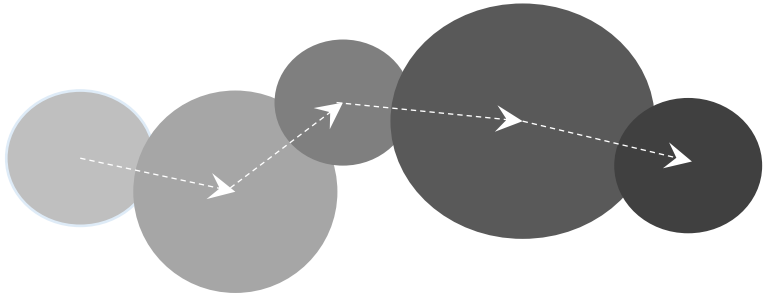

What drives the growth of earthquake clusters?

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Charles University

GFZ
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POTSDAM

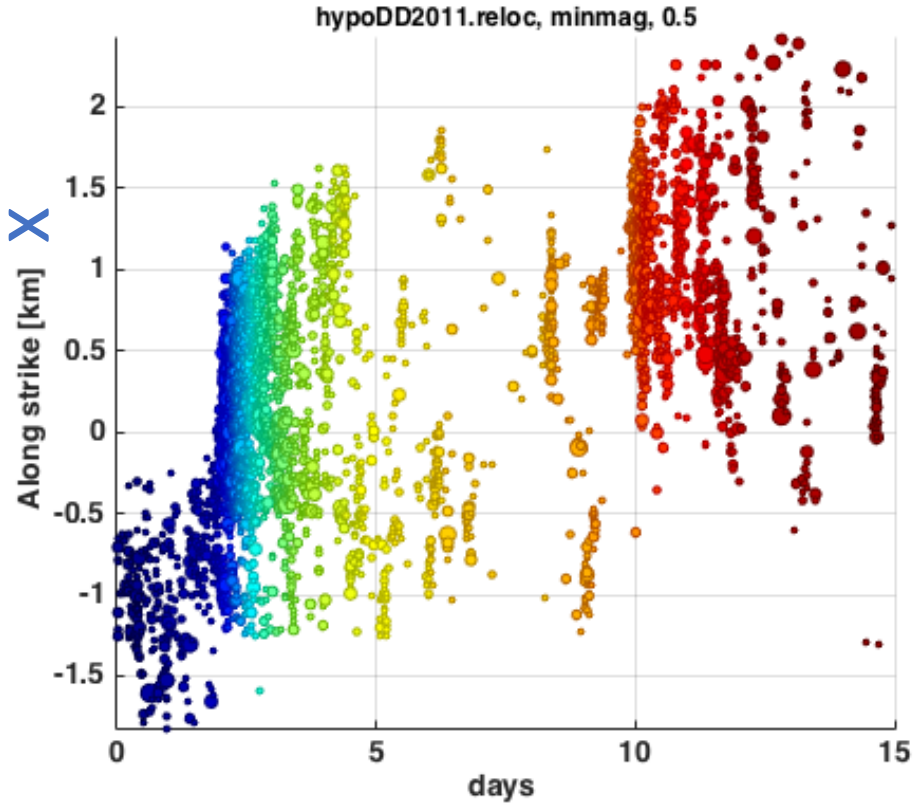
Outline

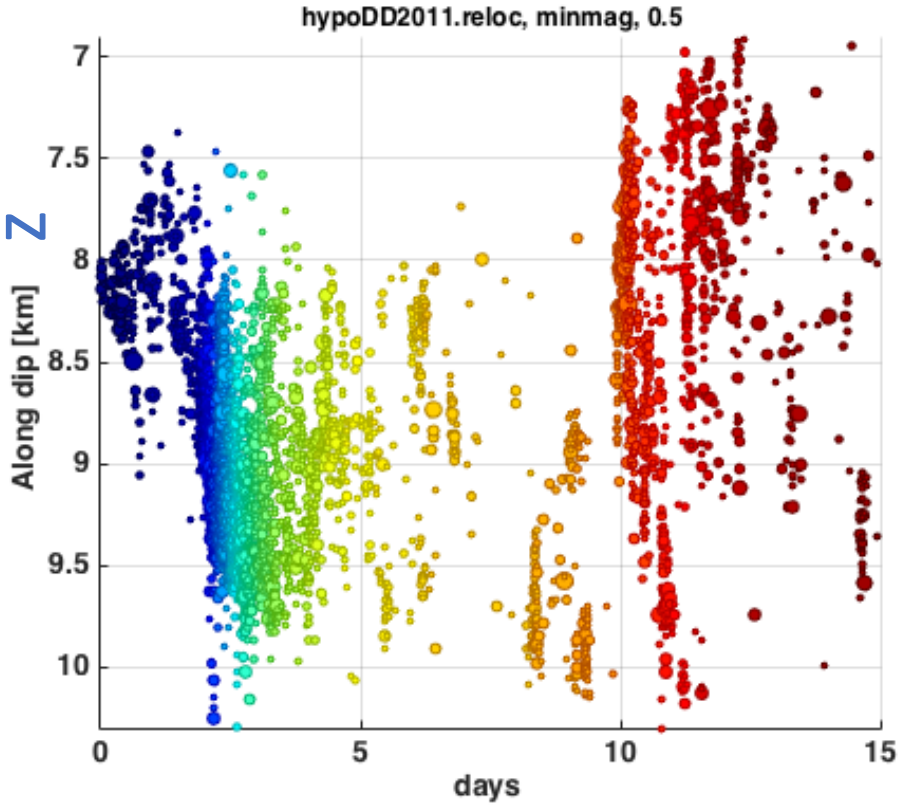
- Representing and understanding migration of swarms and induced seismicity
- External / Internal loading - $X(t)$ or $X(N)$ plots ?
- Observations
- Model
- Application to seismic swarm data
- Summary

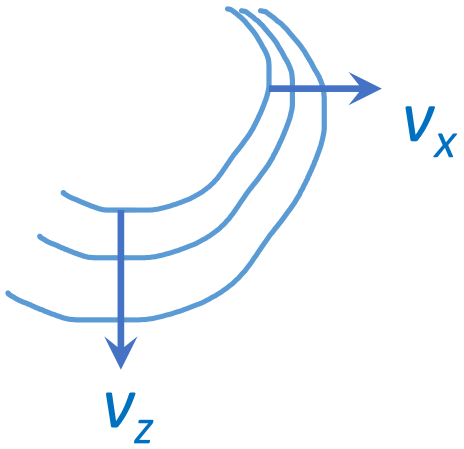
Based on Fischer T. J. and Hainzl S., 2021. The growth of earthquake clusters, Front. Earth Sci. 9:638336. doi: 10.3389/feart.2021.638336

Understanding hypocenter migration

Hypocentre migration – coordinate-time plot

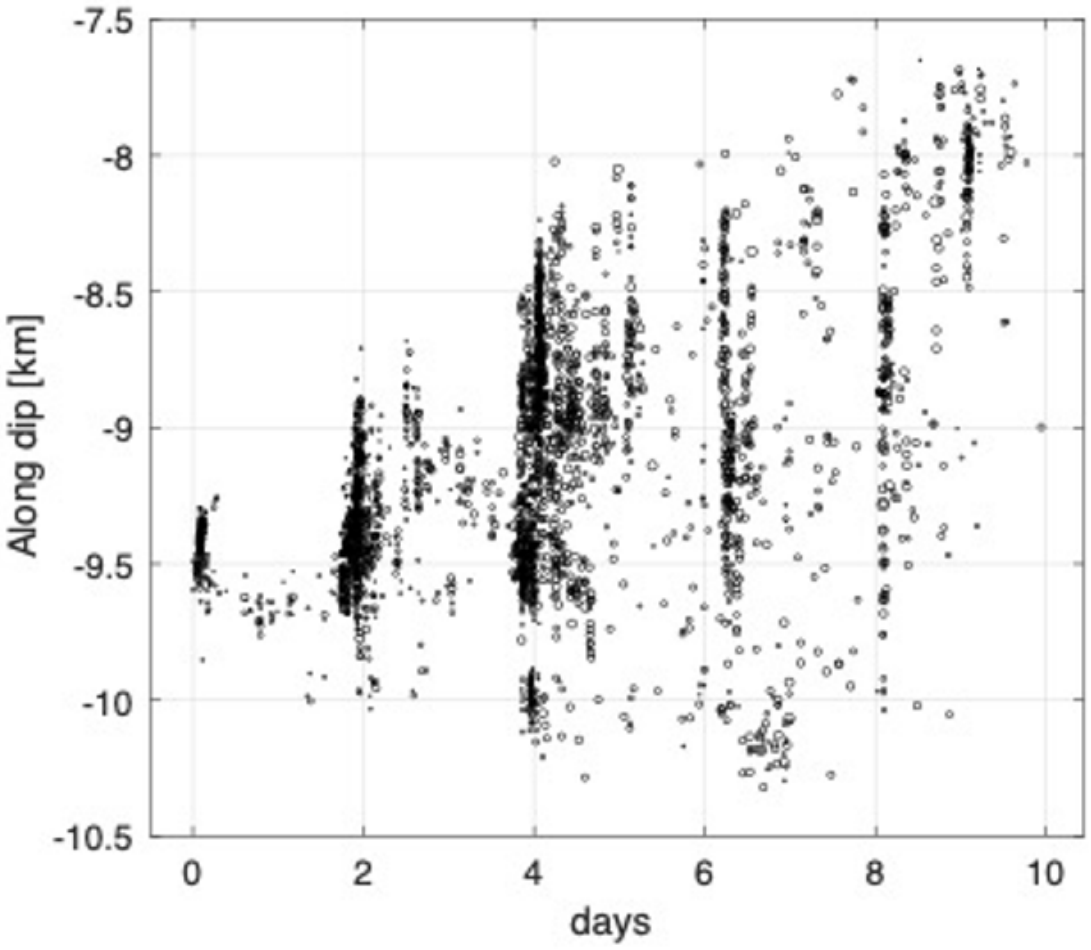




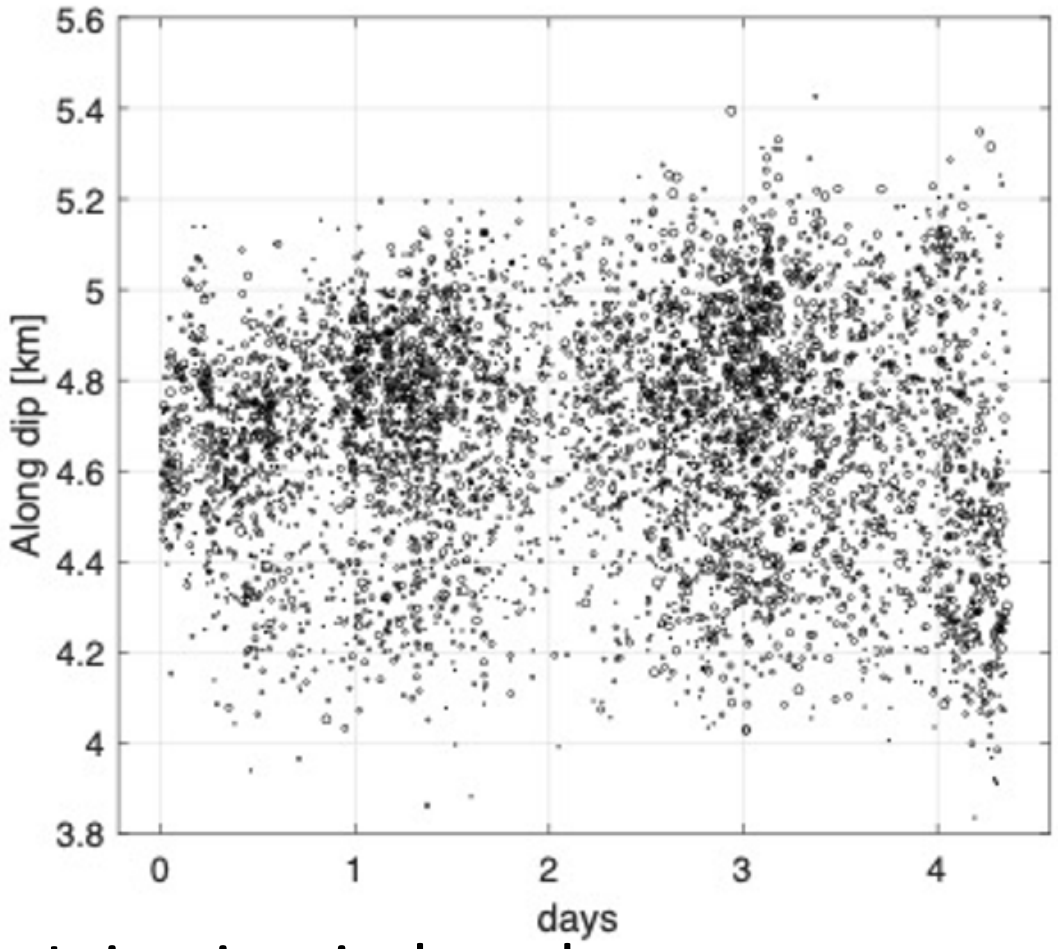


Fine structures of the hypocentre migration cannot be explained by pore pressure diffusion

