Modeling seismic swarms triggered by aseismic transients

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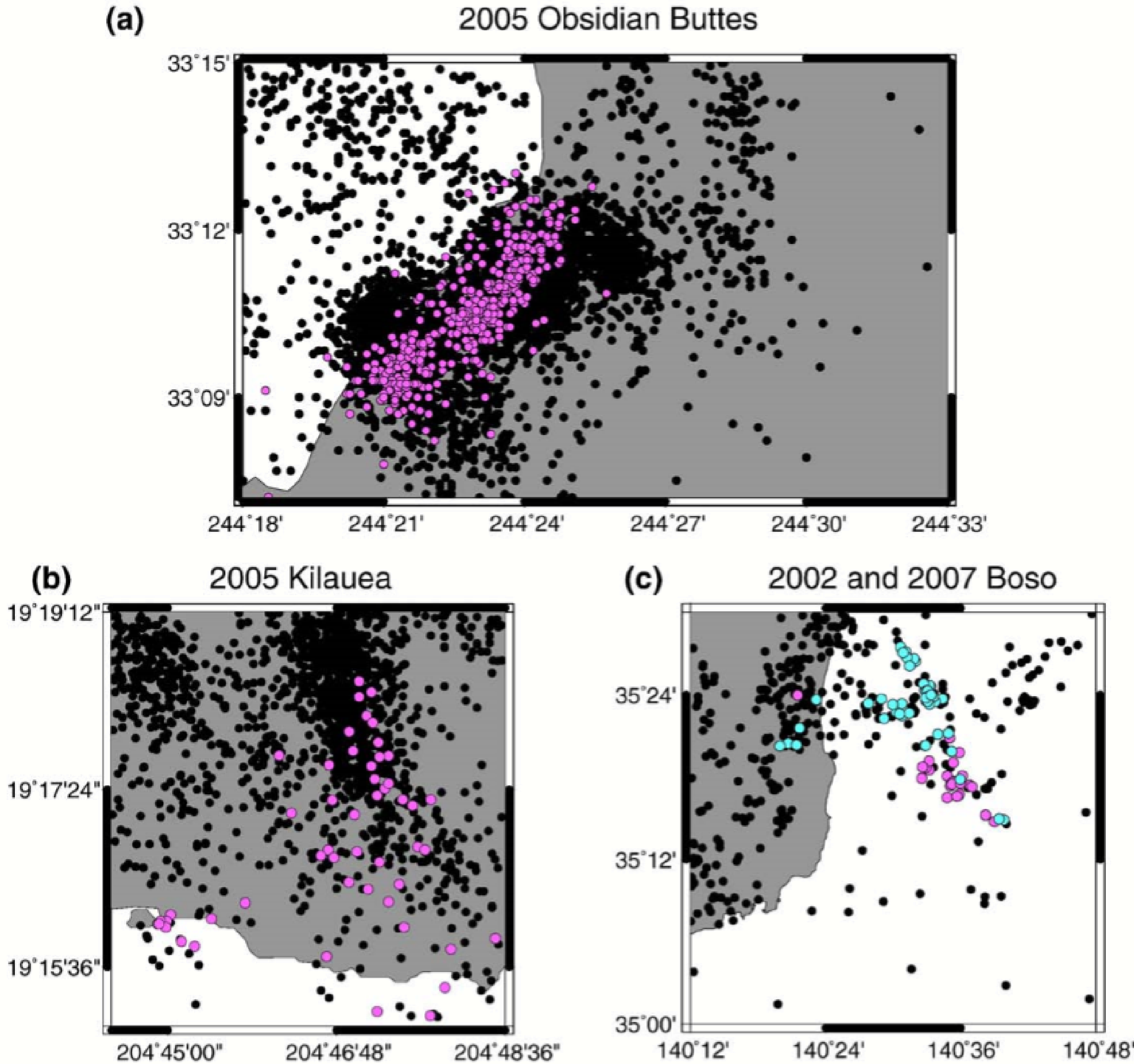
(June 26th, Uemura Kansuke)


(a)
2005 Obsidian Buttes
33°15'
33°12'
33°09'
244°18'
244°21'
244°24'
244°27'
244°30'
244°33'
(b)
2005 Kilauea
19°19'12"
19°17'24"
19°15'36"
204°45'00"
204°46'48"
204°48'36"
(c)
2002 and 2007 Boso
35°24'
35°12'
35°00'
140°12'
140°24'
140°36'
140°48'

ETAS model

$$R(t) = \mu + \sum_{t_i \leq t} \frac{K e^{\alpha(M_i - M_c)}}{(t - t_i + c)^p}$$

