Dolomite
Mintaro Shale
Gilbert Range Quartzite

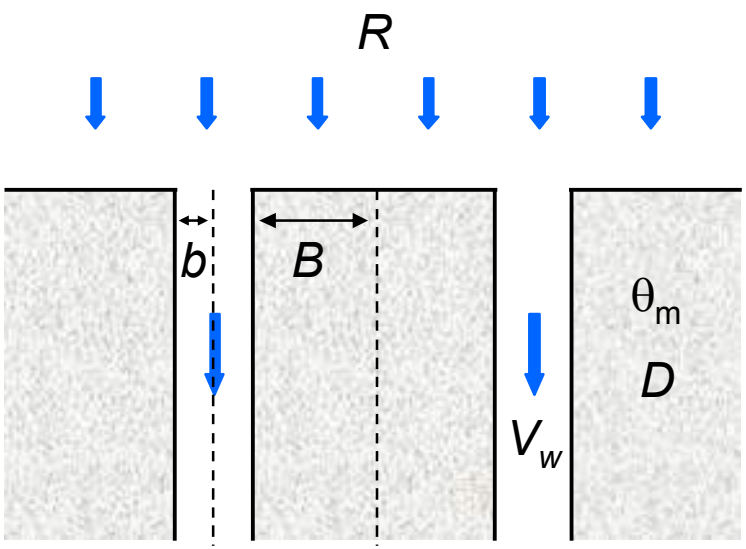
Nested Piezometer Installations



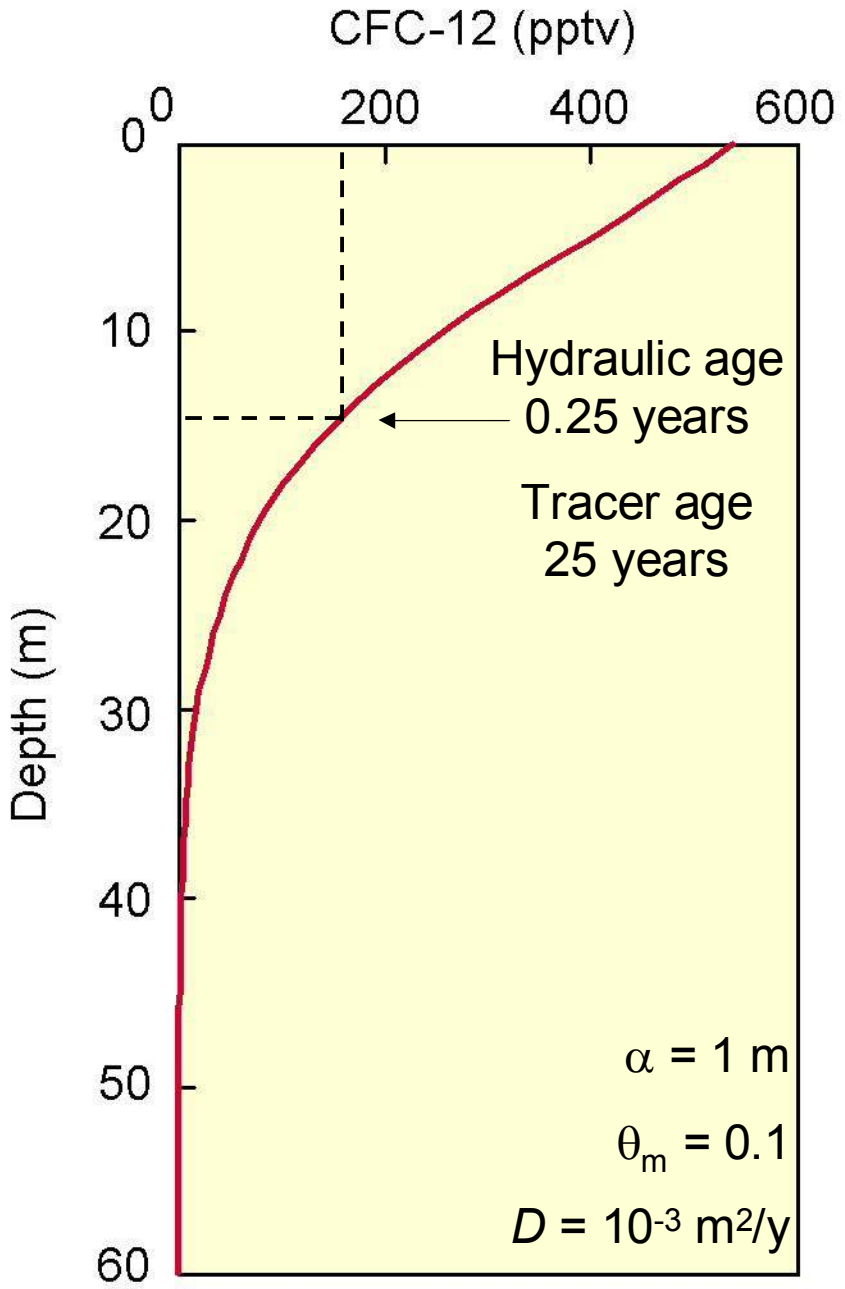



^{14}C (pmC)
CFC-12 (pptv)
^{36}Cl (10^6 atoms L^{-1})
^{3}H (TU)
Depth (m)
