Groundwater dating: a comprehensive approach to discovering hidden pathways

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AIH Montpellier - 2016

A third of global river discharge derives from groundwater that was recharged by precipitation less than a few months earlier
(*Jasechko et al. 2016*)

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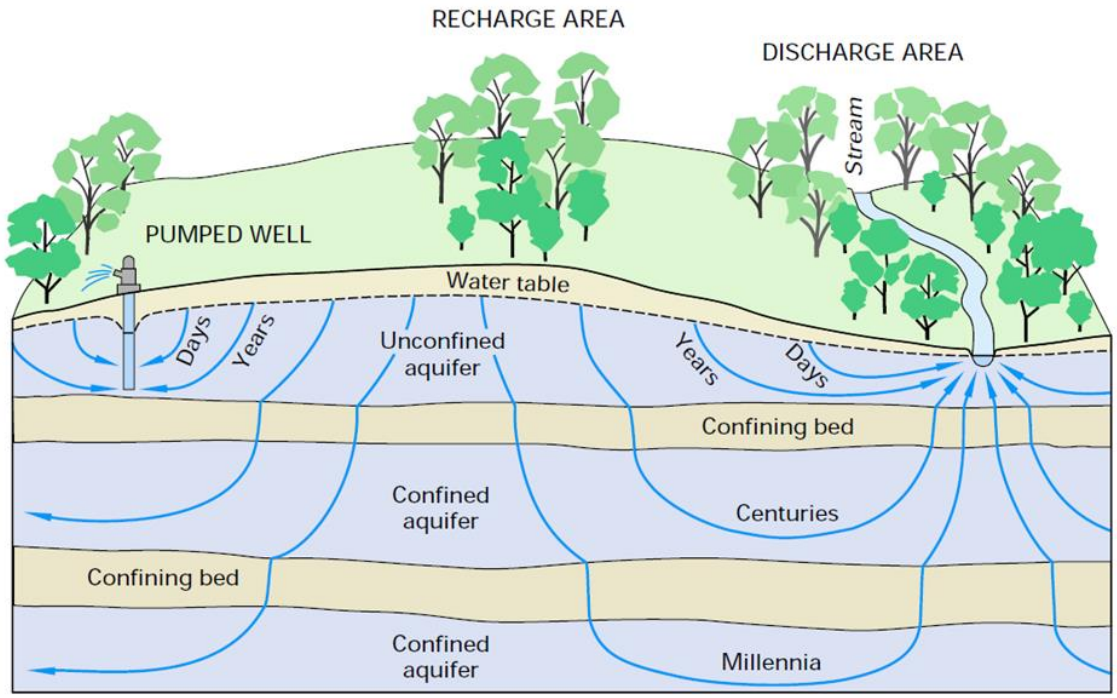
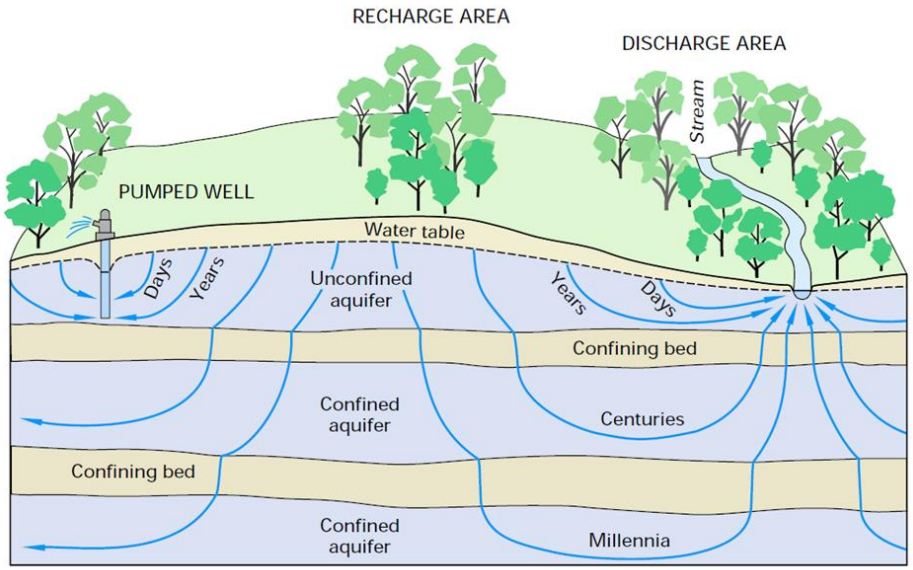
(*Jasechko et al. 2016*)

Less than 6% of the total global groundwater store was recharged less than 50 years ago
(*Gleeson et al. 2016*)


RECHARGE AREA
DISCHARGE AREA
Stream
PUMPED WELL
Water table
Days
Years
Unconfined aquifer
Years
Days
Confining bed
Confined aquifer
Centuries
Confining bed
Confined aquifer
Millennia

(***Fan, 2016***)

Very young age suggests that the groundwater comes from recent and local precipitation



(***Fan, 2016***)

Norilsk City
Credit: darkroastedblend.com

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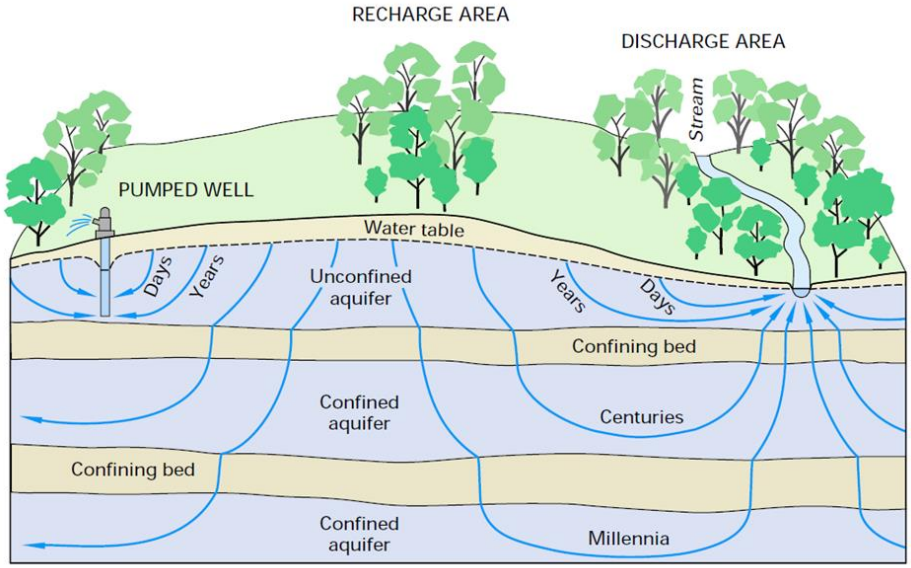


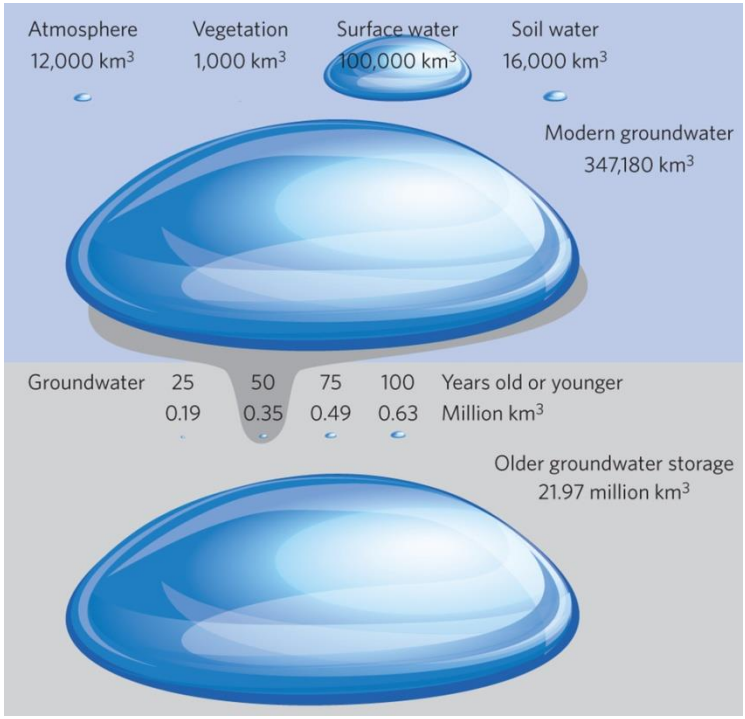
(***Fan, 2016***)

Norilsk City darkroastedblend.com

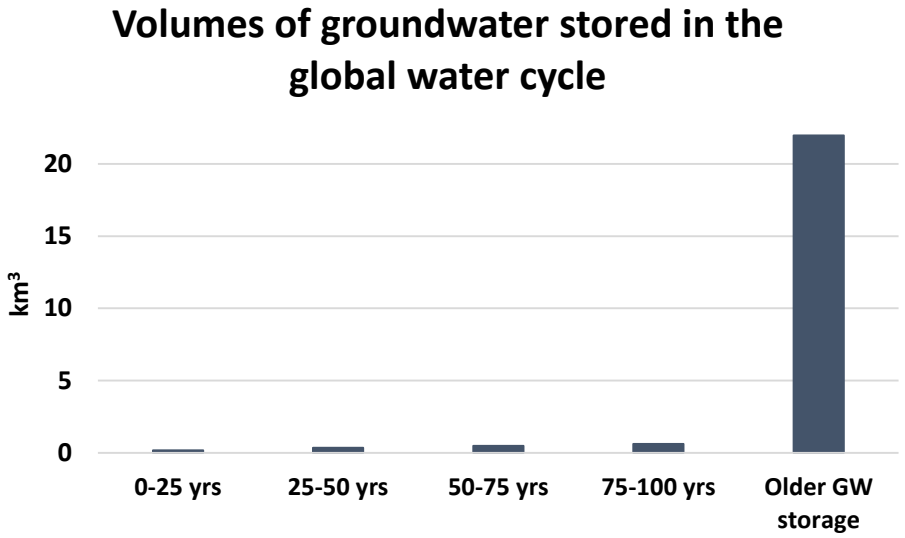
Very old age suggests that groundwater was recharged long ago

Le forage d'Aïn Galaka, Tchad. panoramio.com

How much and how old?



(*Gleeson et al. 2016*)



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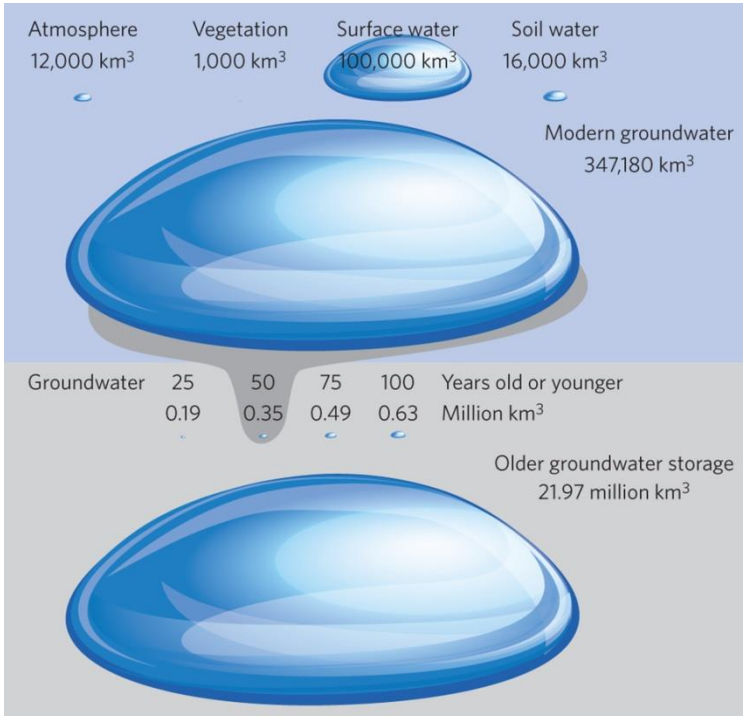

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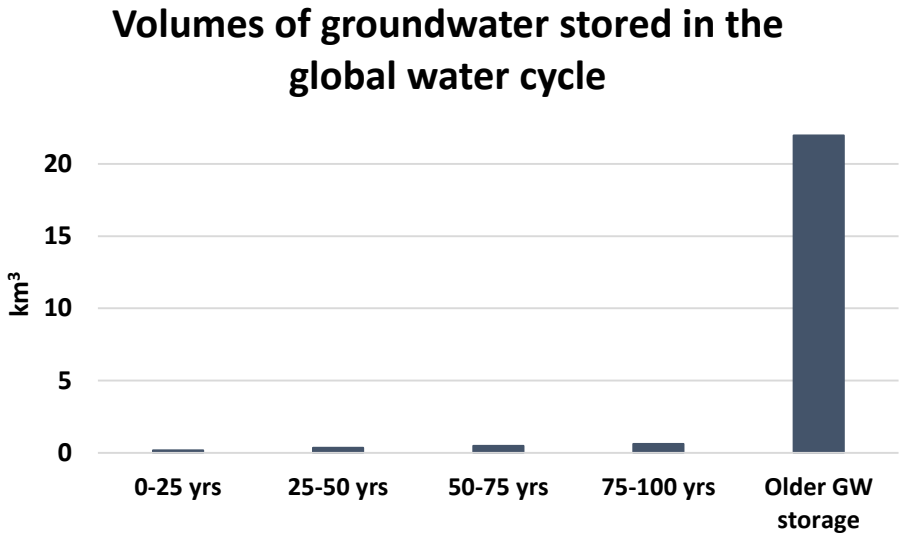

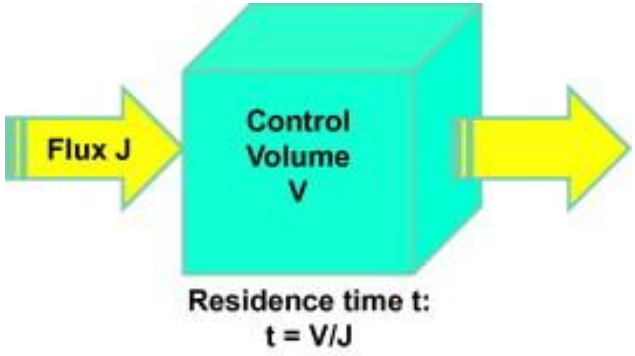

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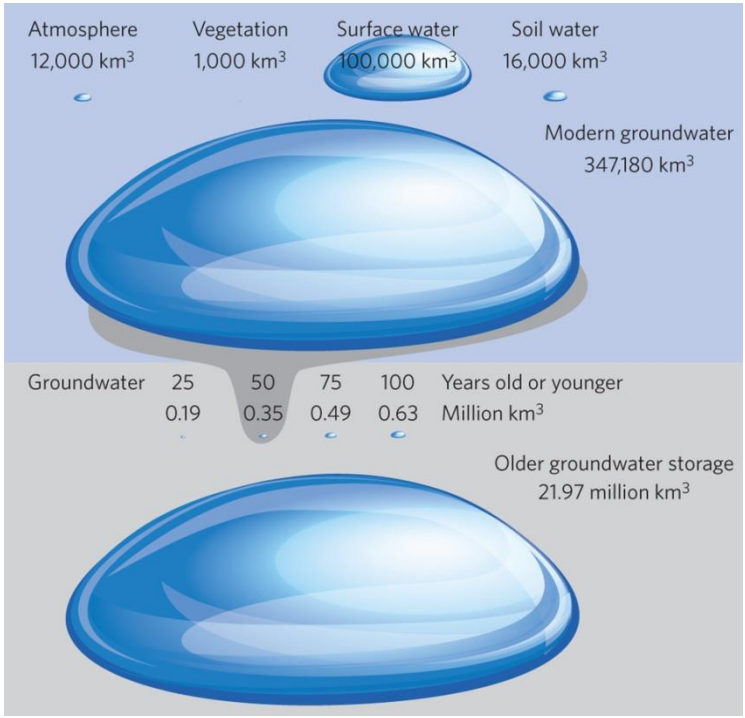

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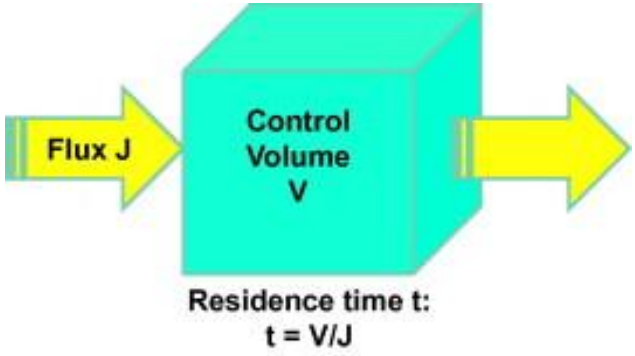

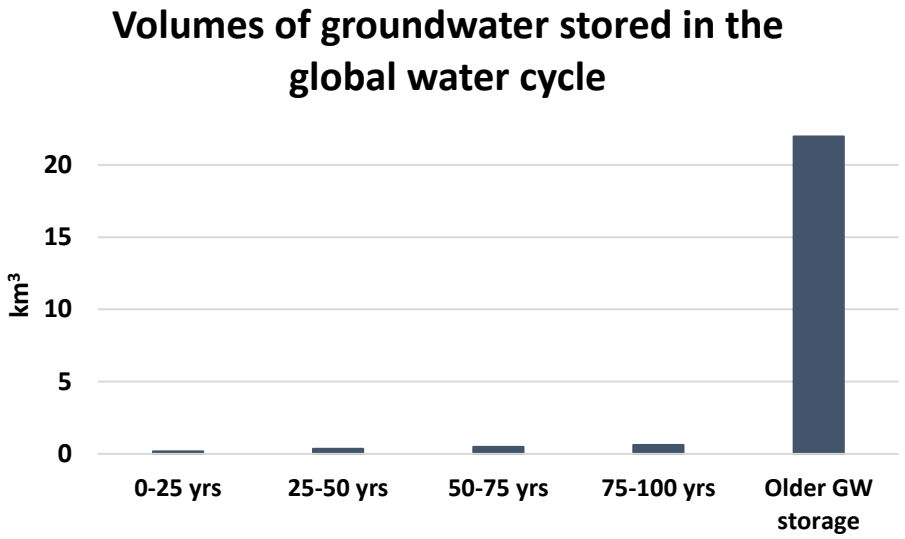

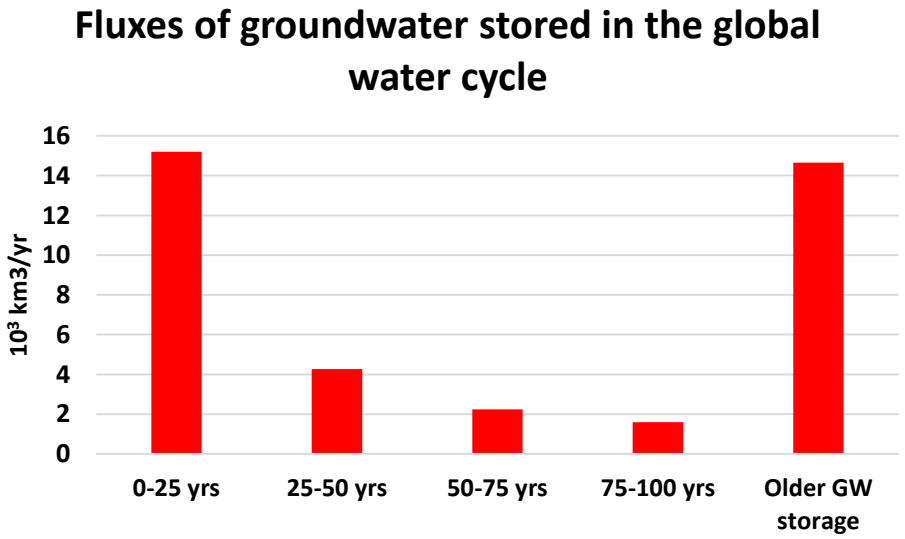

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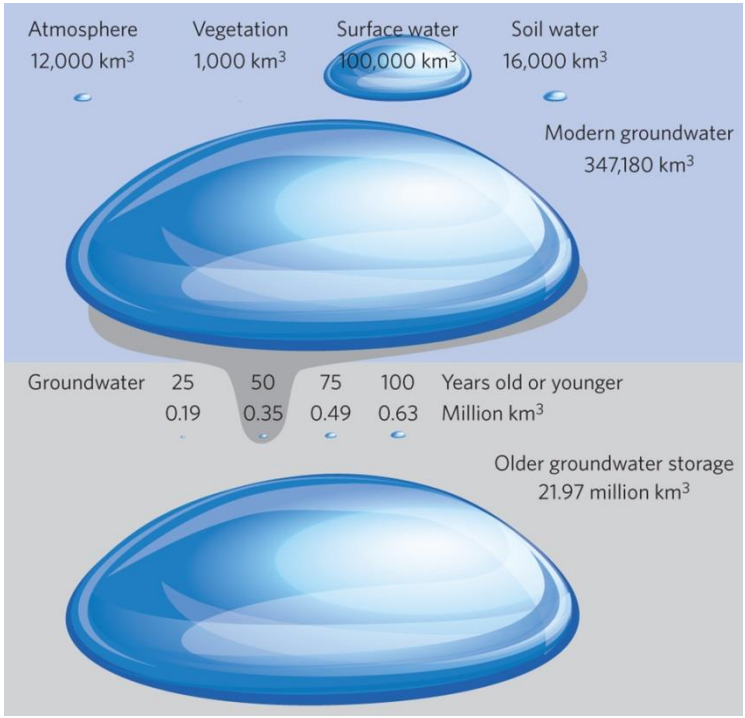