Cumulative function: cumulative number of events predicted by ETAS

$$\Lambda(t) = \int_0^t R(s) \mathrm{d}s$$

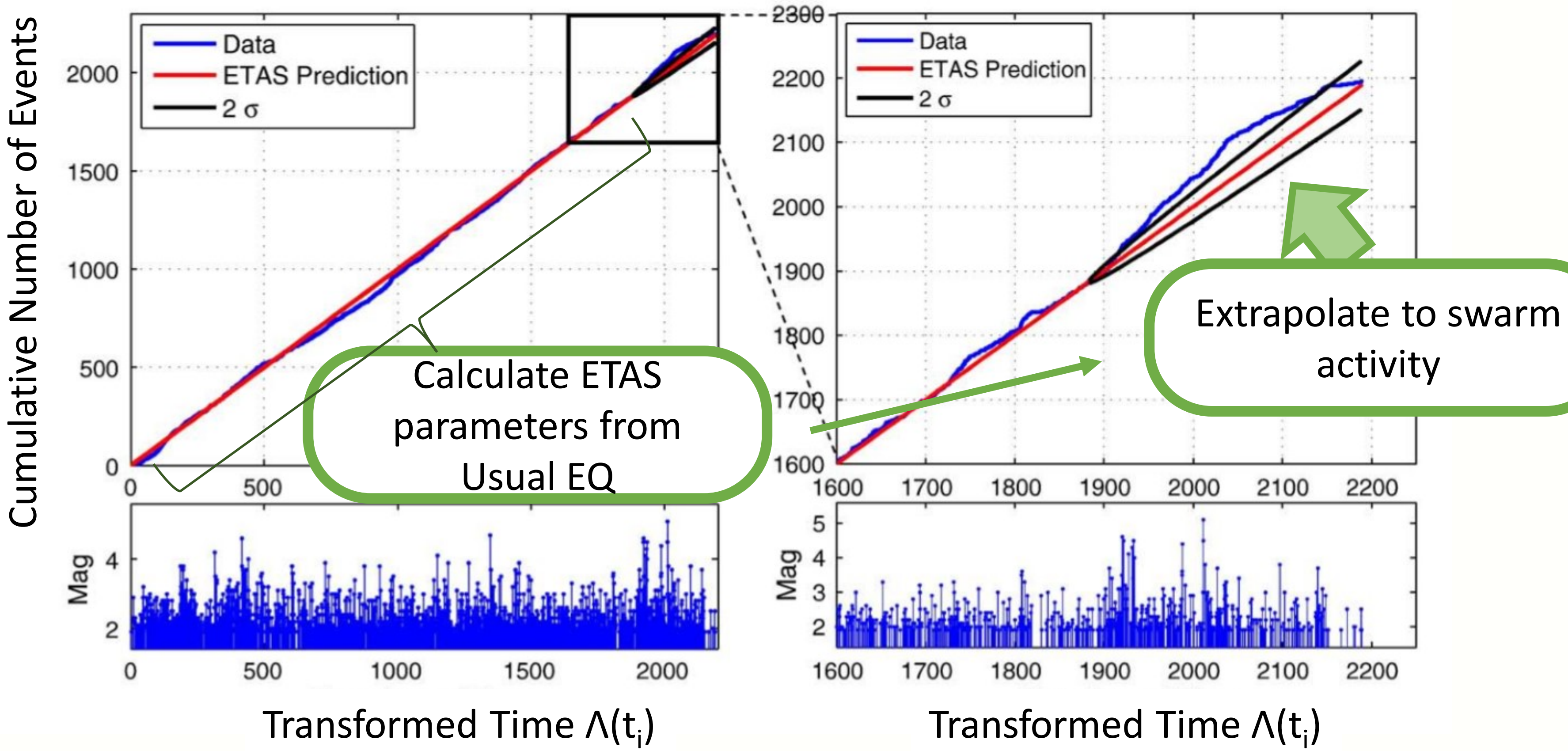
Transformed time:

