Monitoring natural CO2 flow in the mofettes of the West Bohemia seismoactive region

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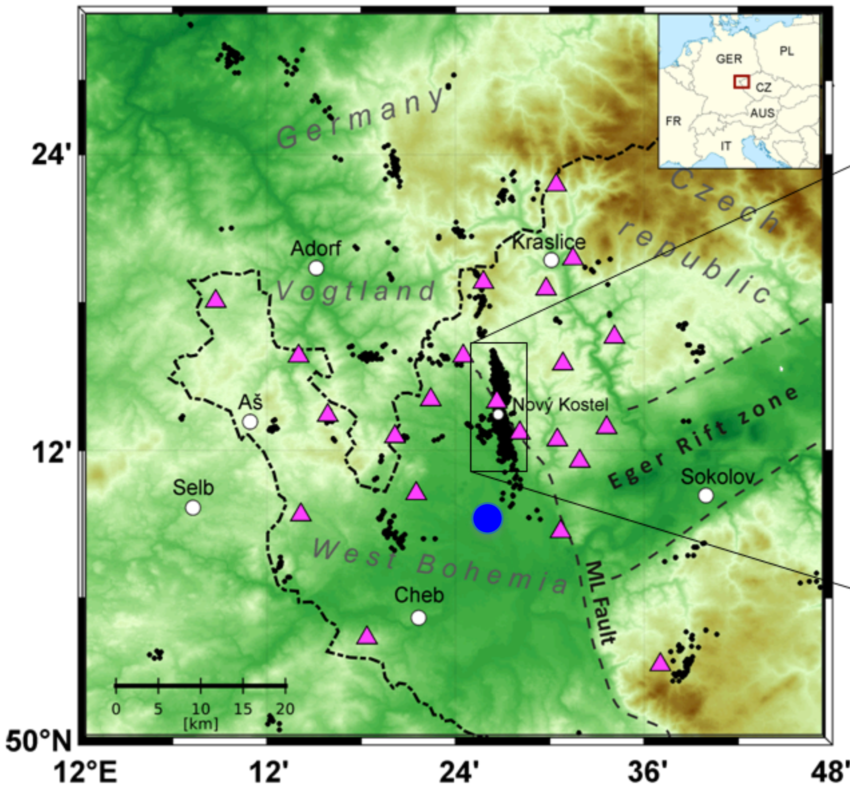
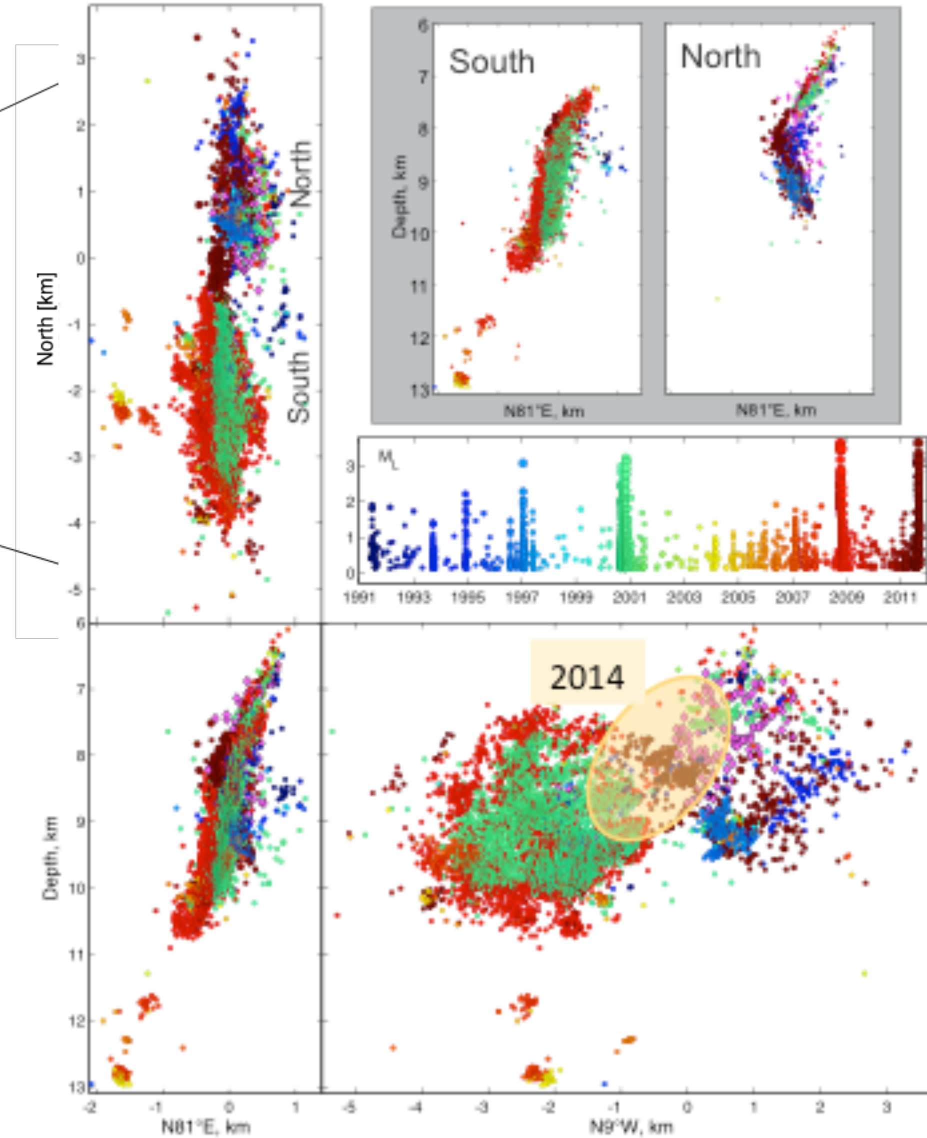
Outline

- Earthquake swarms and CO_2 degassing in West Bohemia/Vogtland
- Methods of CO_2 flow monitoring
- Coseismic CO_2 increase during the 2014 sequence - fault valve model
- Monitoring data for 2007-2019
- Interpretation
- Summary

West Bohemia/Vogtland - Nový Kostel zone swarms





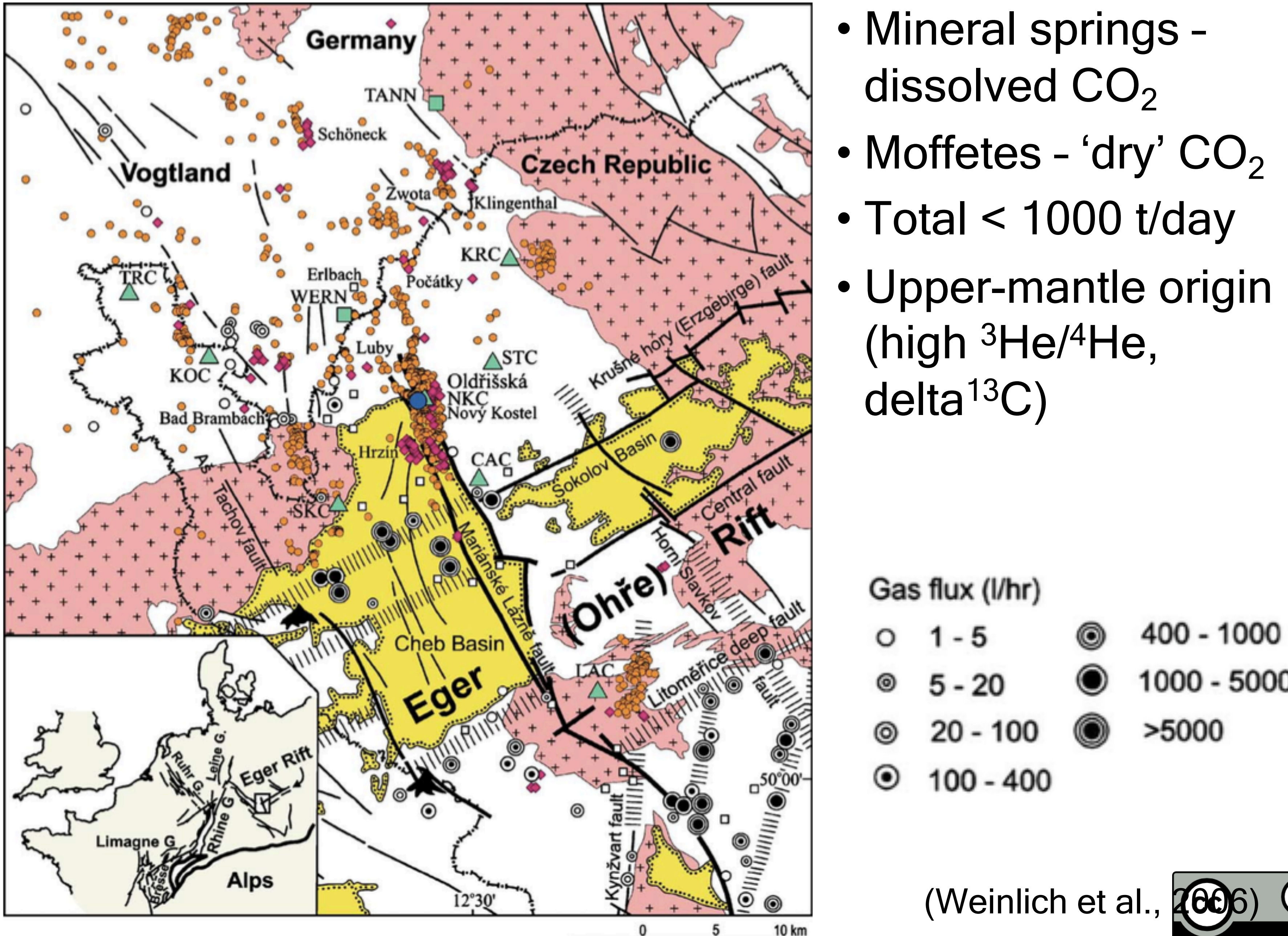
Main focal zone (Nový Kostel)