0 40 80 120
0 100 200 300 400
0 100 200 300
0 1 2 3 4
0 20 40 60 80 100
0 100 200
0 1 2 3 4

Analytical Modelling

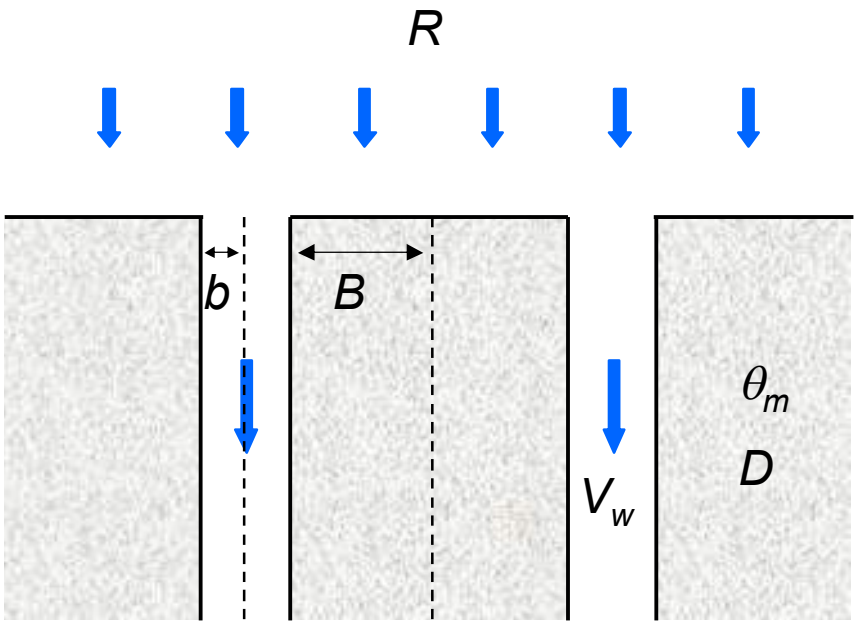


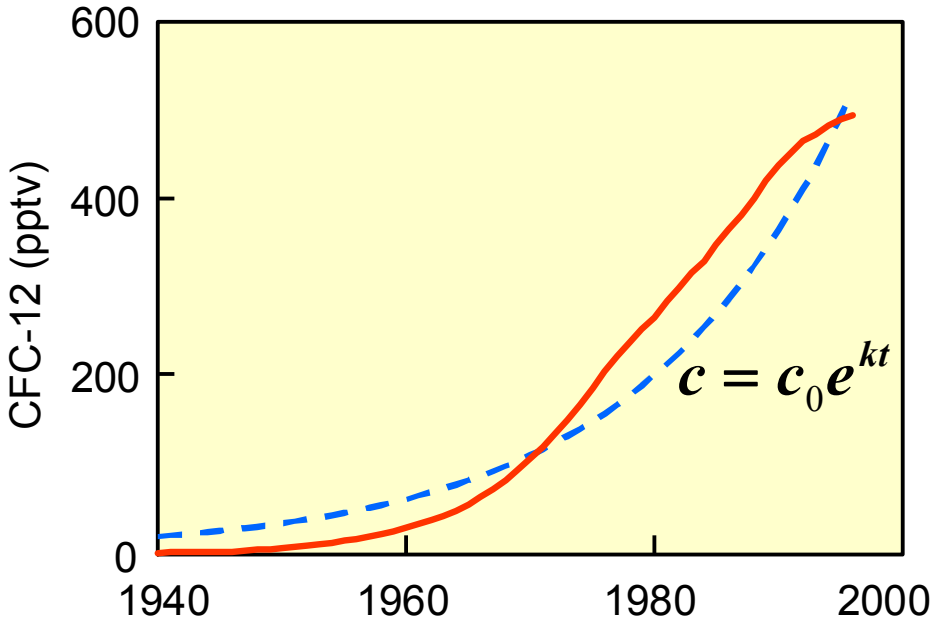
R (mm/y)	60
V_w (m/y)	60
b (μm)	50
B (m)	0.05



