GEO 200

I 200 anni dell'utilizzo industriale del sito di Larderello: una geotermia sostenibile – Pisa 7-8.05.2018

CO_2 and heat fluxes in the Apennines, Italy

RELATORE: Giovanni Chiodini – INGV, Bologna

La presentazione riporta i risultati di molti ricercatori che collaborano alle tematiche dei flussi terrestri di CO_2 e della geotermia, fra questi:
Giovanni Chiodni (INGV, BO), Rosario Avino (INGV, Na), Giulio Beddini (UniPg), Stefano Caliro (INGV, Na), Carlo Cardellini (UniPg), Giovanni Chiodini (INGV, Bo), Marco Donnini (CNR-IRPI), Angelo Rosiello (UniPg), Dmitri Rouwet (INGV, Bo), Giancarlo Tamburello (INGV, Bo).

CO_2 and heat fluxes in the Apennines, Italy

Chiodini, 2018

CO_2 emission and heat flow were investigated during 1990's to attempt a global estimation of the CO_2 degassing from high heat flow regions of the Earth.

ELSEVIER

Chemical Geology 121 (1995) 285–293

CHEMICAL GEOLOGY
INCLUDING
ISOTOPE GEOSCIENCE

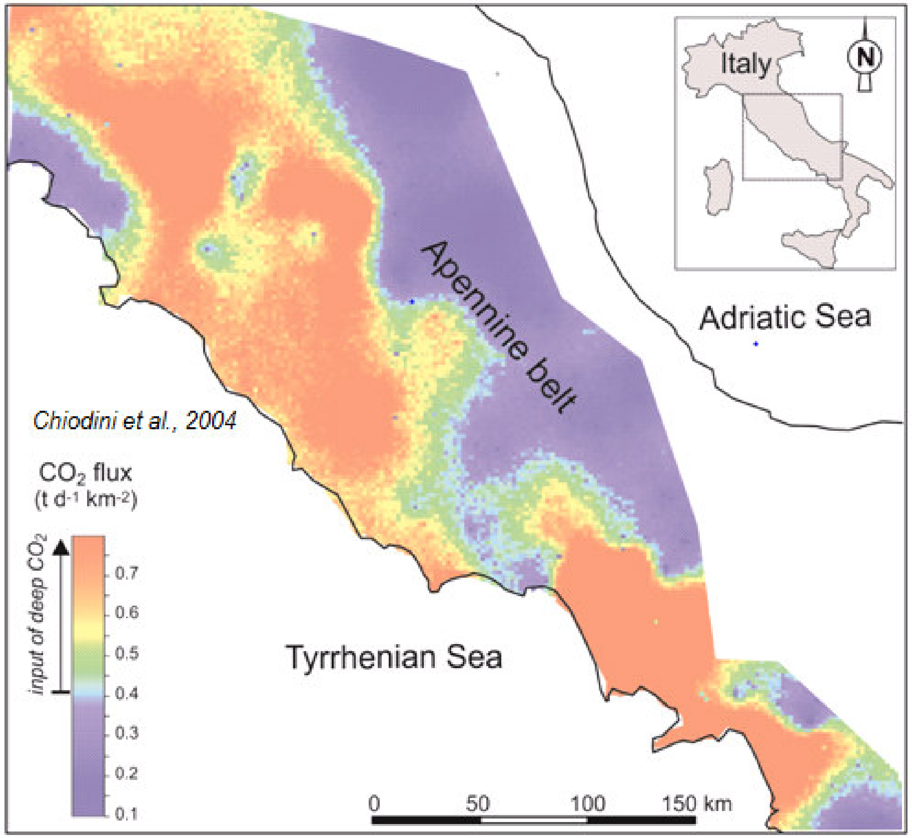
Convective hydrothermal CO_2 emission from high heat flow regions

Derrill M. Kerrick[a], Michael A. McKibben[b], Terry M. Seward[c], Ken Caldeira[d]

CO_2 and heat fluxes in the Apennines, Italy

Chiodini, 2018

CO_2 emission and heat flow were investigated during 1990's to attempt a global estimation of the CO_2 degassing from high heat flow regions of the Earth.
Some years later, at the beginning of 2000's, we published this map of the CO_2 emission from central Italy.



Outline

1) Map of CO_2 Earth degassing in Italy
2) Origin of the gas
3) CO_2 and heat fluxes

1. Map of CO_2 Earth degassing in Italy

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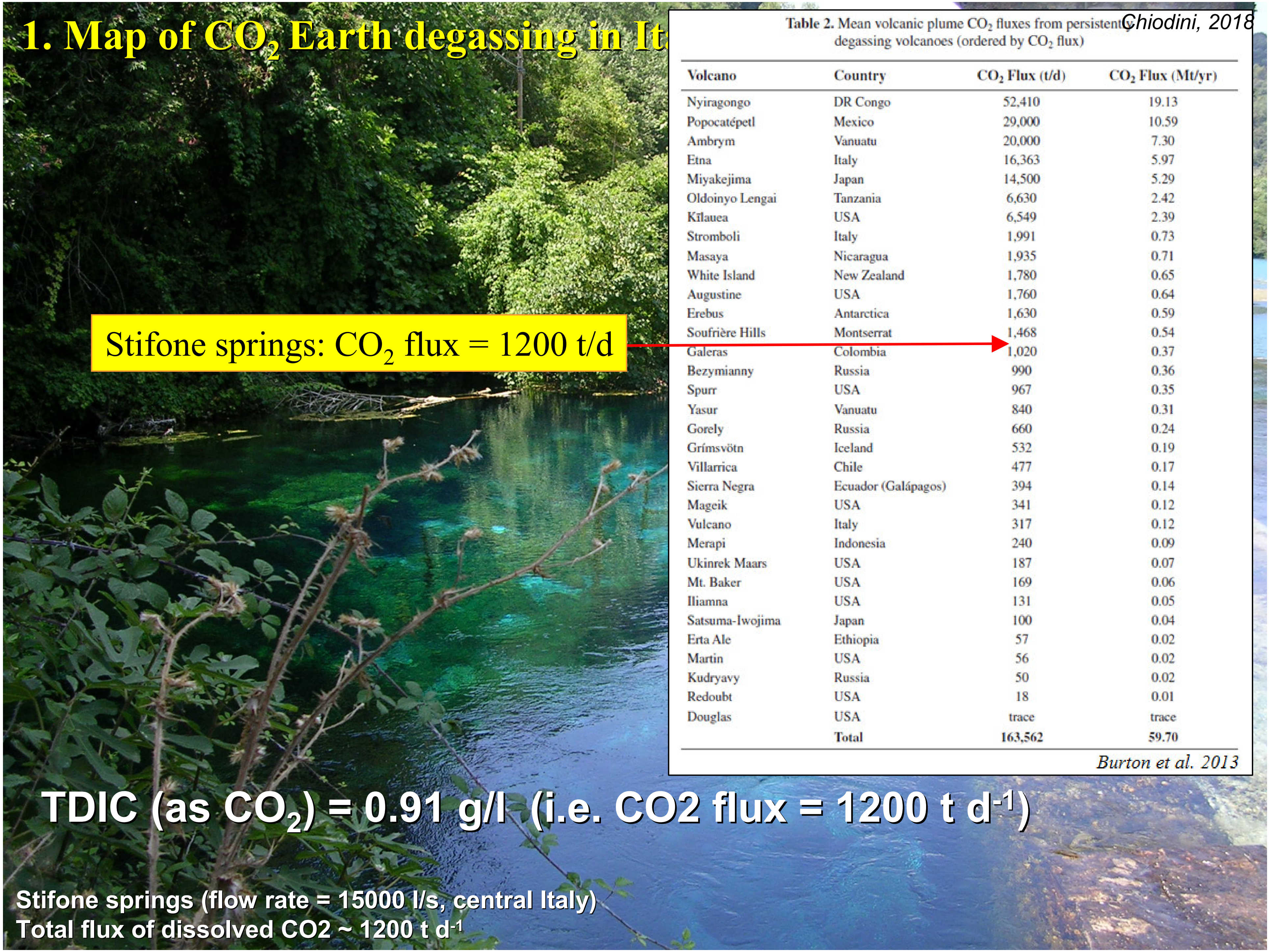


Chiodini, 2018

Stifone springs: CO_2 flux = 1200 t/d

Table 2. Mean volcanic plume CO_2 fluxes from persistently degassing volcanoes (ordered by CO_2 flux)

Volcano	Country	CO_2 Flux (t/d)	CO_2 Flux (Mt/yr)
Nyiragongo	DR Congo	52,410	19.13
Popocatépetl	Mexico	29,000	10.59
Ambrym	Vanuatu	20,000	7.30
Etna	Italy	16,363	5.97
Miyakejima	Japan	14,500	5.29
Oldoinyo Lengai	Tanzania	6,630	2.42
Kīlauea	USA	6,549	2.39
Stromboli	Italy	1,991	0.73
Masaya	Nicaragua	1,935	0.71
White Island	New Zealand	1,780	0.65
Augustine	USA	1,760	0.64
Erebus	Antarctica	1,630	0.59
Soufrière Hills	Montserrat	1,468	0.54
Galeras	Colombia	1,020	0.37
Bezymianny	Russia	990	0.36
Spurr	USA	967	0.35
Yasur	Vanuatu	840	0.31
Gorely	Russia	660	0.24
Grímsvötn	Iceland	532	0.19
Villarrica	Chile	477	0.17
Sierra Negra	Ecuador (Galápagos)	394	0.14
Mageik	USA	341	0.12
Vulcano	Italy	317	0.12
Merapi	Indonesia	240	0.09
Ukinrek Maars	USA	187	0.07
Mt. Baker	USA	169	0.06
Iliamna	USA	131	0.05
Satsuma-Iwojima	Japan	100	0.04
Erta Ale	Ethiopia	57	0.02
Martin	USA	56	0.02
Kudryavy	Russia	50	0.02
Redoubt	USA	18	0.01
Douglas	USA	trace	trace
	Total	**163,562**	**59.70**

Burton et al. 2013

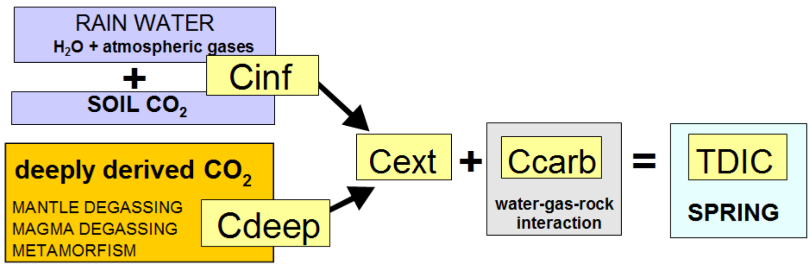
TDIC (as CO_2) = 0.91 g/l (i.e. CO2 flux = 1200 t d^{-1})

Stifone springs (flow rate = 15000 l/s, central Italy)
Total flux of dissolved CO2 ~ 1200 t d^{-1}

1. Map of CO_2 Earth degassing in Italy

Chiodini, 2018

Carbon mass balance of aquifers



This mass balance can be solved using:

- **the carbon isotopic composition of the total dissolved inorganic carbon** (TDIC)
- hydrogeochemical **modeling of water-gas-rock interaction**

(Chiodini et al., 1999, 2000, 2004, 2009; Karlstrom et al., 2013; etc.)

