Schatzalp Induced
Seismicity Workshop

Swiss Seismological
Service

Seismic valve as a driving mechanism of the 2014 aftershock sequences in West Bohemia

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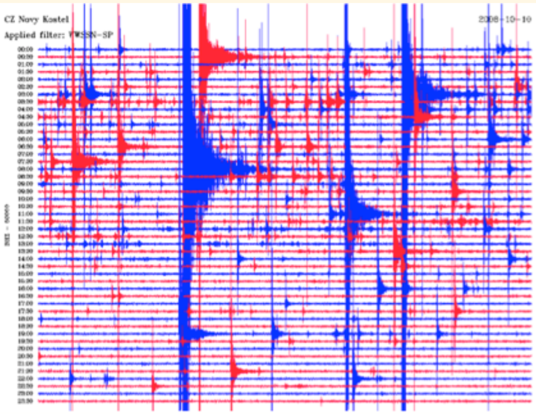
NATURAL ANALOG OF INJECTION-INDUCED SESMICITY



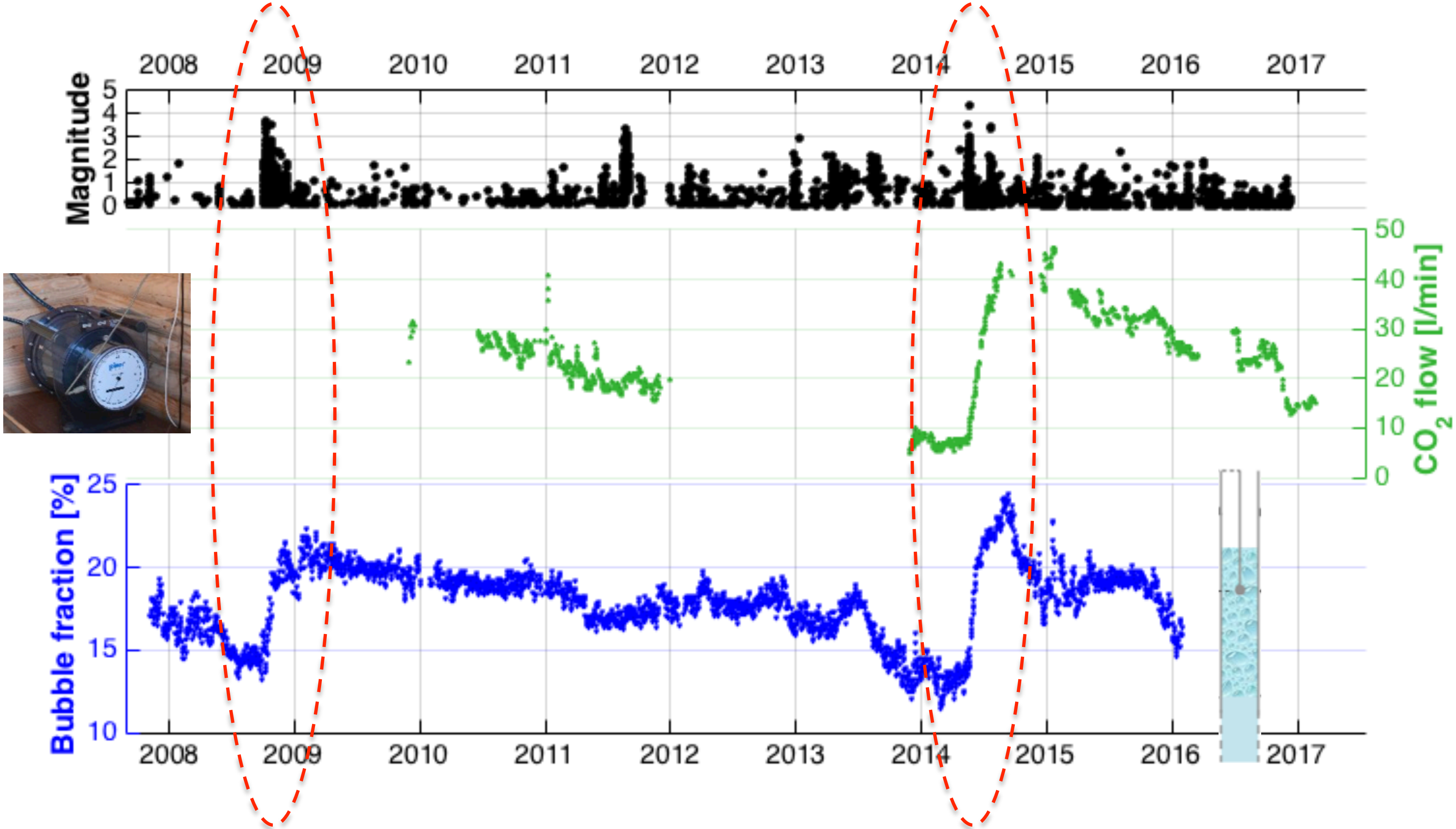
Outline

WEST BOHEMIA EARTHQUAKES AS NATURAL ANALOG OF INJECTION-INDUCED SESMICITY

- Earthquake swarms and CO2 degassing in WB/Vogtland
- Seismic activity in 2014: mainshock-aftershock character – no swarms
- Tracking CO2 at depth 2014 seismicity
  - aftershocks driven by fluids
- Tracking CO2 at surface – 2014 gas increase
- Summary

CO_2 mofettes

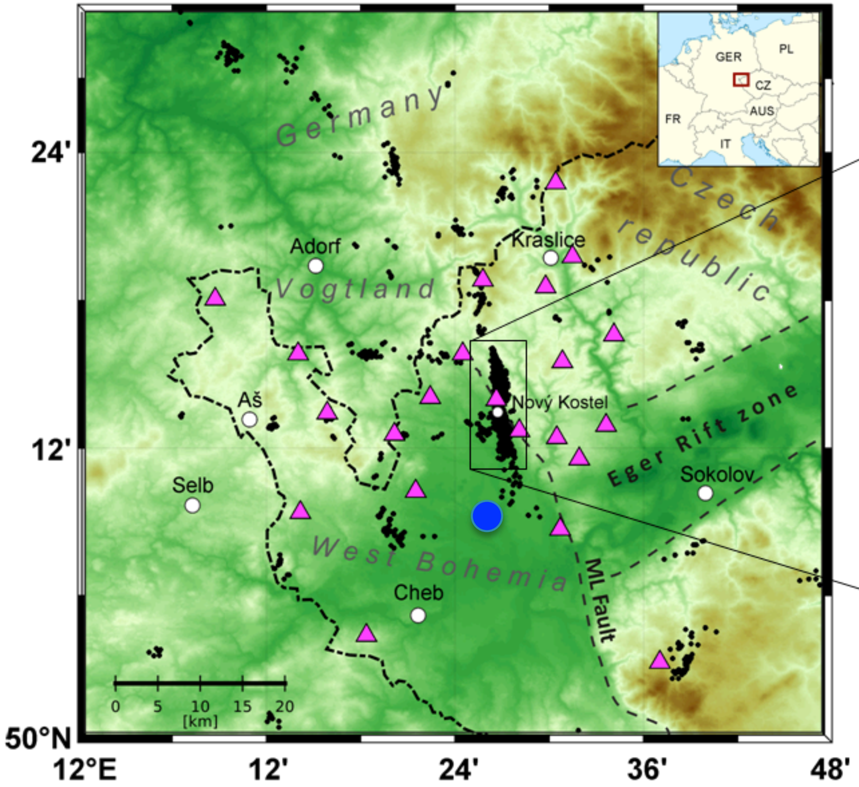
Seismicity, gas flow, bubble fraction in a mofette

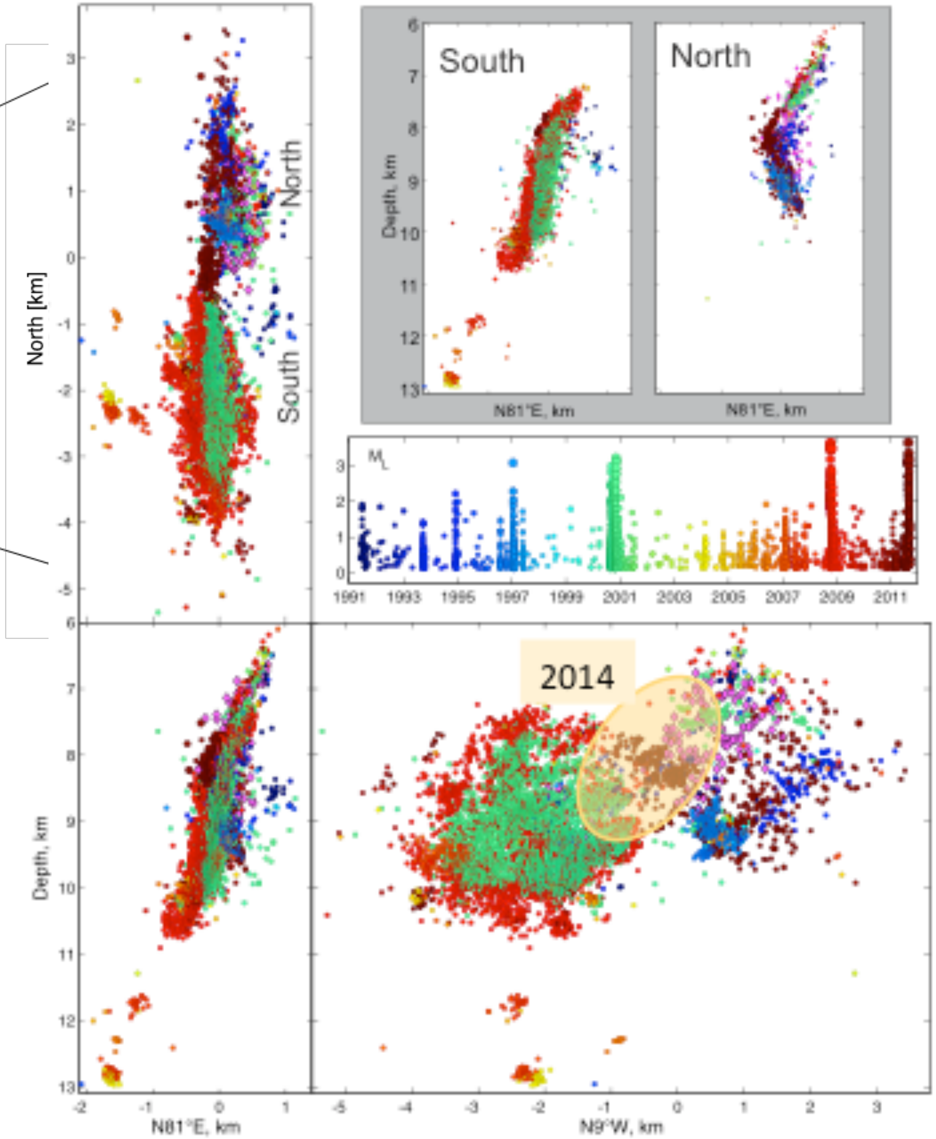


Repeated post-seismic massive increase of CO2 production in 2008 and 2014

WHAT IS THE MECHANISM?