- steeply dipping focal zone
- composed of principal fault and associated minor faults

Swarms

- 1985/86 M4.6
- 1997, 2000, 2008, 2011, 2017 M3+
- 2014, 2018 M4+

CO_2 degassing



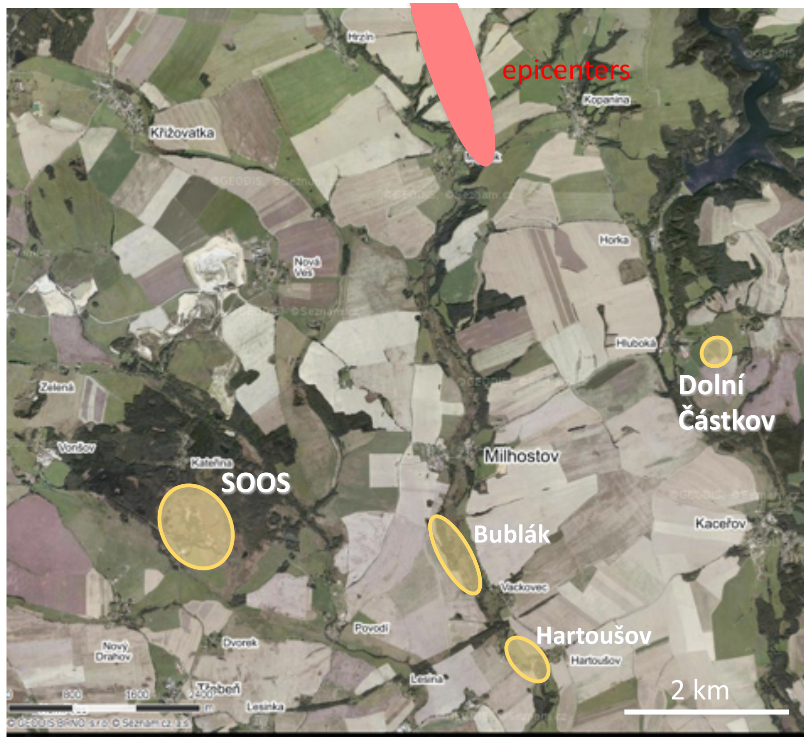
- Mineral springs - dissolved CO_2
- Moffetes - 'dry' CO_2
- Total < 1000 t/day
- Upper-mantle origin (high $^3He/^4He$, delta^{13}C)

(Weinlich et al., 2006)

CO_2 flow monitoring network

GSM network with near-real time data transfer

Hartoušov F1 borehole



Soos mofettes

Bublák mofettes

Hartoušov F2 borehole

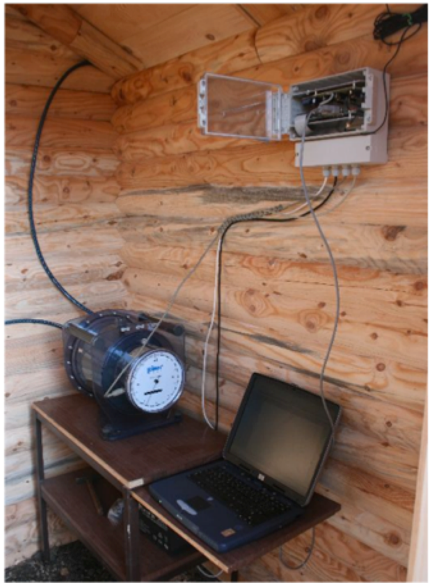
Hartoušov mofette

Dolní Částkov borehole

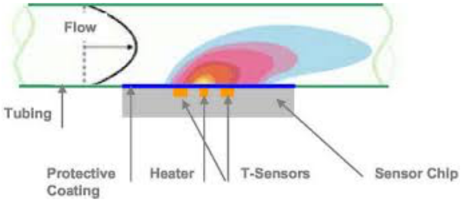
How to reliably measure CO_2 flow ?

Direct methods

- Chamber gas counter - filled by liquid, gas collected in chambers; problems in the field:
  - Evaporation of the liquid, condensation of moisture
  - Freezing temperatures

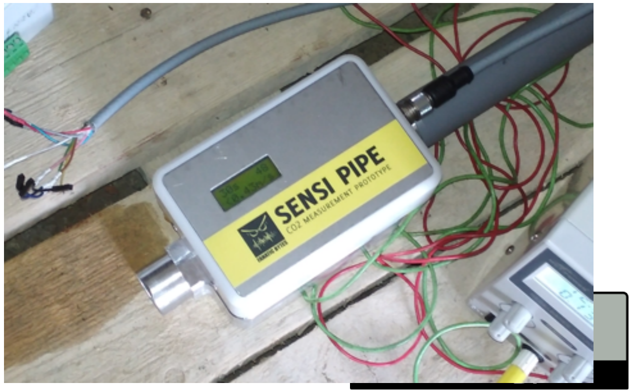


- MEMS gas flowmeters – damaged in the case of condensation of water from the gas



- Venturi tube – condensation and temperature sensitive

- Acoustic method – sound speed in opposite directions (being tested)



How to reliably measure CO_2 flow ?

Indirect methods

- Fraction Φ of gas bubbles in a borehole

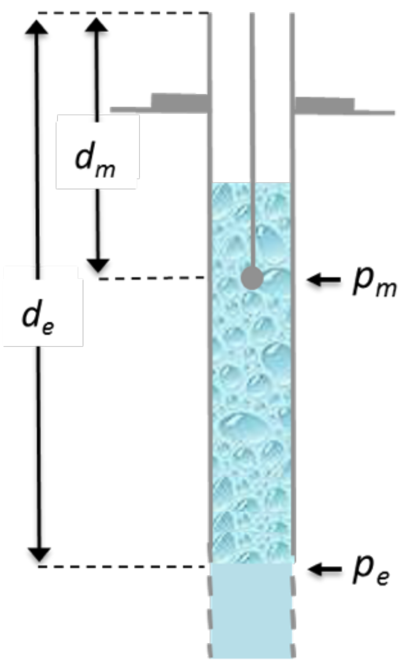
  a) based on electric conductivity of water

