

International Symposium on Earthquake Forecast/5th International Workshop on Earthquake Preparation Process  
May 25-27, 2018, Chiba Univ.

20-min Machine-gun Lecture,  
Crash Course of **Statistics** and **Seismogenesis**

Opening Remark/Lecture

**Short-Term Precursors, Why do I care?**

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- Primary interest is “Precursor.”
- “Prediction/Forecast” is of secondary concern.

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Hello, world. Thank you everyone for coming. I’m Masao Nakatani, dicta**tor** of the symposi**um**. As a preparation, I give you crash course on statisti**cs** and seismogenesis.

Speaking of myself, I’m a rock mech**an**ic. Like Chris Scholz and Jim Dieterich, I break and slide rocks in the lab. Being opini**on**ated about precurs**or** is the tradition of rock mech**an**ics, so I’m here. Yes, Kiyoo Mogi, of course.

The symposi**um**’s subject is the short-term precurs**or**, as I told you in solici**ta**tion e-mails. However, most everybody replied like, “yeah, your symposi**um** about predi**ct**ion sounds interesting...” Fair enough! They’re so deeply related. But, of course, they don’t mean the same. You’ll see the difference as we go.

Oh, a small remark. We shall not care the disti**n**ction between predi**ct**ion and fore**ca**st. If we start arguing about that, time will fly. All right. (49+)

## Foremost Concern

- ▶ **My Concern:**  
What do precursors signify, in terms of earthquake occurrence or [Seismogenesis](#)?

- ▶

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My main concern is this. What do precursors signify, in terms of physical processes culminating in earthquake occurrence, or Seismogenesis for short. I'm saying this because I've been already persuaded, on some observational basis, that precursors do exist. I don't mind you calling me a pro-precursor person, or a believer. However, about this issue, what do precursors signify, my view is quite different from many of pro-precursor people. I warned you. (31)

### Foremost Issue

▸ **My Concern:**

What do precursors signify, in terms of earthquake occurrence or **Seismogenesis**?

▸ **Most people's concern:**

Do **such** things, earthquake precursors, **really exist**?

O.K, but I have to start with your concern first. Many legitimate scientists, in the mainstream seismology and geodesy, well, JGR-solid people, are mostly non-believers. They are skeptical about the existence of short-term precursors. So, this question, “Do such things as earthquake precursors really exist? Proven on observational-basis?” is the main issue of the symposium. Many speakers will focus on this point. So, let me take care of this side first, which is the chapter 0. (30)

## Chapter 0: The Existence (Precursor) Claim

► One-on-one Claim:

► Statistical Claim:

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Do precursors really exist? A big problem here is that most people, believers and non-believers alike, do not understand one simple point. “What is the exact proposition of the existence claim?”

There are two kinds of existence claims. One-on-one claim versus Statistical claim.

## Chapter 0: The Existence (Precursor) Claim

► **One-on-one Claim:**

**This rare phenomenon** that shortly preceded that earthquake appeared because the earthquake was about to occur. (i.e., **was precursory** to that earthquake.)

► **Statistical Claim:**

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One-on-one claim says “**This** rare phen**o**menon that shortly preced**e**d **that** earthquake appe**e**ared, because the earthquake was about to occur. Claims in 70s, 80s, were mostly of this type.

Our special invit**e**e, Dr. Max Wyss, sitting over there, used to be the chief IASPEI special invest**e**igator of “real precursor aw**a**rd.” He spent hard days, trying to judge this type of one-on-one claims. You know, Wakita-sensei’s Radon claim was the only one Max did not disreg**a**rd. (50–)

## Chapter 0: The Existence (Precursor) Claim

### ► One-on-one Claim:

**This rare phenomenon** that shortly preceded that earthquake appeared because the earthquake was about to occur. (i.e., **was precursory** to that earthquake.)

- **Hard to believe unless obvious physical causality is shown.**
- **A huge, accelerating crustal deformation would be the only believable case...**

### ► Statistical Claim:

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But, such judgment is virtually impossible. That's why Max is so well-aged like that. O.K., I would believe, if the anomaly is something that is obviously related to the big earthquake via simple causal mechanism. But, the only such possibility is the huge crustal deformation. Dr. Sagiya and Dr. Itaba will talk about that. (19)

## Chapter 0: The Existence (Precursor) Claim

### ► One-on-one Claim:

**This rare** phenomenon that shortly preceded that earthquake appeared because the earthquake was about to occur.  
(i.e., **was precursory** to that earthquake.)

- **Hard to believe unless obvious physical causality is shown.**
- **A huge, accelerating crustal deformation would be the only believable case...**

### ► Statistical Claim:

**Some of those** similar phenomena that shortly preceded earthquakes appeared because an earthquake was about to occur.  
(i.e., **were precursory** to the earthquakes that followed.)

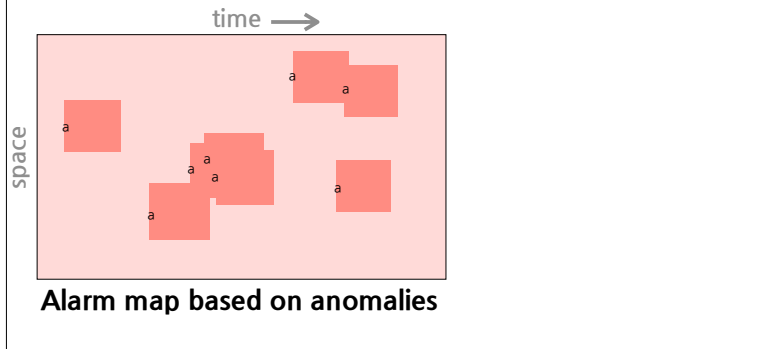
- **Easy to prove by trial forecasting.**

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However, these days, precursor claims are mostly of this other type. Statistical Claim. It says “**SOME** of those similar phenomena that shortly preceded earthquakes appeared because an earthquake was about to occur.” This claim is very easy to prove. Now, I will show, how to make proof by trial forecasting. (21)

## Trial Forecasting

1. Name your target EQs and test regions.  
e.g.,  $M > 8$ , where your  $R_n$  detectors are available
2. Name your algorithm to produce forecast.  
e.g. anomaly threshold, alarm duration, alarm radius
3. Produce your space-time Alarm map (not Anomaly map).



O.K. Trial Forecast. How to do that.

First, define your target, like Magnitude 8+, around Japan.

Second, Define your anomaly, like anomaly threshold. And more importantly, Make your forecasts based on the anomaly. So, you need to set additional parameters, like alarm duration and the radius of alarm area. You can set all these, just as you like.

Step 3. You paint red for certain radius of area, for certain duration after each anomaly. Then, you get a space-time alarm map like this. These small 'a's are anomalies.

Remember, you need to make forecasts. Anomalies themselves cannot be evaluated; Precursory claim includes the time lag and spatial offset between anomaly and hypocenter. Please submit as a forecast. (46)



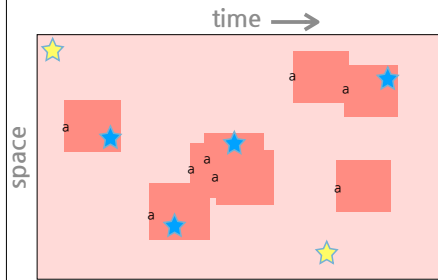
## Evaluate your Forecast Map

1. Measure **Alarm Fraction (警報分率):  $AF = 18\%$**

- weighting of area according to the regional seismicity difference (e.g., RI) is needed, depending on the type of anomalies used.