$$\tau_i = \Lambda(t_i)$$

t_i: occurrence time of i_{th} event

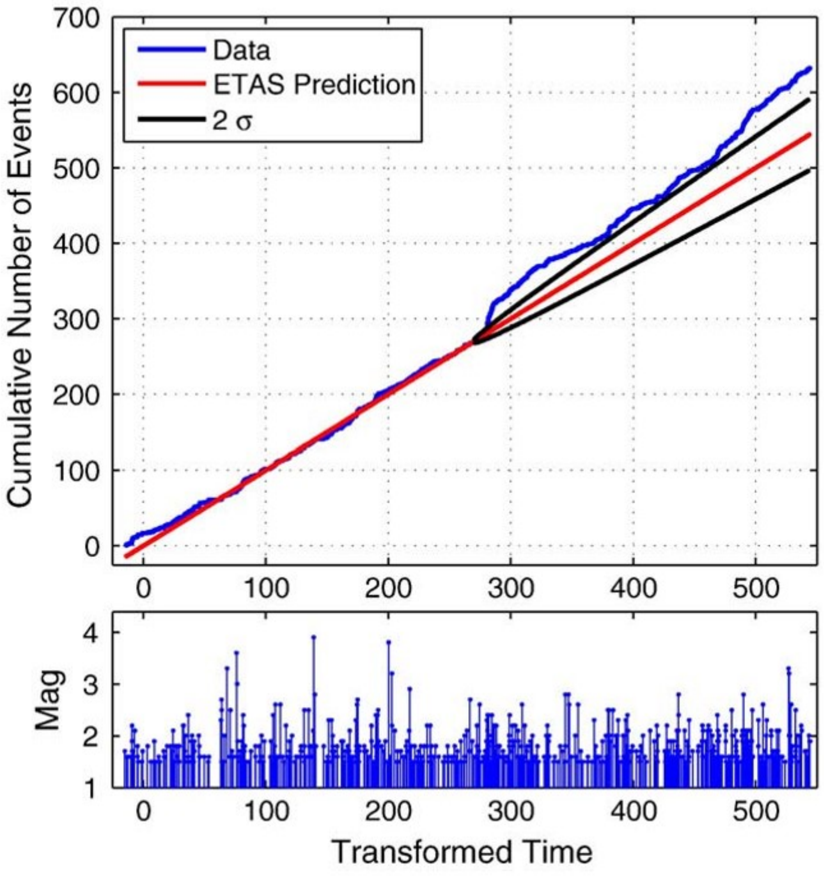
Usual EQ and swarm

From 2005 Obsidian Buttes catalog



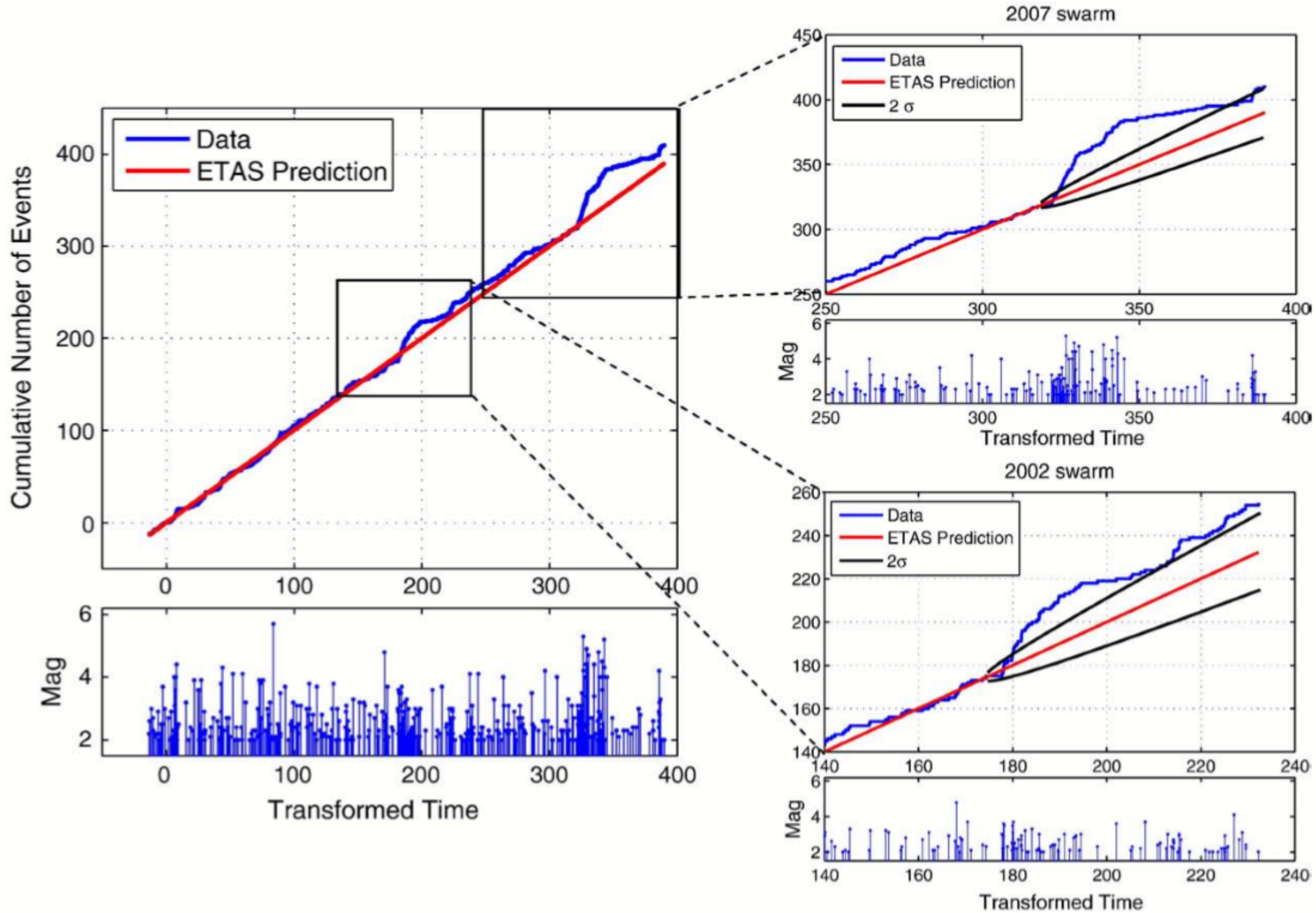
Usual EQ and swarm

From 2005 Kilauea catalog



Usual EQ and swarm

2002&2007 Boso swarms



ETAS model and swarms

- ETAS lacks a quantitative relationship between seismicity rate and stress/stressing rate.
- Swarms = EQs which do not obey Omori's law
  = anomaly of aseismic stressing rate.

Stress perturbations due to …

- magma intrusions
- dike intrusions
- movements of volatiles(e.g., CO_2)
- aqueous fluid flow
- slow slips

Obsidian Buttes

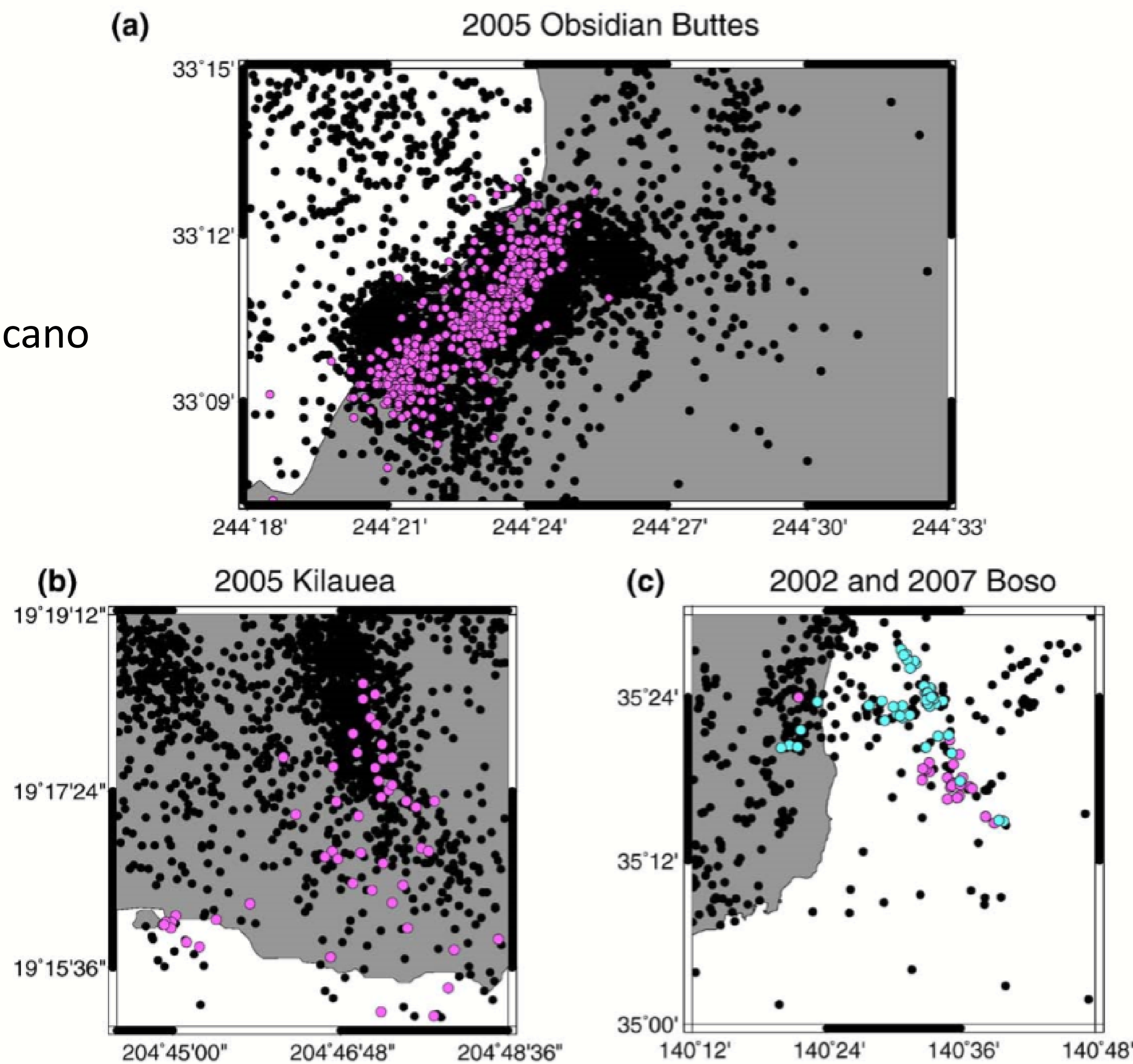
- Strike slip
- Slow slip

Kilauea

- South flank of Kilauea Volcano
- Slow earthquake

Boso

- Recurring slow slip



Swarms driven by slow slip

- Slow slip = geodetic data
  Swarms = seismic data
- Energy release
  - Slow slip: Mw $\simeq$ 6.5 ⇔ Swarm : Mw $\simeq$ 4