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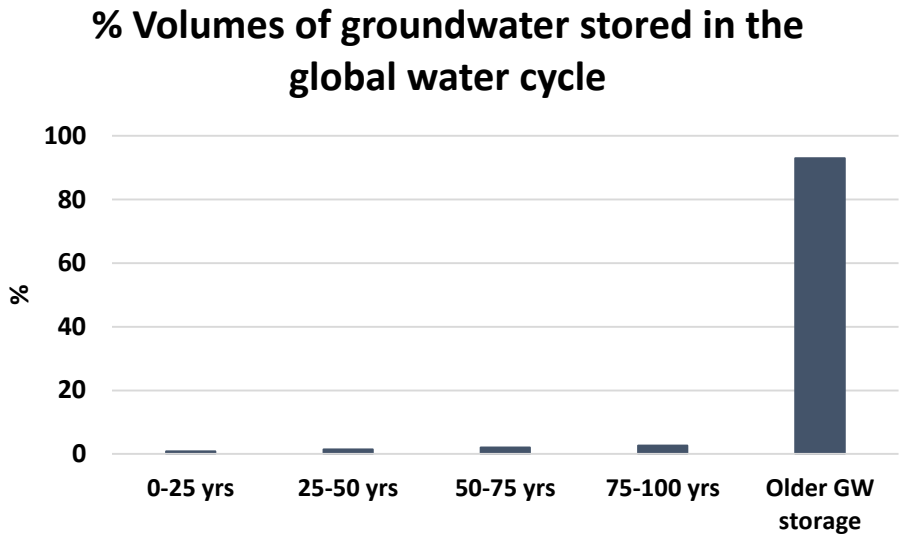

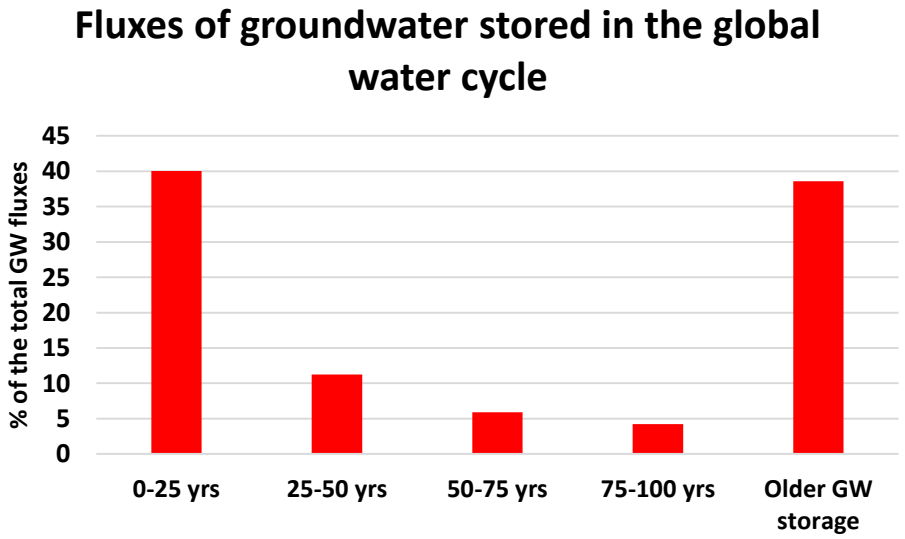

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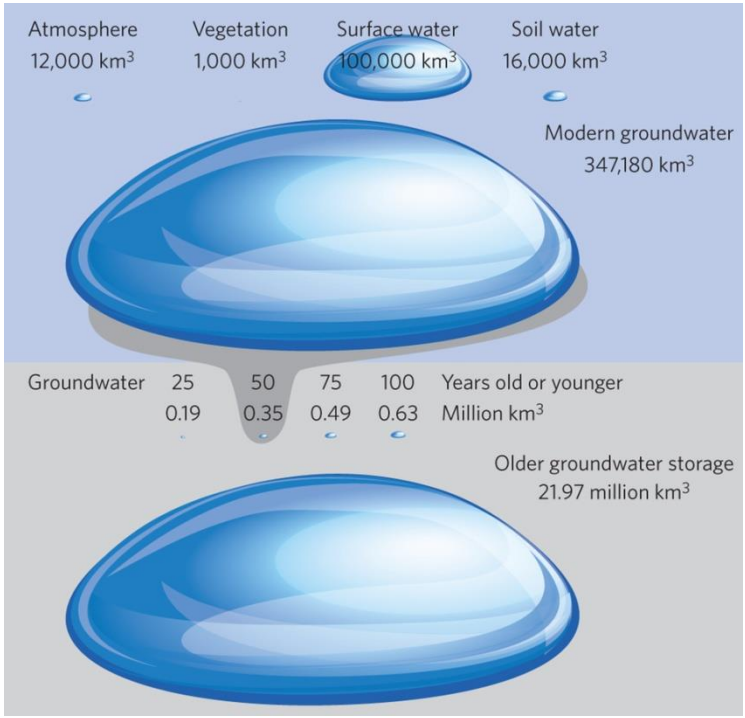

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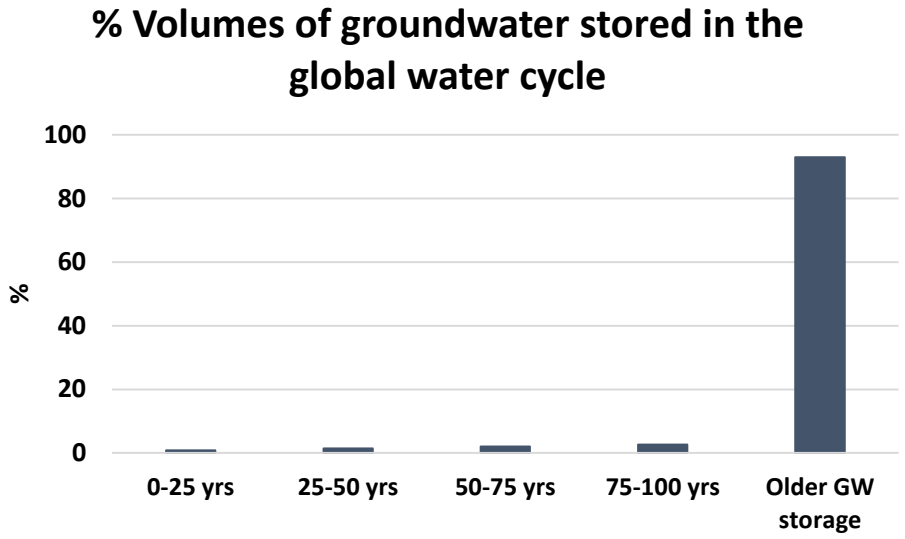
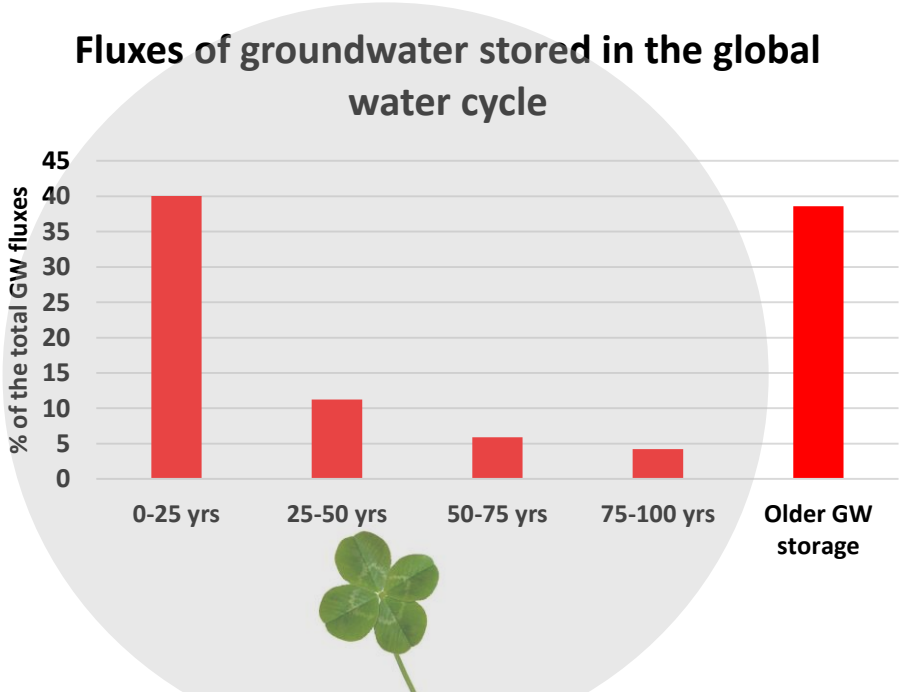
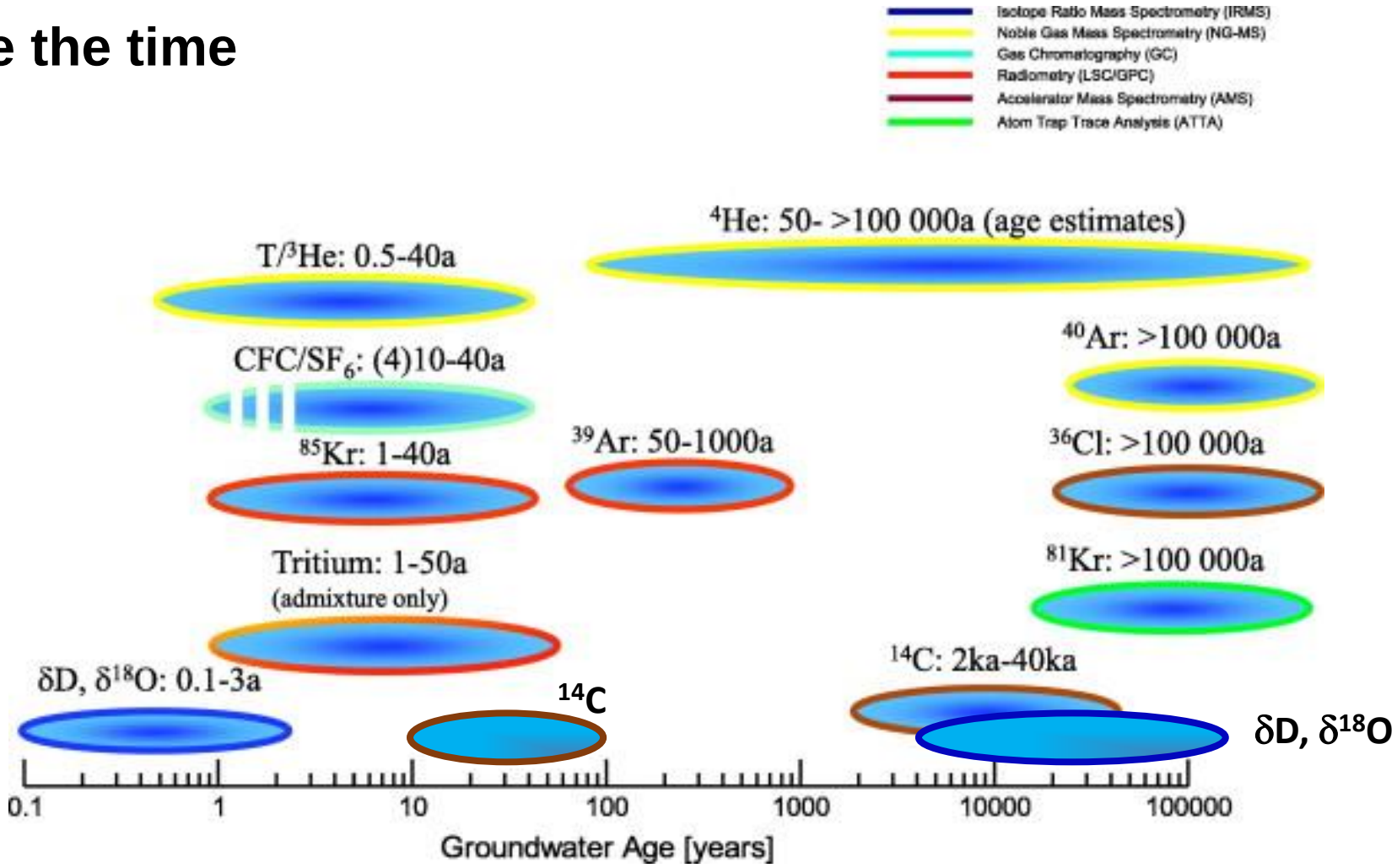




Trace the time



(Modified from Suckow *2014, Baudron 2014, Bartyzel & Rozanski 2016*)

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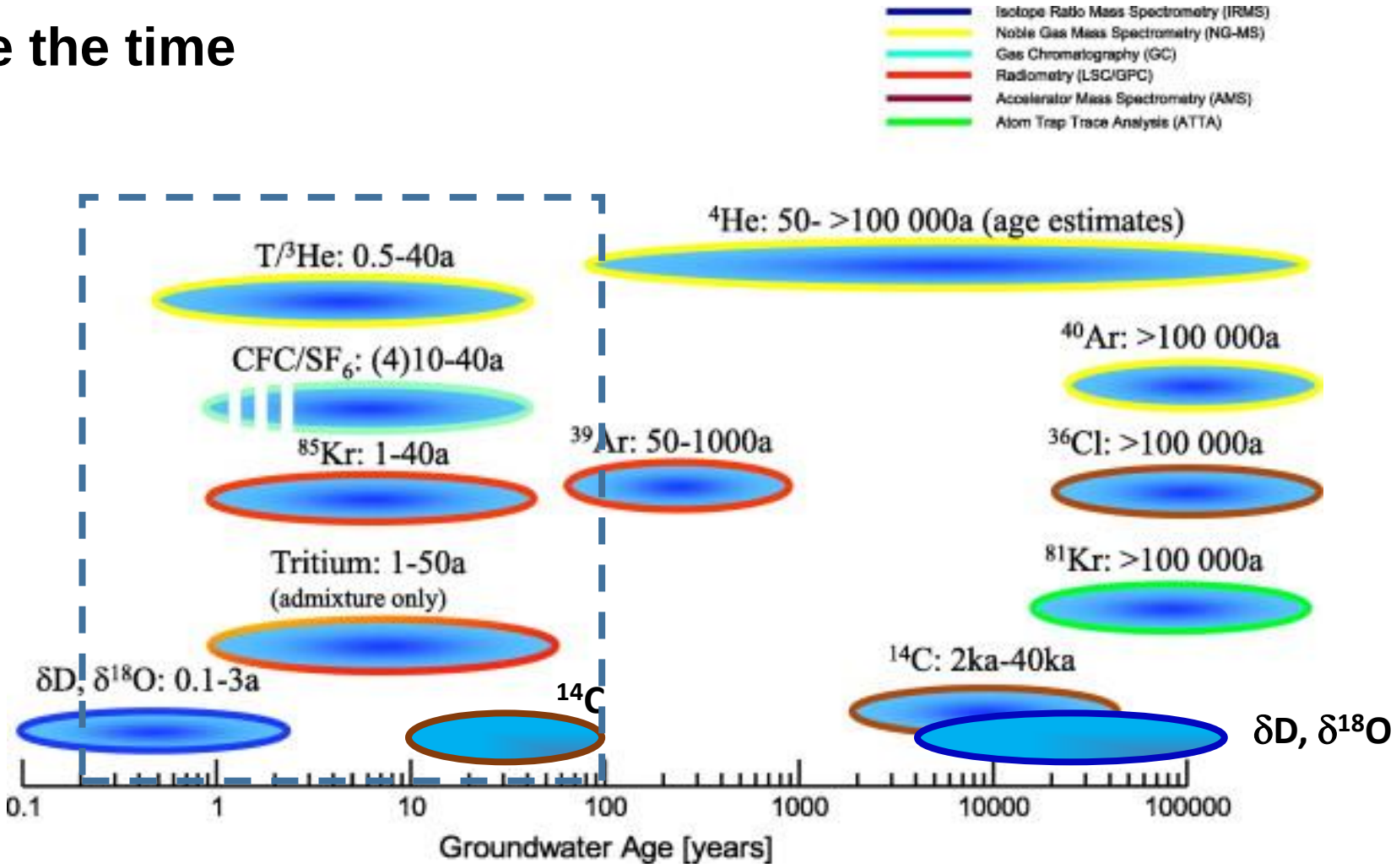
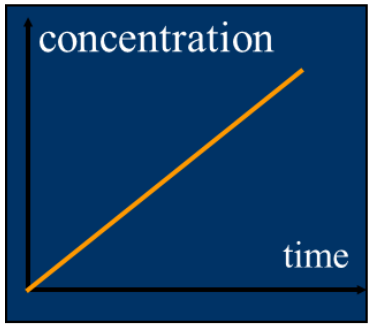
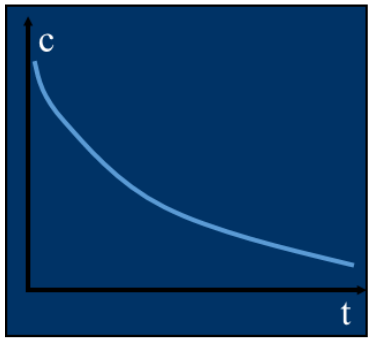


- **Basics on few tracers**
- **Examples**

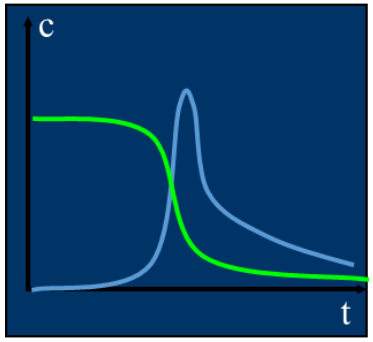
Trace the time



- **Accumulation:** decay of radioactive elements whitin the aquifer ^{4}He, ^{40}Ar,….