Cook et al. (2005)

Approximate Analytical Solution





$$\frac{\delta t_a}{\delta z} = V_w^{-1}\left[1 + \frac{\theta_m D^{1/2}}{bk^{1/2}} \tanh\left(BD^{-1/2}k^{1/2}\right)\right]$$

Large $\frac{\delta t_a}{\delta z}$ can arise due to small V_w, but also small b, large B or large D

Coupling Tracers with Hydraulics

Apparent Age	$$\frac{\delta t_a}{\delta z} = V_w^{-1}\left[1 + \frac{\theta_m D^{1/2}}{b k^{1/2}} \tanh\left(B D^{-1/2} k^{1/2}\right)\right]$$

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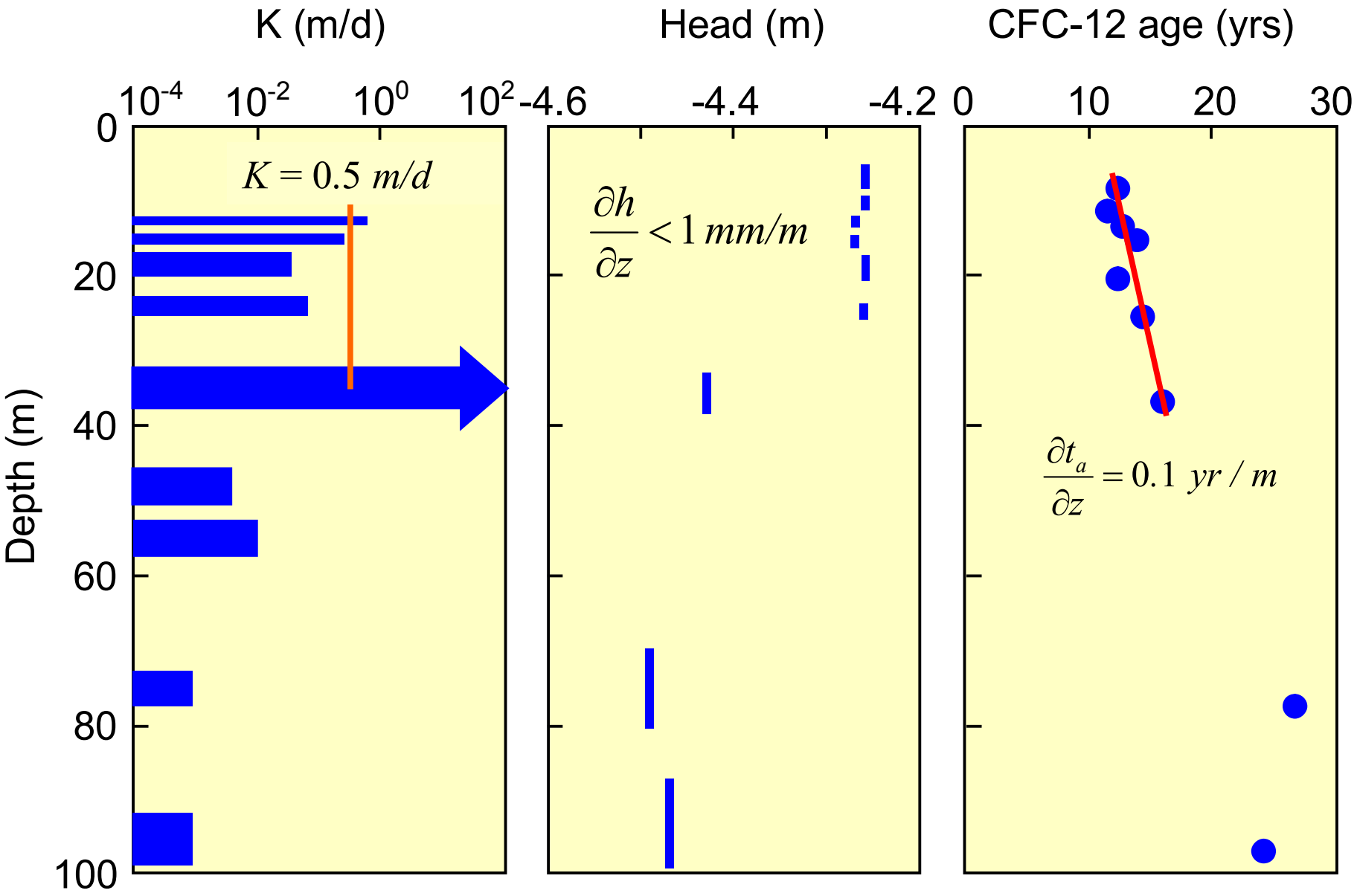