    (repeating slow EQ at offshore of central Honshu; Ozawa et al., 2007)
  - Slow slip: Mw $\simeq$ 5.7 ⇔ Swarm : Mw $\simeq$ 5.5

    (strike-slip fault in the Salton Trough; Lohman and McGuire, 2007)

Swarms: seismicity that cover unusually large area for their cumulative seismic moment. (Vidale and Shearer, 2006)

Combining the ETAS and rate-state model

- ETAS lacks a quantitative relationship between seismicity rate and stress/stressing-rate.
- Swarms = EQs which do not obey Omori's law
  = anomaly of aseismic stressing rate.
- Rate-state model of Dieterich(1994) can handle temporal change in stressing rate.

DIETERICH + ETAS

= [ETAS with stressing rate] model?

Rate-state model by Dieterich(1994)

Seismicity rate $R = \frac{r}{\gamma \dot{S}_r}$

Reference seismicity rate (r)

State variable (γ)

Reference stressing rate ($\dot{S}_r$)

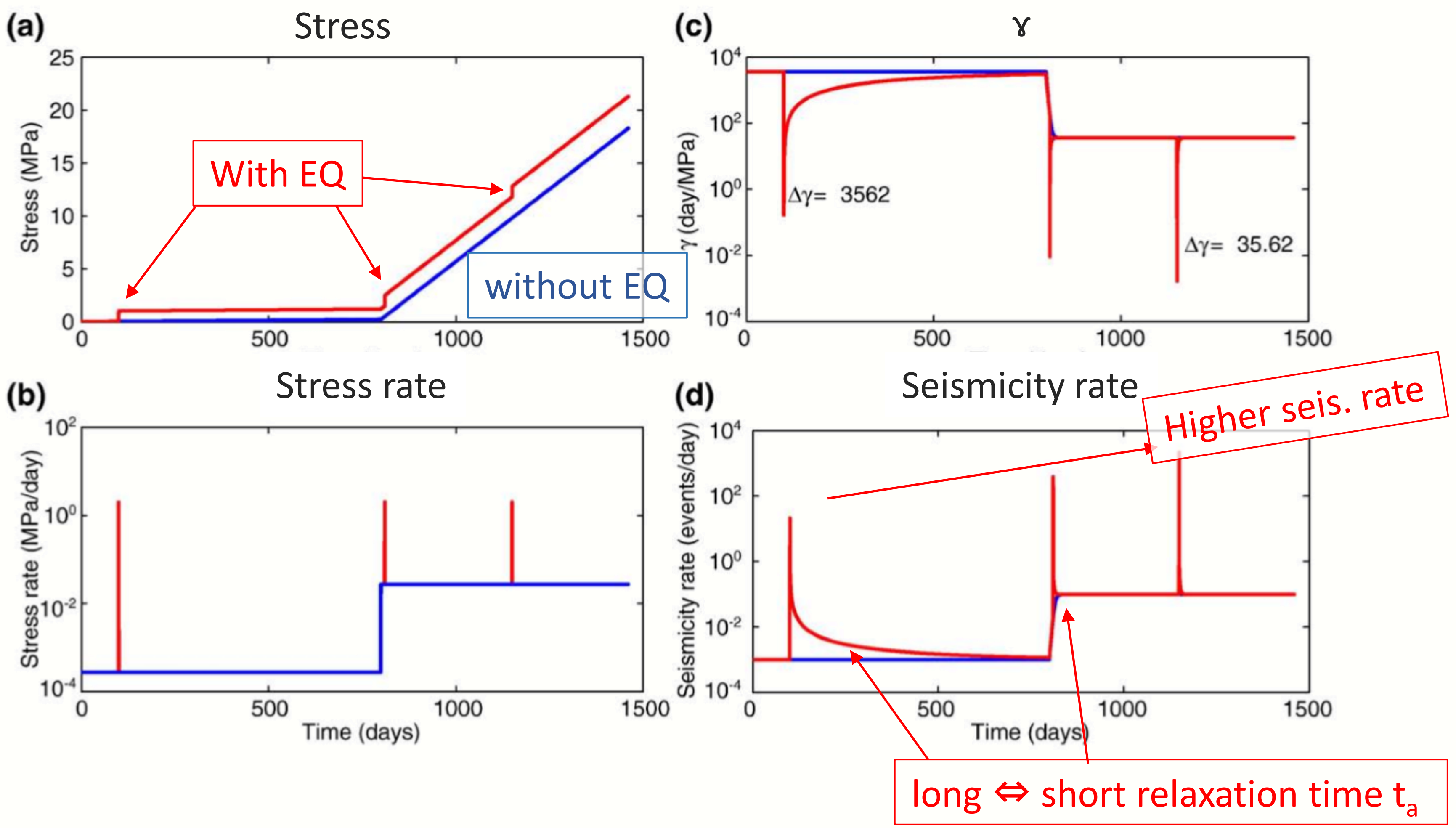
$$d\gamma = \frac{dt}{A\sigma}\left(1 - \gamma \dot{S}\right)$$

Stressing rate ($\dot{S}$)

If S, Aσ: constant ⇒ $\gamma = \frac{1}{\dot{S}} + Ce^{-\frac{\dot{S}}{A\sigma}t}$,

characteristic relaxation time: $t_a = \frac{A\sigma}{\dot{S}}$

Rate-state model by Dieterich(1994)



Rate-state model by Dieterich(1994)

$$R = \frac{r}{\gamma \dot{S}_r} \qquad d\gamma = \frac{dt}{A\sigma}\left(1 - \gamma \dot{S}\right)$$

