Multi-tracer groundwater dating for the characterization of a thermal flow system

Case of the Avène-thermal spring water

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Introduction

- Avène, a little village in the north of the Hérault

Introduction - A brief history on Avène Water

1736 Discovery of the curative properties of the **A**vène **T**hermal **S**pring **W**ater

1826 ATSW recommended by eminent dermatologists

1871 ATSW exported to Chicago to treat the victims of the great fire

1874 The medical properties of ATSW are recognized by the French Academy of Medecine: Avène water is declared of public interest

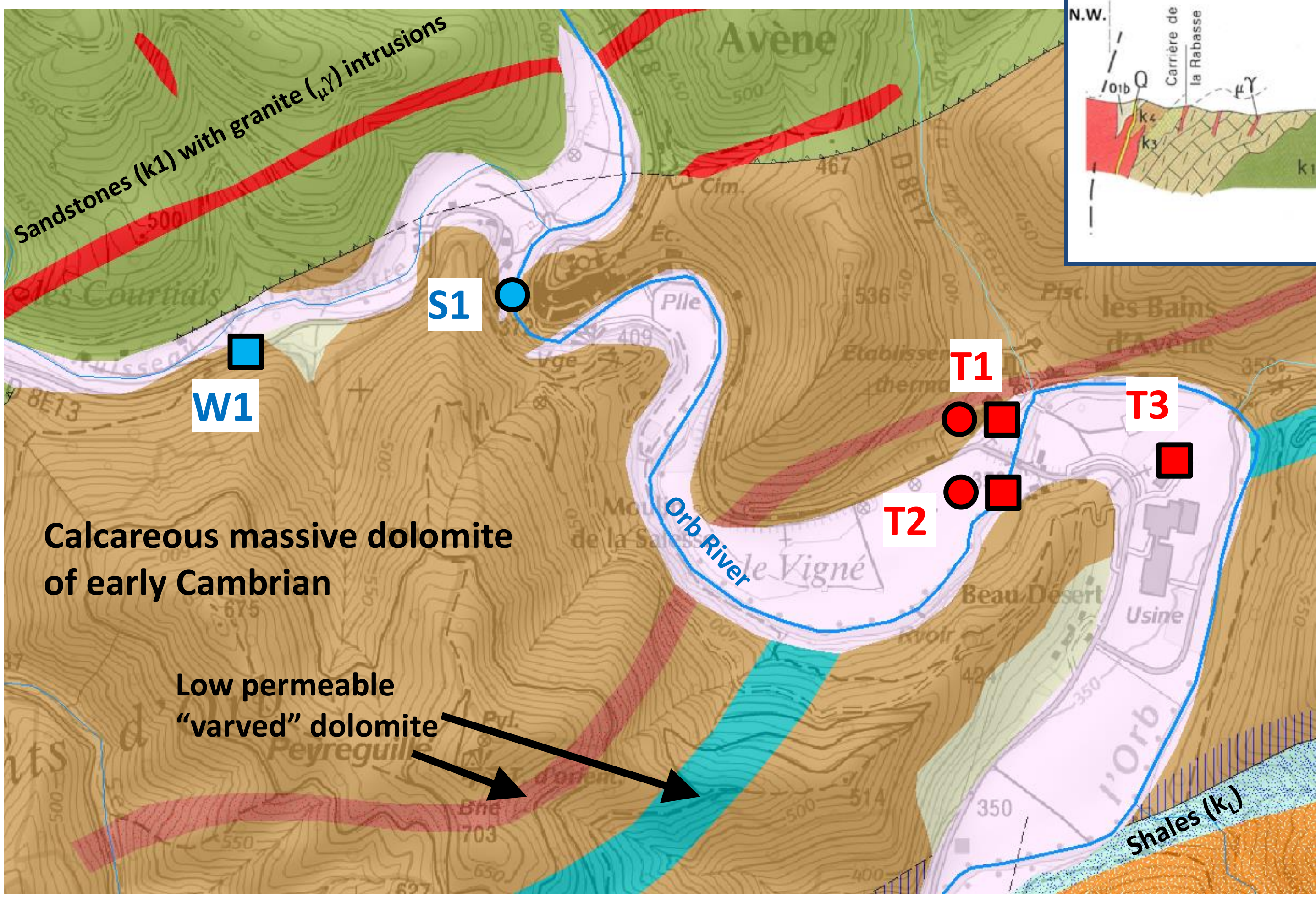
1975 The Pierre Fabre Group takes over the hydrotherapy center at Avène and starts an extensive study program (scientific thermalism) on ATSW

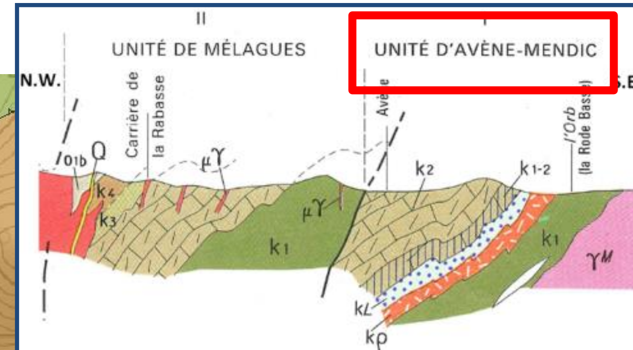
1990 A new hydrotherapy center dedicated to atopic dermatitis and psoriasis; birth of the brand Avène

2008 A water laboratory, guarantor of the water quality

25-29th September 2016
43rd IAH congress

Introduction - Geology





Cold/thermal springs

Cold/thermal wells

1 km

Introduction - Hydrogeology

Two groundwater (GW) types

- Avène thermal water
  - naturally emerges at thermal springs
  - pumped from wells for thermal water production
  - calcic and magnesium bicarbonate water
  - ~25°C and low mineral content
- "Cold" karst water
  - ~11°C (= mean recharge temperature)
  - major ions composition is relatively close to Avene thermal water

Mixing/exchange of water ?
→ Vulnerability to human pressure

Introduction - Context

- Avène Water lab.
  - Check physico-chemical stability of thermal water
  - Conduct hydrogeological studies on the recharge area (historical data from the 80's)

- New scientific questions
  - Residence Time Distribution (RTD) and Mean Residence Time (MRT)
  - Thermal flow transfer and mixing between thermal and "cold" karst end-members

