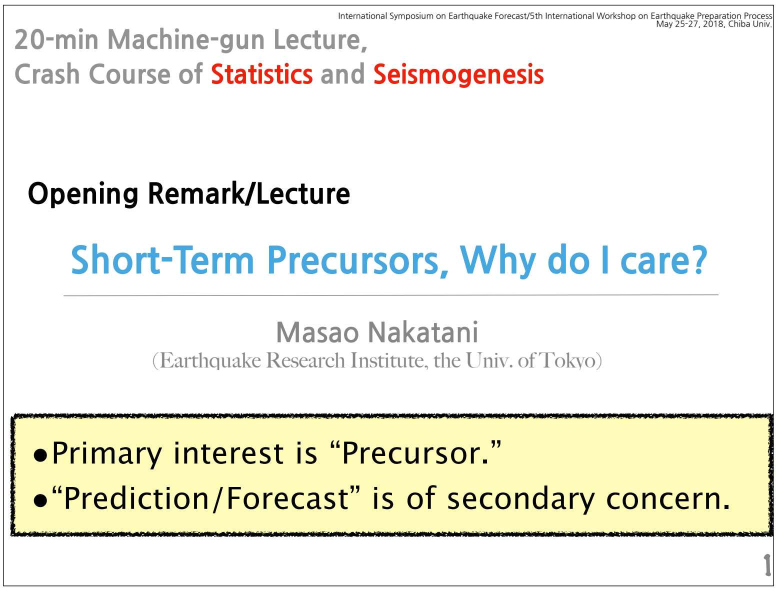


Hello, world. Thank you everyone for coming. I'm Masao Nakatani, dictator of the symposium. As a preparation, I give you crash course on statistics and seismogenesis.

Speaking of myself, I'm a rock mechanic. Like Chris Scholz and Jim Dieterich, I break and slide rocks in the lab. Being opinionated about precursor is the tradition of rock mechanics, so I'm here. Yes, Kiyoo Mogi, of course.

The symposium's subject is the short-term precursor, as I told you in solicitation e-mails. However, most everybody replied like, "yeah, your symposium about prediction 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.

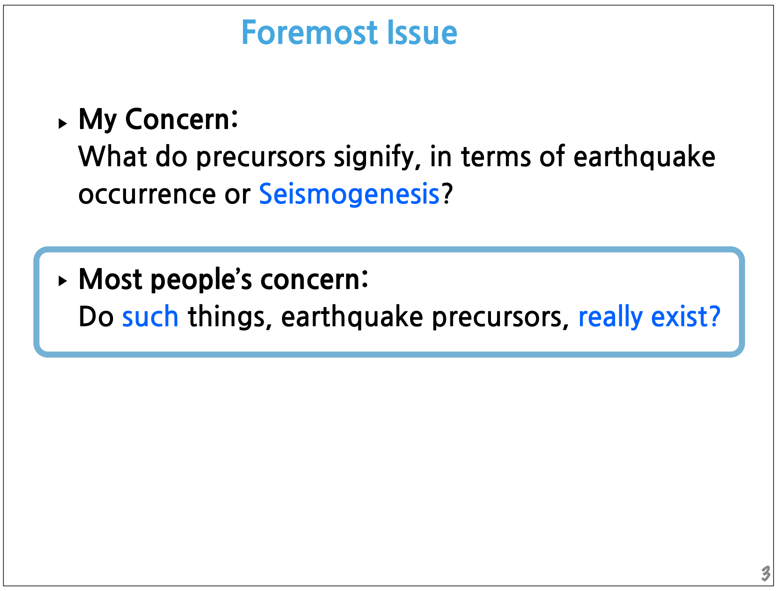
Oh, a small remark. We shall not care the distinction between prediction and forecast. If we start arguing about that, time will fly. All right. (49+)