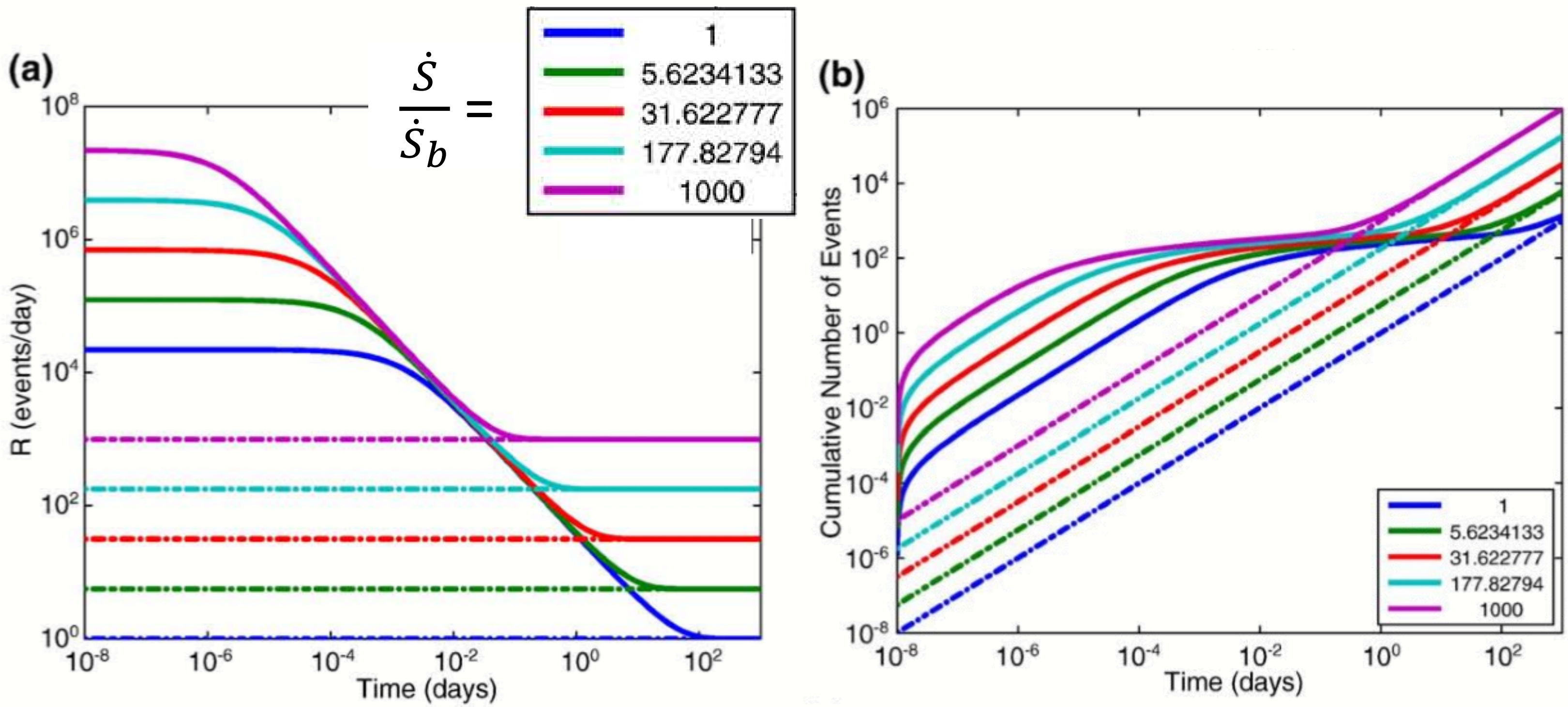
For sudden change of stress ΔS
under constant stressing rate $\dot{S}$

$$\gamma = \gamma_0 \exp\left[\frac{-\Delta S}{A\sigma}\right]$$

$$R(t) = \frac{r\frac{\dot{S}}{\dot{S}_r}}{\left[\frac{\dot{S}}{\dot{S}_r}\exp\left(\frac{-\Delta S}{A\sigma}\right) - 1\right]\exp\left[\frac{-t}{t_a}\right] + 1}, \quad \dot{S} \neq 0$$

$$R(t) = \frac{r\frac{\dot{S}}{\dot{S}_r}}{\left[\frac{\dot{S}}{\dot{S}_r}\exp\left(\frac{-\Delta S}{A\sigma}\right) - 1\right]\exp\left[\frac{-t}{t_a}\right] + 1}, \quad \dot{S} \neq 0$$

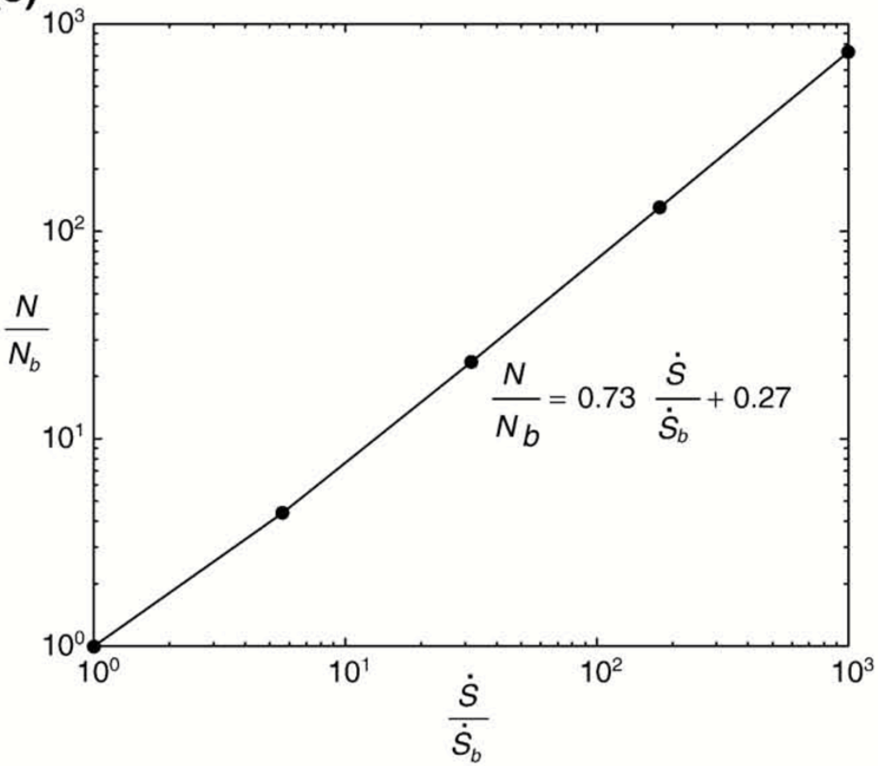
For stress perturbation of same magnitude: ΔS= 0.1MPa,
(and assuming that background stressing-rate is stationary)