West Bohemia/Vogtland - Nový Kostel zone swarms





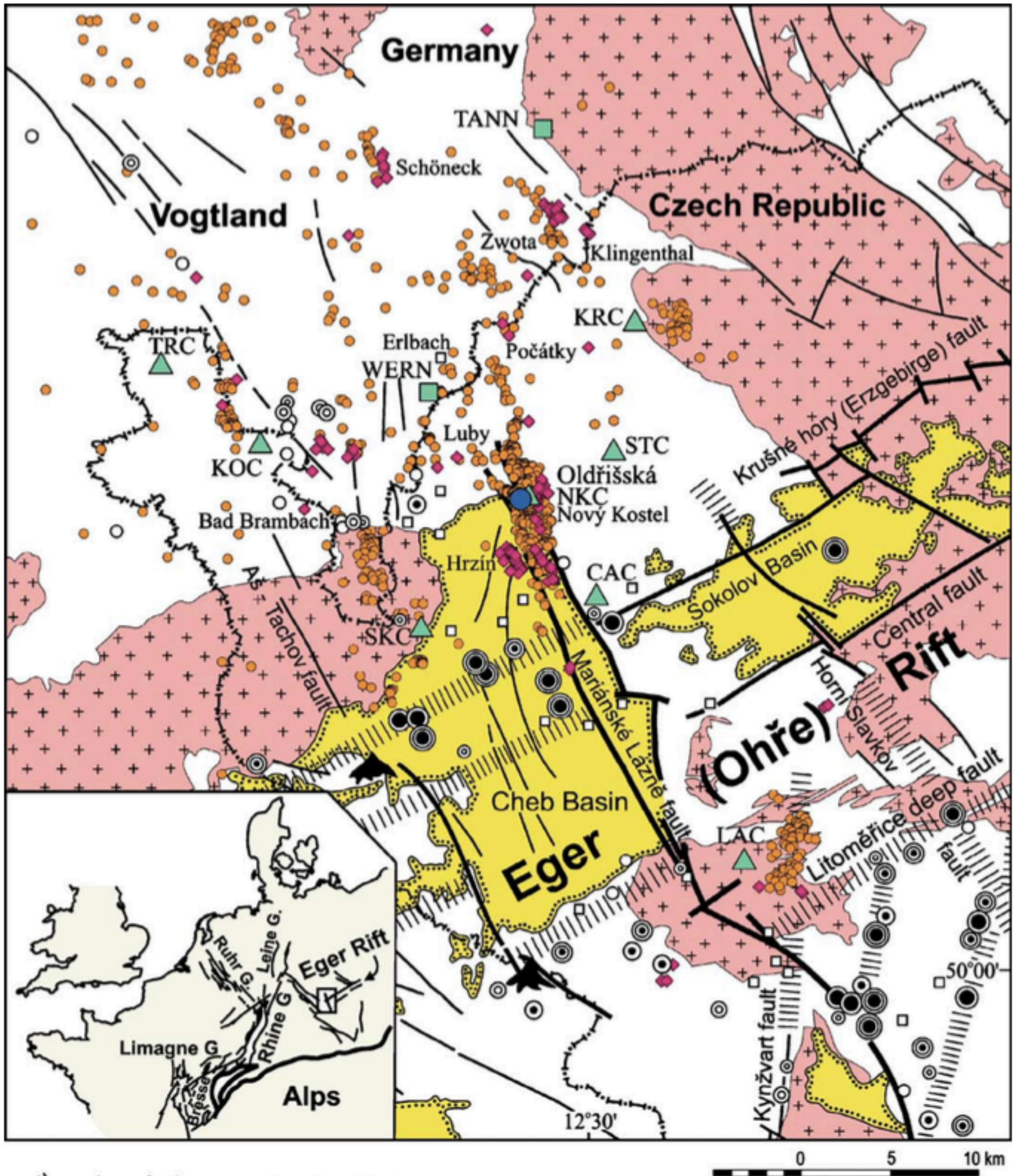
Main focal zone (Nový Kostel)

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

Swarms

- 1985/86 M4.6
- 1997, 2000, 2008, 2011 M3+
- 2014 M4.4

CO_2 degassing

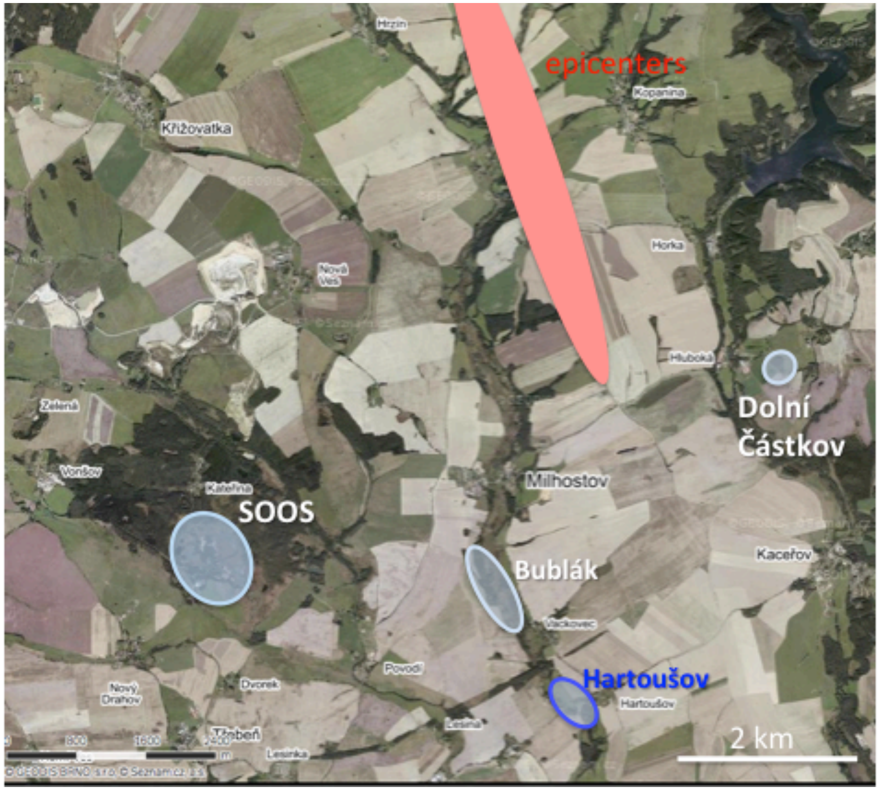


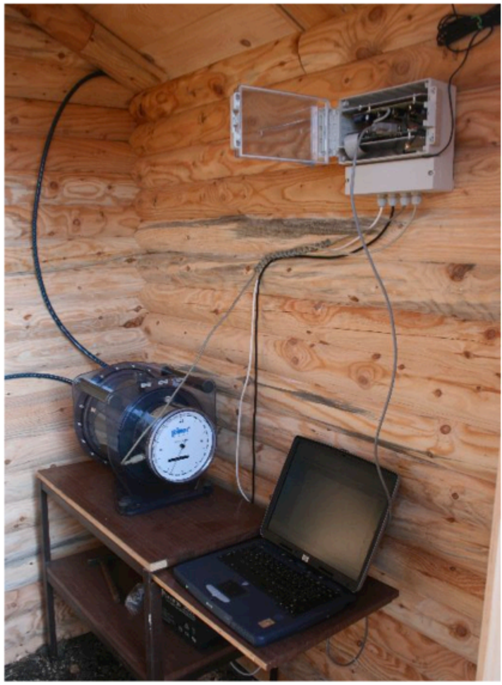
- Mineral springs – dissolved CO_2
- Moffetes – 'dry' CO_2
- Total >500 m^3/h
- Upper-mantle origin (high $^3He/^4He$)

(Weinlich et al., 2006)

CO_2 flow monitoring

Hartoušov mofettes



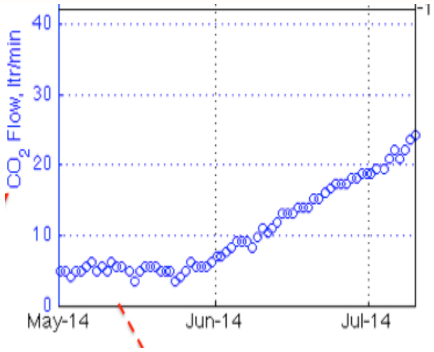


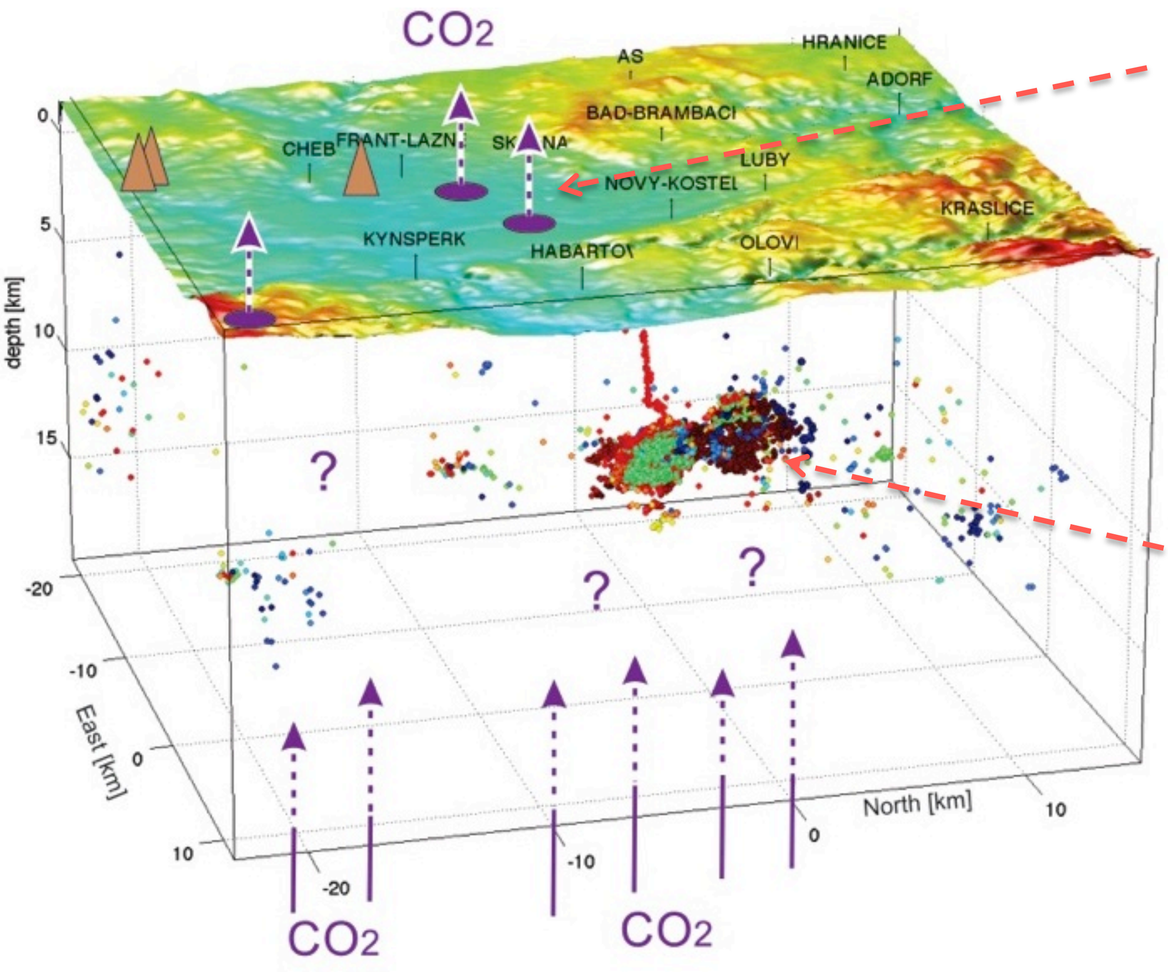
Monitoring in the well (30 m deep)

- CO_2 od 2009
- GWL from 2007

Relation of CO_2 and earthquake activity

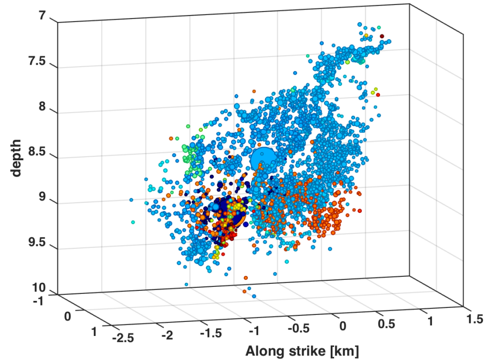
CO_2:
- Passes through seismogenic depth (deeper origin) !
- Takes part in fault rupture processes ?