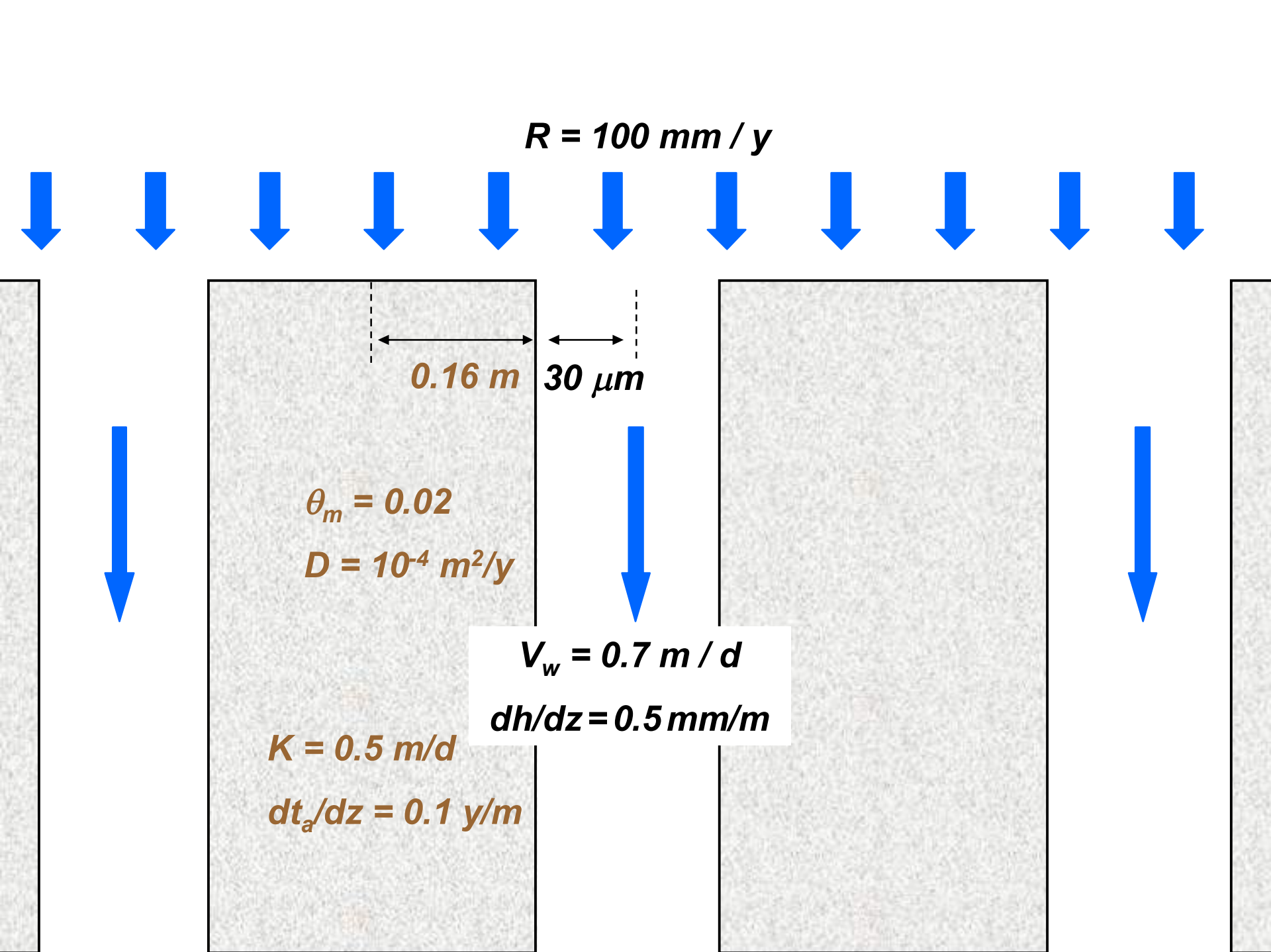
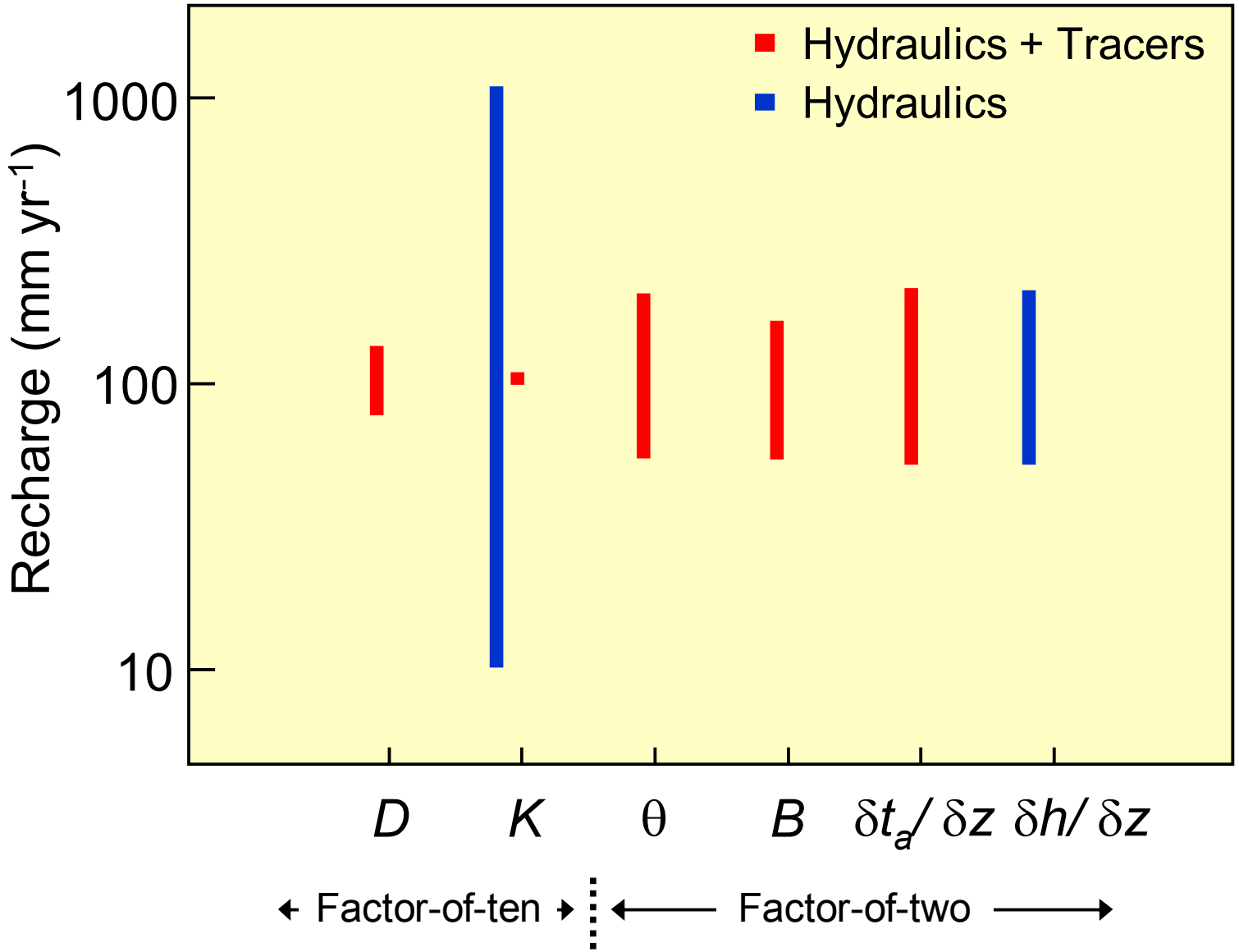
Darcy's Law	$$R = K\frac{\delta h}{\delta z}$$
Vertical Velocity	$$V_w = R\frac{B}{b}$$
Hydraulic Conductivity	$$K = \frac{(2b)^3}{2B}\frac{\rho g}{12\mu}$$