$A\sigma = 0.01$ MPa, $\dot{S}_b = 0.1$ MPa/yr, $\Delta S = 0.1\ MPa$

$$R(t) = \frac{r\frac{\dot{S}}{\dot{S}_r}}{\left[\frac{\dot{S}}{\dot{S}_r}\exp\left(\frac{-\Delta S}{A\sigma}\right) - 1\right]\exp\left[\frac{-t}{t_a}\right] + 1}, \quad \dot{S} \neq 0$$

(c)



$$\frac{N}{N_b} = \frac{\text{(number of aftershock)}}{\text{(bg seis. along the aftershock seq.)}}$$

$$\frac{\dot{S}}{\dot{S}_b} = \frac{\text{(stressing–rate)}}{\text{(bg stressing–rate)}}$$

Higher stressing rate brings

→ More aftershocks

→ Higher K-value!!

Combining the ETAS and rate-state models

α: is related to spatial extent of a stress step / independent of stressing rate.

p: is essentially 1 from eq.5(below).

$$R(t) = \frac{r\frac{\dot{S}}{\dot{S}_r}}{\left[\frac{\dot{S}}{\dot{S}_r}\exp\left(\frac{-\Delta S}{A\sigma}\right) - 1\right]\exp\left[\frac{-t}{t_a}\right] + 1}, \quad \dot{S} \neq 0$$

(Though,there said to be influence of other factors, such as heterogeneity in temperature/heat flow or structure on fault, which is independent of stressing rate)

Combining the ETAS and rate-state models

c: can be analytically derived from RSF-model. However, c can not be clearly obtained from observation, so it is not worthwhile discussing stressing rate dependence of c.

K: relationship is unclear, but rate-state model predicts K increases with stressing rate.

μ: relationship is unclear, though rate-state model predicts that bg seismicity rate depends on stressing rate.

Rate-state model predicts that …

α is **independent** of stressing rate.

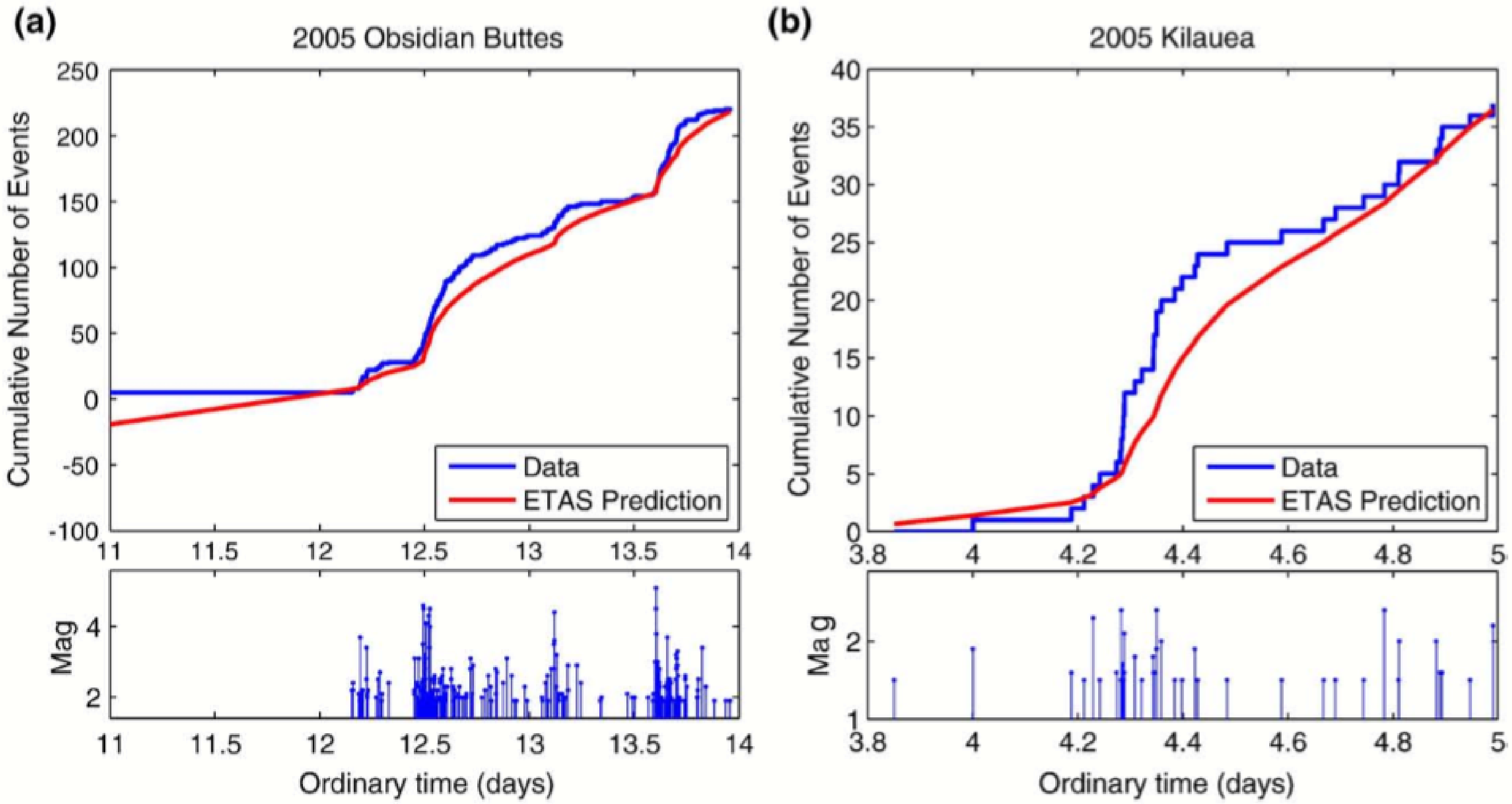
p is essentially **1**

c is **not worth discussing**, as it cannot be well determined by observation.