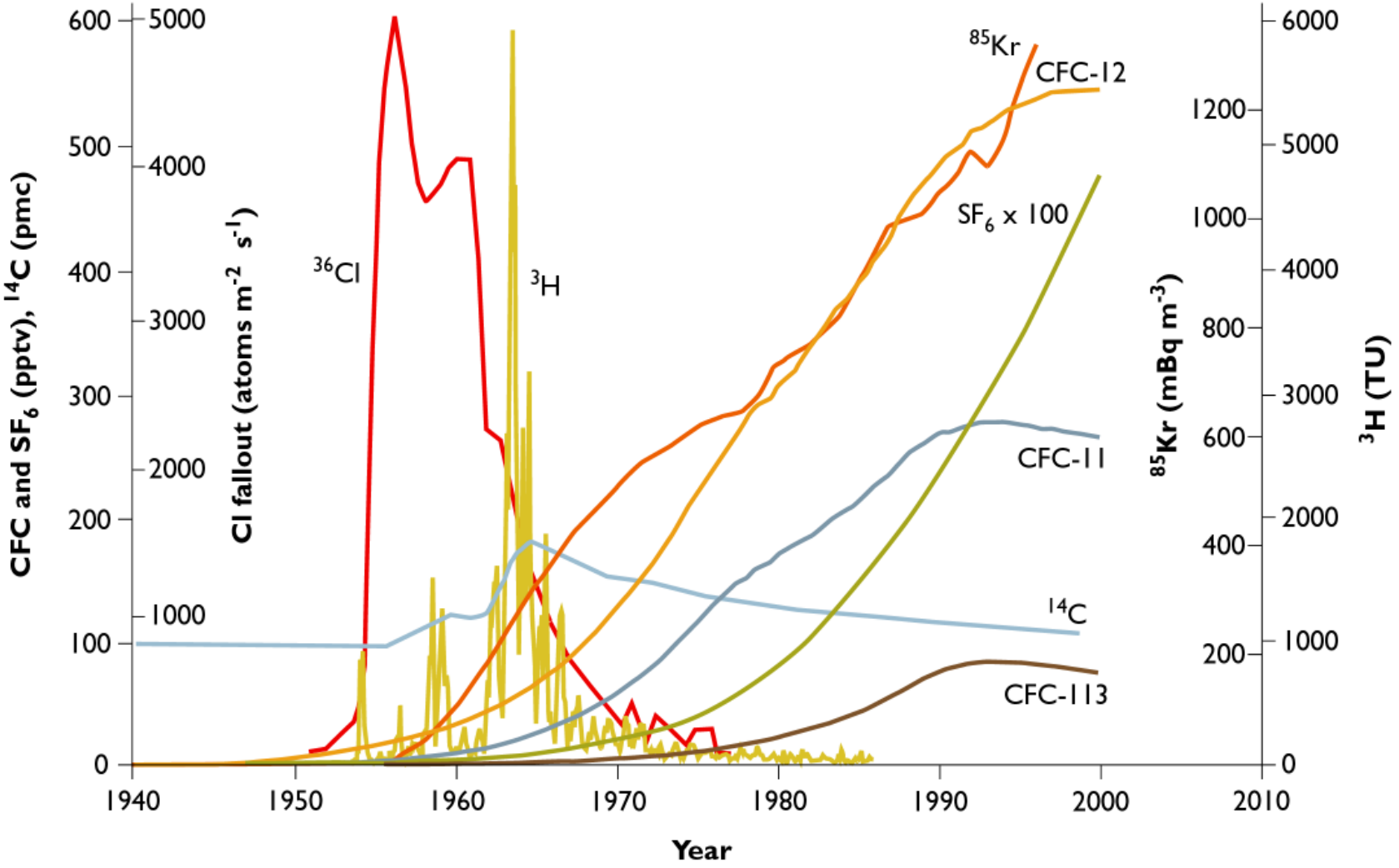


- **Radioactive tracers:** decay of a initial activity ^{3}H, ^{85}Kr, ^{39}Ar, ^{14}C, ^{81}Kr



- **Transient tracers :** variable input, related to human activities (^{3}H), (^{14}C), CFC, SF_6, ^{2}H-^{18}O

Trace the time



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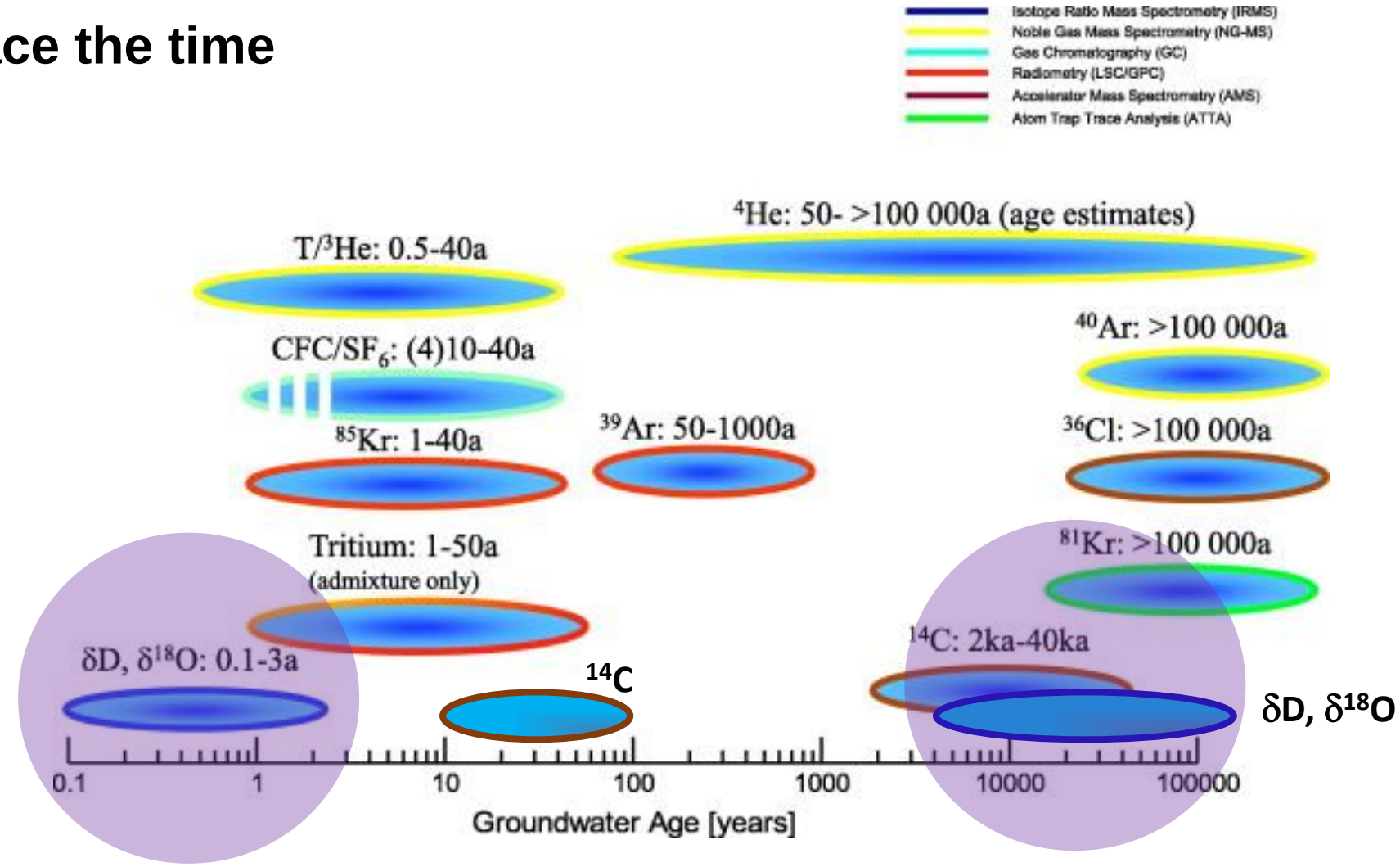
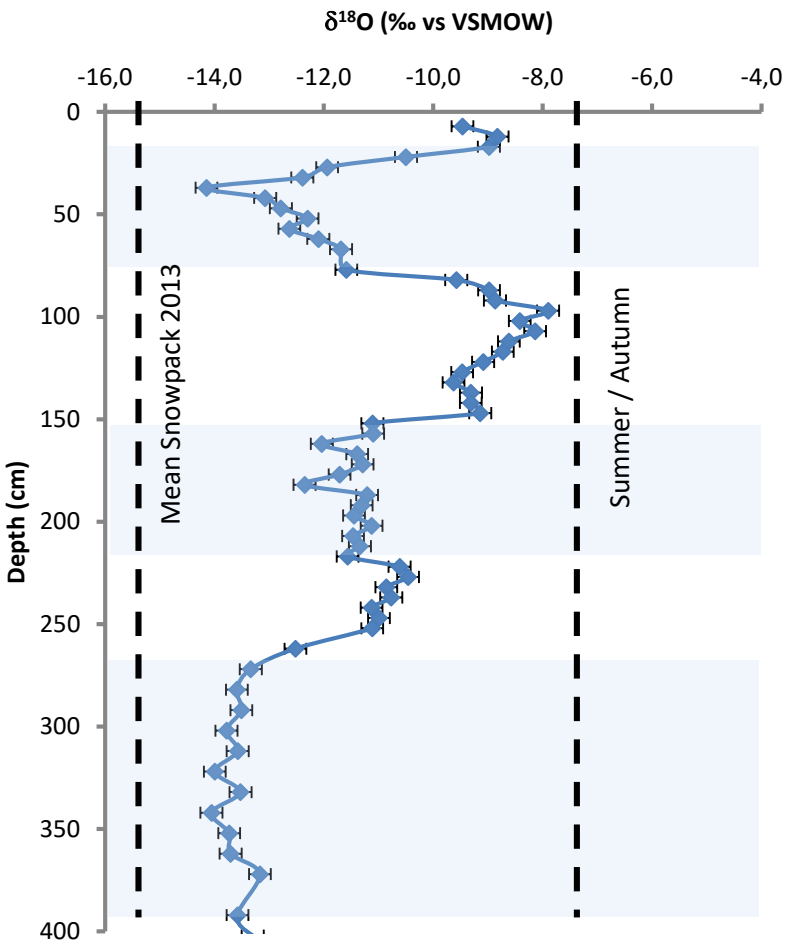


(Modified from Suckow *2014, Baudron 2014, Bartyzel & Rozanski 2016*)

Trace the time using stable isotopes



Snowpack melting

(Barbecot et al, 2014)

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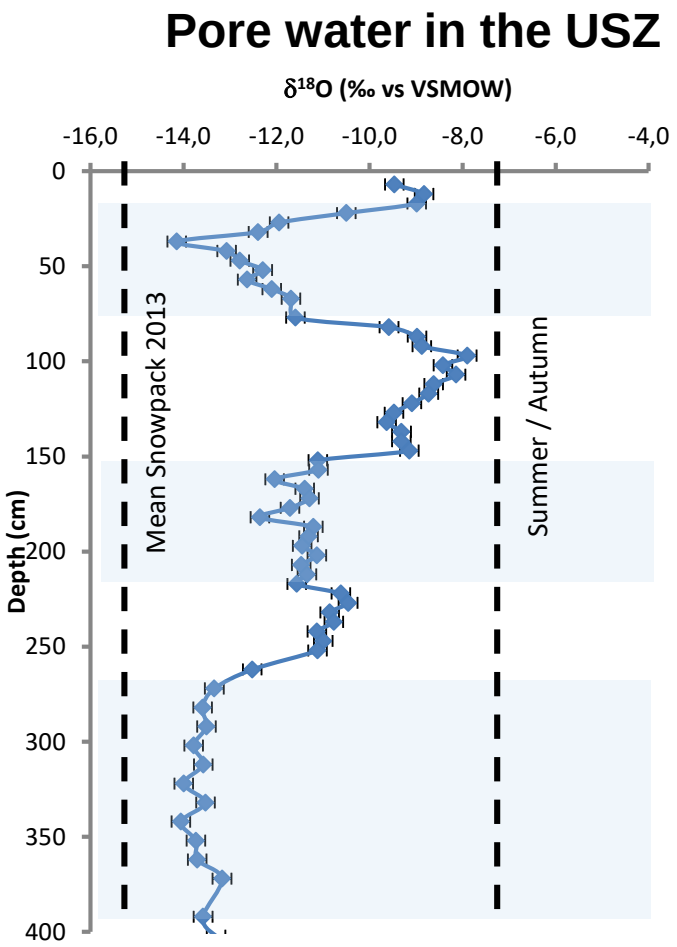
IRRES : Infrastructure de Recherche sur la Recharge des Eaux Souterraines

Research facility on Groundwater recharge (IRRES)

Trace the time using stable isotopes



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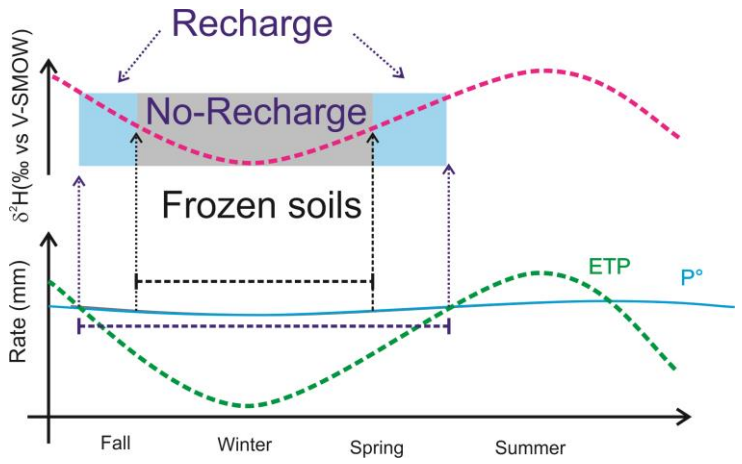

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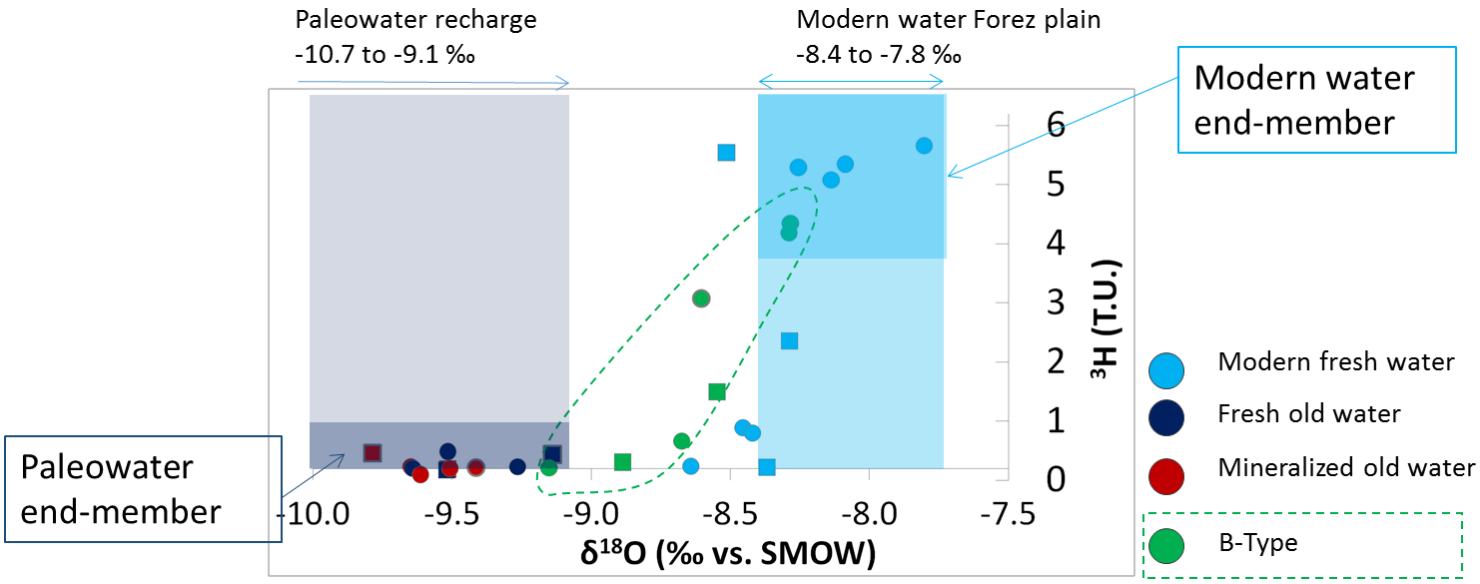
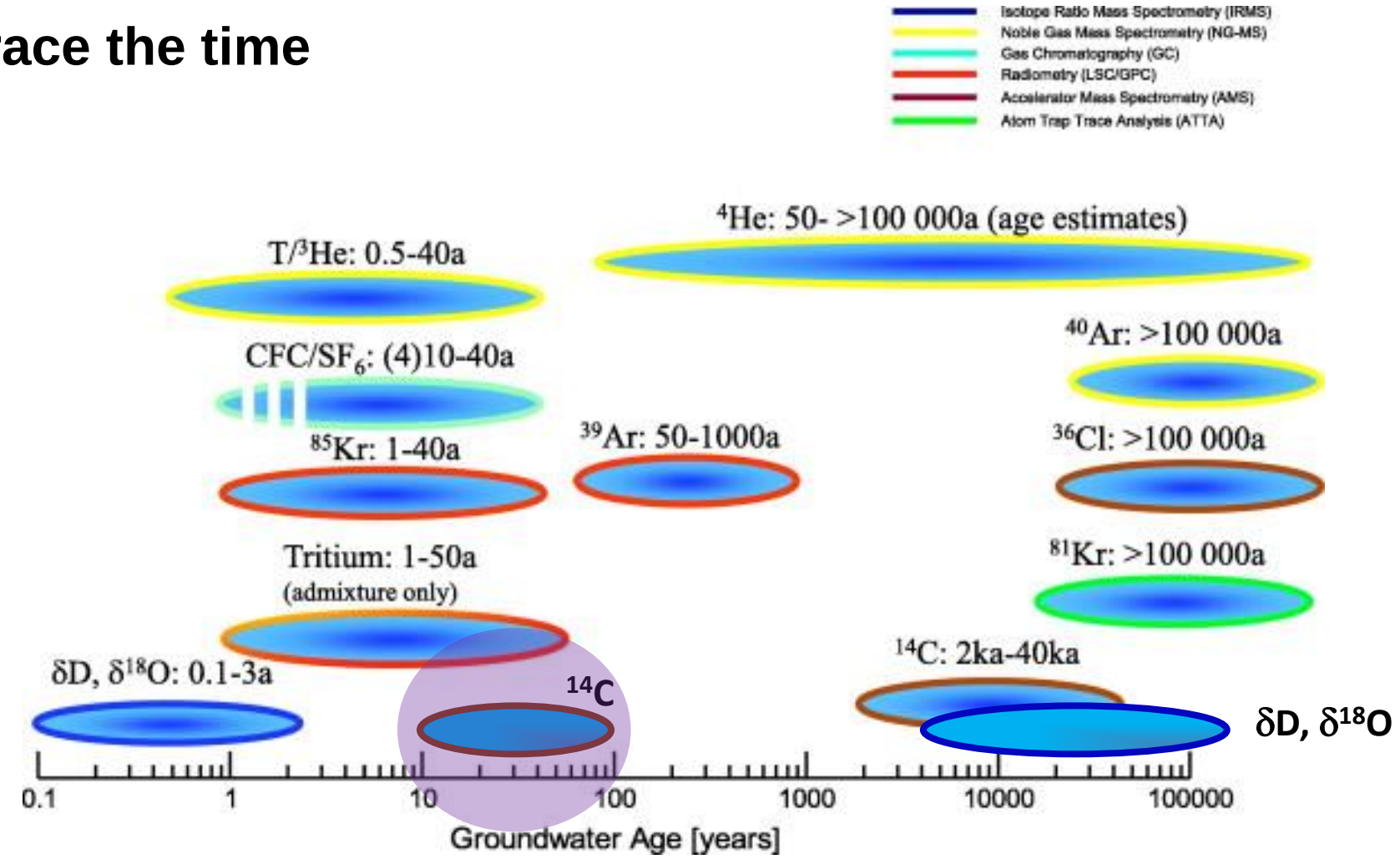