Function of time: the migration often appears discontinuous

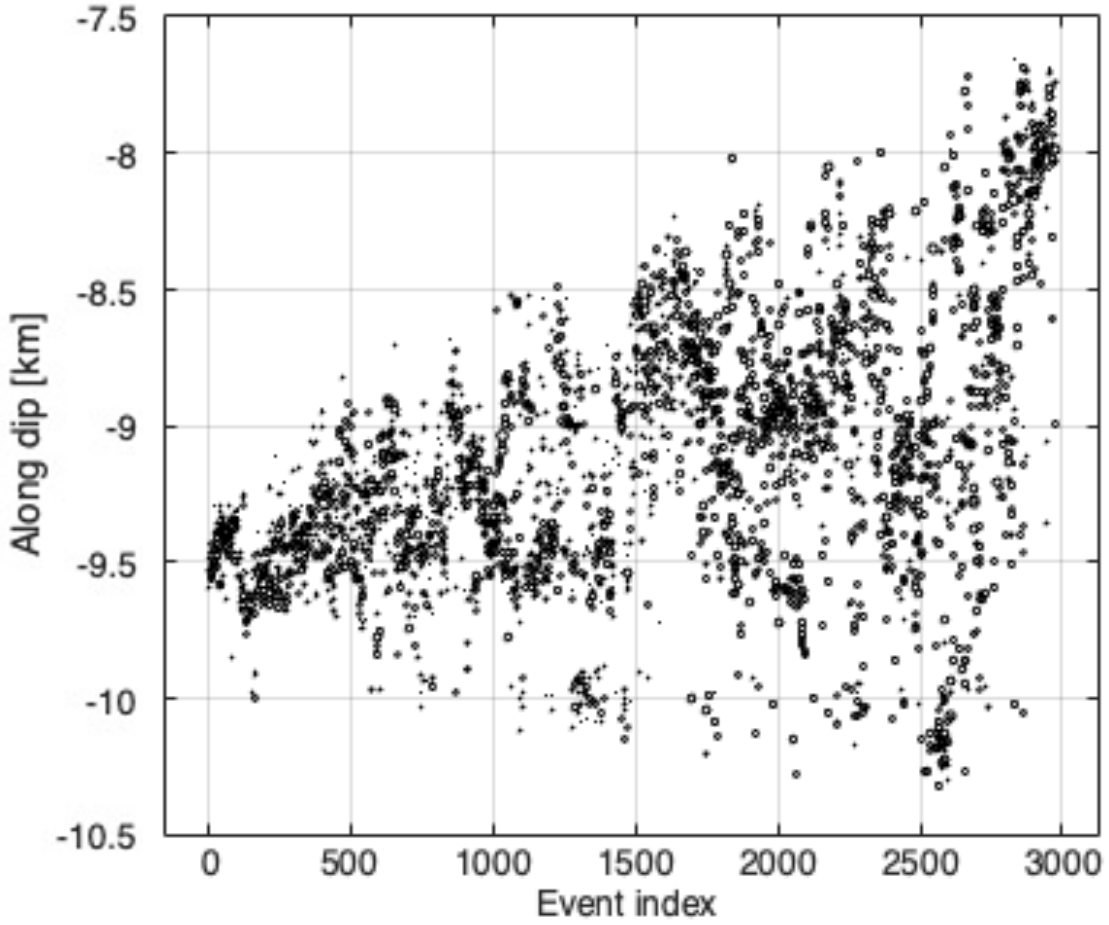


Swarm

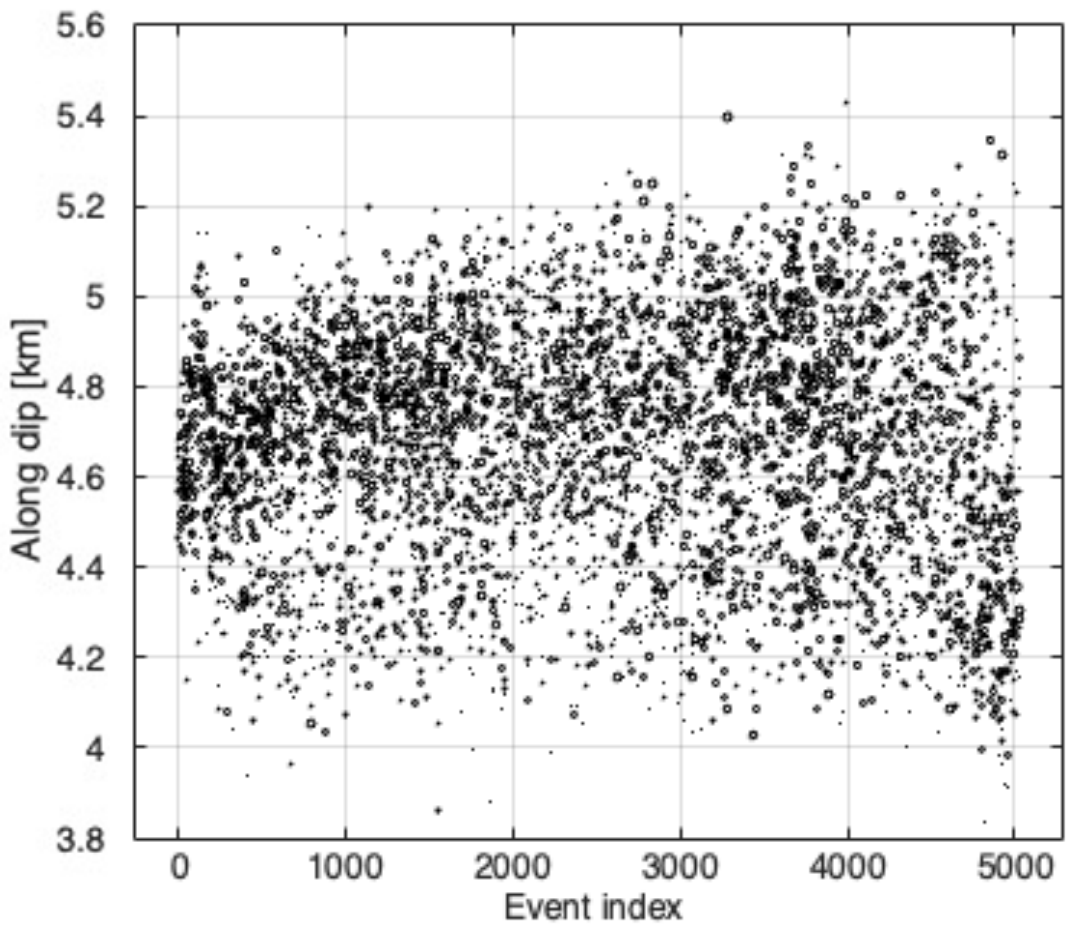


Injection-induced

Function of event index: the migration becomes more continuous

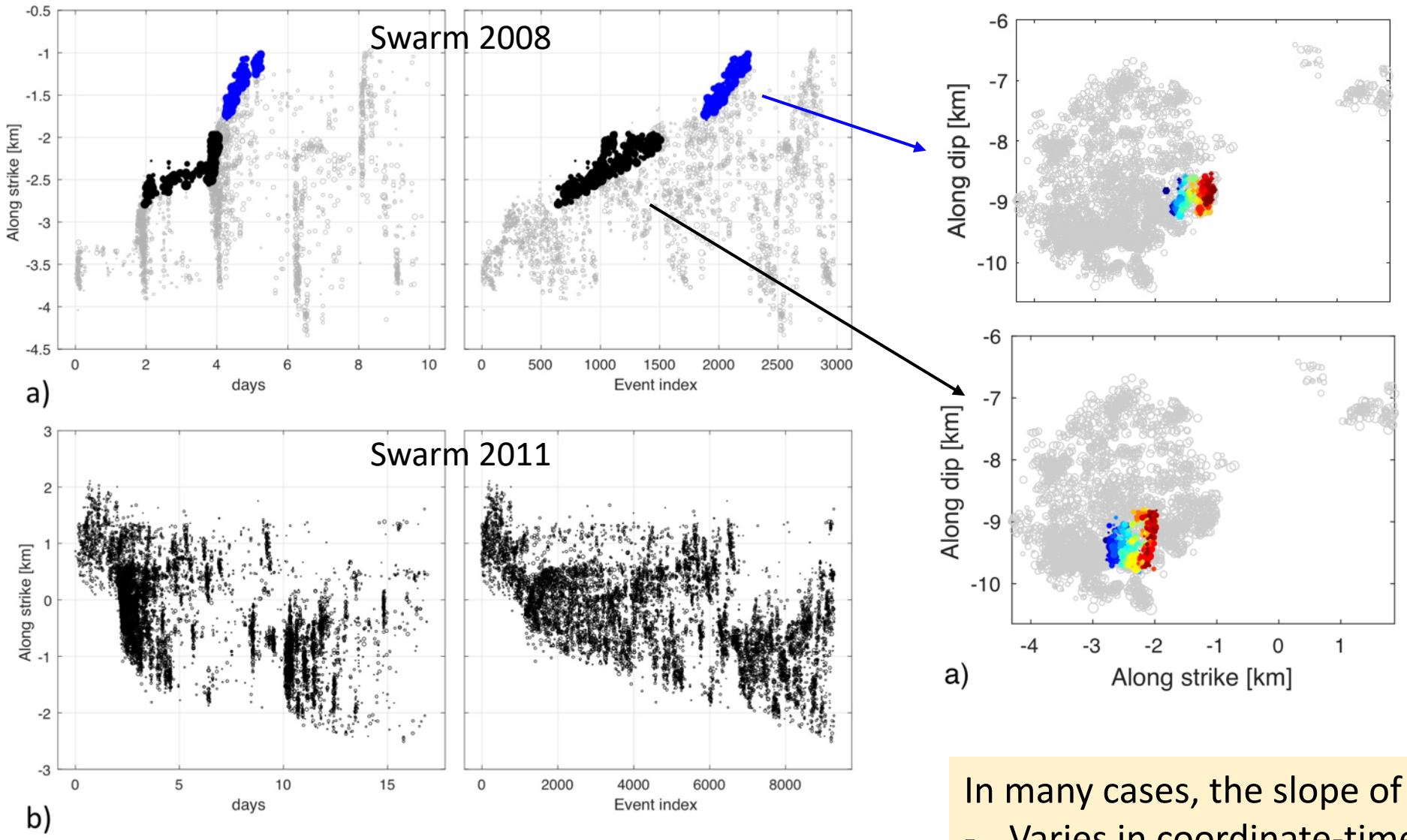


Swarm



Injection-induced

Comparison of coordinate-time and coordinate-event index plot



In many cases, the slope of seismicity growth

- Varies in coordinate-time plot
- Is constant in coordinate-event index plot

Loading of seismic front advance (migration)

External (aseismic) loading

Seismicity growth is controlled by the time dependent external process (injection) modelled by

- Pore pressure diffusion
  (Shapiro et al. 1997)
- Hydraulic fracture growth
  (Fischer, Hainzl and Dahm, 2009)

=> Seismicity is time dependent

–> coordinate-time X(t) plots

Internal (seismic) loading

Seismicity growth is controlled by earthquake ruptures themselves

- the rupture allows for nucleation of adjacent new rupture
- Seismic rupture is first, fluid flow follows (Yamashita 1999)

=>

No time dependence of seismicity

The process itself measures the 'time'

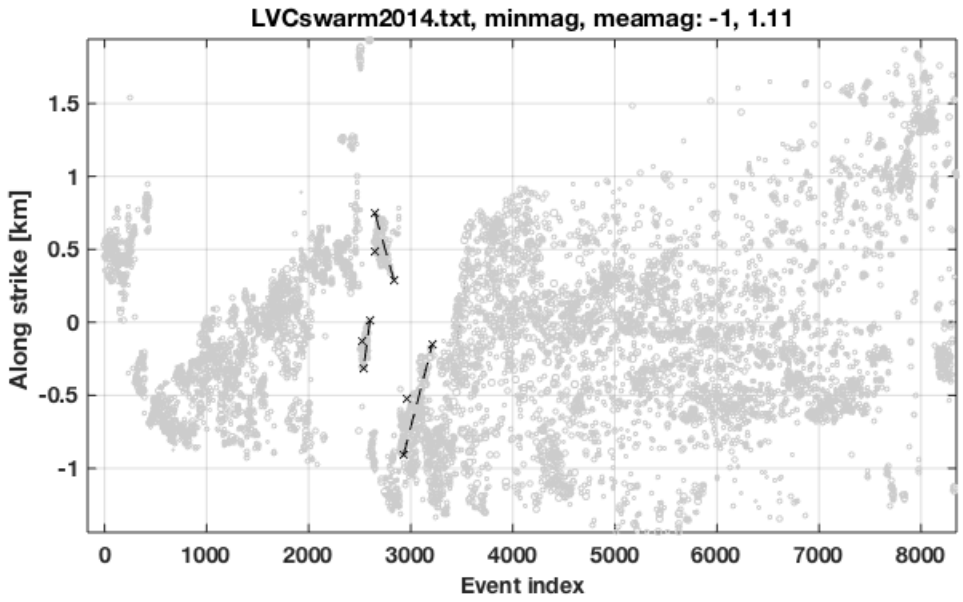
Event occurrence = time tick

"NATURAL TIME"