2. Calculate **Anomaly Appearance Rate:  $AAR = 4/6 = 67\%$**

- a.k.a. alarm rate, prediction rate, 予知率, 1 - miss rate, ...



Alarm map based on anomalies

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Now, let's evaluate. We only need two numbers.

First number. Alarm Fraction, which is the percentage of the alarmed space-time against the total space-time of your forecast. In this example, about 18% is painted red.

Second is the Anomaly Appearance Rate. In this case, 1-2-3-4, 4 of the 1-2-3-4-5-6, 6 target earthquakes occurred in the alarmed space-time, so AAR is 4/6, 67%. (27)

## Is Probability Gain > 1?

1. Measure **Alarm Fraction (警報分率):**  $AF = 18\%$

- weighting of area according to the regional seismicity difference (e.g., RI) is needed, depending on the type of anomalies used.

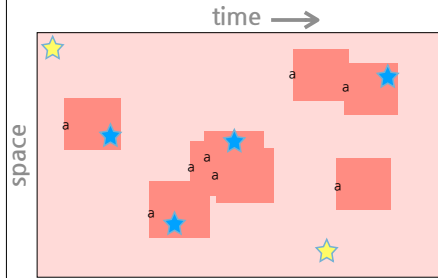
2. Calculate **Anomaly Appearance Rate:**  $AAR = 4/6 = 67\%$

- a.k.a. alarm rate, prediction rate, 予知率, 1 - miss rate, ...

► **Probability Gain:**

$$PG = 67/18 = 3.7 > 1!$$

- also means 3.7 times more risk in the alarmed region.



**Alarm map based on anomalies**

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Now, the time of verdict! If all the anomalies were irrelevant to the impending earthquakes, AAR should've been about equal to the alarm fraction, 18%. But, the observed AAR was 67%, 3.7 times higher. Congratulations, Mr. Believer! Earthquakes preferred the space-time you alarmed. (22)

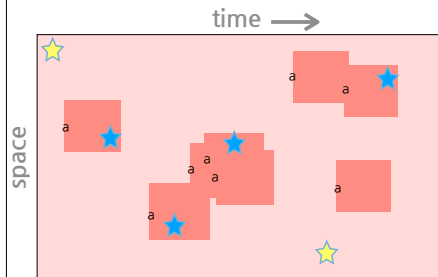
## Some of the pre-EQ anomalies were precursory?

### 1. Measure **Alarm Fraction** (警報分率): $AF = 18\%$

- weighting of area according to the regional seismicity difference (e.g., RI) is needed, depending on the type of anomalies used.

### 2. Calculate **Anomaly Appearance Rate**: $AAR = 4/6 = 67\%$

- a.k.a. alarm rate, prediction rate, 予知率, 1 - miss rate, ...



**Alarm map based on anomalies**

#### ► **Probability Gain:**

$$PG = 67/18 = 3.7 > 1!$$

- also means 3.7 times more risk in the alarmed region.

#### ► **Binomial Probability:**

4 or more success in 18% lottery = 0.012 (= *p-value*)

But, this could be just by luck. O.K. Lets's do the high-school binomial probability. The chance you get 4 or more successes in the 6 drawings of the 18% winning chance, is only 1.2%. This is the p-value to your precursor claim. So, some of the anomalies that preceded these 4 blue earthquakes **were** precursory indeed. Bit more calculation further shows, at least 2 of the 4 blue earthquakes were indeed preceded by precursors. (27)

## Lesson from Chapter 0

Forecast is a tool for precursor study.

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Chapter 0 done. Forecast is a tool to prove the existence of precursor.  
But, I know, that most people have more healthy mindset. (8)

## Practical Merit?

► Front-side value of precursor: Prediction/Forecast

A measure of Practical value:  $Q_{ON}$

The probability of EQ occurrence within the alarmed RT zone.

- a.k.a. success rate, 適中率, 1-false-alarm rate,

$$Q_{ON} = 1 - \exp \left\{ - \iint_{R,T} PG(\mathbf{x},t) \lambda_0(\mathbf{x},t) d\mathbf{x} dt \right\} \sim R \cdot T \cdot PG \cdot \lambda_0$$

alarm area
alarm duration
secular base rate

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Forecast may have a practical merit. Here, I introduce another measure of forecast  $Q_{on}$ , which is the probability that a big earthquake occurs in the space-time zone of your alarm. Let's see. (13)

## Practical Merit?

► Front-side value of precursor: Prediction/Forecast

A measure of Practical value:  $Q_{ON}$

The probability of EQ occurrence within the alarmed RT zone.

- a.k.a. success rate, 適中率, 1-false-alarm rate,

$$Q_{ON} = 1 - \exp \left\{ - \iint_{R,T} PG(\mathbf{x},t) \lambda_0(\mathbf{x},t) d\mathbf{x} dt \right\} \sim \underbrace{R \cdot T}_{\text{alarm duration}} \cdot \underbrace{PG}_{\text{alarm area}} \cdot \underbrace{\lambda_0}_{\text{secular base rate}}$$

Ex., M8 Nankai Earthquakes, average recurrence 100 yr.

Alarm:  $R = 200\text{km}$ ,  $T = 3 \text{ days} (= 1\text{E-}4 \text{ of } 100\text{yr}) \Rightarrow RT\lambda_0 = 1\text{E-}4$ .

$PG = 100 \Rightarrow Q_{ON} = 1\%$

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Consider M8 Nankai Earthquakes, which occur about once in 100 years. Let's say you have a precursor to produce an alarm of 3 days duration. Usually, the probability of M8 in 3 days is 1E-4, or .01%. When the precursor is observed, the region is 100 times more dangerous than usual. You know this from the past experience. So, your alarm is saying an M8 will occur in 3 days, at a chance of 1%. 1% in 3 days would be about the minimum probability that people may react. To my knowledge, foreshocks are the only precursor achieving PG of 100 or more. So, emphasizing a practical merit is often a bad idea. (47)

## Back-side value of precursor

► Front-side value of precursor: Prediction/Forecast

A measure of Practical value:  $Q_{ON}$

The probability of EQ occurrence within the alarmed RT zone.

- a.k.a. success rate, 適中率, 1-false-alarm rate,

$$Q_{ON} = 1 - \exp \left\{ - \iint_{R,T} PG(x,t) \lambda_0(x,t) dx dt \right\} \sim R \cdot T \cdot PG \cdot \lambda_0$$

alarm area  
alarm duration      secular base rate

Ex., M8 Nankai Earthquakes, average recurrence 100 yr.

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$PG = 100 \Rightarrow Q_{ON} = 1\%$

► Back-side value: Unique constraints on Seismogenesis  $\Rightarrow$  (Chapter 1)

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I would rather emphasize an academic value. Precursor should give a unique constraints on Seismogenesis. (6)

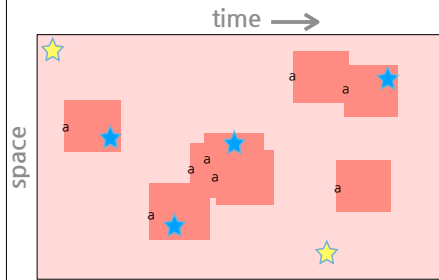
## Percentage of EQs that were really precursed

### 4. Measure Alarm Fraction: $AF = 18\%$

- weighting of area according to the regional seismicity difference (e.g., RI) is needed, depending on the type of anomalies used.