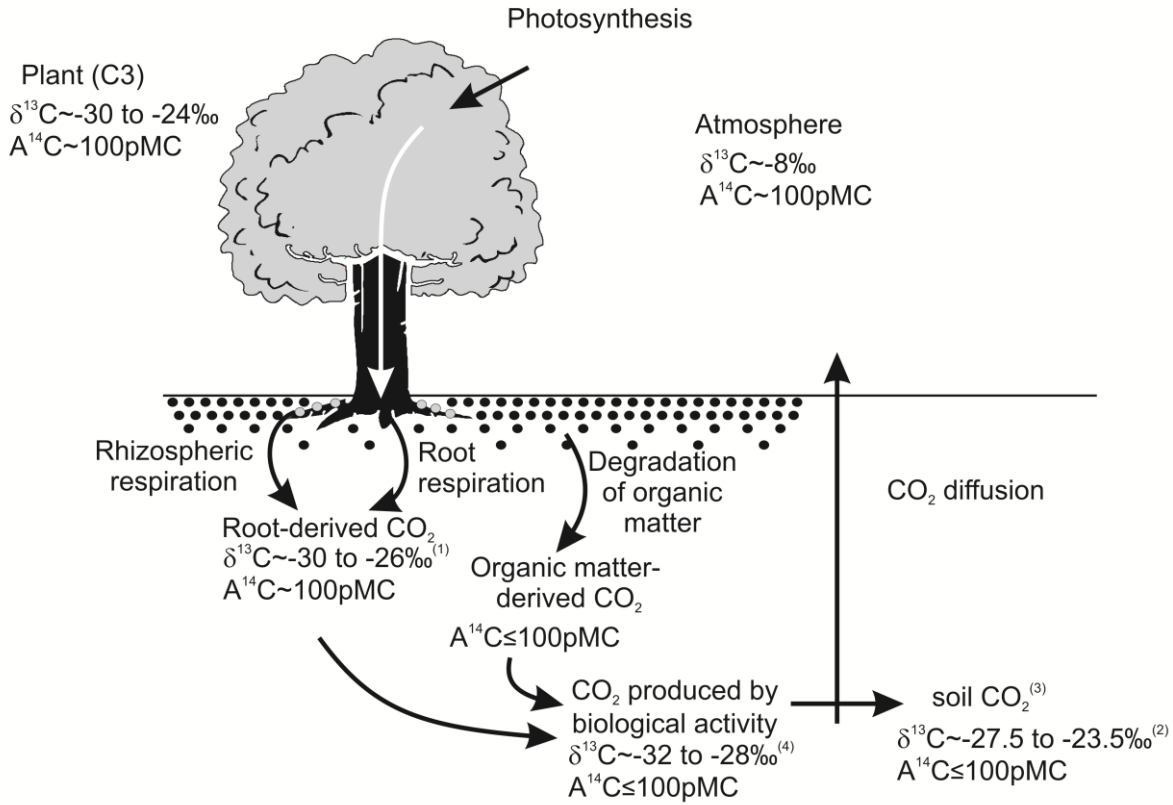
M. Alazard et al (session 8.04, #2037) Origin of groundwater and CO_2 in the crystalline environment of Saint Galmier, France

Trace the time



(Modified from Suckow *2014, Baudron 2014, Bartyzel & Rozanski 2016*)

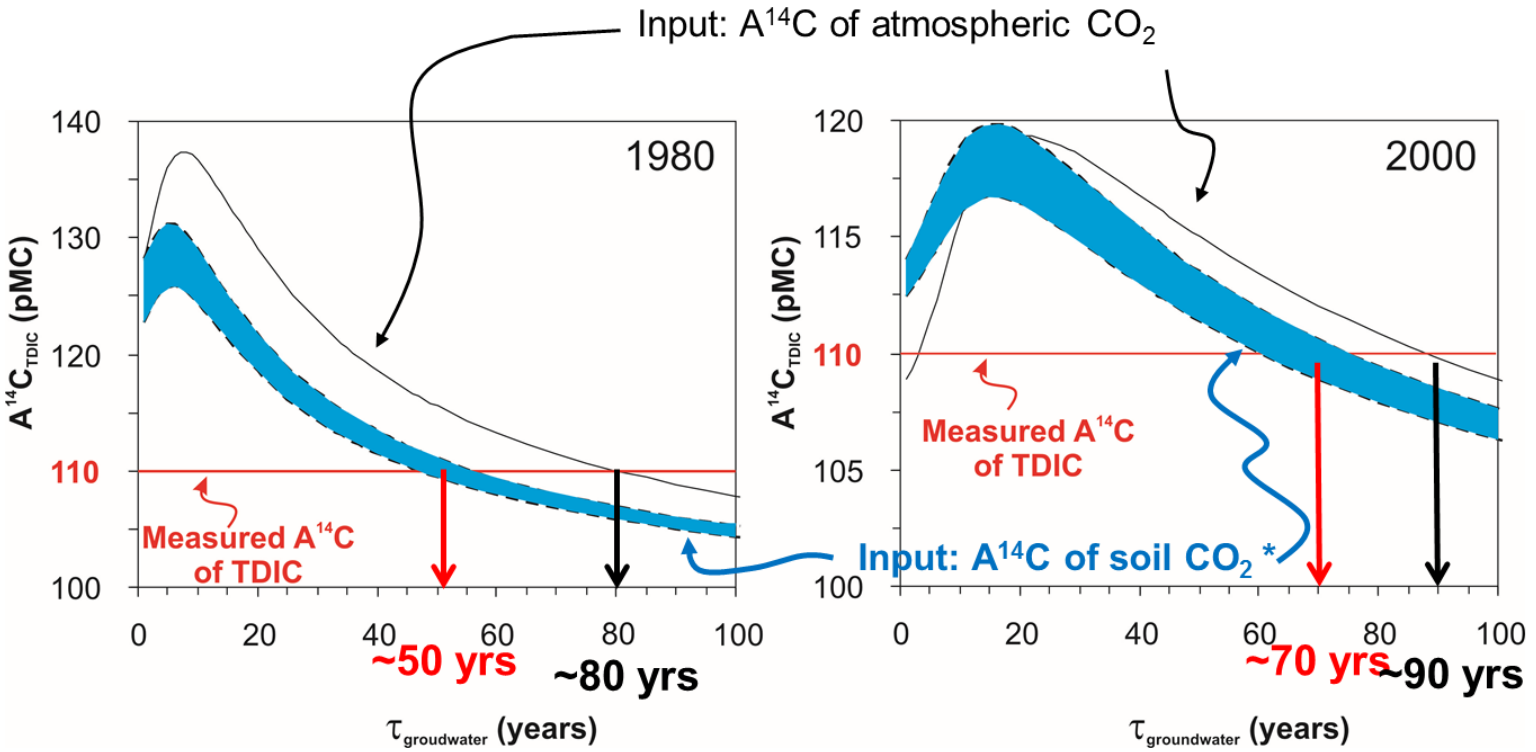
A deep understanding of tracer transfer within the USZ



(1) from literature (Lichtfouse et al., 1995; Lin et al., 1999; Krull et al., 2002; Badeck et al., 2005; Chemidlin Prévost-Bouré et al., 2009; Marron et al., 2009),
(2) from soil CO_2 data in Fontainebleau sands site,
(3) The diffusion of CO_2 from soil to atmosphere leads to a ^{13}C enrichment of +4.4‰ between soil CO_2 and the CO_2 produced by biological activity (Cerling et al., 1991; Davidson, 1995)
(4) from soil CO_2 data and the enrichment factor associated to diffusion

(Gillon et al, 2012)

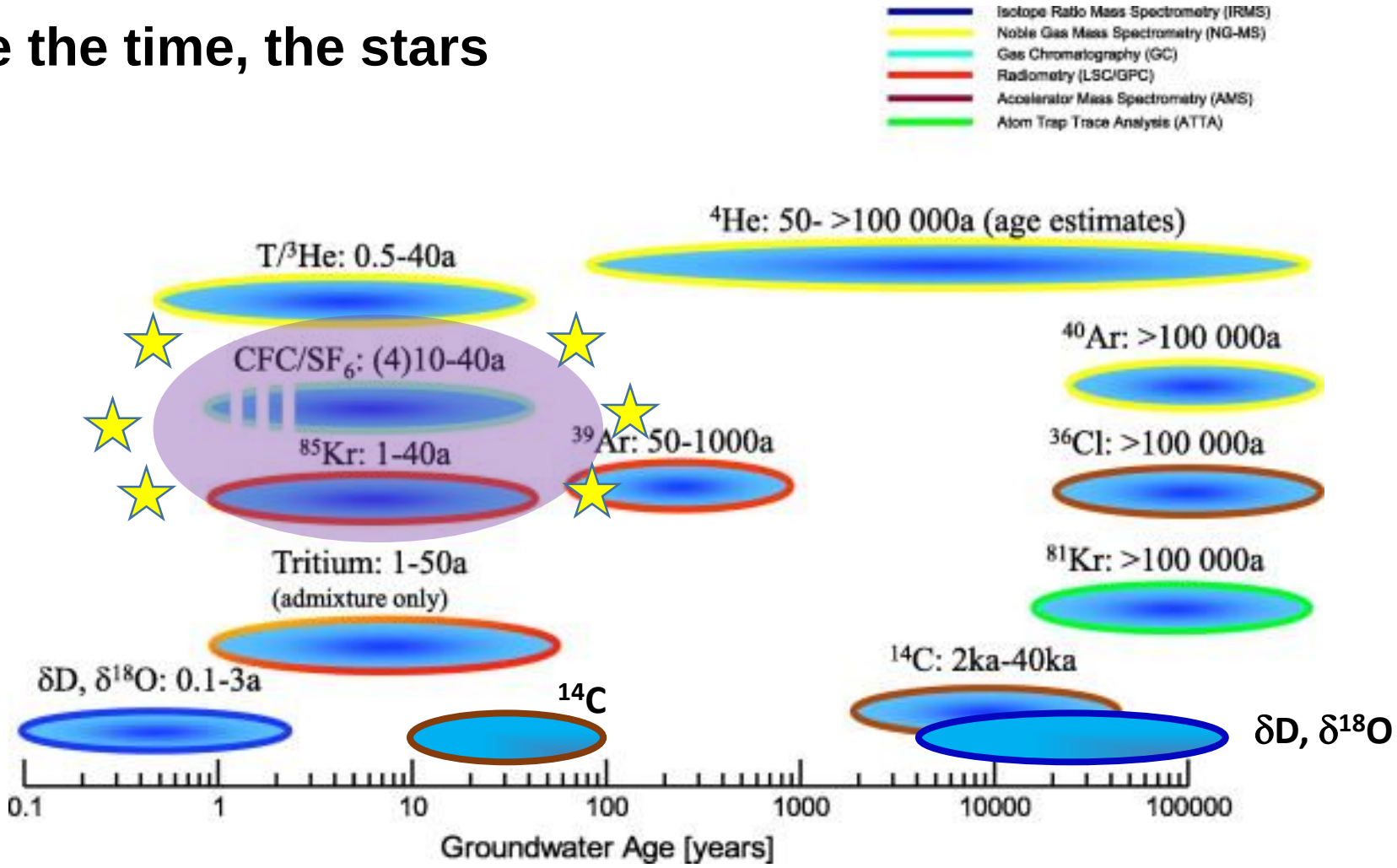
Radiocarbon in modern water



(Gillon et al, 2012)

~ 20 yrs uncertainty on the starting blocks ..

Trace the time, the stars



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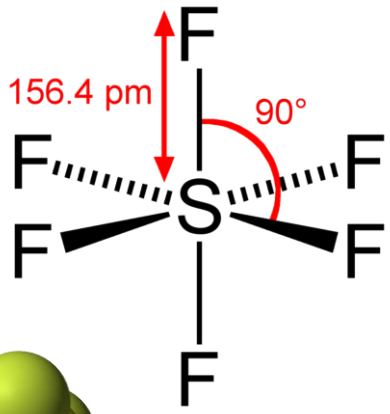
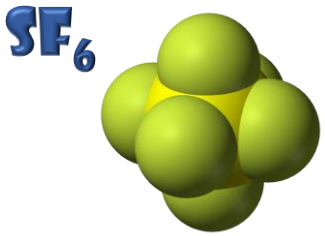
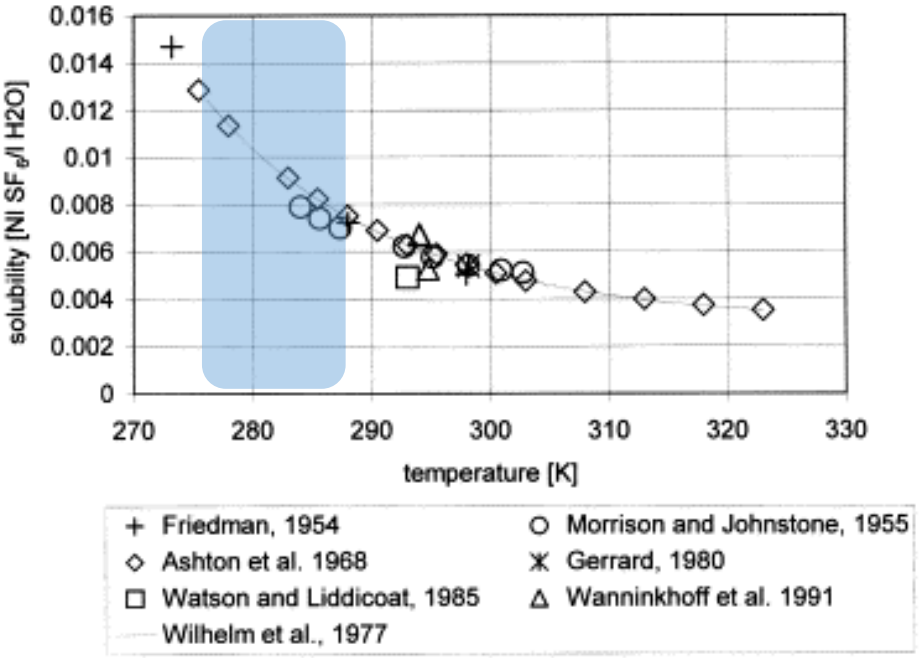
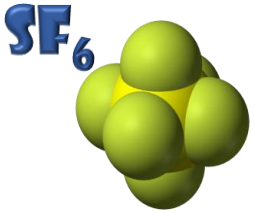




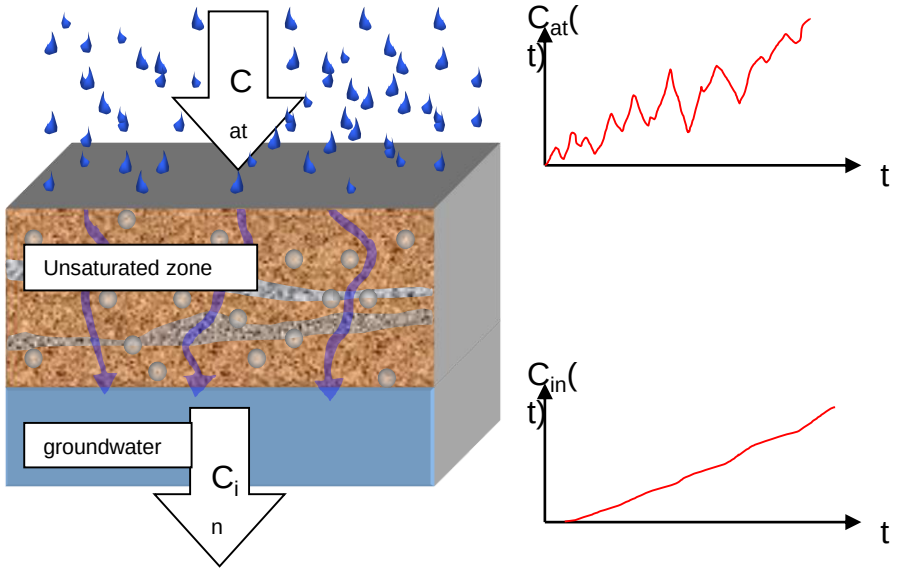


(Klump, 2007)

- inorganic, colorless, odorless, non-flammable, **extremely potent greenhouse gas**
- excellent electrical insulator.
- High atmospheric residence time : up to 3200 yrs ***(Ravishankara et al., 1993)***
- Low solubility + T dependence



Sampling the USZ in the Paris Basin

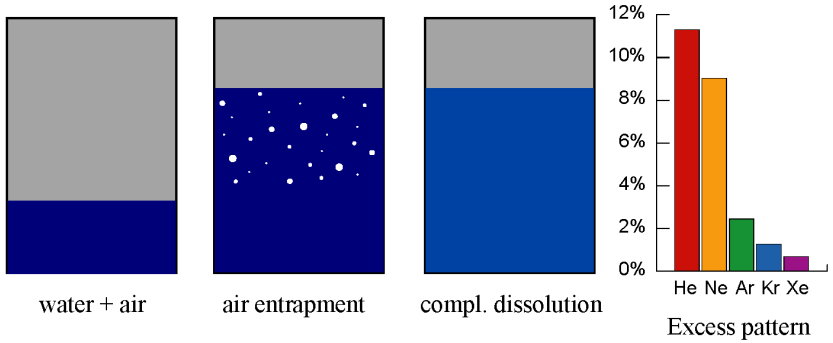


- USZ buffer the atmospheric variability ([SF_6] and T)

(Klump et al, 2008; Corcho et al, 2007; Gooddy et al 2006)