Carbon mass balance of Stifone springs

Organic source (infiltration)		Deep source		Carbonate dissolution		
C_{inf} **190 t d^{-1}**	+	C_{deep} **640 t d^{-1}**	+	C_{carb} **370 t d^{-1}**	=	TDIC **1200 t d^{-1}**

- $q = 1.3 \times 10^9$ l d^{-1}
- C_{deep} = 0.011 mol l^{-1} = 0.49 g l^{-1} (expressed as CO_2)
- Deeply derived CO_2 (C_{deep} x q) = 640 t d^{-1}
- A (area of the hydrogeological basin) = 740 km^2
- **Flux of deep CO_2 = 640 / 740 = 0.86 t km^{-2} d^{-1}**

Each spring can be used as a measuring point of the average flux of deep CO_2 affecting large areas, typically from tens to hundreds km^2 in the Apennines

Stifone springs (flow rate = 15000 l/s, central Italy)
Flux of deeply derived CO2 dissolved in the water ~ 638 t d^{-1}

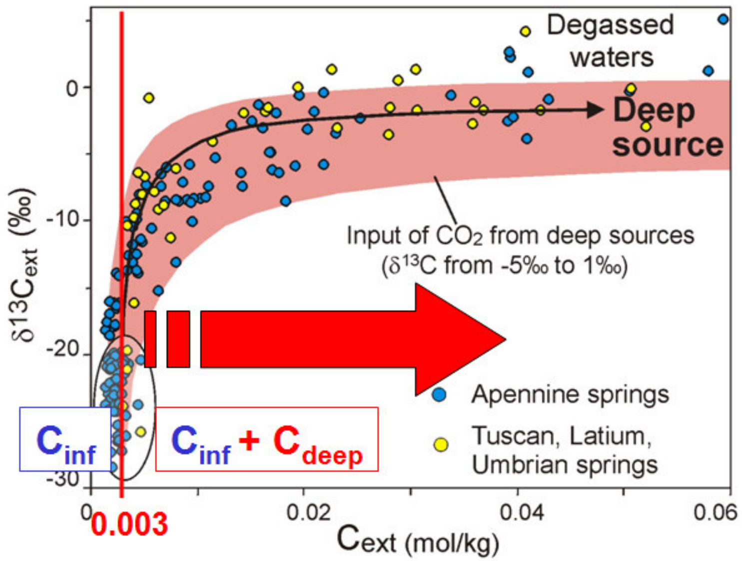
1. Map of CO_2 Earth degassing in Italy

Chiodini, 2018

Data set – Carbonate aquifers

	n°	Q (l/s)	Q_{mean}
Apennines	154	231000	1500
Toscana-Umbria-Lazio	52	15600	300

The sampled springs represents the 61% of the total flow rate discharged by Apennine aquifers.



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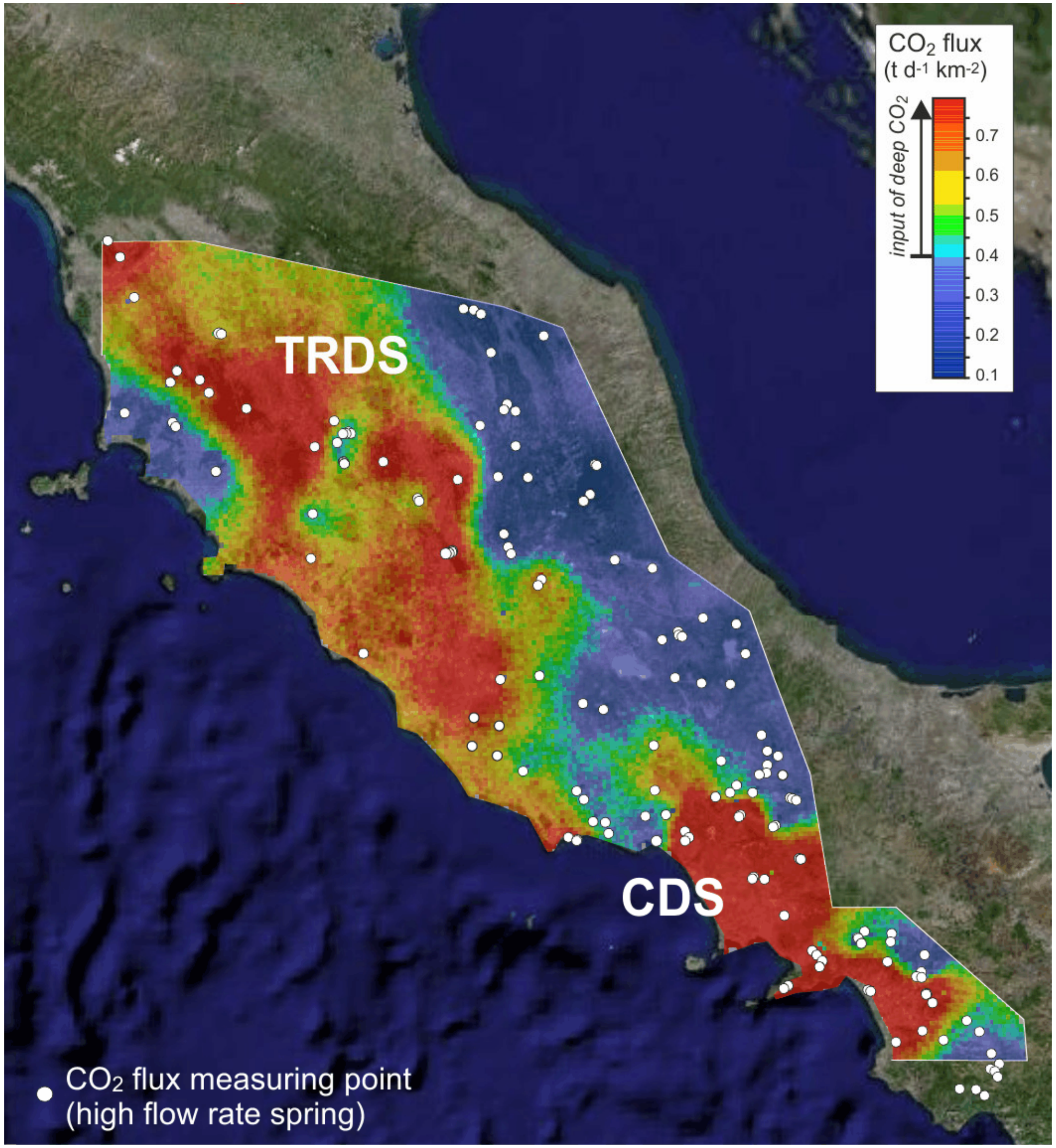
1. Map of CO_2 Earth degassing in Italy

Chiodini, 2018



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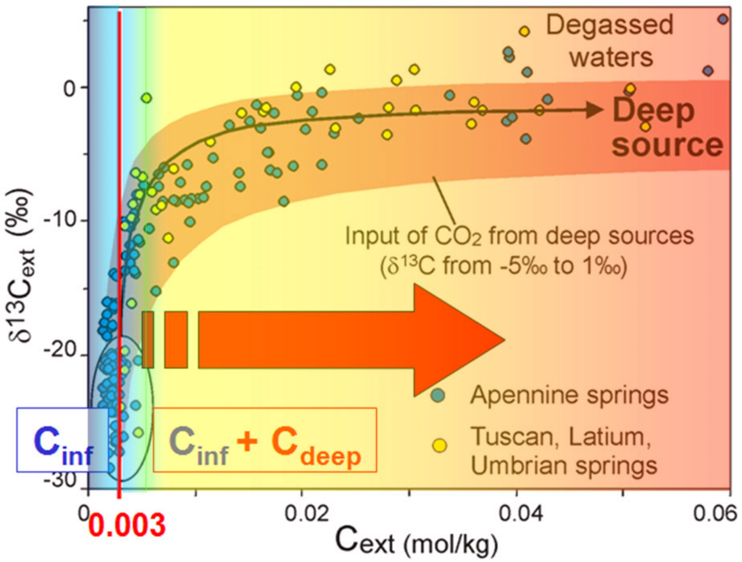

