Piano Triennale della Ricerca e Terza Missione (2021-2023)
Dipartimento di Fisica e Geologia

10-11 gennaio 2022

Earth degassing, global changes and natural risks

Carlo Cardellini, Francesco Frondini, Artur Ionescu, Lisa Ricci, Alessandra Ariano, Giovanni Chiodini

10.01.2022 Speaker: Francesco Frondini

A.D. 1308
unipg
DIPARTIMENTO
DI FISICA E GEOLOGIA

Aula A - Dipartimento di Fisica e Geologia

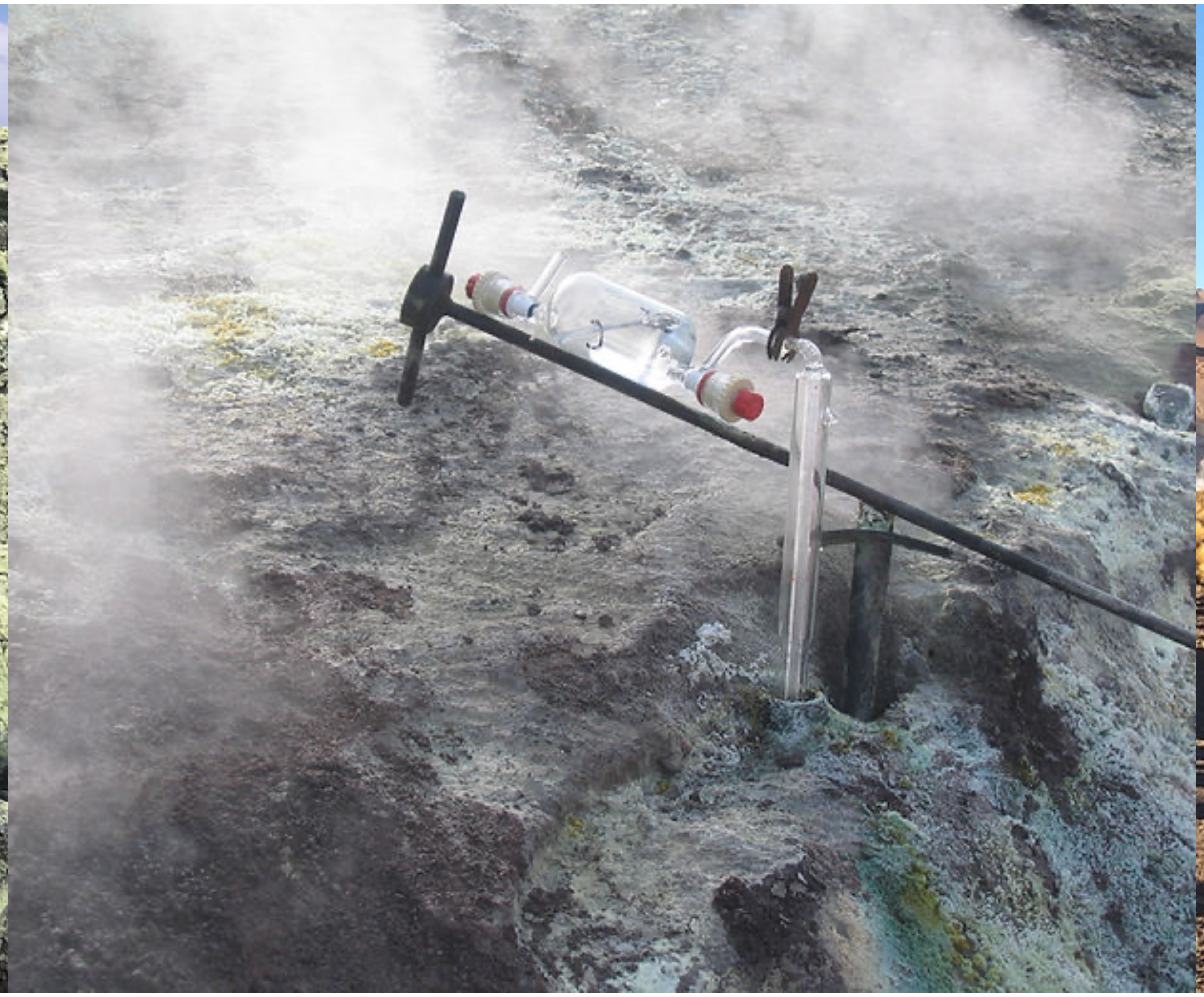
Why studying the geologic carbon cycle?

Studying the geologic carbon cycle and in particular the fluxes of carbon bearing gases (CO_2-CH_4) from the solid Earth to the atmosphere is of crucial importance for the comprehension of numerous natural processes at different time scales:

- the evolution of the atmosphere and climate,

- the role of crustal fluids in geodynamic processes (volcanism and seismicity),

- the convective heat transfer from the deep Earth to the surface.


When and how we started?

1995 - Using CO_2 for geothermal prospection

Geothermics
Volume 24, Issue 1, February 1995, Pages 81-94

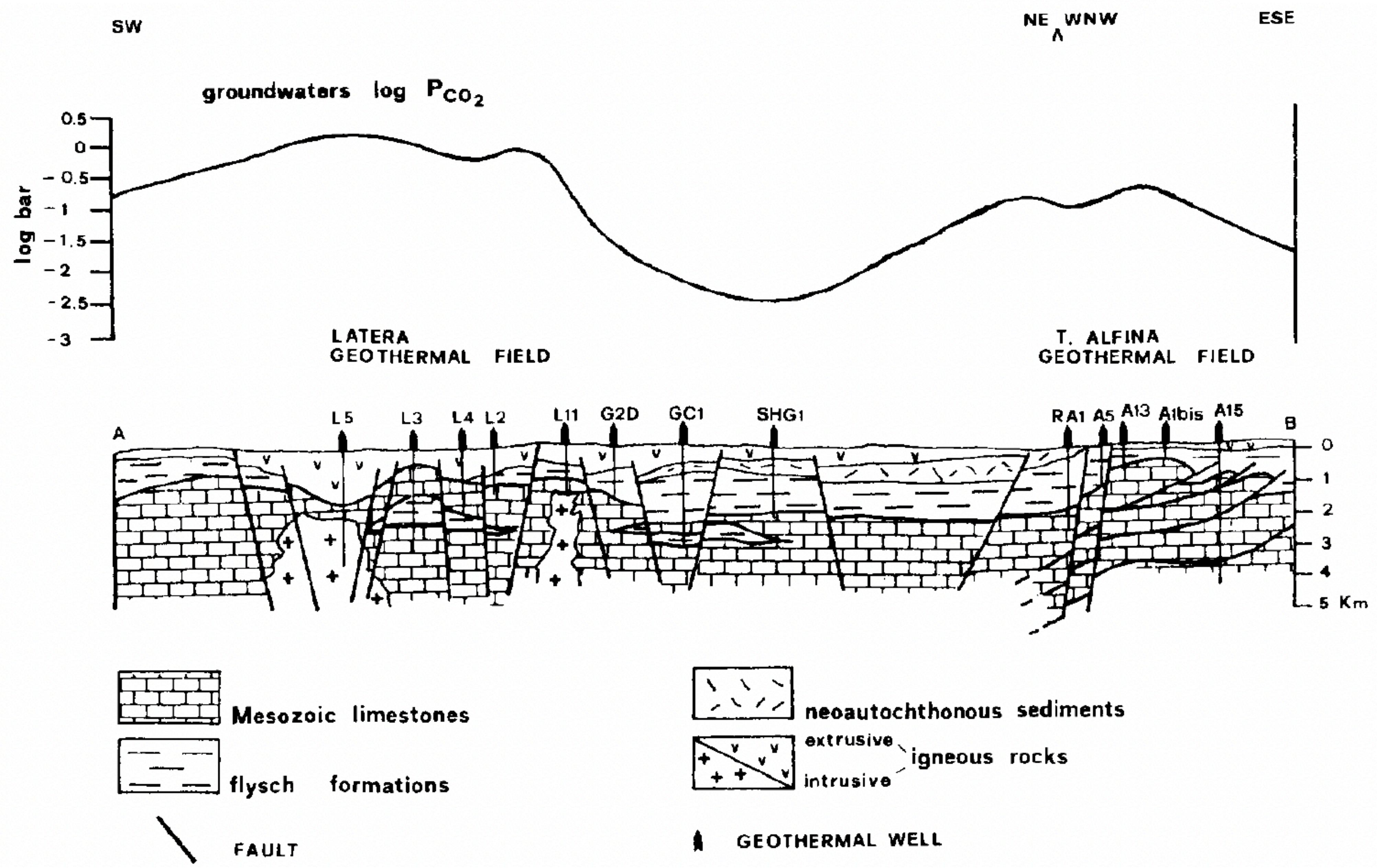
0375–6505(94)00023–9

DEEP STRUCTURES AND CARBON DIOXIDE DEGASSING IN CENTRAL ITALY

G. CHIODINI, F. FRONDINI and F. PONZIANI

Department of Earth Sciences, University of Perugia, Piazza Università, 06100 Perugia, Italy

(*Received January* 1994; *accepted for publication June* 1994)



Deep geothermal systems can cause a CO_2 anomaly at the surface

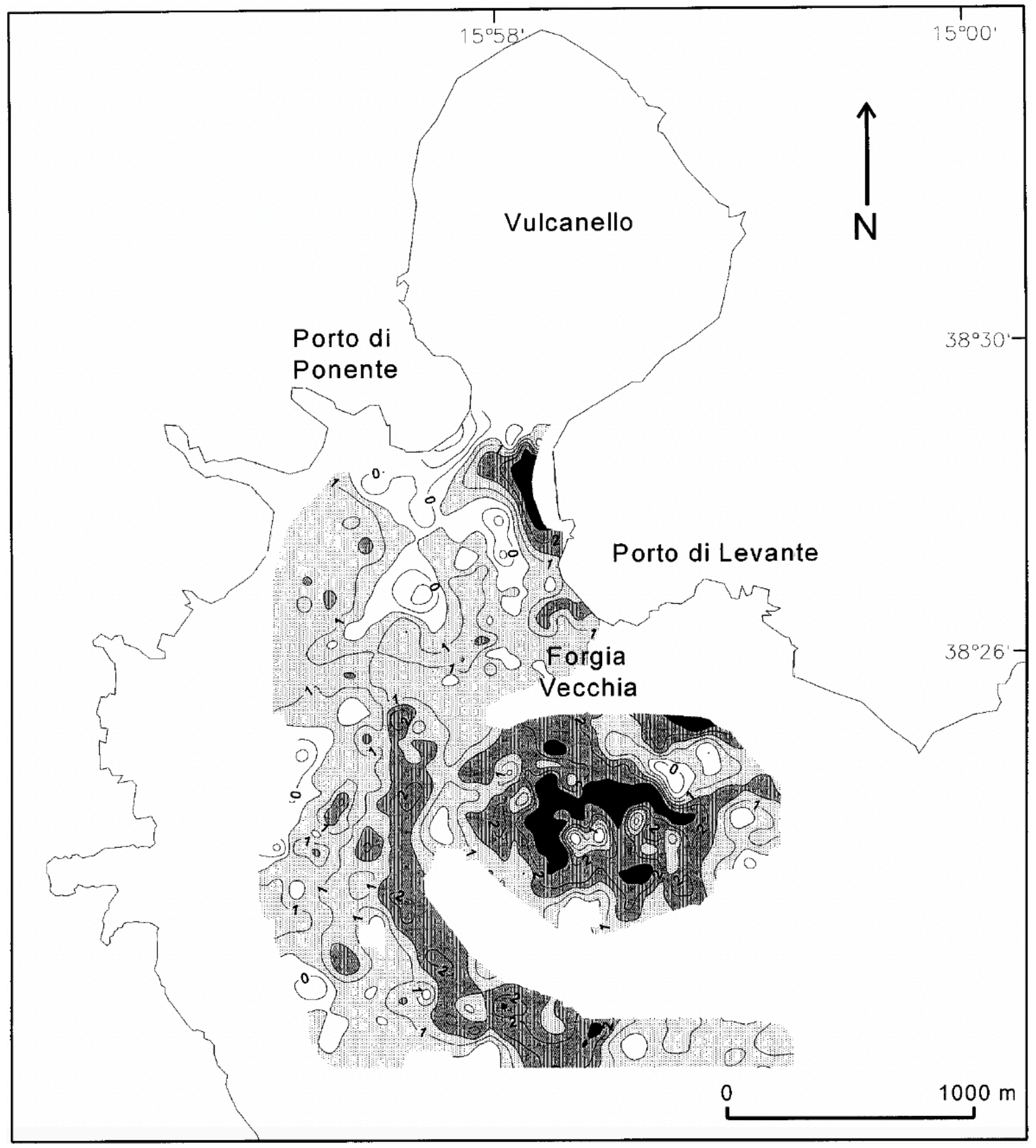
1996 - Measuring soil CO_2 fluxes from volcanoes

Bull Volcanol (1996) 58:41–50

ORIGINAL PAPER

G. Chiodini · F. Frondini · B. Raco

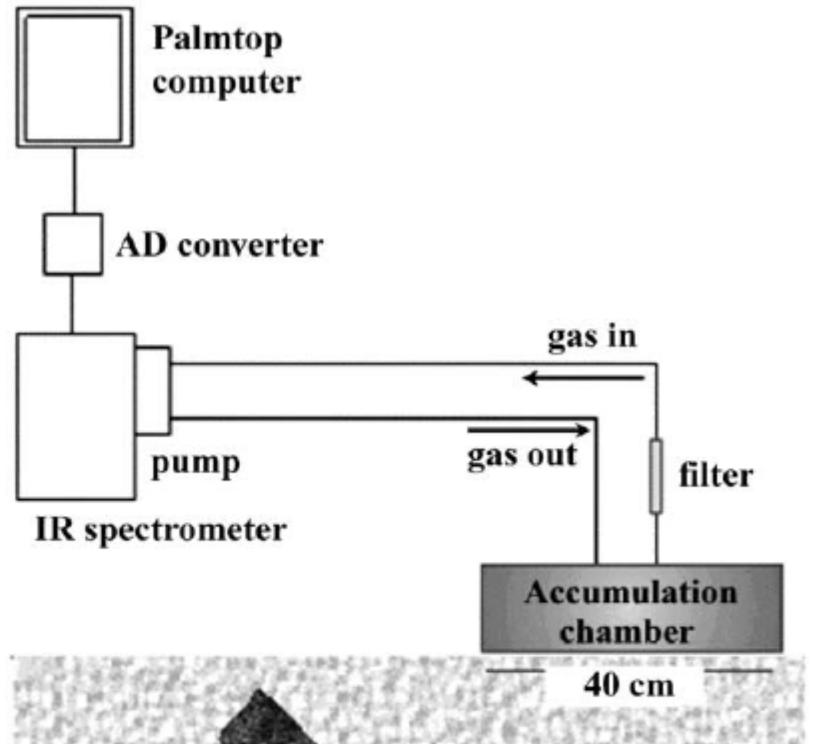
Diffuse emission of CO_2 from the Fossa crater, Vulcano Island (Italy)



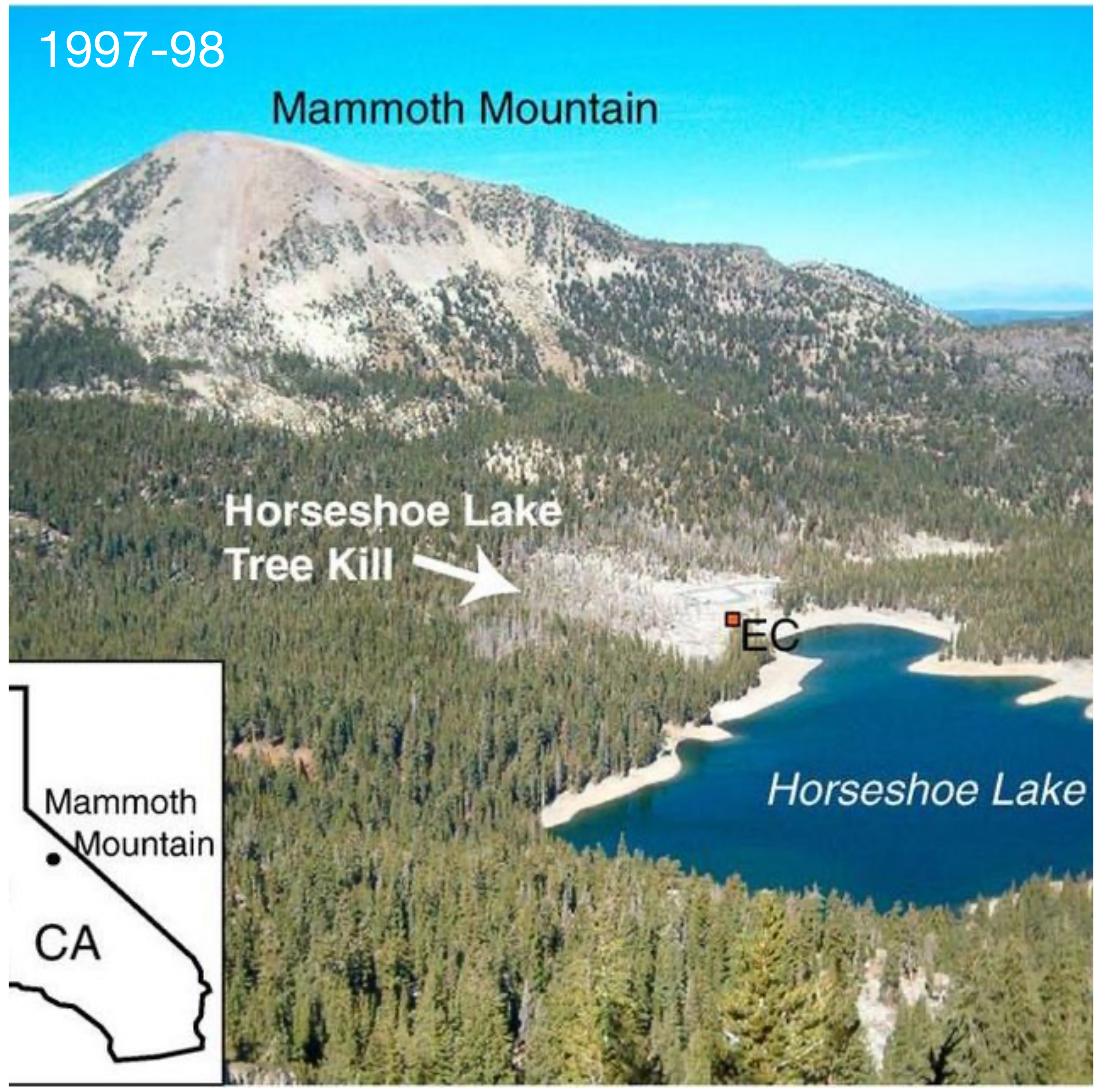
For the first time, the flux of carbon dioxide from a volcano was measured, using the accumulation chamber method