→ Collaboration between PFDC and BRGM

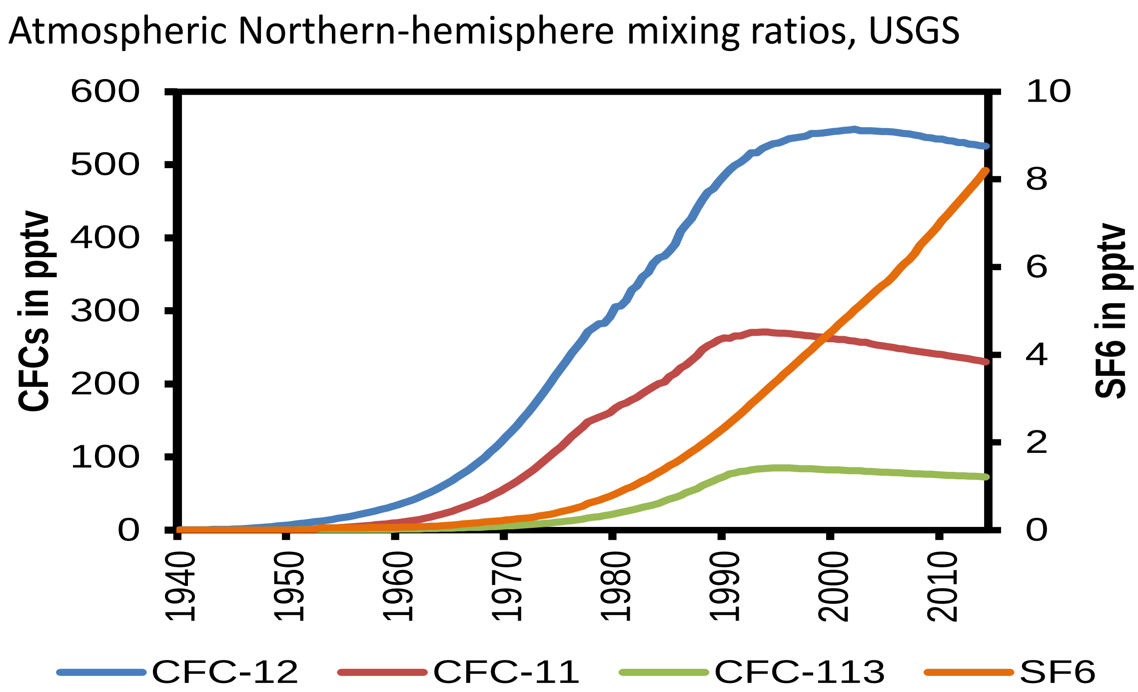
Objectives and methods

- **Multi-tracer GW dating to distinguish « cold » karst transfer from thermal flow system**
  - Long and short time scale: $^{14}A/\delta^{13}C_{DIC}$ and CFCs, SF_6,^{3}H
  - Spatial…
    - Geochemical/age dating end-members
    - Lumped transfer model for the whole flow system
  - … and temporal approaches
    - Historical database (^{3}H) to validate transfer model

- **Validation with other natural tracers**
  - Stable isotopes of water
  - Sr isotopes

Define a conceptual model of thermal flow system that focuses on GW exchanges and transfer

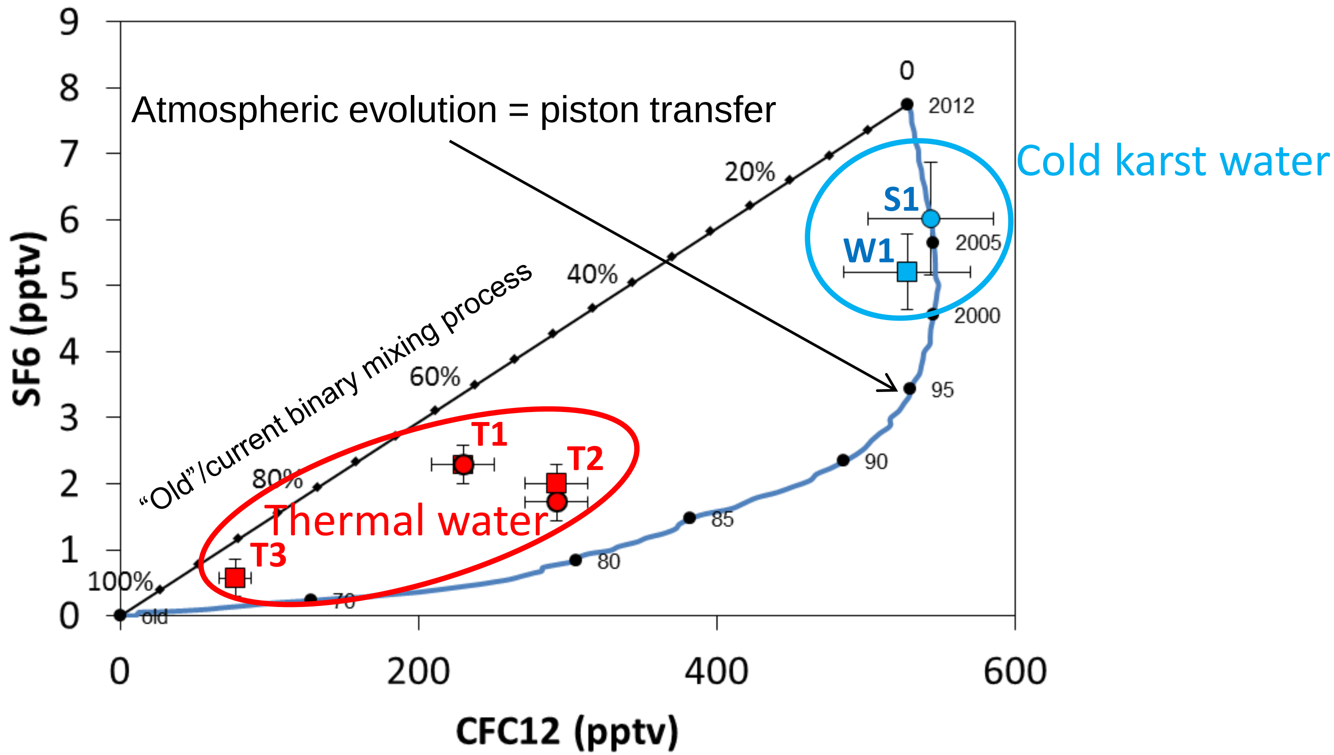
Results – Dissolved gases analyses



- **Atmospheric evolution is known**
- **The value in water at a given time reflects**
  - **Piston transfer: signal is not modified (only a lag)**
  - **each signal is modified at each time step => Exponential Model (EM)**
  - **Binary mixing between 2 flow systems**