### 5. Calculate Anomaly Appearance Rate: $AAR = 4/6 = 67\%$

- a.k.a. alarm rate, prediction rate....



Alarm map based on anomalies

### ► Probability Gain:

$$PG = 67/18 = 3.7 > 1!$$

- also means 3.7 times more risk in the alarmed region.

### ► Binomial Probability:

4 or more success in 18% lottery = 0.012 (= *p-value*)

$$\text{net AAR} \approx \text{gross AAR} - AF = 67 - 18 = 49\%$$

- percentage of earthquakes really preceded by a precursor

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Look at this alarm map again.

Here, I introduce another performance index, net AAR. The gross AAR was 4/6, 67%. But, chances are, 1 of the 4 successes was a mere coincidence. So, the net AAR is about 67 - 18, is 49%. Only 49% of earthquakes are really preceded by precursors. Well, 49% is not negligible at all. Seismogenesis must explain this. Constraints from precursor. (33)



Chapter 1:

Your precursor signifies what of seismogenesis?

(Why I care the short-term precursor.)

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So, chapter 1 begins. Precursor signifies what of seismogenesis? You know, it's precursor of earthquake, so must be signifying something of seismogenesis. (11)

### Your precursor signifies what of seismogenesis?

► Most pro-precursor people propose 'mechanism' of precursors; they invoke anomaly-generation processes like

- micro cracks
- piezo effects
- stream current
- stress/deformation-activated mobile p-hole
- Radon emanation, and resulting water condensation
- Lithosphere-Air-Ionosphere Coupling

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People, especially believers, talk about mechanisms of their precursors. Like micro-cracking, piezos, p-hole, Radon... (9)

### Your precursor signifies what of seismogenesis?

▸ Most pro-precursor people propose 'mechanism' of precursors; they invoke anomaly-generation processes like

- micro cracks
- piezo effects
- stream current
- stress/deformation-activated mobile p-hole
- Radon emanation, and resulting water condensation
- Lithosphere-Air-Ionosphere Coupling

Sorry, I'm not much interested.

Please explain why they were 'precursory.'

Please.

19

But, sorry, that's not the most pertinent point. We study pre-cursor of earthquake. You must explain why your processes occur just before the earthquakes. Why are they precursory? (12)

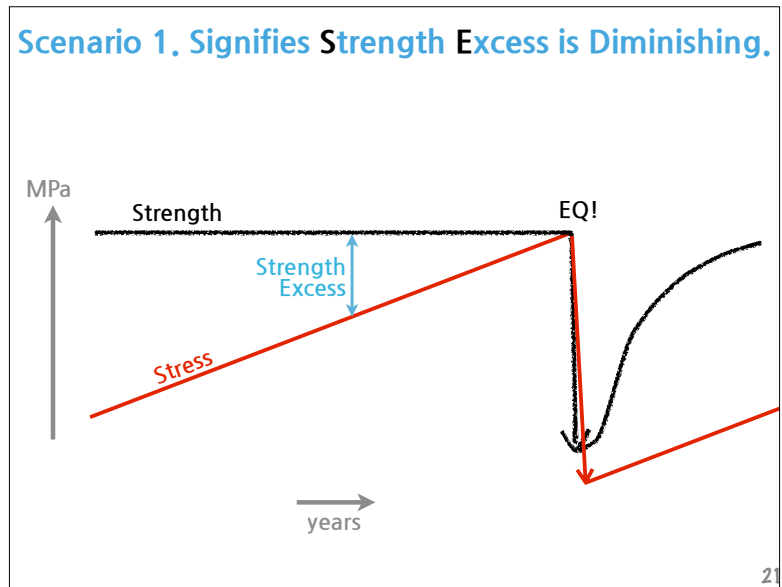
### Your precursor signifies what of seismogenesis?

- ▶ Most pro-precursor people propose 'mechanism' of precursors; they invoke anomaly-generation processes like
  - micro cracks
  - piezo effects
  - stream current
  - stress/deformation-activated mobile p-hole
  - Radon emanation, and resulting water condensation
  - Lithosphere-Air-Ionosphere Coupling
- ▶ They rarely propose why they occurred at the timings shortly before big earthquakes.
- ▶ You must put your precursor-generating processes into the seismogenesis scenario.
- ▶ In the rest, I will remind you how difficult it is. Most theories are demonstrably wrong.

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Explanation of precursoriness means you gotta put your process into the seismogenesis scenario. Nobody's been successful. But, I will remind you of two best ones from the past, and will discuss why they failed. (12)

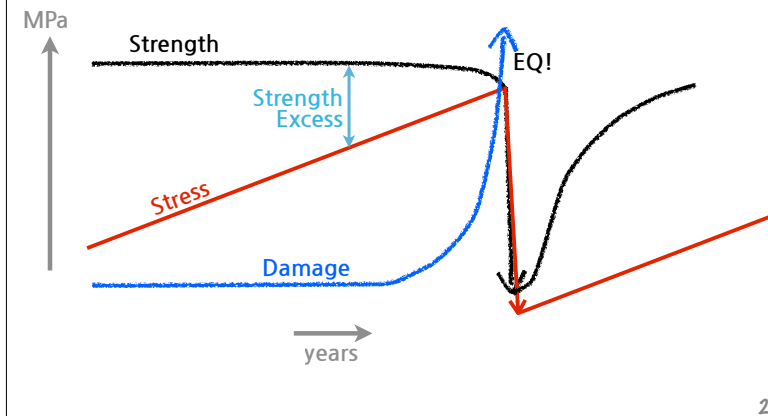
Scenario 1. Signifies Strength Excess is Diminishing.



Scenario 1 is very easy. You know, the Reid's earthquake cycle. Stress slowly increases due to tectonic loading, and eventually reaches the strength of the fault, and an earthquake occurs. A brittle failure. (13)

### Scenario 1: Derives from physical damages at +0 SE

- ☑ Brittle failure is always a delayed failure, preceded by the accumulation of damages such as microcracks etc.

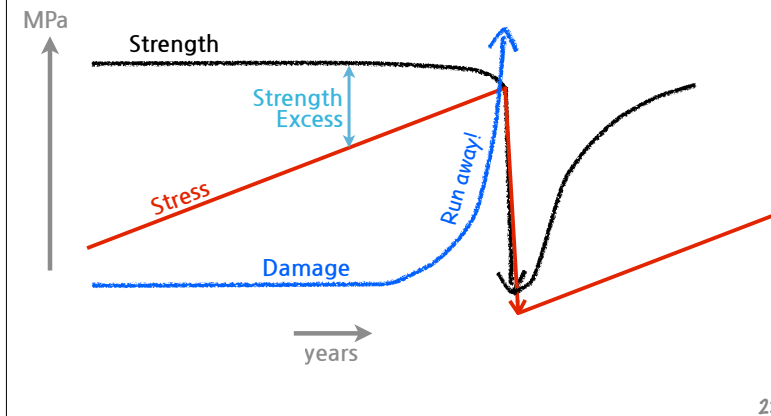


But, the real world is more interesting. Any brittle failure is a delayed failure, and hence, is necessarily preceded by microscopic damage. Lots of them.