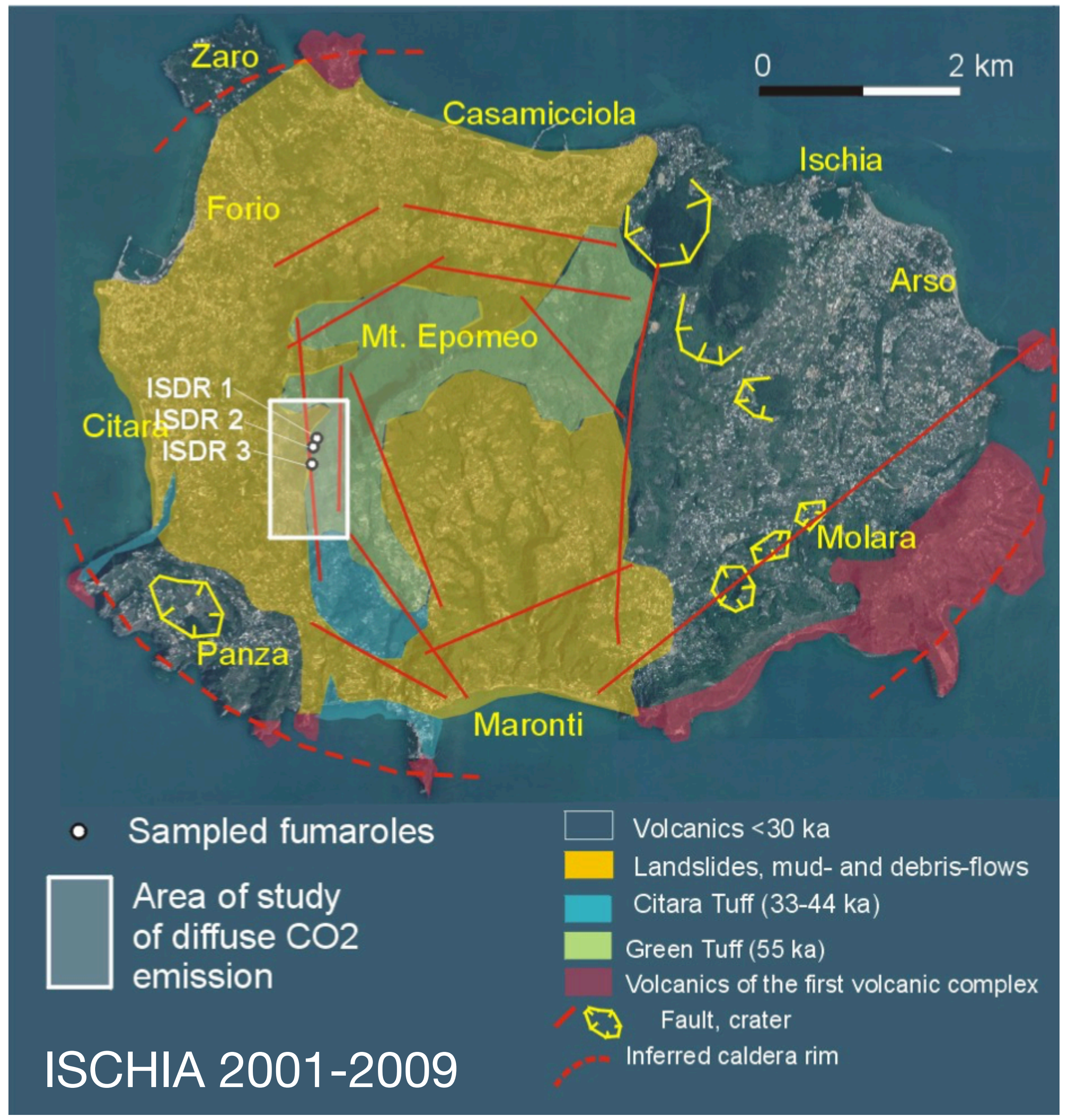
200 t/d of CO_2

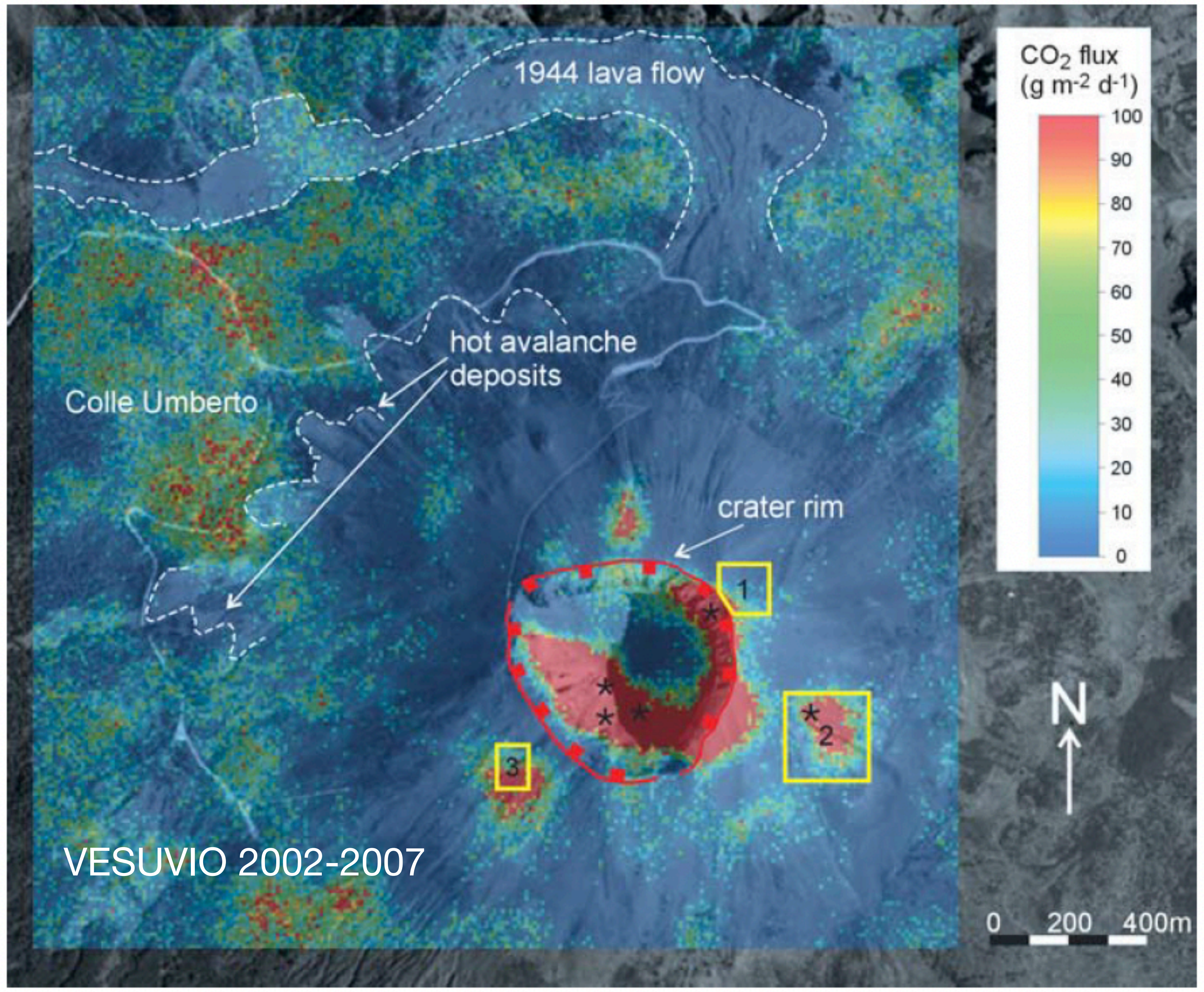
1000 t/d steam



We enjoyed measuring CO_2 fluxes, from volcanoes all over the world…



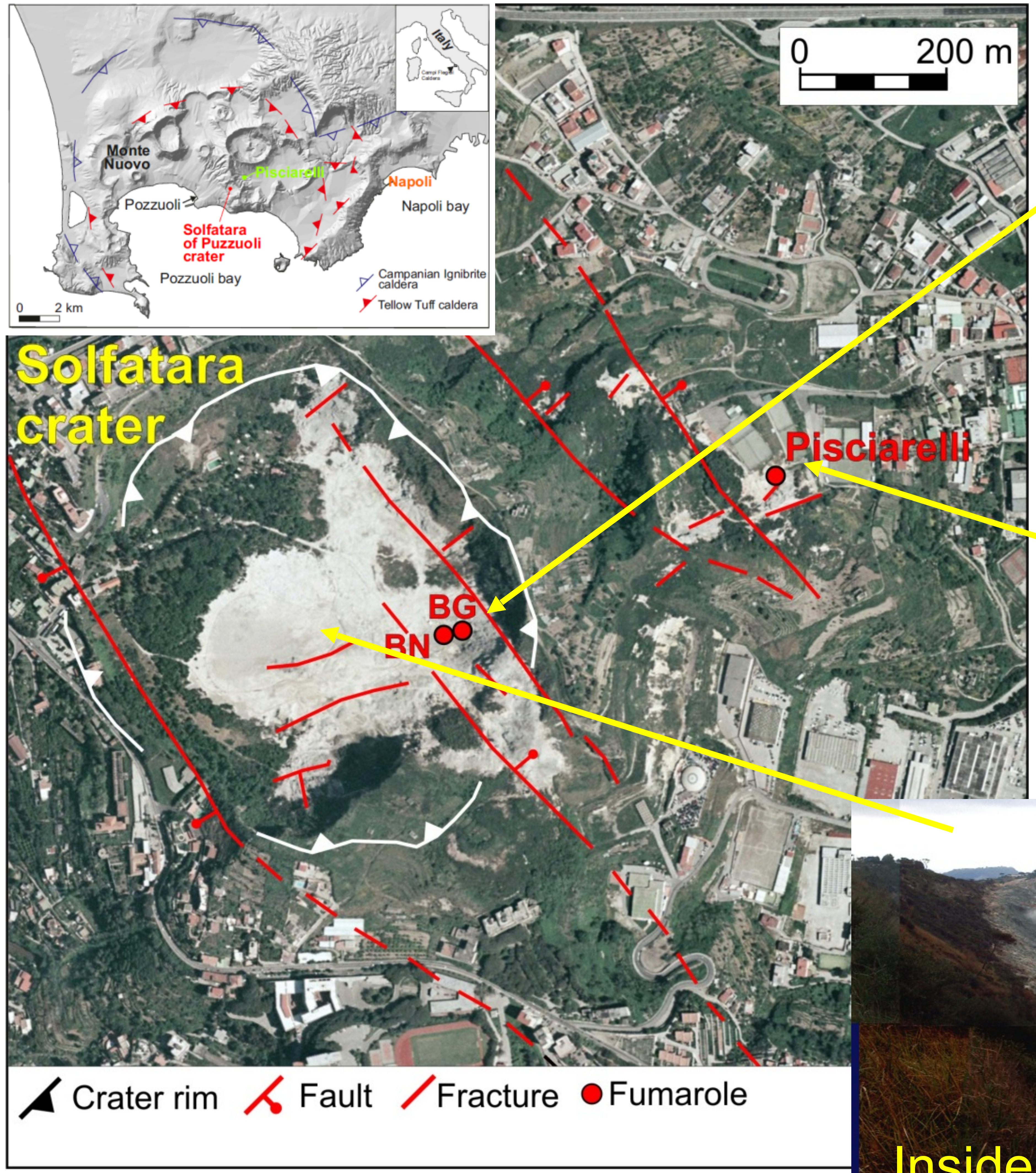




… but our favourite place has always been Solfatara!

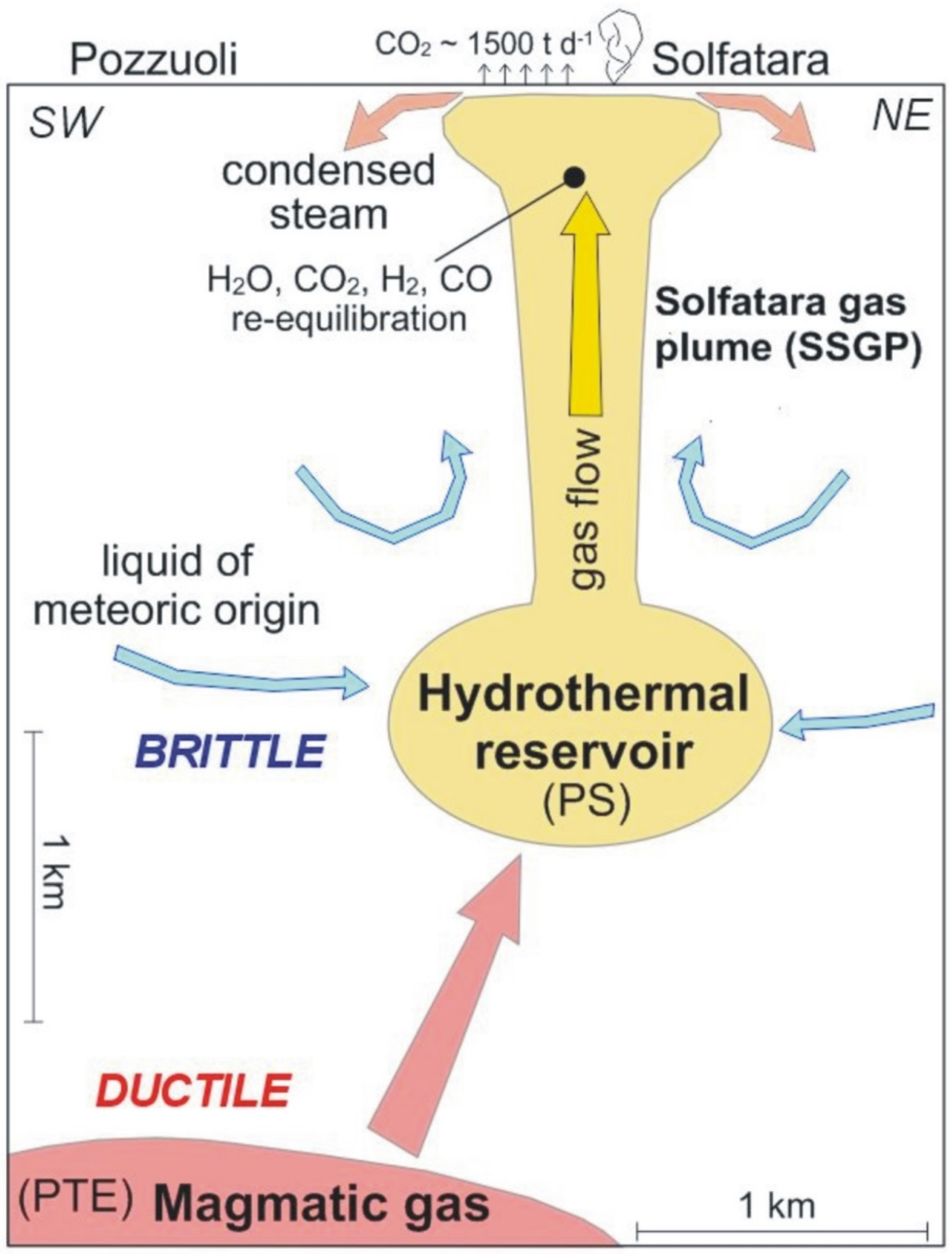
Monitoring diffuse volcanic degassing during volcanic unrests: the case of Campi Flegrei (Italy)

Most of the sub-aerial **hydrothermal activity** of Campi Flegrei concentrates at Solfatara of Pozzuoli were are located **fumarolic emissions** and **a large area of CO_2 soil diffuse degassing**



The system feeding the degassing

Fumarolic emissions and **CO_2 soil diffuse degassing** are fed by Solfatara hydrotermal system.