Foremost Concern

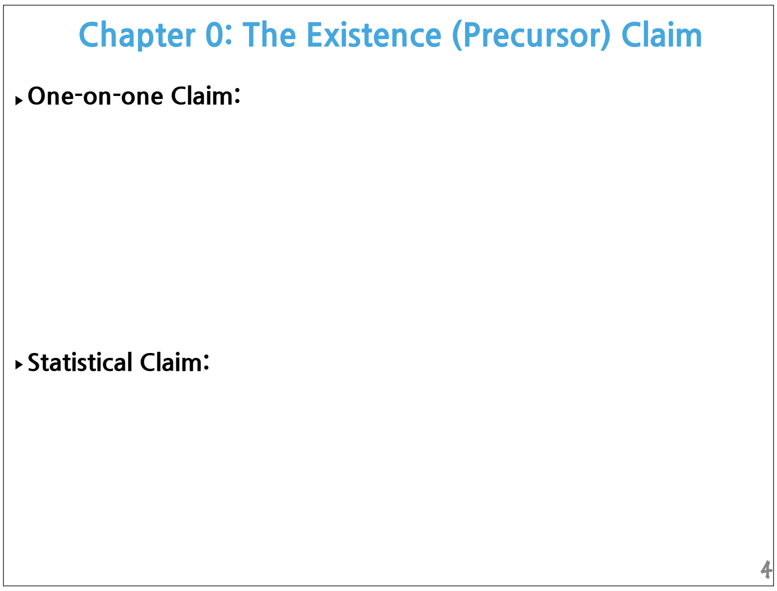
- **My Concern:**
  What do precursors signify, in terms of earthquake occurrence or Seismogenesis?

2

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)

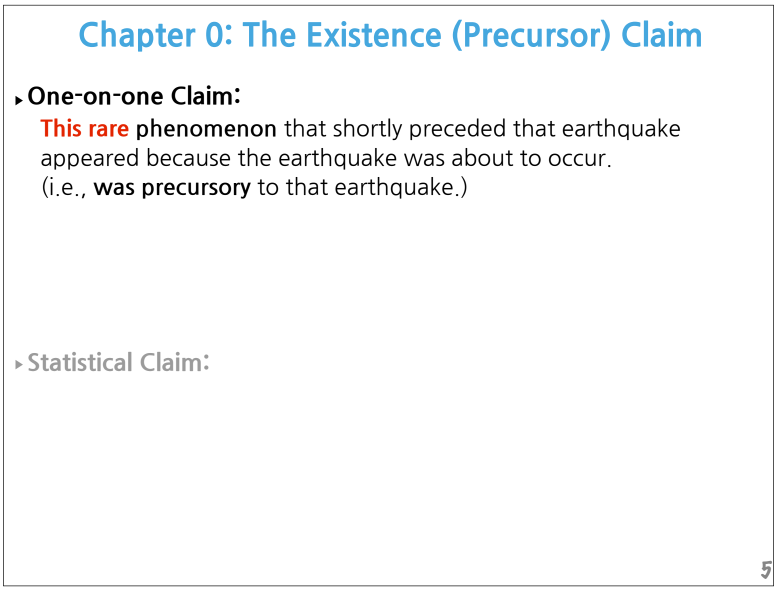


O.K, but I have to start with your concern first. Many legitimate scientists, in the mainstream seismology and geodesy, well, JGR-solid people, are mostly non-believers. They are skeptical about the existence of short-term precursors. So, this question, "Do such things as earthquake precursors really 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)



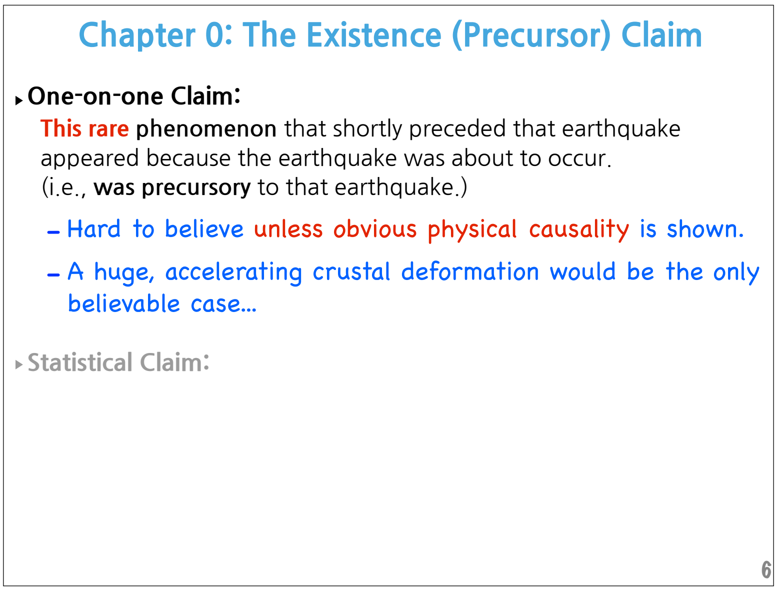
Do precursors really exist? A big problem here is that most people, believers and non-believers alike, do not understand one simple point. “What is the exact proposition of the existence claim?”