The damage starts occurring when the stress comes pretty close to the strength, like, 95%. So, it is a sensor noticing the diminishing strength excess, and hence the imminence of earthquake. (22)

### Scenario 1: Derives from physical damages at +0 SE

✓ This is an ideal precursor, really sensing the imminence of the earthquake or +0 SE. Unskippable as well.

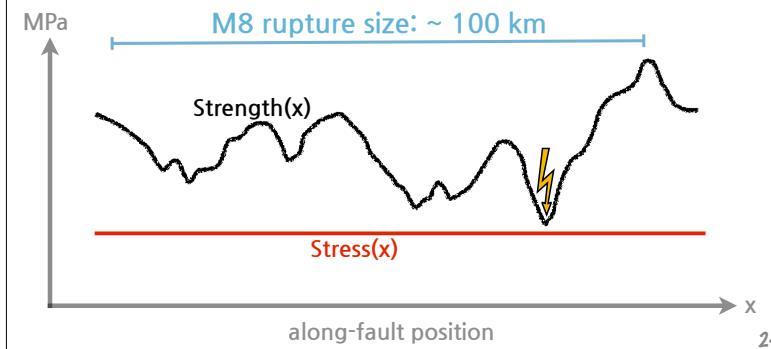


Furthermore, damage reduces the strength, making a positive feedback loop. Accelerates toward the macroscopic failure. Culmination, man!

This is really an ideal precursor; the damage starts and accelerates because it's about time, or stress is about the strength. You cannot skip this stage because stress cannot reach the strength before it almost reaches the strength. Beautiful, huh? (22)

### Scenario 1: What's wrong?

- It is unrealistic that +0 SE occurs over the broad region of a Big EQ rupture, in such **good sync as days scale**.
- Scholzy [1973] was too naive.....



However, as you know, the precursor fever of 70s ended miserably. Many earthquakes occurred without signals from those damage. What's wrong?

Look at this figure. For simplicity, I assume stress is uniform along the fault, but strength is heterogeneous.

Let's say stress is here now. So, this part of the fault is screaming, Danger! I'm about to bump. But, other parts of this big fault still have much strength excess. So, a small earthquake will occur here as warned, but it's just a small earthquake.

An implicit assumption behind this type of theory is that nearly-zero strength excess is achieved over a broad region along the fault, in such good synchronization of days scale, emitting loud short-term precursors, warning a big earthquake.

Given the heterogeneity of faults, you better forget such an unrealistic scenario.

(50)



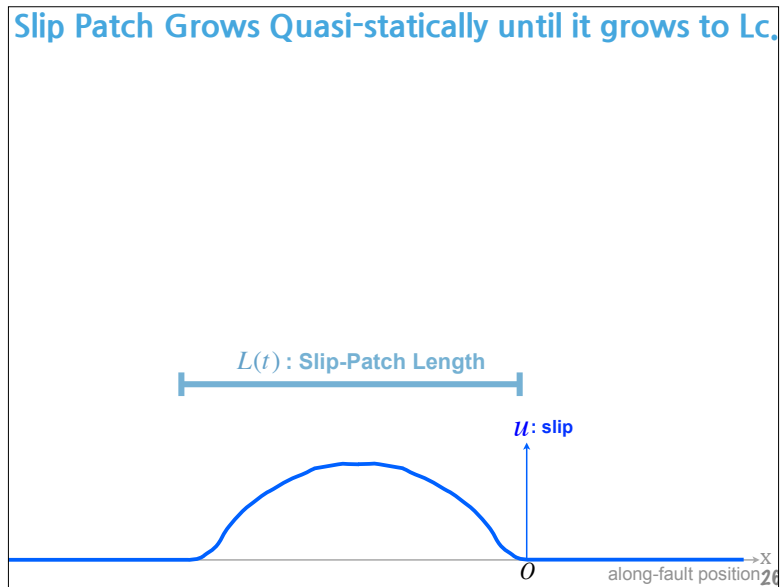
## Scenario 2: Slow Beginning of EQ (nucleation)

- ▶ Griffith's Energy Balance Criterion tells:  
Runaway rupture (EQ) needs a preslip-patch of certain size  $L_c$ .  
Stress reaching the stress in too small a region is not enough. It's still self-stabilizing, so the preslip patch grows only quasi-statically until the certain size  $L_c$ .

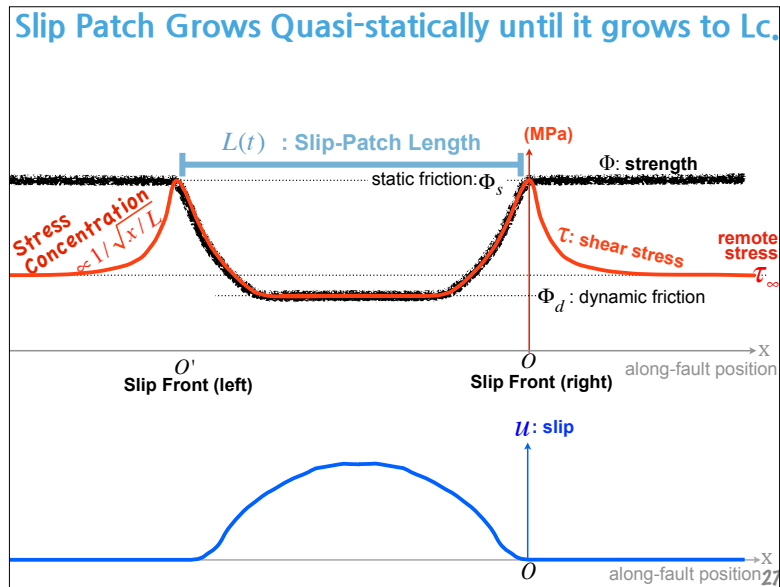
25

Now, we move to another beautiful scenario called nucleation. The point is, nucleation is the slow initiation of an earthquake, and it occurs only in a limited portion of the big fault that will bump soon.

But, we're talking about brittle faults. How the hell can nucleation be slow? Actually, slow nucleation is a theoretical requirement from the classical fracture mechanics, the Griffith Energy Balance. Let me try if I can lecture it in 4 minutes. (25)

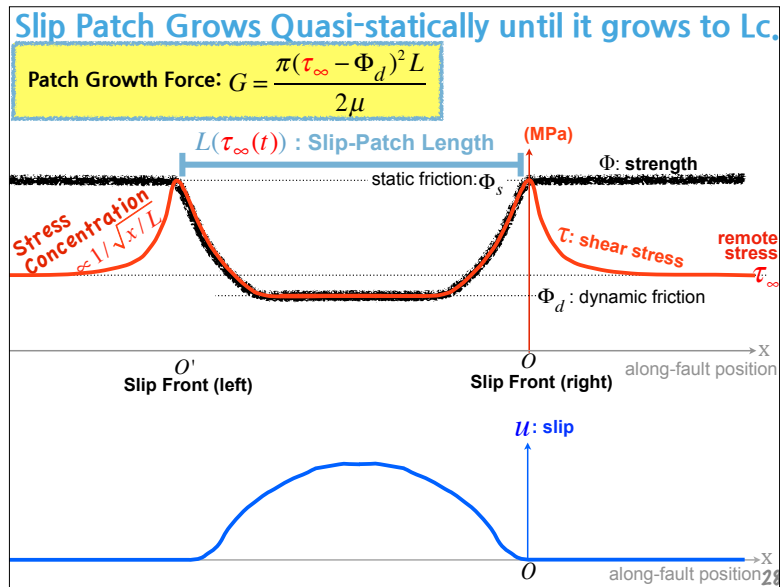


Here, this blue curve is the slip profile along the fault. Only this part, length  $L$ , has slipped and released the stress, down to the dynamic friction. Let's see the stress. (9).