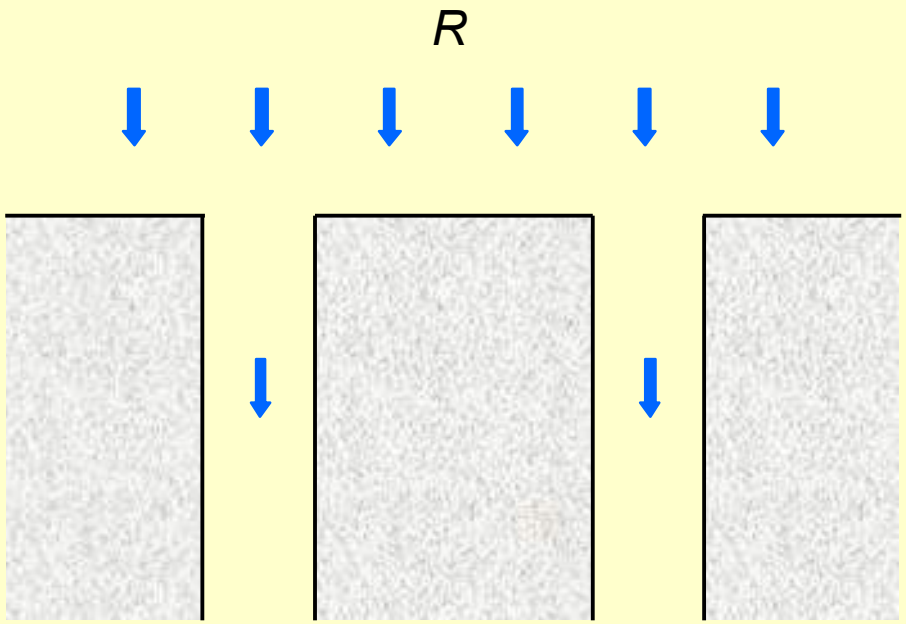

K (m/d)
Head (m)
CFC-12 age (yrs)
10^{-4}
10^{-2}
10^{0}
10^{2}
-4.6
-4.4
-4.2
0
10
20
30
Depth (m)
0
20
40
60
80
100
$K = 0.5\ m/d$
$\frac{\partial h}{\partial z} < 1\ mm/m$
$\frac{\partial t_a}{\partial z} = 0.1\ yr/m$


R = 100 mm / y
0.16 m
30 μm
θm = 0.02
D = 10-4 m2/y
Vw = 0.7 m / d
dh/dz = 0.5 mm/m
K = 0.5 m/d
dta/dz = 0.1 y/m