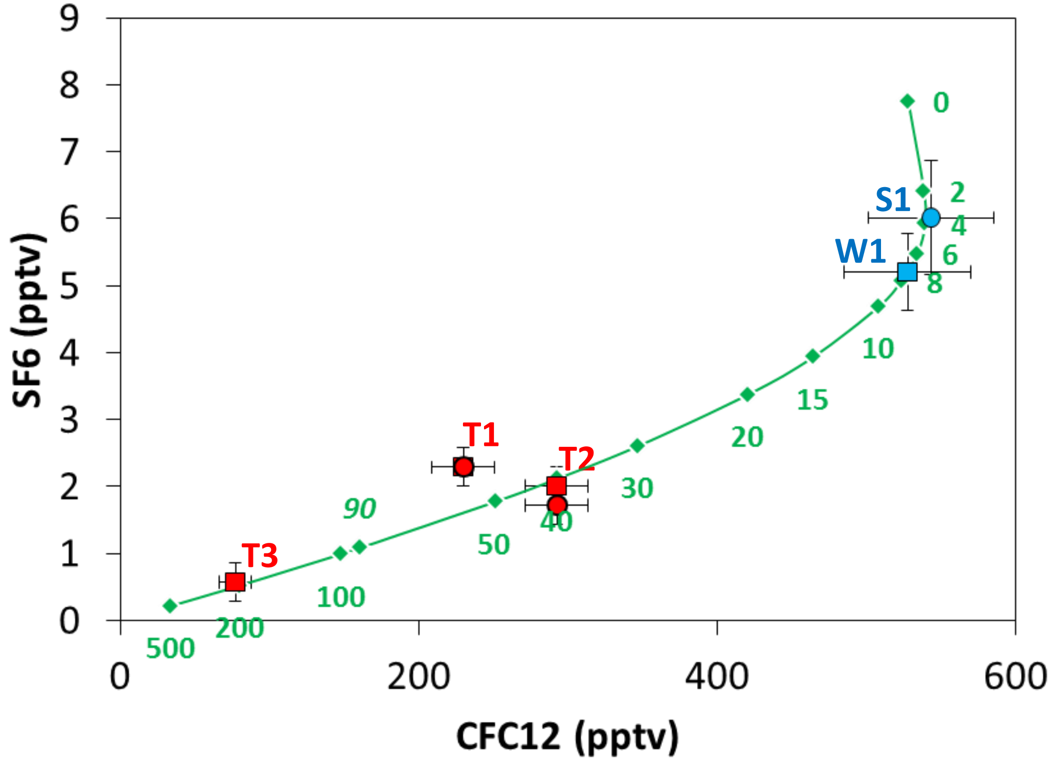
Results – CFC12 vs. SF6 in 2012

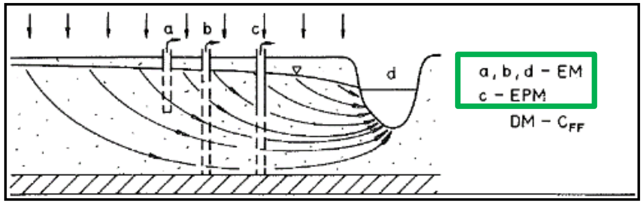
Baseflow conditions after long recession



Neither a simple piston transfer nor a mixing between « old » and current water can explain the values for thermal water

Results – CFC12 vs. SF6 in 2012

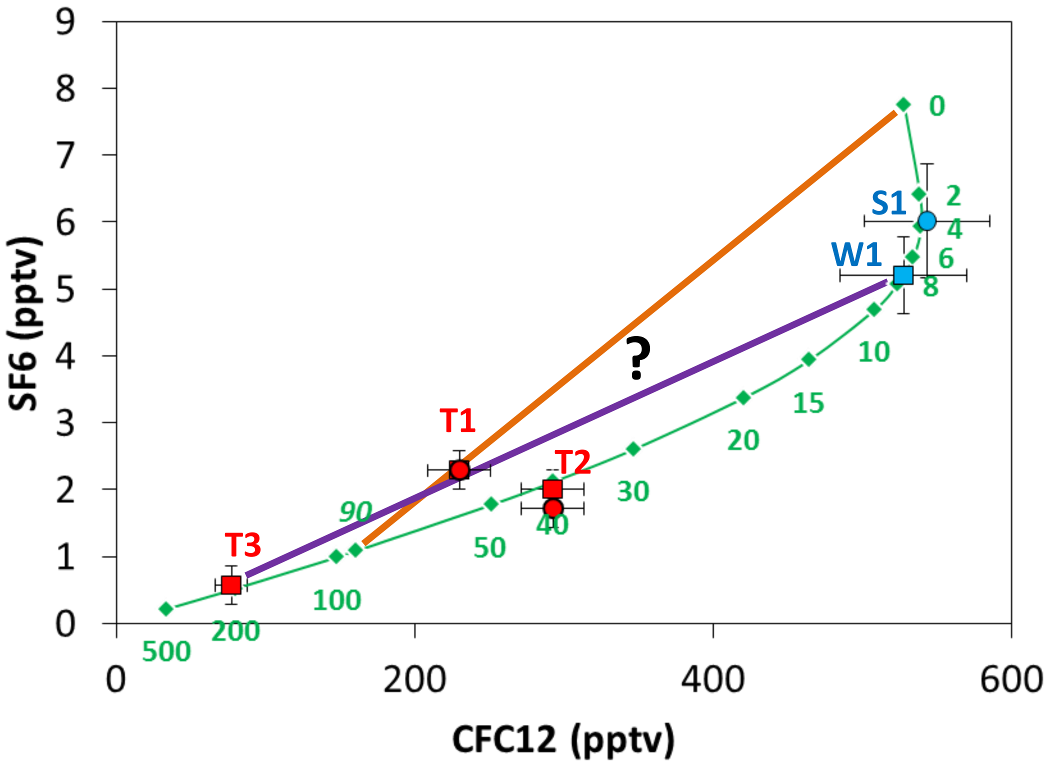


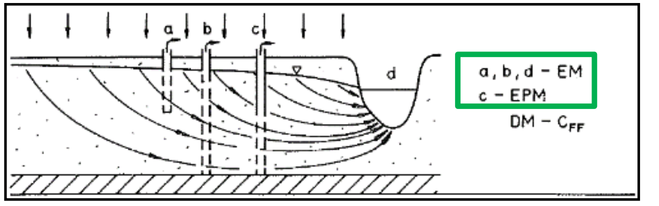


(Maloszweski and Zuber, 1982)

- EM fit most data - consistent for an unconfined aquifer
- Mean Residence Time (MRT) range from 4 to 200 years
- Wells associated to thermal springs (T1 and T2) show the same results
- **T1?**