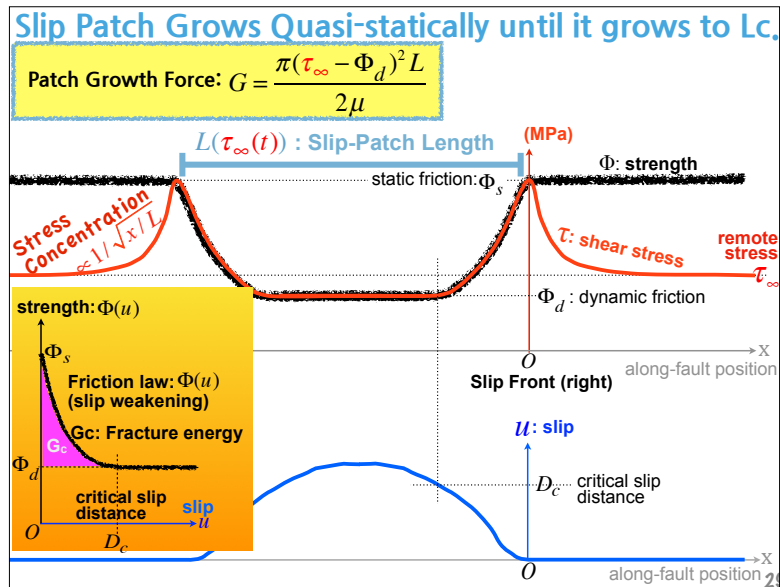
This red curve is the stress profile, and the dynamic friction is here, the low level. Outside the patch, the fault is still locked by the static friction. This creates the stress concentration around the patch front, due to elasticity.

The peak stress is truncated by static friction, so always the same. What really matters is the width of the stress concentration zone. It becomes broader as the slip patch grows larger. (26)

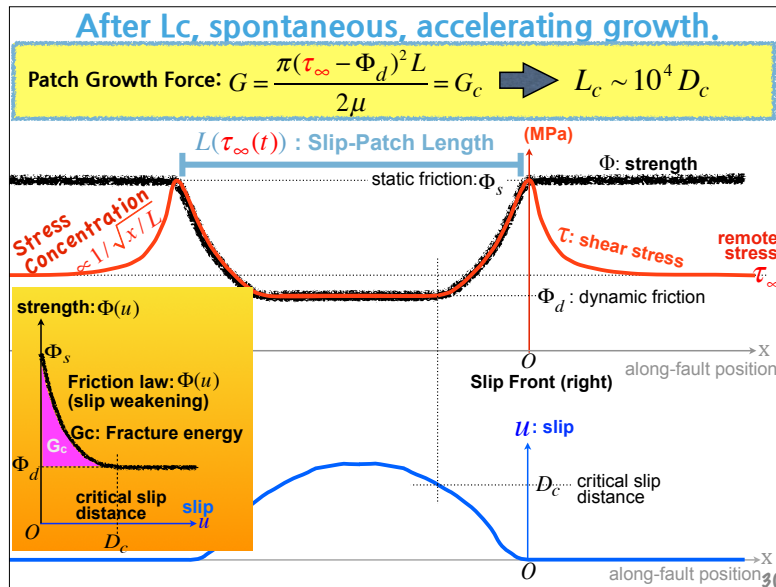


The elastic energy available for patch extension is this  $G$ , in the yellow banner.  $G$  is proportional to the patch length  $L$ . When  $G$  is still less than a fault property called fracture energy  $G_c$ , the elastic energy released by the advancement of the patch front is less than the frictional loss  $G_c$ , so the system is self-stabilizing. The slip patch can grow only quasi-statically, which means growth is in accordance with the slow increase of remote tectonic stress  $\tau_\infty$ . So, this is a very slow process.

However, one day,  $L$  becomes large enough so that  $G$  reaches  $G_c$ , then, growth becomes spontaneous. (40)



The fracture energy  $G_c$  is explained in the orange inset. The curve is the local friction law. Frictional strength decreases from static friction to dynamic friction, as a function of slip.  $G_c$  is this magenta area, energy consumed to break the extra atomic bonds of static friction. The slip distance required for this frictional weakening is called  $D_c$ . (23–)



Once the patch has reached  $L_c$ , or  $G$  has reached  $G_c$ , the rest is spontaneous. I mean, the patch grows in an accelerating way due to the positive feedback through the even broader stress concentration as the patch grows further. It does not need help from further tectonic loading. Eventually it becomes an earthquake, a fast dynamic rupture expanding at the speed of elastic wave, 3 km/s. The spontaneous, accelerating stage begins when the patch reaches  $L_c$ , given by the yellow-banner energy balance. With typical stress drop, rigidity and stuff, it is about 10 thousand times the  $D_c$ . (36)

## Scenario 2: Slow Beginning of EQ (nucleation)

- ✓ Griffith fracture energy theory tells:  
Runaway rupture (EQ) needs a preslip-patch of certain size  $L_c$ .

$$\text{Patch Growth Force: } G = \frac{\pi(\tau_\infty - \Phi_d)^2 L}{2\mu} = G_c \Rightarrow L_c \sim 10^4 D_c$$

Stress reaching the stress in too small a region is not enough. It's still self-stabilizing.

- This slow nucleation stage is **unskippable**.
- Let's catch it at the quasi-dynamic (accelerating) stage, which means the earthquake **has already started**. It's a **red-handed arrest!**
- Necessary and Sufficient condition of EQ onset, i.e. **SILVER BULLET**.

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Completo. This slow nucleation is unskippable. And once we see accelerating patch growth, it will necessarily proceed to an earthquake. So, this is a sufficient condition, too. Must be a Silver Bullet.

So, how big is  $L_c$ ? Is it a detectable size? (18)

## Scenario 2: Slow Beginning of EQ (nucleation)

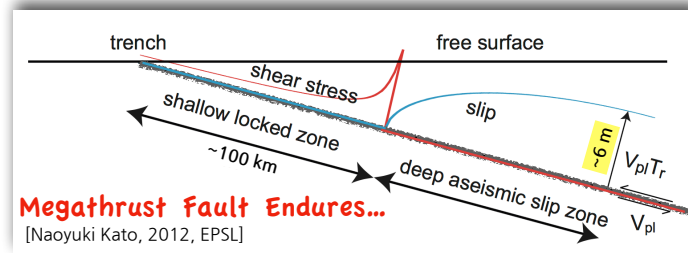
- How big is  $L_c$ ?

● [N. Kato, 2012] :

The locked region of M8 earthquakes endures huge stress concentration from the meters of dislocation imposed at its deeper edge (~20 km depth)

● This leads to an estimation of  $L_c \sim 10$  km, 1/10 of the EQ rupture length.

● This is M6-worth of moment, should have been geodetically detected in some cases, already.



How big is  $L_c$  for natural faults? Naoyuki Kato has solved this long-standing problem by a very simple argument. He was like, hey, locked part of M8 megathrust fault endures the huge stress concentration from meters of dislocation, on the creeping down-dip extension.  $L_c$  must be big!