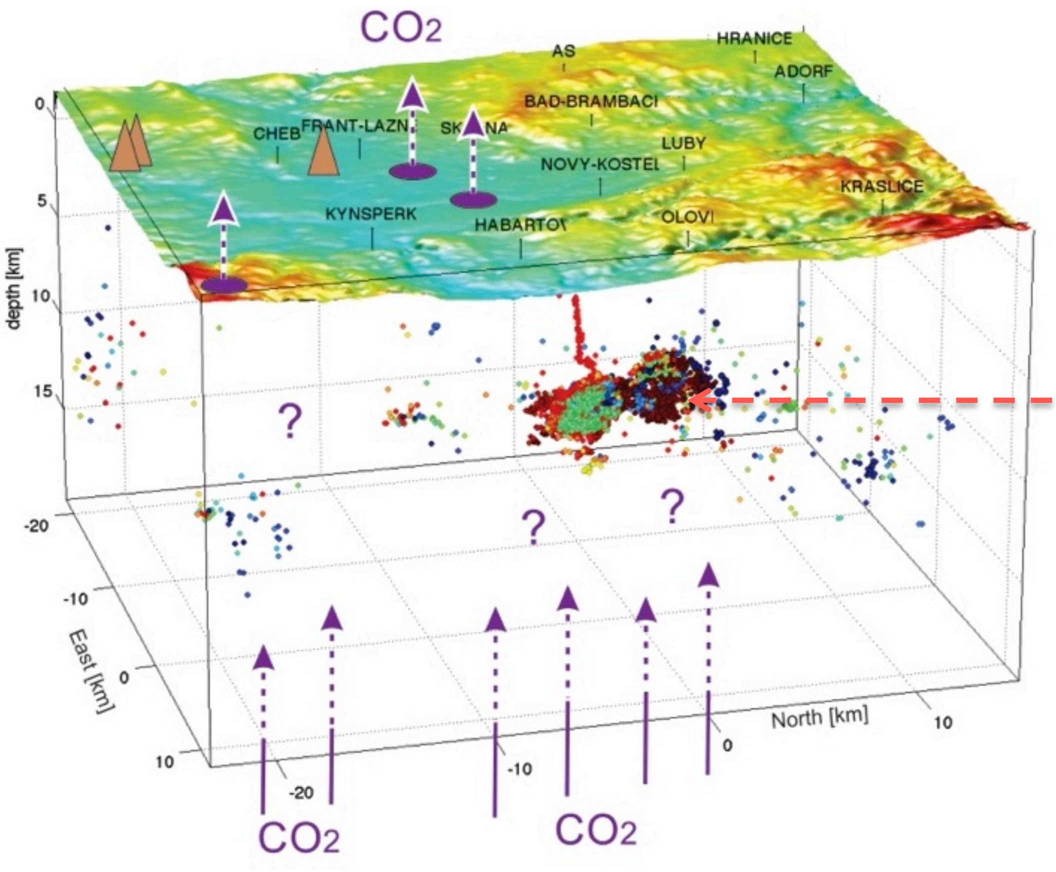


2014 postseismic CO_2 increase at Hartoušov mofette

2014 aftershocks



Tracking CO_2 at depth

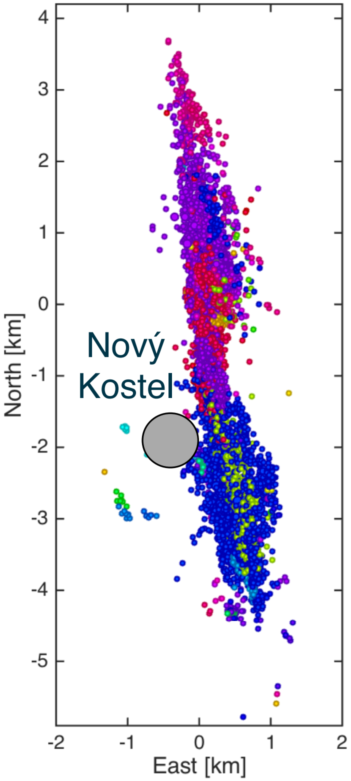


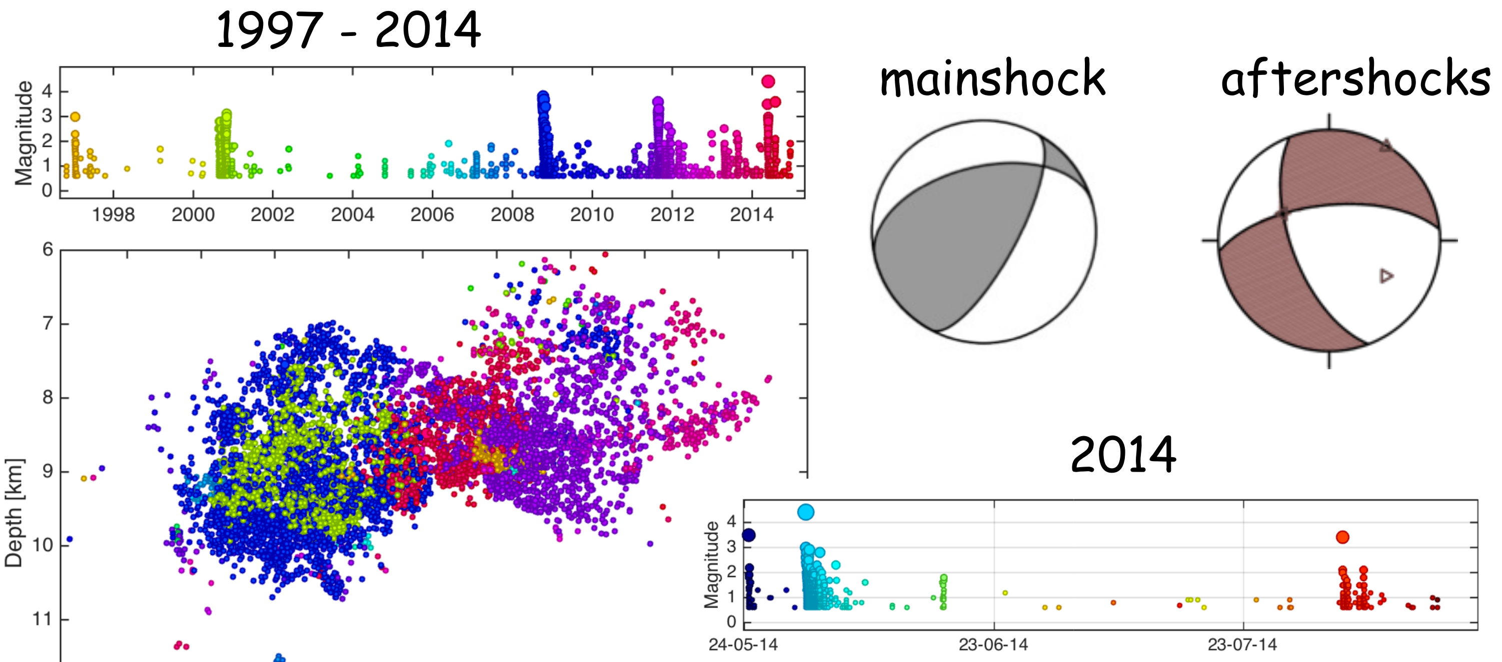
2014 earthquakes

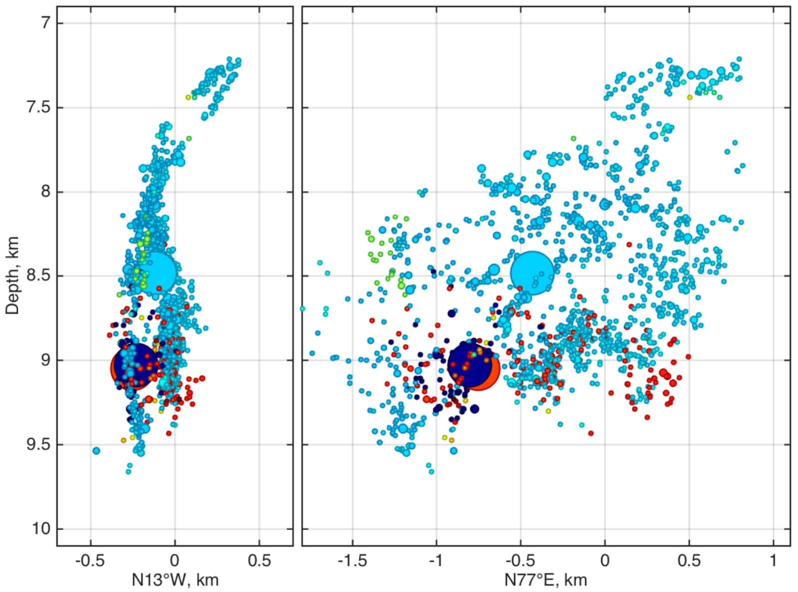
What is their origin?

(Hainzl et al., JGR 2016)