Results – CFC12 vs. SF6 in 2012

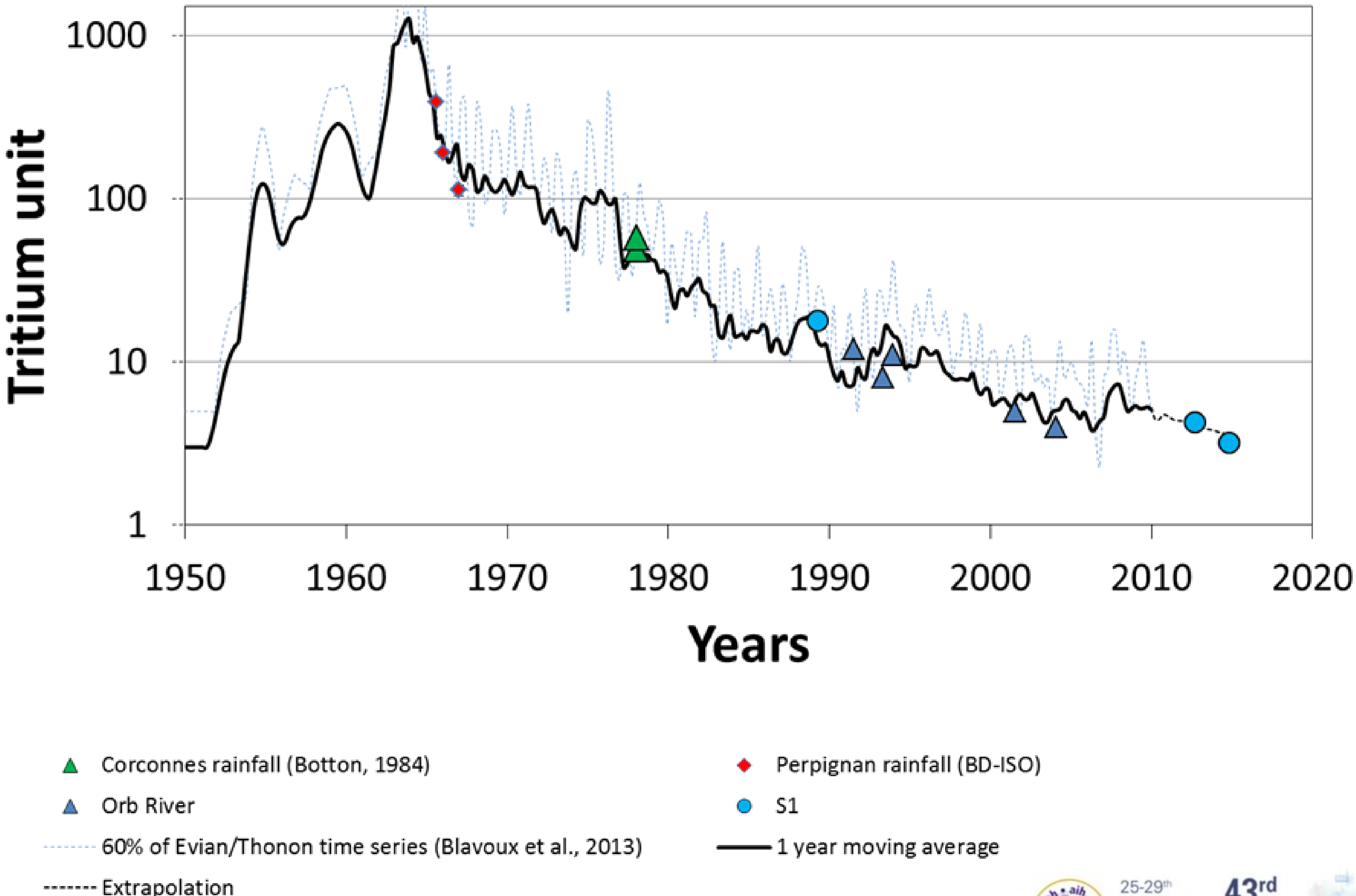




(Maloszweski and Zuber, 1982)

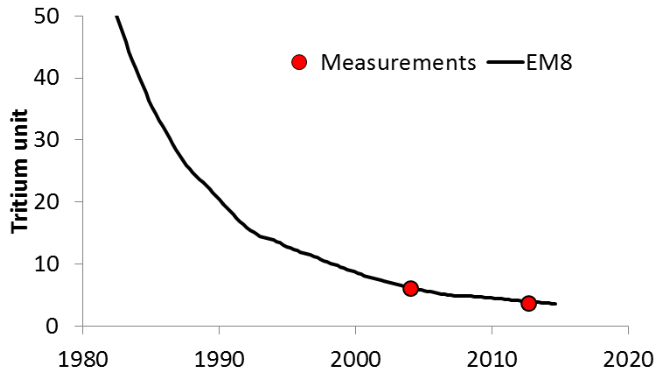
- 2 main assumptions of binary mixing (dilution)
  - **Thermal water of relatively low residence time (EM90) with 20% current water**
  - **Thermal water (EM200, T3 type) with 35% “cold” karst water (EM8, W1 type)**

Use of ^3H – Input function

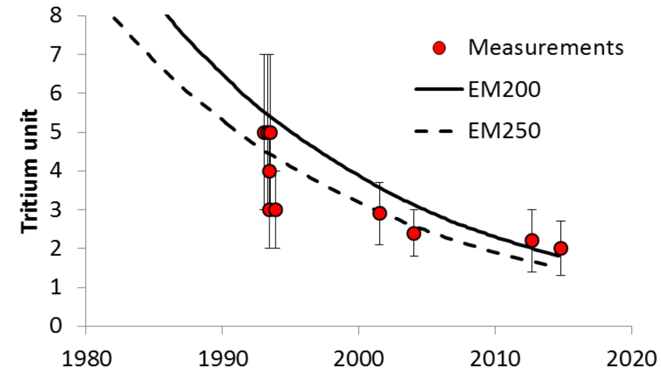


Use of 3H – Results

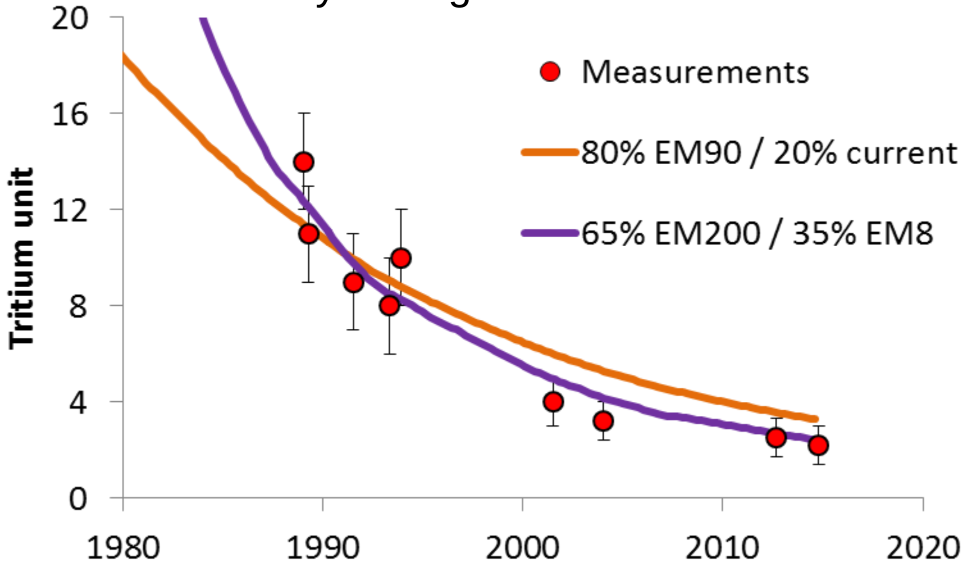
W1 : « Cold » karst end member



T3 : Thermal end member



T1 : 2 binary mixing scenarios



- EM models are validated through time with ^3H data
  - Cold karst end-member ⬄ EM8
  - Thermal end-member ⬄ EM~200
- The two mixing assumptions are consistent with ^3H data.

Comparison with other natural tracers

- **Objectives**
  - Can T1 water be explained by a binary mixing between thermal and « cold » karst water types?
  - Does-it give the same relative contributions?