Sensitivity to K is reduced with tracers



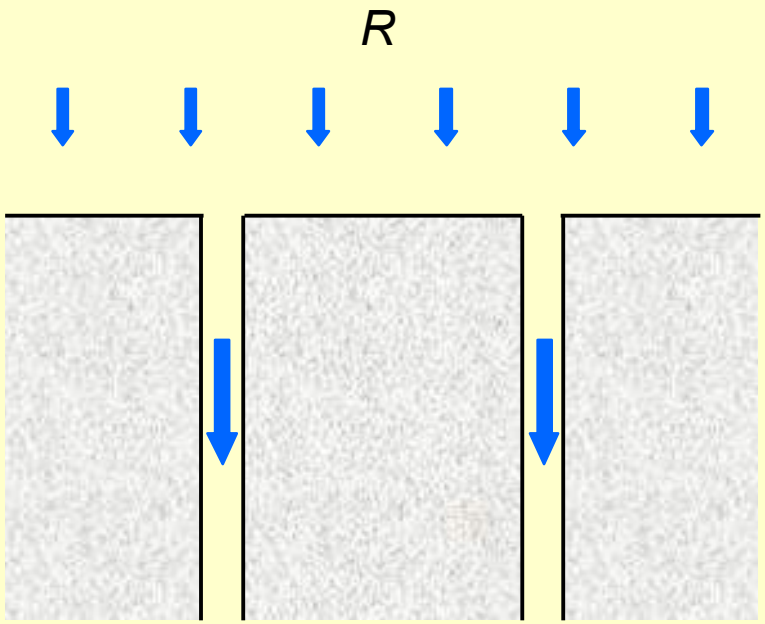
Insensitivity of tracers to K



Low V_w

Large Residence Time

Low Surface Area / Volume



High V_w

Short Residence Time

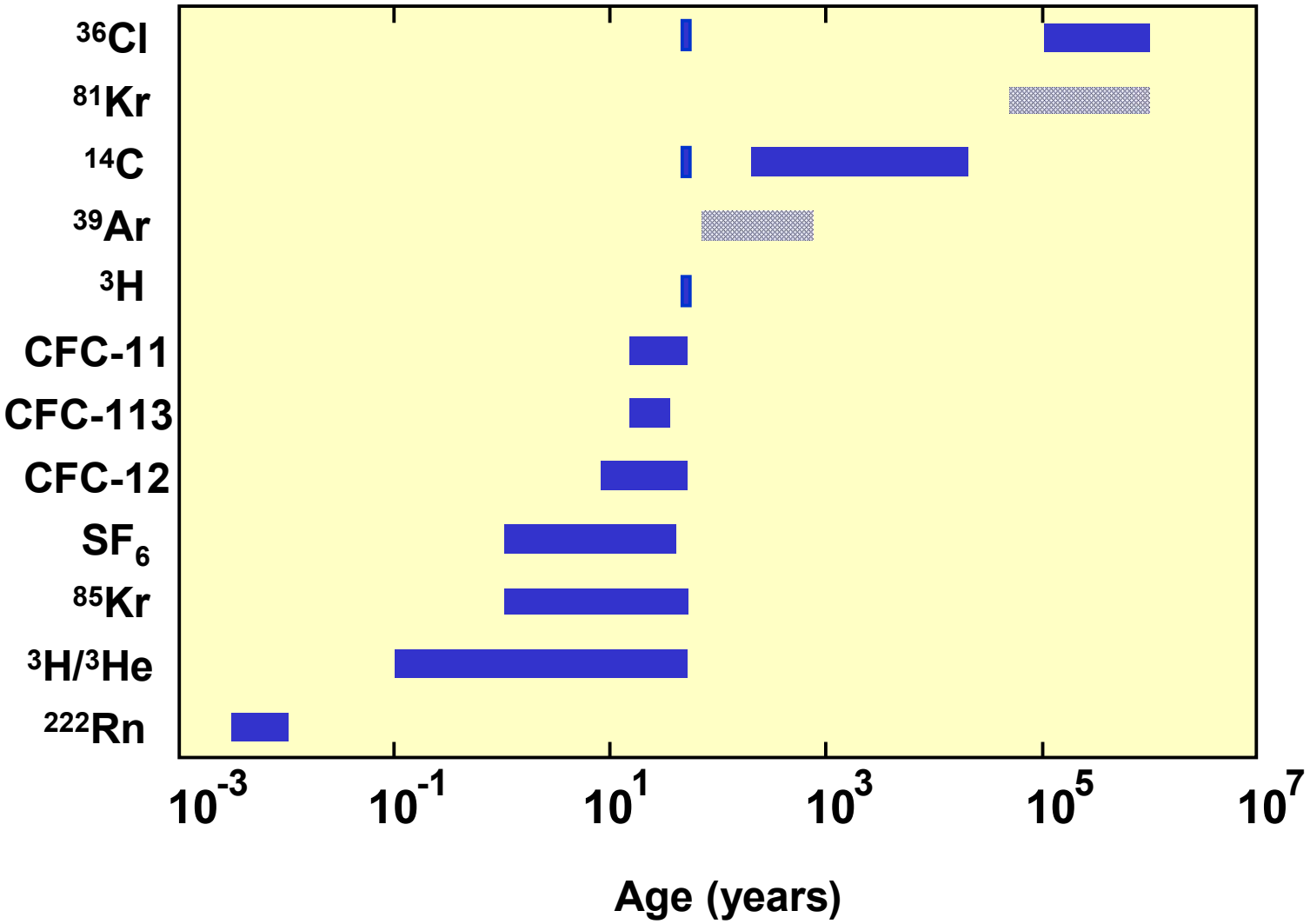
High Surface Area / Volume

Things I Haven't Told You About

- Not all environmental tracers behave conservatively in all environments:
  - chemical reactions involving ^{14}C
  - degradation of CFCs

- Background concentrations
  - natural source of SF_6 in some igneous rocks
  - local contamination of CFCs in urban areas