2014 seismic sequence







Three series

24.5.2014 mainshock: M_L 3.5, M_w 3.4

> 200 aftershocks

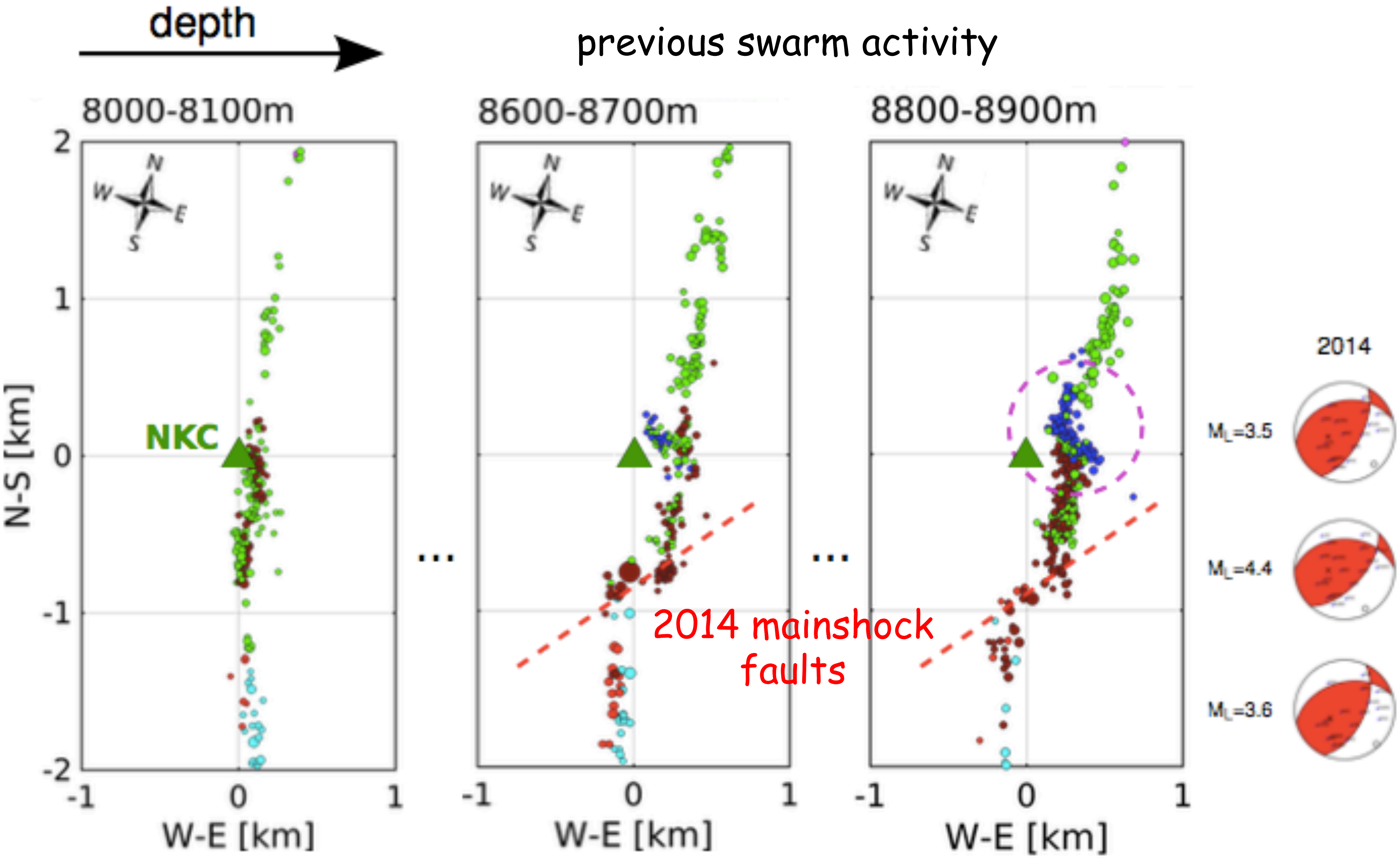
31.5.2014 mainshock: M_L 4.4, M_w 3.8

- 3000 aftershocks

3.8.2014 mainshock: M_L 3.5, M_w 3.4

- 440 aftershocks

Fault zone structure , depth slices



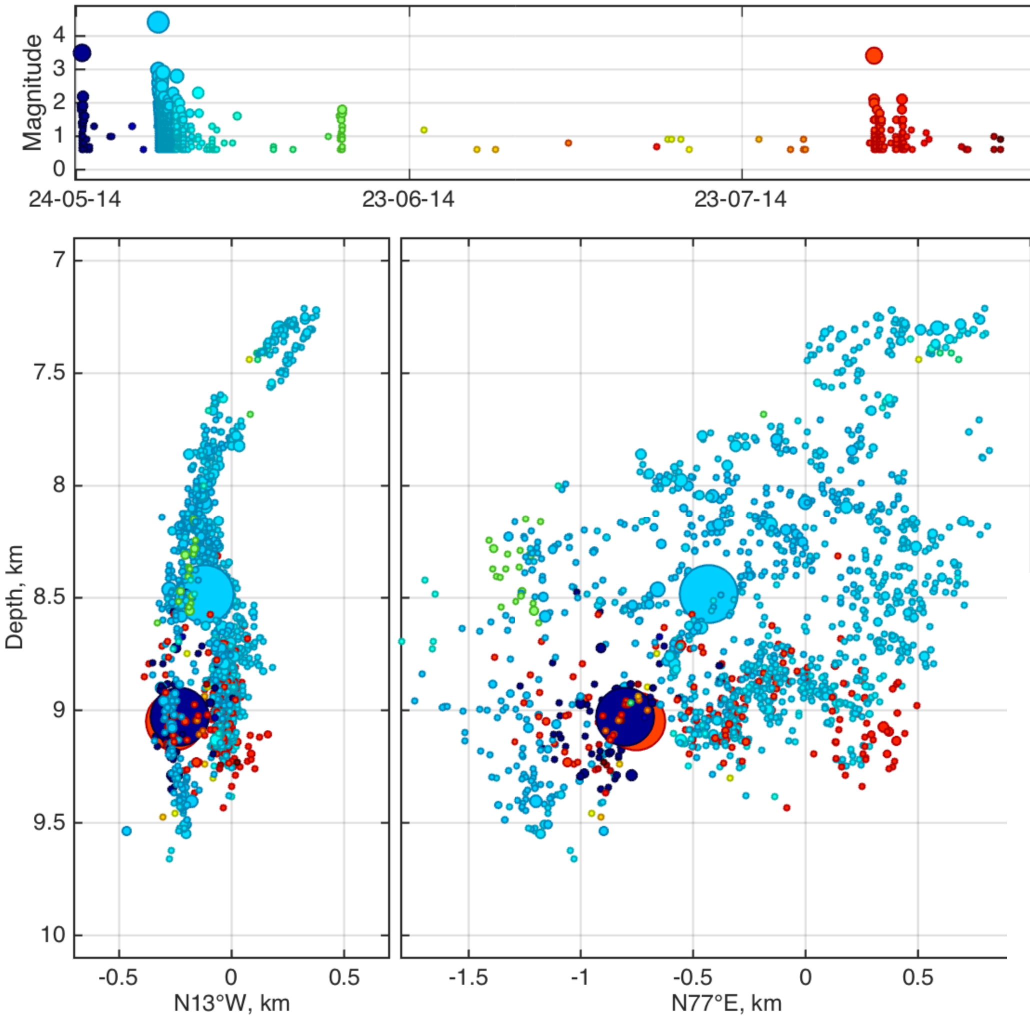
depth

previous swarm activity

2014 mainshock faults

2014 mainshocks occurred at fault step-over of <400m ofset

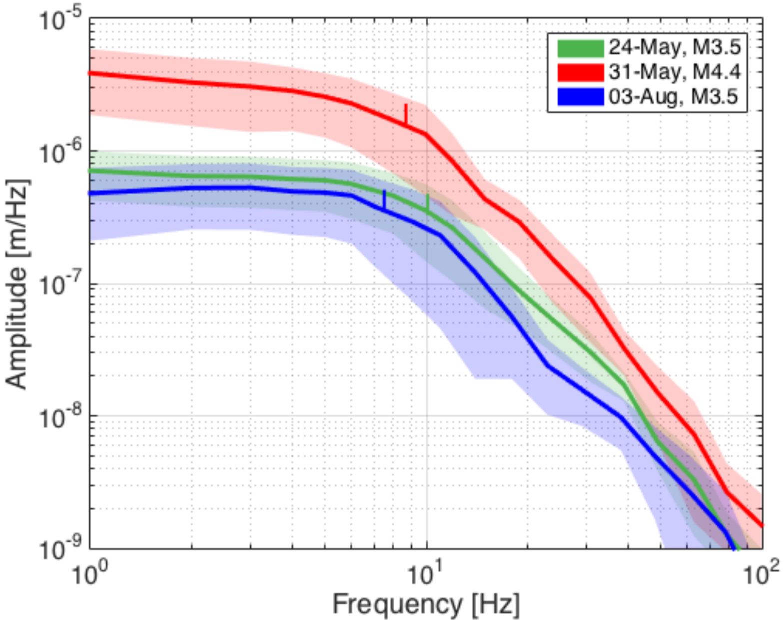
2014 fault geometry



Mainshocks M_L 3.5 – 4.4

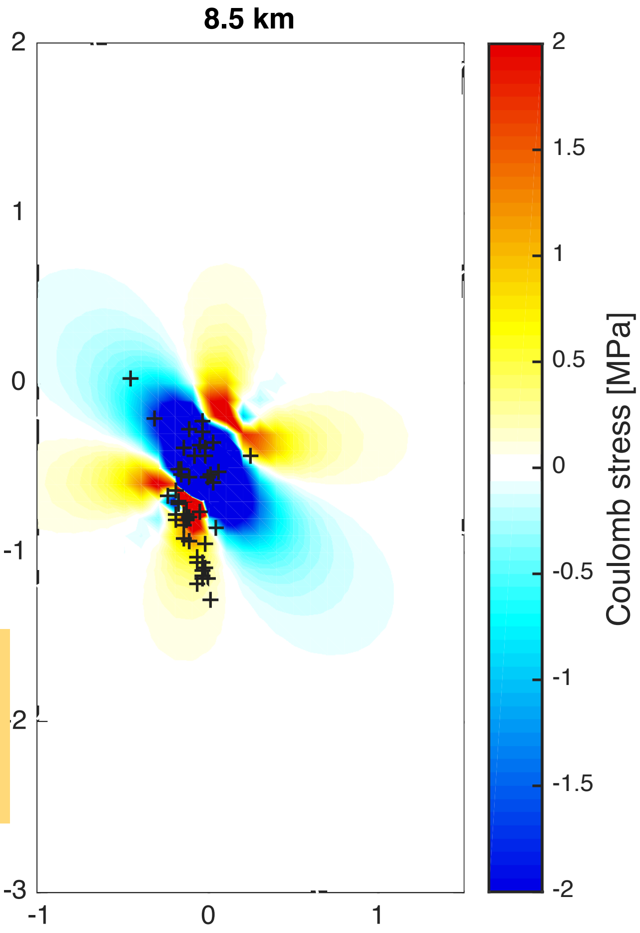
- high corner frequencies
- R: 110 – 150 m
- high stress drops 20 - 120 MPa

=> small ruptures



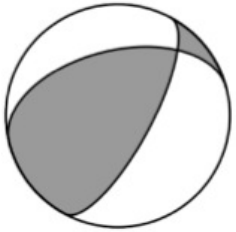
Origin of aftershocks
Coulomb stress change after mainshock M_L 4.4

1st 50 events

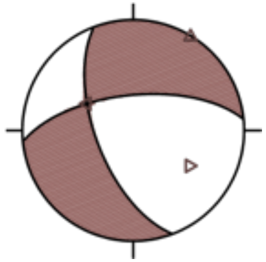


1st events were most probably triggered by Coulomb stress

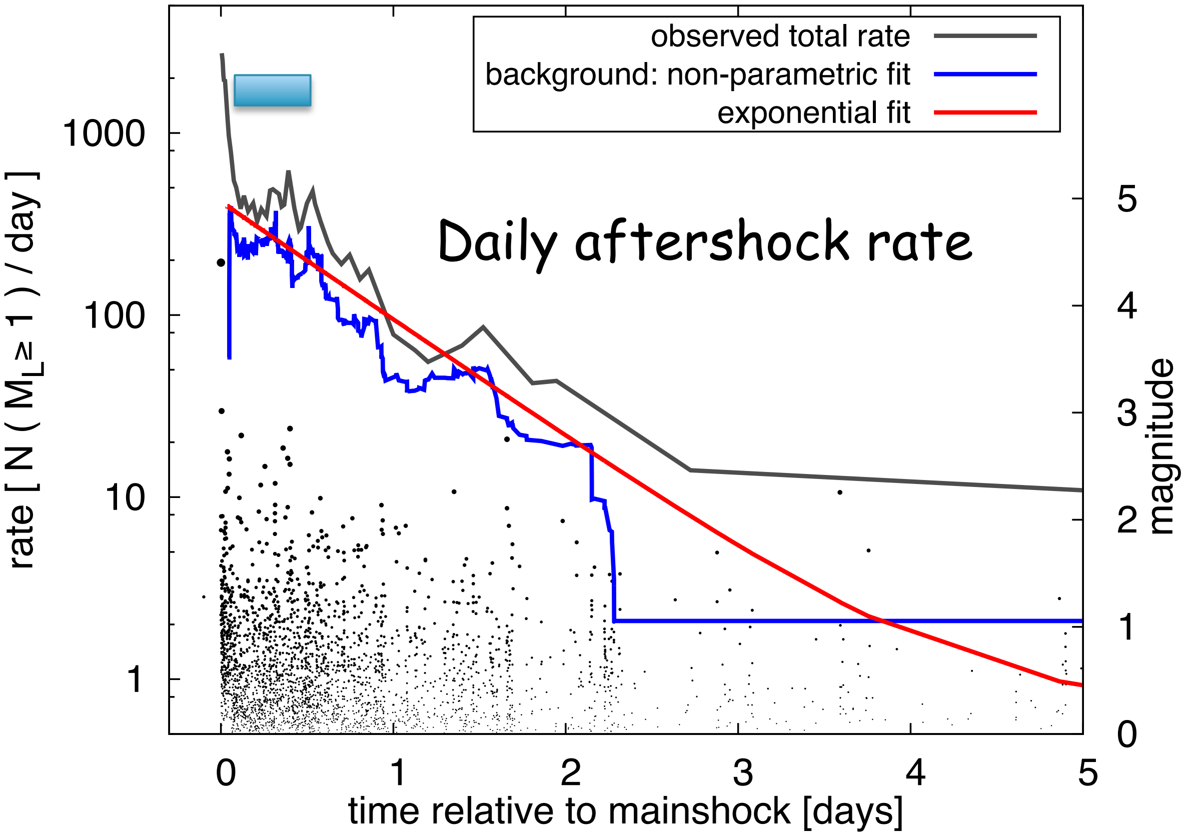
Source faults:
2nd mainshock mechanism



Receiver fault:
aftershock mechanisms



M_L 4.4 aftershocks decay



- constant rate between 0.2 and 0.6 days
- later Omori decay

Additional force ?

Epidemic Type Aftershock Sequence (ETAS) analysis:

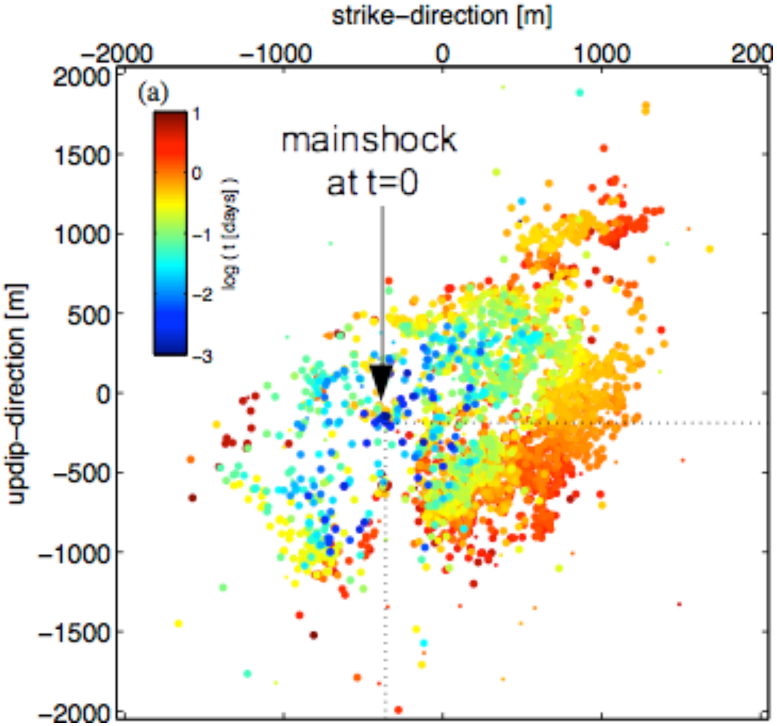
- 60% of events needed external forcing to be triggered
- these are best explained by exponential decaying source - fluid ?