- **Methods**
  - Stable isotopes of water (^{2}H vs. ^{18}O)
  - Sr isotopic ratios ($^{87}Sr/^{86}Sr$ vs. $1/Sr$)

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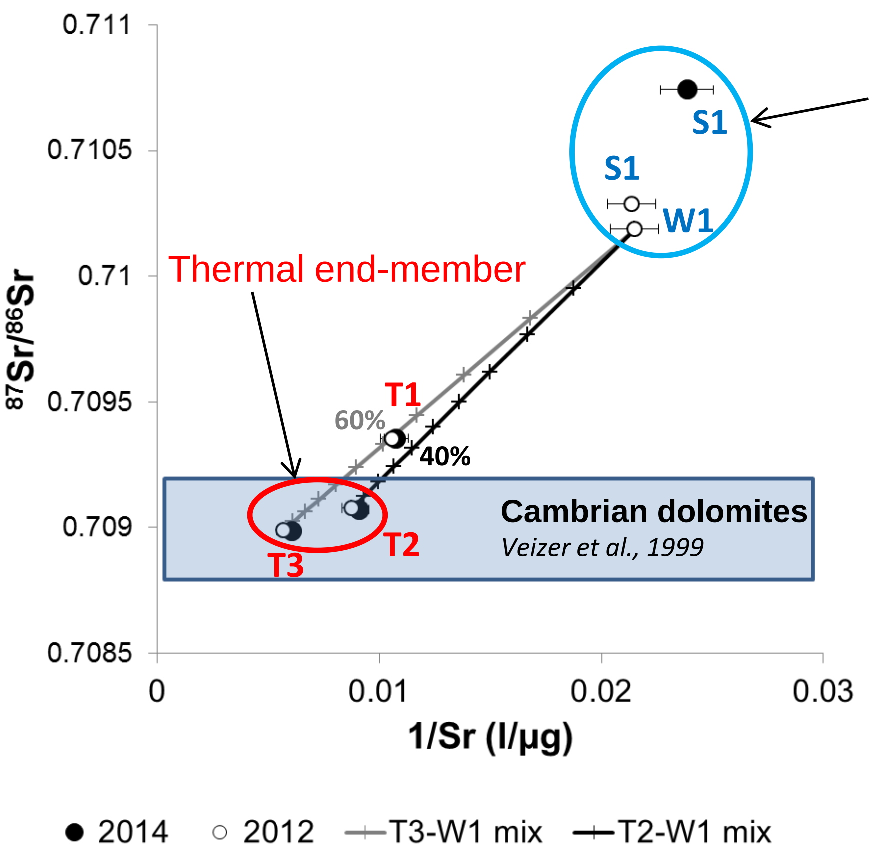
Strontium isotopes - Results



« Cold » karst end-member
Very high isotopic ratios not consistent with water/rocks interactions with Cambrian dolomites
⇨ radiogenic influence (allogenic recharge from siliclastic and metamorphism rocks)

- T1 water is a binary mixing between:
  - Thermal water in equilibrium with Cambrian dolomites (0.7090±0.0002)
  - «Cold» and radiogenic karst water (dilution)

- % dilution
  - Highly sensitive to the choice of the thermal end-member
  - Consistent with age dating results when using T2

Conclusion

- A large scale flow system
  - A local flow system through a shallow karst aquifer

    « Short » MRT (<10y) for the « cold » karst systems
  - A regional flow system with deep circulation

    Relatively old thermal water (~200-300 years of MRT with EM)

    Compartmentalization due to low permeable “varved” dolomites sequences

- Thermal flow transfers and GW exchanges
  - Thermal water from T2 and T3 show various degree of evolution along thermal flowpaths within Cambrian dolomites
  - T1 is a mixing of 30 to 40% of karst GW with thermal water
  - Water abstraction from wells (T2 or T3) prevent from diluting thermal water

Perspectives – Targeted new acquisition

- Can we monitor the karst contribution at T1 spring?

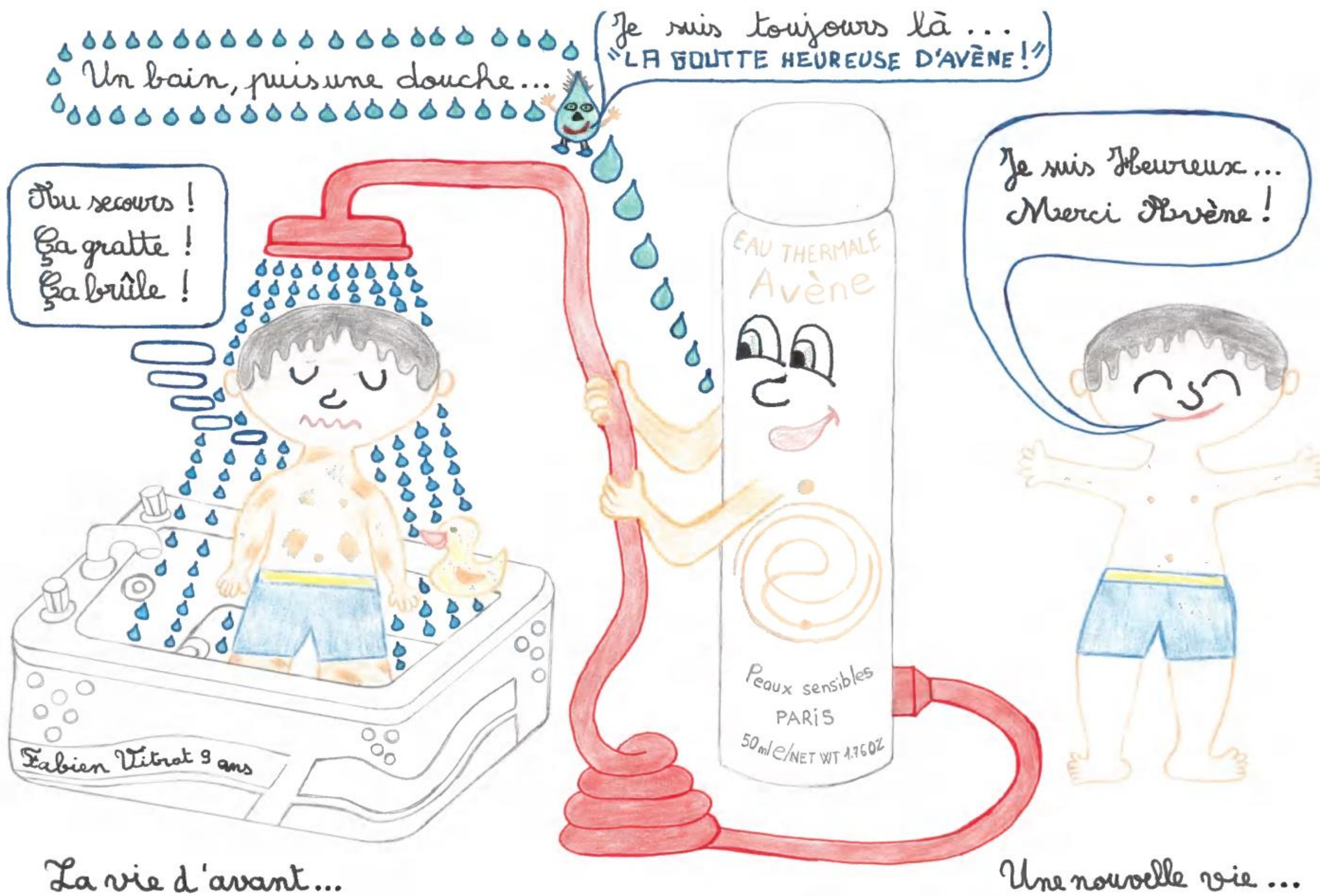
  ⇨ New monitoring focusing on fast infiltration (if any):

    - High frequency monitoring to detect natural fluorescence of organic compounds
    - 3D fluorescence sampling after recharge events
    - Water-level and discharge to understand hydrodynamic interaction

➡ Improve our knowledge to better protect the resource

Thank you for your attention

- Any questions?