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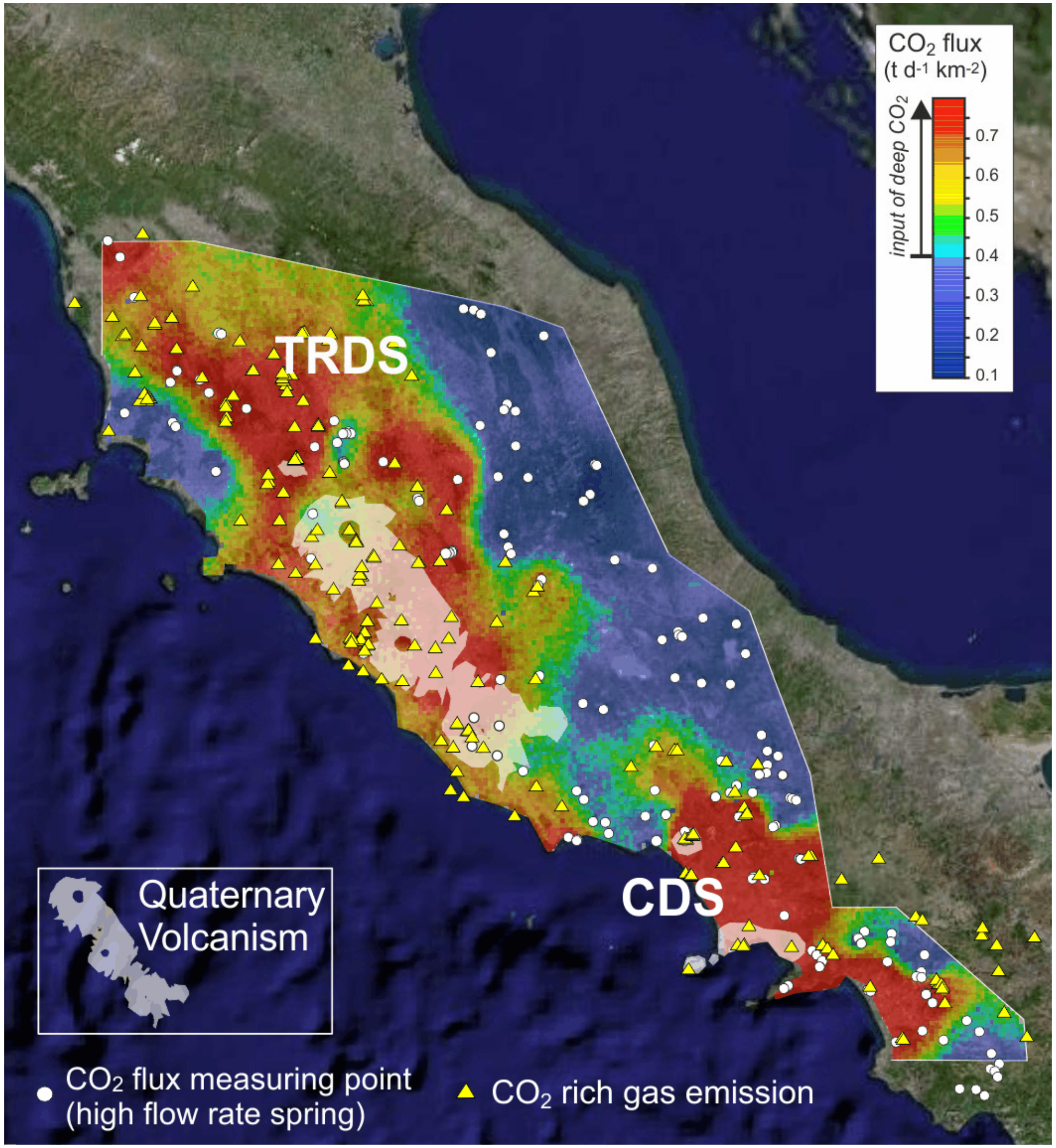
1. Map of CO_2 Earth degassing in Italy

Chiodini, 2018



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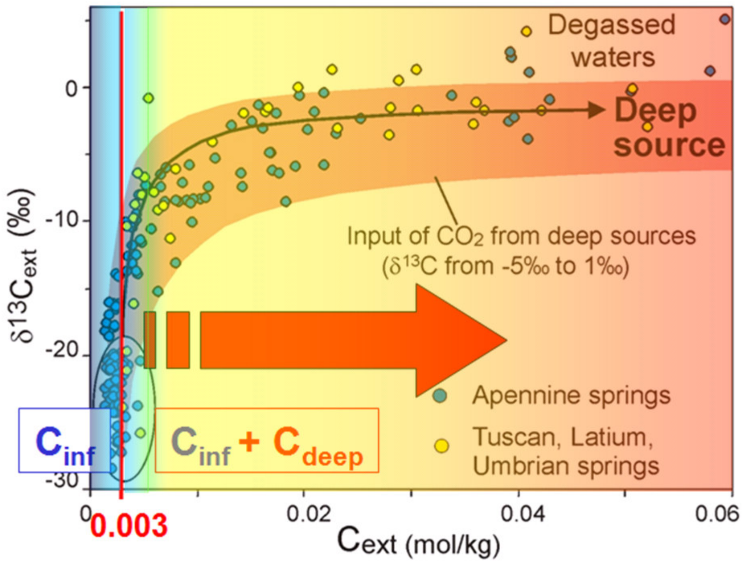
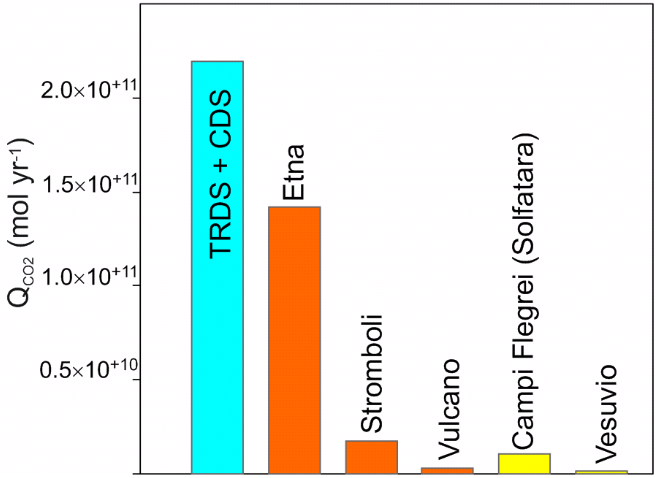


Each spring can be used as a measuring point of the average flux of deep CO_2 affecting large areas, typically from tens to hundreds km^2 in the Apennines

1. Map of CO_2 Earth degassing in Italy

Chiodini, 2018

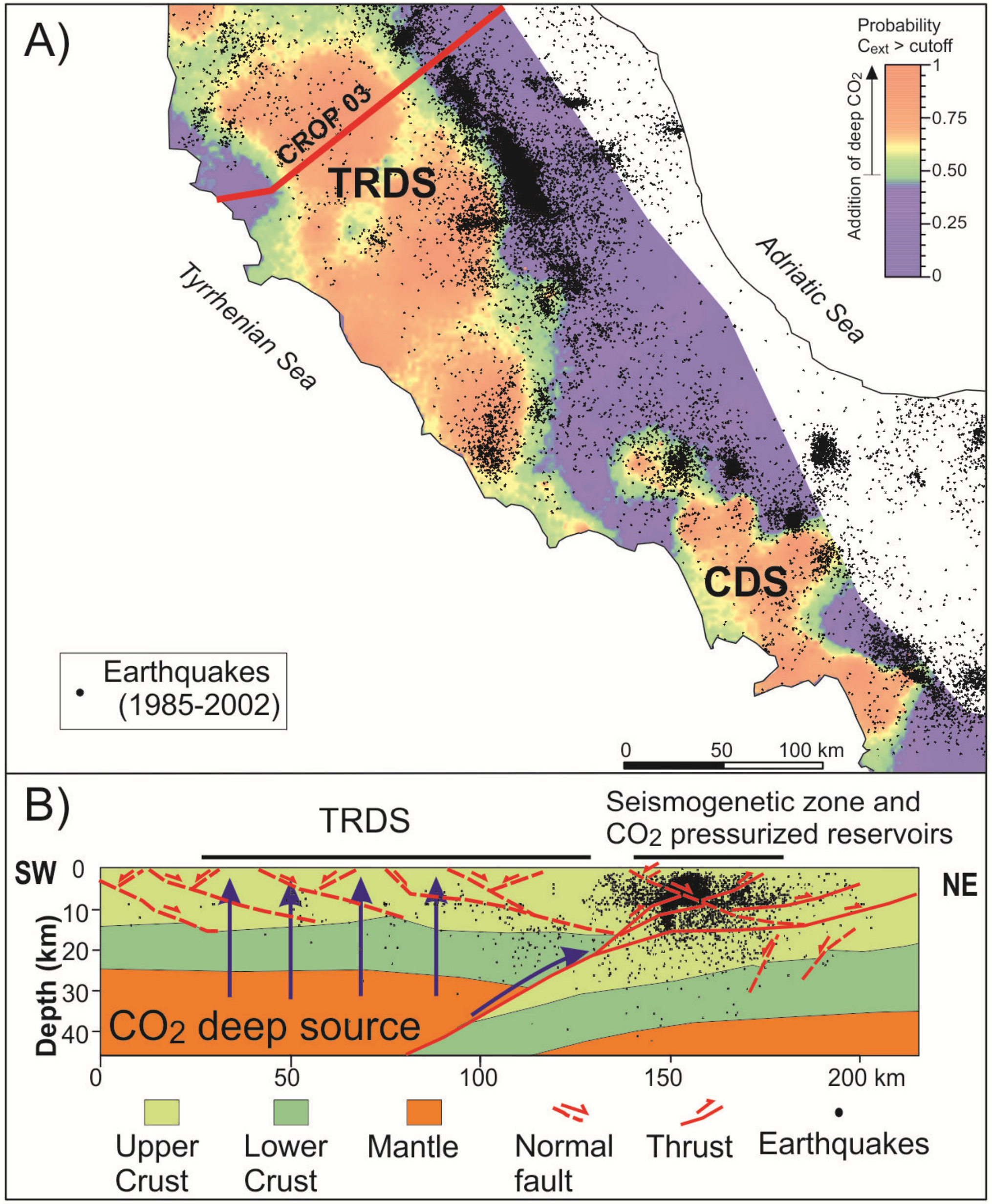
CO_2 flux ~ 10 Mt/yr



The amount of CO_2 released by TRDS and CDS is larger than the amount released by the active volcanoes of Italy