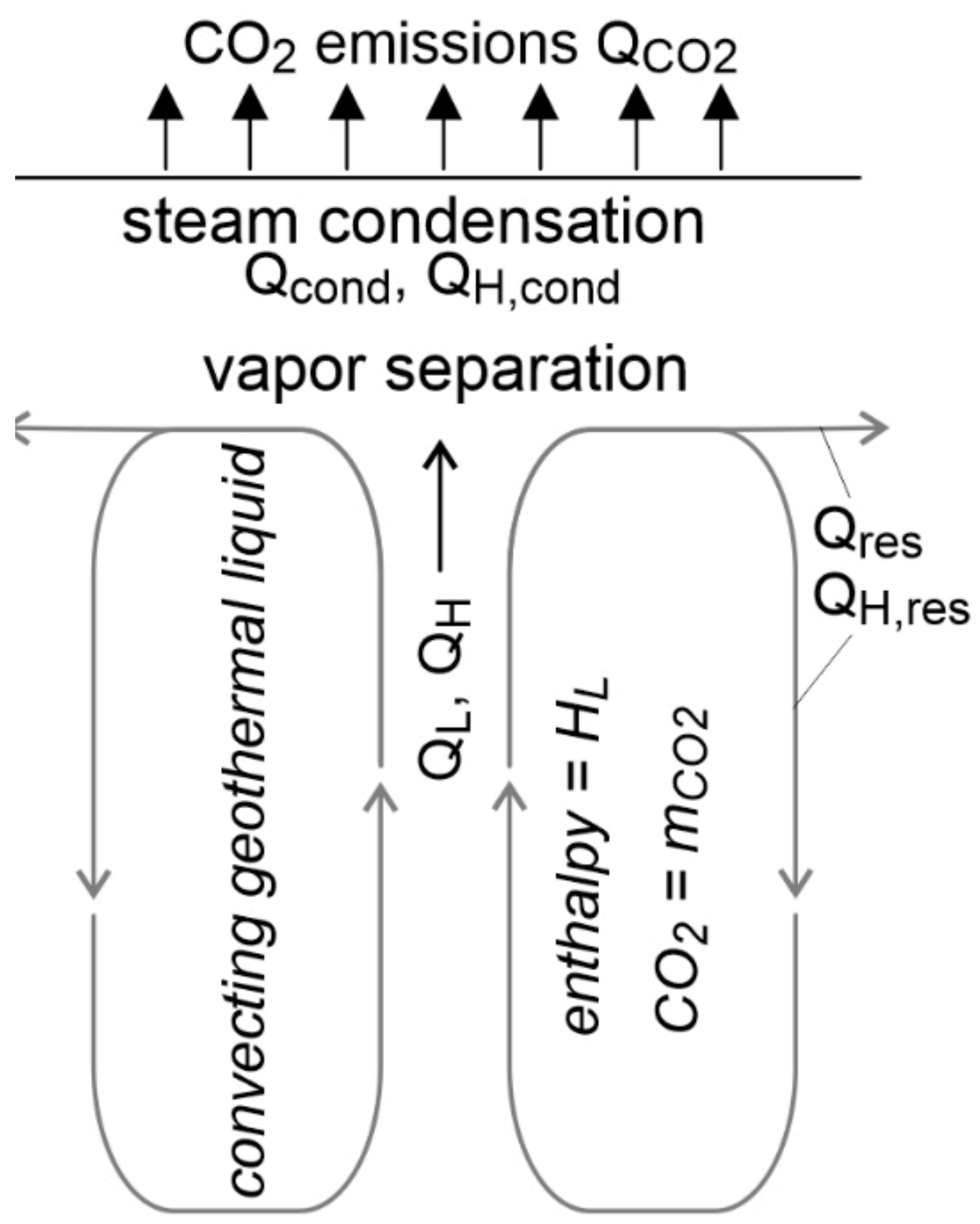
From Chiodini et al., (2015)

The main features of the hydrothermal are:

1) **a deep zone of gas accumulation** ('magmatic gas') which is located at ~4km in depth (Vanorio et al., 2005), and which supplies hot gas to the system.

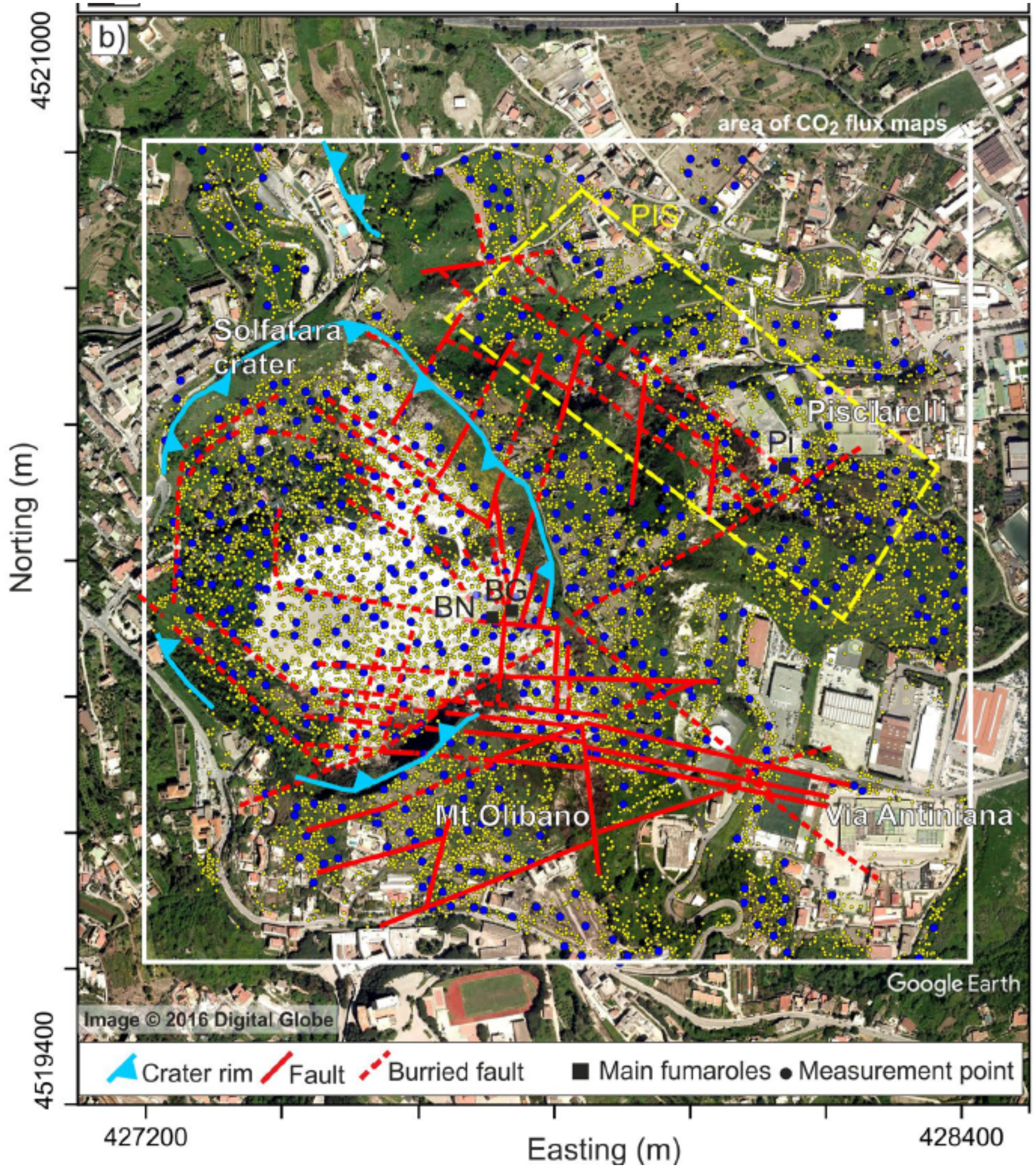
2) **a shallower reservoir** (~2km), where magmatic fluids mix and vaporize liquid of meteoric origin, that forms the **Solfatara vapor plume**.

This scheme was first inferred from geochemical interpretations (e.g., Caliro et al., 2007, 2014; Chiodini et al., 2012), highlighted by the re-interpretation of seismic tomography (Chiodini et al., 2015; Battaglia et al 2008, Zollo et al., 2006) and supported by inversion of the ground deformations (Amoruso et al., 2014).



Measurements of CO_2 fluxes fromdiffuse soil degassing

Since 1998 soil CO_2 fluxes were measured over an **area of ~ 1.2 km²** including the Solfatara crater and the Pisciarelli area (Chiodini et al., 2001; Cardellini et al., 2017)



30 surveys

in the period 1998-2016

Each survey included from

~370 to ~580 measurements

Total CO_2 flux measurements 13,158

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 106, NO. B8, PAGES 16,213–16,221, AUGUST 10, 2001

CO_2 degassing and energy release at Solfatara volcano, Campi Flegrei, Italy

G. Chiodini,[1] F. Frondini ,[2] C. Cardellini,[2] D. Granieri,[1] L. Marini,[3] and G. Ventura [1]

SCIENTIFIC REPORTS

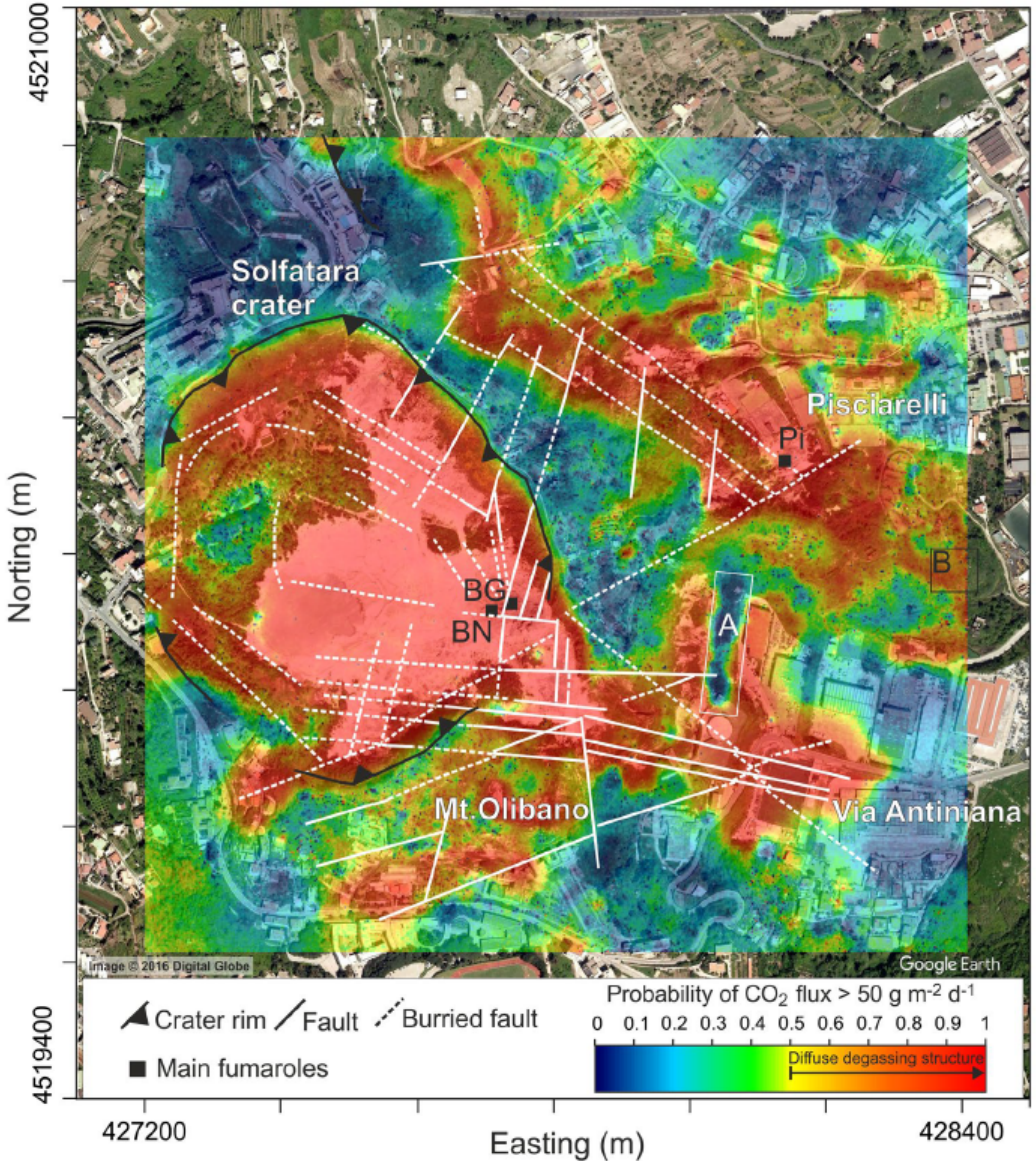
OPEN

Monitoring diffuse volcanic degassing during volcanic unrests: the case of Campi Flegrei (Italy)

Received: 20 March 2017
Accepted: 19 June 2017
Published online: 28 July 2107

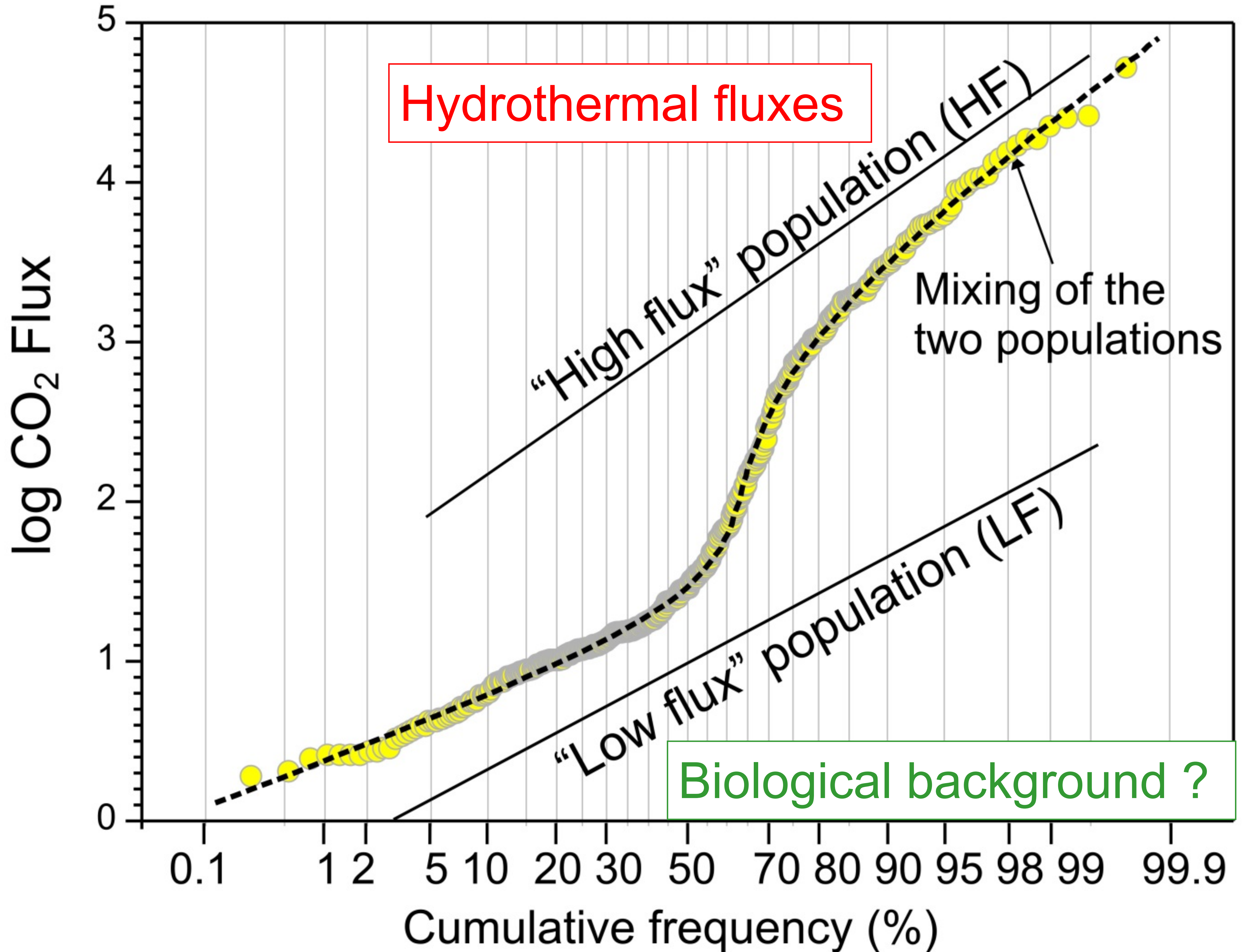
C. Cardellini[1], G. Chiodini[2], F. Frondini[1], R. Avino[3], E. Bagnato[1], S. Caliro[3], M. Lelli[4] & A. Rosiello[1]

Solfatara diffuse degassing structure (DDS)