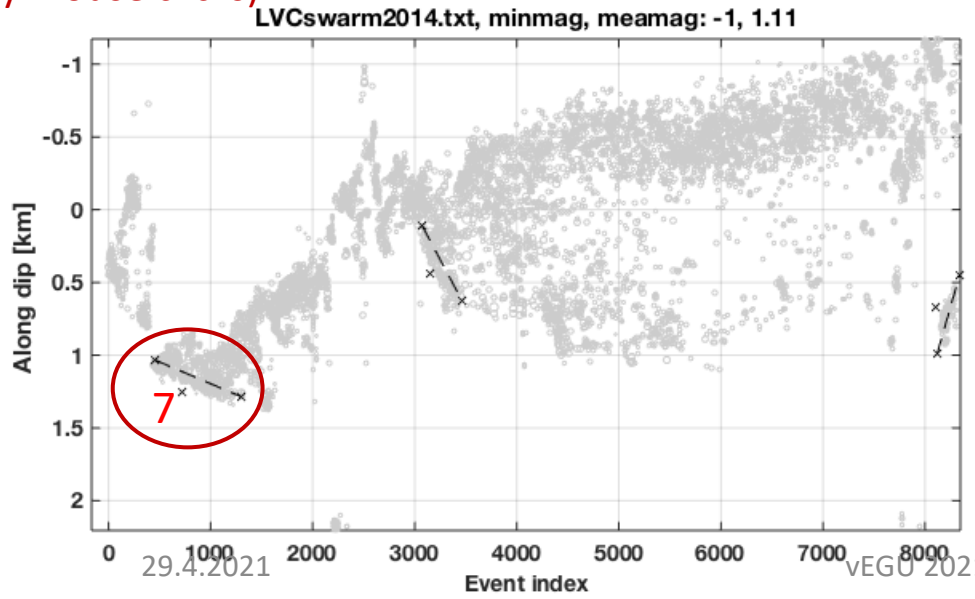
–> coordinate-event-index X(N) plots

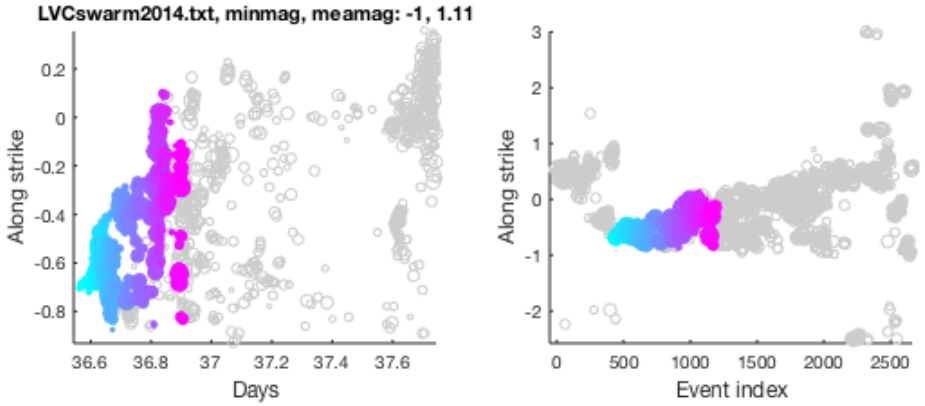
Observations

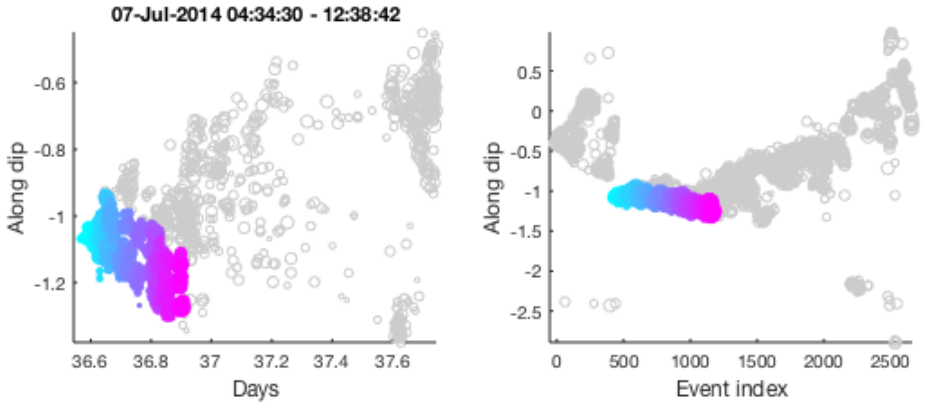
Linear clusters - *streaks*

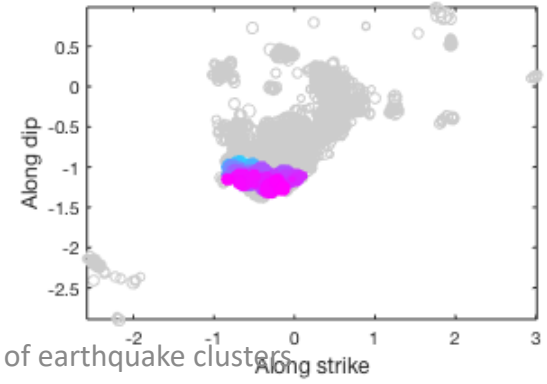


Selection of streak in the coordinate-event index plot (by mouse clicks)

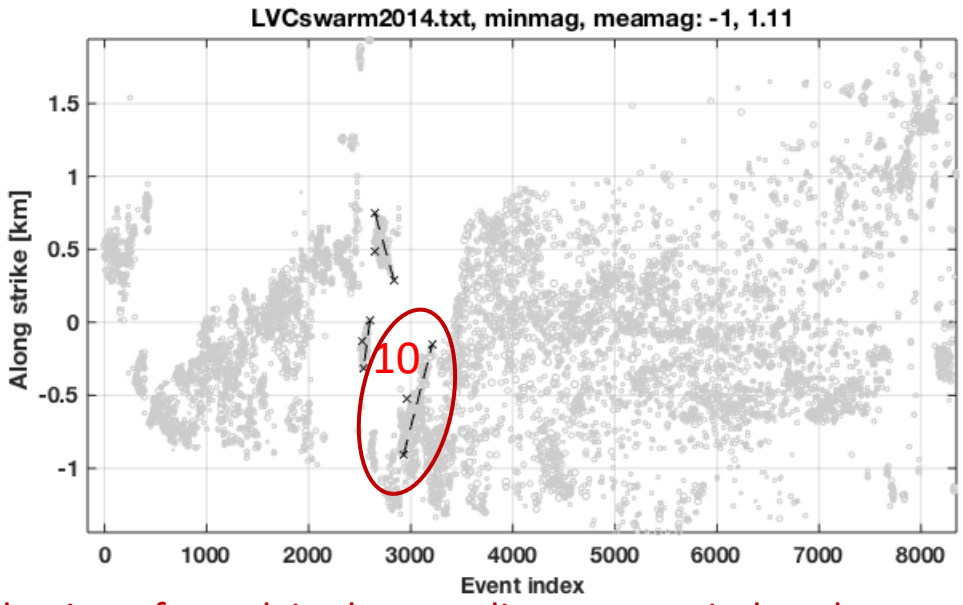




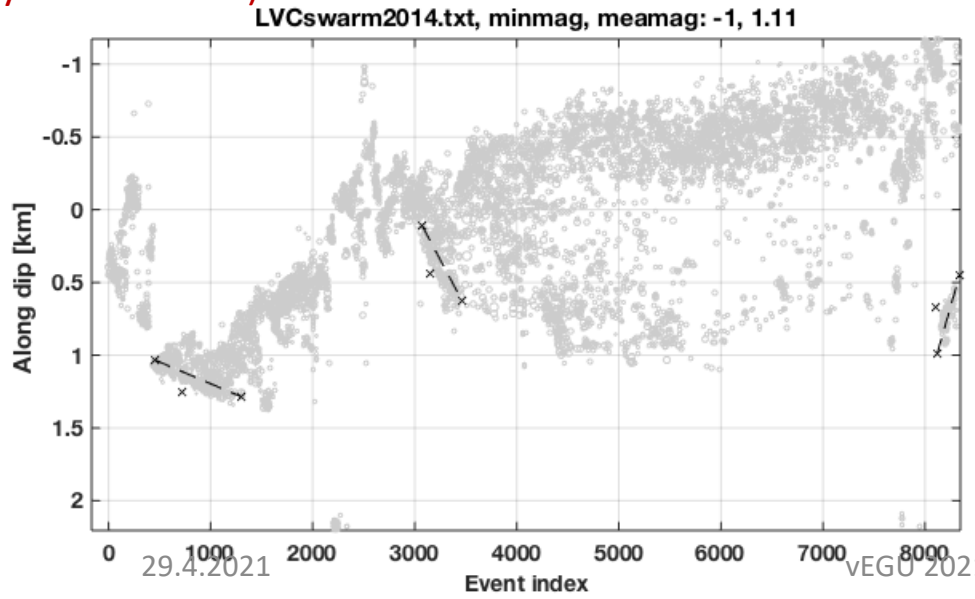


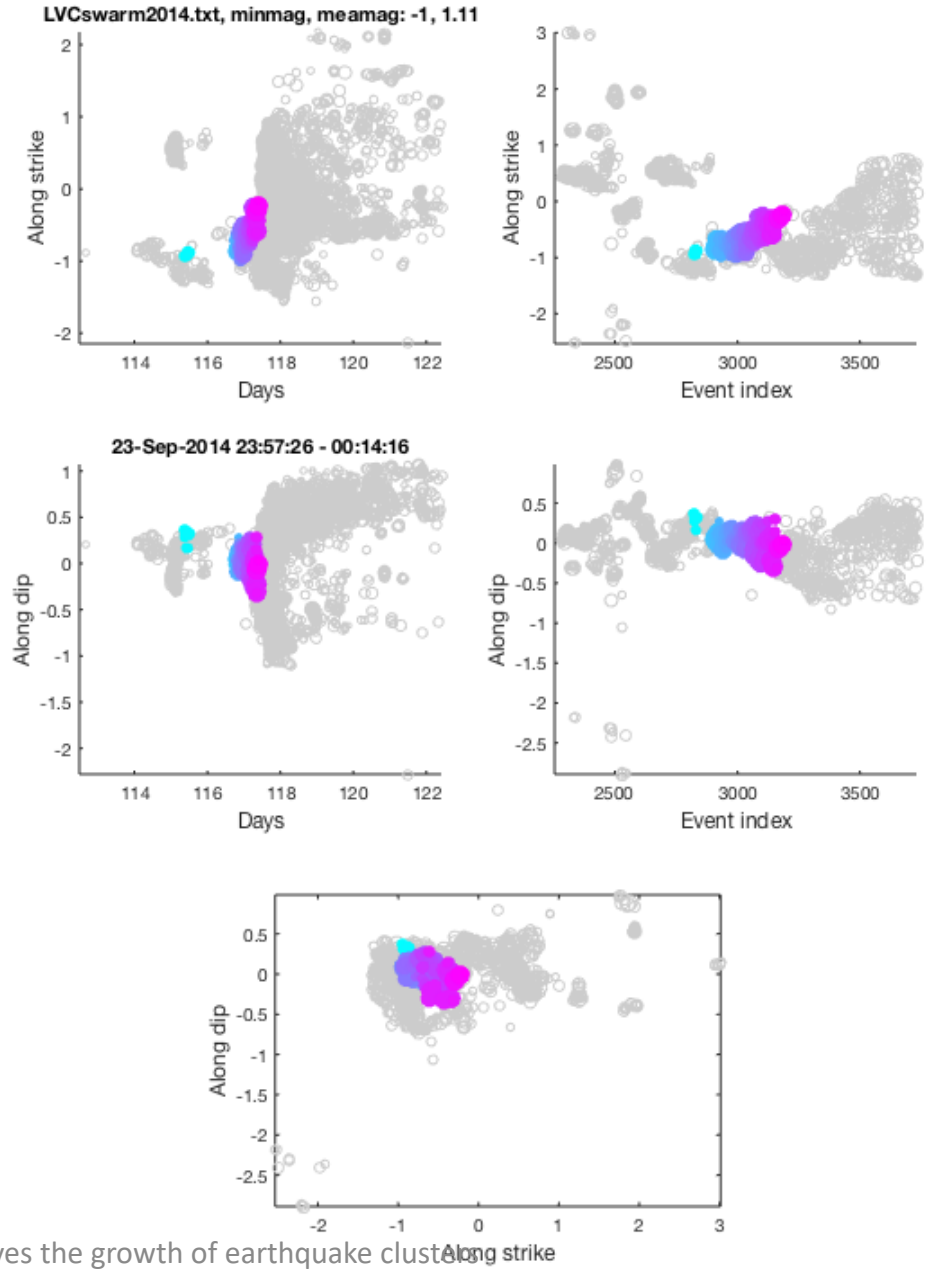


Linear clusters - *streaks*

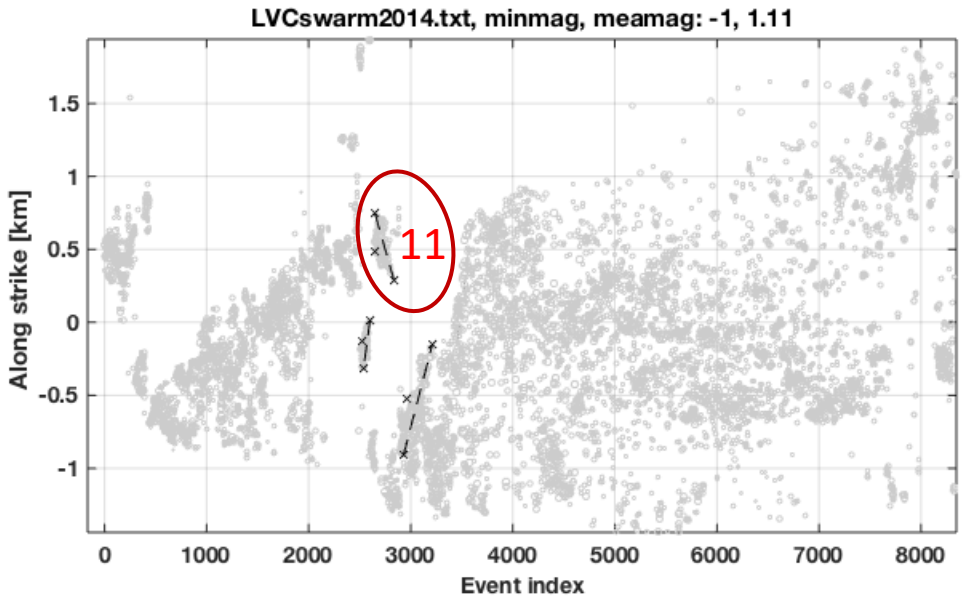


Selection of streak in the coordinate-event index plot (by mouse clicks)