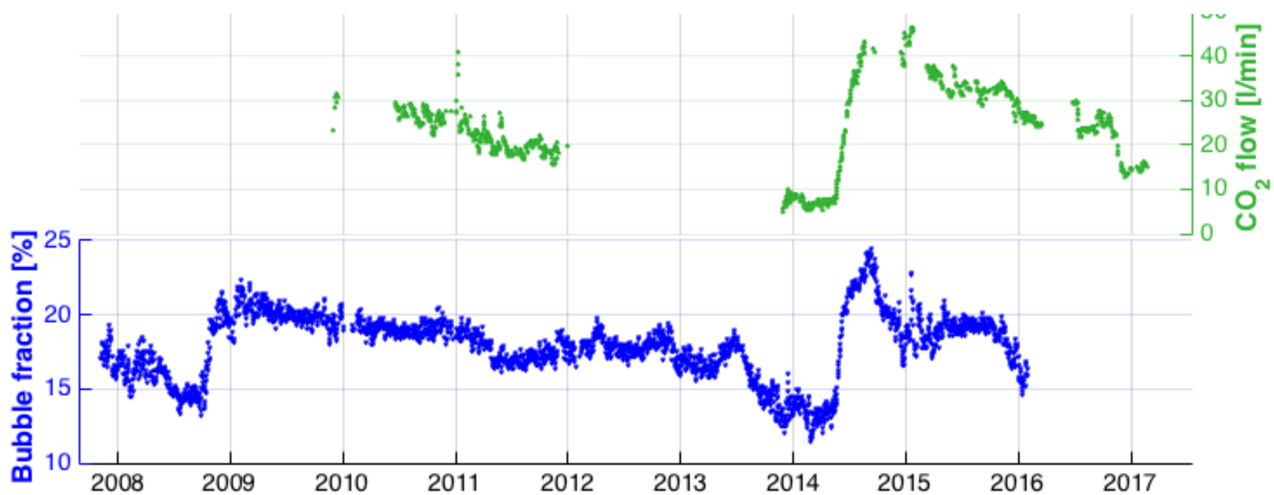
  $$\phi(t) = 1 - c\ R_R(t)/R_M(t)$$

  R_R - reference resistivity of water free of bubbles
  R_M - resistivity of mixture of water with bubbles

  b) based on differential pressure in water

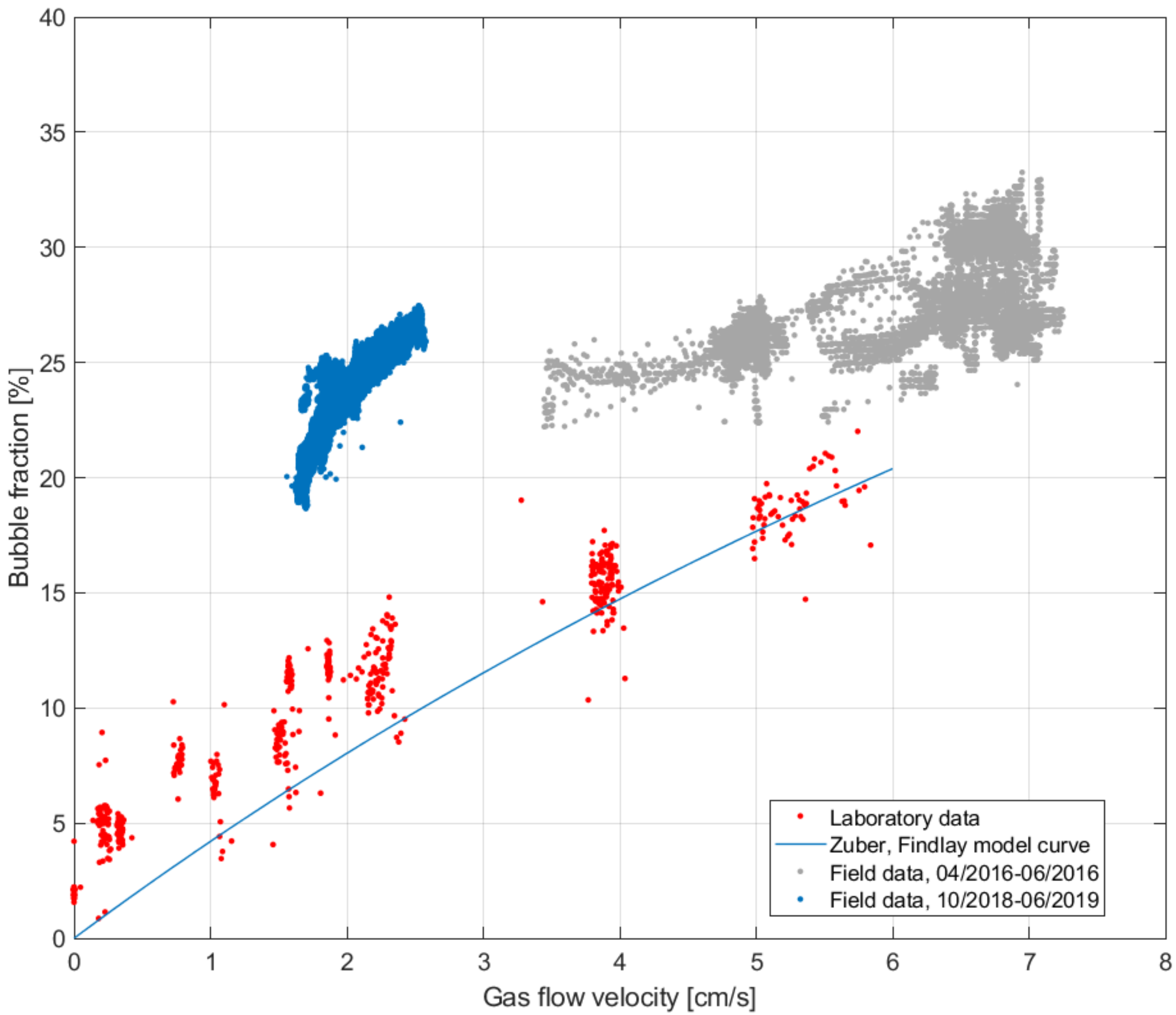
  $$\phi(t) = \frac{p_e(t) - p_m(t)}{d_e - d_m}$$





Tests of the bubble fraction method

Compare the flow velocity and bubble fraction in the laboratory, field - Hartoušov F1 borehole and with the empirical relation of Zuber and Findlay (1965).



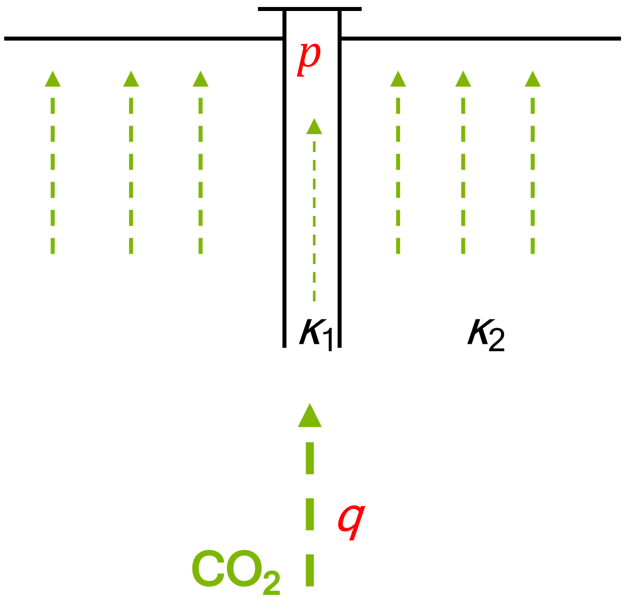
Laboratory (air, flow velocity 0-6 cm/s): good fit with the Zuber relation

Hartoušov (natural CO_2, two periods, 1.7 – 7.3 cm/s): bubble fraction overestimated, further research needed

How to reliably measure CO_2 flow ?

Indirect methods

Pressure in a closed borehole



- Relation of pressure to deep flow

$$p = \frac{q}{\kappa_1 + \kappa_2}$$

- Closed borehole (κ_1 = 0) - pressure controlled by soil permeability κ_2 (leakage) only
- Recommended to allow for controlled vent (increase κ_1) in the wellhead to reduce the sensitivity to varying soil conditions

Barometric effects to gas flow

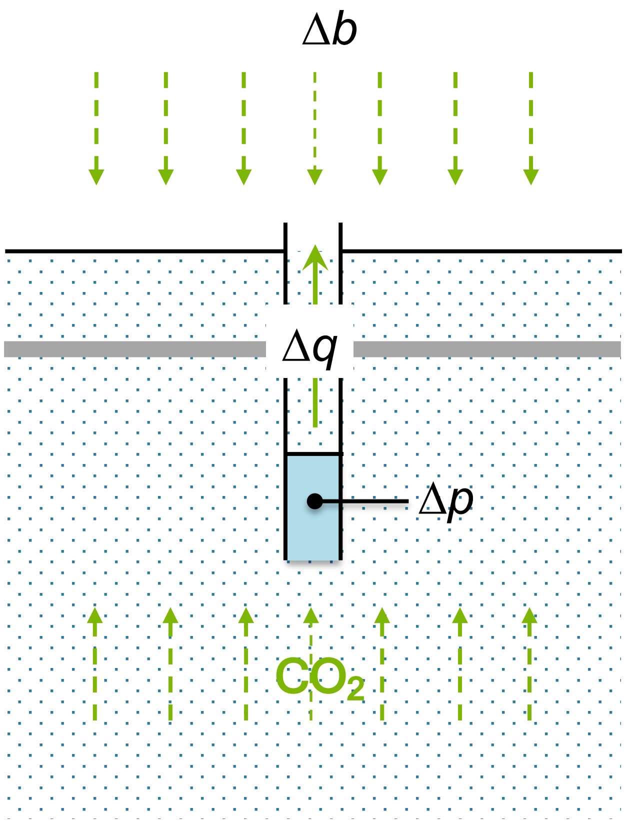
<u>Groundwater level response Δp</u>

- Barometric efficiency

$$E_B = \frac{\Delta p}{\Delta b} = \rho\, g \frac{\Delta h}{\Delta b}$$

- Related to porosity θ and compressibility of the rock α and water β

$$E_B = \frac{\theta\beta}{\theta\beta + \alpha}$$



- E_B = 0.2 - 0.7 for confined aquifers
- High E_B if rock is not compressible (granite) of water is compressible (gas bubbles)