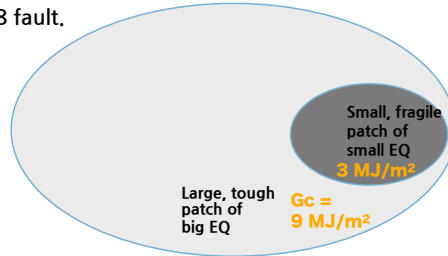
So,  $L_c$  seems to be about one tenth of the earthquake rupture. So, for M8, like the Tokachi-oki, 2003, the nucleation should be observed as the crustal deformation equivalent to M6, which is observable to Japanese geodesists. But, there was none. Americans also failed, in the Parkfield 2004.

What was wrong with this beautiful nucleation scenario? (41)



### What scenario 2 overlooked.

- ▶ Recall that some small earthquakes occur on the big fault of M8. There should be **fragile (low- $G_c$  and hence small- $L_c$ ) spots** within the large, tough M8 fault.

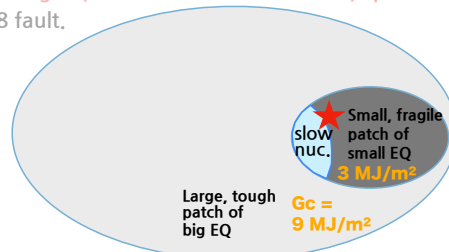


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Here's the hint. We know, some small earthquakes occur on the fault of M8. This means, there are small **fragile** spots on the largely tough M8 fault. (10)

### 'Large' nucleation can be skipped by cascade-up.

- Recall that some small earthquakes occur on the big fault of M8. There should be **fragile (low- $G_c$  and hence small- $L_c$ ) spots** within the large, tough M8 fault.



A small earthquake occurs in the small fragile patch, preceded by a small, slow nucleation there, too small to detect. However, the resultant coseismic slip of the small-patch earthquake is already enough to start the dynamic rupture of the surrounding tough part ...

Nucleation of the large-, tough-patch EQ is done through the cascade of small, then medium earthquakes. The **cascade-up** sequence, i.e., **dynamic nucleation** is what people perceive as the early part of the big EQ's dynamic rupture [Ide's talk].

In such **fragile**, low- $G_c$  spots,  $L_c$  is small, so a small earthquake **nucleates** in secret and then **bumps**. Now, the coseismic slip patch of the small earthquake is already large enough to **overcome** the higher  $G_c$  around. This is the bloody **cascade-up** scenario, which crushed all our dreams. Dr. Ide will talk about that. (20)

**I have not given it up completely, though.**

▸ o.k., fine. But, I have shown that large EQs can be initiated by large, slow nucleation **as well**.

**Large nucleation before large earthquakes is sometimes skipped due to cascade-up—Implications from a rate and state simulation of faults with hierarchical asperities**

Hiroyuki Noda,<sup>1</sup> Masao Nakatani,<sup>2</sup> and Takane Hori<sup>1</sup> [\[Title of 2013 JGR, solid\]](#)

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However, the nucleation theory is too good to give up completely. So, I wrote a paper like this. Here's the official title. Reads, "Large nucleation before large earthquakes is sometimes skipped due to cascade-up."

But if you read this paper, you actually find, (15)

**I have not given it up completely, though.**

▸ o.k., fine. But, I have shown that large EQs can be initiated by large, slow nucleation **as well.**

**Large nucleation before large earthquakes is sometimes skipped due to cascade-up , but only sometimes.**

Hiroyuki Noda,<sup>1</sup> Masao Nakatani,<sup>2</sup> and Takane Hori<sup>1</sup> [[Contents of 2013 JGR, solid](#)]

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this paper rather **e**mphasizes the **o**pposite. “But only sometimes.” (4)

**I have not completely given it up.**

▸ o.k., fine. But, I have shown that large EQs can be initiated by large, slow nucleation as well.

**Large nucleation before large earthquakes is sometimes skipped due to cascade-up , but only sometimes.**

Hiroyuki Noda,<sup>1</sup> Masao Nakatani,<sup>2</sup> and Takane Hori<sup>1</sup> [[Contents of 2013 JGR, solid](#)]

futile?

悪あがき?

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haha, futile? (2)

## A Lesson from the two failed scenarios

Does your short-term precursor tell the size of the coming earthquake?

Equivalently, does your precursor tell when the earthquake will Stop, not only when it will start?

### Size of Earthquakes (as observed)

M8 : (100 km)<sup>2</sup> dislocates for 4 m in 50 sec.

M6 : (10 km)<sup>2</sup> dislocates for 0.4 m in 5 sec.

M4 : (1 km)<sup>2</sup> dislocates for 0.04 m in 0.5 sec.

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Well, a remark. In a sense, the two scenarios failed for the same reason. You know, they may tell when the earthquake will start, but they do not tell when the earthquake will stop.

As you know, earthquake size is the same thing as when the rupture stopped. (15)

### Scenario?3: Fake Precursor

- ▶ **Real precursor** signifies:
  - special physical preparation processes culminating in a big EQ.
    - scenario 1
    - scenario 2
  - # physical precursors.
  - # could be a silver bullet.
  
- ▶ **Fake precursor** :

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Now I lecture the last topic, which is a real brain twister.

Here, I want to raise a concept of **real** precursor versus **fake** precursor. Both satisfies the statistical claim of existence. Real precursor is the precursor that signifies physical preparation process culminating in a big earthquake. I already showed two scenarios for that. They are mostly physical precursors, I mean, physical damage on the fault, rather than elastic stress. Their role in seismogenesis suggests potential to be a silver bullet. (34)

### Scenario?3: Fake Precursor

- ▶ **Real precursor signifies:**
  - special physical preparation processes culminating in a big EQ.
    - scenario 1
    - scenario 2
  - # physical precursors.
  - # could be a silver bullet.
  - physical conditions where a big EQ is about/ready to occur.
    - long time since last one (accumulation of stress/slip deficit)
    - episodic loading from deep SSEs, tidal stress, etc.
    - smoothed irregularity for easy rupture propagation (criticality)
    - # Some are **tectonic** precursors. More for **medium-term** precursors.
    - # merely a necessary condition, never a silver bullet.
- ▶ **Fake precursor :**

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Also, so-called tectonic precursors, typically signifying the regional stress level is high, are real precursors. But, these scenarios are more for medium-term precursors. So, I don't dig in. They signify merely necessary conditions, and hence never make a silver bullet. (17)



### Scenario?3: Fake Precursor

- ▶ **Real precursor signifies:**
  - special physical preparation processes culminating in a big EQ.
    - scenario 1
    - scenario 2
  - # physical precursors.
  - # could be a silver bullet.
  - physical conditions where a big EQ is about/ready to occur.
    - long time since last one (accumulation of stress/slip deficit)
    - episodic loading from deep SSEs, tidal stress, etc.
    - smoothed irregularity for easy rupture propagation (criticality)
  - # Some are tectonic precursors. More for medium-term precursors.
  - # merely a necessary condition, never a silver bullet.
- ▶ **Fake precursor :**
  - **not the manifestation of any special physical preparation/conditions**
  - **leads to PG > 1 forecasts (satisfies the 'existence (precursor) claim')**
    - typically a **stochastic trigger** of the big EQ.
    - # neither a necessary or sufficient condition, never a silver bullet.