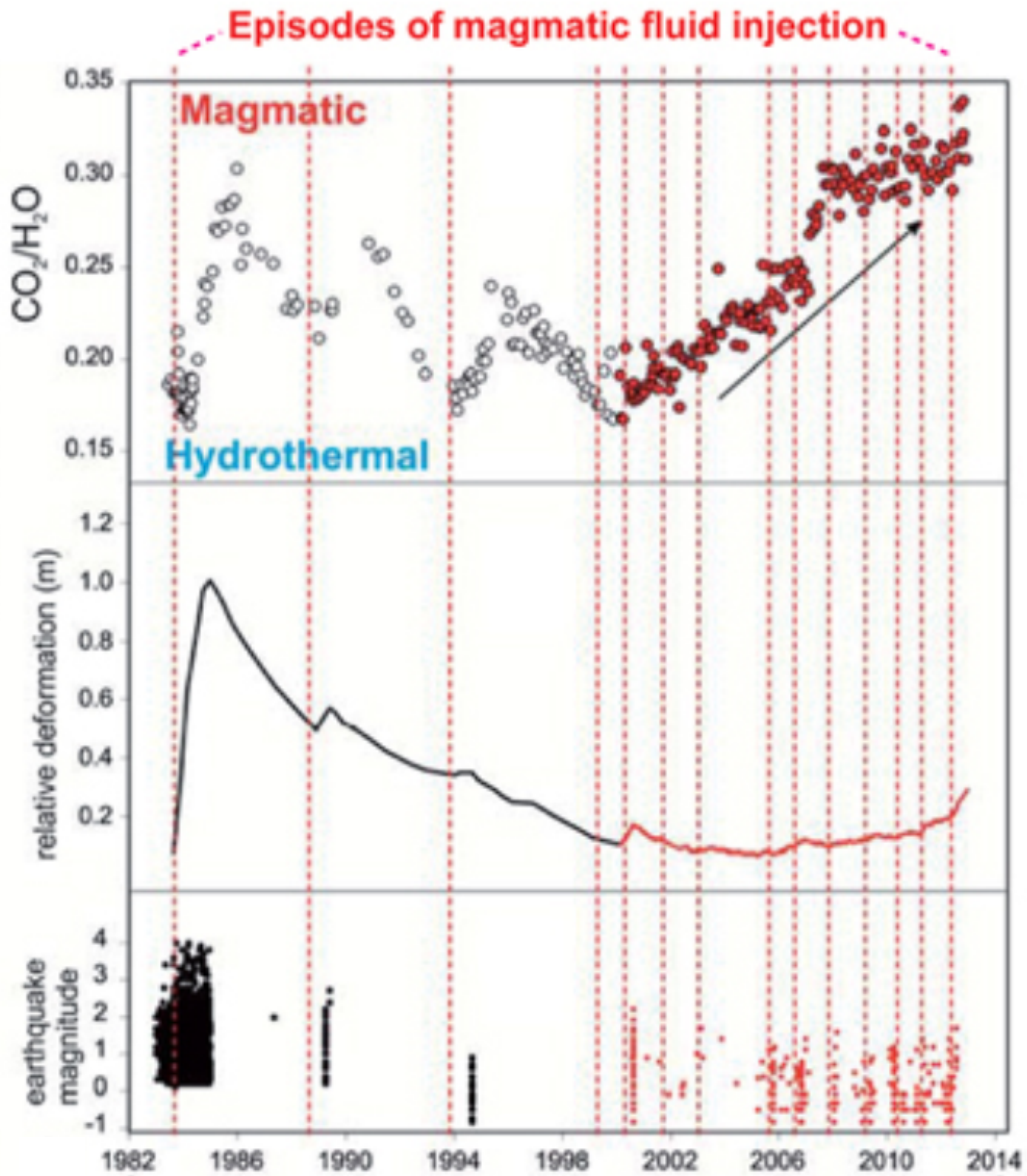


CO_2 fluxes from soil: sources feeding soil degassing

The soil CO_2 fluxes distribute in a wide range of values and the data of each survey plot along a bimodal curves which can be modelled as the **mixing of two lognormal CO_2 flux populations**



The system feeding degassing

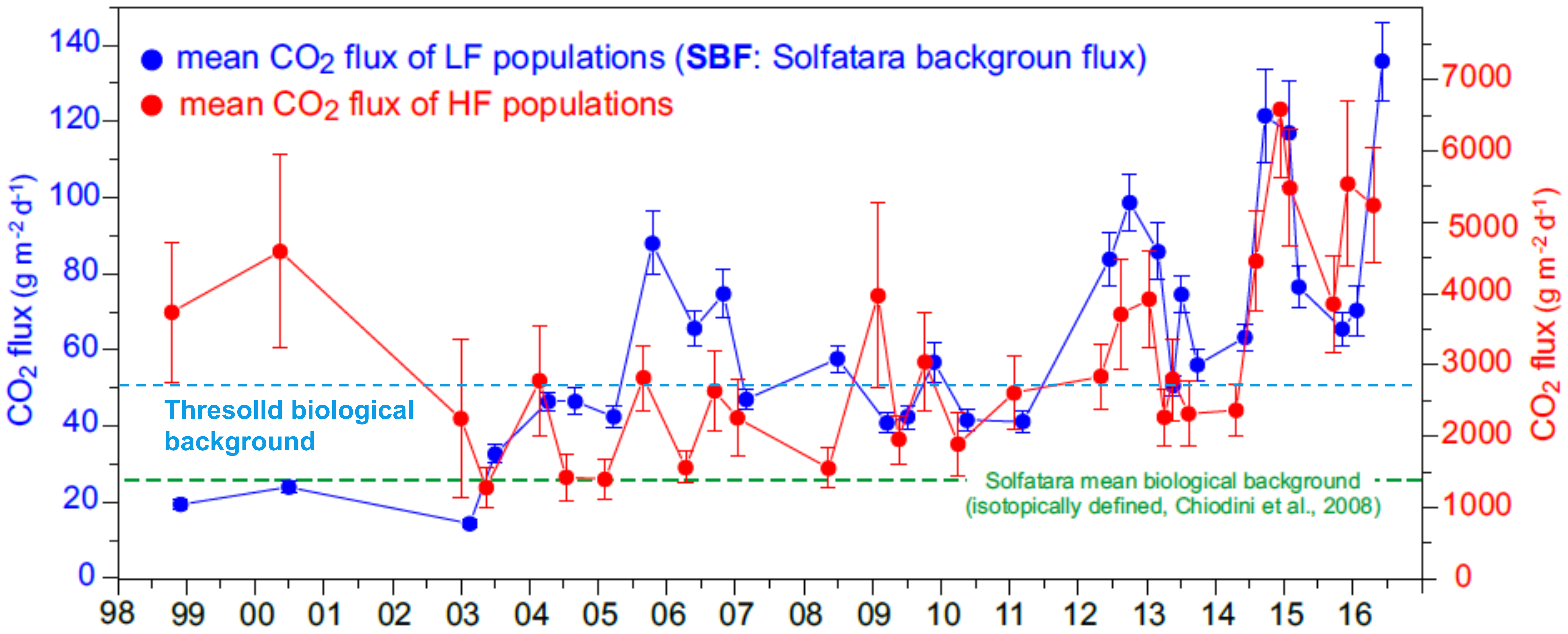


From Acocella and Chiodini (2015)

Periodic injections of magmatic gas into the Campi Flegrei hydrothermal system, with an increasing frequency since 2005, and a **progressive heating** of the system drive the ground deformation especially in the last unrest phase (Chiodini et al 2015)

Based on the CO2/H2O ratio of high temperature fumaroles we estimate that the system releases more than $1.9*10^{13}$ J/d (>138 MW) of thermal energy - one order of magnitude higher than conductive heat flux and several times higher than the energy associated to the seismic crises and deformation events

Time variations of CO_2 fluxes from soil

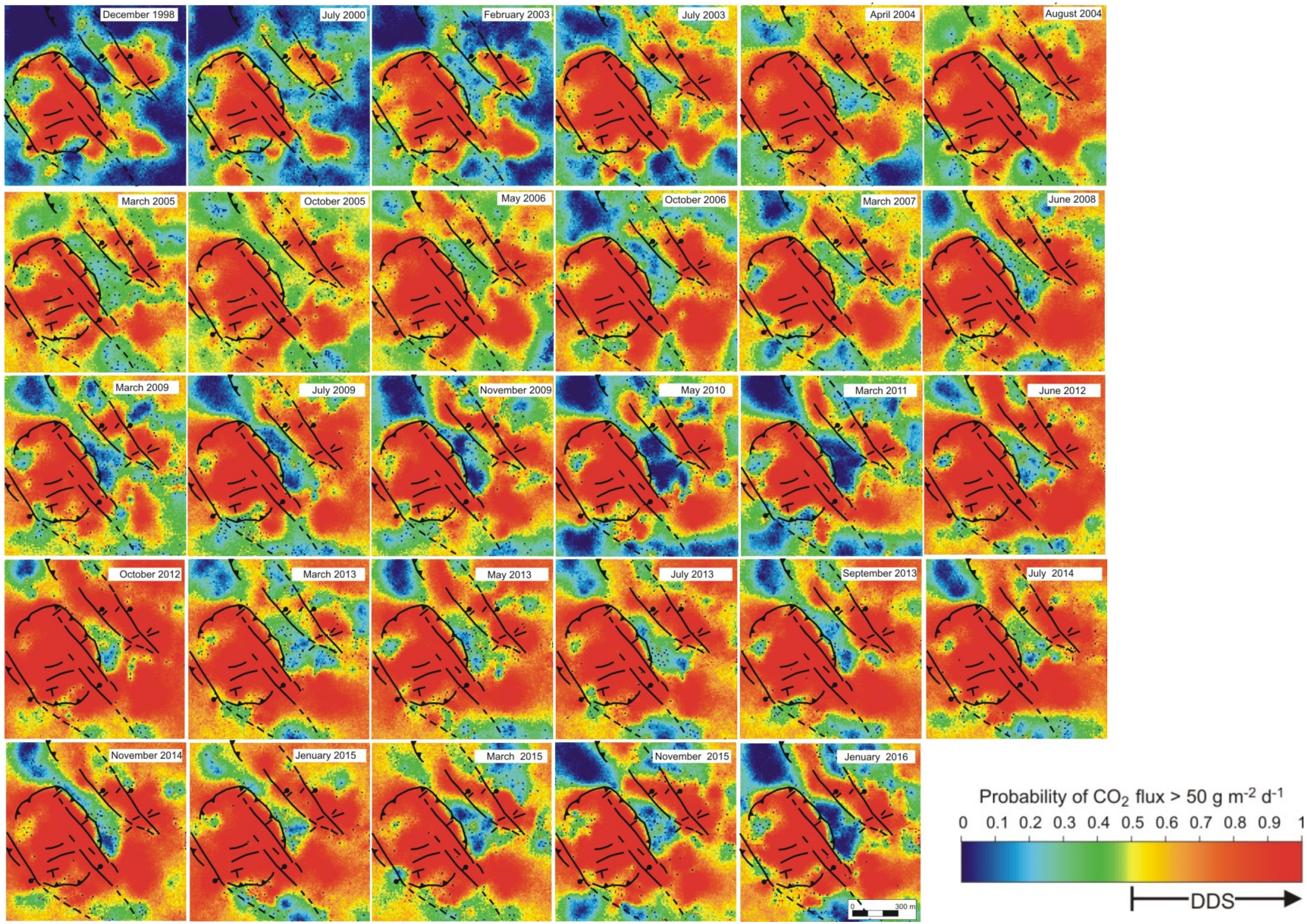


Both LF and HF showed relevant variations

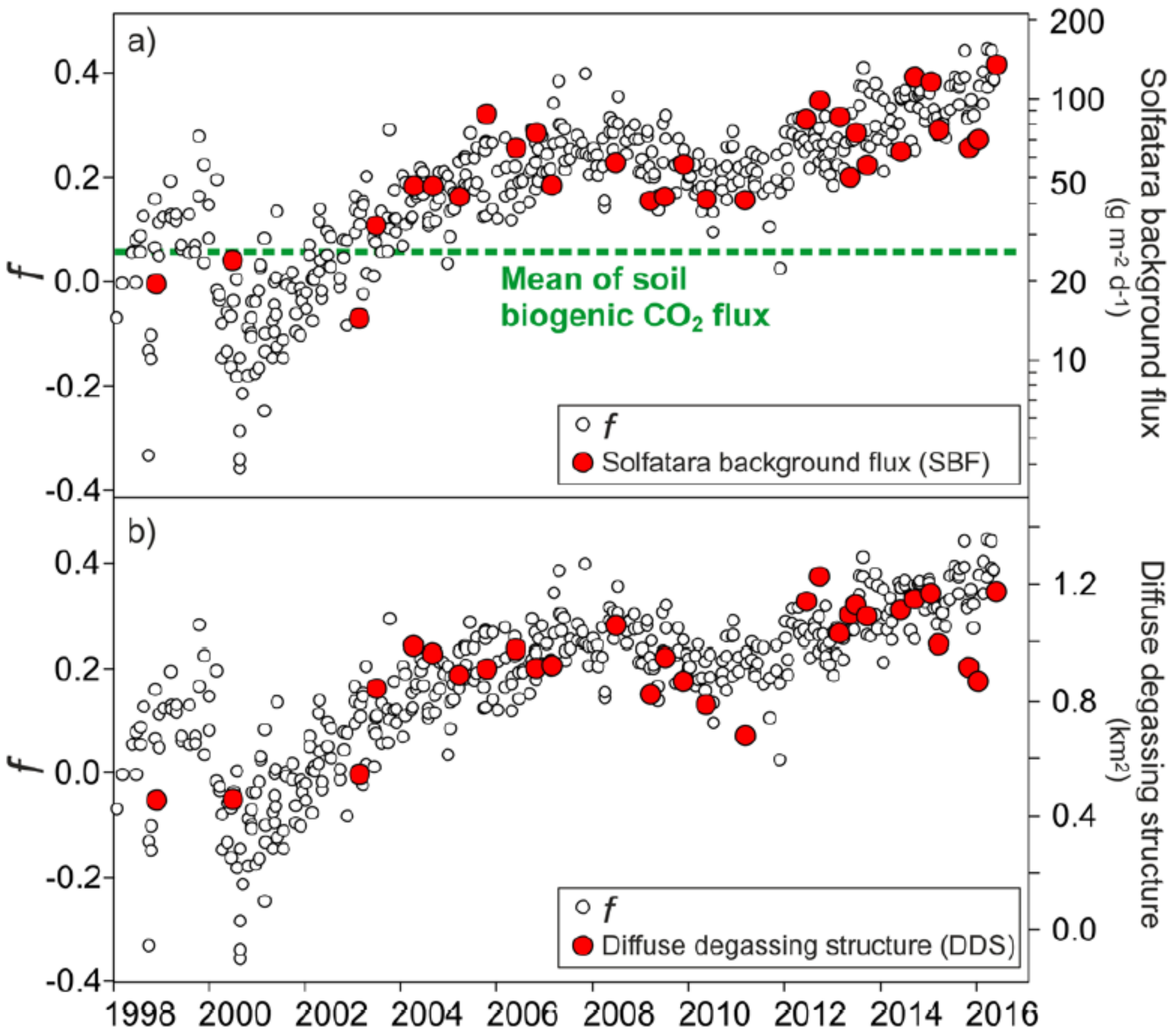
Since 2003-2004 LF Population was no more representing the biological background.

Since from 2010-2011 LF and HF showed the same trend of variation suggesting generalized increase in the degassing.

Time variation of the diffuse degassing structure (DDS) extent



Time variation of the diffuse degassing structure (DDS)

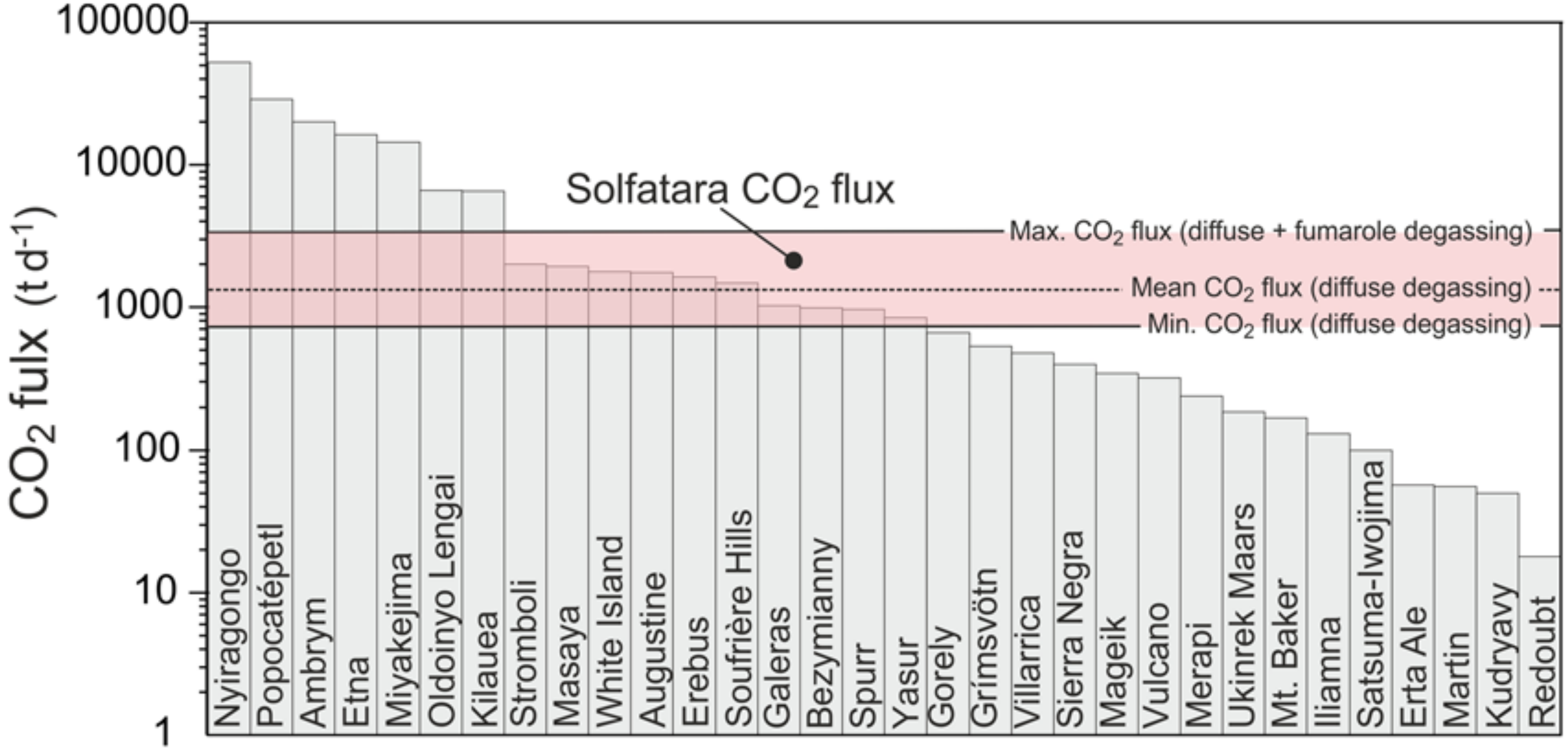


From Cardellini et al., 2017
Chiodini et al., 2015

f = the fraction of the water removed (f > 0, condensation) or added (f < 0, addition of water) in secondary processes during the transfer of the vapor from the equilibration zone to the fumaroles. Computed by the compositions of BG and BN fumaroles