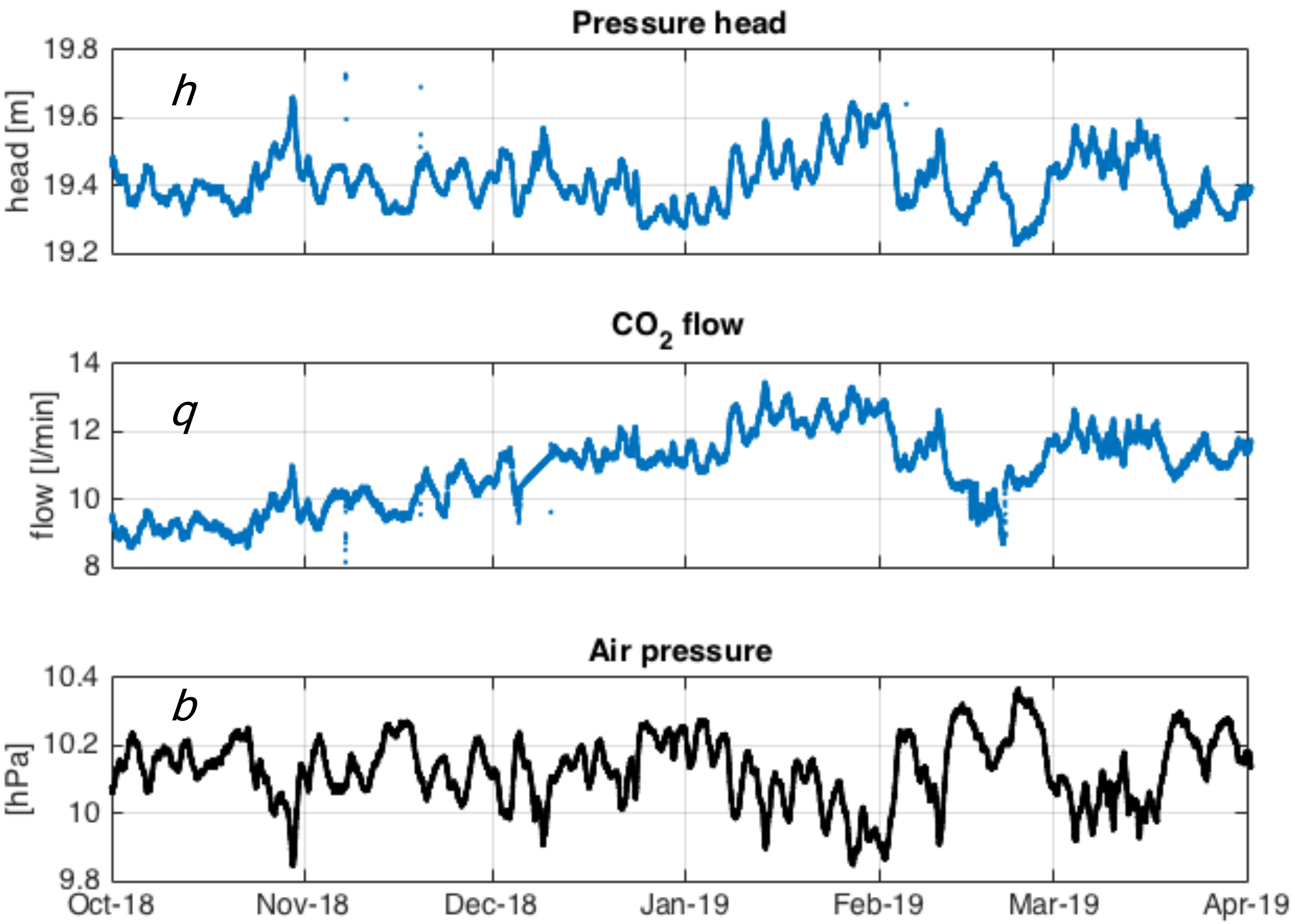
<u>Gas discharge response Δq</u>

- Barometric efficiency

$$T_B = \frac{\Delta q}{\Delta b} \quad \left[\frac{\text{l/s}}{\text{kPa}}\right]$$

Barometric effects to gas flow

- Remove air pressure influence as
  $h_{corr} = h - E_B \Delta b$; $q_{corr} = q - T_B \Delta b$
  by condition of minimum cross-correlation of original and corrected data