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



One-on-one claim says “This rare phenomenon that shortly preceded that earthquake appeared, because the earthquake was about to occur. Claims in 70s, 80s, were mostly of this type.

Our special invitee, Dr. Max Wyss, sitting over there, used to be the chief IASPEI special investigator of “real precursor award.” 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 disregard. (50-)



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)

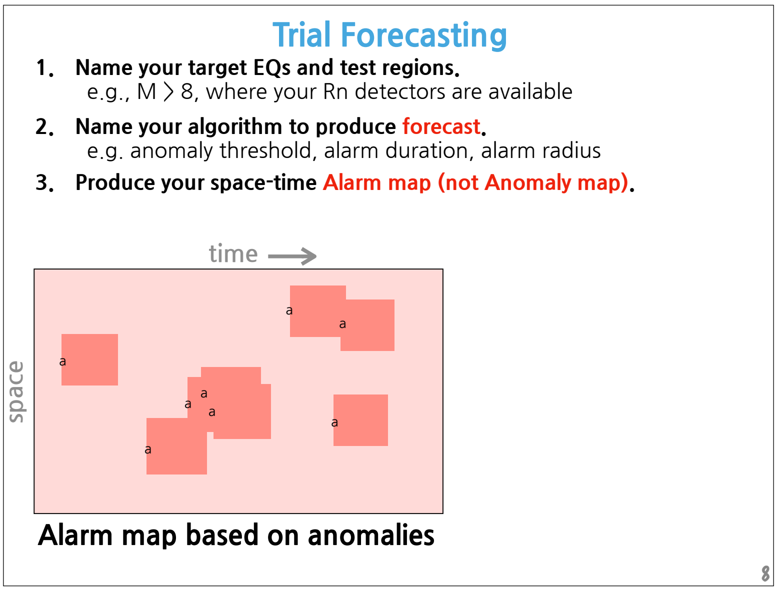
Chapter 0: The Existence (Precursor) Claim

- **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.

7

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)



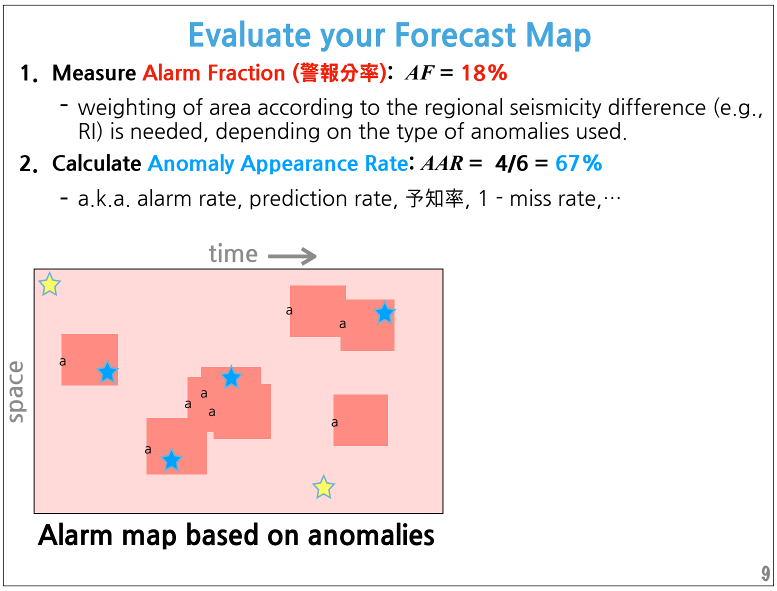
O.K. Trial Forecast. How to do that.

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.