K increases with stressing rate, though relationship is unclear.

μ depends on stressing rate, though relationship is unclear.

Adopting ETAS to swarm



Poor quality of fit may be because μ was treated as constant, and it suggest stressing rate is time-variable.

Parameters of Obsidian Buttes Before & during swarm

Event	K	μ	α	p	c
Boso (2002)	0.13 0.07	0.022 2.09	0.56 0.9	1.11 1.0	0.096 0.0005
Kilauea (2005)	0.28 0.96	0.16 0.89	1.24 0.61	1.21 0.92	0.002 0.003
Obsidian Buttes	0.61 1.4	0.031 225	0.88 1.05	1.1 1.0	0.001 0.001
Boso (2007)	0.20 0.61	0.013 2.4	0.55 1.37	0.88 1.0	0.0004 0.0008

K does not increase so much…

× 2 - 4

× 10-1000

× ～2

No change

No change

Is K stressing-rate dependent?

Helmstetter and Sornette, 2003

$$N = \frac{K}{1-n} 10^{\alpha(M - M_c)}$$

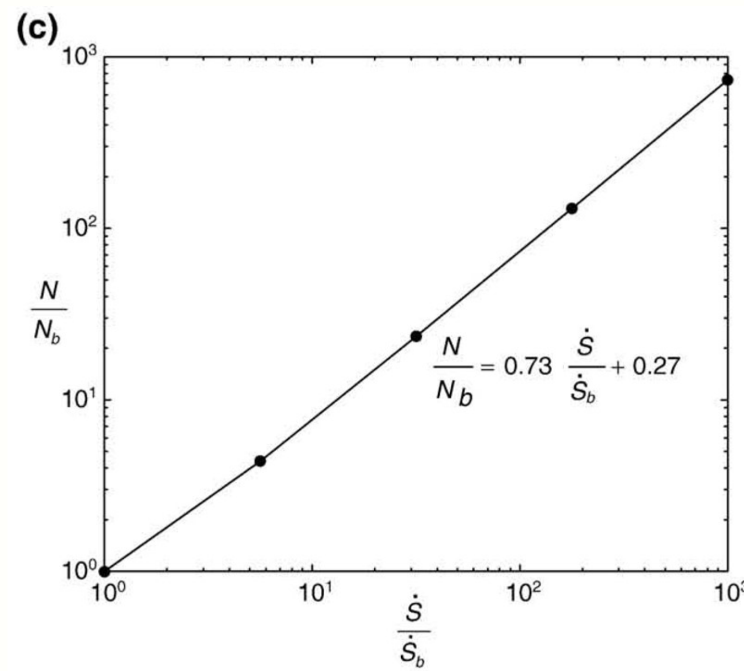
n=Kb/(b-α)

From geodetic data, stressing-rate was estimated to be

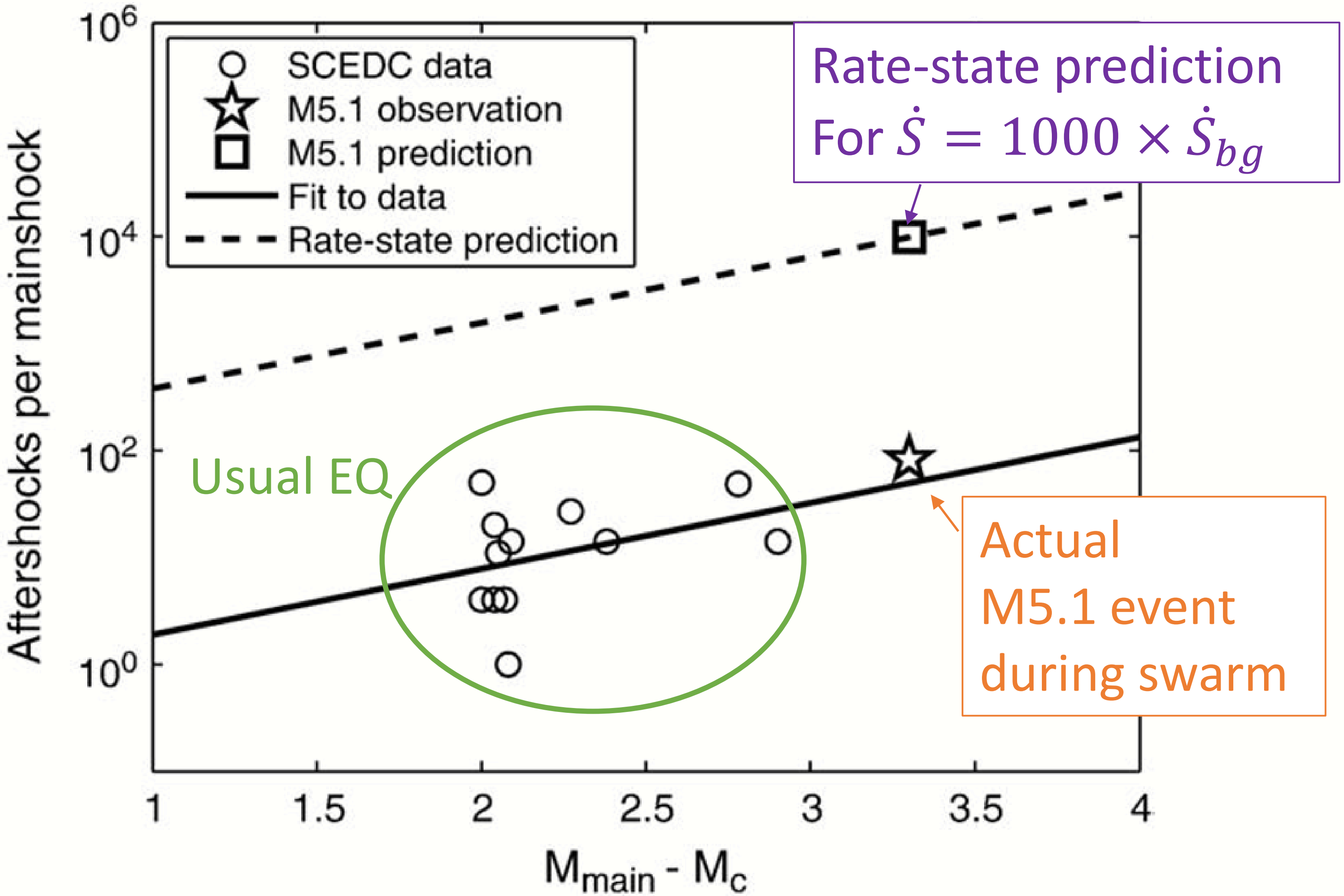
$$\dot{S} \sim 1000 \times \dot{S}_{bg}$$

during 2005 Obsidian swarms.

$$K \sim 1000 \times K_{usual} \, ???$$



Rate-state prediction and actual aftershocks



Contribution of Aσ…?