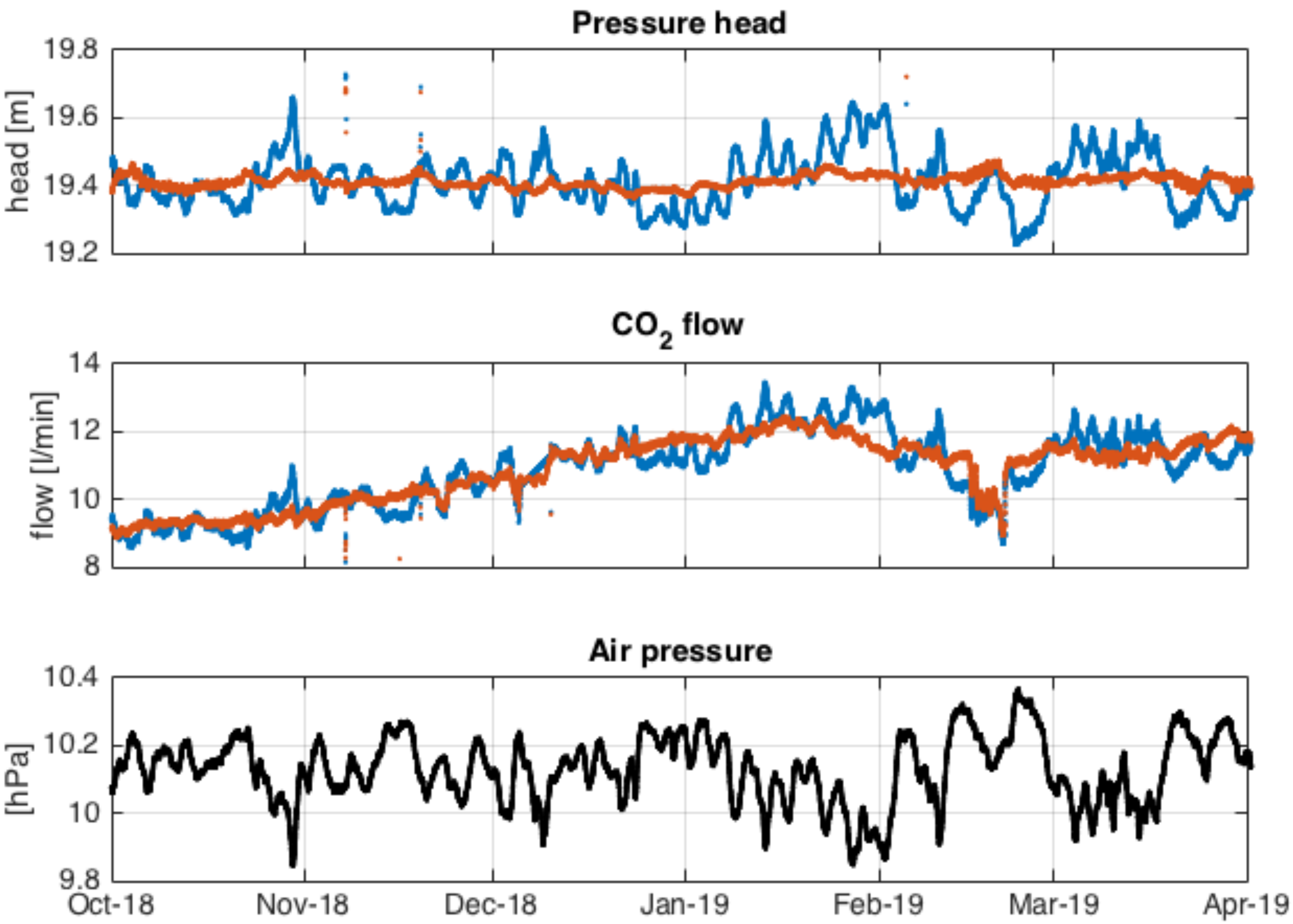


$h_{corr} = h - E_B \Delta b$

$q_{corr} = q - T_B \Delta b$

Barometric effects to gas flow

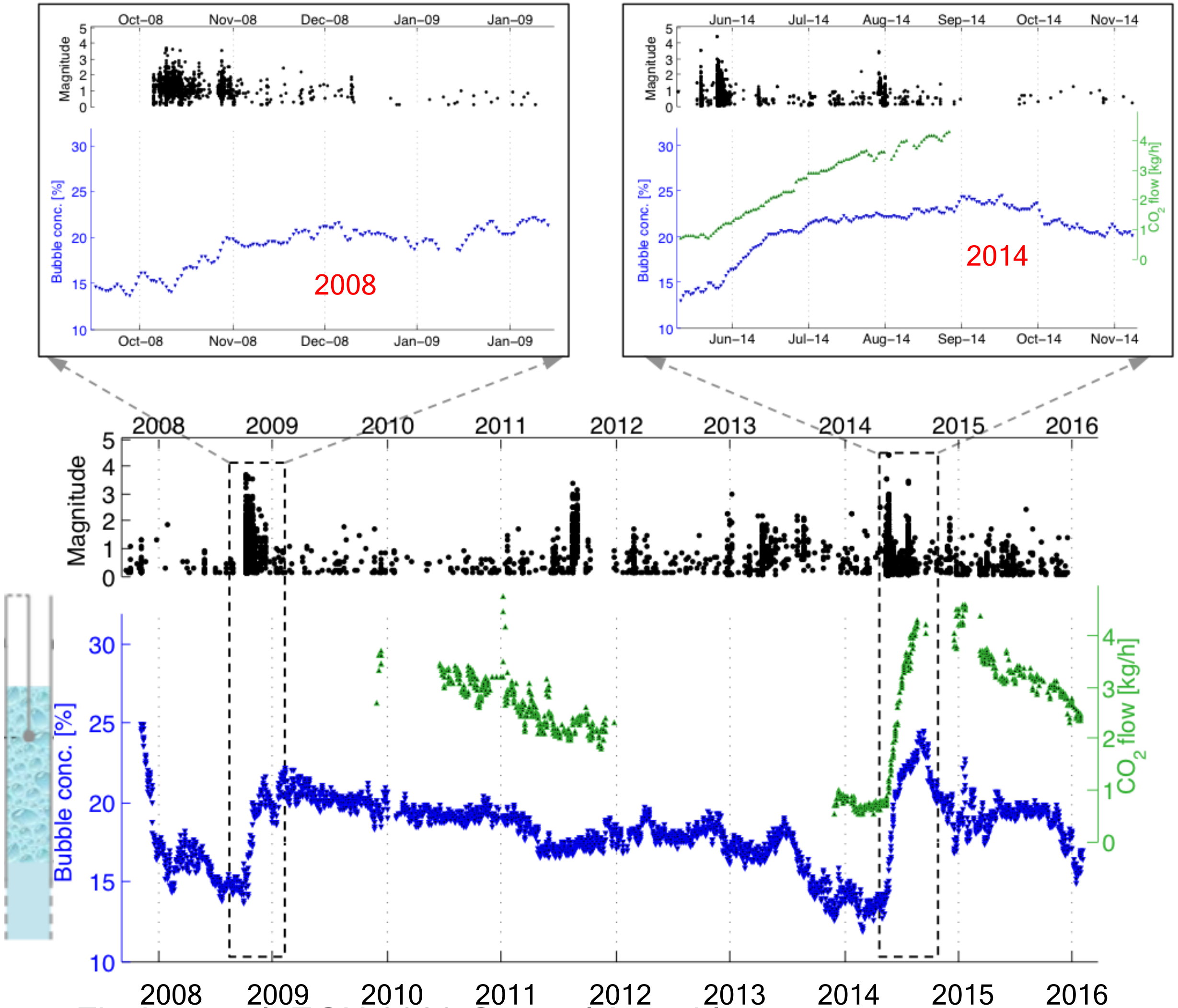
High barometric efficiency of 0.76 caused by bubbles in water (high compressibility of the mixture)