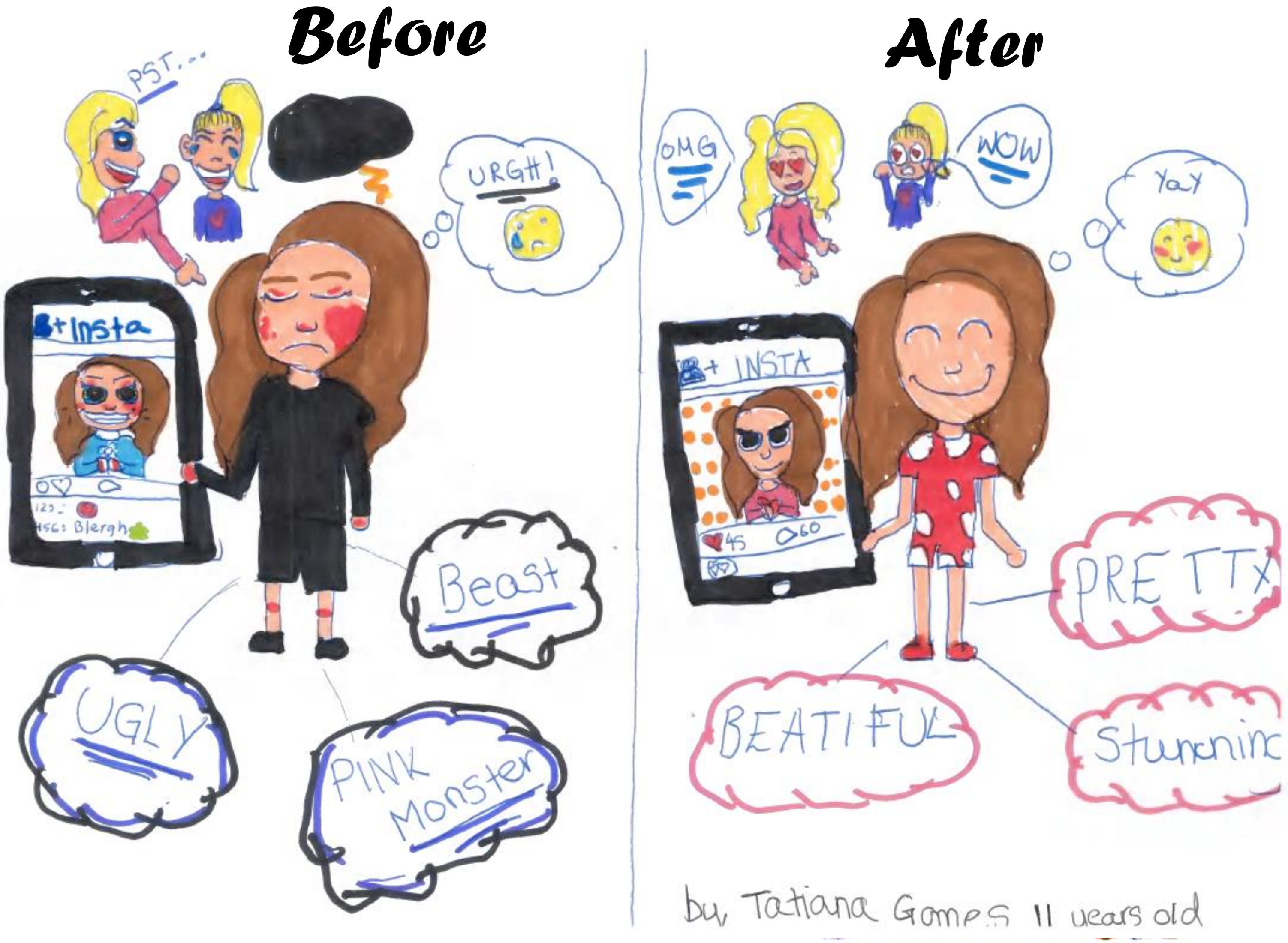


Before **After**

25-29th September 2016
Montpellier, France
CORUM CONFERENCE CENTER
43rd IAH congress

Thank you for your attention

- Any questions?



Results – C isotopes

- ^{14}A in pCM (%)

Site	^{14}A (%) in 1993	^{14}A (%) in 2012	Change in conventional Radiocarbon Age (years)
T1	55.7	60.93 +/- 0.21	- 860
T3	50.6	58.11 +/- 0.21	- 1270

- – Uncorrected age shows a decrease of ~1000 years from 1993 to 2012.
- – Calculated initial activities are lower than the measured values.

⇨ 'Atom Bomb' effect that increased pMC, but the input function is unknown…

➡ Age dating is impossible with C isotopes
A non negligible part of the thermal water is relatively recent

Strontium isotopes

- $^{87}Sr/^{86}Sr$ vs. 1/Sr gives a straight line for a binary mixing (Faure 1986)