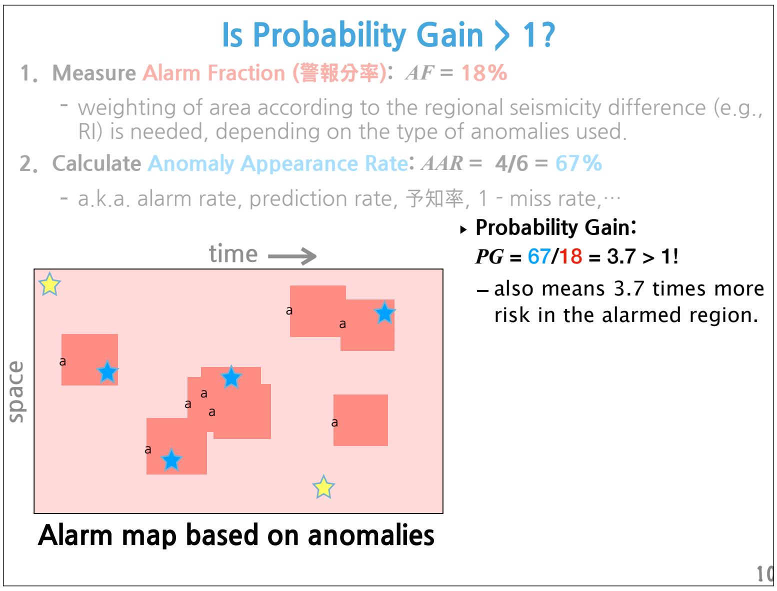
Remember, you need to make forecasts. Anomalies themselves cannot be evaluated; Precursory claim includes the time lag and spatial offset between anomaly and hypocenter. Please submit as a forecast. (46)



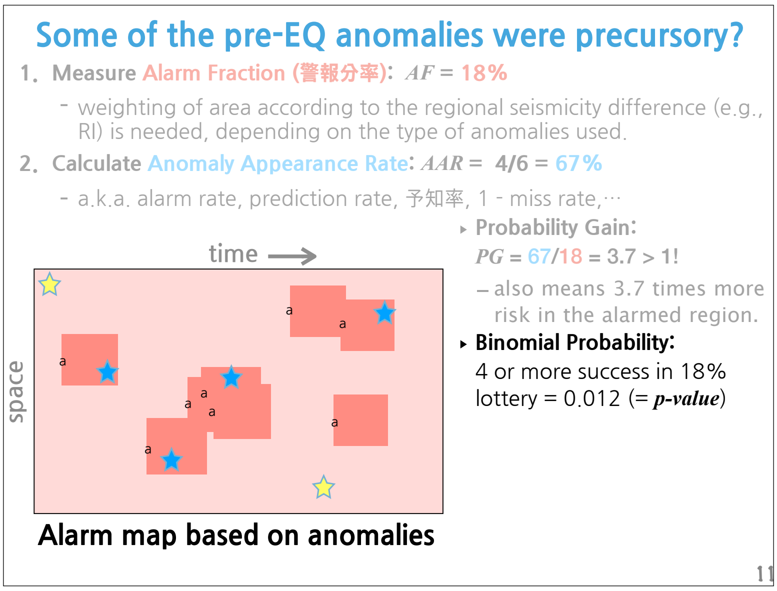
Now, let's evaluate. We only need two numbers.

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)



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)



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.

12

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}

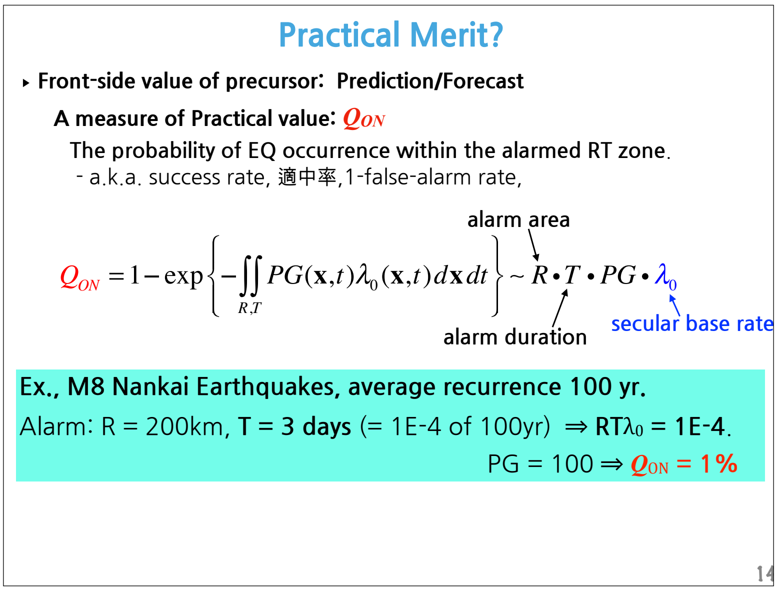
  The probability of EQ occurrence within the alarmed RT zone.