Origin and composition of excess air

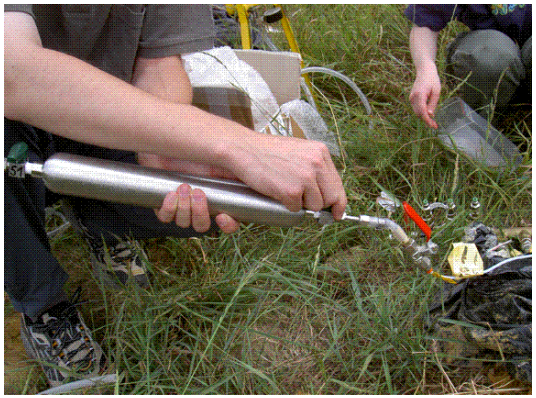
Classical model: Complete dissolution of entrapped air bubbles
$\Rightarrow$ composition of excess air = composition of atmospheric air



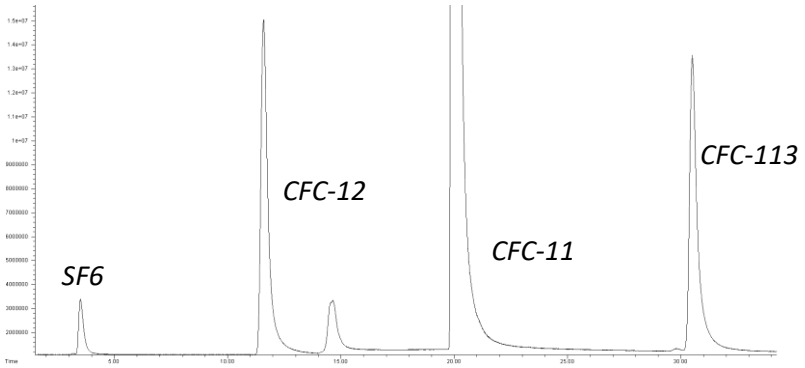
$$C_i = C_i^{eq}(T,S,P) + Az_i$$

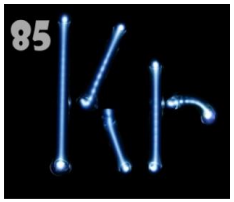
A: Concentration of excess air

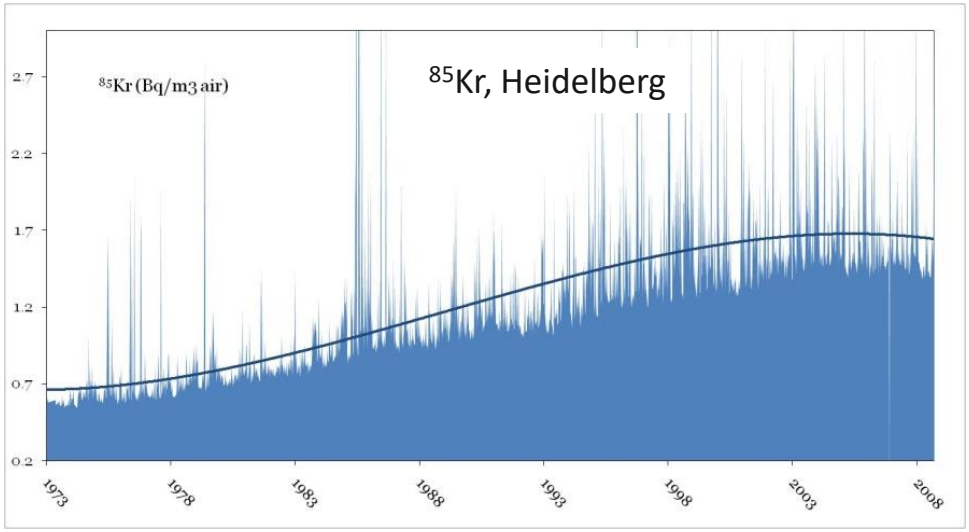
From W. Aeschbach-Hertigb

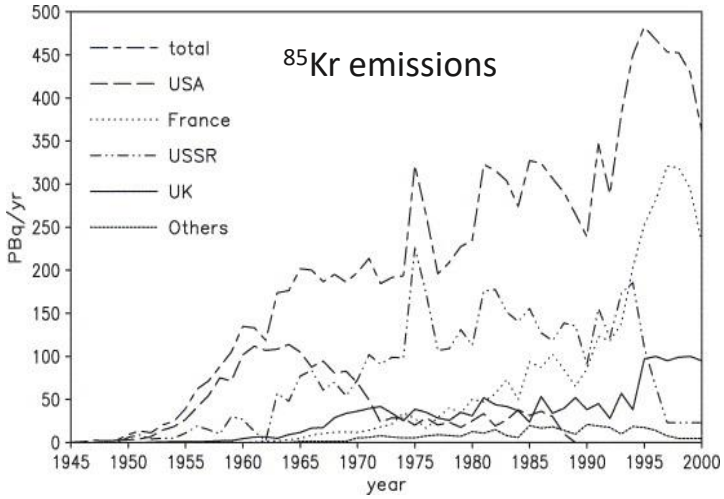


- Head space + chromatographic separation
- GC + ECD
- ~ 0,5 L of water



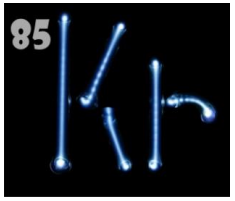






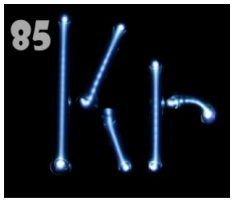
(Winger et al , 2005)

- Noble Gas
- 6 IS + ~10 IR
- ^{85}Kr radioactif, $T_{1/2}$= 10.76 yrs
- From U & Pu fission
- Reprossessing nuclear fuel
- Well documented
- 1 to 2 Bq / m^3 air



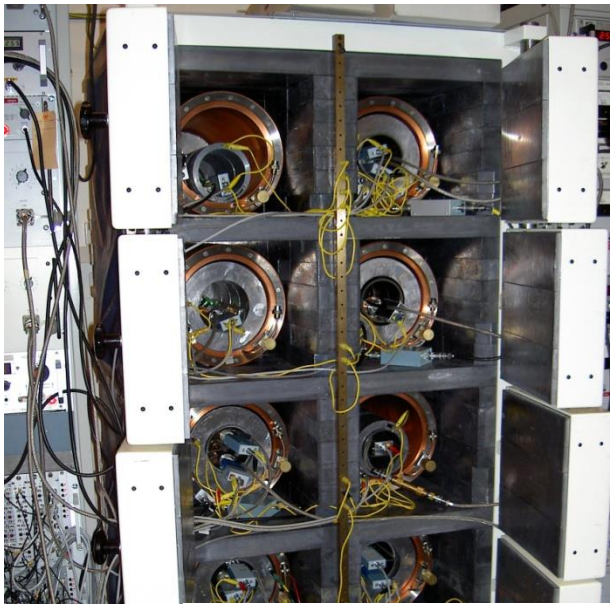
- ^{85}Kr activity normalized to stable Kr content : don't care about solubility or excess air
- Low contents
- Need of ~ 300 L (Kr)
- Degazed on field

Water inlet
Extraction cylinder
Water outlet
Pumps, Compressor
Electronic controller
Sample tank



- Separation of Kr
- Low level β^- couting

$$^{85}Kr \rightarrow {}^{85}Rb + e^- + n$$

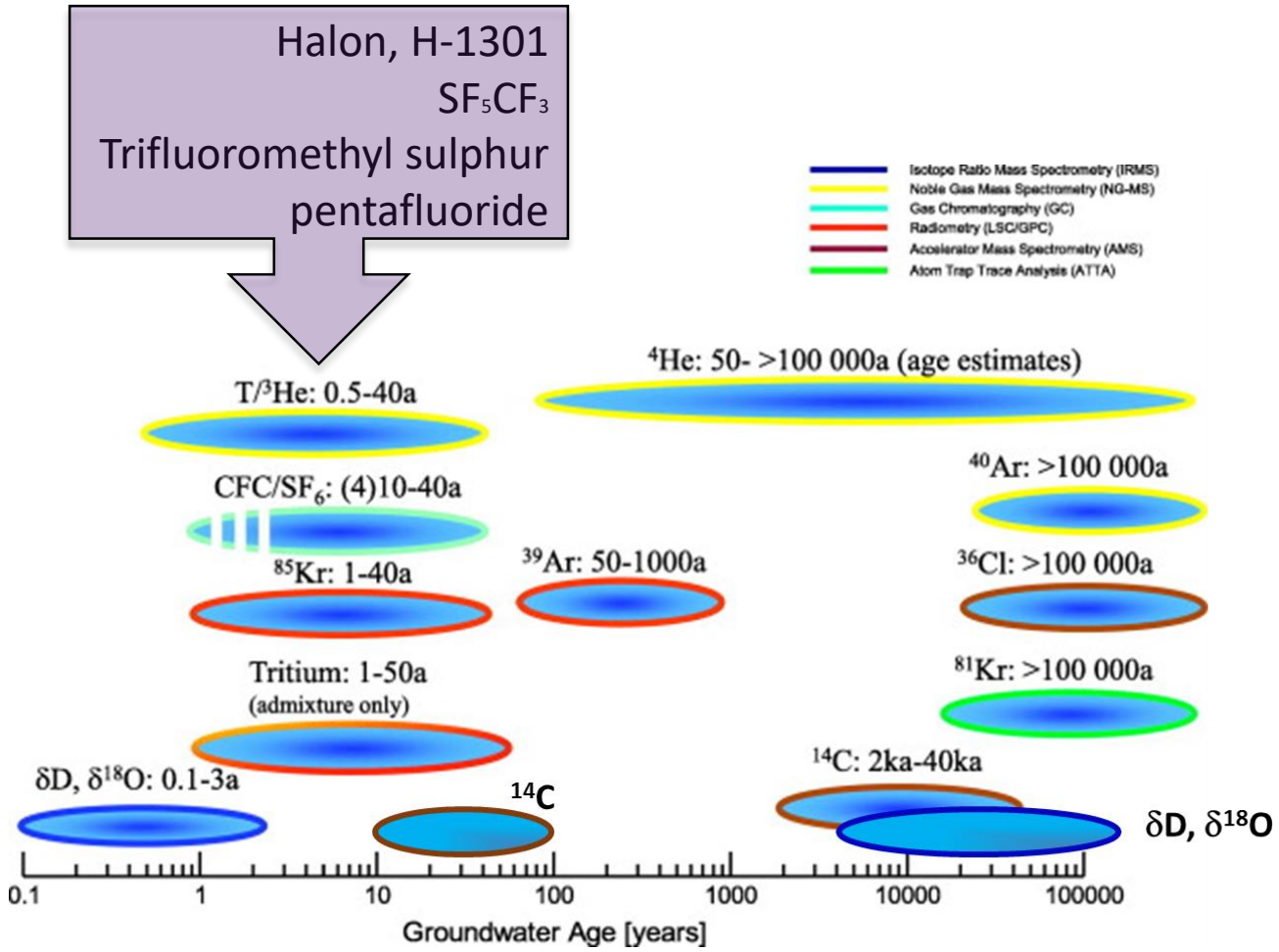


(Loosli et al 1999)

Climate and Environmental Physics

Roland Purtschert,
Climate and Environmental Physics
Physics Institute
University of Bern
email: purtschert@climate.unibe.ch

Trace the time with other tracers



(Modified from Suckow *2014, Baudron 2014, Busenberg and Plummer 2008, Bartyzel & Rozanski 2016*)

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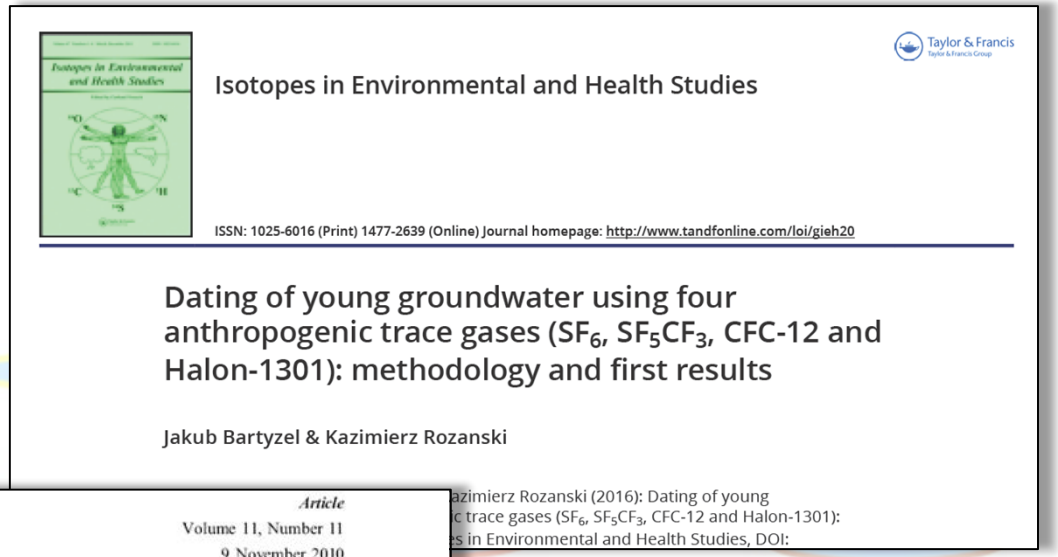


Isotopes in Environmental and Health Studies

ISSN: 1025-6016 (Print) 1477-2639 (Online) Journal homepage: http://www.tandfonline.com/loi/gieh20

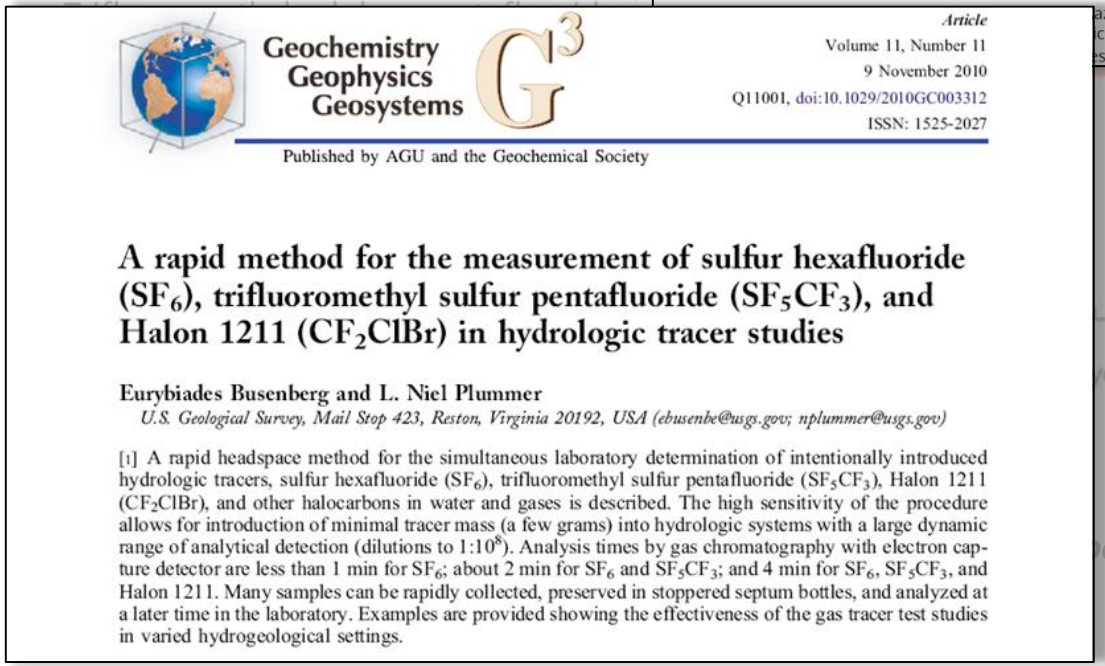
Dating of young groundwater using four anthropogenic trace gases (SF_6, SF_5CF_3, CFC-12 and Halon-1301): methodology and first results

Jakub Bartyzel & Kazimierz Rozanski

azimierz Rozanski (2016): Dating of young
ic trace gases (SF_6, SF_5CF_3, CFC-12 and Halon-1301):
es in Environmental and Health Studies, DOI:

Halon, H-1301

SF_5CF_3



Geochemistry Geophysics Geosystems G3

Article
Volume 11, Number 11
9 November 2010
Q11001, doi:10.1029/2010GC003312
ISSN: 1525-2027

Published by AGU and the Geochemical Society

A rapid method for the measurement of sulfur hexafluoride (SF_6), trifluoromethyl sulfur pentafluoride (SF_5CF_3), and Halon 1211 (CF_2ClBr) in hydrologic tracer studies

Eurybiades Busenberg and L. Niel Plummer
U.S. Geological Survey, Mail Stop 423, Reston, Virginia 20192, USA (ebusenbe@usgs.gov; nplummer@usgs.gov)

[1] A rapid headspace method for the simultaneous laboratory determination of intentionally introduced hydrologic tracers, sulfur hexafluoride (SF_6), trifluoromethyl sulfur pentafluoride (SF_5CF_3), Halon 1211 (CF_2ClBr), and other halocarbons in water and gases is described. The high sensitivity of the procedure allows for introduction of minimal tracer mass (a few grams) into hydrologic systems with a large dynamic range of analytical detection (dilutions to $1:10^8$). Analysis times by gas chromatography with electron capture detector are less than 1 min for SF_6; about 2 min for SF_6 and SF_5CF_3; and 4 min for SF_6, SF_5CF_3, and Halon 1211. Many samples can be rapidly collected, preserved in stoppered septum bottles, and analyzed at a later time in the laboratory. Examples are provided showing the effectiveness of the gas tracer test studies in varied hydrogeological settings.