  (compared to constant rate and non-parametric fit)

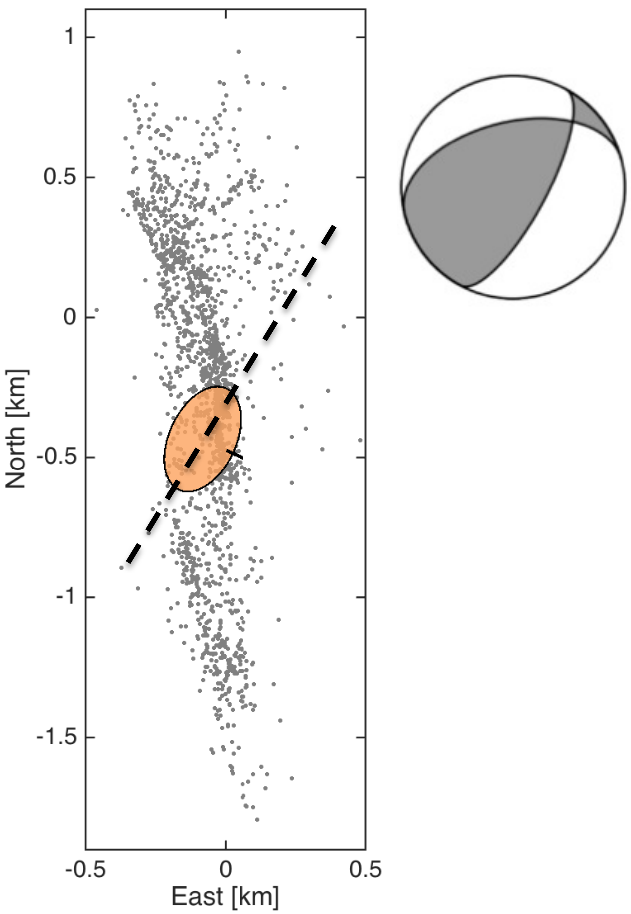
Each event characterized by probability to be triggered by external force

M_L 4.4 aftershocks are not typical

migrated from a point-like source close to mainshock



activated off-plane (preexisting) fault – not typical aftershocks

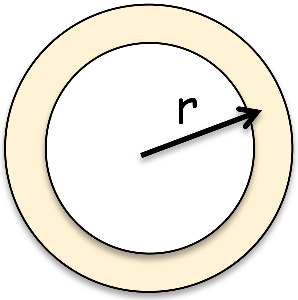


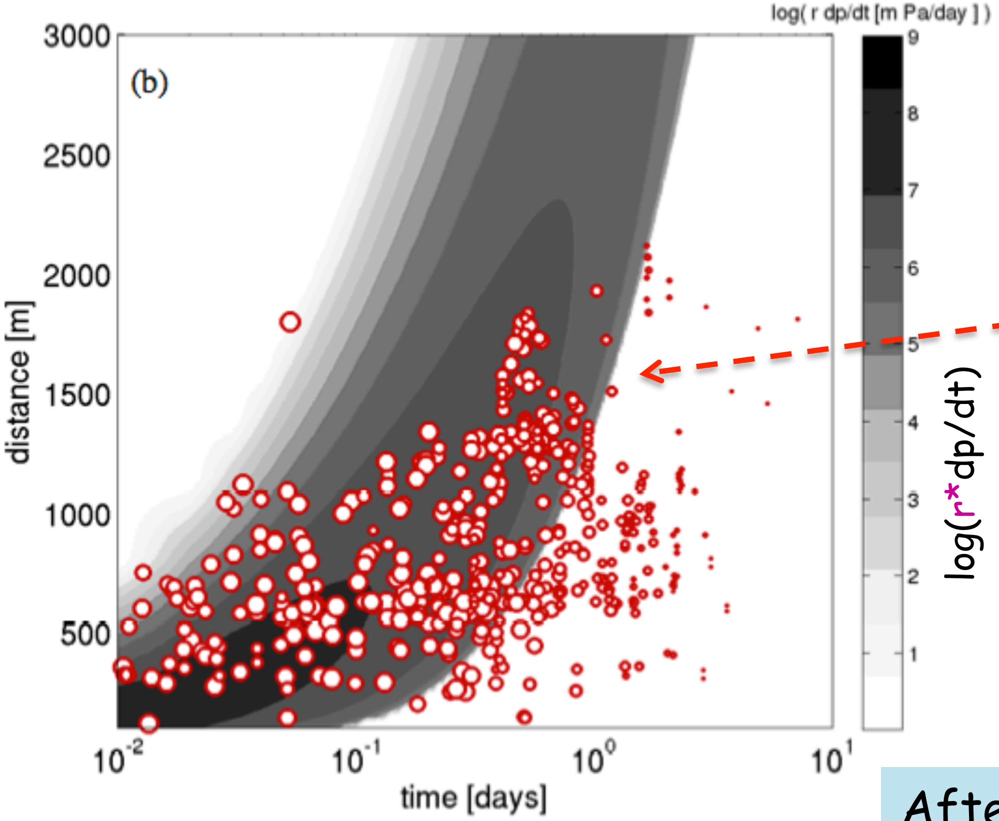
Fluid intrusion at t=0 with $q(t) = C\exp(-1.5t)$;

(exponential decay comes from ETAS analysis)

Pore pressure modelling

- Pressure field in the fault due to exponential decaying flow as a triggering force – 1D model
- Instant triggering: earthquake rate expected to be proportional to
  - area of annulus, i.e. ~r
  - dp/dt (if >0)



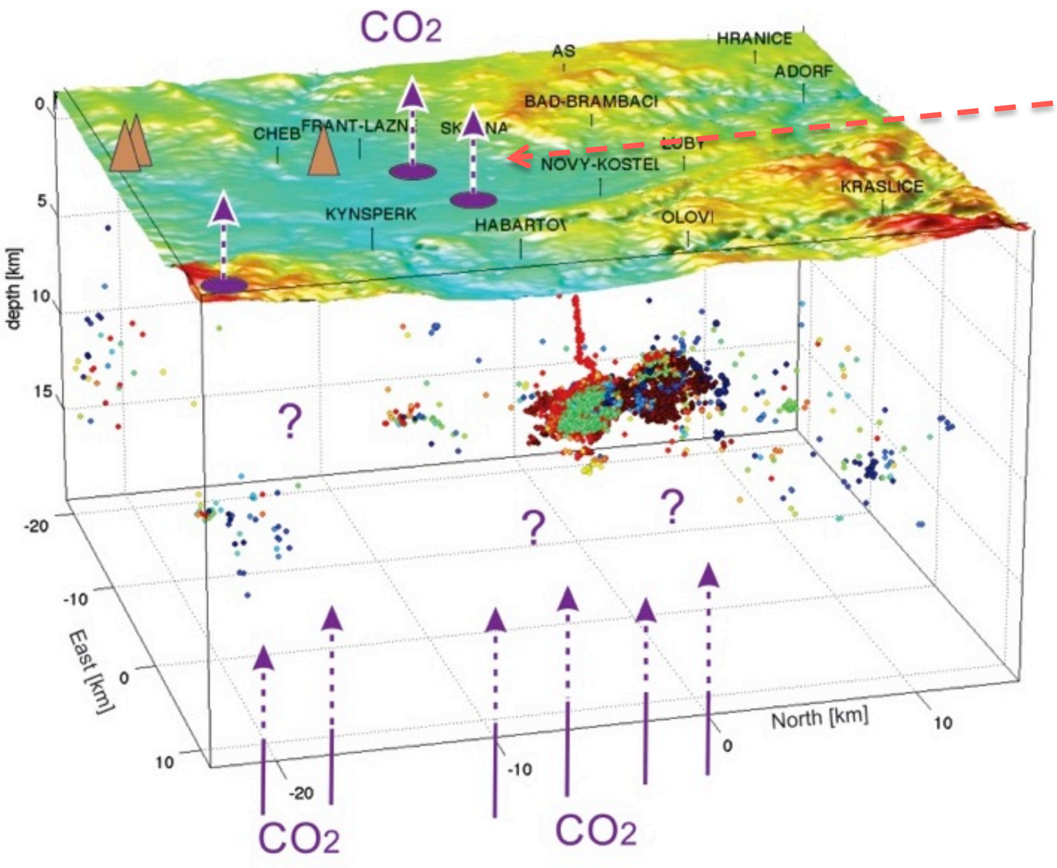


Earthquake symbol size scaled by ETAS-probability to be triggered by aseismic source

optimal fit for
D = 10 m^2/s

Aftershocks appear to be triggered by pressure of fluid released by mainshock

Tracking seismic signal in CO_2 flow

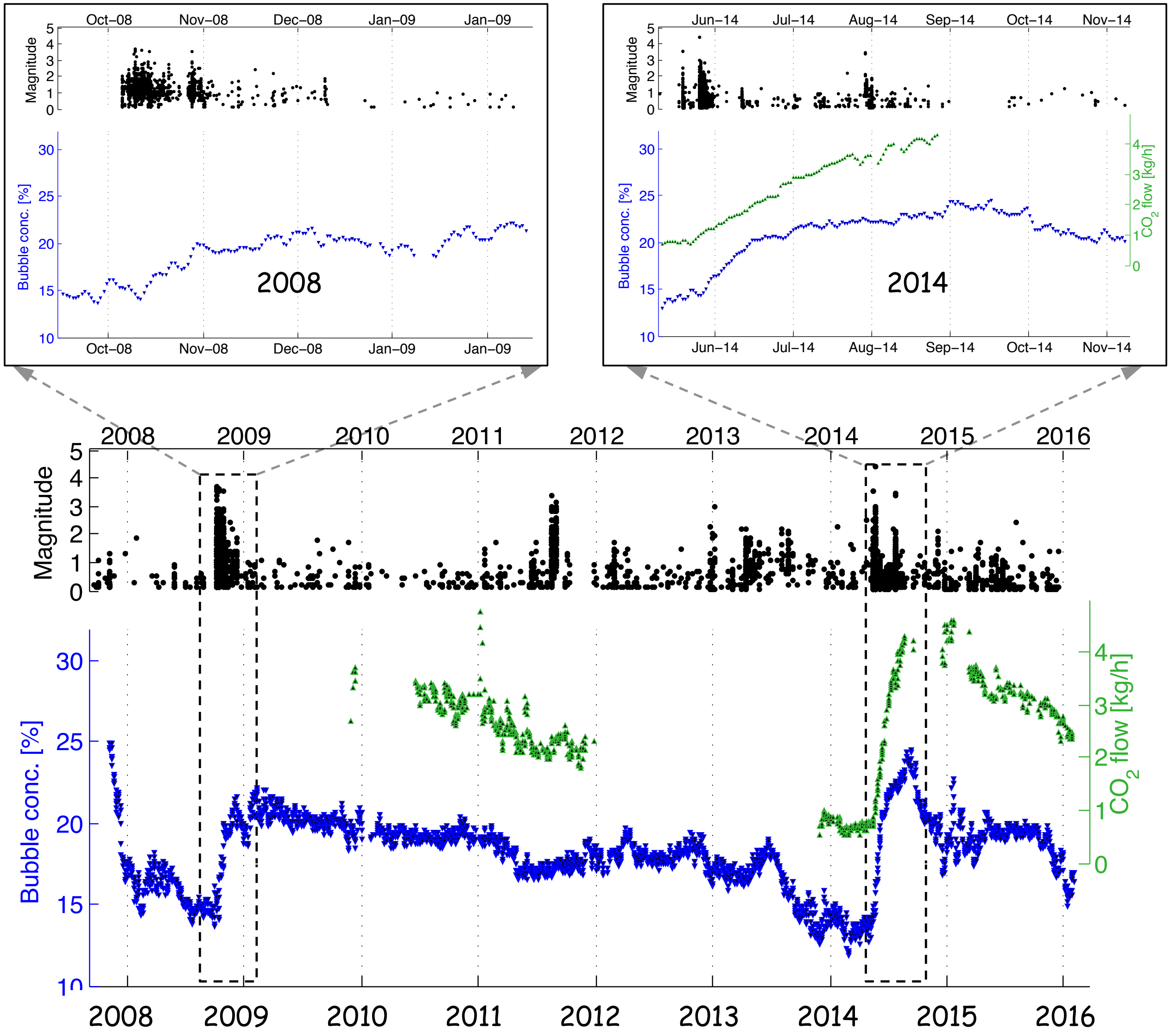


Postseismic CO_2 increase at Hartoušov mofette

Is it explainable by seismic activity?

