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
- 2014, 2018 M4+
CO₂ degassing

- Mineral springs - dissolved CO₂
- Moffetes - ‘dry’ CO₂
- Total < 1000 t/day
- Upper-mantle origin (high $^3$He/$^4$He, delta$^{13}$C)

(Weinlich et al., 2006)
CO$_2$ flow monitoring network

GSM network with near-real time data transfer

Hartoušov F1 borehole

Hartoušov F2 borehole

Hartoušov mofette

Soos mofettes

Bublák mofettes

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 $\text{CO}_2$ flow?

**Indirect methods**

- Fraction $\Phi$ of gas bubbles in a borehole
  
  a) based on electric conductivity of water
  
  $\Phi(t) = 1 - c \frac{R_R(t)}{R_M(t)}$
  
  $R_R$ - reference resistivity of water free of bubbles
  
  $R_M$ - resistivity of mixture of water with bubbles

  b) based on differential pressure in water
  
  $\Phi(t) = \frac{p_e(t) - p_m(t)}{d_e - d_m}$

  $p_e$ - differential pressure
  
  $d_e$ - depth of water
  
  $d_m$ - depth of mixture

  $p_m$ - pressure in mixture

  $c$ - constant
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 CO₂ flow?

Indirect methods

Pressure in a closed borehole

- Relation of pressure to deep flow

\[ p = \frac{q}{\kappa_1 + \kappa_2} \]

- Closed borehole \((\kappa_1 = 0)\) - pressure controlled by soil permeability \(\kappa_2\) (leakage) only

- Recommended to allow for controlled vent (increase \(\kappa_1\)) in the wellhead to reduce the sensitivity to varying soil conditions
Barometric effects to gas flow

Groundwater level response $\Delta \rho$

- Barometric efficiency
  \[ E_B = \frac{\Delta \rho}{\Delta b} = \rho g \frac{\Delta h}{\Delta b} \]
- Related to porosity $\theta$ and compressibility of the rock $\alpha$ and water $\beta$
  \[ E_B = \frac{\theta \beta}{\theta \beta + \alpha} \]
- $E_B = 0.2 - 0.7$ for confined aquifers
- High $E_B$ if rock is not compressible (granite) of water is compressible (gas bubbles)

Gas discharge response $\Delta q$

- Barometric efficiency
  \[ T_B = \frac{\Delta q}{\Delta b} \quad \left[ \frac{1}{s} \right] \quad \left[ \text{kPa} \right] \]
Barometric effects to gas flow

- Remove air pressure influence as
  \[ h_{corr} = h - E_B \Delta b; \quad q_{corr} = q - T_B \Delta b \]

by condition of minimum cross-correlation of original and corrected data.
Barometric effects to gas flow

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

\[ E_B = 0.76 \]

\[ T_B = 0.46 \text{ l/s/kPa} \]
Postseismic CO$_2$ flow increase in the Hartoušov well

- 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

Sealing layer

\[ D_f \quad D_1 \quad D_2 \quad D_3 \]

No sealing layer

\[ D_f \quad D_1 \quad \quad \quad \quad D_3 \]

8 km

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

\[
\frac{\partial p}{\partial t} = \text{div} (D \ \text{grad}(p))
\]

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: $D_f = 12 \text{ m}^2/\text{s}$
upper crust: $D_1 = 0.012 \text{ m}^2/\text{s}$
seal: $D_2 = 0.0024 \text{ m}^2/\text{s} \rightarrow 0.24 \text{ m}^2/\text{s}$
lower crust: $D_3 = 0.012 \text{ m}^2/\text{s}$

! 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\textsubscript{2} flow measurements 2007 - 2019

- coseismic CO\textsubscript{2} rise during 2008 a 2014 activities
- postseismic slow decrease
- missing CO\textsubscript{2} rise during 2011, 2017 and 2018 swarms
Why no CO$_2$ flow response observed during the 2011, 2017 and 2018 swarms?

Possible reasons:
- Small volume of CO$_2$ released
- Missing permeable channel to the surface from the swarms located in the northern cluster (2011, 2017, 2018)

Onset of 2008 and 2014 swarms
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 $\sim 12$ m$^2$/s
• Only two of five seismic swarms showed correlated CO$_2$ increase - could be caused by different location of the other swarms