$E_B = 0.76$

$T_B = 0.46$ l/s/kPa

Postseismic CO_2 flow increase in the Hartoušov well

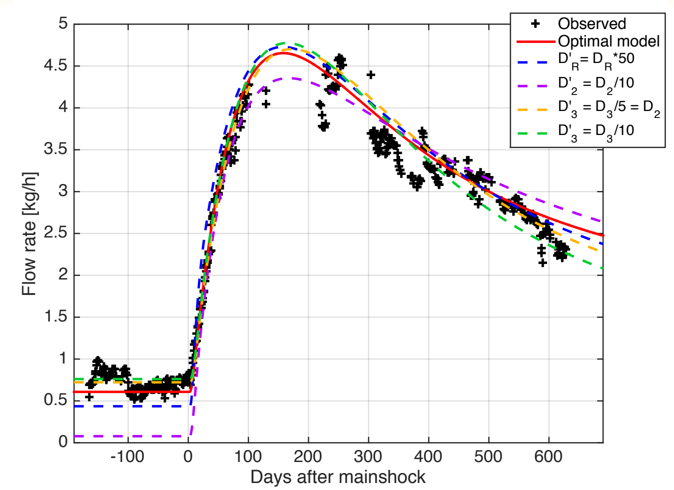


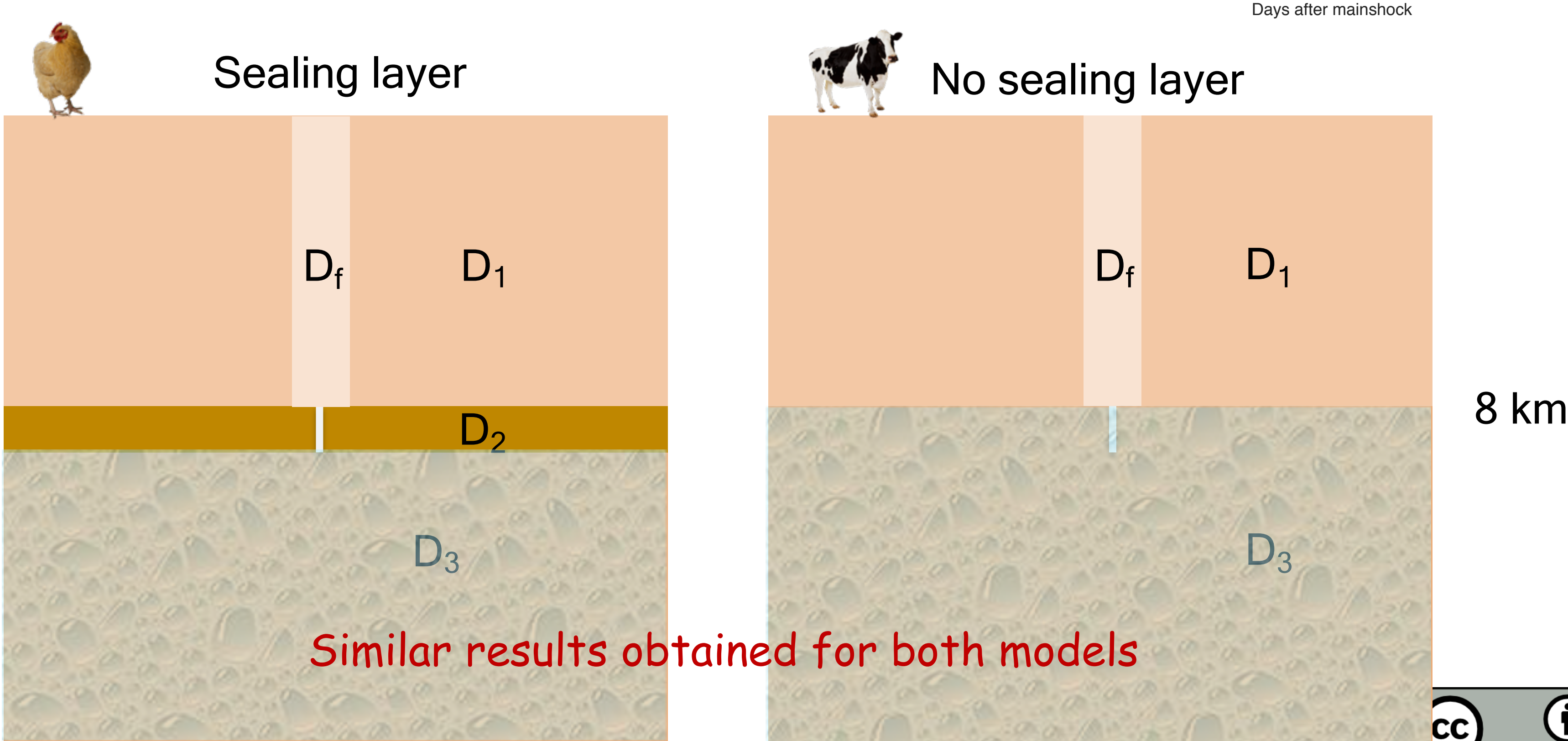
Fischer et al, EGU 2020 General Asembly

- Long-term decay of CO_2 flow from 3.6 kg/h in 2010 to 0.7 kg/h in spring 2014
- Flow increase following only 4 days after the M_L 3.5 mainshock
- Gradual increase to 4 kg/h for >100 days period
- Bubble fraction in the well shows similar trend - also after the 2008 swarm

Simple crustal models to explain the data

Sibson's fault valve model





Similar results obtained for both models

Numerical model of the 2014 coseismic anomaly
- releasing fluid reservoir -

2-D model

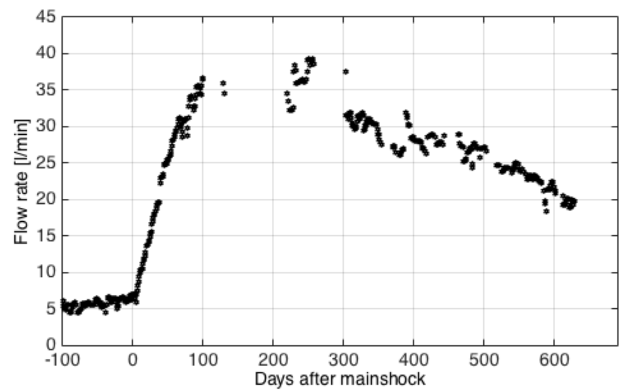
- Linear diffusion equation solved by FD

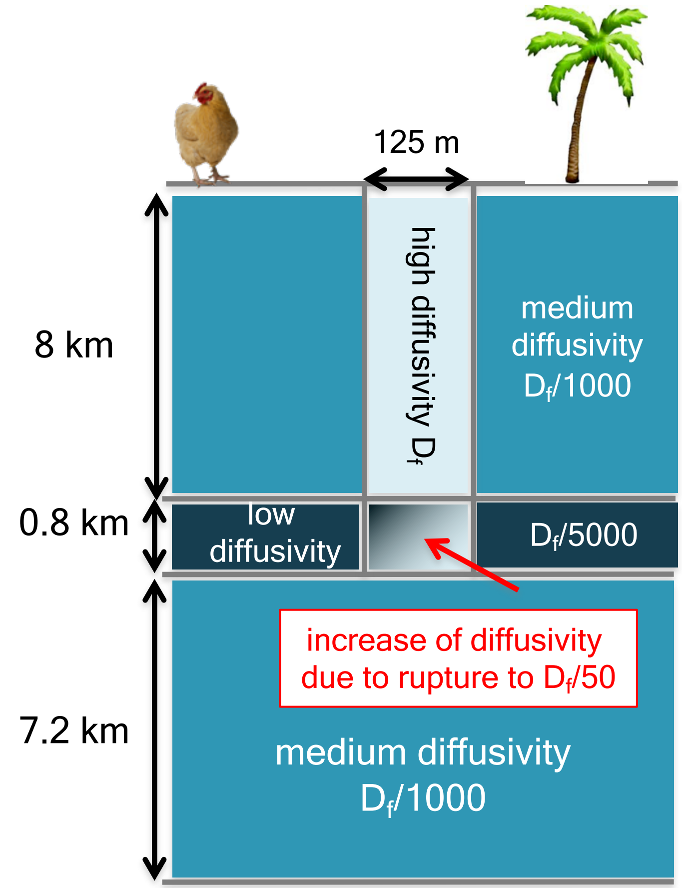
$$\frac{\partial p}{\partial t} = div\,(D\;grad(p))$$

Conditions:

- *p* =0 on top; *p* =1 at bottom
- Steady-state flow before rupturing
- Sudden increase of diffusivity in the seal

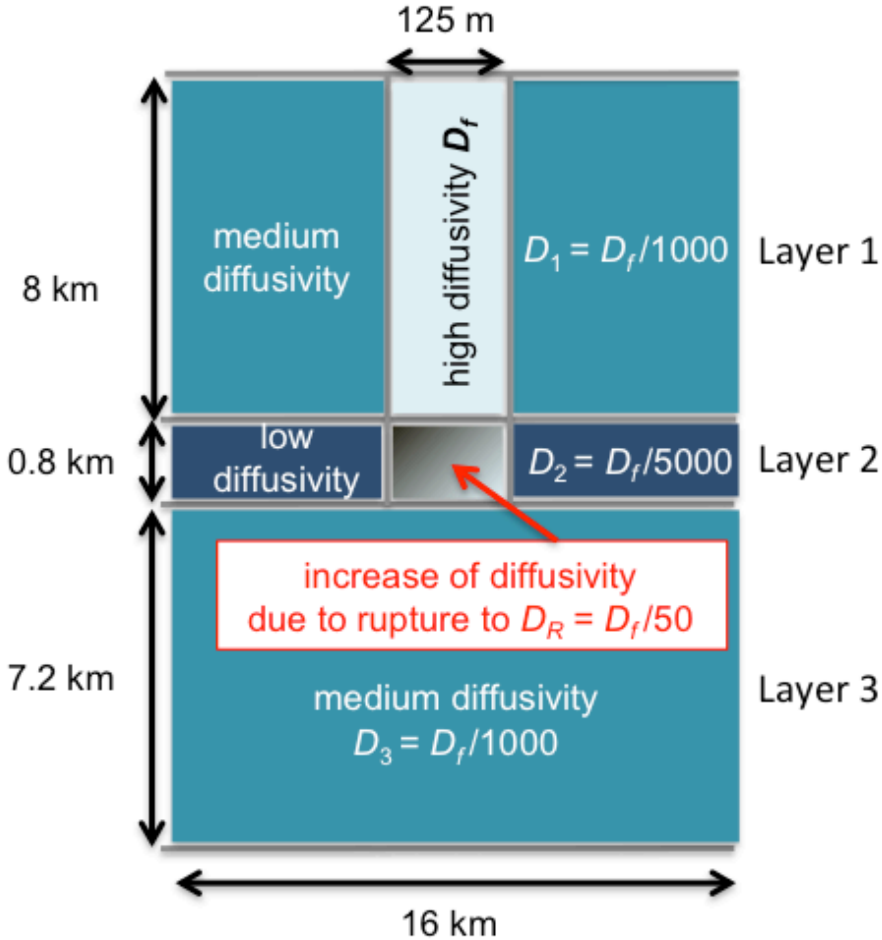
Data: Flow rate at Hartoušov 2014 - 2016





(Fischer, Matyska and Heinicke, EPSL 2017)