(Fischer et al., EPSL 2017)

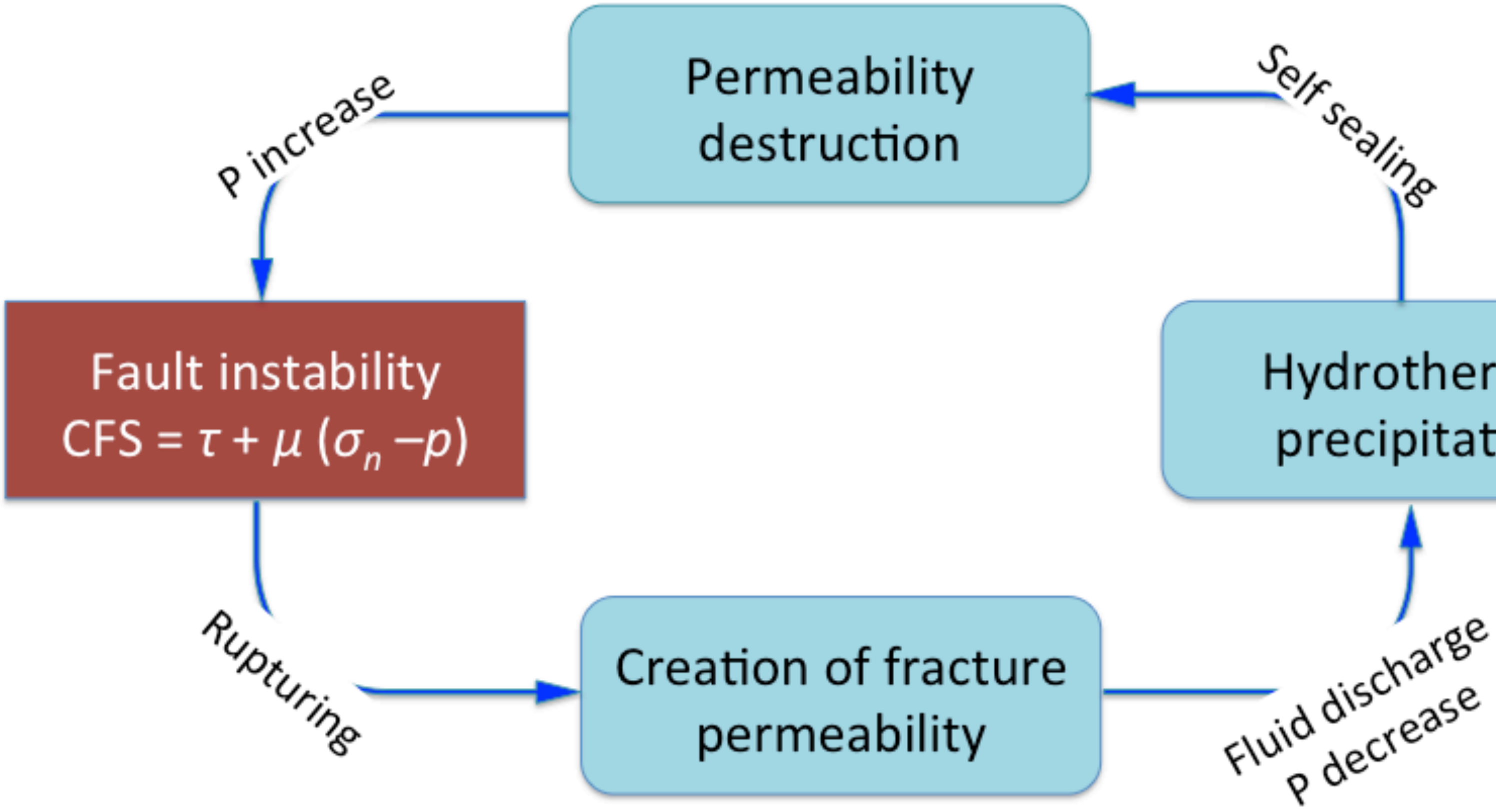
CO_2 flow rate in the Hartoušov well



- Long-term decay of CO_2 flow from 3.6 kg/h in 2010 to 0.7 kg/h in spring 2014
- Fast response of CO_2 flow to the M_L 3.5 earthquake of 24 May 2014: flow increase after only 4 days
- Gradual increase to 4 kg/h for >100 days period
- Bubble fraction in the well shows similar trend – also after the 2008 swarm