^{81}Kr: >100 000a

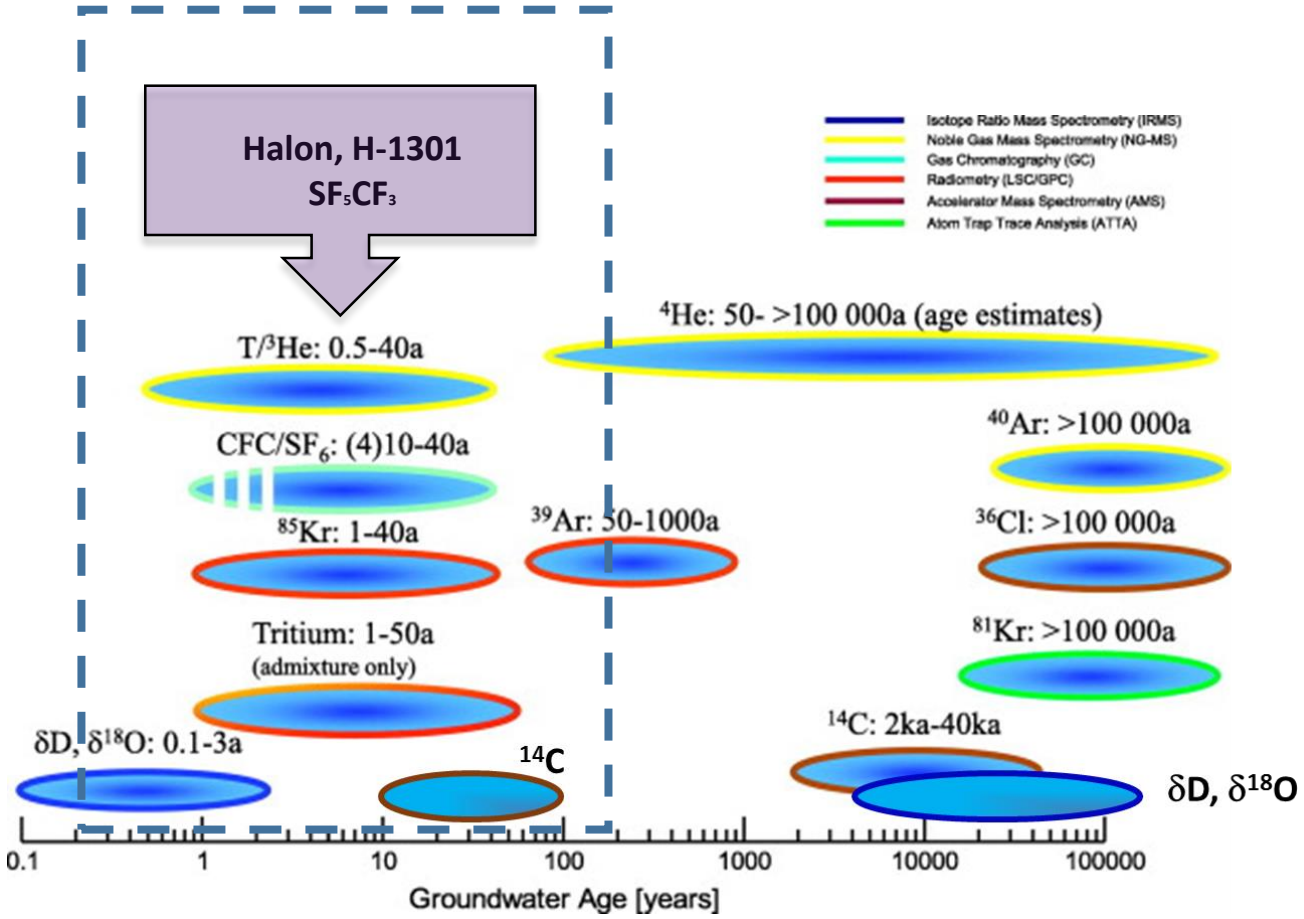
^{14}C: 2ka-40ka

δD, $\delta^{18}O$

1000 10000 100000

years]

berg and Plummer 2008, Bartyzel & Rozansk

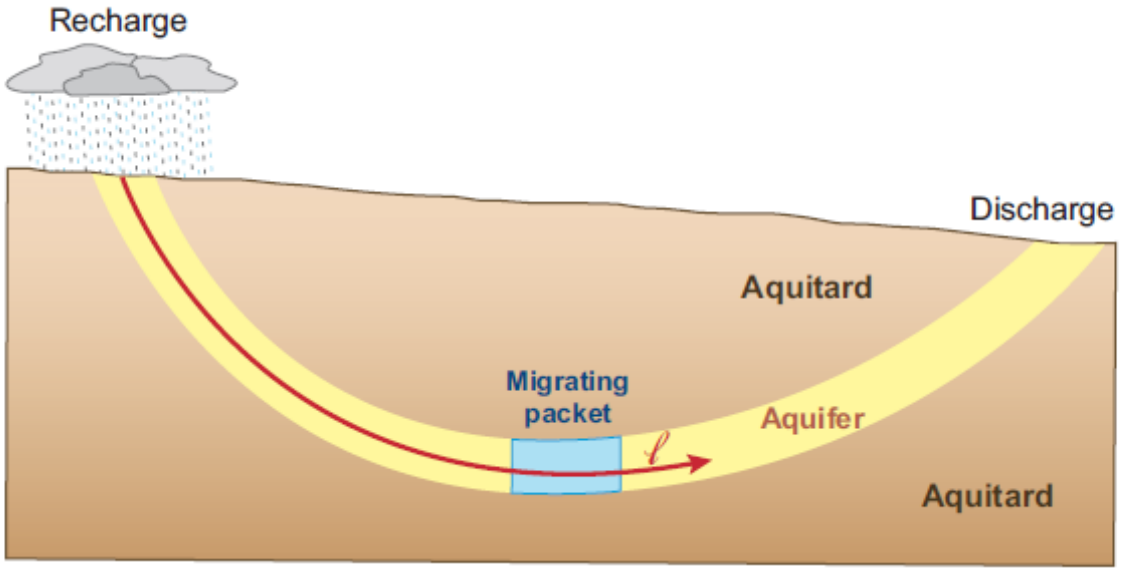


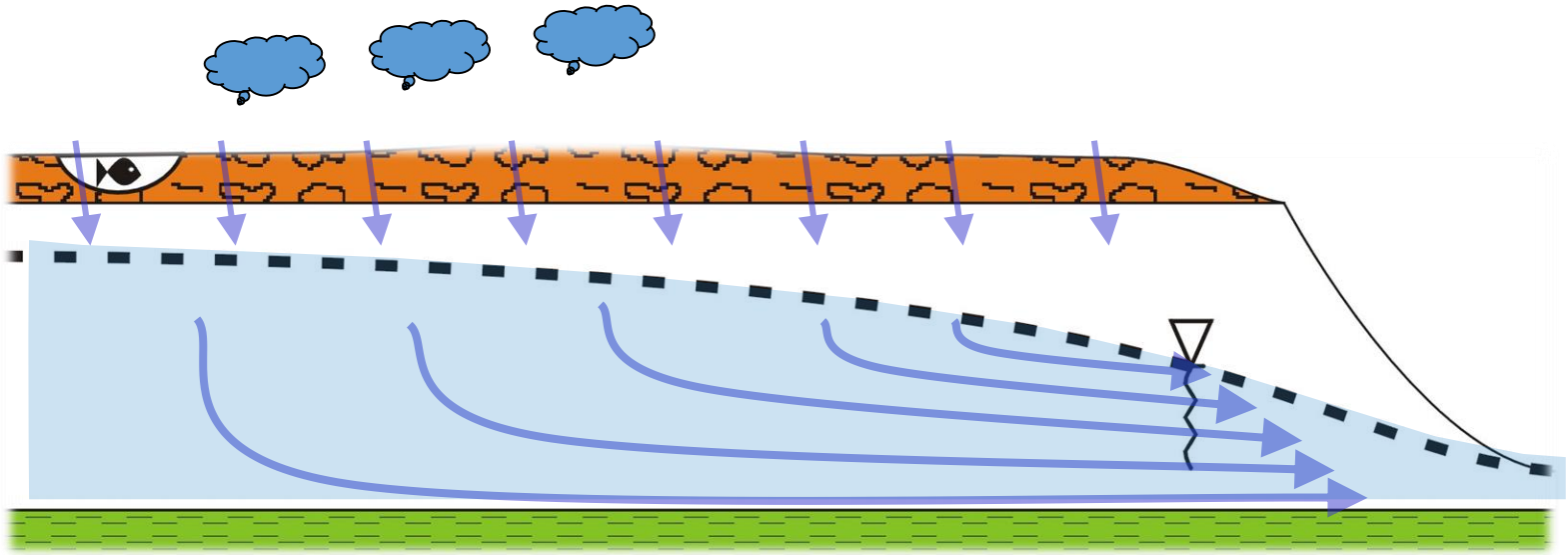
(Modified from Suckow *2014, Baudron 2014, Busenberg and Plummer 2008, Bartyzel & Rozanski 2016*)

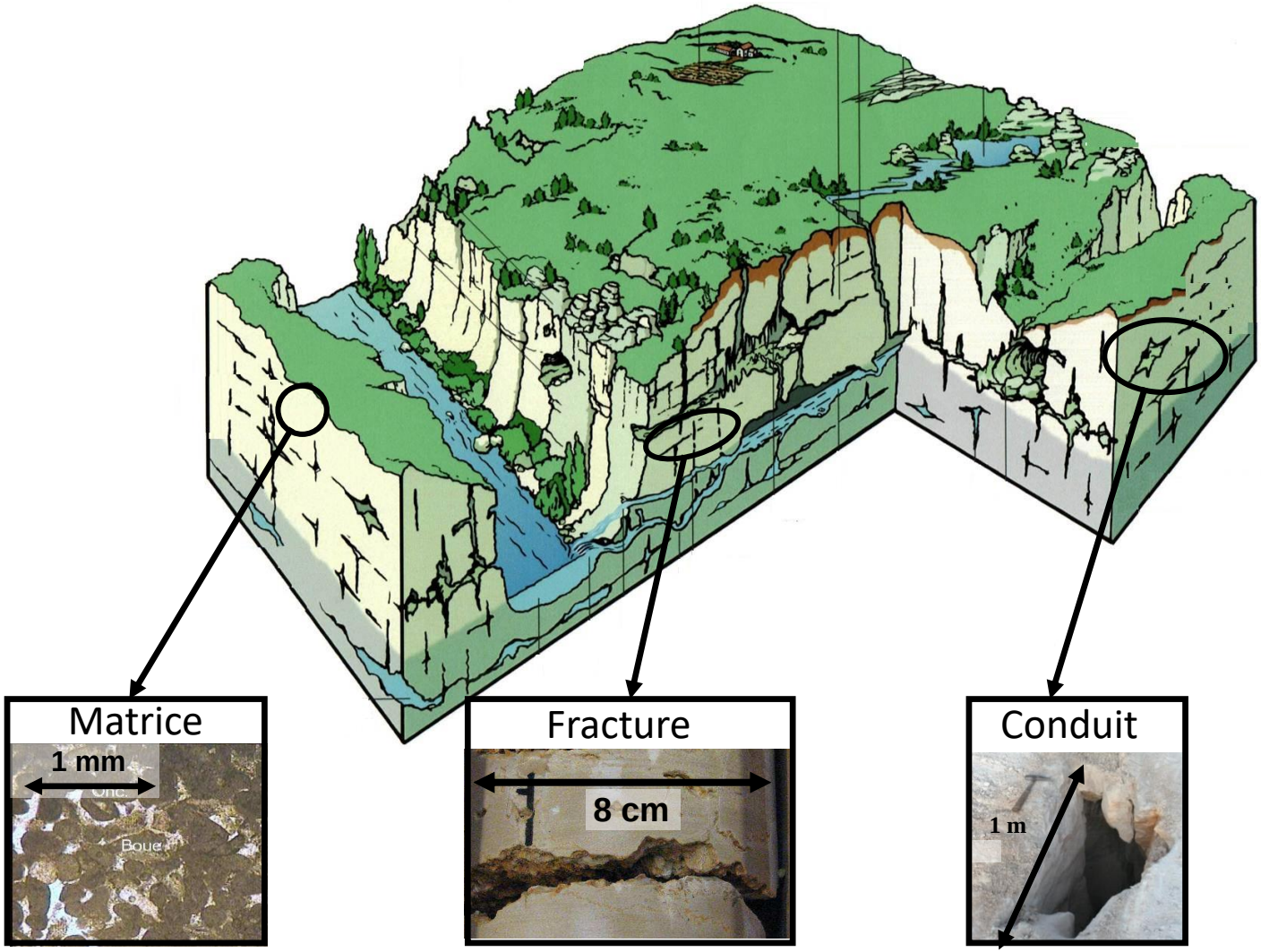
In a nutshell, Hydrogeochemists transform the dark side of human activity into tools for environmental management !

neonmag.fr

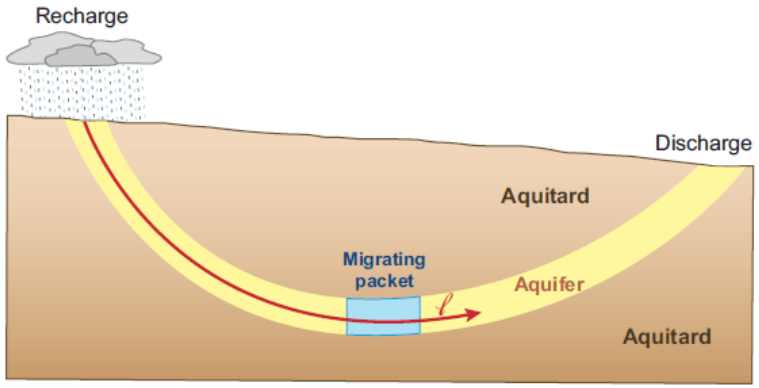
Trace the time, not the age !

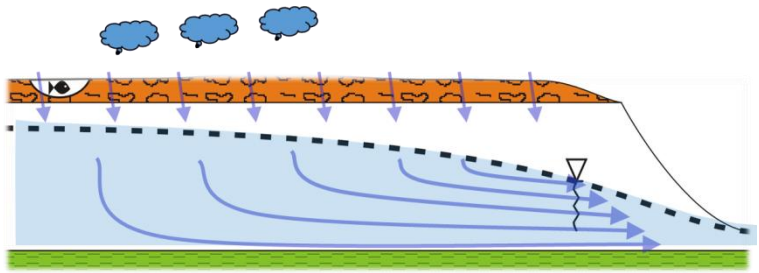


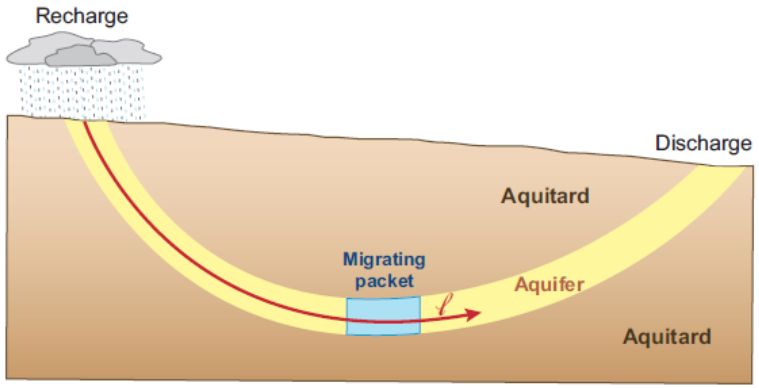


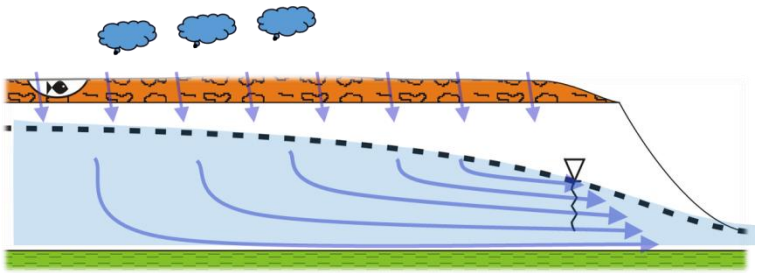


(Modified from Bakalowicz, 2003 in Delbart 2013)

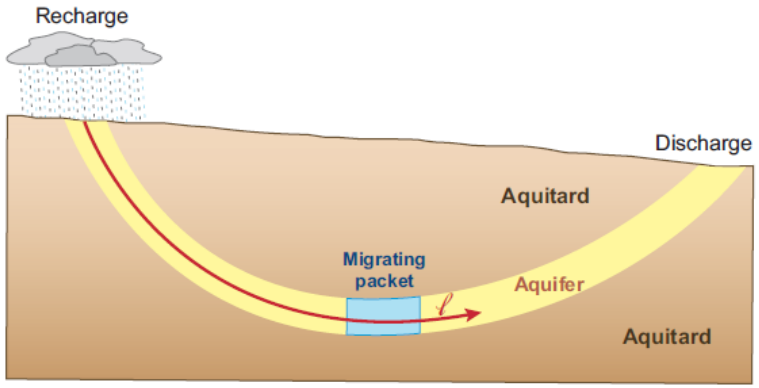

Recharge
Discharge
Aquitard
Migrating
packet
Aquifer
Aquitard

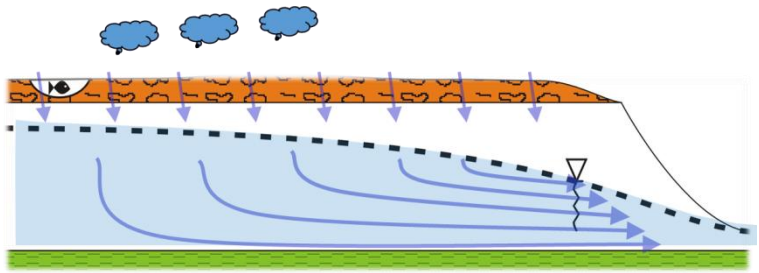






My age is 400 kdays ±1





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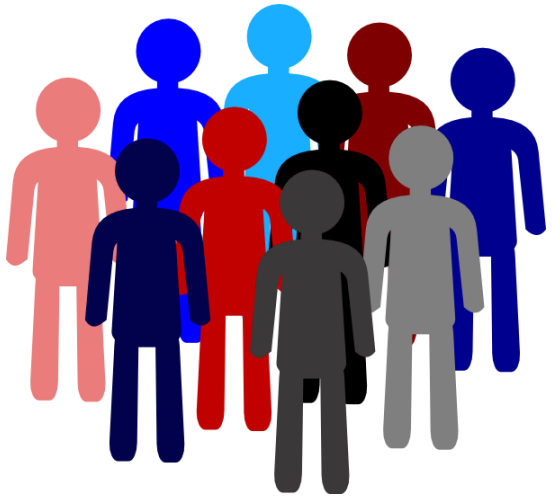

The IAH assembly “age” is a nonsense

Applied Geochemistry 50 (2014) 222–230

Contents lists available at ScienceDirect

Applied Geochemistry

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Review

The age of groundwater – Definitions, models and why we do not need this term

Axel Suckow *

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National Centre for Groundwater Research and Training (NCGRT), Flinders University, School of the Environment, Adelaide, Australia

ARTICLE INFO

Article history:
Available online 24 May 2014

ABSTRACT

The use of environmental tracers to characterise time scales when investigating groundwater is a technology that has been in use for half a century. Its usefulness is beyond controversy. However, the use of the word "age" for groundwater connected with these techniques is misleading due to its inherent connection to the general understanding of human age. "Age" as in the understanding of human age cannot be

The AIH assembly "age" is a nonsense

Le LHGI, avril 1989

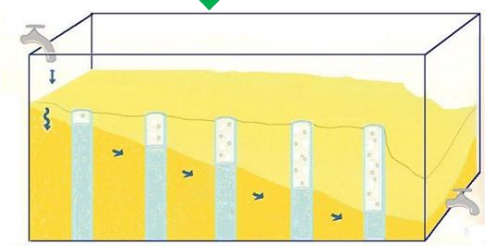
… the “age” of a groundwater sample corresponds generally to a time distribution of many elementary flows. Thus, except in the theoretical case of a pure piston flow system, or of stationary waters entrapped in a geological formation, the concept of groundwater age has little significance.