Fit of simulation



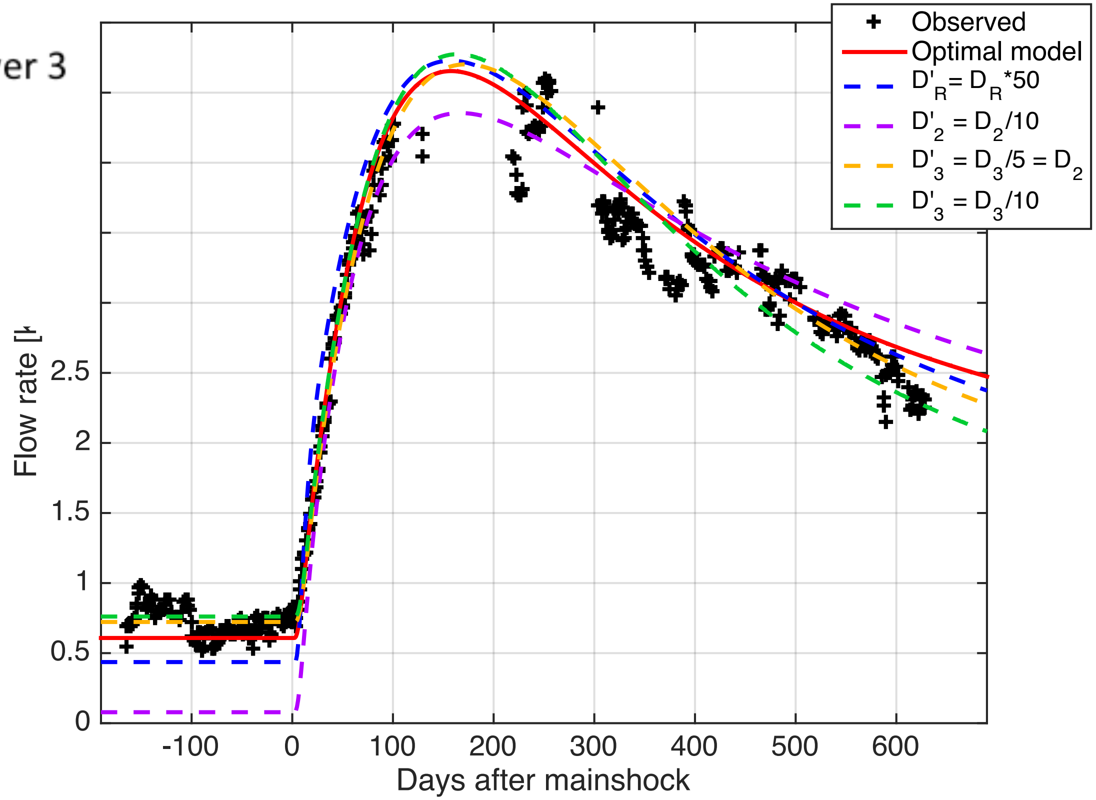
channel: $D_f = 12\ m^2/s$

upper crust: $D_1 = 0.012\ m^2/s$

seal: $D_2 = 0.0024\ m^2/s$ -> $0.24\ m^2/s$

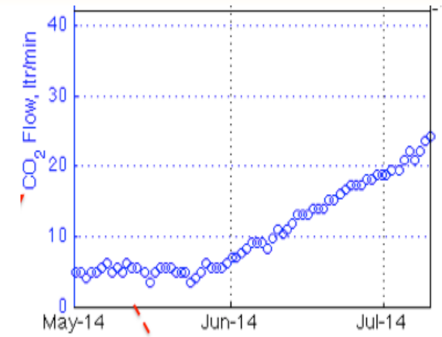
lower crust: $D_3 = 0.012\ m^2/s$

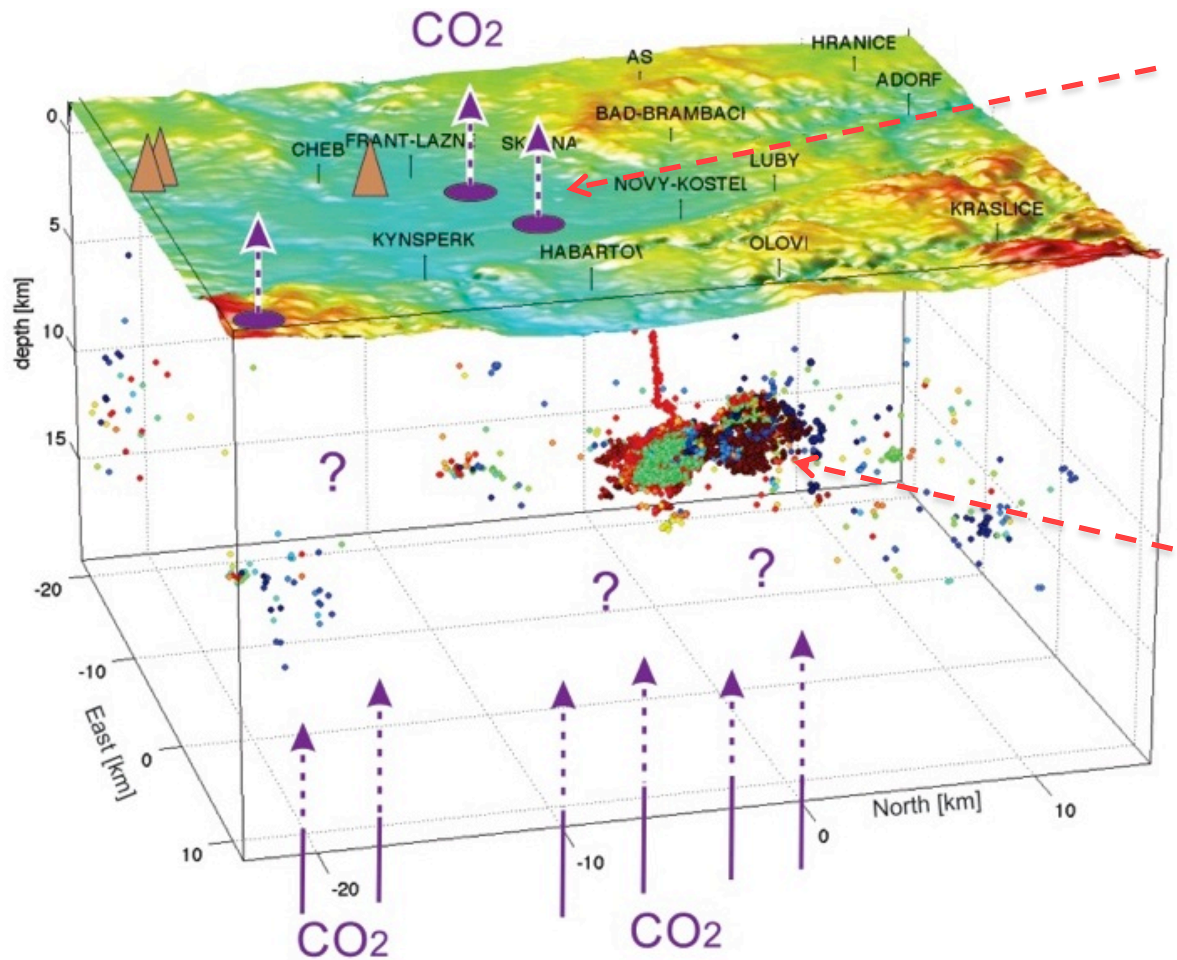
! no precipitation-related fault sealing necessary !



Relation of CO_2 and earthquake activity

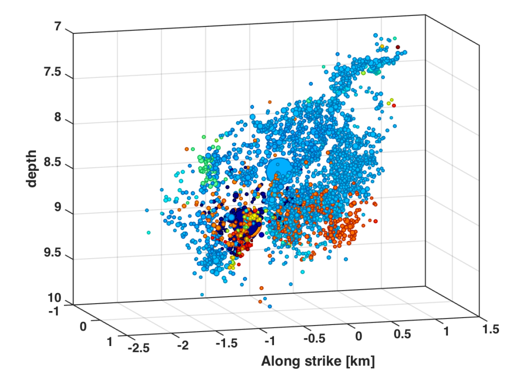
=> CO_2 passes through seismogenic depth and takes part in fault rupture processes