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

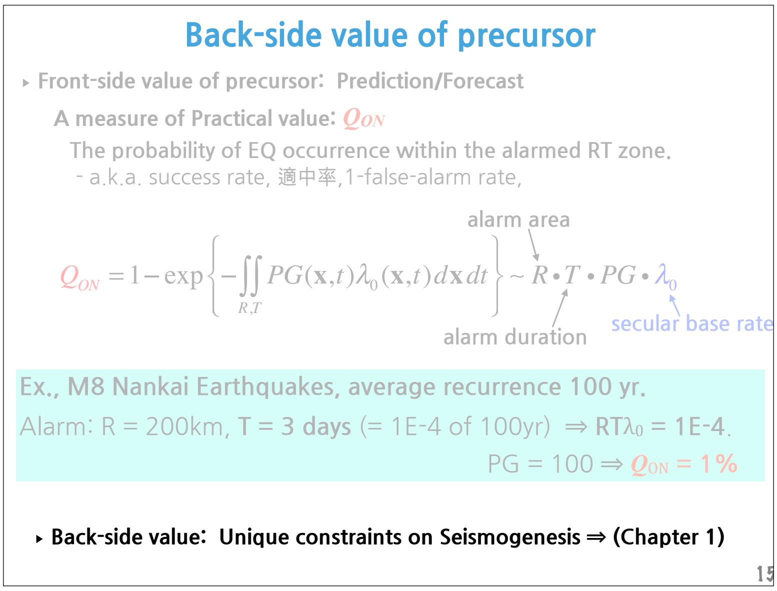
$$Q_{ON} = 1 - \exp\left\{ -\iint_{R,T} PG(\mathbf{x},t)\lambda_0(\mathbf{x},t)\,d\mathbf{x}\,dt \right\} \sim R \bullet T \bullet PG \bullet \lambda_0$$

(R: alarm area; T: alarm duration; λ_0: secular base rate)

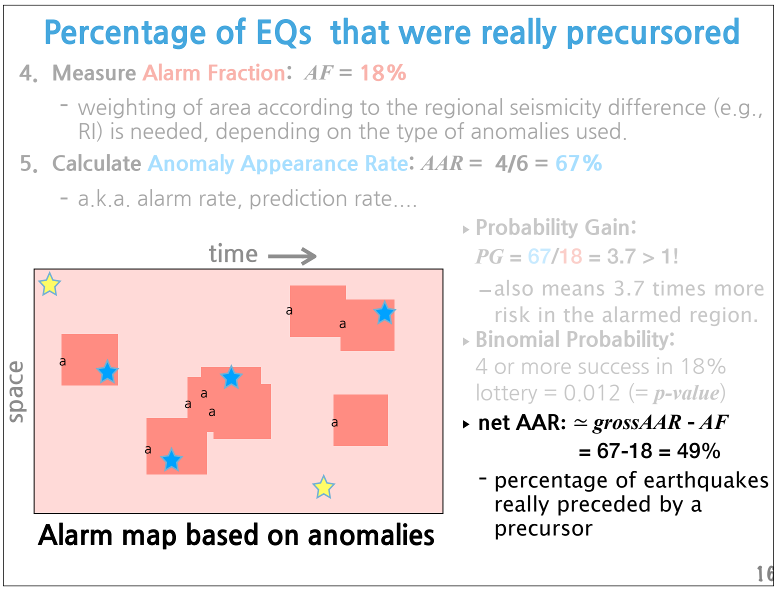
Forecast may have a practical merit. Here, I introduce another measure of forecast Qon, which is the probability that a big earthquake occurs in the space-time zone of your alarm. Let'see. (13)



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)