Sibson‘s (1982) fault valve model

derived from exhumed paleo faults, no recent observations exist



Permeability destruction

P increase

Fault instability
CFS = $\tau + \mu\,(\sigma_n - p)$

Rupturing

Creation of fracture permeability

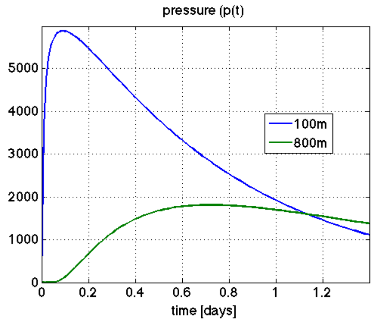
Fluid discharge
P decrease

Hydrothermal precipitation

Self sealing

Numerical model of a releasing fluid reservoir

Seismic analysis
=> fluid pulse in the
mainshock area

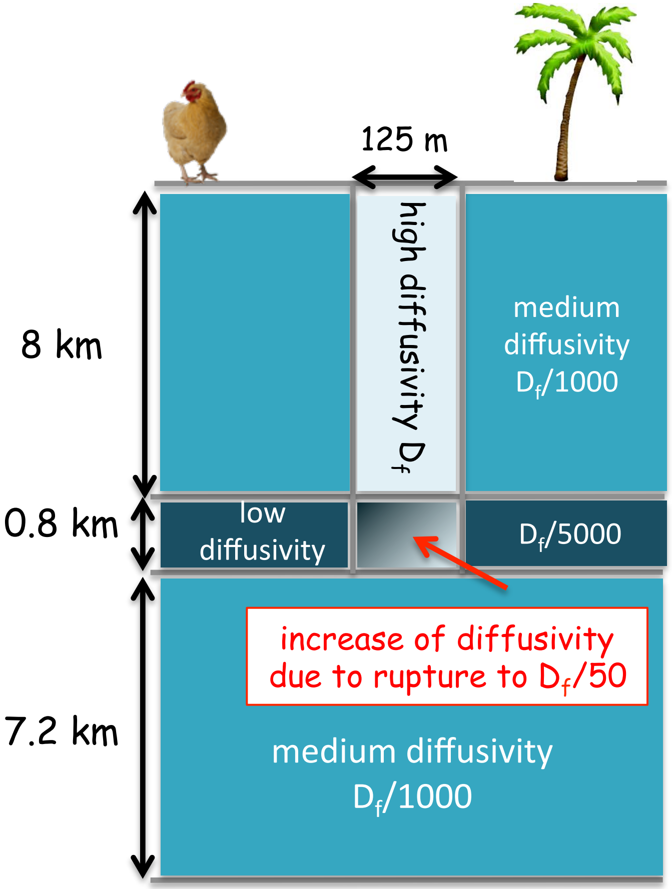


2-D model

- Linear diffusion equation solved by FD

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

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


125 m

8 km

high diffusivity D_f

medium diffusivity $D_f/1000$

0.8 km

low diffusivity

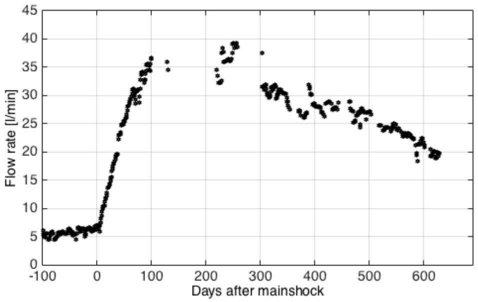
$D_f/5000$

increase of diffusivity due to rupture to $D_f/50$

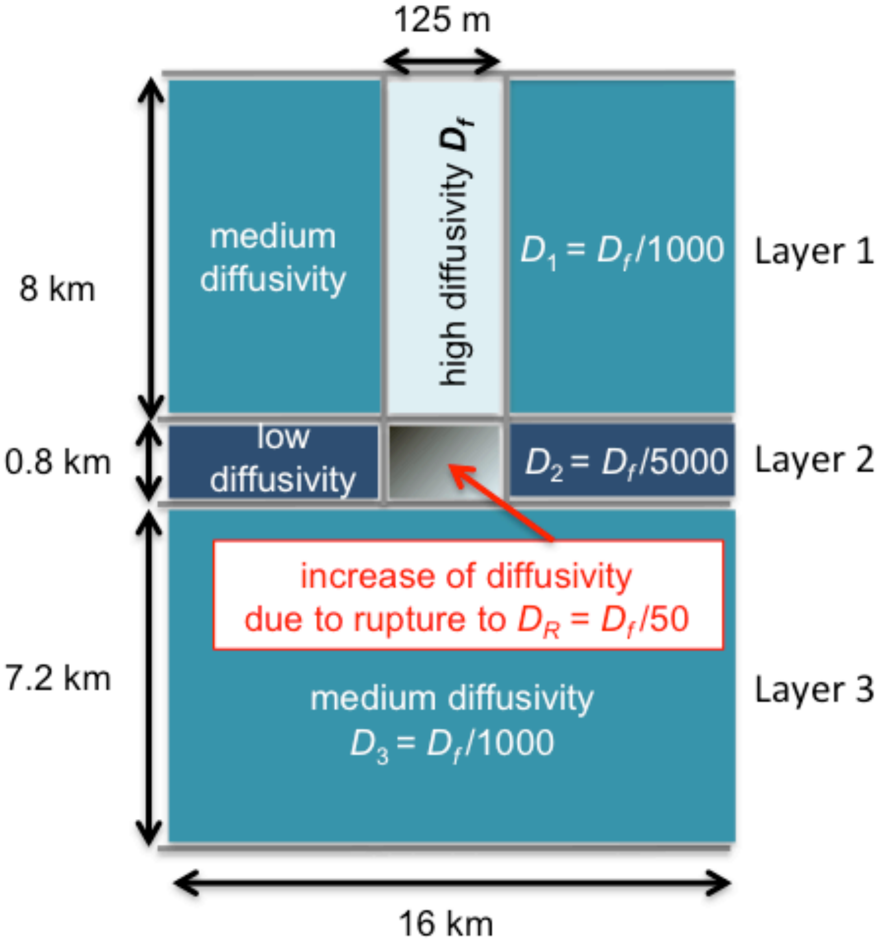
7.2 km

medium diffusivity $D_f/1000$

- Data:
  - Flow rate at Hartoušov 2014 – 2016

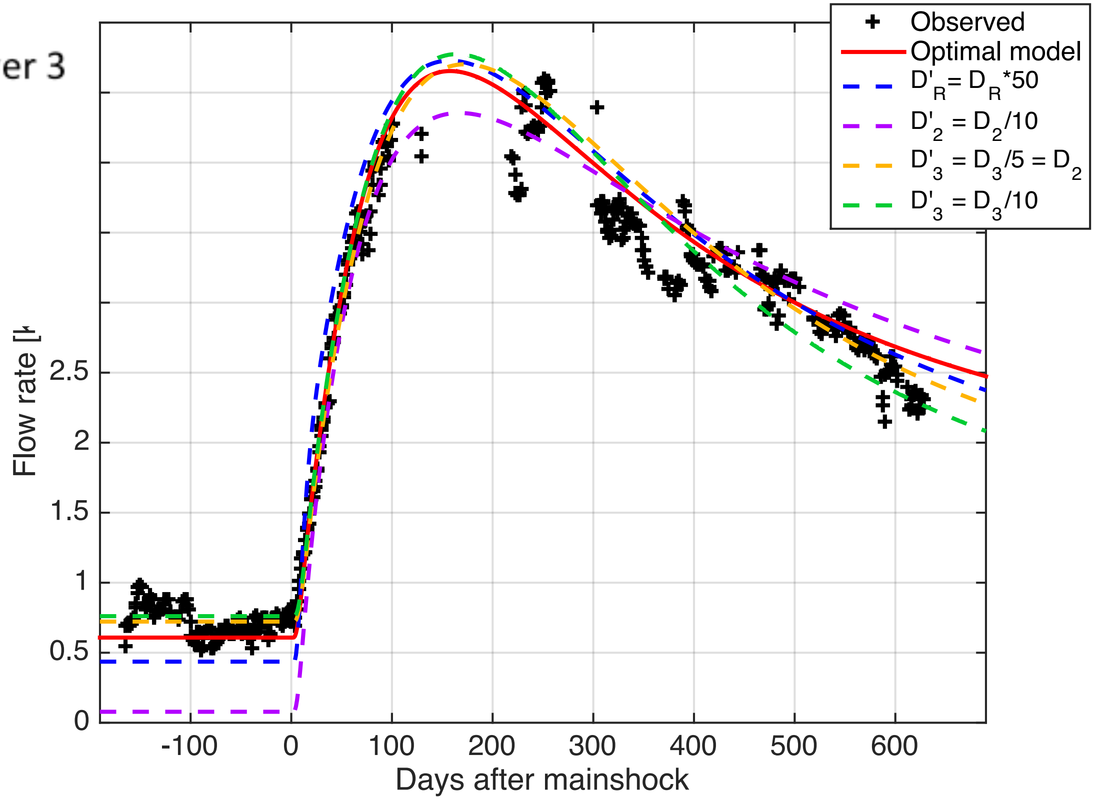


Fit of simulation

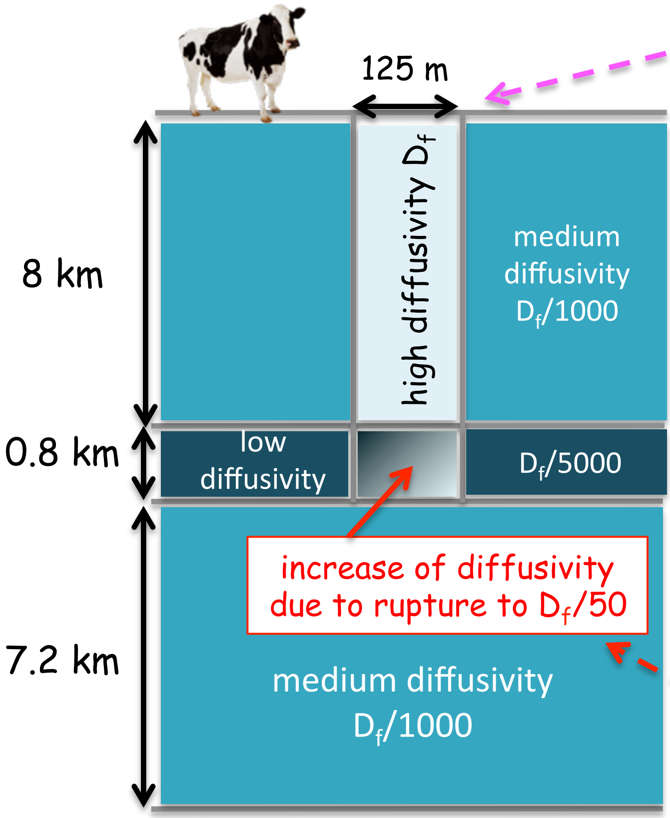


channel: $D_f = 12\ m^2/s$
upper crust: $D_1 = 0.012\ m^2/s$
seal: $D_2 = 0.0024\ m^2/s \rightarrow 0.24\ m^2/s$
lower crust: $D_3 = 0.012\ m^2/s$

! no precipitation related fault sealing included !



Modelling results



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high diffusivity D_f

medium diffusivity $D_f/1000$

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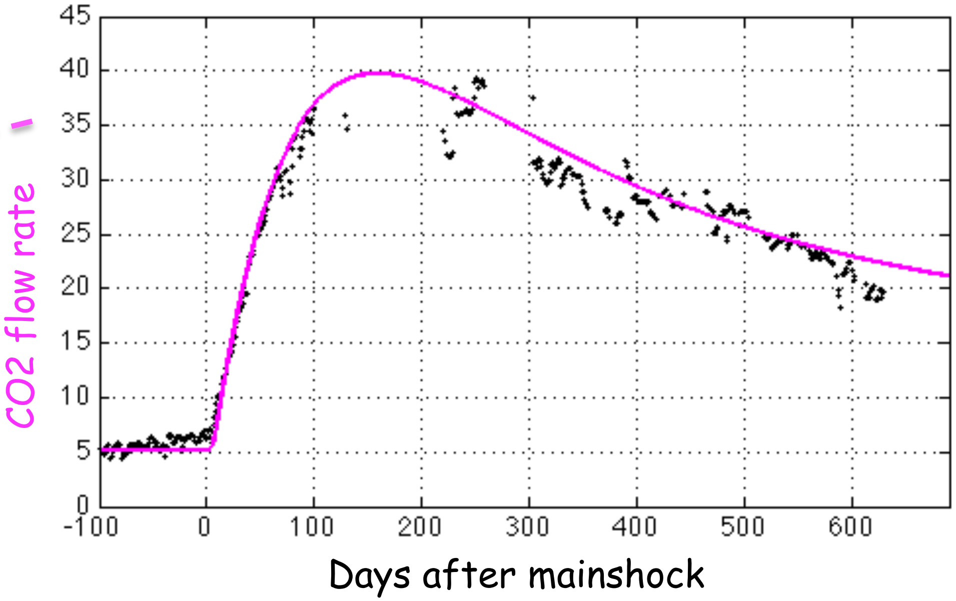
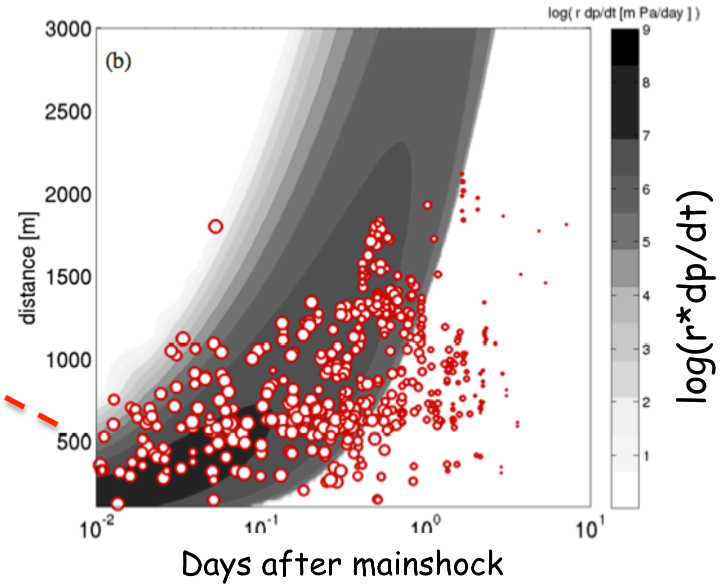
increase of diffusivity due to rupture to $D_f/50$

medium diffusivity $D_f/1000$

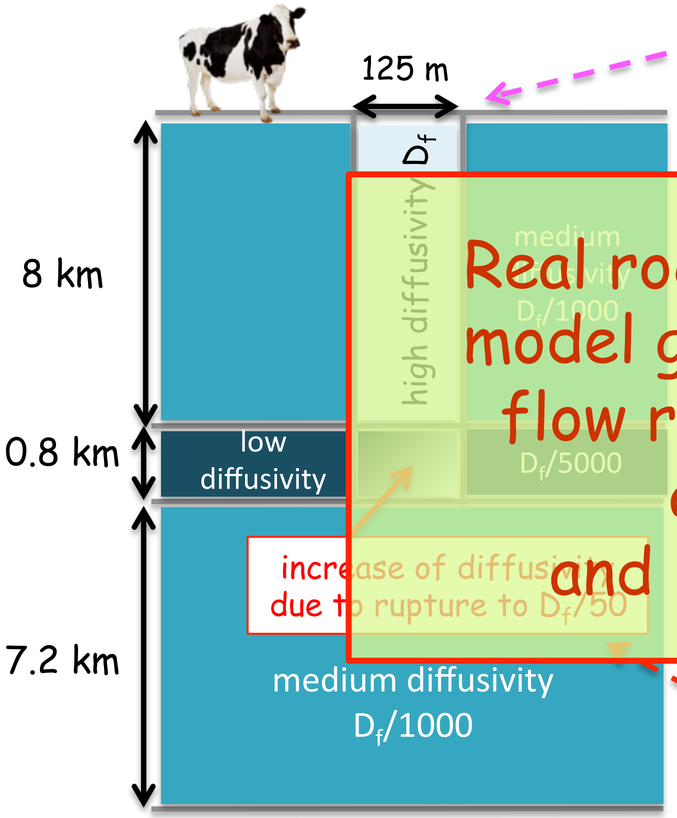


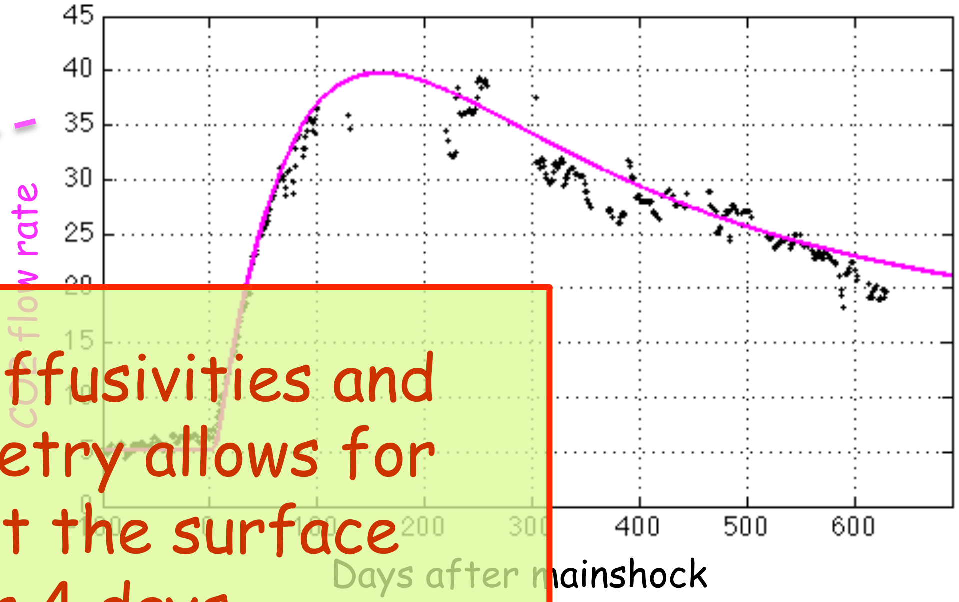


Optimal channel diffusivity D_f = 12 m^2/s

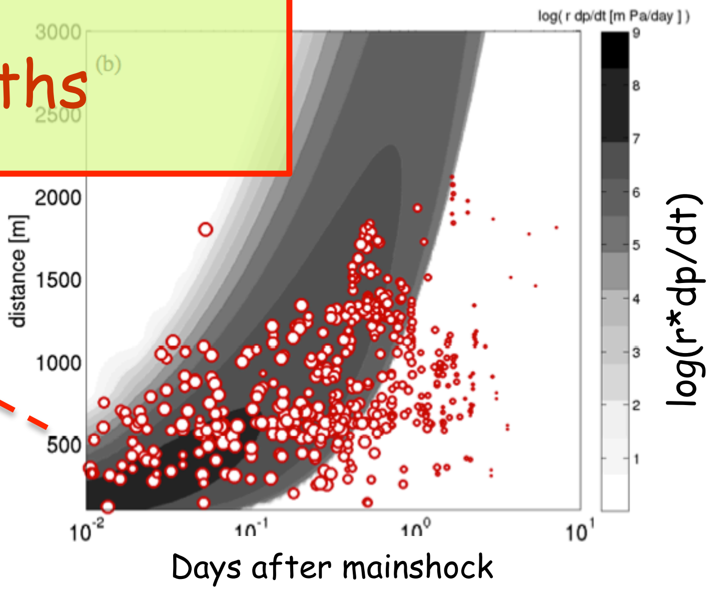
Diffusivity of faults (Talwani et al. 2007): 0.1 – 10 m^2/s

Modelling results





Real rock diffusivities and model geometry allows for flow rise at the surface after 4 days and lasting 4 months