Compare aftershock productivity N of ΔS = 1MPa

Under two case:

N1: bg stressing rate ($\dot{S}_{bg}$ = 0.2MPa/yr)

N2: 3 days after $\dot{S}$ has changed to $10^1 \sim 10^4 \times \dot{S}_{bg}$

$t_{a,\,bg}$

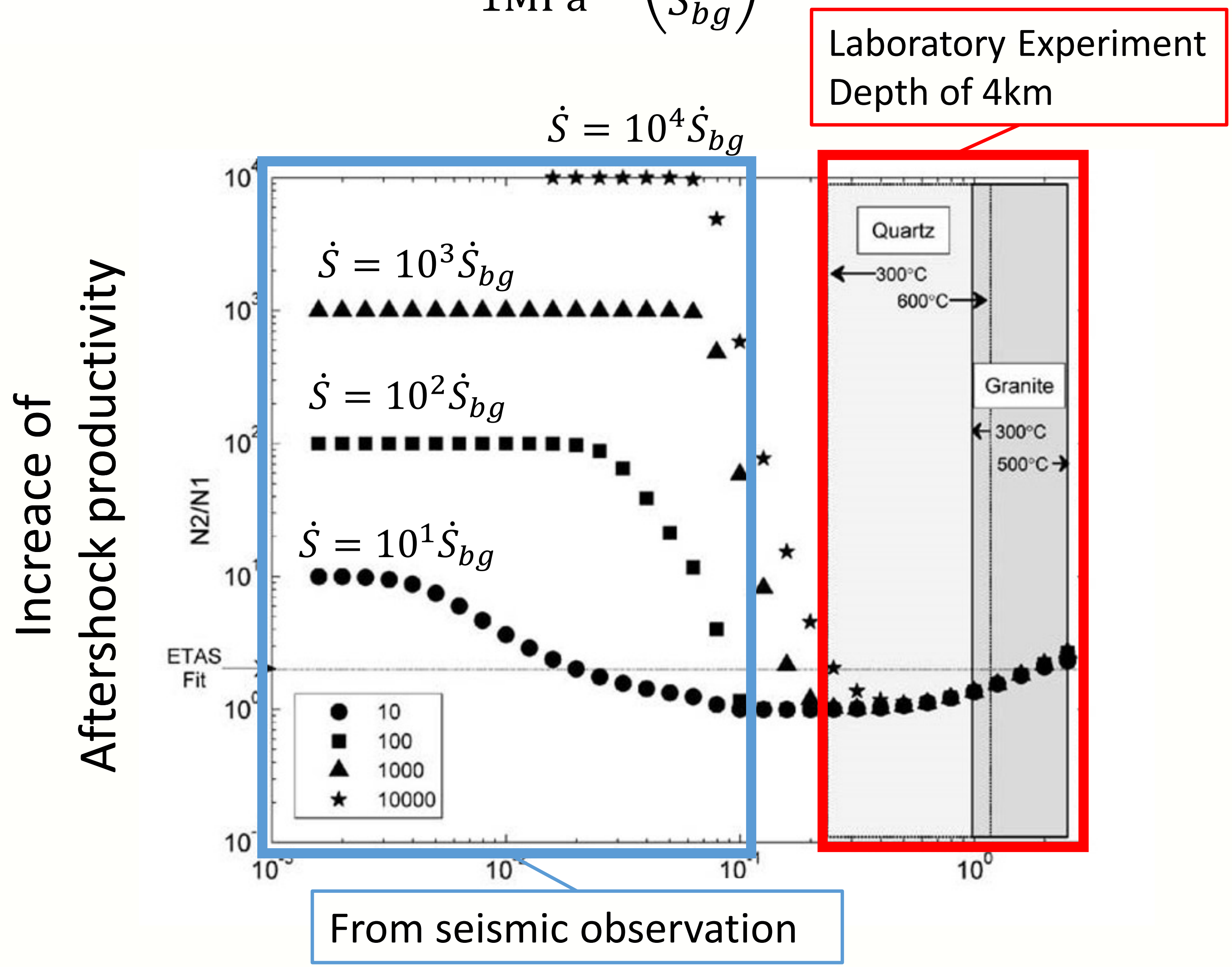
Aσ = 10^{-3}

Aσ = 1

2005 Obsidian Buttes M5.1 occurred 3 days after stressing rate change.

$$t_a(A\sigma, \dot{S}) = 1800\text{days} \times \frac{A\sigma}{1\text{MPa}} \times \left(\frac{\dot{S}}{\dot{S}_{bg}}\right)^{-1}$$

$$t_a(A\sigma, \dot{S}) = 1800\text{days} \times \frac{A\sigma}{1\text{MPa}} \times \left(\frac{\dot{S}}{\dot{S}_{bg}}\right)^{-1} \quad \leftrightarrow \quad 3\text{days}$$



In short,

During swarm,

- Substantial Increase of seismicity (μ)
- Small increase in aftershock (K)

was observed, but

those two cannot happen at once in rate-state model

CORRECTION OF ETAS MODEL

$$R = R_A + R_C = R_A + \sum_{t_i \leq t} \frac{K e^{\alpha(M_i - M_c)}}{(t - t_i + c)^p}$$

$$R_A = R - R_C = R - \sum_{t_i \leq t} \frac{K e^{\alpha(M_i - M_c)}}{(t - t_i + c)^p} = \frac{r}{\dot{S}_r \gamma}$$

$$\mathrm{d}\gamma = \frac{\mathrm{d}t}{A\sigma}\left[1 - \gamma\left(\dot{S}_A + \dot{S}_b\right)\right]$$

Combining the ETAS and rate-state model

- ETAS does not explicitly include information of stress.
- Swarms = anomaly of tectonic stressing rate.

- Rate-state model of Dieterich(1994) can treat change in stressing rate.

DIETERICH + ETAS
= [ETAS + stressing rate] model