Earth degassing and seismicity

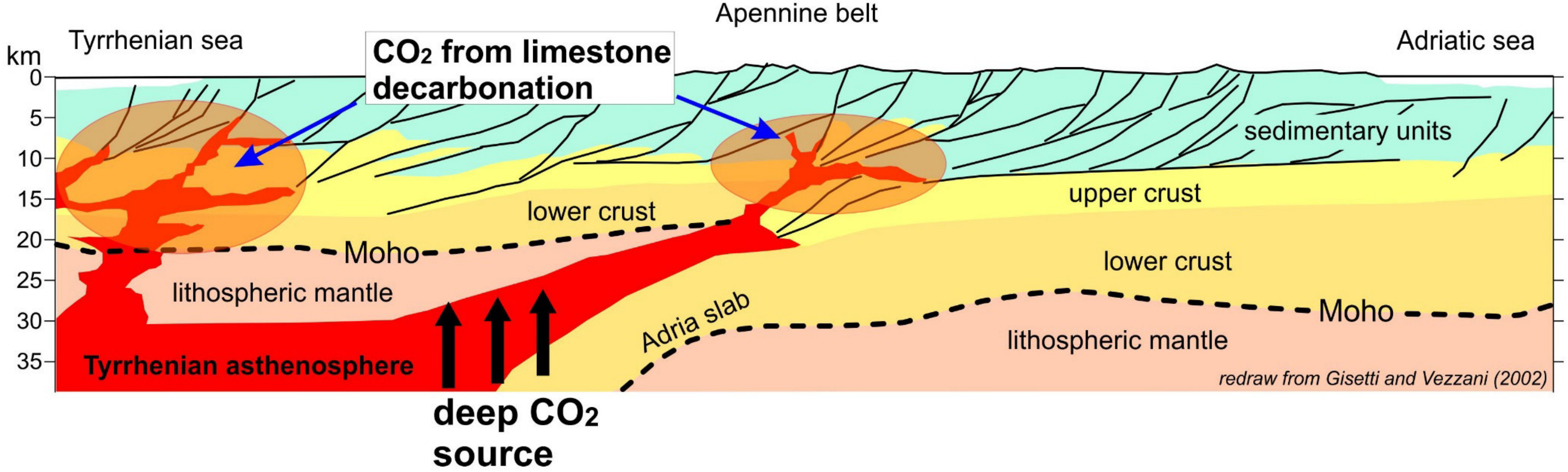
- *The anomalous flux of CO_2 suddenly disappears in the Apennine in correspondence with a narrow band where most of the seismicity concentrates.*
- *Here, at depth, the gas accumulates in crustal traps originating overpressurised reservoirs that favour seismicity*

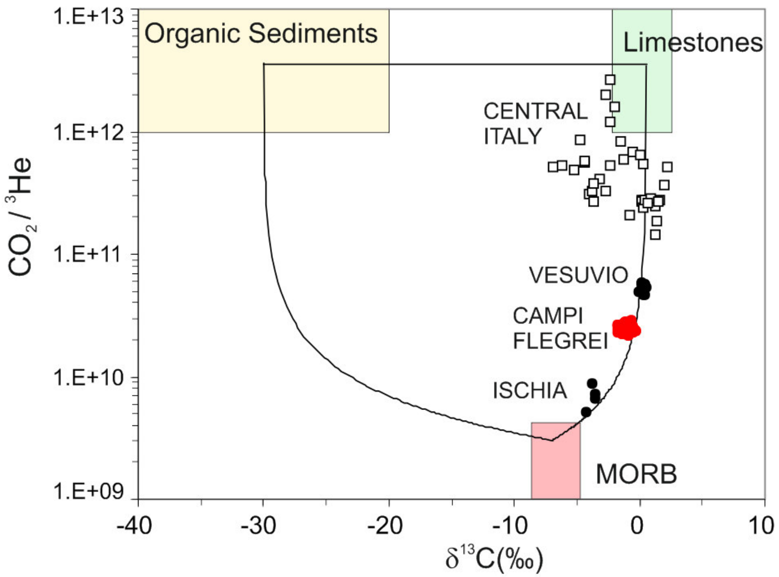


Chiodini et al., 2004

2. Origin of the gas

Chiodini, 2018

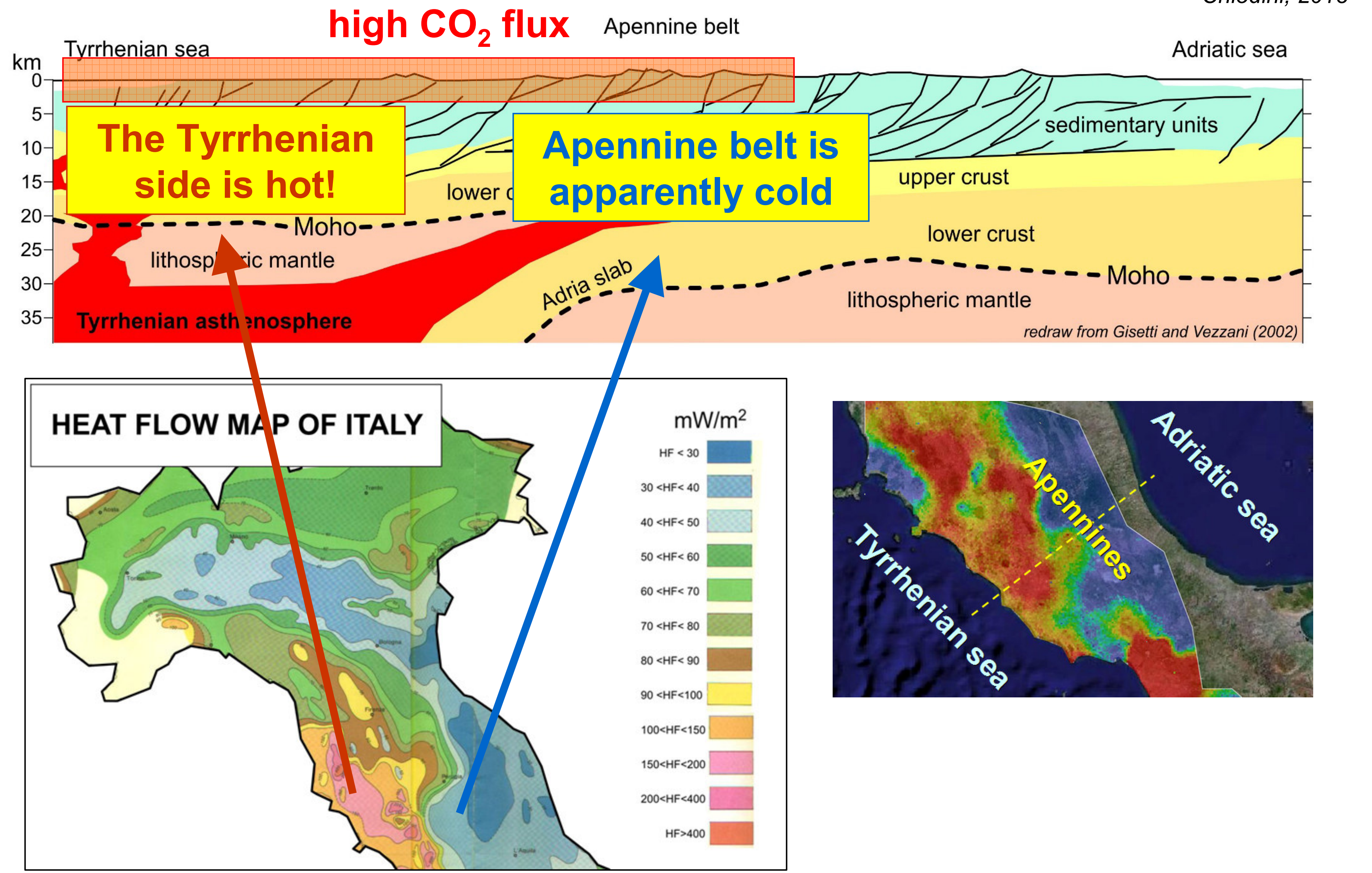




CO_2, ^3He, ^{13}C data suggest that the gas is produced mainly by the mixing between a MORB source with fluids deriving from decarbonation of limestone

Advective heat transport associated to regional Earth degassing in central Apennine (Italy)

Chiodini, 2018



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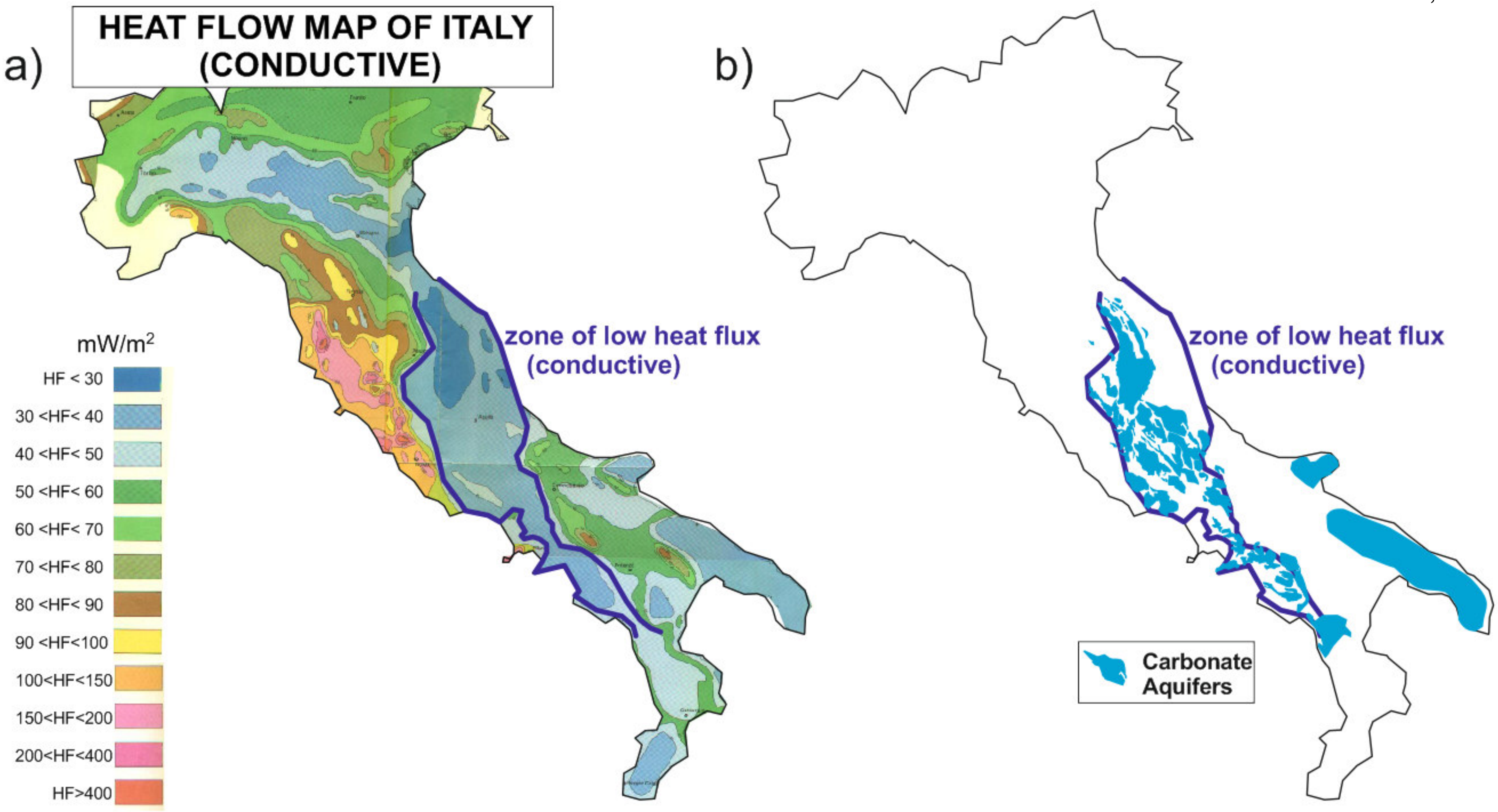