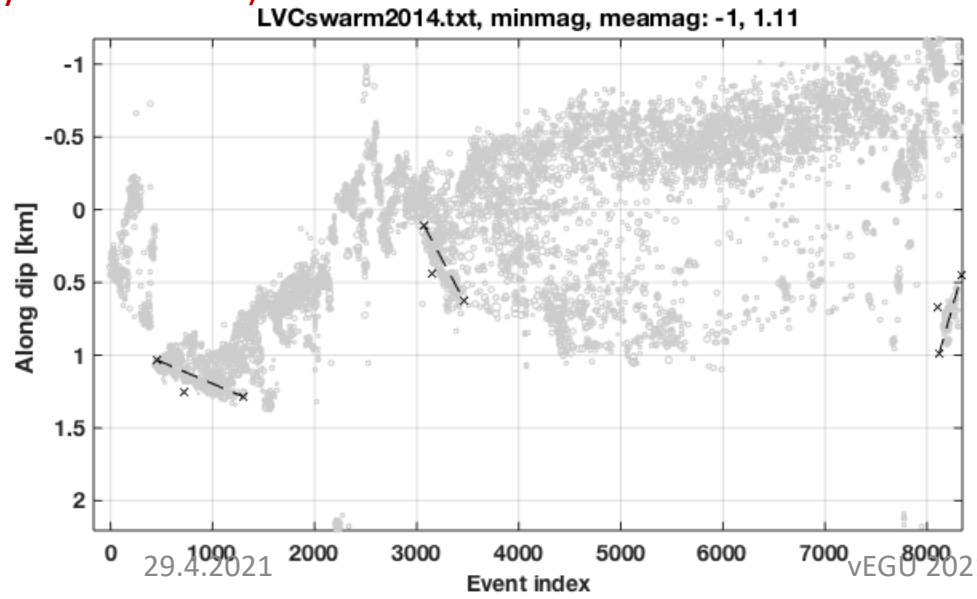


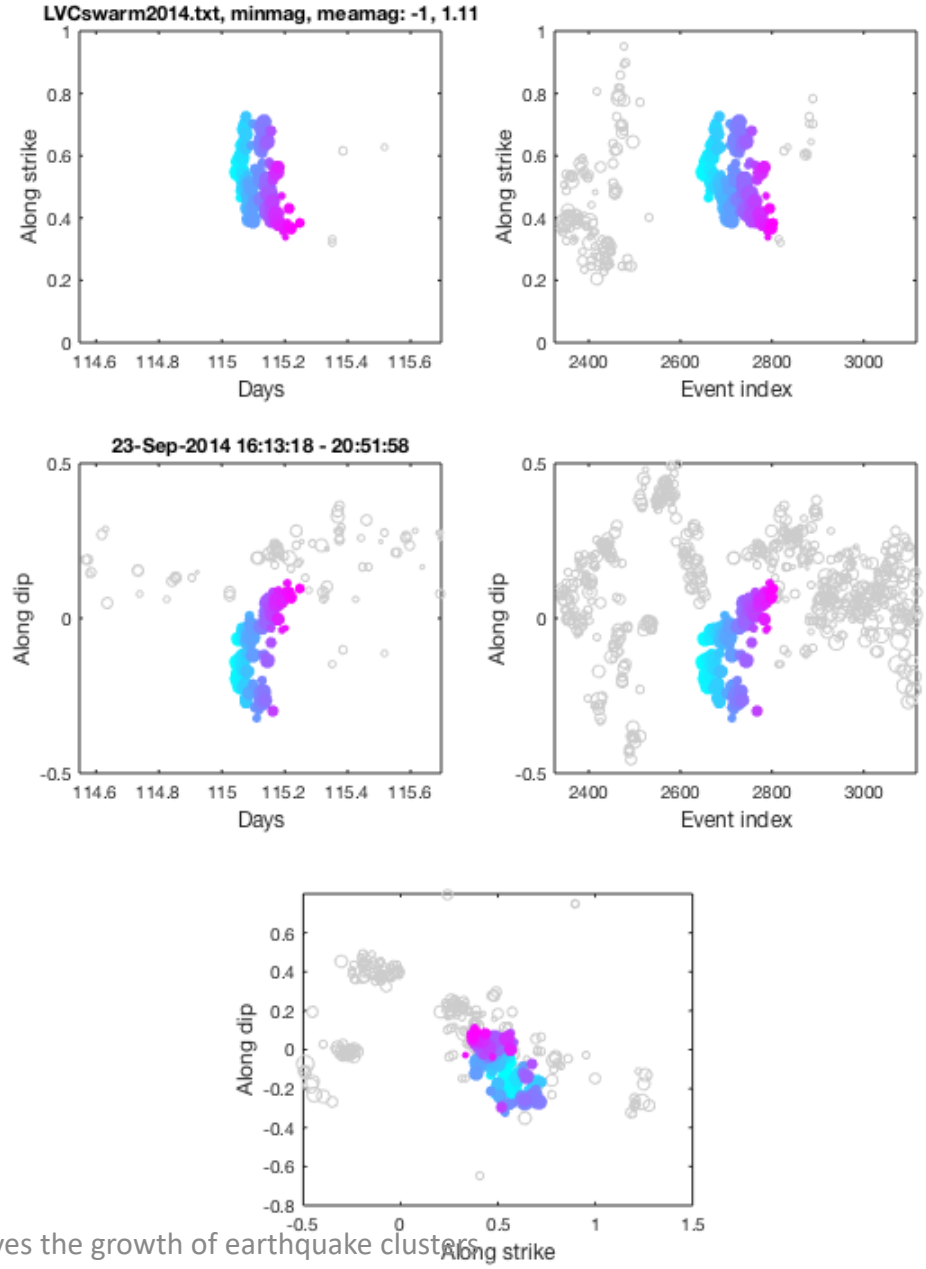


Linear clusters - *streaks*



Selection of streak in the coordinate-event index plot (by mouse clicks)



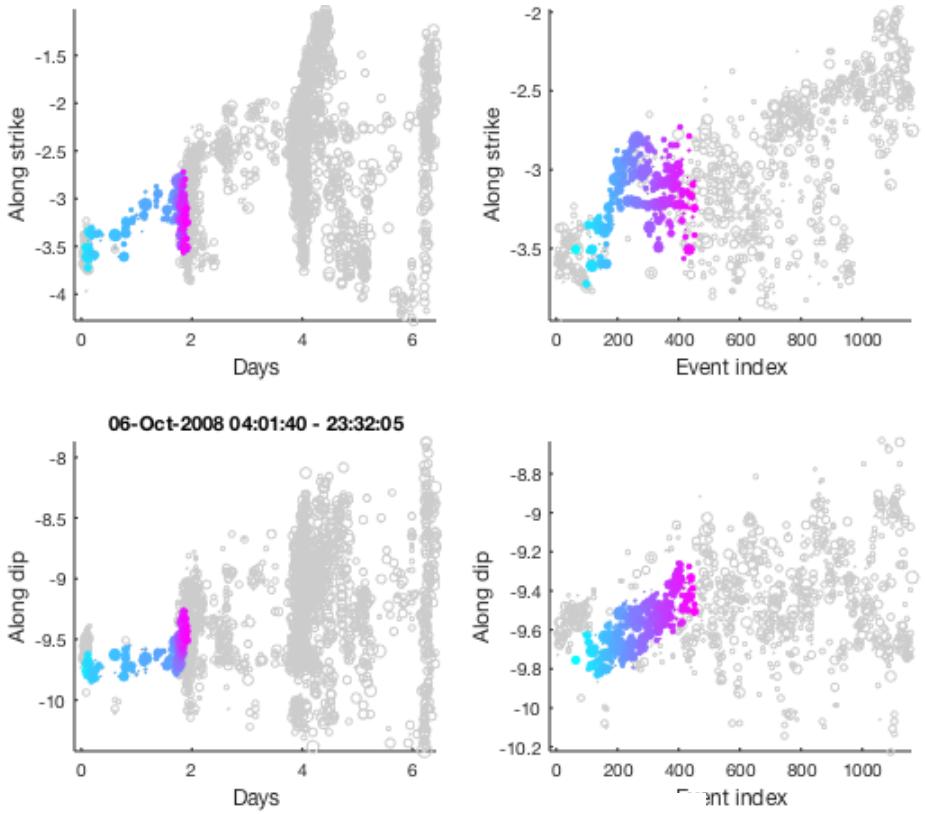


Examples of time and event-index migration plot

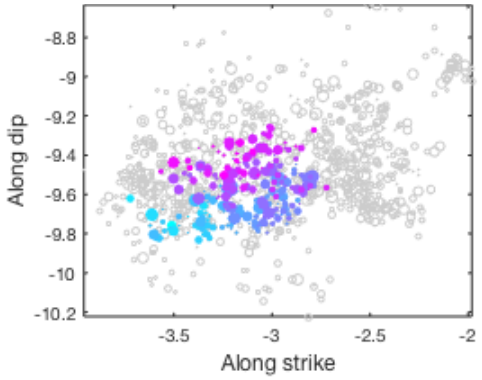
West Bohemia swarm 2008

Coordinate-time plot

Coordinate-index plot

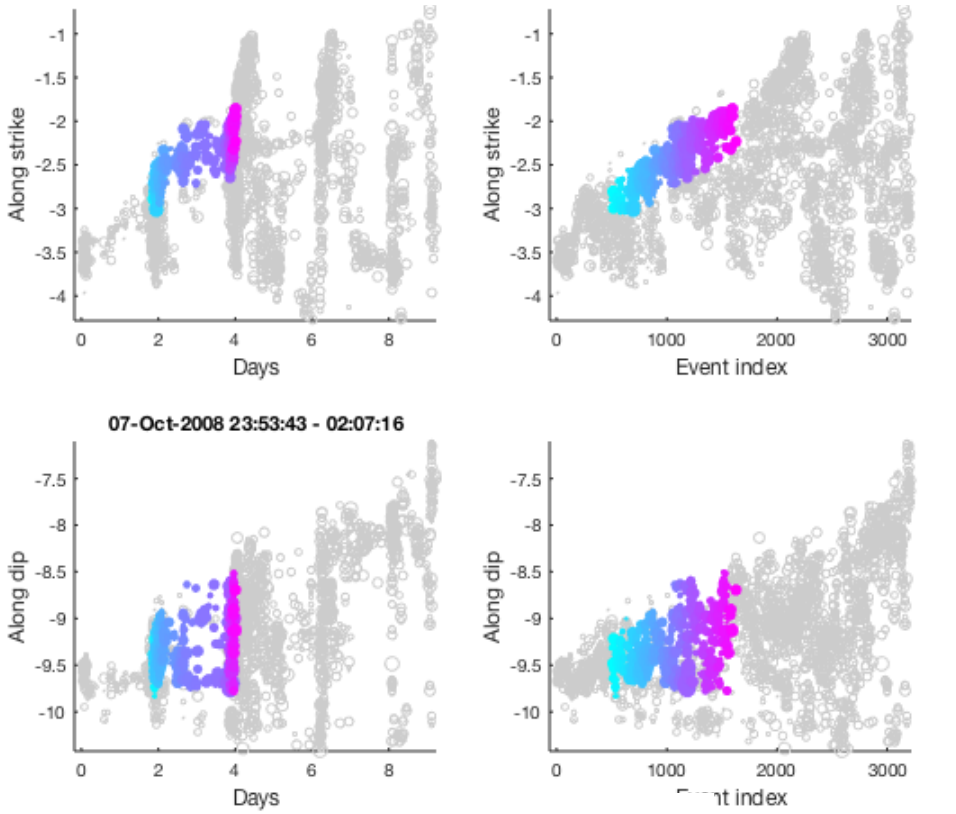


Hypocenter section

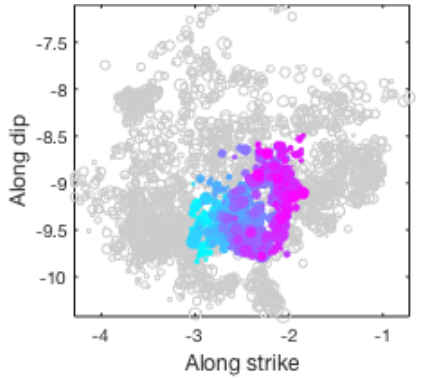


Coordinate-time plot

Coordinate-index plot

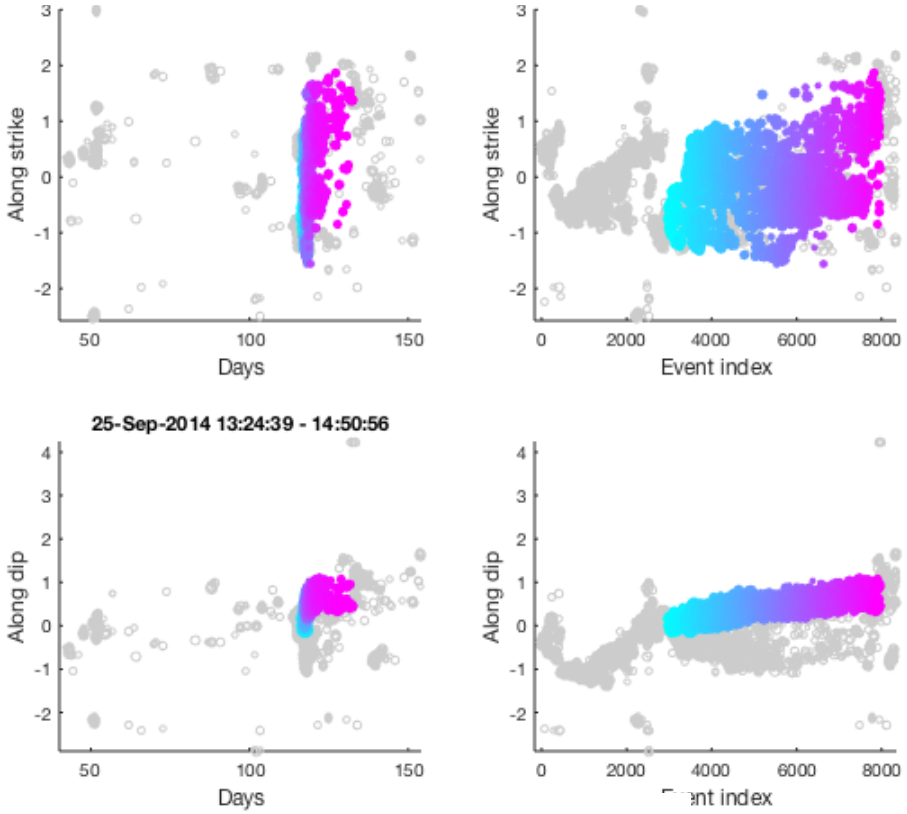


Hypocenter section

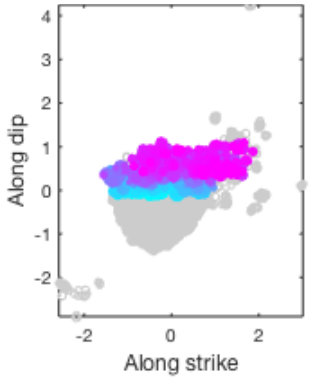


Examples of time and event-index migration plot

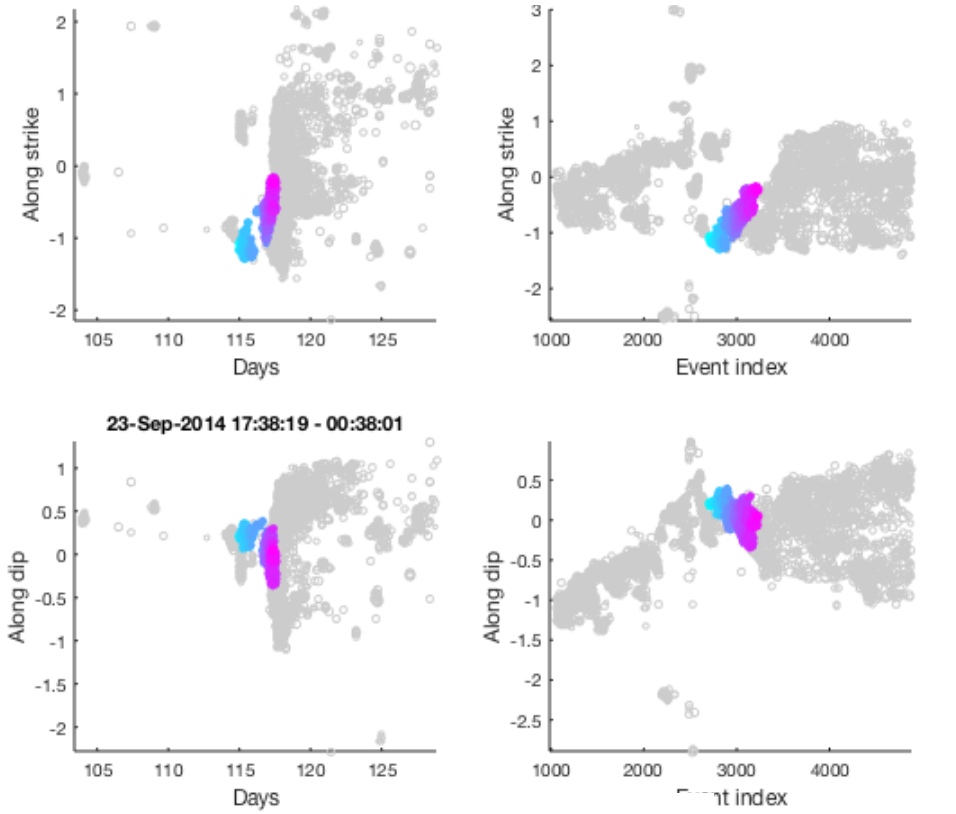
Coordinate-time plot | Coordinate-index plot