→ Mean Residence Time (MRT)

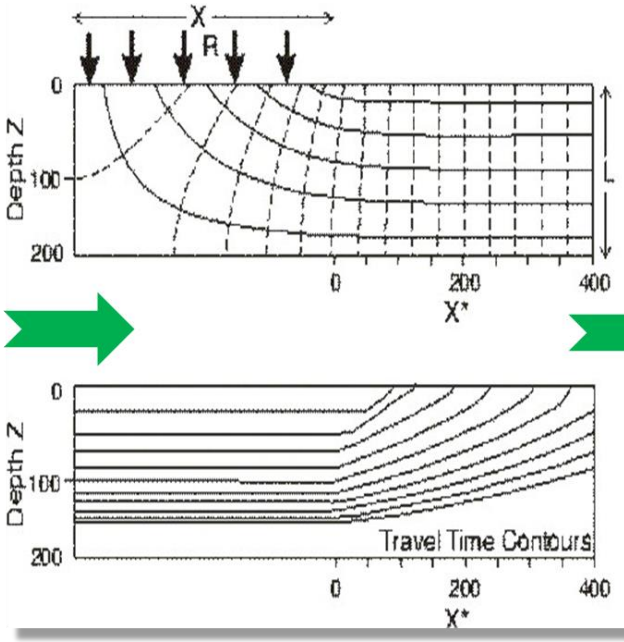
J.-Ch. Fontes (1983) in Guidebook on Nuclear Techniques in Hydrology, IAEA

Hunting the MRT

Natural Site

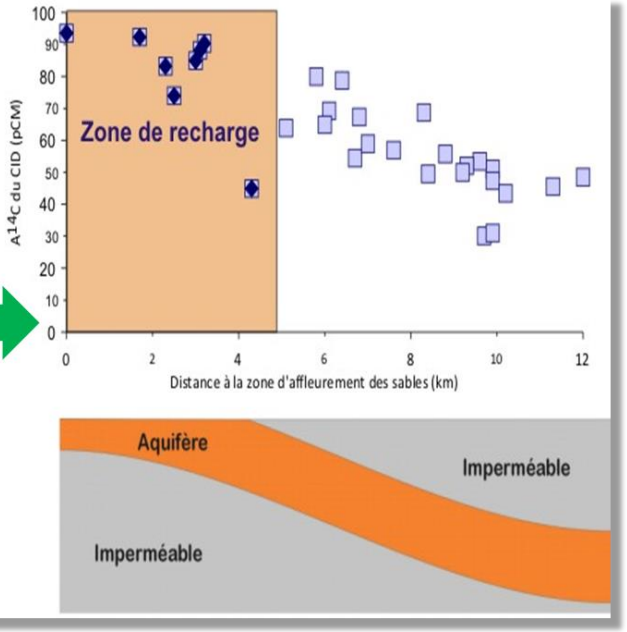


Schematic flow



(Cook & Herczeg, 1999)

Age distribution



(C. Chabault, 2006)

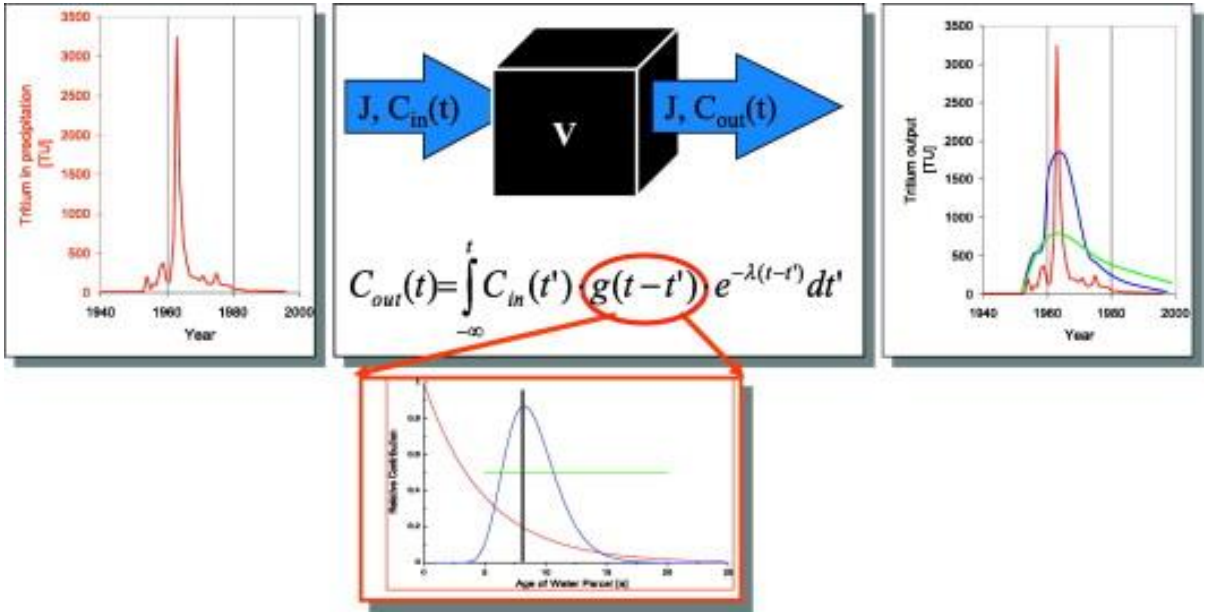
Adapted sampling

We only find what we look for

Lumped parameter models

Standard procedure (Forward Modeling)

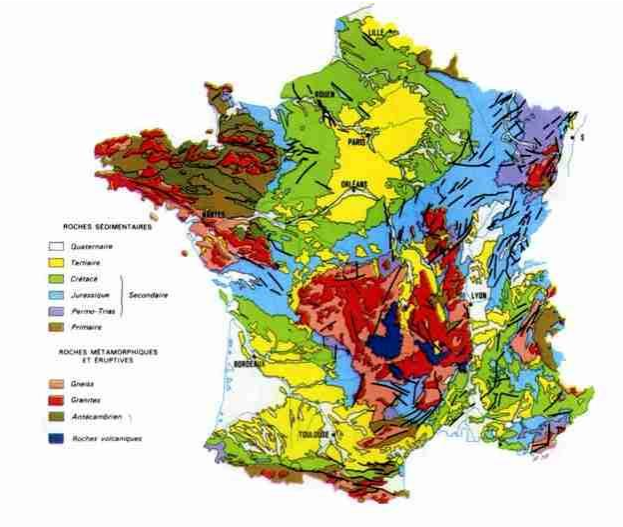
Tracer concentration → → → **MRT**



age-dependent weight function

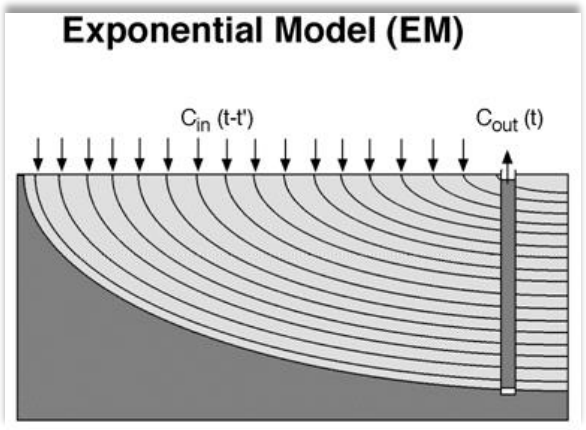
(Modified from Suckow *2014*)

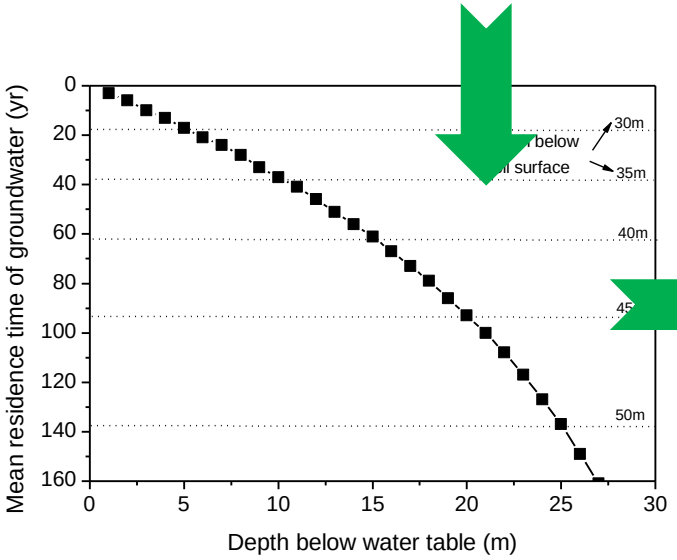
Finding the right sample



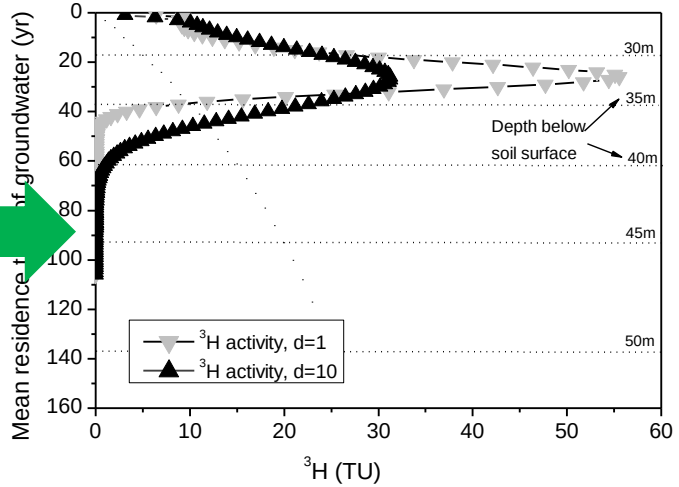
Anticipate age stratification

Flow distribution





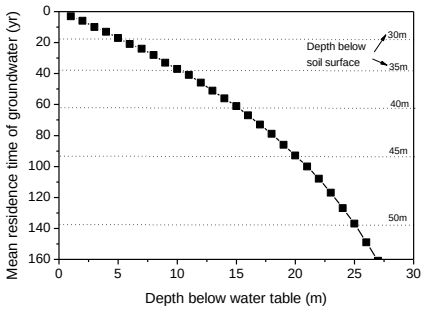
MRT distribution

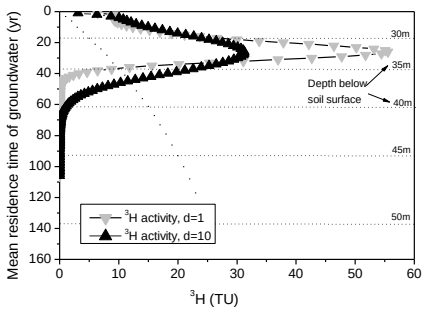


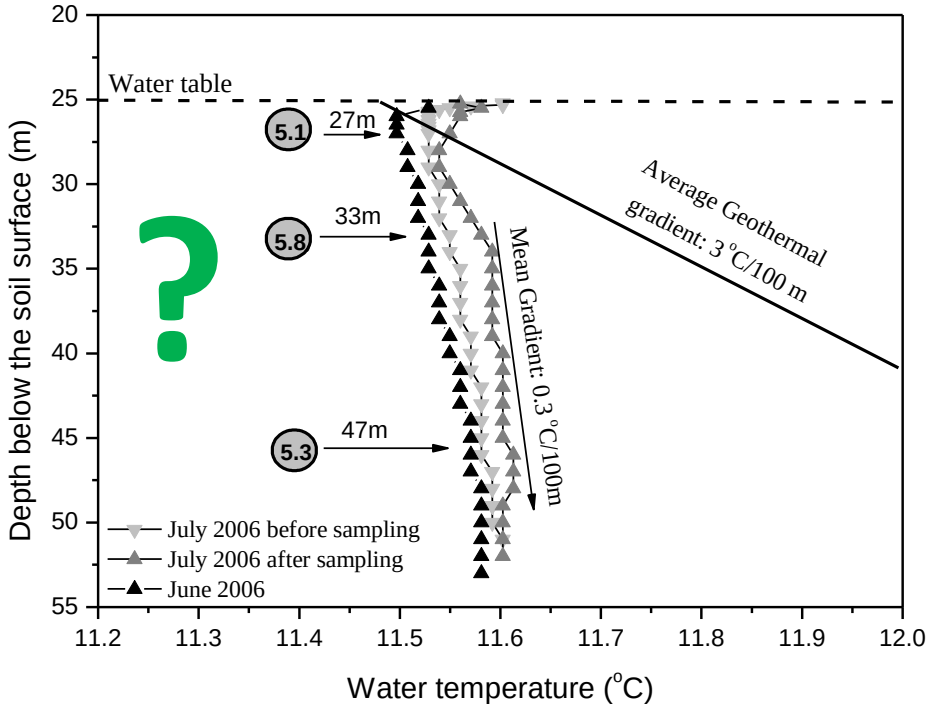
Tracer distribution

(Corcho, *2009*)

Anticipate age stratification





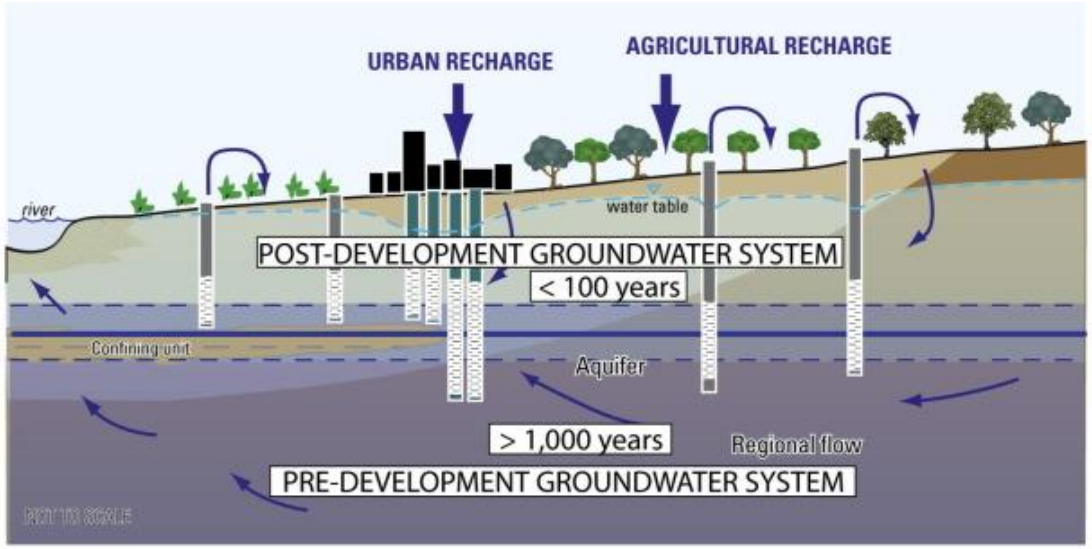


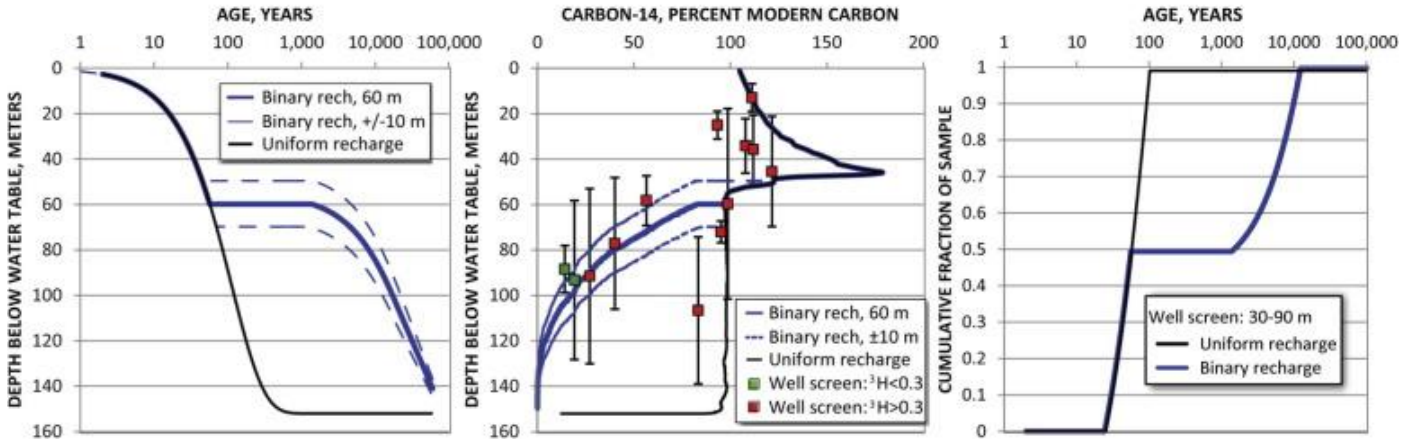
(Corcho, *2009*)

Piezometers are not geochemists best friends….

First discrepancy between model and flow

Anticipate age stratification



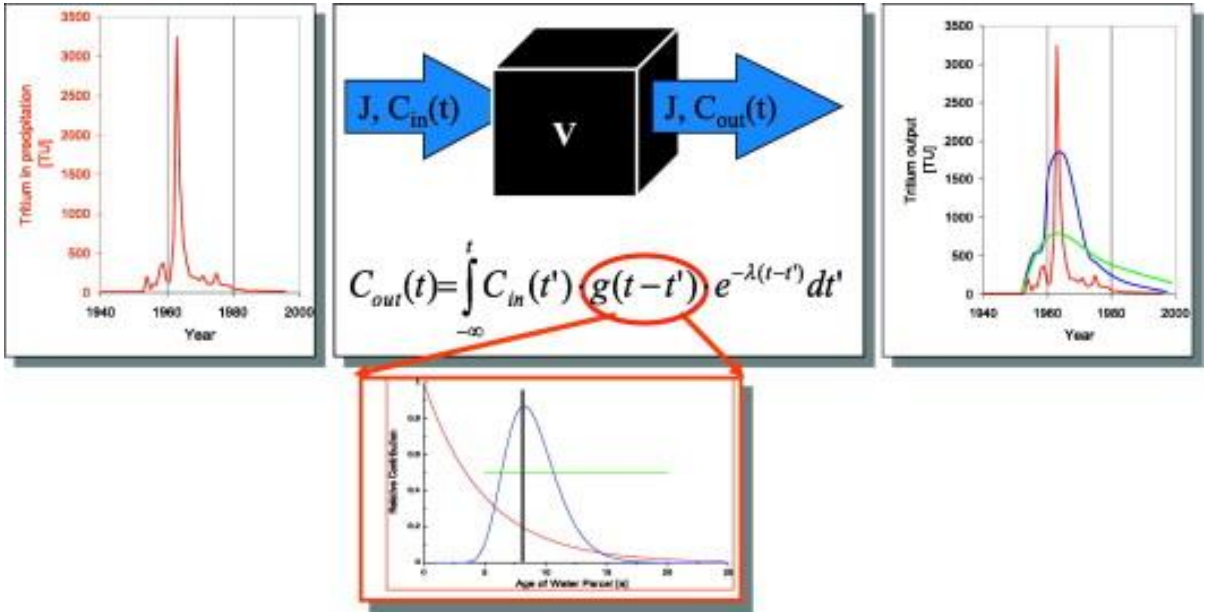


(Jurgens, 2016)

Lumped parameter models / Multi tracers

Standard procedure (Forward Modeling)