The map of the heat flux of Italy shows a N-S band of low heat fluxes that corresponds to the area of the Apennine aquifers. **Meteoric waters deeply circulate in these areas, cooling the crust, transporting an unknown amount of heat and possibly causing the measured low heat flux of the area.**

Advective heat transport associated to regional Earth degassing in central Apennine (Italy)

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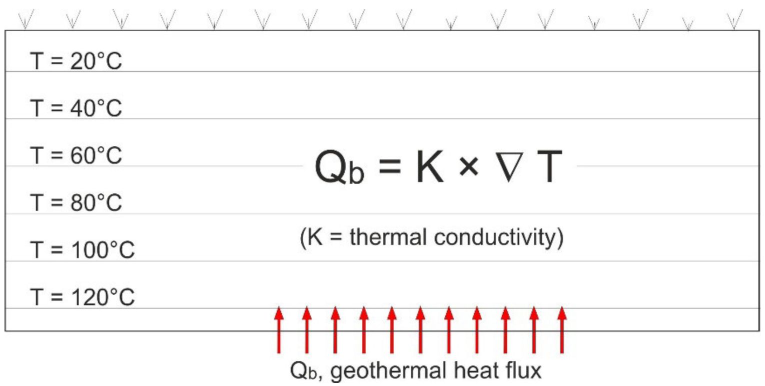
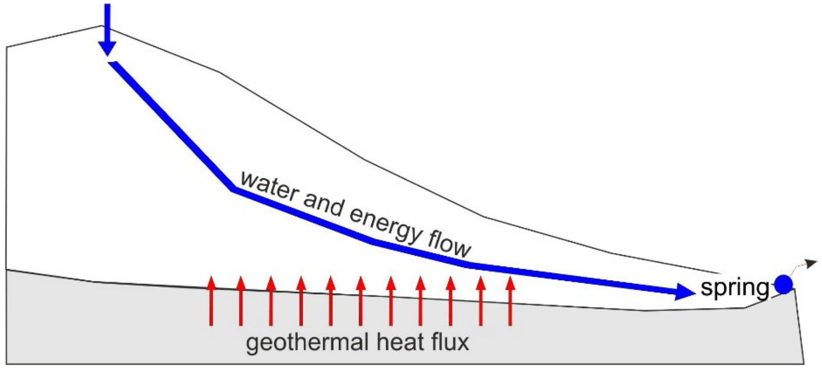




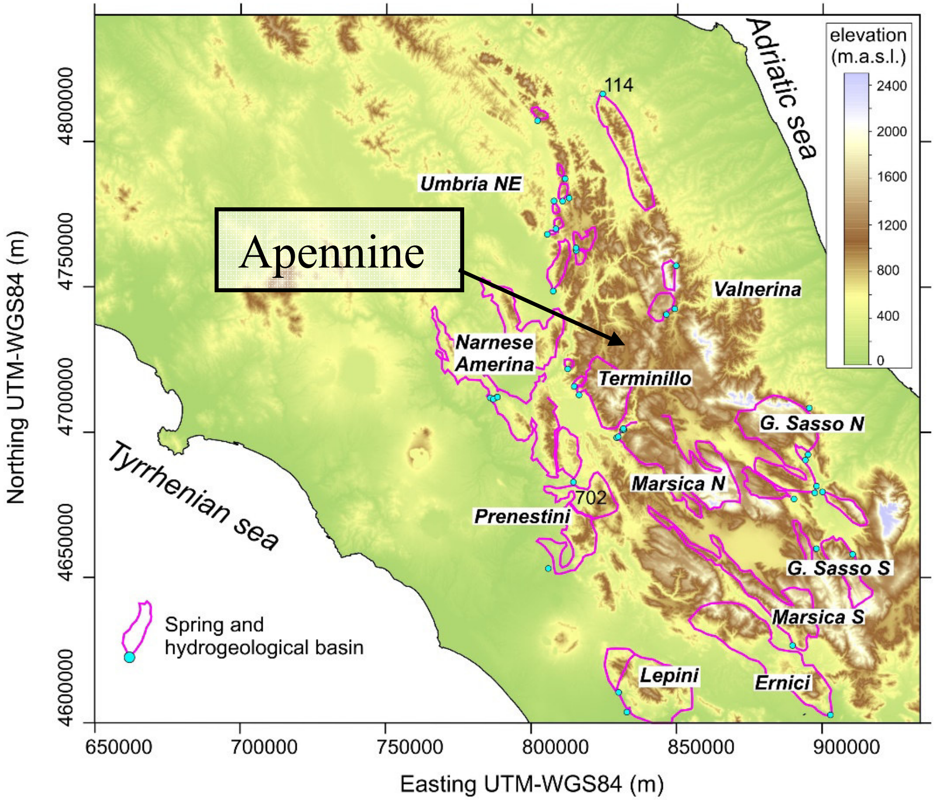
- At the Earth surface the heat flux is normally conductive and its direction is vertical. The heat flux is estimated based on the data of boreholes (measurements of thermal gradient and of the thermal conductivity of the rocks);

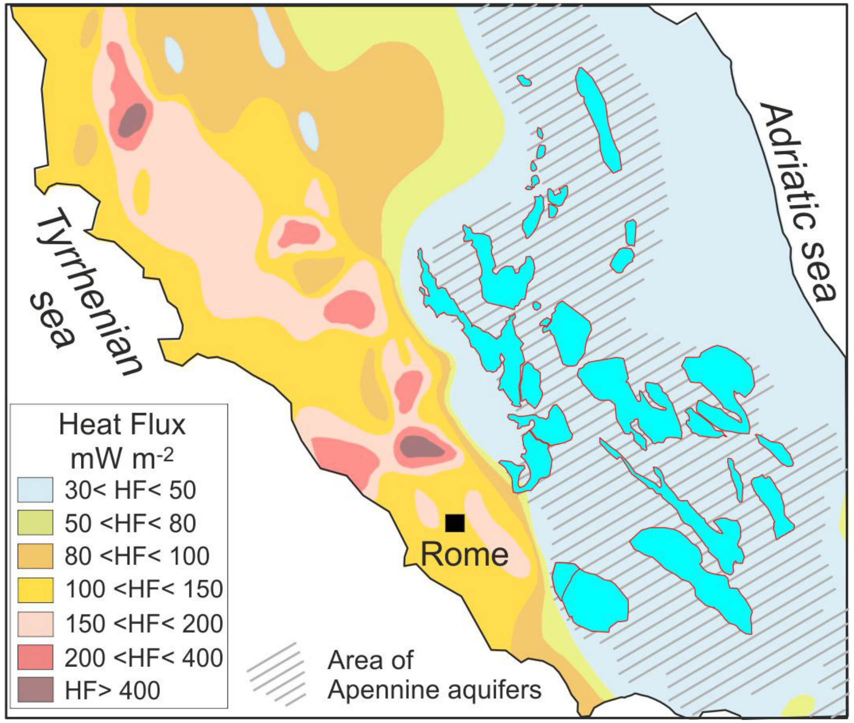
- In mountainous regions characterised by a high permeability of near-surface rocks and high water recharge rates, groundwater flow makes the estimates of heat flux based on a conductive model unreliable. In these regions, due to the abundant groundwater circulation, **the advective heat flow can be the dominant form of heat transfer**, and the temperature of the spring water can be used to estimate more realistic values of geothermal heat flux (Ingebritsen et al., 1989; Ingebritsen and Mariner 2010; Manga, 1998; Chiodini et al., 2013).