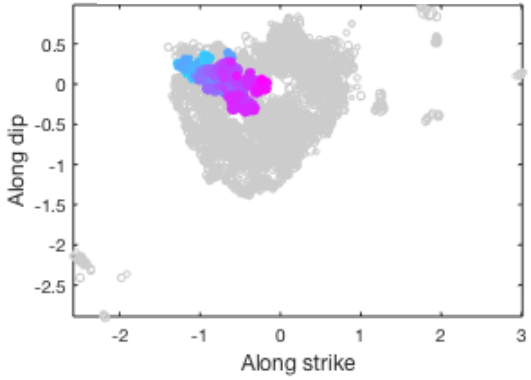
Hypocenter section



Coordinate-time plot | Coordinate-index plot



Hypocenter section



Long-Valley Caldera swarm 2014

In many cases, interrupted growth in time becomes continuous (and linear) in event index

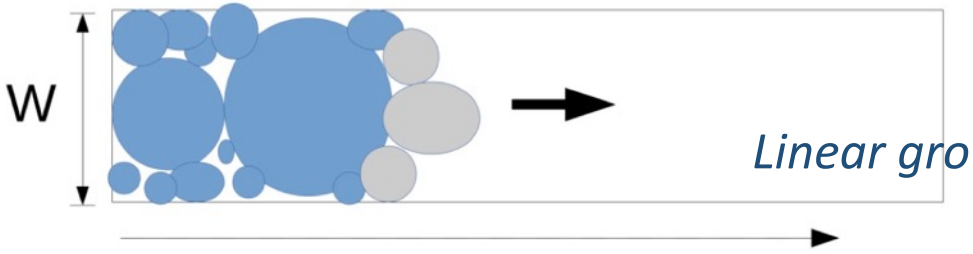
What is behind?

Hypocentre migration model – event-index dependent

migration is a result earthquake occurrence

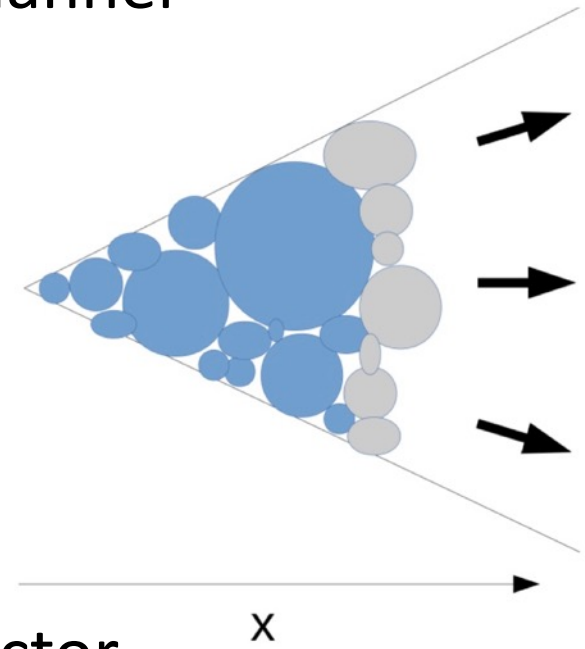
- Every rupture facilitates nucleation of further ruptures (new rupture occurs at the edge of the previous one, facilitated by fluid inflow into the previous rupture)
- 2D – two models:
  - channel model C
  - sector model S
- speed

$$x(N) = \begin{cases} \frac{\langle A \rangle}{W} N = \nu N & \text{model C} \\ \sqrt{\frac{360}{\pi\theta} \langle A \rangle} \sqrt{N} = \sqrt{DN} & \text{model S} \end{cases}$$



Channel

Linear growth of x(N)



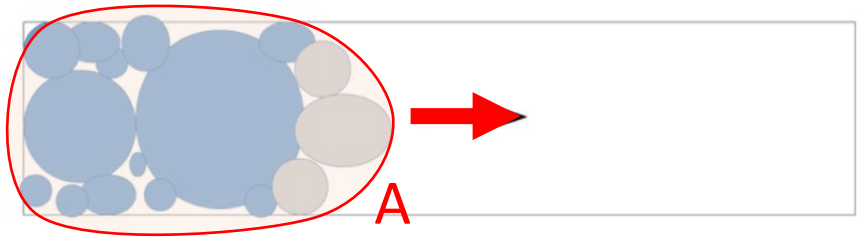
Sector

Square-root growth of x(N)

Linear growth $A = \langle A \rangle \cdot N$

Hypocenter migration model – growth speed ⟨A⟩

Observed growth of ruptured area



Measure the convex area covered by earthquake ruptures

$$A = \langle A \rangle \cdot N$$

Rupture area predicted by the rupture model for

- Each event magnitude *m*

or

- The mean effective magnitude <M_{eff}> of the cluster

$$M_0 = f \Delta\sigma A^{3/2} \qquad \log M_0 = c + d\,m$$

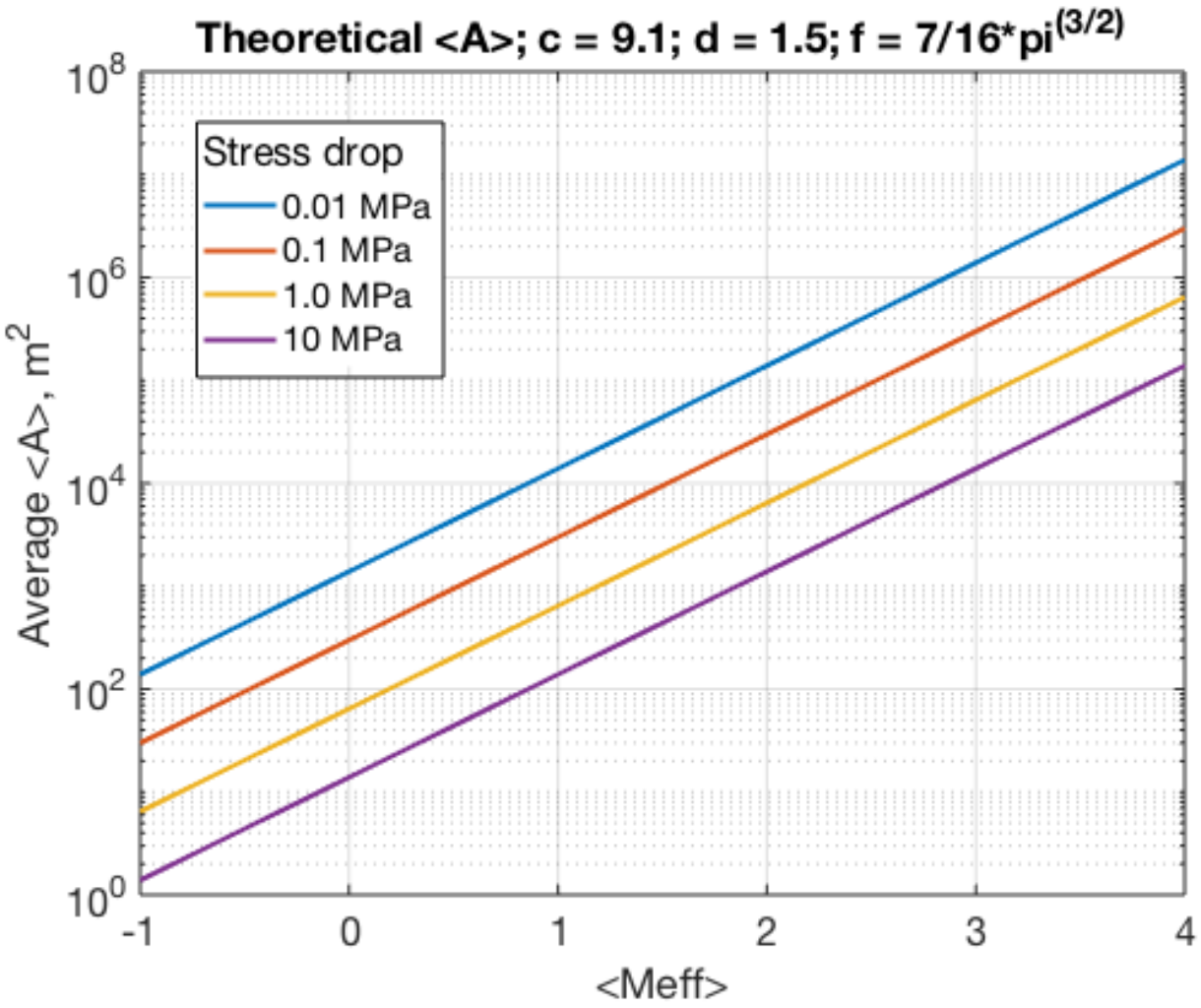
$$\langle A \rangle = \left(\frac{10^{c+d\,m}}{f \Delta\sigma} \right)^{2/3}$$

Δσ - static stress drop

Moment magnitude: c = 9.1, d = 1.5

Brune circular model: $f = (7/16)\,\pi^{3/2}$

Model-based prediction of dependence of ⟨A⟩ and ⟨M_{eff}⟩



- Power-law increase of predicted <*A*> with *M*

  $A \sim M^{(2/3)d}$,

where *d* shows the moment – magnitude scaling

$$\log M_0 = c + d\,M$$

- Decrease of predicted <*A*> with effective stress drop

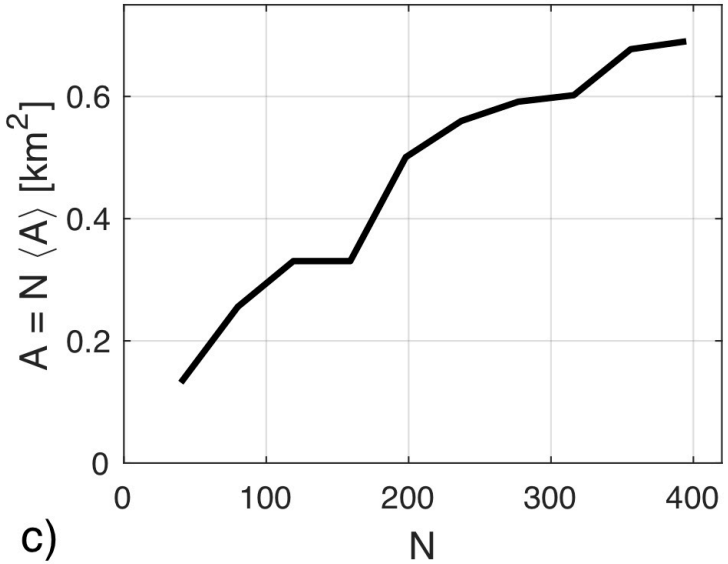
Application to data

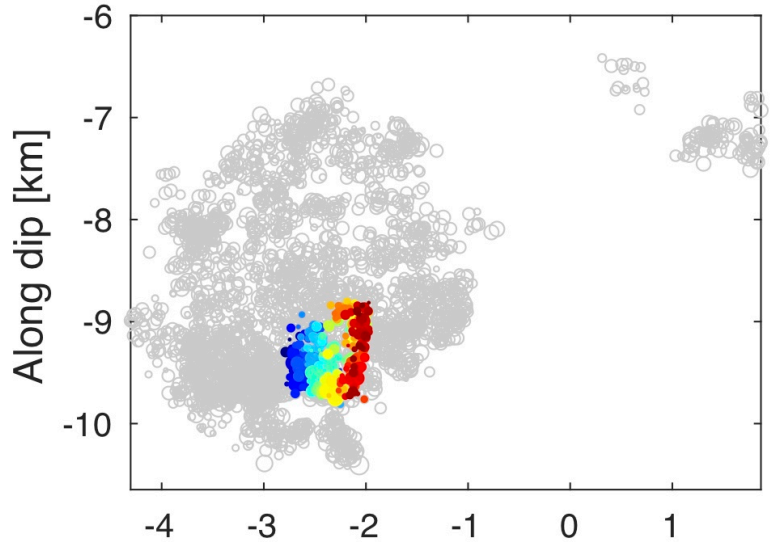
Application to data - Observation of ⟨A⟩ and ⟨M_{eff}⟩

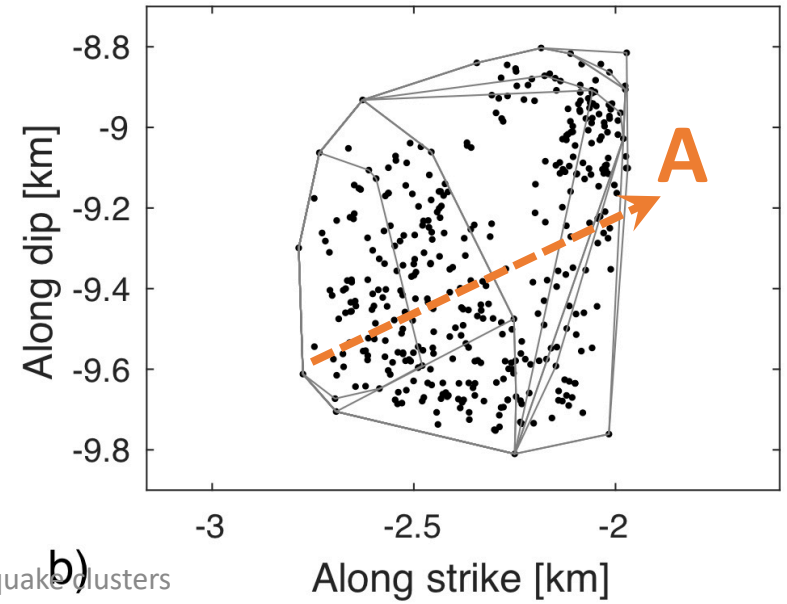
Method:

<*A*> is measured as convex area per event of the growing cluster (convhull) in a sequence of windows