The trend of variation of the extent of DDS area well correlates with the increasing in water condensation (inducing a temperature increase) **within and at the border of the Solfatara gas plume** in 2005-2015, **caused by the increase of the flux of the magmatic fluids** in to the hydrothermal system (Chiodini et al., 2015)

CO_2 degassing at Solfatara compared with mean volcanic plume CO_2 fluxes from persistently degassing volcanoes



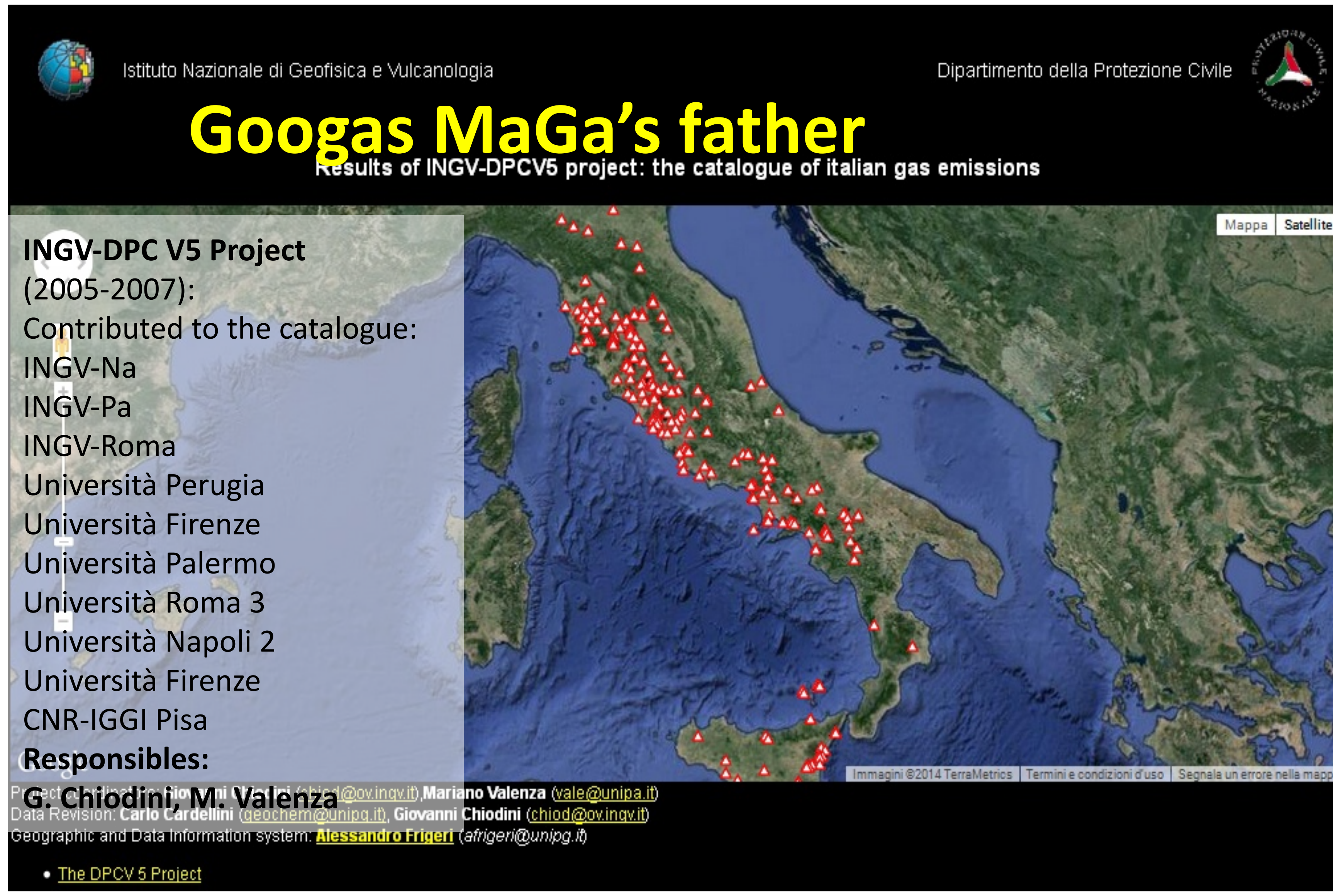
Volcanic plumes from Burton et al., 2013

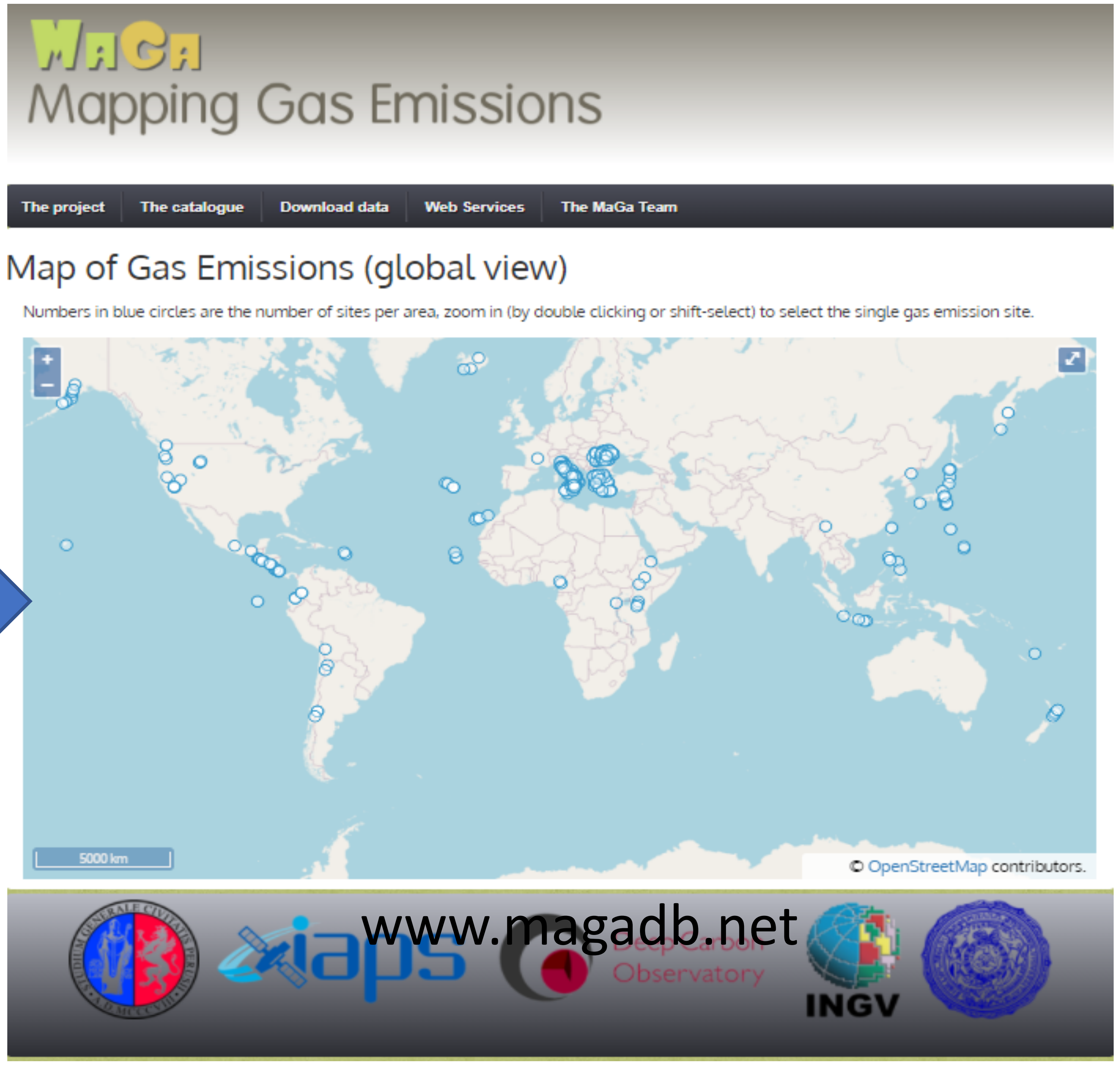
The amount of CO_2 released by the degassing of the hydrothermal system of Solfatara is comparable to the CO_2 released by medium-large volcanic plume

… sharing our data…

MaGa Mapping Gas emissions

a collaborative web environment for collecting and share data





a tool to aggregate and share information and data to support the research and improve the knowledge on Earth degassing and natural CO_2 fluxes to the atmosphere

Partially funded by MIUR — MINISTERO DELL' ISTRUZIONE, DELL'UNIVERSITÀ E DELLA RICERCA; DEEP CARBON OBSERVATORY RESERVOIRS AND FLUXES

Italian Ministry of Education, University Research, PRIN project 2008/S89Y8R Observations and Modelling of Gas Emissions from the source to the Atmosphere (2008). PI: Francesco Frondini
From a static catalogue to a dynamic collaborative environment for data collection non volcanic gas emission

DCO-sub Contract (2014)
Data mining and ingestion, web improvements

DCO-Mini Grant (2014)
User manual and web page improvements, explore interoperability

DCO-Grant (2013) A database for volcanic/non volcanic CO_2 emissions in the Mediterranean area PI: Carlo Cardellini
- **Design of the new Maga database structure to include emission types from volcanic degassing**
- **Data mining and ingestion for Mediterranean Volcanoes**

MaGa’s state of the art

At the present time the MaGa database includes:

- **~ 1000 gas emission sites** including volcanic plumes, fumaroles, diffuse degassing areas and gas vents at **volcanoes and degassing non volcanic regions.**
- Emission sites from **158 volcanoes** in **30 country**
- **~ 2000 data of gas flux** and gas composition (under implementation)

Hosted by: Hetzner Online GmbH • Industriestr. 25 • 91710 Gunzenhausen • Germany

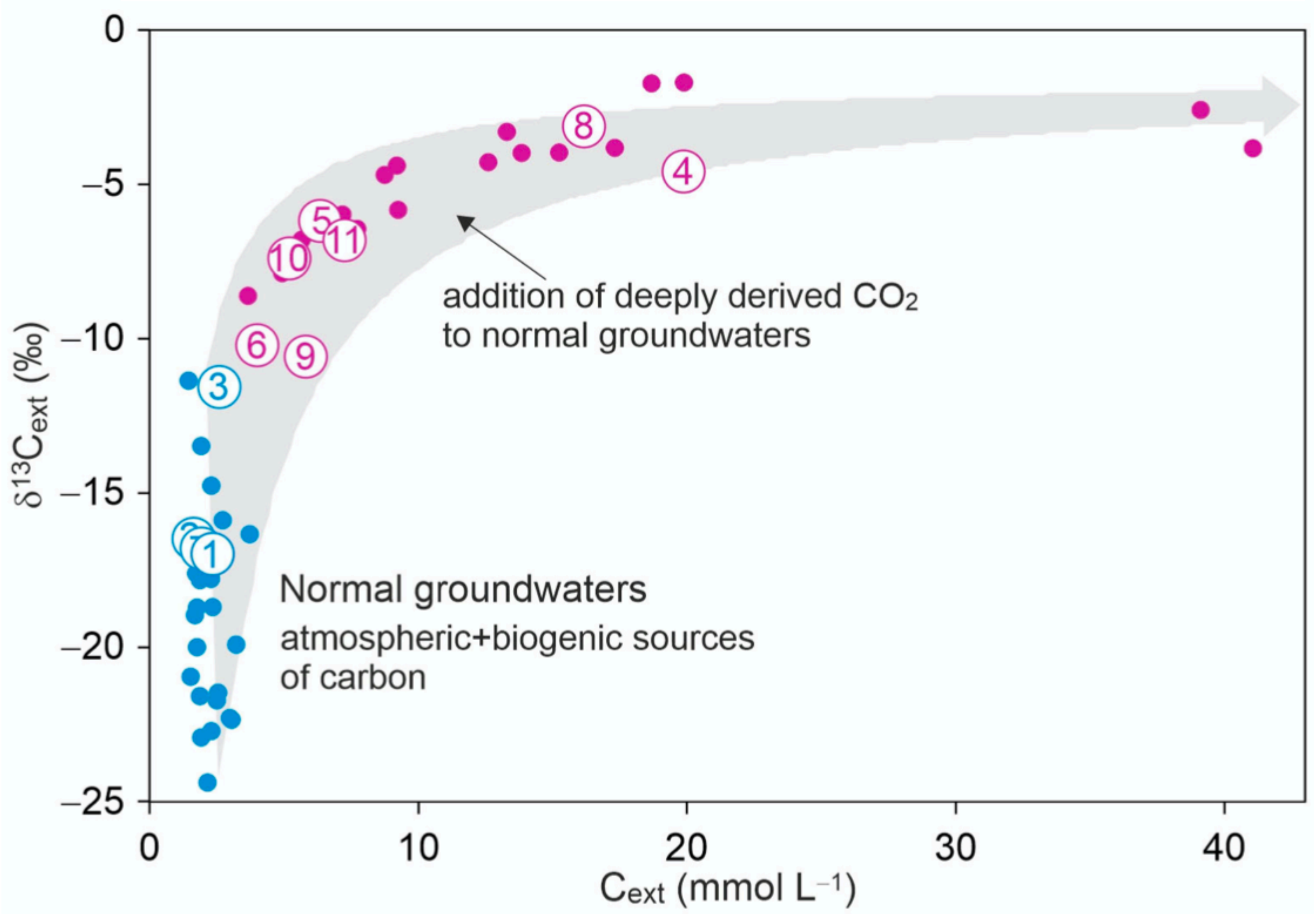
In the meantime we started measuring the CO_2 dissolved in groundwater and we discovered that it was a huge amount…. maybe a new missing source was found…

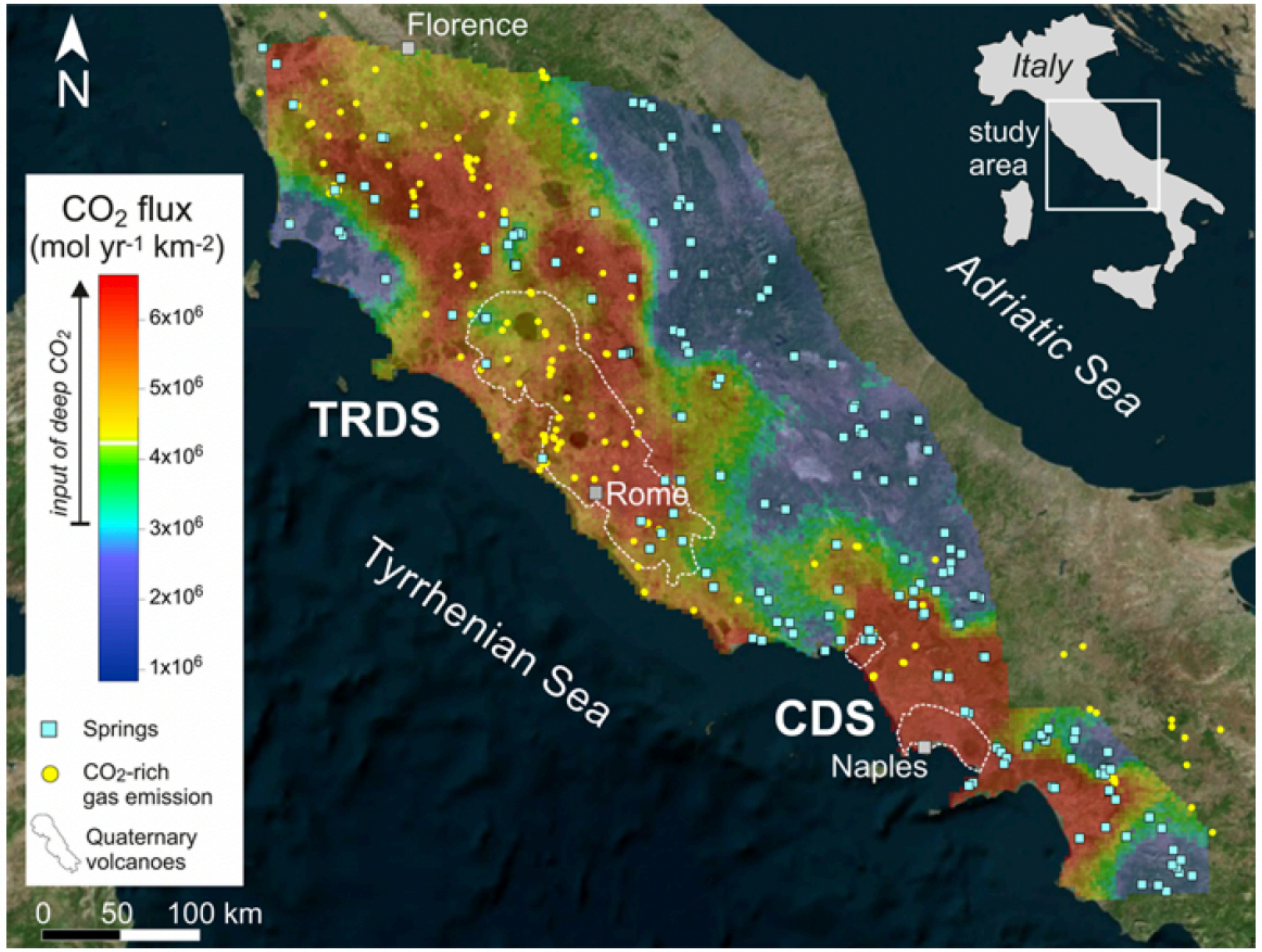
The carbon mass and isotopic balance of regional aquifers is a powerful tool to quantify the diffuse degassing of deep inorganic carbon sources because the method integrates the CO_2 flux over large areas (Chiodini et al., 2000; Chiodini et al., 2014; Frondini et al., 2019).