- 2 end-members
  1. « Cold » karst end-member

     Karst water from a well to lower seasonal effects and filter fast infiltration

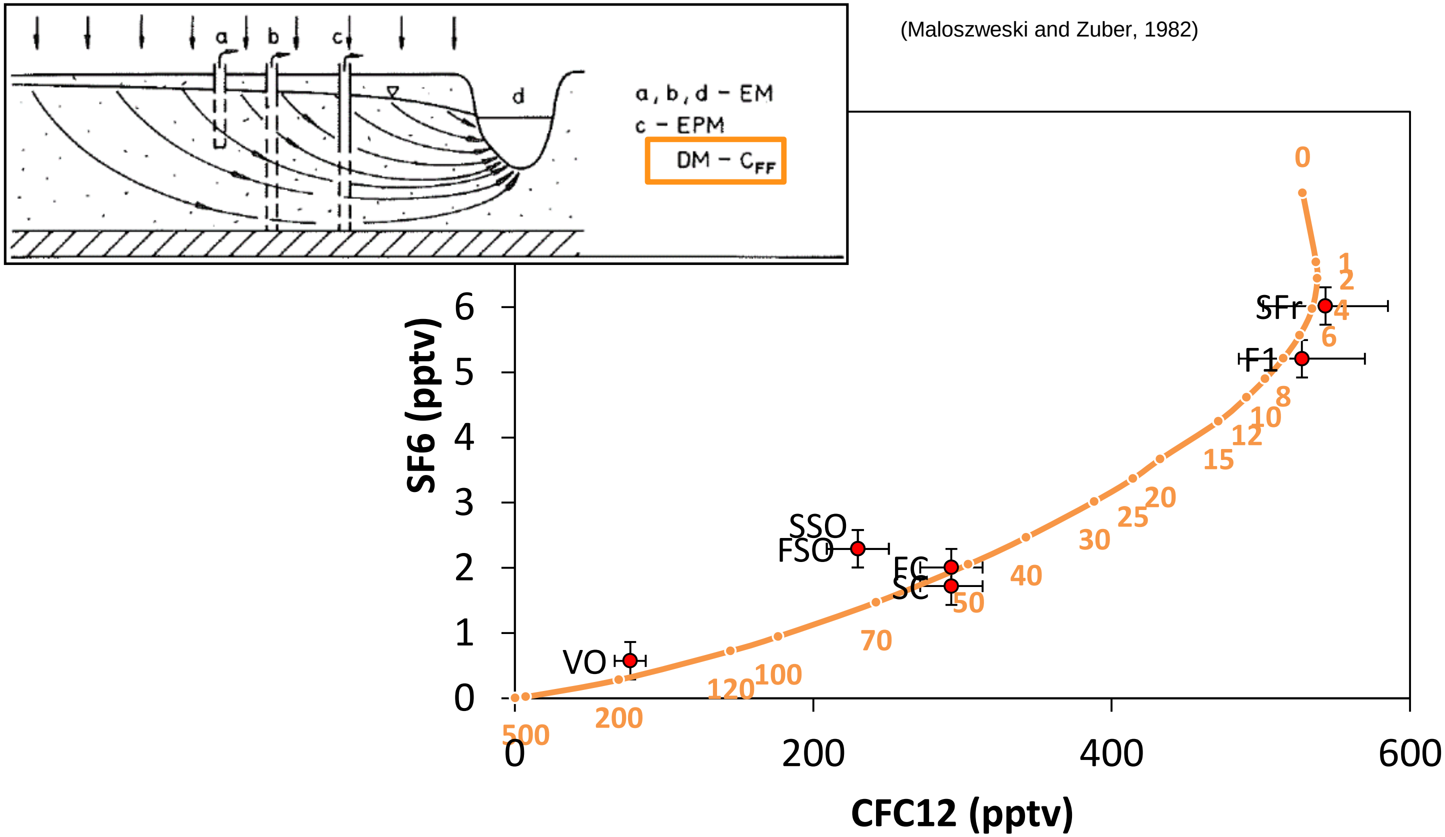
     ➔ W1
  2. Thermal end-member

     Thermal water in equilibrium with Cambrian dolomites without mixing with "cold" karst

     ➔ T2 or T3

Results – CFC12 vs. SF6 in 2012

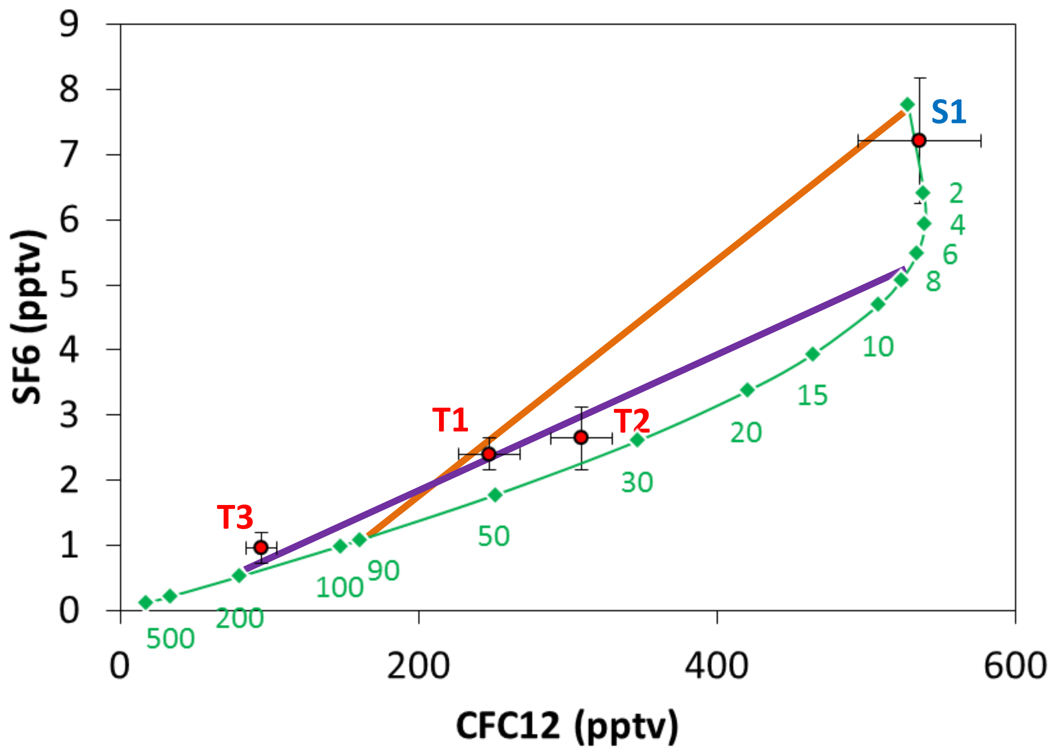
(Maloszweski and Zuber, 1982)



- The best DM model is not better (Pe=1)
- Mean Residence Time (MRT) are slightly higher for Cresson
- FSO well and SSO spring are still unexplained

New sampling campaign (2014)