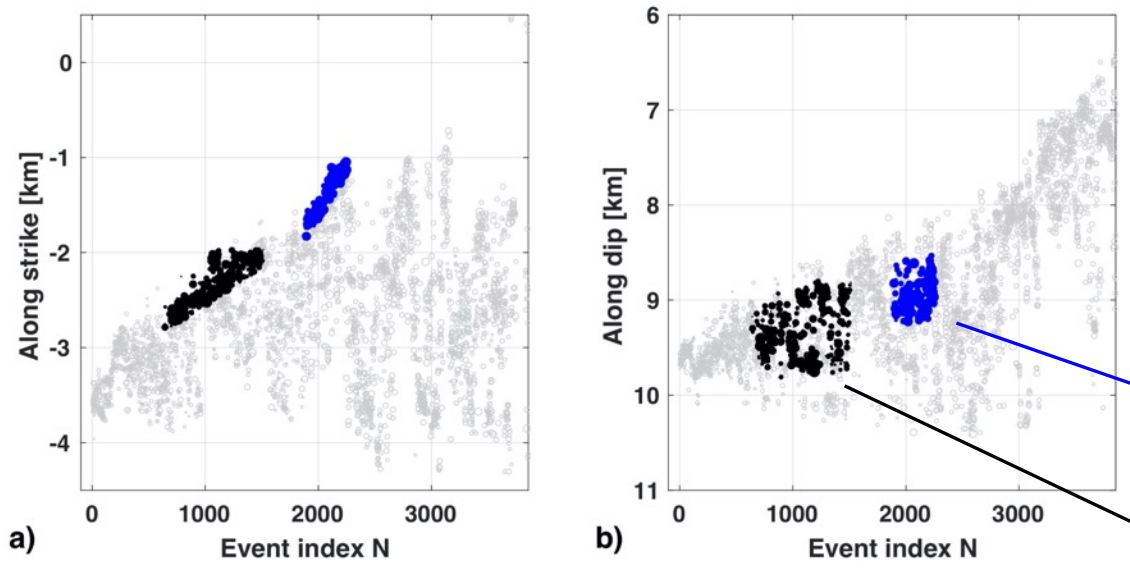
<M_{eff}> is derived from the mean seismic moment of a growing cluster



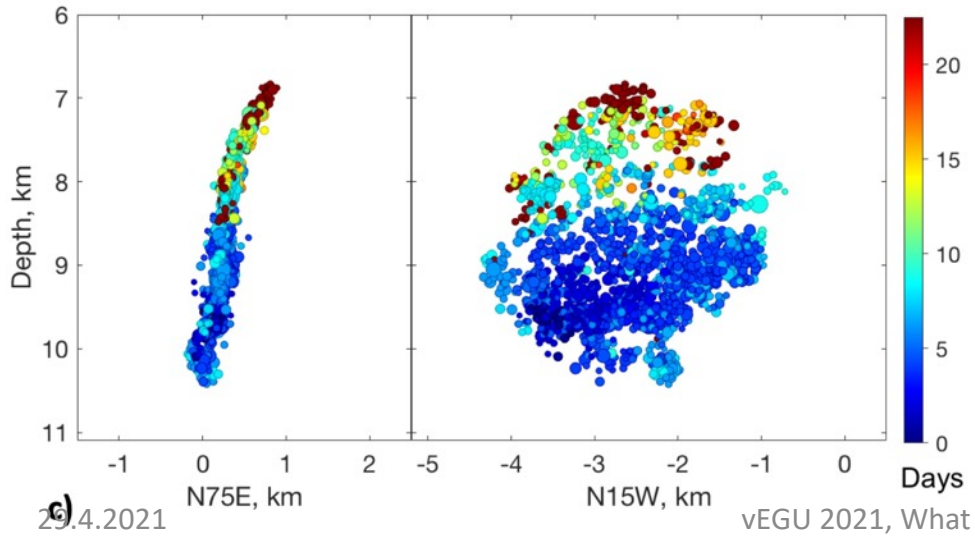


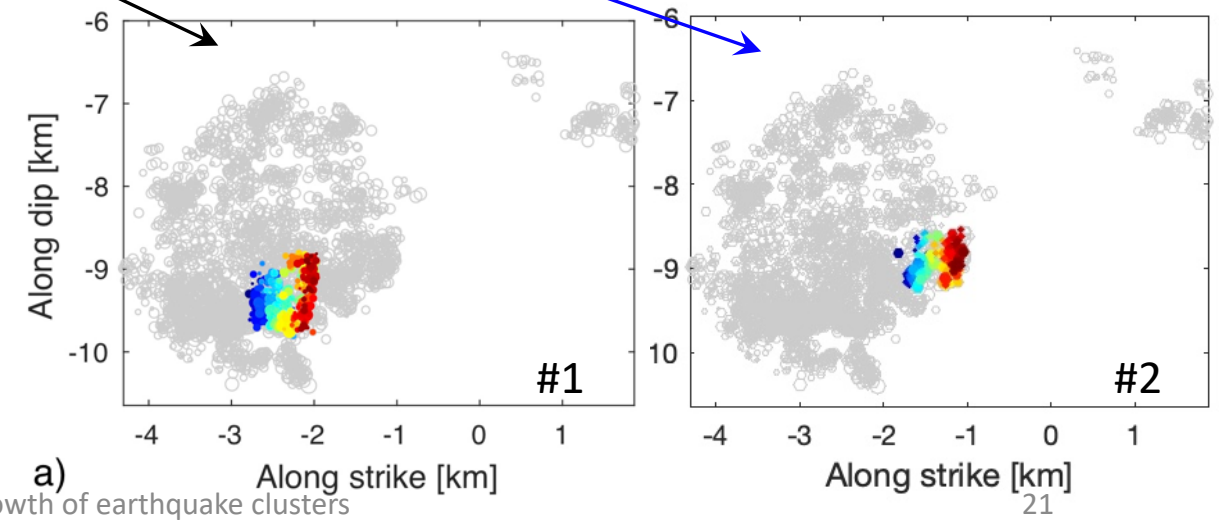


Test on the 2008 West-Bohemia swarm - data



- Two clusters selected at the migration front in the strike direction
- Hypocenters projected to the best fitting plane





⟨A⟩ growth for cluster #1 of the 2008 West-Bohemia swarm

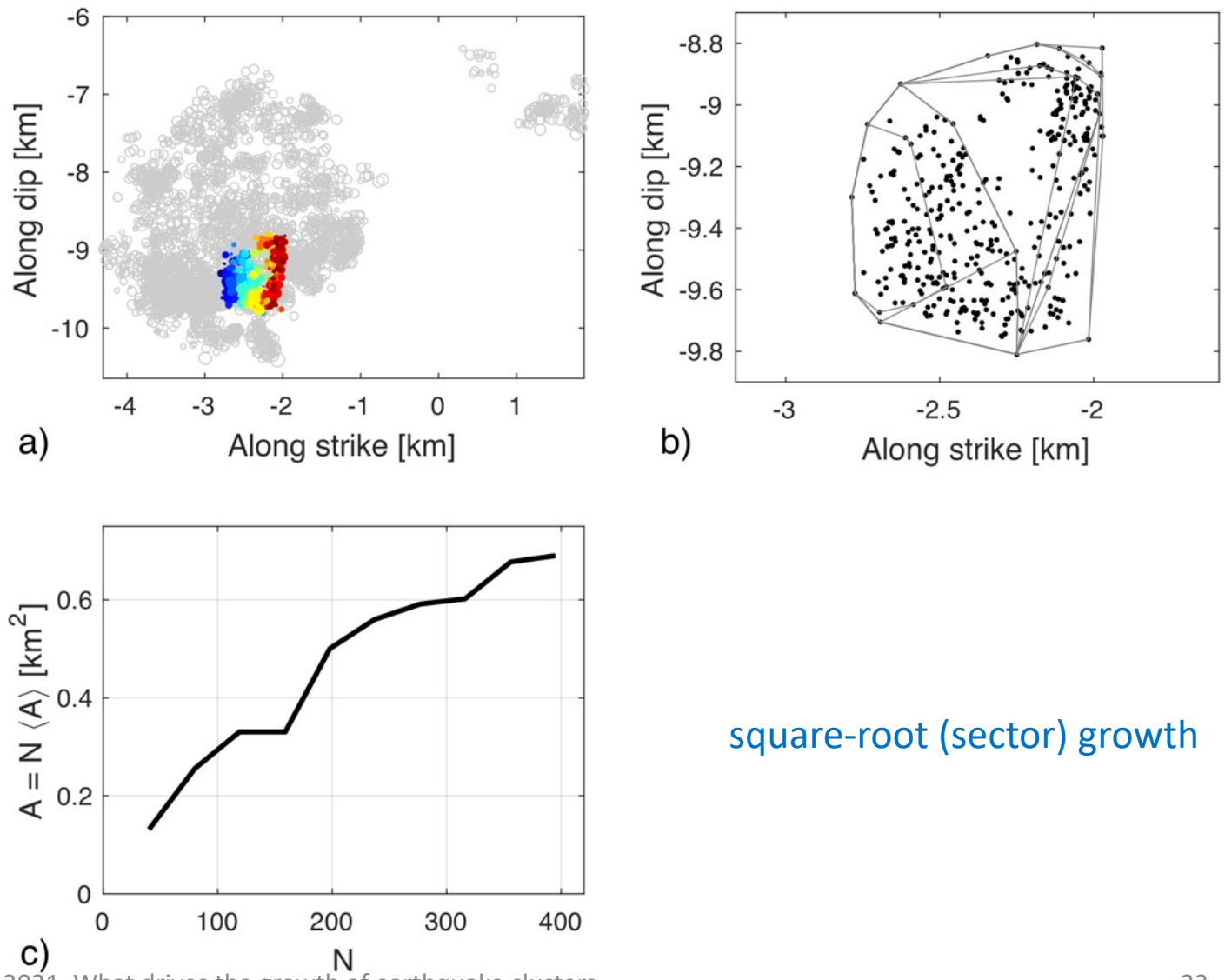
$\langle A \rangle = 1750\ m^2/event$

$W \sim 740\ m$

$v = \langle A \rangle / W = 2.4\ m/event$

(340 m/day)

$\langle M_{eff} \rangle = 1.1$



square-root (sector) growth

⟨A⟩ growth for cluster #2 of the 2008 West-Bohemia swarm

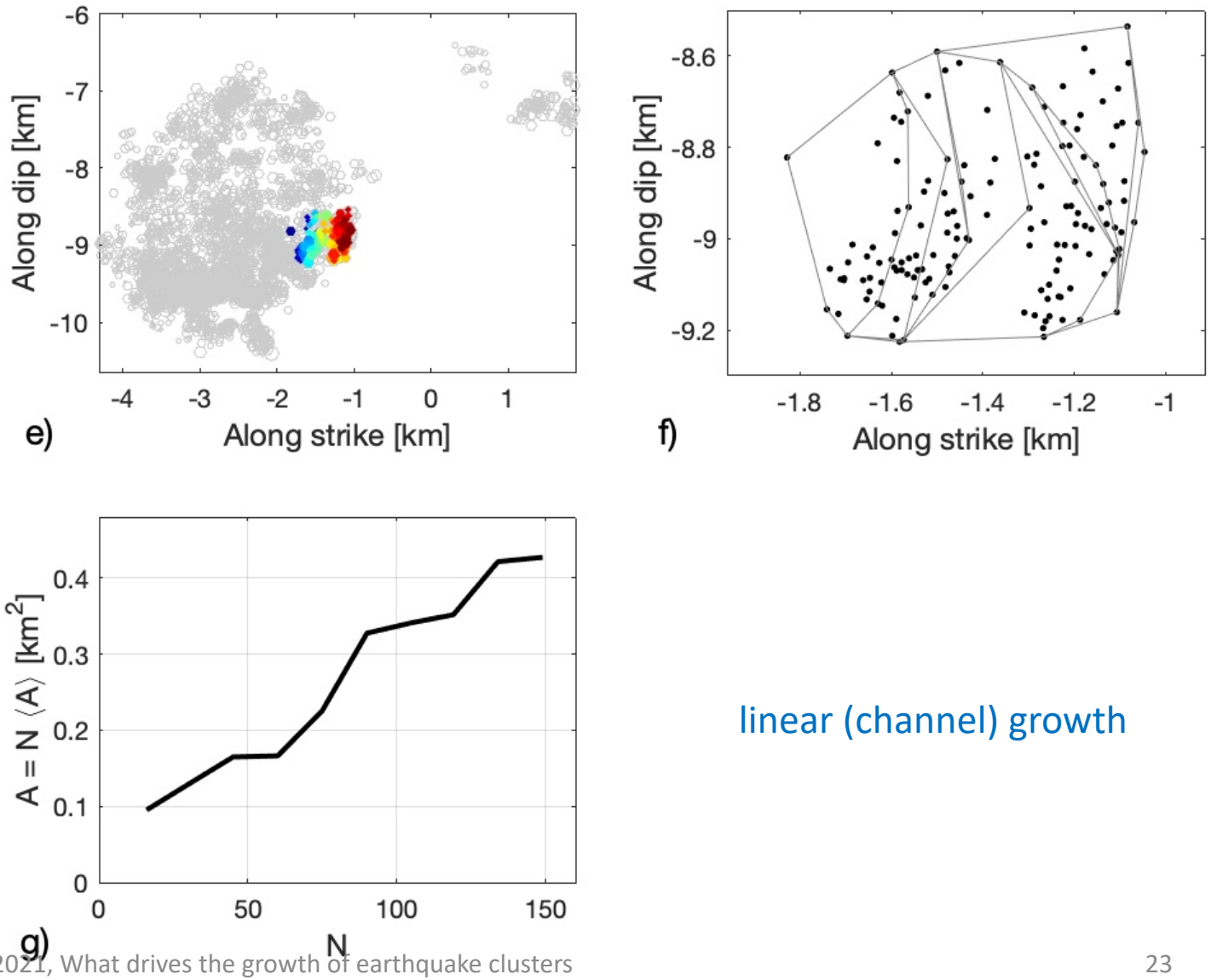
$\langle A \rangle = 2870\ m^2/event$

$W \sim 630\ m$

$v = \langle A \rangle / W = 4.6\ m/event$

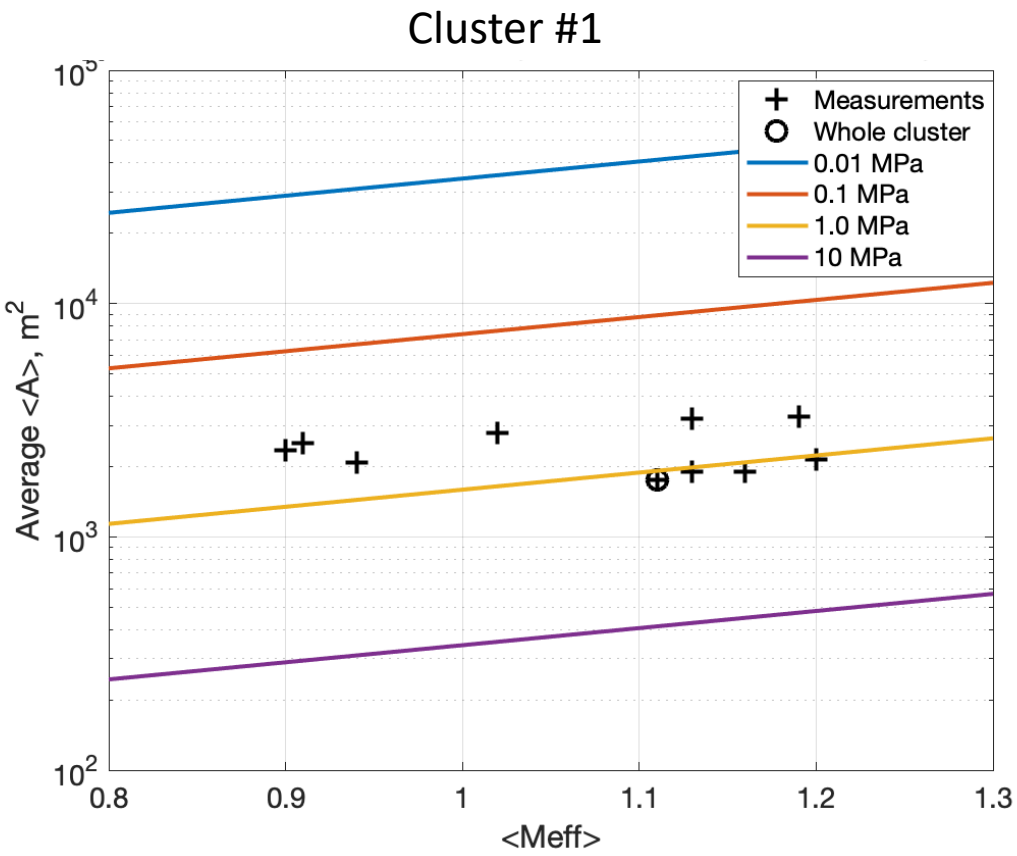
(720 m/day)