The evolution of the TDIC and $^{13}C/^{12}C$ ratio of natural water systems is described by the following equations:

$$d(\mathrm{TDIC}) = \sum_{i=1}^{N} dI_i - \sum_{i=1}^{M} dO_i \qquad (1)$$

$$d(R_{\mathrm{TDIC}}) = \sum_{i=1}^{N} R_i^* dI_i - \sum_{i=1}^{M} R\alpha_{i-s} dO_i \qquad (2)$$





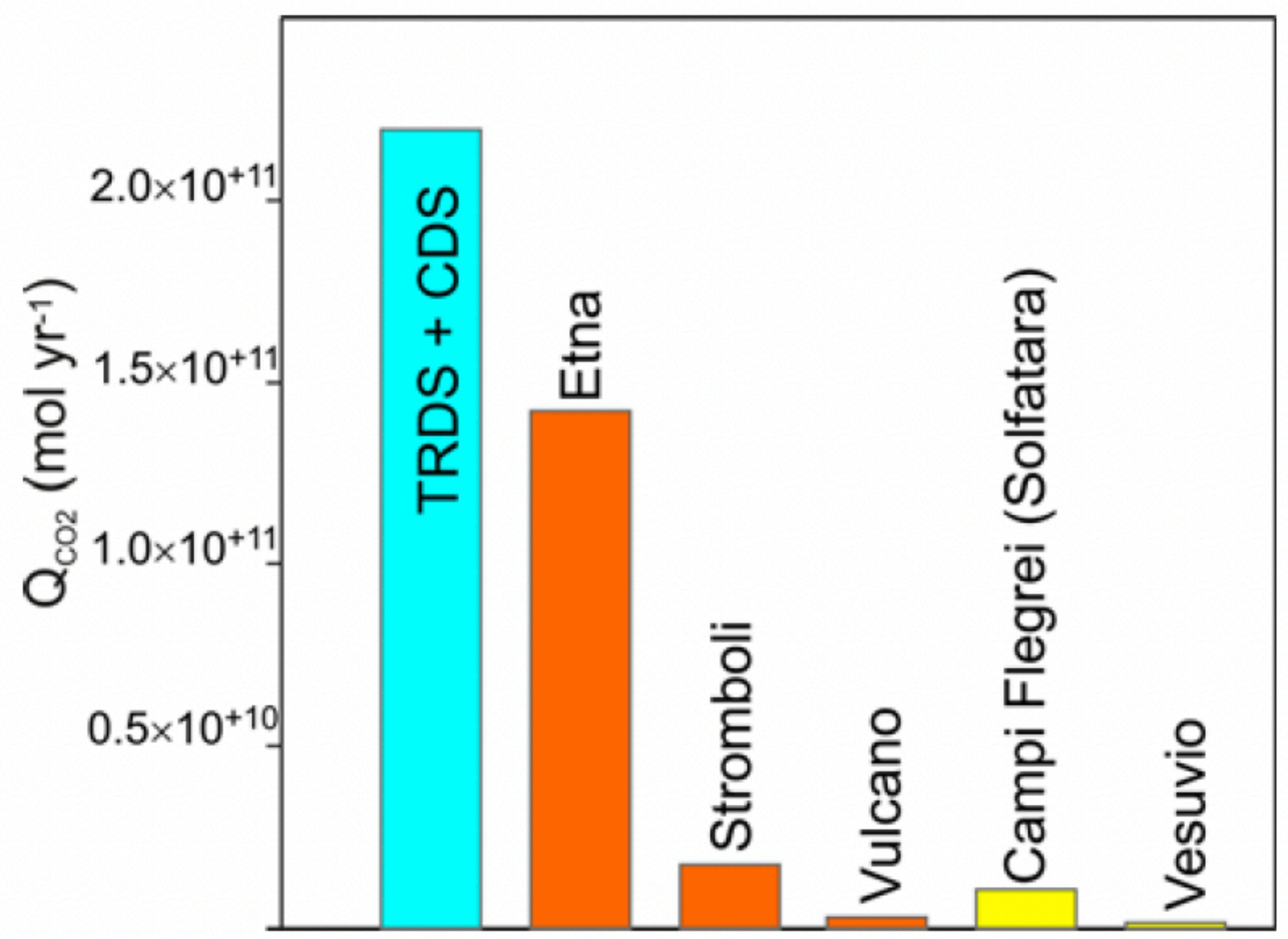


Fig. 6. Output of deeply derived CO_2 in Italy from volcanoes with hydrothermal systems (yellow), volcanoes emitting SO_2 (red), and from regional diffuse degassing structures in central Italy (blue).

total CO2 flux estimates cannot be reliably quantified without the investigation of groundwaters, which in permeable orogens of tectonically young and active areas can dissolve most, if not all, the CO_2 rising from depth.

CO2 and seismicity

SCIENCE ADVANCES | RESEARCH ARTICLE

GEOCHEMISTRY

Correlation between tectonic CO_2 Earth degassing and seismicity is revealed by a 10-year record in the Apennines, Italy

G. Chiodini[1], C. Cardellini[1,2]*, F. Di Luccio[3], J. Selva[1], F. Frondini[2], S. Caliro[4], A. Rosiello[2], G. Beddini[2], G. Ventura[3,5]

10-year record (2009–2018) of tectonic CO2 flux in the Apennines (Italy) during intense seismicity.

The gas emission correlates with the evolution of the seismic sequences: Peaks in the deep CO2 flux are observed in periods of high seismicity and decays as the energy and number of earthquakes decrease.

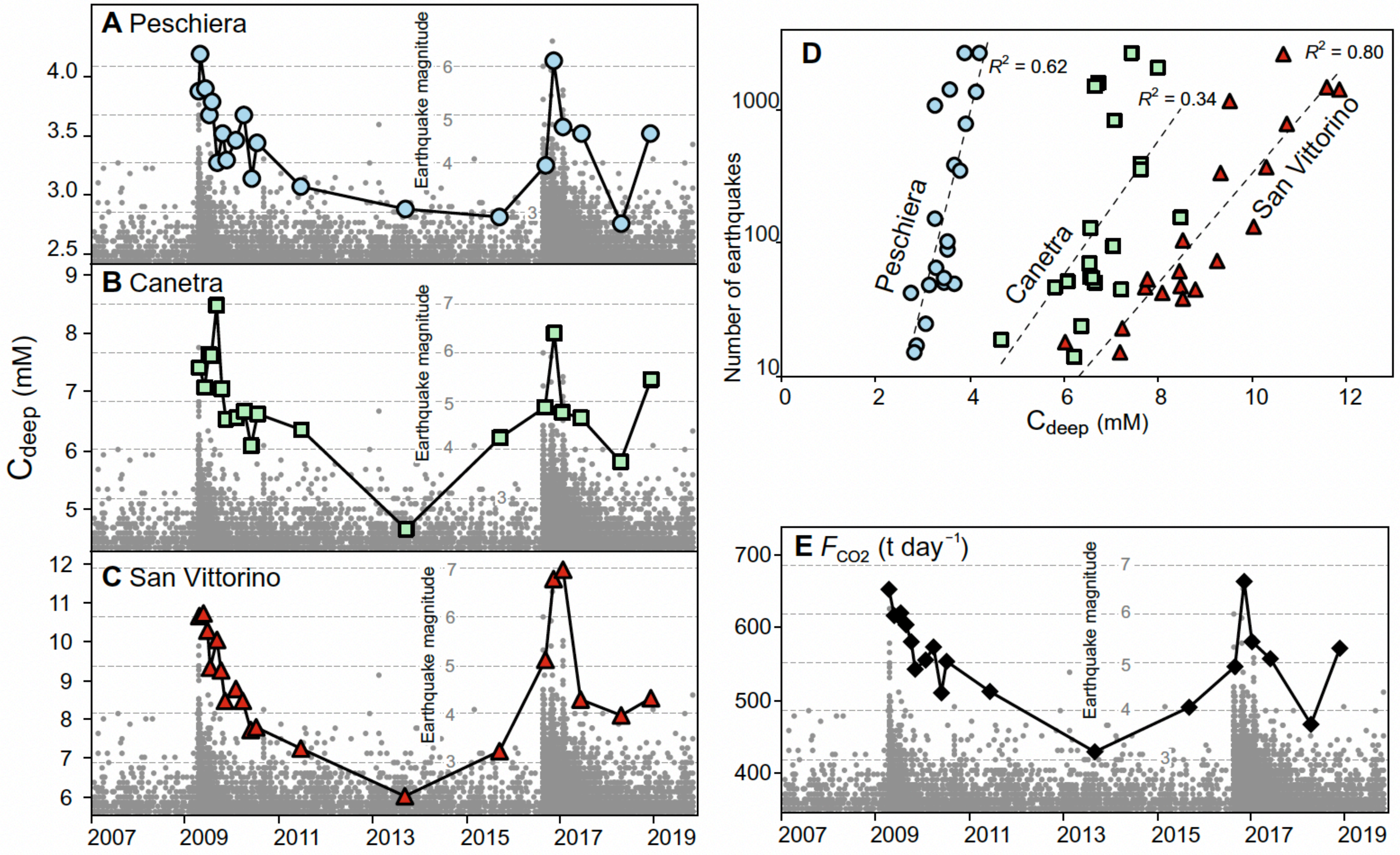


Fig. 2. Temporal evolution of CO_2 degassing and seismicity. (**A** to **C**) Chronograms of the earthquake magnitudes compared with the concentration of deeply derived carbon (C_{deep}) in the monitored springs. (**D**) Binary plots of C_{deep} of the monitored springs against the log number of the earthquakes occurred at distances <45 km in a period of 80 days centered at any sampling date. (**E**) Chronogram of the earthquake magnitudes compared with the daily amount of deeply derived CO_2 dissolved by the groundwaters of the Velino aquifer (F_{CO2}).

The evolution of seismicity is modulated by the ascent of CO2 accumulated in crustal reservoirs and originating from the melting of subducted carbonates.

This large-scale, continuous process of CO2 production favors the formation of overpressurized CO2-rich reservoirs potentially able to trigger earthquakes at crustal depth.

Implications for climate and paleo-climate

Global CO_2 flux from tectonically active areas in the framework of global carbon budget… is there a gap of knowledge??

GEOLOGY, April 2013; v. 41; no. 4; p. 495–498; Data Repository item 2013129 | doi:10.1130/G34007.1 | Published online 20 February 2013

Mantle ^3He and CO_2 degassing in carbonic and geothermal
Colorado and implications for neotectonics of the Rocky M

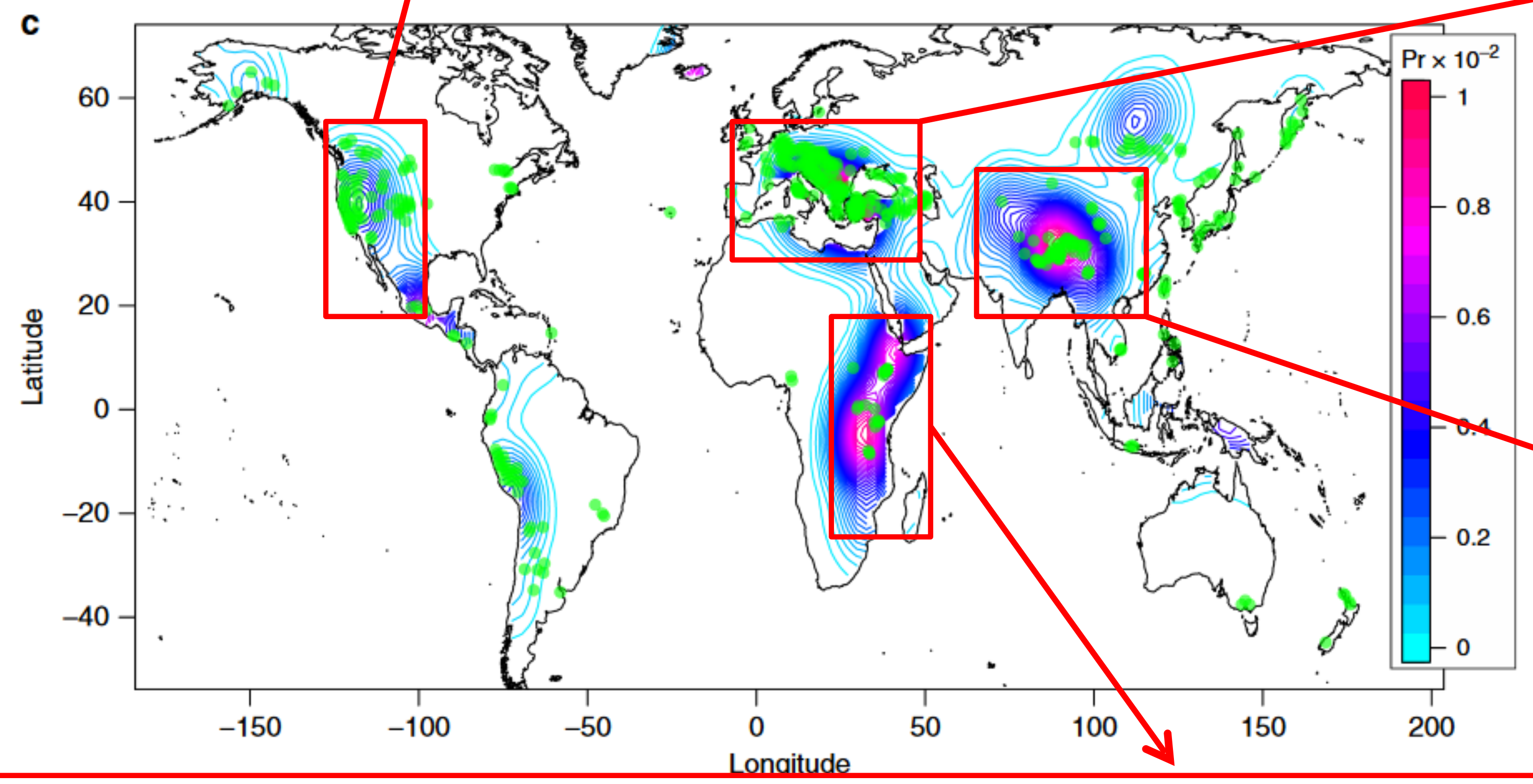
Karl E. Karlstrom[1*], Laura J. Crossey[1], David R. Hilton[2], and Peter H. Barry[2]
[1]Department of Earth and Planetary Sciences, University of New Mexico, Albuquerque, New Mexico 87131, USA
[2]Geosciences Research Division, Scripps Institution of Oceanography, La Jolla, California 92093, USA

CO_2 flux (mol y^{-1})
3.0×10^8

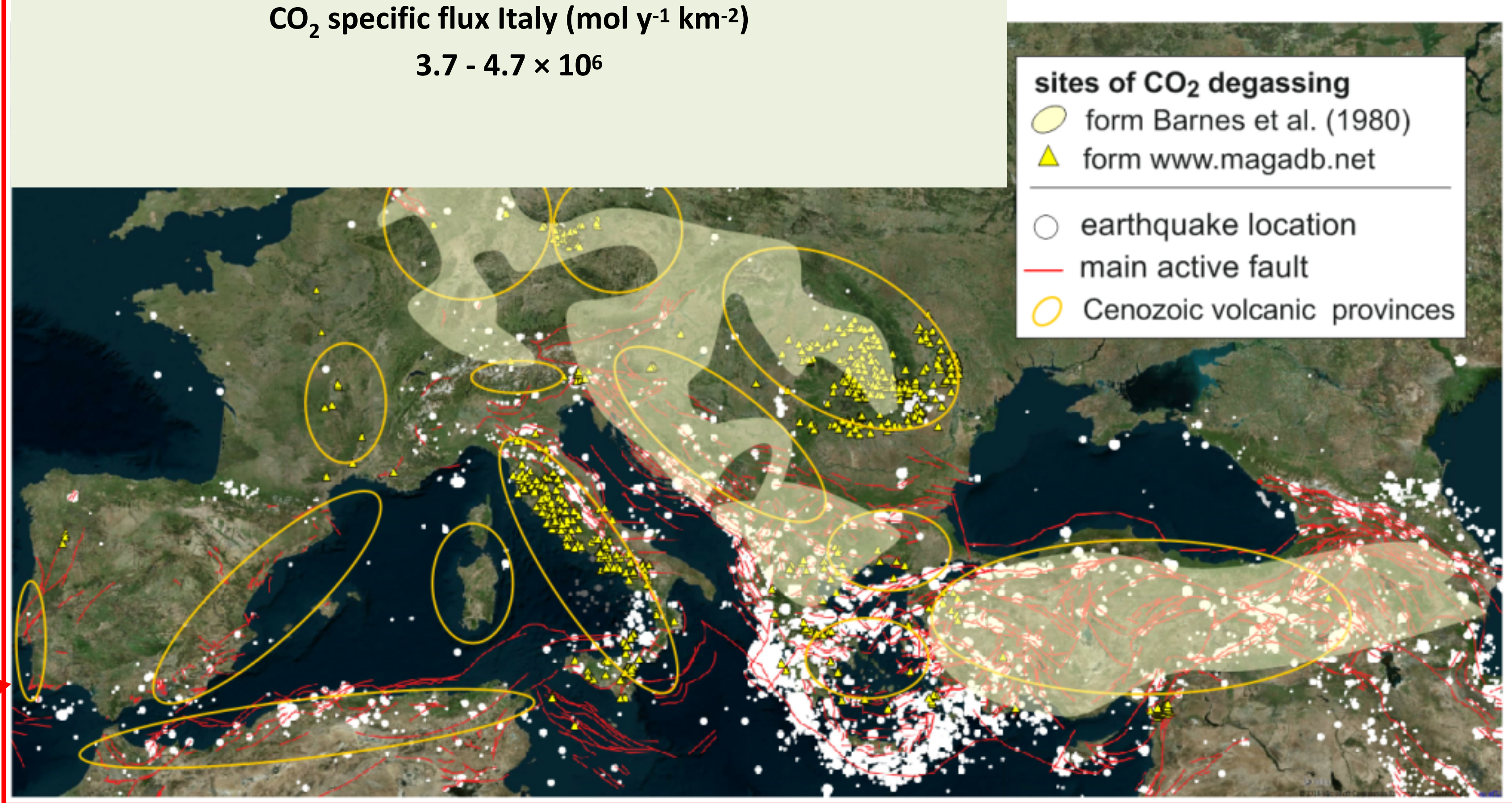
Degassing of mantle-derived CO_2 and He from springs in the southern Colorado Plateau region—Neotectonic connections and implications for groundwater systems