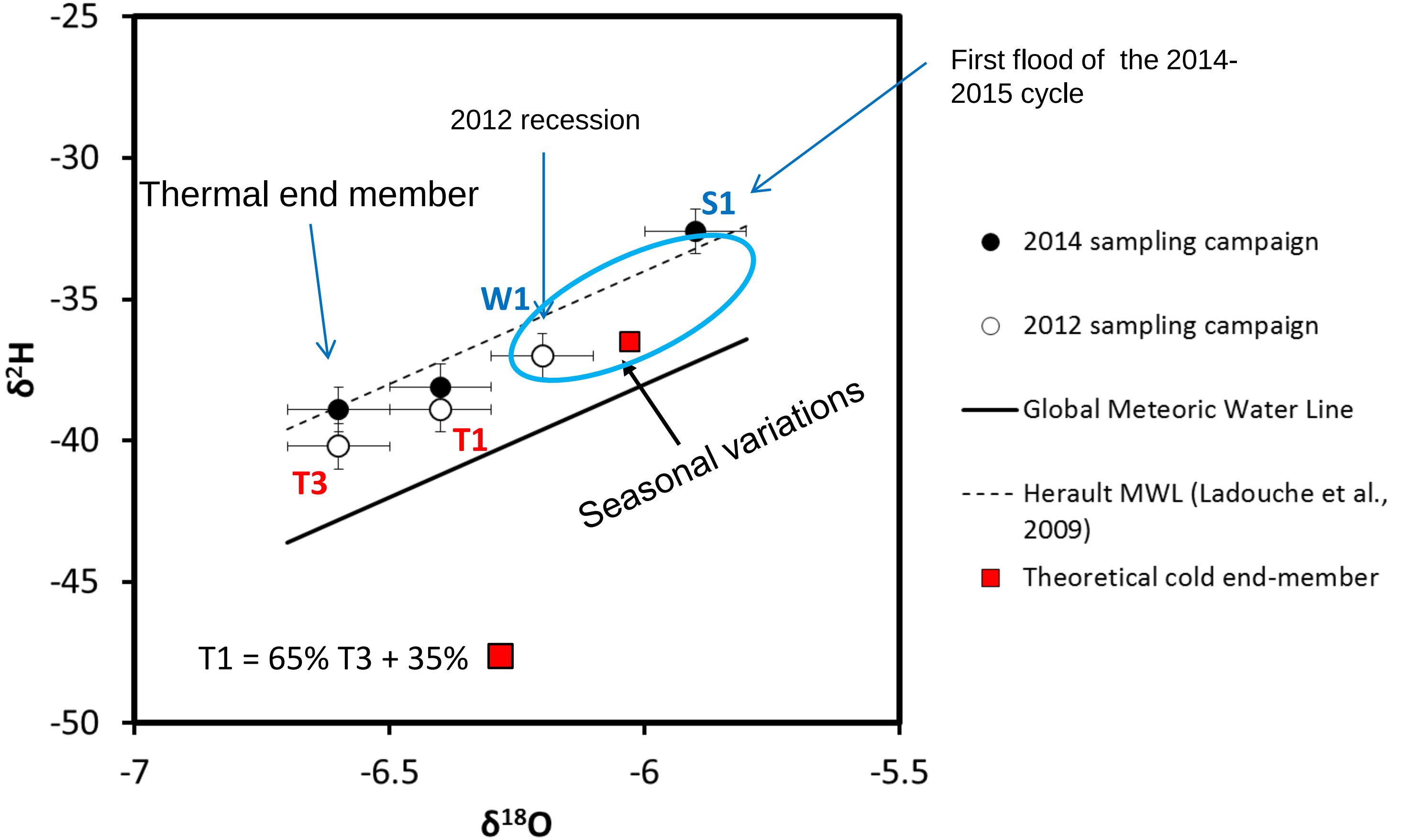
<u>Medium flow</u> conditions following the first flood event



> <u>T2, T3 and S1</u>:
- Relatively more SF_6, but it is not significant without knowing EA
- A large scale EM model is still valid. Ages are lowered, especially for SFr.

> <u>T1</u>:
- The 2 main assumptions about mixing are still valid, with the same ratios

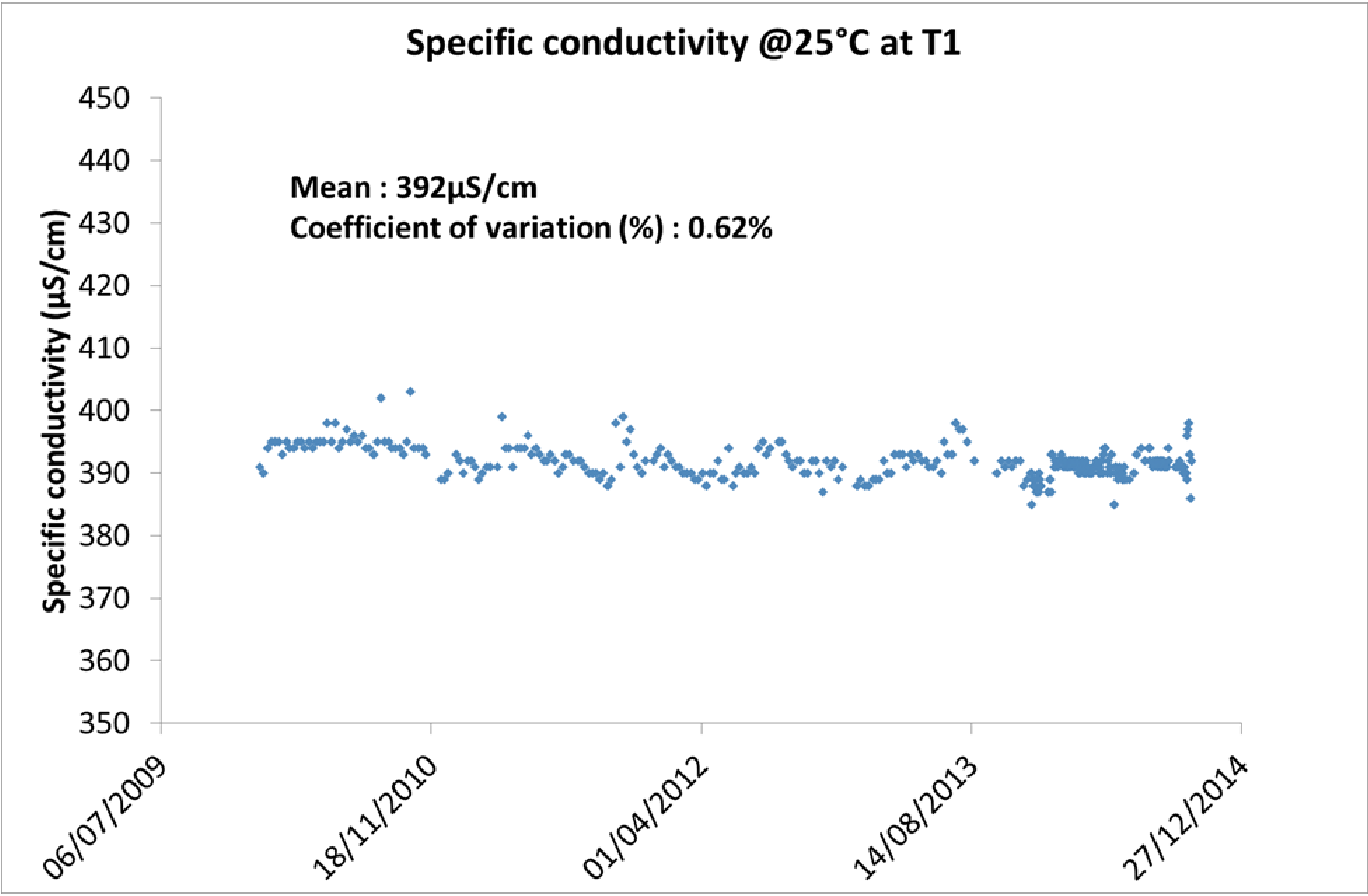
Stable isotopes of water



Results – Dissolved gases analyses

- **Gas dissolution**
  - T°C: ~ mean temp. (vadose zone>10m) = 11°C
  - Pressure
    - Excess air is unknown… but should be low (<3cc/mL) because of low groundwater level changes in response to recharge events (few meters)
    - Recharge altitude around 600 masl

- **Graphical analysis**
  - The value in water at a given time reflects
    - air/water equilibrium at recharge date: **Piston transfer**
    - transfer of air/water equilibrium signal to the spring
      - Exponential Model (**EM**)
      - 1D Advective/Dispersive model (**DM**)
      - …
    - Binary mixing between 2 flow systems


Specific conductivity @25°C at T1
Mean : 392µS/cm
Coefficient of variation (%) : 0.62%
Specific conductivity (µS/cm)
450
440
430
420
410
400
390
380
370
360
350
06/07/2009
18/11/2010
01/04/2012
14/08/2013
27/12/2014