Time Windows of Dating Tools



Changing Role of Tracers

Previously …

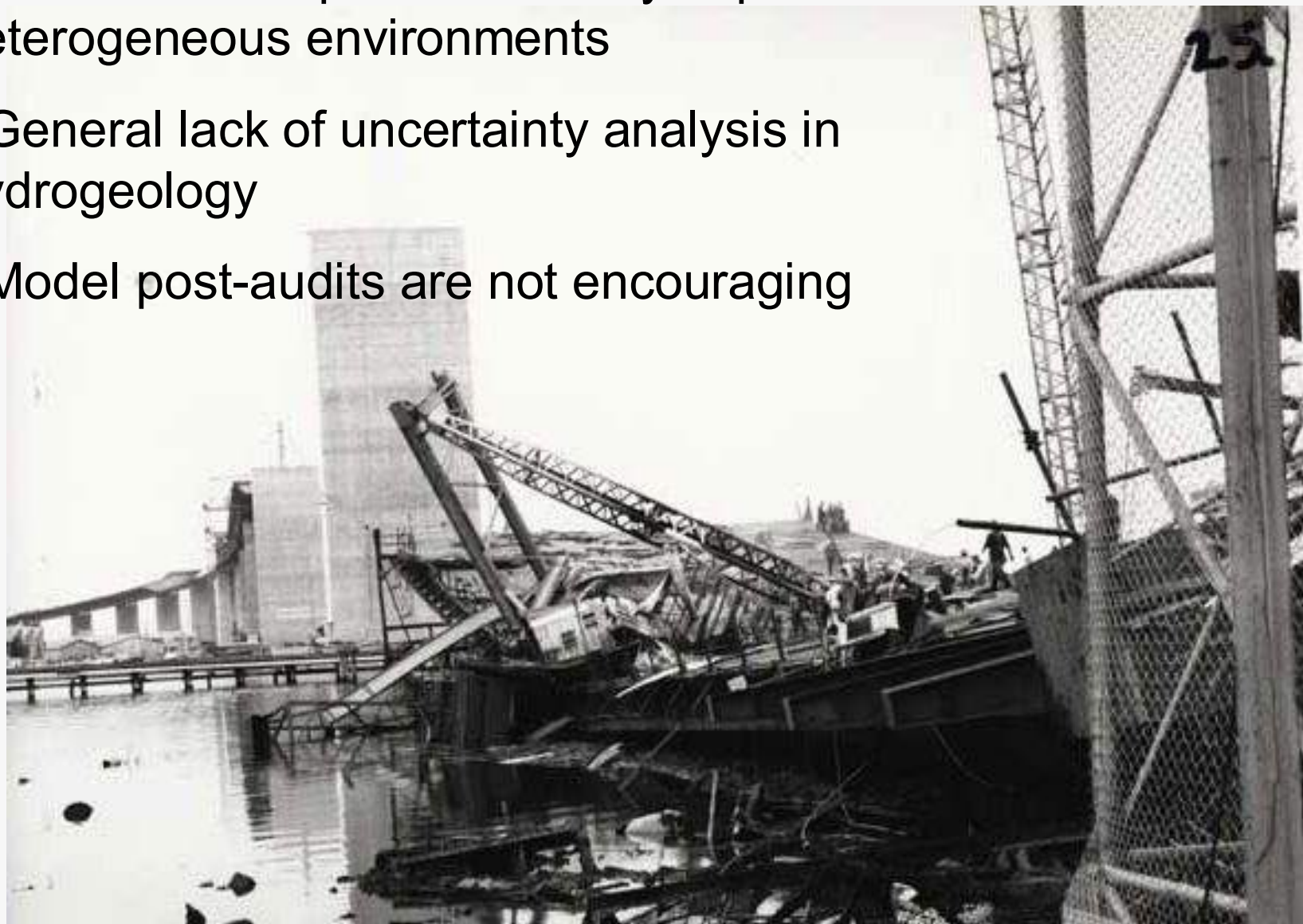
- reconnaissance tool used in remote areas
- quantitative interpretation based on highly idealized models

Today …

- there is an important role for tracers used in conjunction with hydraulics to improve prediction, particularly in heterogeneous systems

Importance of Uncertainty Analysis

- Tracers can improve accuracy of prediction in heterogeneous environments
- General lack of uncertainty analysis in hydrogeology
- Model post-audits are not encouraging



Conclusions

In homogeneous aquifers, both hydraulic and environmental tracer approaches can accurately characterise groundwater flow.

In heterogeneous aquifers, tracers may have advantage over hydraulics because they provide spatially averaged information.

In moderately heterogeneous aquifers, environmental tracers can be used in conjunction with hydraulics, to improve calibration of groundwater models.

In highly heterogeneous systems, uncertainty of hydraulics is so high, that perhaps we have no alternative than to pursue environmental tracer methods for estimating rates of groundwater flow.

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