Laura J. Crossey[1,*] Karl E. Karlstrom[1], Abraham E. Springer[2], Dennis Newell[1,3], David R. Hilton[3], Tobias Fis
[1]Department of Earth and Planetary Sciences, University of New Mexico, Albuquerque, New Mexico 87131, USA
[2]Department of Geology, P.O. Box 4099, Northern Arizona University, Flagstaff, Arizona 86011, USA
[3]Geosciences Research Division, Scripps Institution of Oceanography, La Jolla, California 92093, USA

CO_2 flux (mol y^{-1})
1.0×10^9



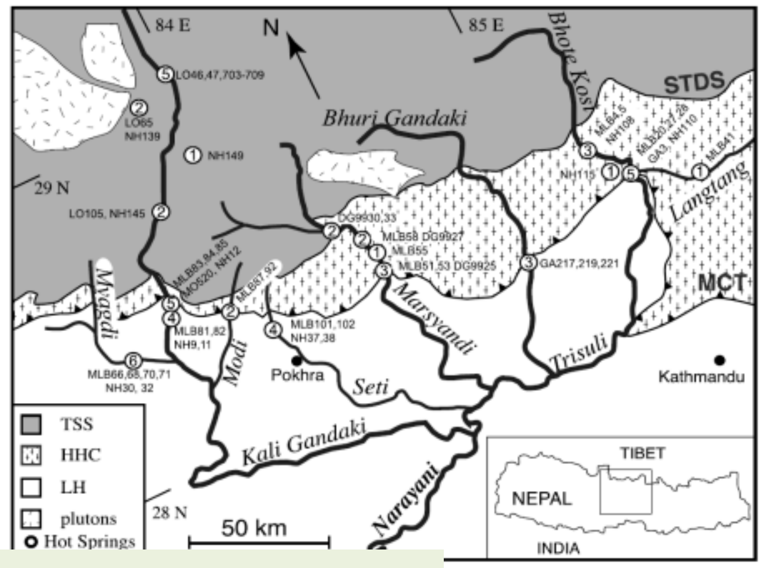
CO_2 specific flux Italy (mol y^{-1} km^{-2})
3.7 - 4.7×10^6



Geochemistry Geophysics Geosystems G3
AN ELECTRONIC JOURNAL OF THE EARTH SCIENCES
Published by AGU and the Geochemical Society
Research Letter
Volume 9, Number 4
15 April 2008
Q04021, doi:10.1029/2007GC001796
ISSN: 1525-2027

Degassing of metamorphic carbon dioxide from the Nepal Himalaya

Matthew J. Evans
Chemistry Department, Wheaton College, Norton, Massachusetts 02766, USA (evans_matt@wheatonma.edu)
Louis A. Derry
Department of Earth and Atmospheric Sciences, Cornell University, Ithaca, New York 14853, USA
Christian France-Lanord
CRPG-CNRS, Nancy University, Vandoeuvre-les-Nancy, France

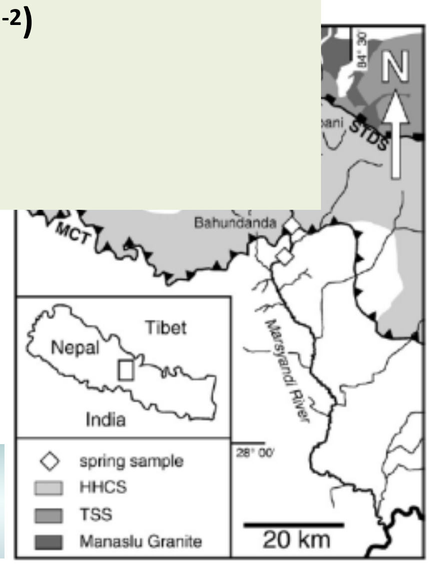


CO_2 specific flux (mol y^{-1} km^{-2})
$1.2 \times 10^5 – 2.67 \times 10^6$

ELSEVIER

Himalayan metamorphic CO_2 fluxes: Quantitative constraints from hydrothermal springs

John A. Becker, Mike J. Bickle*, Albert Galy, Tim J.B. Holland



nature COMMUNICATIONS

Persistent CO_2 emissions and hydrothermal unrest following the 2015 earthquake in Nepal

Frédéric Girault[1], Lok Bijaya Adhikari[2], Christian France-Lanord[3], Pierre Agrinier[4], Bharat P. Koirala[2], Mukunda Bhattarai[2], Sudhan S. Mahat[5], Chiara Groppo[6], Franco Rolfo[6], Laurent Bollinger[7] & Frédéric Perrier[1]

AGU PUBLICATIONS

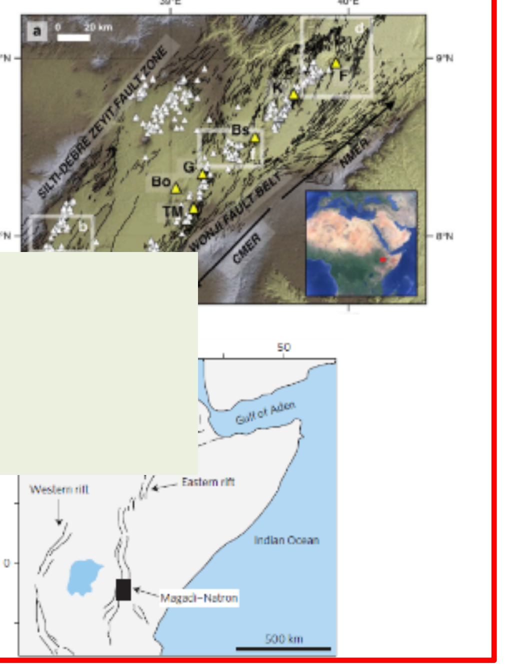
Geochemistry, Geophysics, Geosystems

RESEARCH ARTICLE
10.1002/2017GC006975

Special Section:
Carbon Degassing Through Volcanoes and Active Tectonic Regions

Key Points:
• New gas surveys show that diffuse

Spatially Variable CO_2 Degassing in the Main Ethiopian Rift: Implications for Magma Storage, Volatile Transport, and Rift-Related Emissions



CO_2 specific flux (mol y^{-1} km^{-2})
$4.6 \times 10^6 – 9.7 \times 10^7$

nature geoscience

Massive and prolonged deep carbon emissions associated with continental rifting

Hyunwoo Lee[1*], James D. Muirhead[2], Tobias P. Fischer[1], Cynthia J. Ebinger[3], Simon A. Kattenhorn[2,4], Zachary D. Sharp[1] and Gladys Kianji[5]

How much is the global CO_2 flux from tectonically active areas?

<u>rough computation assuming:</u>

CO_2 specific flux: $10^6 – 10^7$ mol y^{-1} km^{-2}
Tectonically active areas ~ 1-2×10^7 km^2 ?

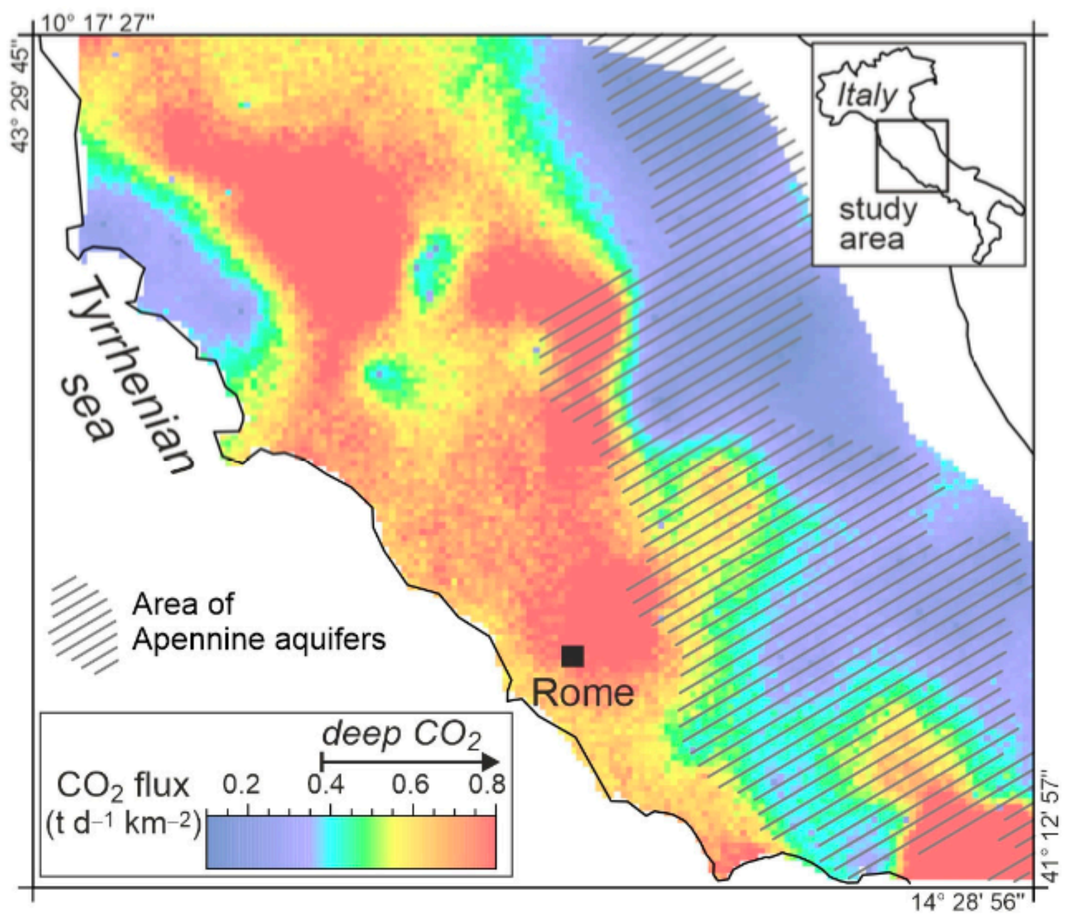
CO_2 flux 0.4 – 9.0 $GtCO_2$ y^{-1} ??

i.e.

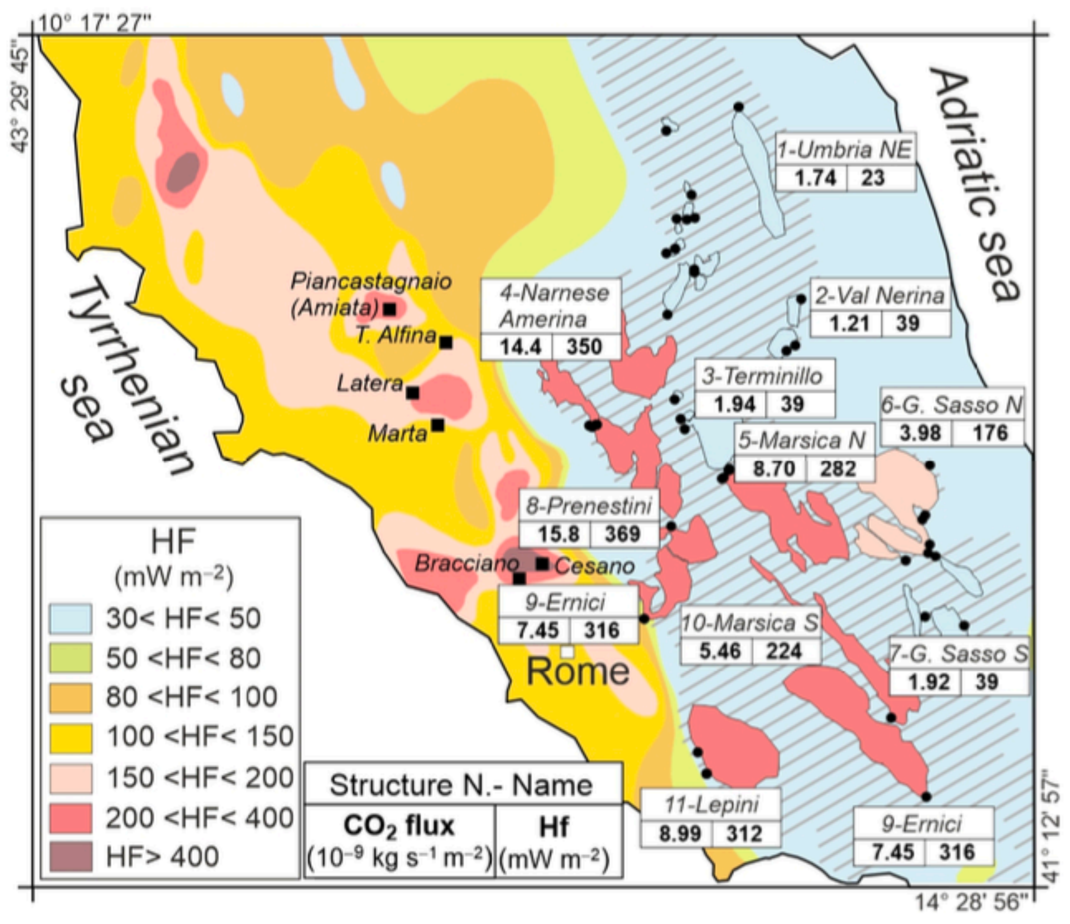
~ 1 - 20% ??? of the anthropogenic CO_2 emission* *(*fossils fuel+industy+land use ~38 $GtCO_2$/y (Le Quéré et al., 2016))*

Geothermal implications

Enthalpy and CO_2 Mass Balances of Regional Aquifers (Frondini et al., 2019; Chiodini et al., 2021).