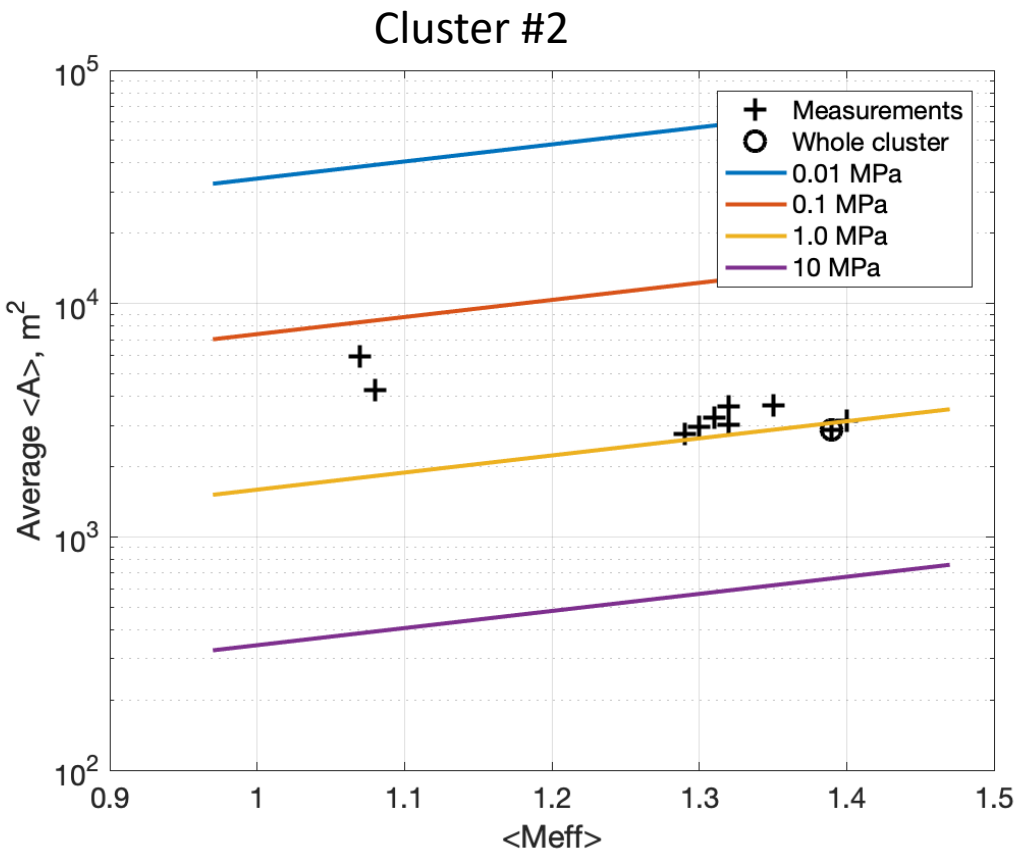
$\langle M_{eff} \rangle = 1.4$



linear (channel) growth

Comparison of measured and theoretical ⟨*A*⟩ - WB 2008 swarm

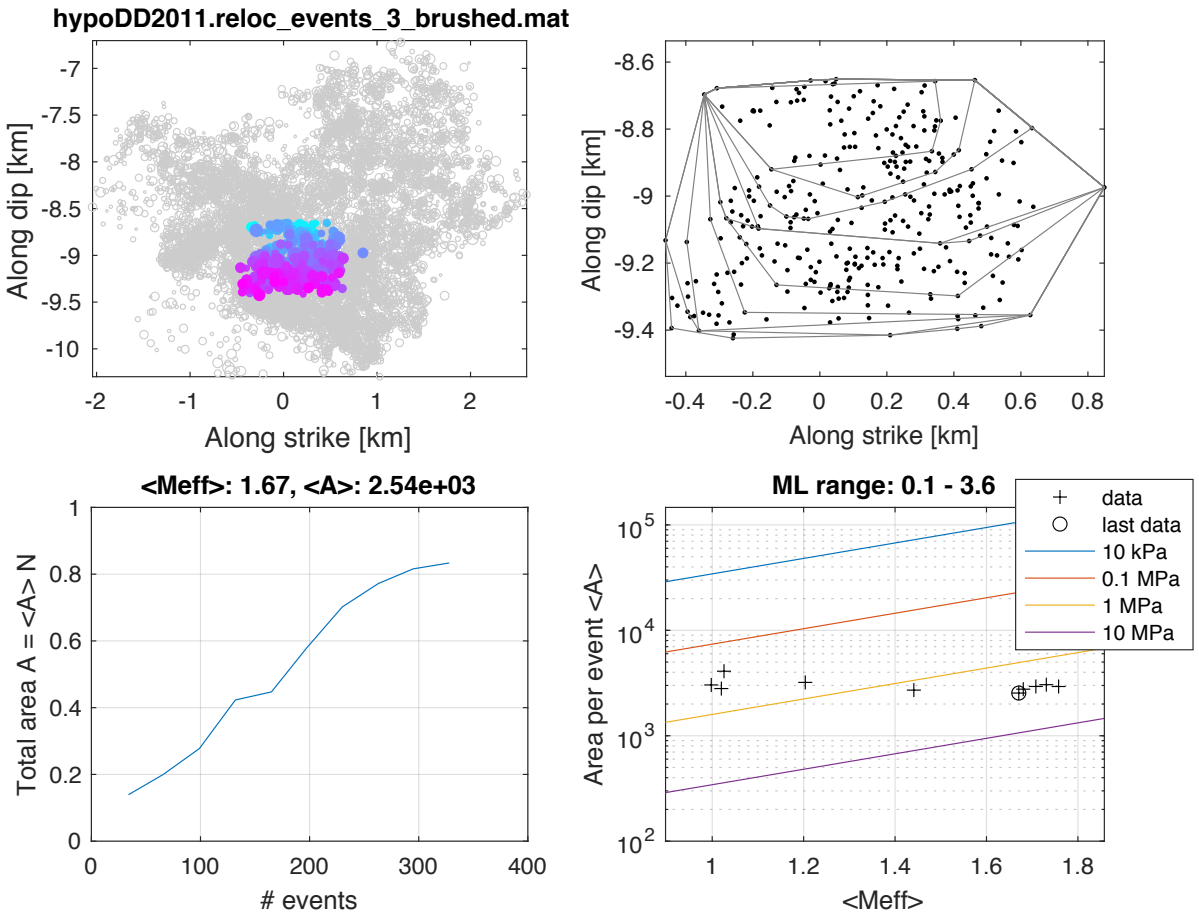




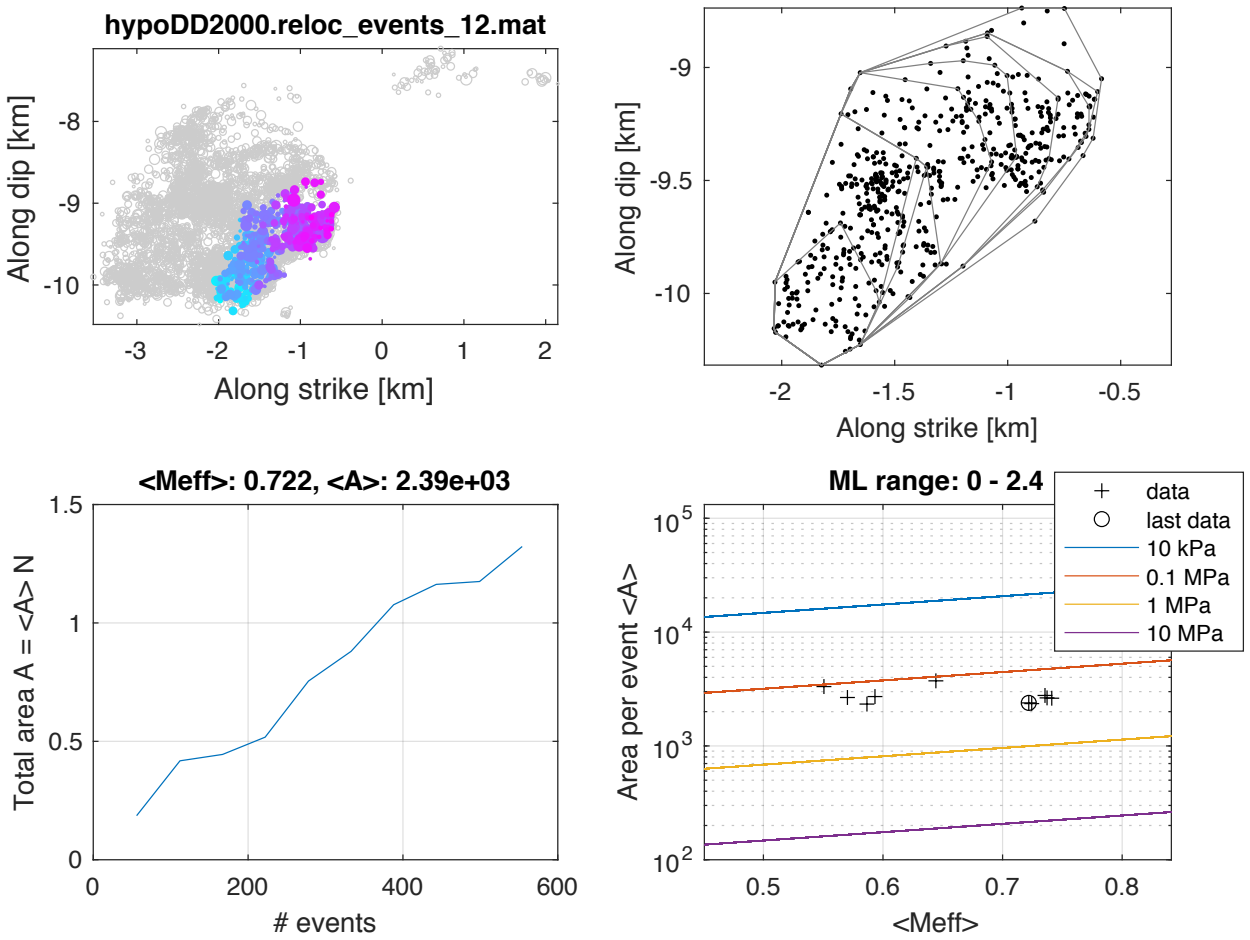
⟨*A*⟩ scales with ⟨M_{eff}⟩ with effective stress drop ranging from 0.1 to 1 MPa