Tracers concentrations → → → **MRT**



age-dependent weight function

Lumped parameter models / Multi tracers

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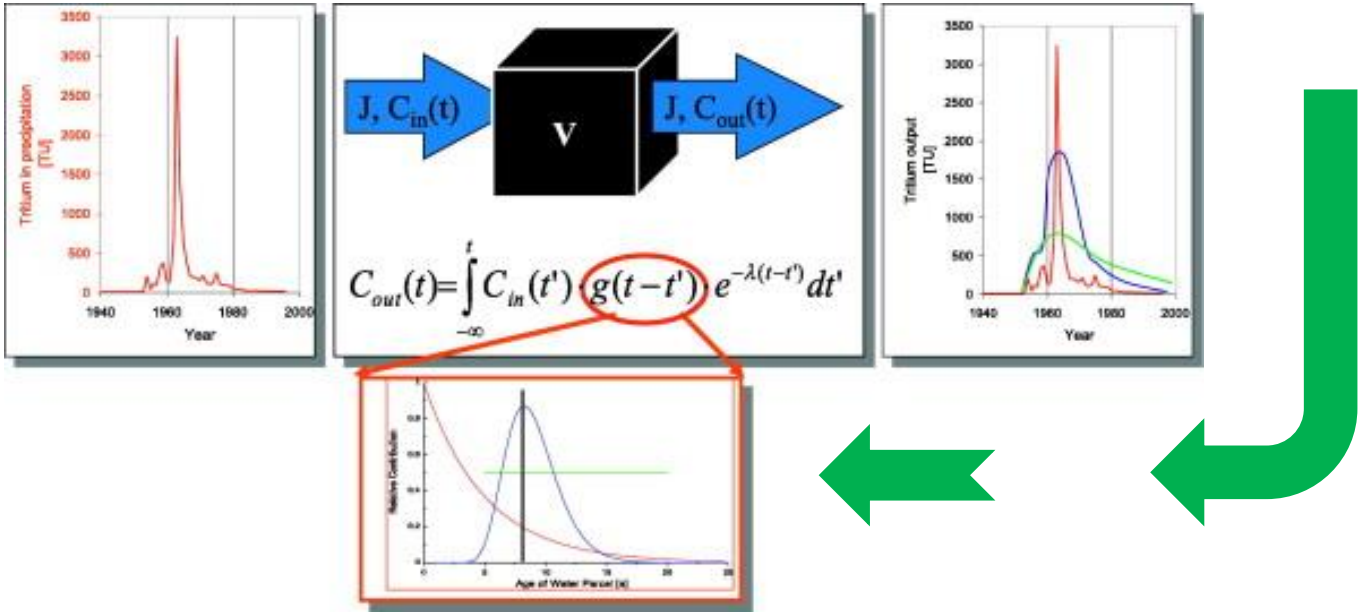
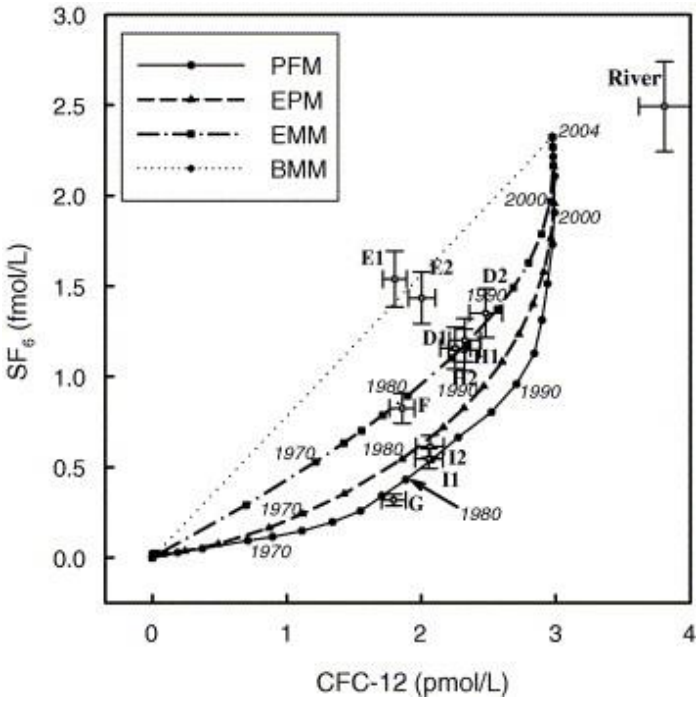
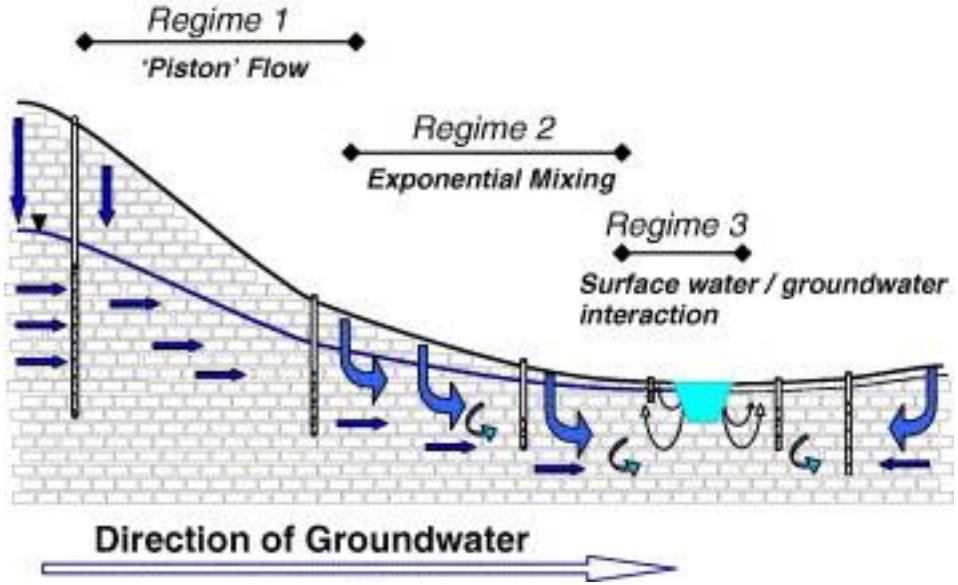


age-dependent weight function

Chalk catchment in southern England

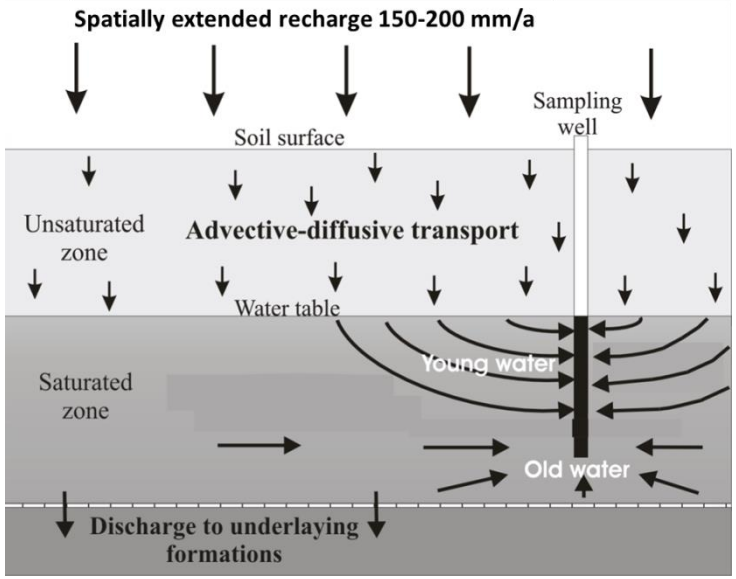
2 tracers, 10 samples

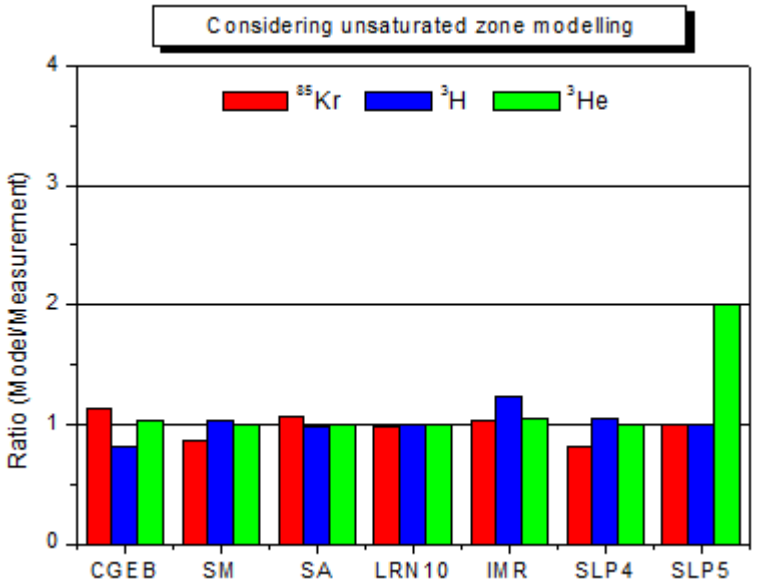




(Gooddy et al, 2006)

Fontainebleau sands aquifer
4 tracers, 7 samples





Need to solve all the equations in a single model :

$$c_{out}^{^{85}Kr}(T,T_m,m) = \int_0^{\infty} c_{in}^{^{85}Kr}(T-t)\cdot\exp(-\lambda_{^{85}Kr}t)\cdot h(t,T_m,m)\cdot dt$$

$$c_{out}^{^{3}H}(T,T_m,m) = \int_0^{\infty} c_{in}^{^{3}H}(T-t)\cdot\exp(-\lambda_{^{3}H}t)\cdot h(t,T_m,m)\cdot dt$$

$$c_{out}^{^{3}He}(T,T_m,m) = \int_0^{\infty} c_{in}^{^{3}He}(T-t)\cdot\left(1-\exp(-\lambda_{^{3}H}t)\right)\cdot h(t,T_m,m)\cdot dt$$

➔ Minimize χ^2 function

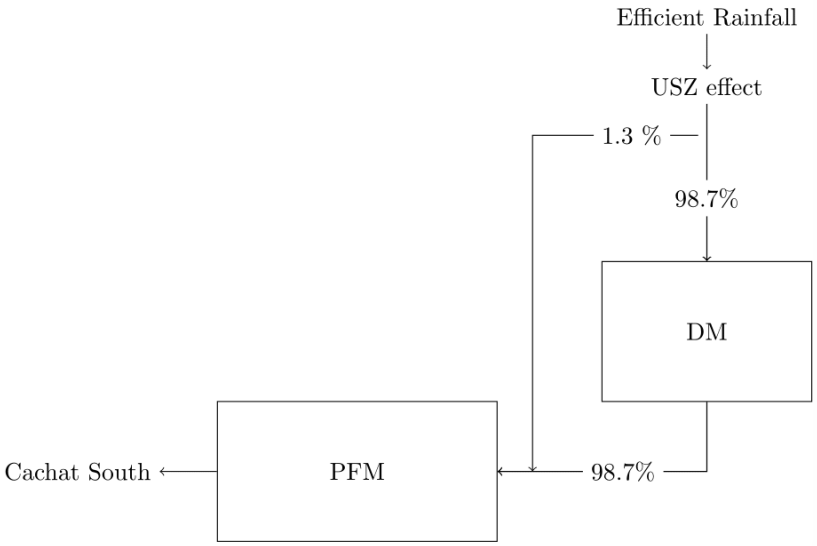
(Corcho et al, 2007)

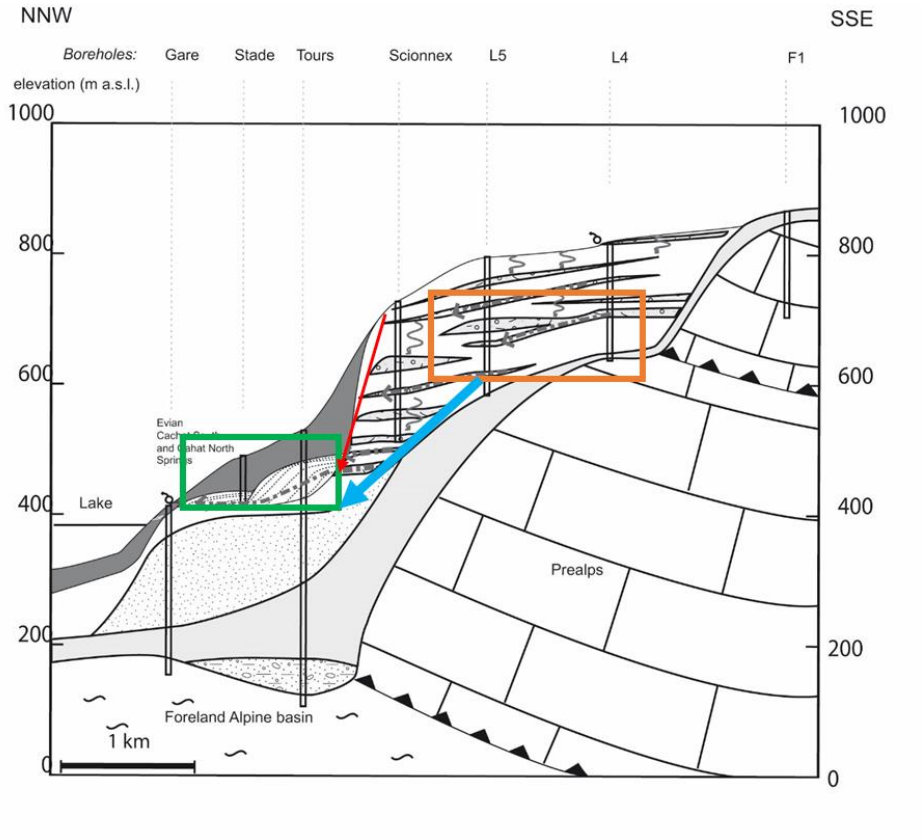
Inferring groundwater ages in complex aquifers using gas tracers and tritium

50-years' time series of a water-bound tracer (^{3}H)

+ a set of ^{85}Kr, ^{39}Ar, CFCs, SF_6 sampled at a single date

A. Henriot et al
(session 8.04, #1919)



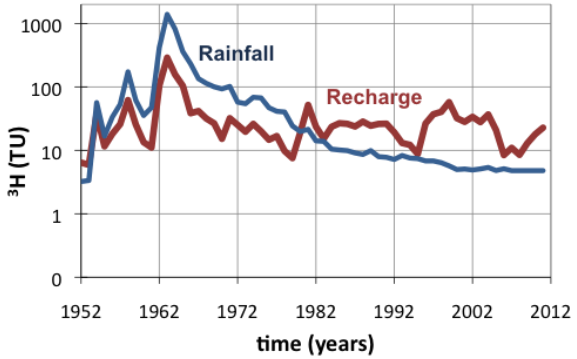


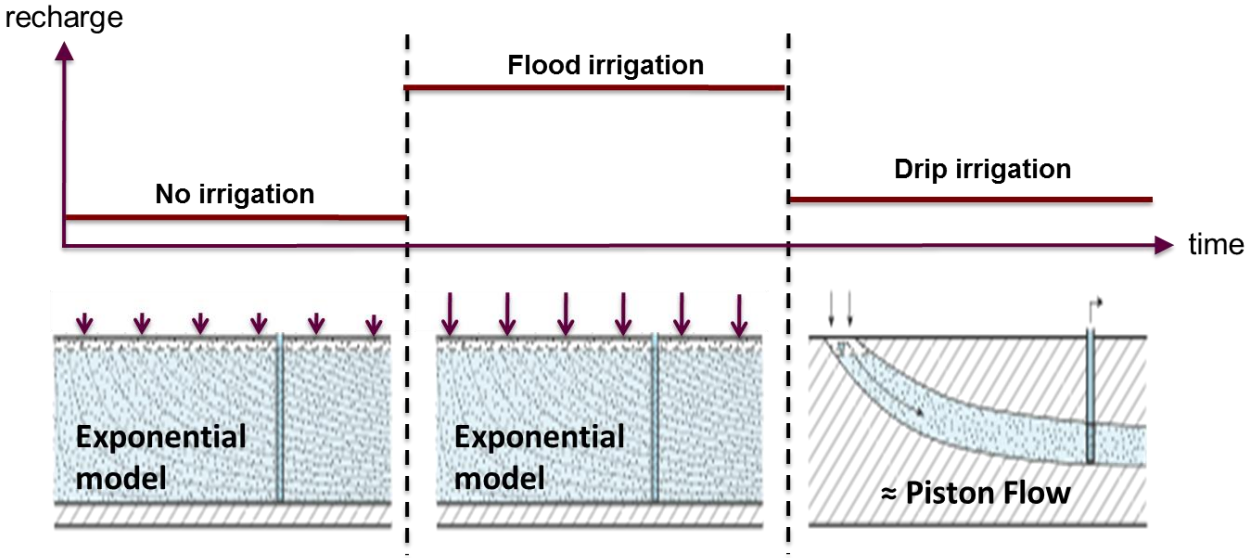
Modern groundwater residence time in a highly anthropized watershed

2 tracers

+ Variable recharge rates

+ Variable tracers input





(P. Baudron et al, 2013)

6 examples, 0 value of MRT

MRT of 25 yrs, ..50 yrs..

6 examples, 0 value of MRT

MRT of 25 yrs, ..50 yrs..

Significant only if :
MRT + a distribution (age structure)

As same MRT may lead to different issue

6 examples, 0 value of MRT

MRT of 25 yrs, ..50 yrs..

Significant only if :
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+

$$\frac{\text{}}{2} \sim$$

6 examples, 0 value of MRT

MRT of 25 yrs, ..50 yrs..

Significant only if :
MRT + a distribution (age structure)

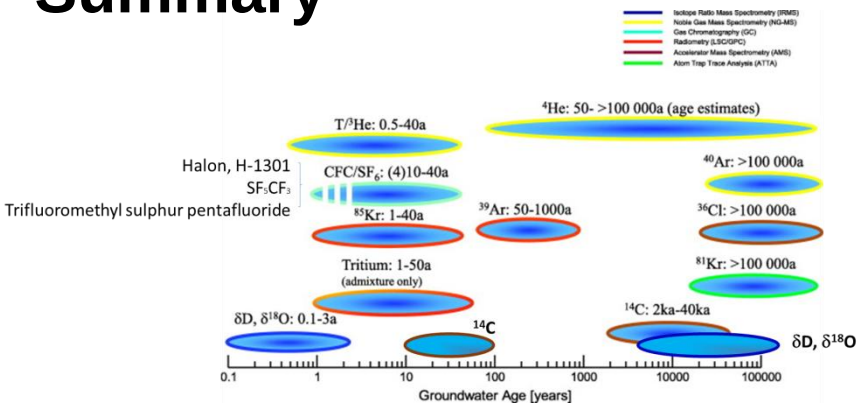
As same MRT may lead to different issue

+

2

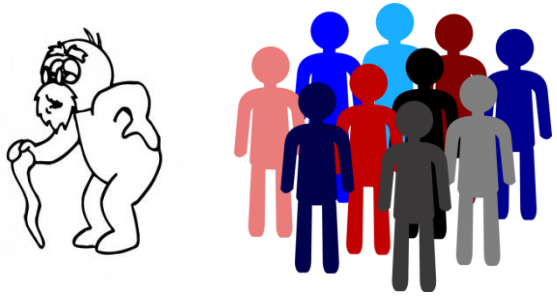
~

Summary

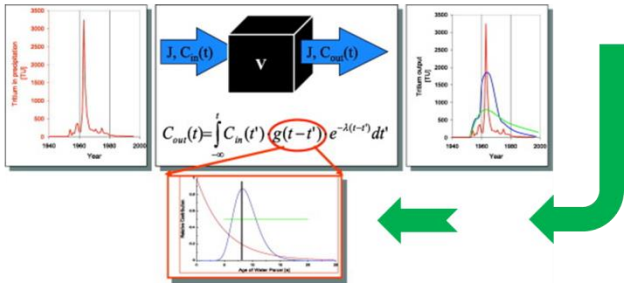


A complete set of tracers in the perfect range of MRT

Avoid "ages" for GW
Use "Mean Residence Time"



Tracers concentrations → → → MRT



Evidence, characterize hidden pathways

Never dissociate MRT and age structure

geotop