Optimal channel diffusivity $D_f = 12\ m^2/s$

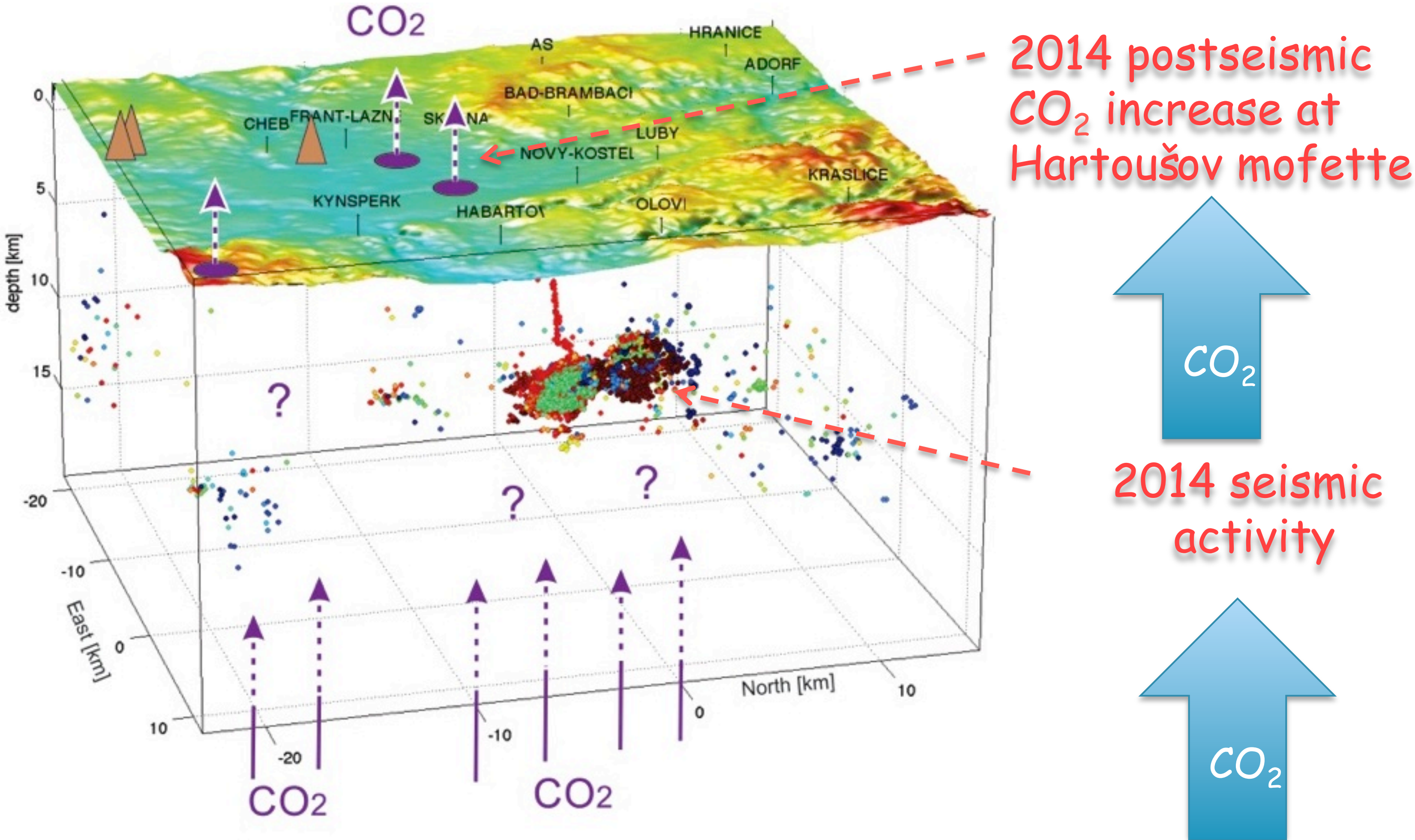
Diffusivity of faults (Talwani et al. 2007): 0.1 – 10 m^2/s

Relation of CO_2 and earthquake activity

Gas:

- passes through seismogenic depth !
- takes part in fault rupture processes ?

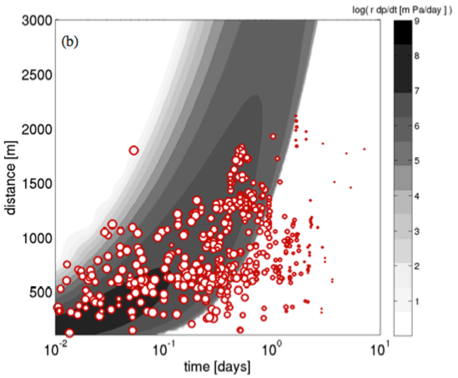
YES !

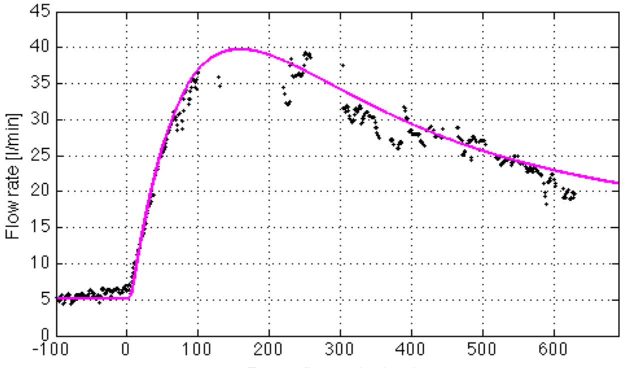


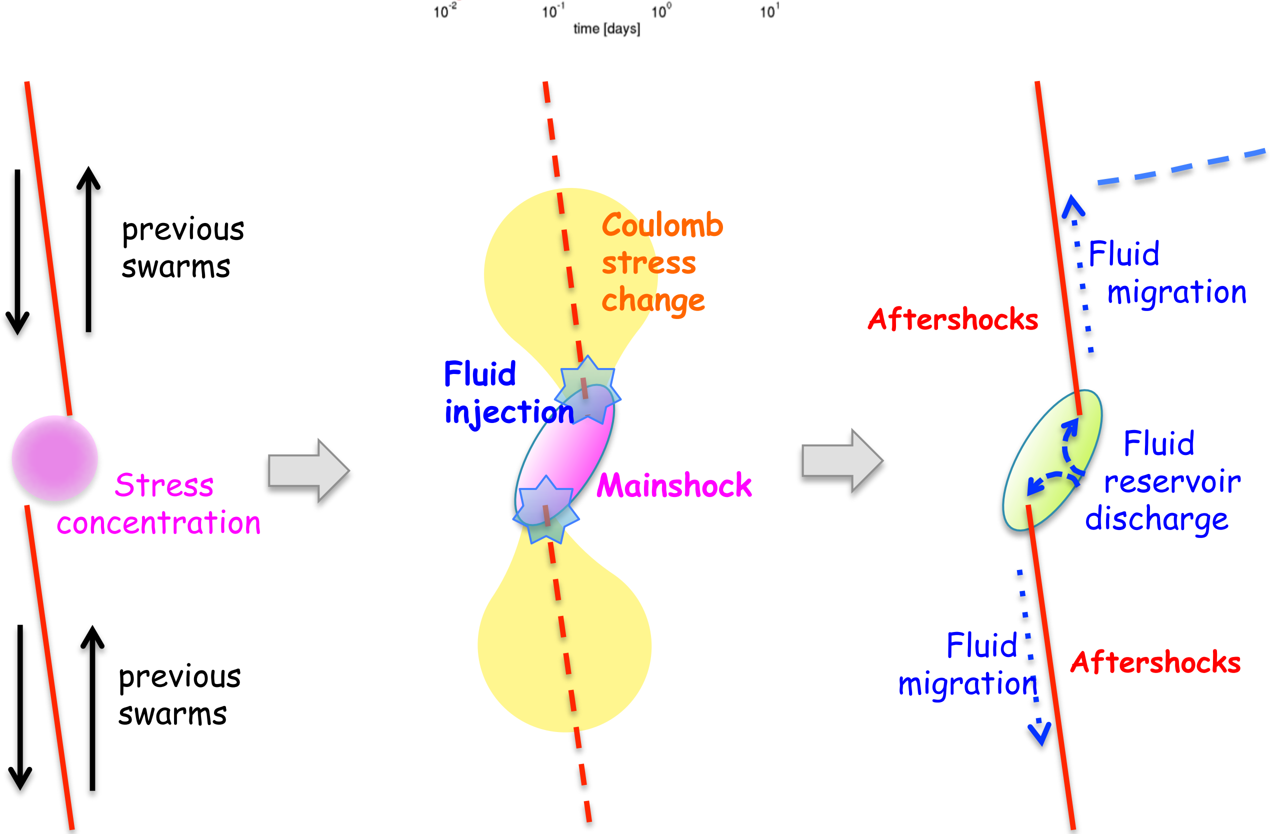
2014 postseismic CO_2 increase at Hartoušov mofette

2014 seismic activity

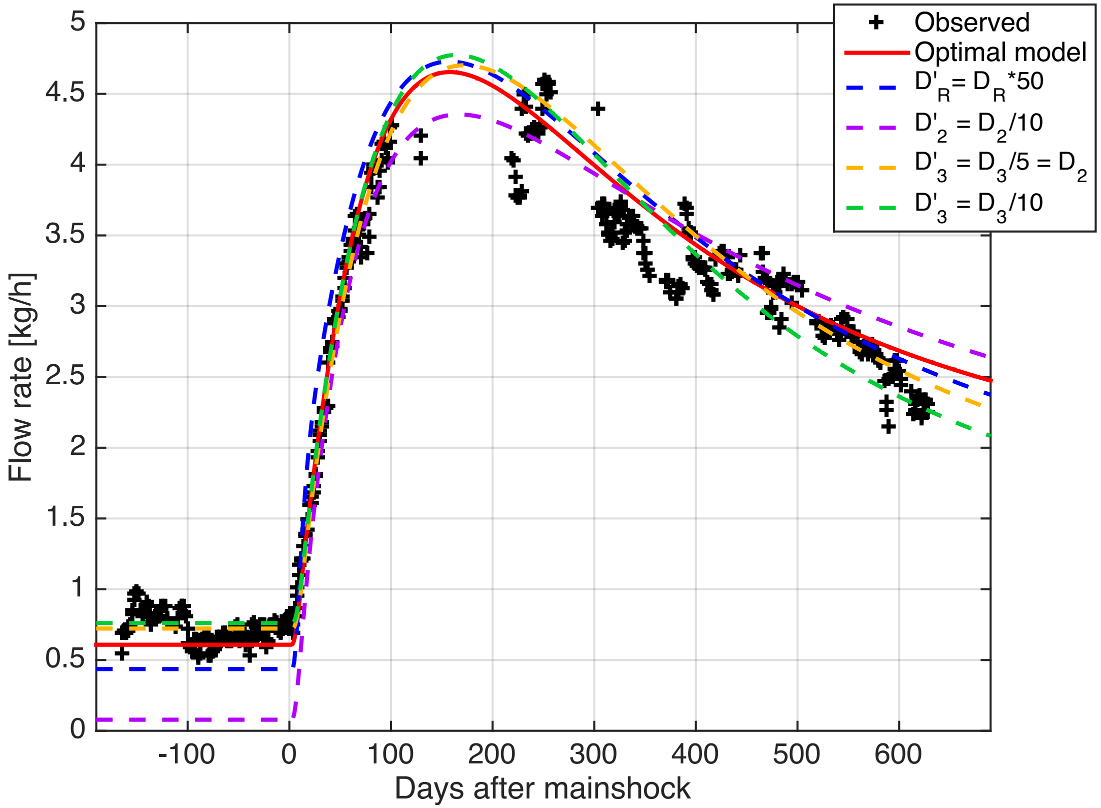
CO_2 activity scenario







Amount of CO2 released after fault valve opening



CO2 in borehole

before eq.:
0.7 kg/h

average after eq.:
3.5 kg/h

excess after eq.:
2.8 kg/h
50 t/2 years

Whole Hartoušov area
50 000 t/2 years

Summary

- The 2014 aftershocks showed anomalous high rate and point-source migration
- The 2014 aftershocks (>60% of them) were most probably driven by external forcing
- Spatiotemporal distribution of the 2014 aftershocks is consistent with propagation of pressure field due to discharging a fluid reservoir
- Fast inrease of CO_2 flow observed in Hartoušov moffete 4 days after the 2008 and 2014 seismic sequences; 2011 swarm not manifested in gas flow
- 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

=> CO_2 of magmatic origin takes part in the seismogenic process in W-Bohemia/Vogtland

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.

thank you

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