Other swarms - measured and theoretical ⟨*A*⟩

West Bohemia 2011 swarm

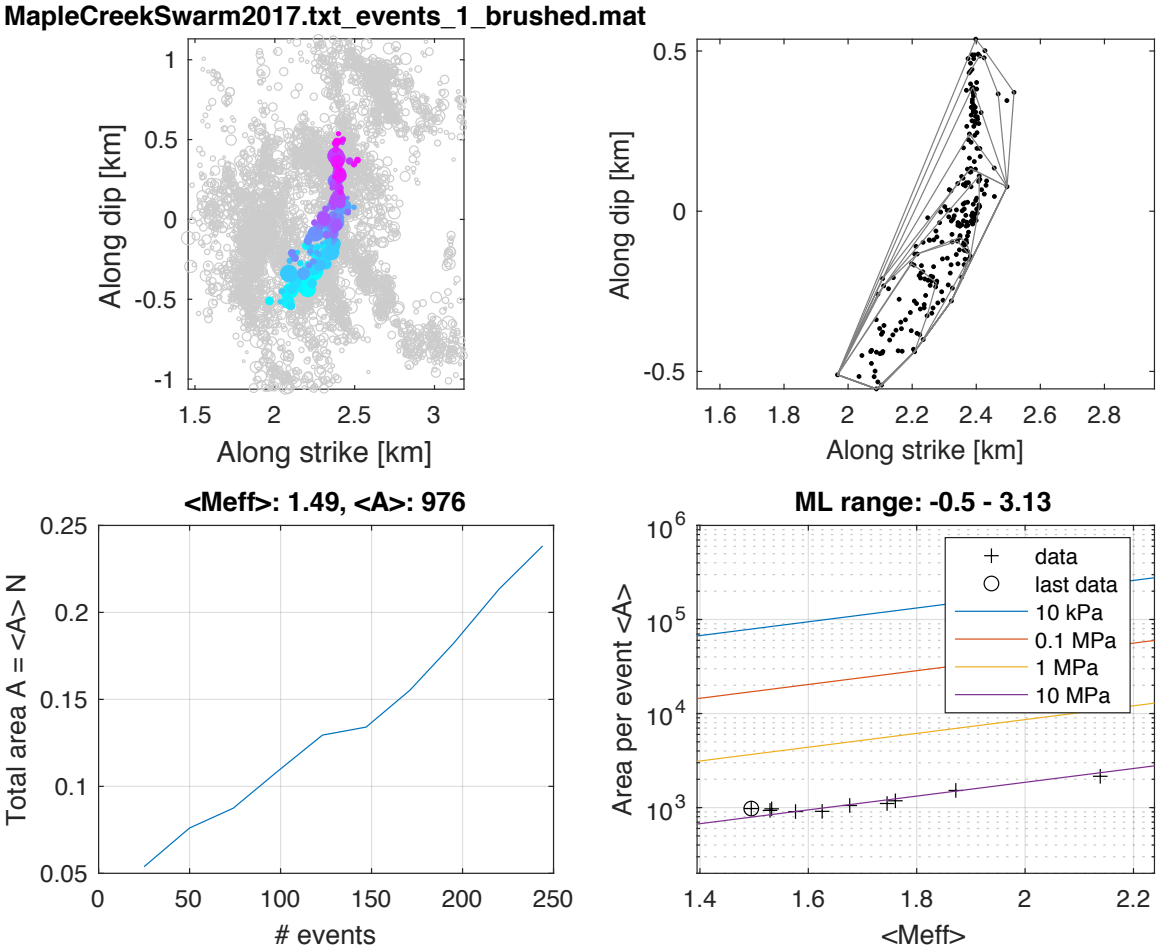


West Bohemia 2000 swarm

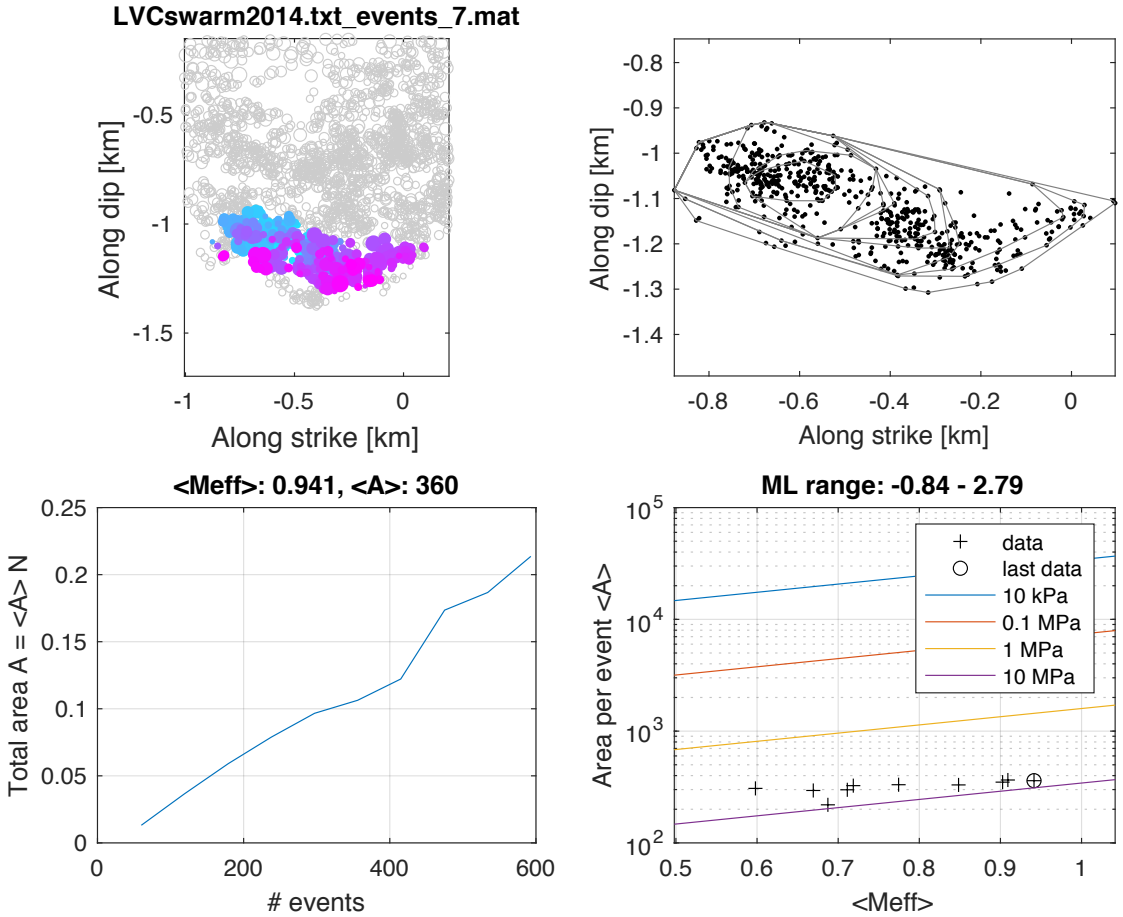


Other swarms - measured and theoretical ⟨*A*⟩

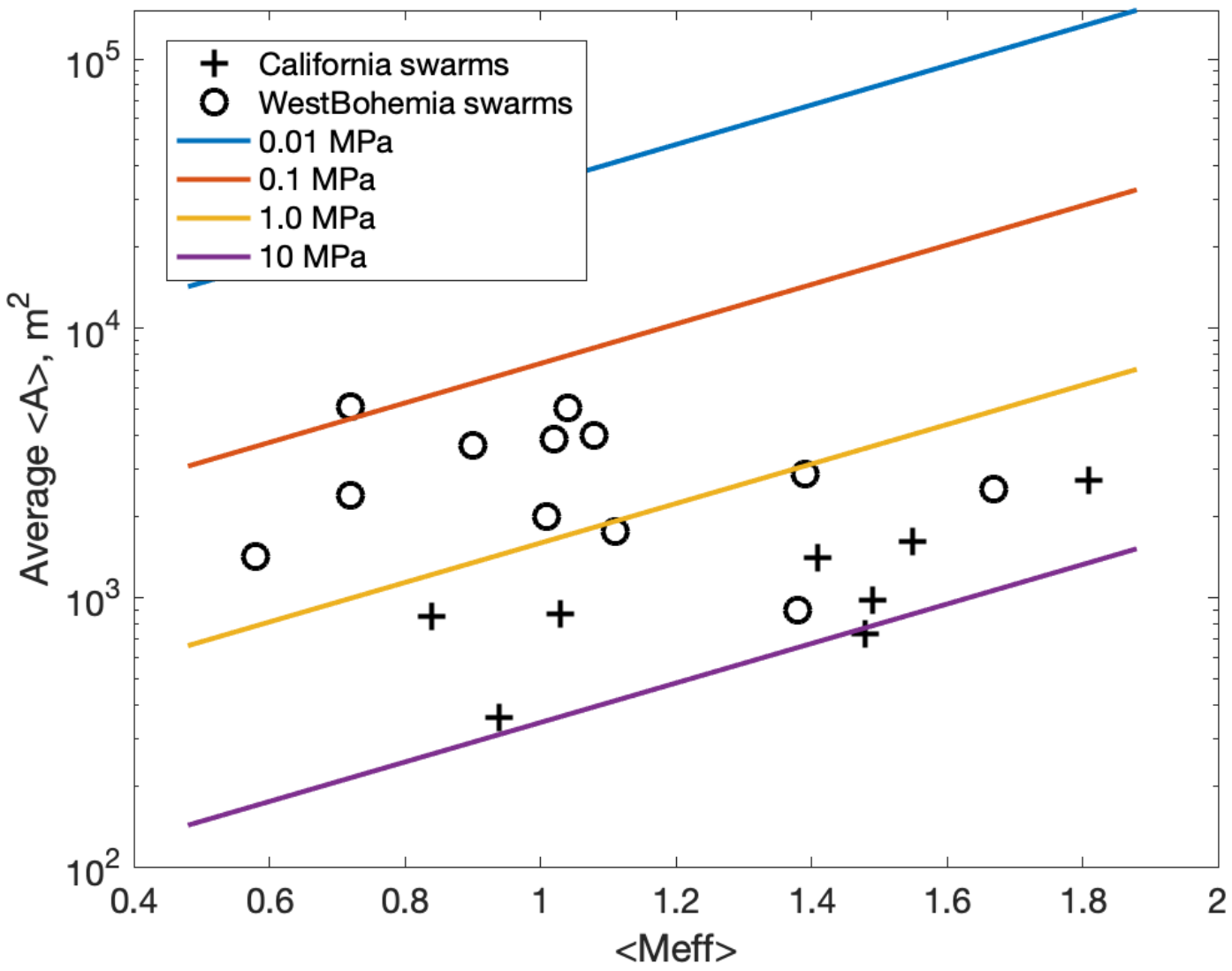
Maple Creek 2017 swarm



Long Valley Caldera 2014 swarm



All swarms - measured and theoretical ⟨*A*⟩



Measurements of selected clusters of swarms in West-Bohemia and California

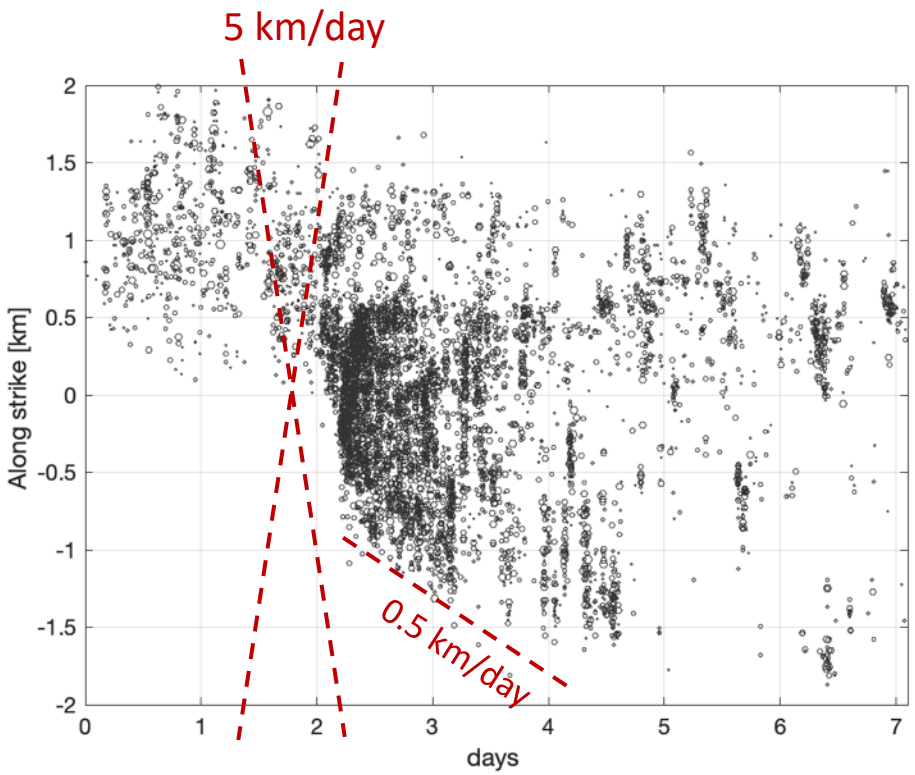
⟨*A*⟩ and ⟨M_{eff}⟩ scale with effective stress drops ranging from

- 0.1 to 5 MPa – West Bohemia
- 2 to 10 MPa – California

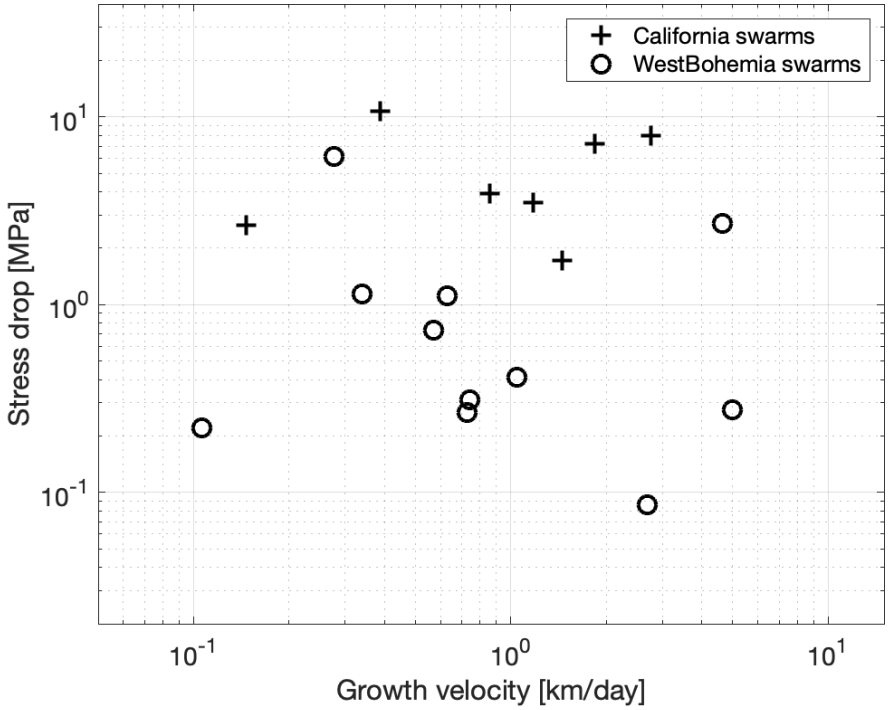
Reasonable values of effective stress drop show that the ruptures are adjacent, and swarm is driven by ruptures formation followed by fluid flow

Comparison of effective stress drop derived from average rupture area and the cluster growth velocity

Varying growth velocities of clusters



Measurements of selected clusters of swarms in West-Bohemia and California



No relation between growth velocity in time domain and stress drop derived in event-index domain

Summary

Hypocenter migration plots shows envelope growth and fine embedded structures growing (linearly) with time

The growth patterns are often interrupted in coordinate-time plots and become continuous in coordinate-event index plots

Two types of event triggering considered
external (*p*-diffusion) and internal (rupture opening)

- *p*-diffusion: $X(t)$ continuous; $X(N)$ continuous
- rupture opening: $X(t)$ interrupted; $X(N)$ continuous

=> discontinuous $X(t)$ plot indicates that the process can be internally driven (self-organized)

Continuous plots ($X(t)$ or $X(N)$) are linear or square-root related to the type of growth (channel or sector)

Summary

Model: event rupture opens path for fluids; new rupture forms at the edge of the previous one

Method: We measure the speed of growth by the total area of the cluster $A = \langle A \rangle . N$, where the average area per event $\langle A \rangle$ should scale with magnitude

If $\langle A \rangle$ does not grow with M => external triggering??

Application to the swarms shows that $\langle A \rangle$ grows with *M, related stress drop ranges from 0.1 to 10 MPa*

=> the swarm earthquakes appear to be driven internally with fluid flow following the rupture opening