Investigated aquifers of central Apennine

Chiodini, 2018

46 springs, flow rates from 0.2 to 18 m^3/s, total sampled flow rate 130 m^3/s

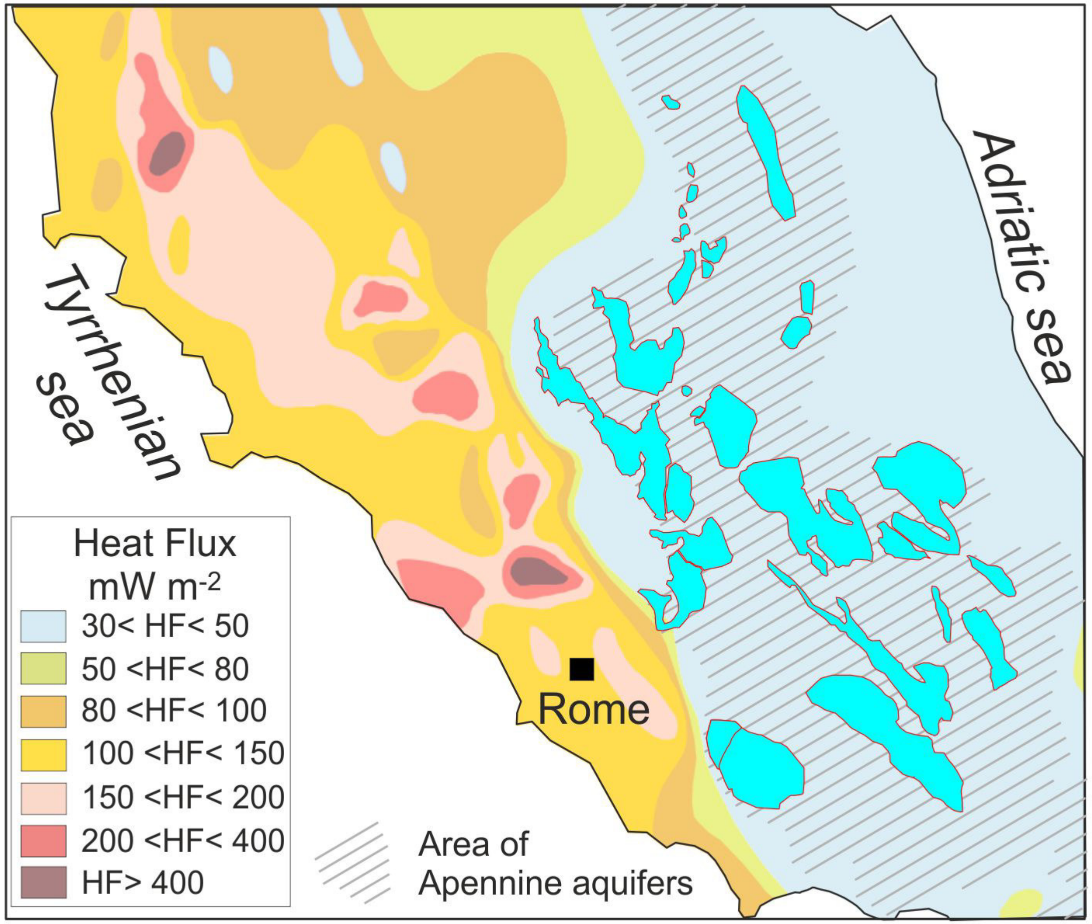


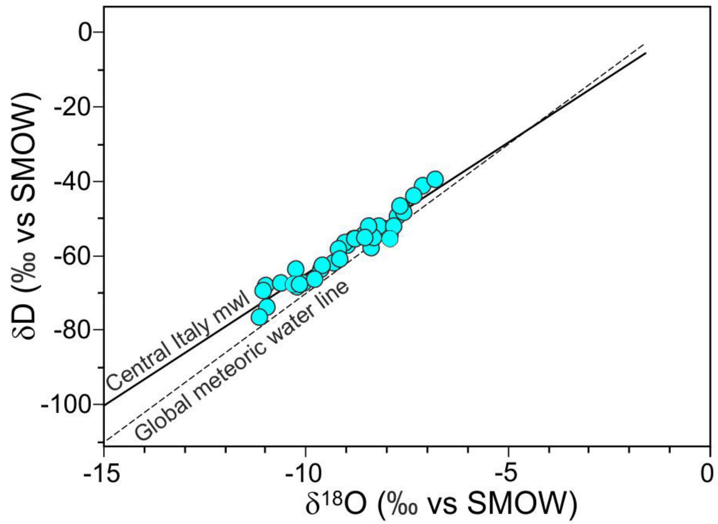


The sampled springs are from 11 carbonate hydrogeological structures which represent a significant portion of the permeable structures of the central Apennine

Chiodini, 2018

CO_2 mass balance of aquifers: results

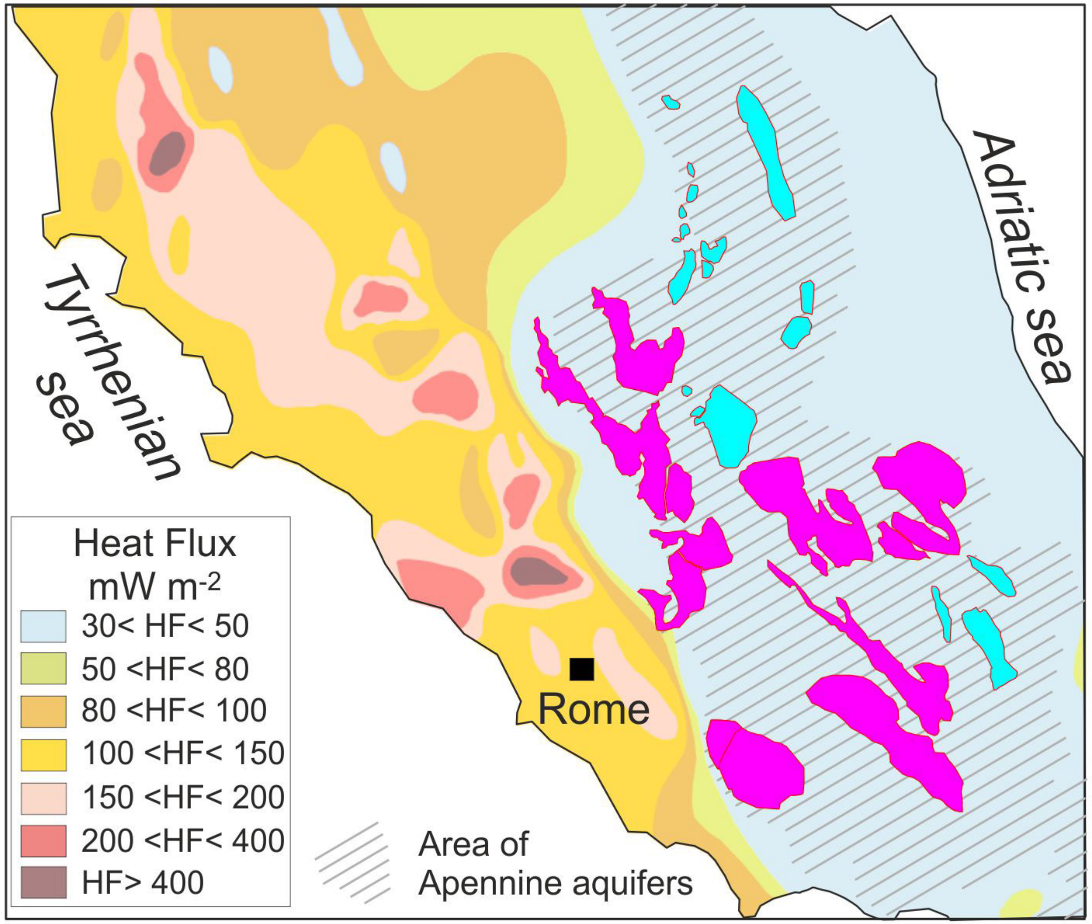




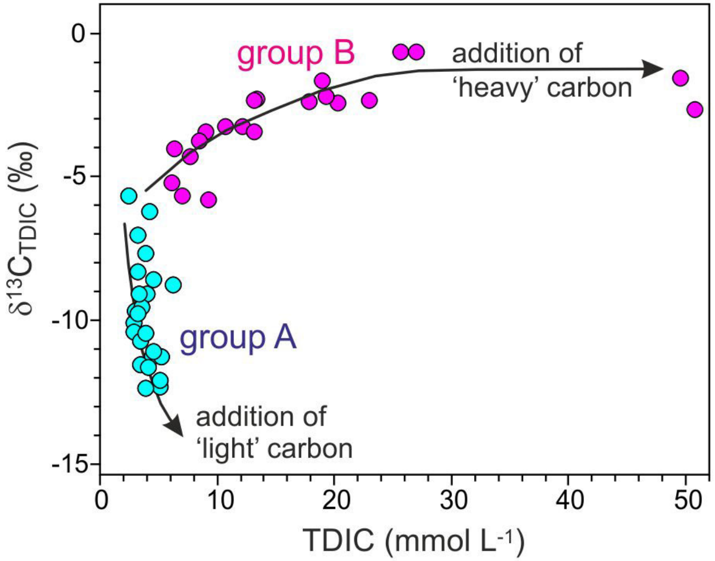
- The water is in each aquifer of meteoric origin

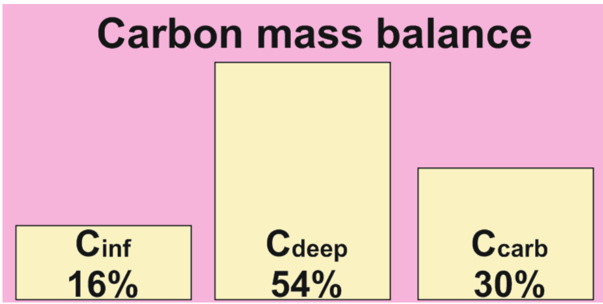
Chiodini, 2018

CO_2 mass balance of aquifers: results



Total input of deep CO_2 in the studied aquifer: **3100 t d^{-1}**





- The water is in each aquifer of meteoric origin
- **In most of the aquifers the carbon mainly derives from the deep source**

Chiodini, 2018

Enthalpy balance of aquifers

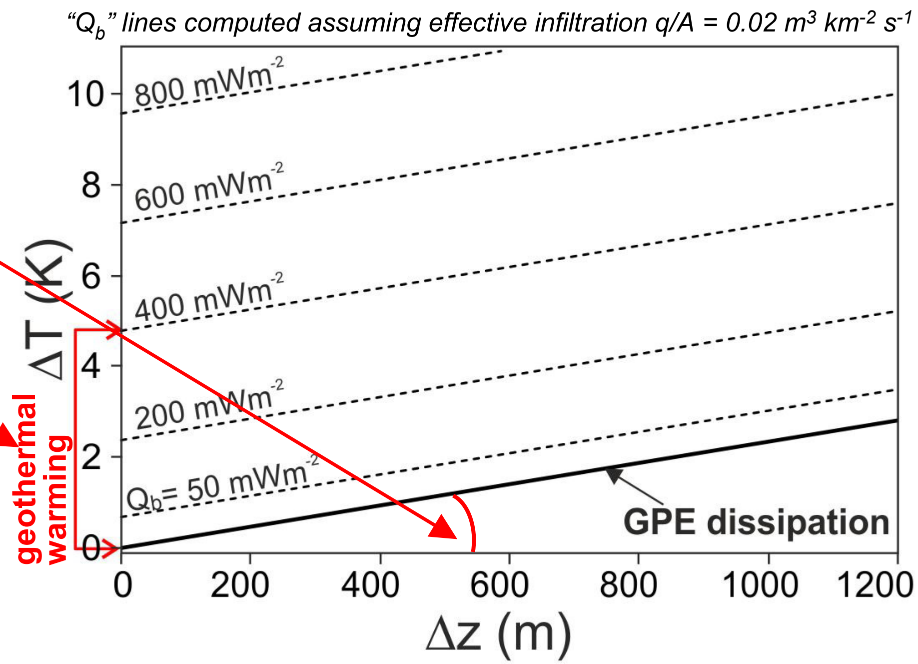
The geothermal heat flux has been computed starting from:

ΔT = water temperature at discharge – water temperature at infiltration and
Δz = difference between the water recharge area and the spring elevations

$$\Delta T = \frac{Q_b}{\rho_w C_w} \times \frac{A}{q} + \Delta z \times \frac{g}{C_w}$$

Geothermal warming

Gravitational potential energy (GPE) dissipation



Where:

Q_b = geothermal heat flux

ΔT = water temperature at discharge – water temperature at infiltration

Δz = difference between the water recharge area and the spring elevations

g = gravitational acceleration constant

ρ_w = water density

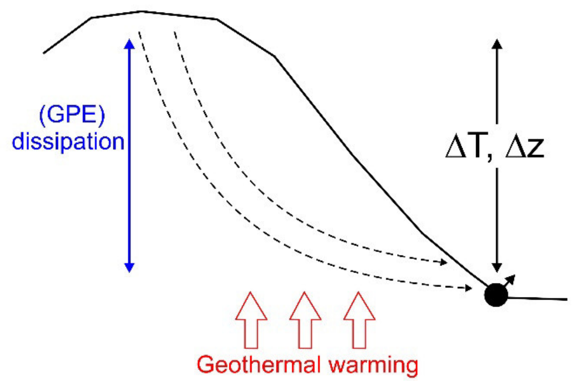
C_w = water heat capacity

A = areal extension of hydrogeological basin of the spring *(based on hydrogeological studies)*

q = spring flow rate

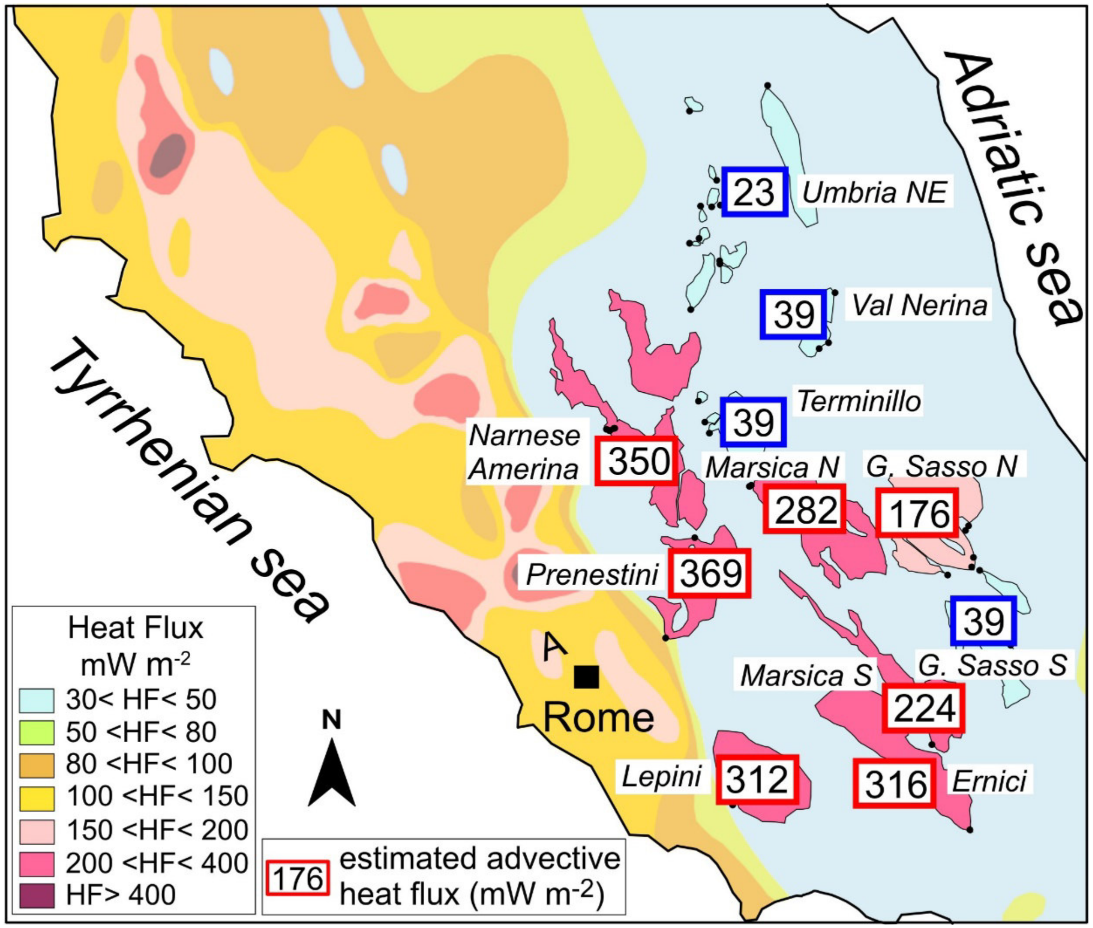
The used equation assumes a negligible effect of the conductive heat transfer from the aquifer to the surface

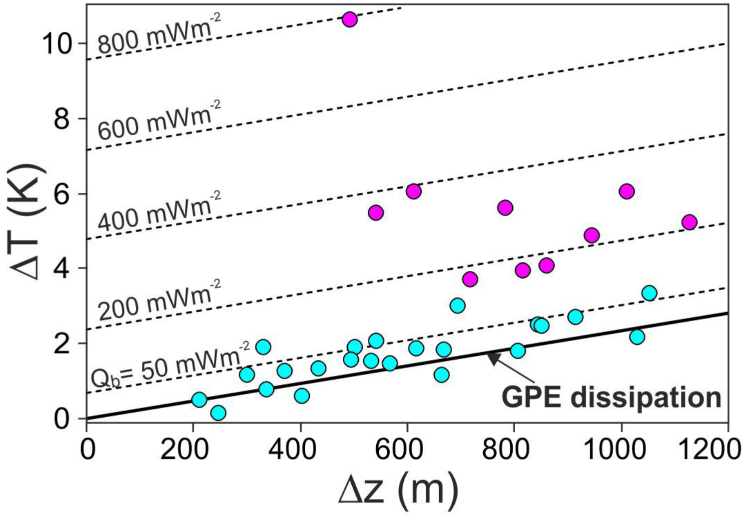
(Manga and Kirchner, 2004)



Enthalpy balance of aquifers: results

Chiodini, 2018





The total input of geothermal energy results in 2.1 GW!

*(i) the double than the geothermal input in the Cascade Range mountains (**~1 GW**, Ingebritsen and Mariner, 2010)*

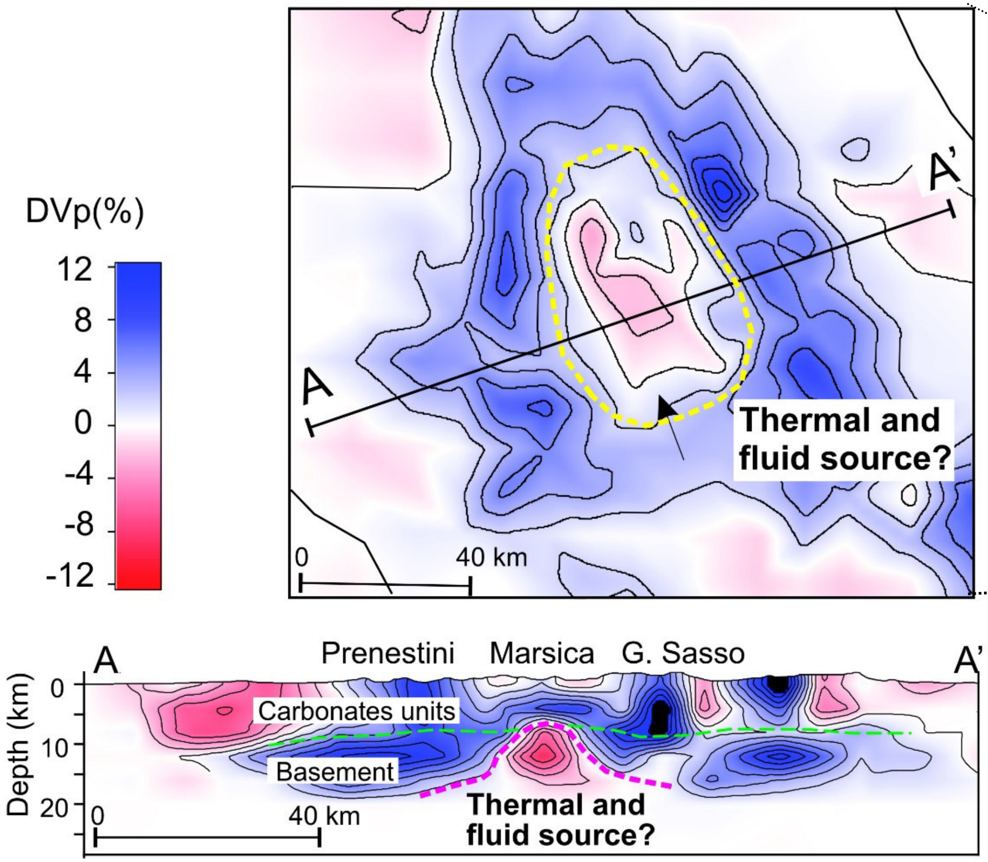
*(ii) 1/3 of the total heat discharged at Yellowstone, i.e. the largest hydrothermal system of the world (**~6 GW**; Fournier, 1989).*

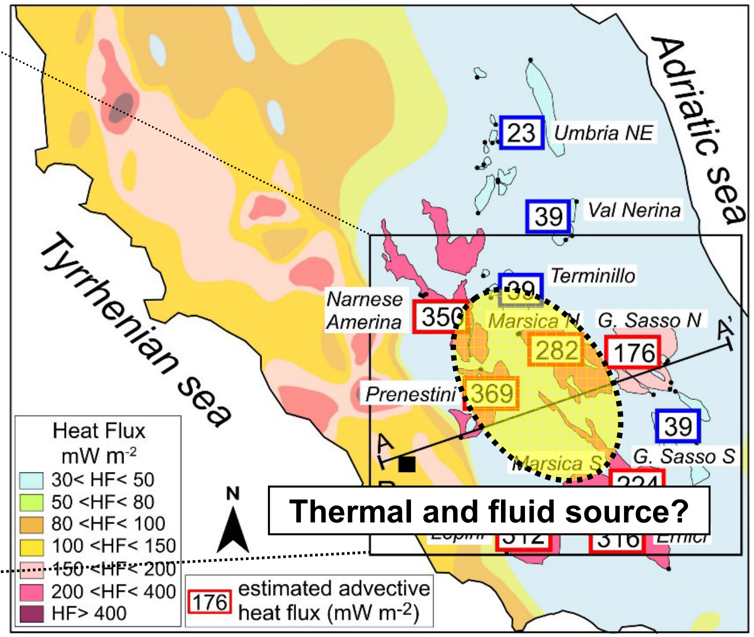
In the aquifers not affected by the input of deep CO_2 the mean advective heat flux (20-40 mW/m^2) practically coincides with the known, low, conductive heat flux.