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Now, fake precursor. The brain-twister.

They are not manifestations of any special physical preparations or conditions. Yet, they lead to successful forecasts. They are typically stochastic triggers to earthquake. What am I talking about? (15)

## ETAS fake foreshocks of Big EQs.

► **ETAS (Epidemic Type Aftershock Sequence) model [Ogata, 1988,1998]:**

The probability ( $\lambda$ , events/sec  $\cdot$  m<sup>2</sup>) of the earthquake occurrence is the sum of a time-independent **background rate** ( $\mu$ ) +  $\Sigma$ **Ogata-law triggering** from recent, nearby earthquakes.

$$\lambda(t; \mathbf{x}) = \underbrace{\mu(\mathbf{x})}_{\text{background seismicity}} + \sum_{t_i < t} \underbrace{K_0}_{\text{past}} \left( 1 + \frac{t - t_i}{t_c} \right)^{-1.1}_{\text{recent}} \left( 1 + \frac{|\mathbf{x} - \mathbf{x}_i|^2}{x_c^2} \right)^{-1.6}_{\text{nearby}} e^{-2.5(m_i - m_c)}_{\text{large}}$$

triggered seismicity (aftershocks of the past seismicity)

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I am talking about foreshocks. We will have 4 talks about foreshocks. I prepare you for their battle in the Highland. Fake foreshocks, appearing in the ETAS synthetic catalog, is the most beautiful, pure pure example of fake precursor.

O.K. ETAS is the stochastic model of seismicity invented by Dr. Ogata, now the gold standard. It basically says that seismicity is a Poissonian process with time-varying occurrence rate lamda, which is the sum of the time-independent background rate mu and the summation term accounting for the chances to have aftershocks from recent, nearby earthquakes. It also captures that larger earthquakes produce more aftershocks. (38)

## ETAS fake foreshocks of Big EQs.

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$$\lambda(t; \mathbf{x}) = \underbrace{\mu(\mathbf{x})}_{\text{background seismicity}} + \sum_{t_i < t} \underbrace{K_0}_{\text{past}} \left( 1 + \frac{t - t_i}{t_c} \right)^{-1.1} \left( 1 + \frac{|\mathbf{x} - \mathbf{x}_i|^2}{x_c^2} \right)^{-1.6} e^{-2.5(m_i - m_c)}$$

triggered seismicity  
(aftershocks of the past seismicity)  
recent      nearby      large

- ▶ **Gutenberg-Richter law:**

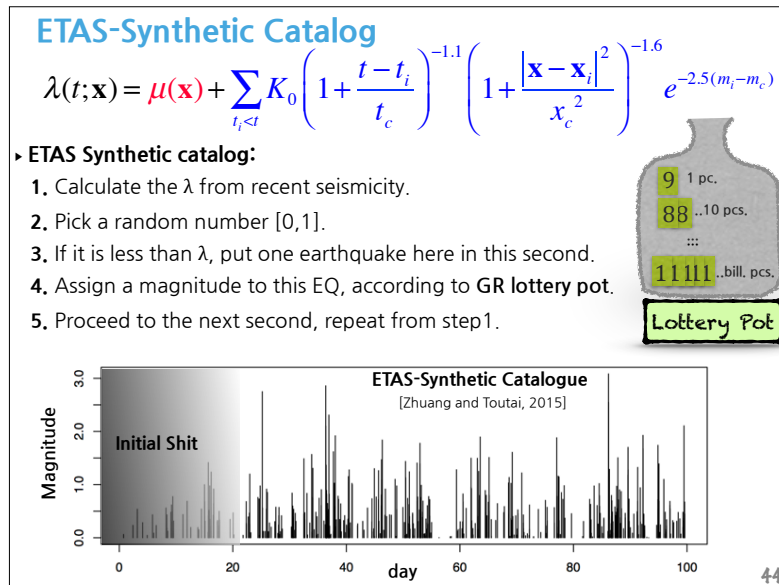
Greater EQs are much rare than smaller EQs.

empirical statistics:  $n(M) \propto M^{-b}$

**GR-lottery-pot** assumption:  $\lambda(M) \propto M^{-b}$

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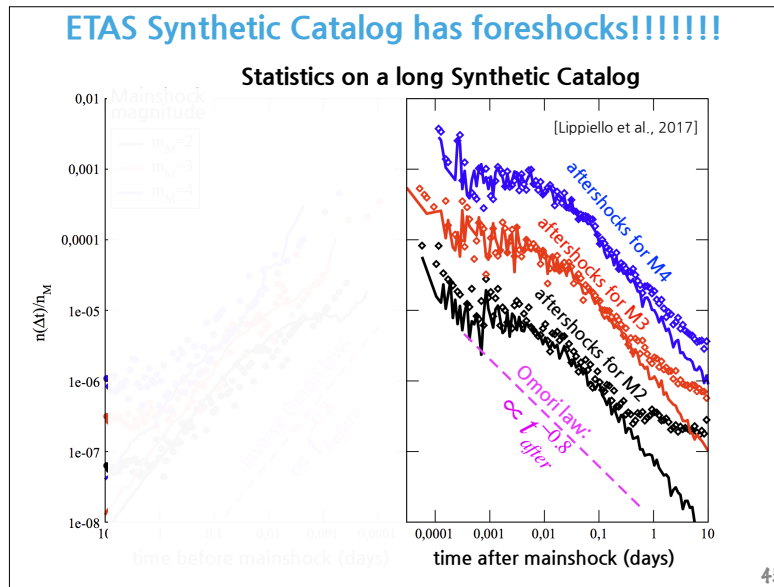
ETAS does not tell anything about the magnitude of the earthquake that will occur, so we assume the GR lottery pot. (6)



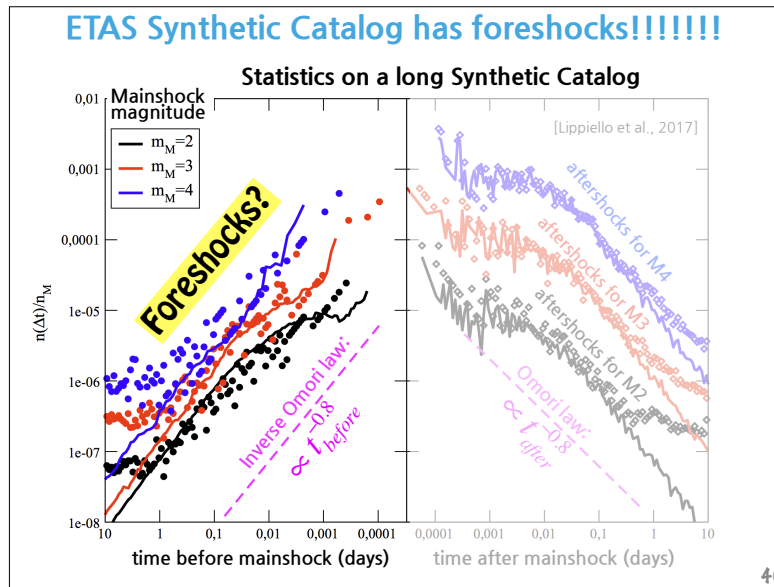
O.K. Let's forge a virtual earthquake catalog, assuming everything is random, except for the sure existence of aftershocks.

Basically, you calculate  $\lambda$ , according to the recent seismicity, then pick a random number to decide if an earthquake occurs in this 1 second, and if an earthquake occurs, give it a magnitude by drawing one card from the GR lottery pot. You repeat this.