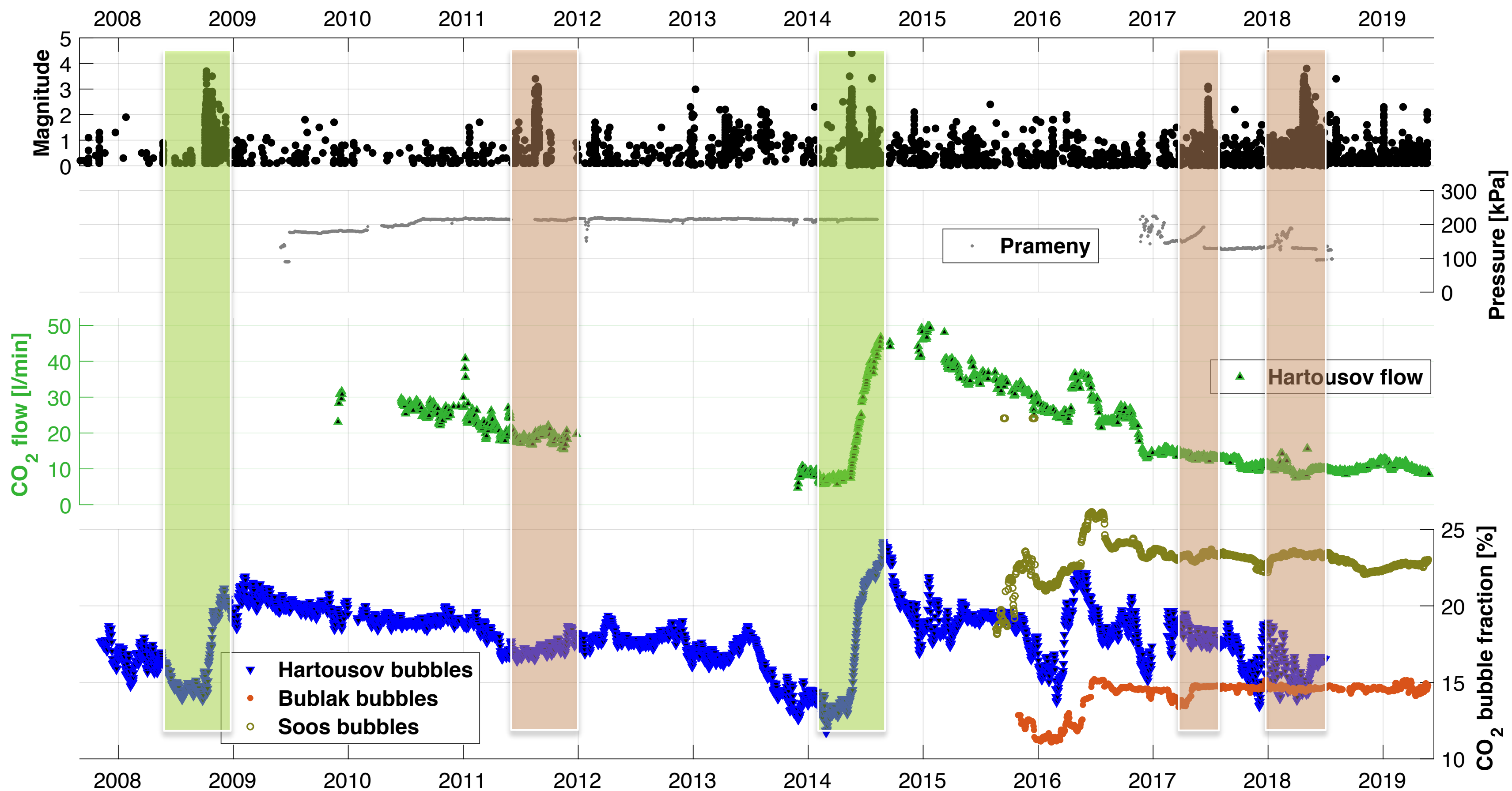
2014 postseismic CO_2 increase at Hartoušov mofette

2014 mainshock + aftershocks

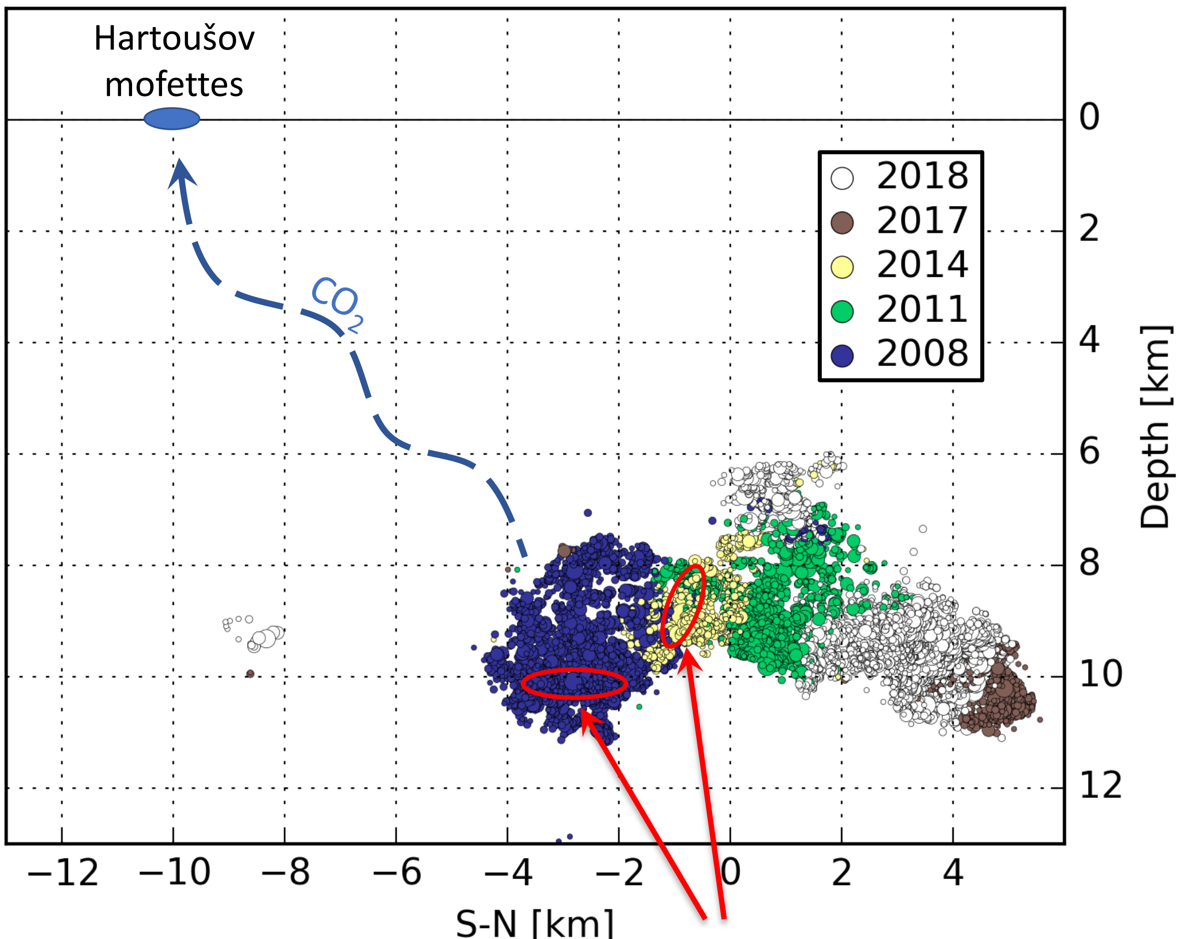


CO_2 flow measurements 2007 - 2019

- coseismic CO_2 rise during 2008 a 2014 activities
- postseismic slow decrease
- missing CO_2 rise during 2011, 2017 and 2018 swarms



Why no CO_2 flow response observed during the 2011, 2017 and 2018 swarms ?



Onset of 2008 and 2014 swarms

Possible reasons

- Small volume of CO2 released
- Missing permeable channel to the surface from the swarms located in the northern cluster (2011, 2017, 2018)

Summary

- Massive discharge of magmatic CO_2 in West-Bohemia /Vogtland
- Online monitoring of gas flow, water level, bubble fraction in 4 mofettes/mineral springs
- Barometric effect to gas flow shows response of the aquifer to periodic loading; high barometric efficiency likely to be caused by high compressibility of water-bubble mixture
- Postseismic increase of CO_2 discharge at Hartoušov mofettes during 2008 and 2014 swarms were followed by long-term decay
- Modelling of fluid flow in 2D model shows that CO_2 observations are consistent with fault-valve model with fault diffusivity of ~12 m^2/s
- Only two of five seismic swarms showed correlated CO_2 increase – could be caused by different location of the other swarms

Thank you

Hainzl, S., Fischer, T., Čermáková, H., Bachura, M. and Vlček, J., 2016. Aftershocks triggered by fluid-intrusion: Evidence for the aftershock sequence occurred 2014 in West Bohemia/Vogtland, J. Geophys. Res. Solid Earth, 121, 2575-2590

Fischer T., Matyska C., and Heinicke J., 2017. Earthquake-enhanced permeability - evidence from carbon dioxide release following the M_L 3.5 earthquake in West Bohemia. Earth Planet. Sci. Lett., 460, 60–67.

Fischer T., Vlček J. and Lanzendorfer M, 2020. Monitoring crustal CO2 flow: methods and their applications to the mofettes in West Bohemia. Solid Earth, accepted. Doi: 10.5194/se-2020-6