In the aquifer affected by the input of deep CO_2 the mean advective heat flux (170-370 mW/m^2) results up to one order of magnitude higher than the conductive heat flux!

Heat and deep fluids source?

Chiodini, 2018





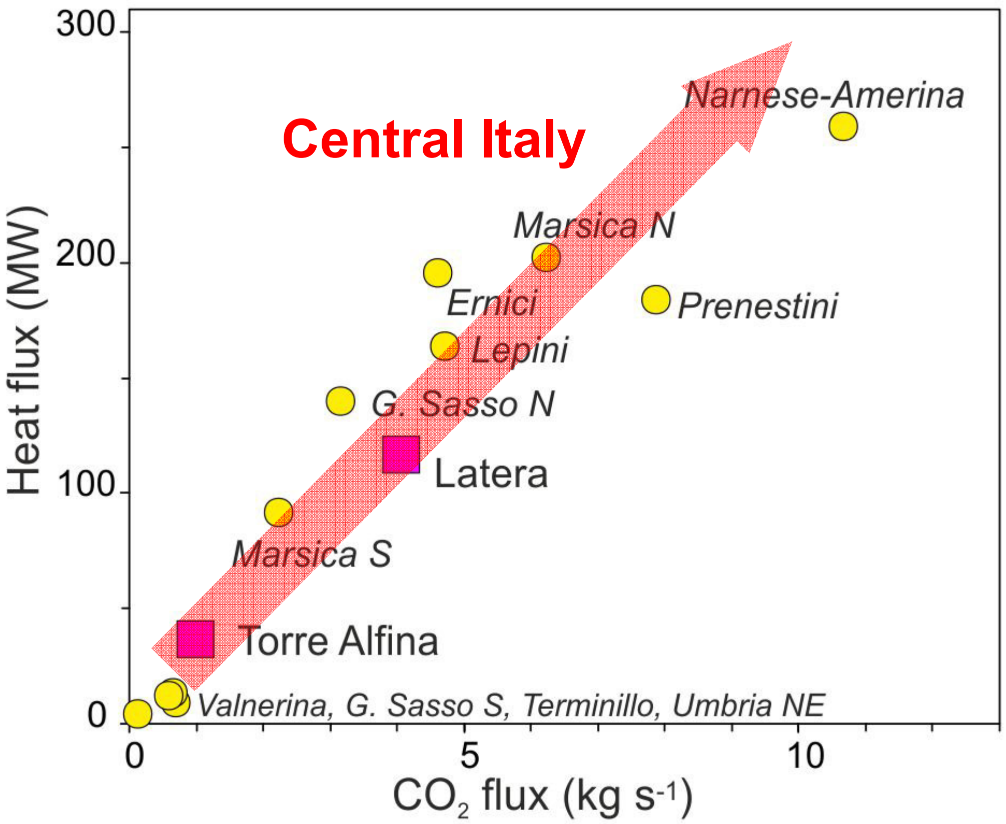
Chiodini et al. (2013)

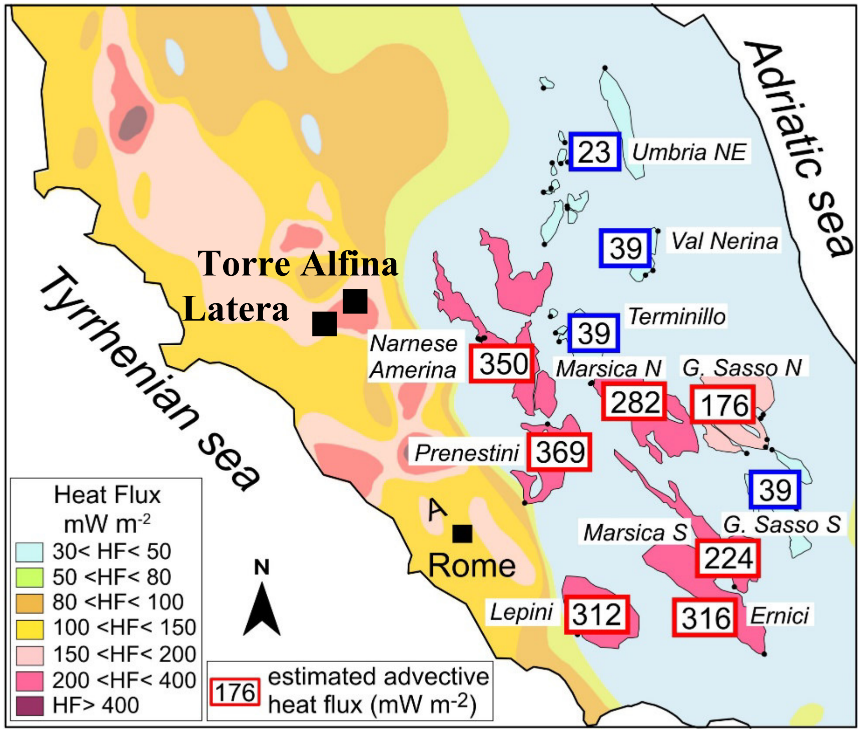
The heat anomaly broadly coincides with a low velocity anomaly in the crust.

A large magmatic intrusion at 10-15 km below the Apennines?

Geothermal heat flux and CO_2 flux

Chiodini, 2018



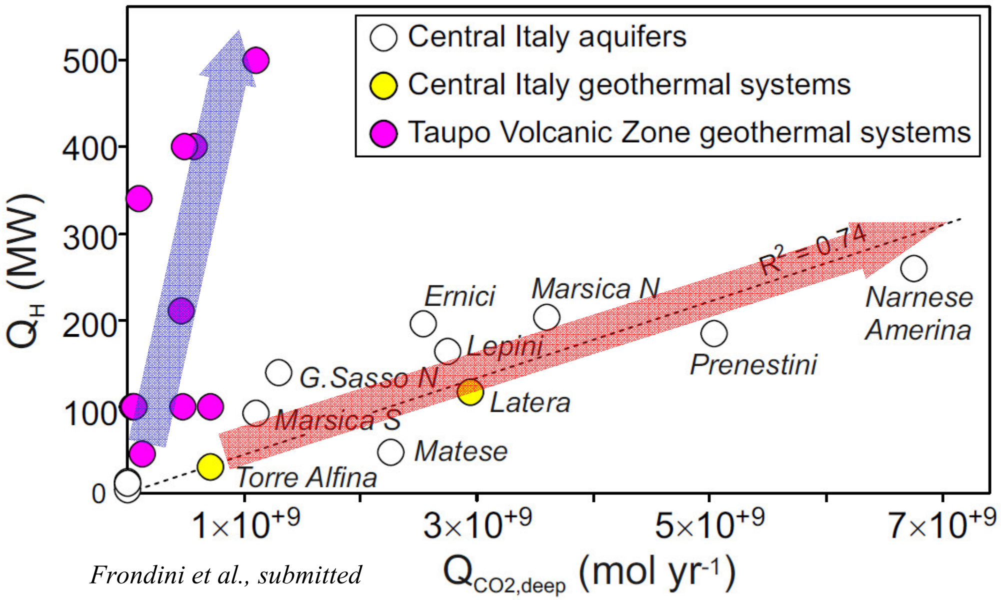


The geothermal heat is transported from depth by CO_2- rich fluids!

The fluids entering in the Apennine aquifers have enthalpy - CO_2 ratios close to that measured in the known geothermal systems of Torre Alfina and Latera

Chiodini, 2018

Geothermal heat flux and CO_2 flux



Geothermal systems from Taupo Volcanic Zone

Table 1
Summary of data (heat flow, temperature, CO_2 content) and CO_2 fluxes for geothermal systems of the Taupo Volcanic Zone[a]

System	Heat flow (MW)	T (°C)	CO_2 (mol kg^{-1})	Flux (10^8 mol yr^{-1})
Kawerau	100	300	0.2	4.7
Mokai	100	300	0.02	0.47
Ohaaki/Broadlands	100	300	0.3	7.1
Orakeikorako	340	250	0.01	0.97
Reporora	45	250	0.1	1.3
Rotorua	400	250	0.05–0.1	5.7
Rotokawa	210	320	0.10	4.6
Tauhara	100	300	0.02	0.56
Waiotapu	500	300	0.1	11
Wairakei	400	260	0.04	4.9

Total CO_2 flux $= 4.1 \cdot 10^9$ mol yr^{-1}.
[a]From Seward and Kerrick (1995).

Kerrick et al. (1995)

The geothermal heat is transported from depth by CO_2- rich fluids!

Kerrick and coauthors during 1990's attempted **a global estimation of CO_2 fluxes from the circum-pacific high heat flux zones** using a heat-CO_2 relation derived from the geothermal system of Taupo Volcanic Zone (NZ). In Italy such relation does not work because **the deep fluids are characterized by a higher CO_2/heat ratio**

Conclusions

- Regional maps and quantitative estimations of CO_2 Earth degassing can be obtained by computing the **carbon mass balance of regional aquifers** (high flow rate discharges rather than low flow rate anomalous springs!)

- Central Tyrrhenian Italy, including Apennines, is affected by a CO_2 flux of **0.4-0.6 t km^2 d^{-1}** (total > 9.1 Mt/yr). The flux of other tectonic zone of the Earth is unknown!

- There are numerous signs of **an active role of CO_2 rich fluids in the seismogenesis** of the Apennines;

- A large sector of Central Apennines is affected by **very high heat fluxes** (estimated as high as 300 mW m^{-2}). **The heat is transported from depth by CO_2 rich fluids**. The source of heat and fluids below the Apennine, is likely **a broad magmatic intrusion**;

- The thermal regime of tectonically young and active areas of the Earth, where large amount of meteoric waters infiltrate and circulate deeply (such as in the entire Alpine-Himalayan belt), should be revised on the basis of mass and **energy balances of the groundwater systems**;

- The heat flow can be used to estimate CO_2 flux at regional scale. **The CO_2 emission is a proxy of the heat flow** once the regional CO_2/heat relation is known.

Burton, M.R., Sawyer, G.M. & Granieri D. 2013. Deep Carbon Emissions from Volcanoes. Reviews in Mineralogy & Geochemistry, Vol. 75 pp. 323-354. doi:10.2138/rmg.2013.75.11

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Cardellini C., Chiodini G., Frondini F., 2003. Application of stochastic simulation to CO2 flux from soil: mapping and quantification of gas release. J. Geophys. Research, 108, 2425. doi:10.1029/2002JB002165.

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