(a)

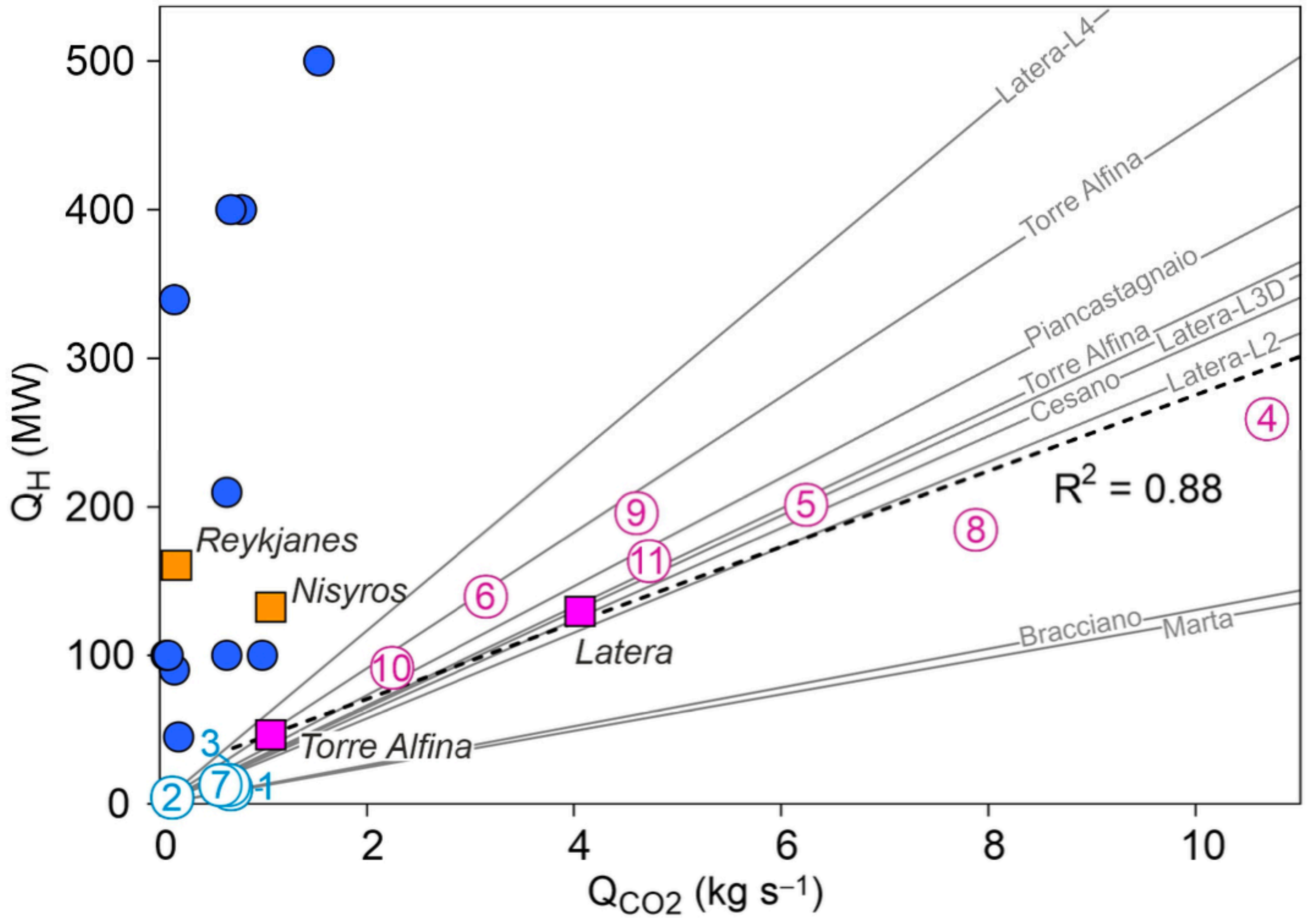


(b)

$$\Delta T = T_s - T_r = (F_H)/(\rho_w \times C_w) \times A/q + \Delta z \times (g/C_w)$$

$$Q_H = F_H \times A$$

N.	Name	Q $m^3\,s^{-1}$	A km^2	Hf $mW\,m^{-2}$	Q_H MW	CO_2 Flux $kg\,s^{-1}\,m^{-2}$	Q_{CO2} $kg\,s^{-1}$
1	Umbria NE	6.73	399	23	9.3	1.74×10⁹	0.69
2	Val Nerina	1.78	105	39	4.1	1.21×10⁹	0.13
3	Terminillo	5.79	340	39	13.2	1.94×10⁹	0.66
4	Narnese-Amerina	15.00	740	350	259.4	1.44×10⁸	10.67
5	Marsica N	22.35	716	282	202.2	8.70×10⁹	6.23
6	G Sasso N	17.95	793	176	139.9	3.98×10⁹	3.16
7	G Sasso S	7.00	309	39	12.2	1.92×10⁹	0.59
8	Prenestini	9.00	499	369	184.3	1.58×10⁸	7.87
9	Ernici	18.00	618	316	195.5	7.45×10⁹	4.60
10	Marsica S	9.80	411	224	91.9	5.46×10⁹	2.24
11	Lepini	14.80	525	312	163.7	8.99×10⁹	4.72



The typical CO_2/heat ratio of central Italy is one order of magnitude higher than that of other geothermal zones of the Earth (e.g., Taupo and Salton Trough geothermal systems).

Besides the potentiality in the exploration phase, the measure of the CO_2 emissions can find valuable applications in evaluating the environmental impact of geothermal exploitation.

The future research

The study of the C production-storage-tranfer processes in different geologic settings will improve our understanding of seismic and volcanic processes, contributing to their mitigation and monitoring, and will contribute to the refinement of the global climate models.

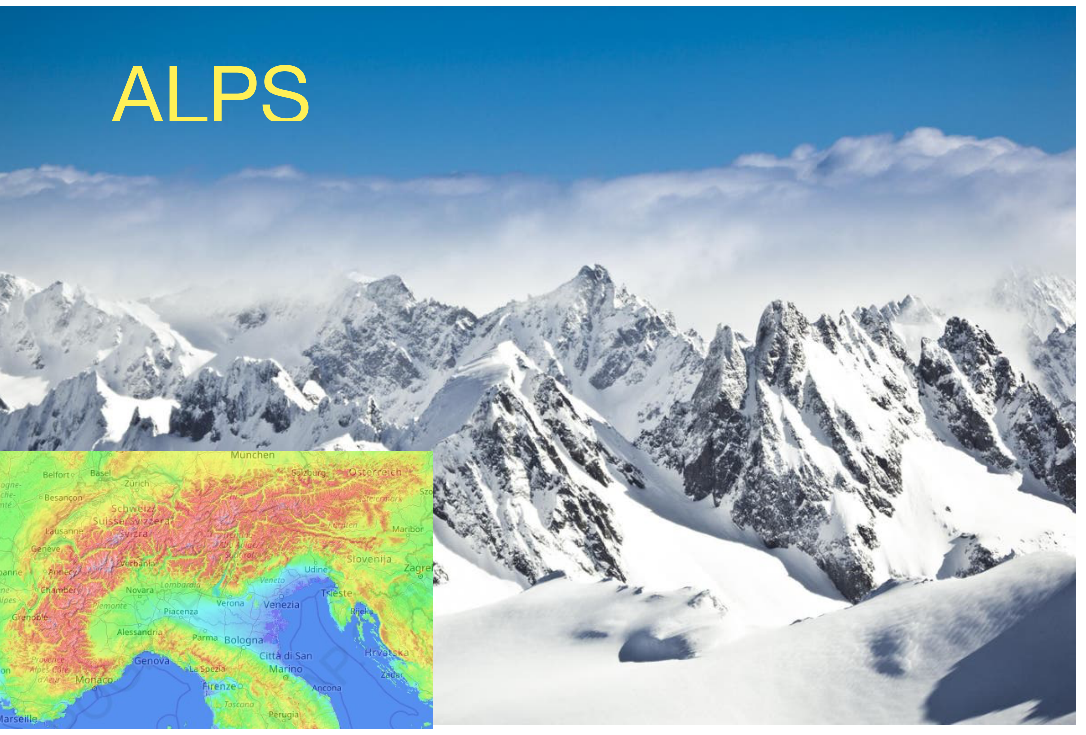
TARGETS

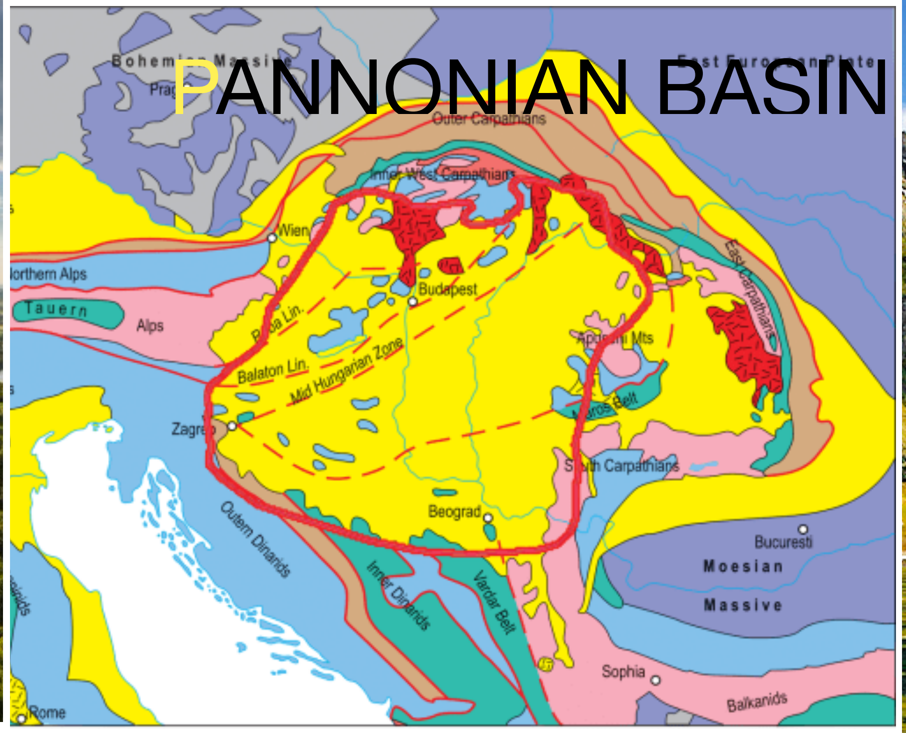
1
How accurate is our current understanding of source processes and pathways governing C cycling through volcanism?

2
How/to what extent do chemical and physical variables (including redox state of fluids and melts) influence the efficiency of C transport from the mantle to the surface?

3
What are the respective roles of mantle and crustal sources in contributing to outgassing of non-volcanic CO2 in tectonically active regions of the globe?

STUDY AREAS



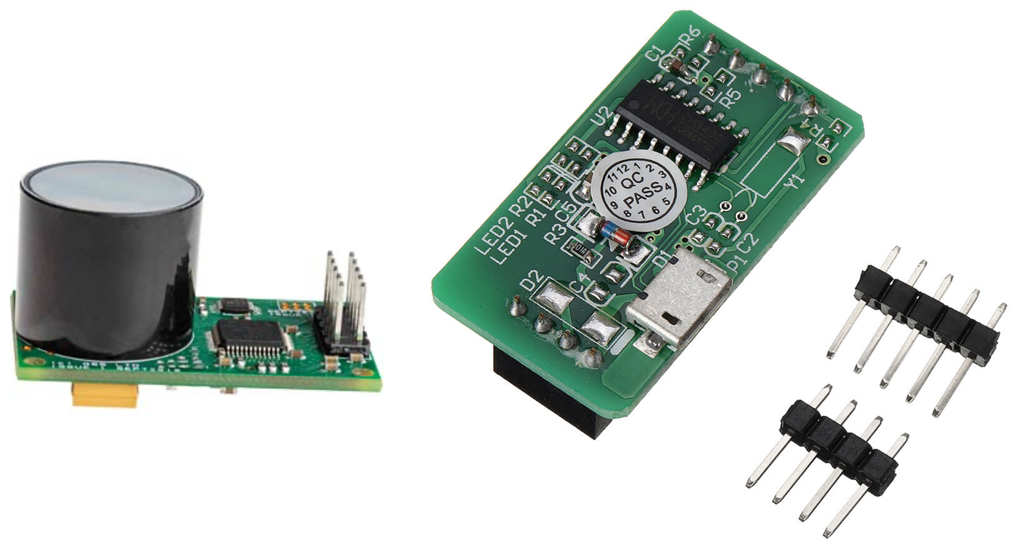


TECHNIQUES: mass and carbon isotope balance - enthalpy balance - noble gas geochemistry - comparison of gas composition with fluid inclusion (in xenoliths) - reverse CO_2 fluxes (CO_2 consumption)

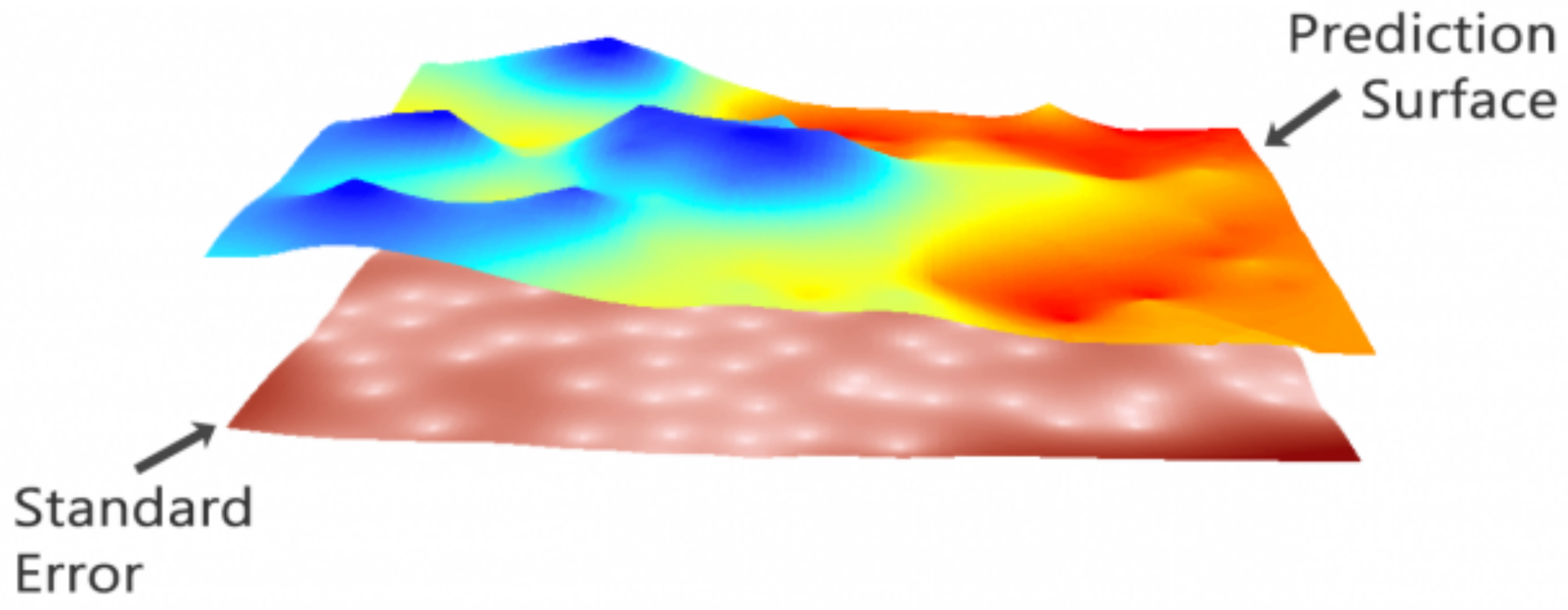
The future research

The development of new measuring and data analysis techniques is fundamental.

- Testing and field trials of new sensors (low cost and low power consumption) for CO_2 in air and groundwater.



- Development and field testing of a new multi-parametric low power consumption accumulation chamber (environmental parameters, CO_2, CH_4, VOC) with Thearen s.r.l.
- Development of an accumulation chamber for reverse flux measurements



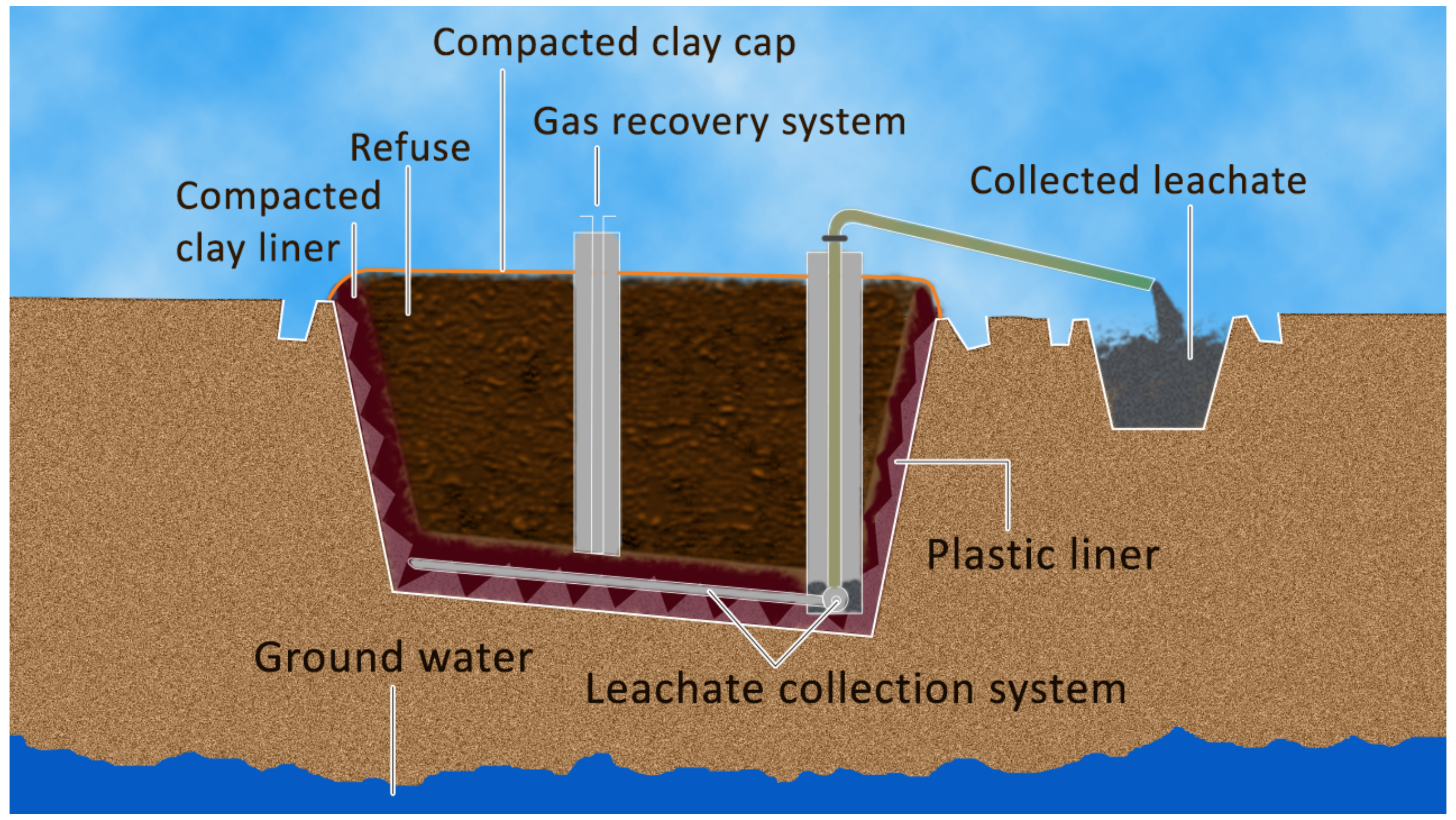
- Development of new geo statistical software for the real-time management of monitoring networks and data validation.

The future research

Further applications

Application of the techniques developed for volcanic surveillance to environmental issues:

monitoring gas emission from dumps



remediation (contaminated sites)

CCS monitoring


Thank you!