Then, you get a catalog like this. Early part is not good, just representing the background seismicity, but later part looks very close to natural seismicity, having aftershocks, of course. (36)



Now, in the synthetic catalog, we pick large earthquakes. Like M4. We call an earthquake the mainshock if it is the largest one in 10 days before and after. The right half of this figure shows aftershock occurrence rate. They follow Omori-law, the aftershock rate decreases with time. The greater the mainshock, the more aftershocks occur. (20)



The left half of this figure shows the earthquake occurrence rate **before** the mainshock.

Seismicity becomes higher as time approaches the mainshock. What? Foreshocks?

Holly cow, this is a pure pure ETAS synthetic catalog, free from any predictionist sort of mechanisms.

And, holly cow, foreshocks are more active if the coming mainshock is greater. This is insane. (23)

## Sad News! ETAS-Synthetic Catalog has Foreshocks!!

- ▶ By construction, the synthetic catalog shouldn't have any 'real' foreshocks signifying preparation for a big EQ.

**Mainshocks are aftershocks of conditional foreshocks:  
How do foreshock statistical properties emerge from  
aftershock laws**

Agnès Helmstetter [et al. 2003 JGR-solid]

implying, there's no such thing as real precursor.  
At least, foreshocks are not the evidence.

### ▶ The Trick:

Earthquakes, small or big, tend to occur following recent, high seismicity due to the summed aftershock-triggering effect. A mainshock is merely the biggest one around, which happened to be big.

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Make No mistake. This is sad news for us, precursor believers. Foreshocks, arguably the top candidate of believable precursors, were not real precursors. That's what Helmstetter argued when she wrote this cool paper. "Mainshocks are aftershocks of foreshocks."

The ETAS fake foreshocks emerges by this yellow trick. Earthquakes, small or big, tend to occur following recent, high seismicity due to the summed aftershock-triggering effect. Big or small. A mainshock is merely the biggest one around, which happened to be big. GR lottery pot. (34)

Further sad news!

ETAS fake foreshocks let you forecast big EQs quite well.

Trial forecasting, on their ETAS synthetic catalog

Helmstetter et al. [2003]

having a large earthquake. Measuring the seismicity rate over a sliding window with flexible length imposed to contain exactly 100 events and fixing the alarm threshold at 0.05 events per day, we are able to predict 20% of the  $M \geq 6$  events with just 0.16% of the time period covered by the alarms. This gives a prediction gain  $g = 129$ .



Anti-Precursor Paper!

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Further teasing us believers, she tried forecasting on her synthetic catalog. Just by turning alarm ON when seismicity is high, she got AAR of 20% with the alarm fraction of mere 0.16%. This means ETAS fake foreshocks earned a Probability Gain of 129.

At the moment, any precursors other than foreshocks give PG greater than 20, I believe. So, this is a strong success. The point is, the success of forecast by foreshocks does not necessarily mean the existence of real preparation process. (36)



**Fake Foreshocks exist, but Real Foreshocks may, as well.**

▶ **ETAS fake foreshocks exist for sure, and sadly help forecasting.**

- Helmstetter et al [2003]: Cursory trial forecasting on ETAS synthetic Catalog.  
Fake foreshocks earned **PG = 129** for M6+.

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But again, make no mistake! Helmstetter's anti-precursor paper only says that foreshocks to the extent ascribable to ETAS cannot be taken as evidence for real preparation process. (10)

## Fake Foreshocks exist, but Real Foreshocks may, as well.

### ▶ ETAS fake foreshocks exist for sure, and sadly help forecasting.

- Helmstetter et al [2003]: Cursory trial forecasting on ETAS synthetic Catalog.  
Fake foreshocks earned  $PG = 129$  for  $M6+$ .

### ▶ Forecast by ETAS on real Catalog

- Hardebeck et al [2013, Fig. S9]: Calculated ETAS-expectance  $\lambda$  before 9  $M6.5+$  in CA.  
4 of the 9 occurred under very high  $\lambda$ ,  $1E2$  to  $1E6$  times the secular base rate  $\lambda_0$ , while the remaining 5 occurred under  $\sim \lambda_0$ . [Nakatani, 2018]
- Lippiello et al [2012]: Binary forecast map based on an arbitrary threshold on ETAS  $\lambda$ .  
Alarmed 5 of 6  $M6+$  in Southern California.  $PG = 5500$ . [Nakatani, 2018]

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Anyway, just by using ETAS, PG of Several thousands, seem to be achievable. (5)

## Fake Foreshocks exist, but Real Foreshocks may, as well.

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- Lippiello et al [2012]: Binary forecast map based on an arbitrary threshold on ETAS  $\lambda$ .  
Alarmed 5 of 6 M6+ in Southern California. **PG = 5500**. [Nakatani, 2018]

### ▶ Real foreshocks exist, too.

- Lippiello et al, [2012, 2017]:  
**Spatiotemporal organization not seen in ETAS** fake foreshocks, which may signify slow nucleation processes.
- Lippiello et al, [2012]  
Combining this 'real-foreshock' feature with the ETAS- $\lambda$  earned some extra PG, bringing their final forecast with **PG = 38,000**. (alarmed 5 of 6 M6+ in Southern California with less alarm fraction)

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However, if there are real foreshocks as Lippiello claims, really high PG is possible. He achieved the PG of 38 thousand, which sometimes gave a strong alarm like, 20% chance of M6+, just there, in 1 day. (15)

## Summary - Opening Lecture

- ▶ Foremost Question: **Do such things as real precursors exist?**
- ▶ In my opinion, some types of anomalies are indeed precursory. **Clearly proven by statistics (AAR > AF, significantly) already.**
- ▶ Foremost Concern: **What do precursors signify?**
  - Strength Excess is diminishing ~0. (scenario 1, died ca. 1985.)
  - Slow beginning of a big earthquake. (scenario 2, died ca., 2003.)
  - **Fake precursors, like probabilistic triggering** rather than derivatives of some preparation process. (scenario 3, non-believers.)
  - scenario 4 (my Sunday talk)
- ▶ By the way, currently highest PG comes from **ETAS effect** (~5000 for M>6), while incorporation of subtle features brings it to ~38,000 [Lippiello et al., 2012.]
- ▶ Among short-term forecasts, only (fake or real) foreshock-based methods are **marginally useful.**

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OK. Grand summary.

Short-term precursors used to look no-brainer. In Scholzy's time. No wonder, there should be such things, of course. Things must start breaking before eventually breaks.

However, little bit of thinking tells, hey, it's difficult. Processes **culminating** in the **onset** of earthquakes do not seem to **control** when the once started earthquake will stop. The size of EQ.

Currently, no silver-bullet precursors have been found. Non-silver-bullet precursors exist, but have not been explained. I mean, how do they **appear** as a **pre-cursor** of **earthquakes**. (32)

Opening Remark

**We shall seek answers to this unpleasant question.**

**Is EQ precursor a good topic for a professional scientist (i.e. employee) to study, whereas the field has been orphaned in developed countries?**

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Lastly, the opening remark, not lecture. This is a warning.

This symposium is not supposed to be much of pleasant experience.

Probably, most acute reason why both the mainstream skepticals and pro-precursor believers have gathered here, is to find the answer to this yellow question.

All right, Enjoy the symposium. (19-)