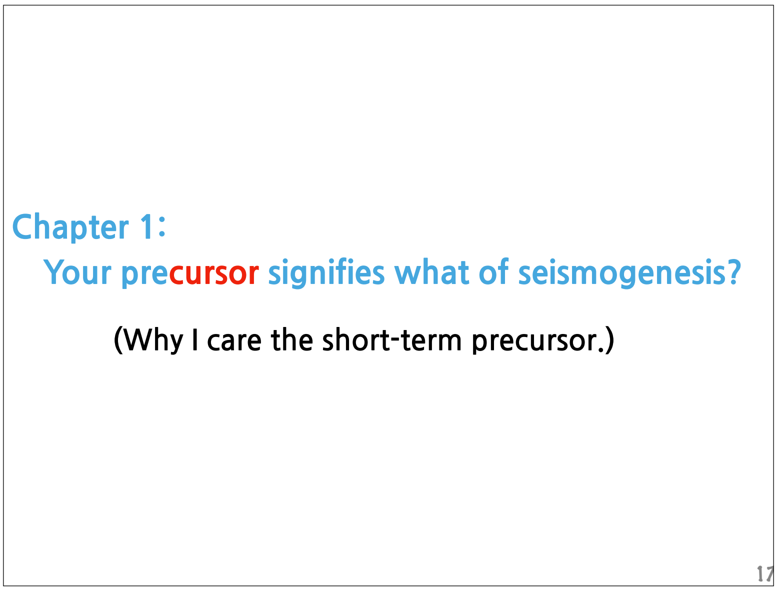


I would rather emphasize an academic value. Precursor should give a unique constraints on Seismogenesis. (6)

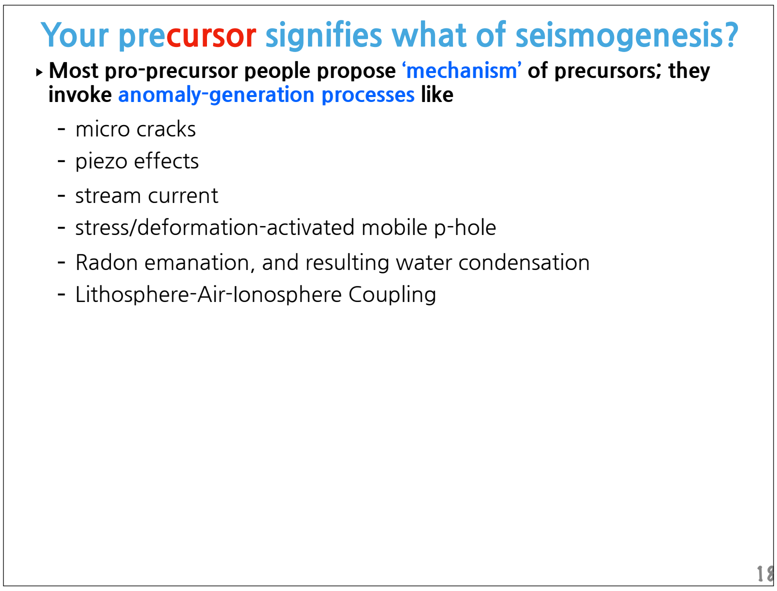


Look at this alarm map again.

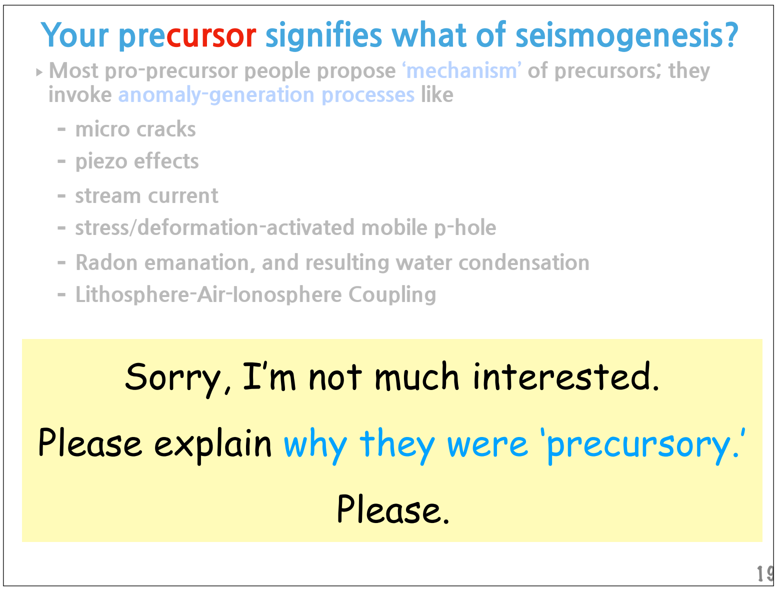
Here, I introduce another performance index, net AAR. The gross AAR was 4/6, 67%. But, chances are, 1 of the 4 successes was a mere coincidence. So, the net AAR is about 67 –18, is 49%. Only 49% of earthquakes are really preceded by precursors. Well, 49% is not negligible at all. Seismogenesis must explain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



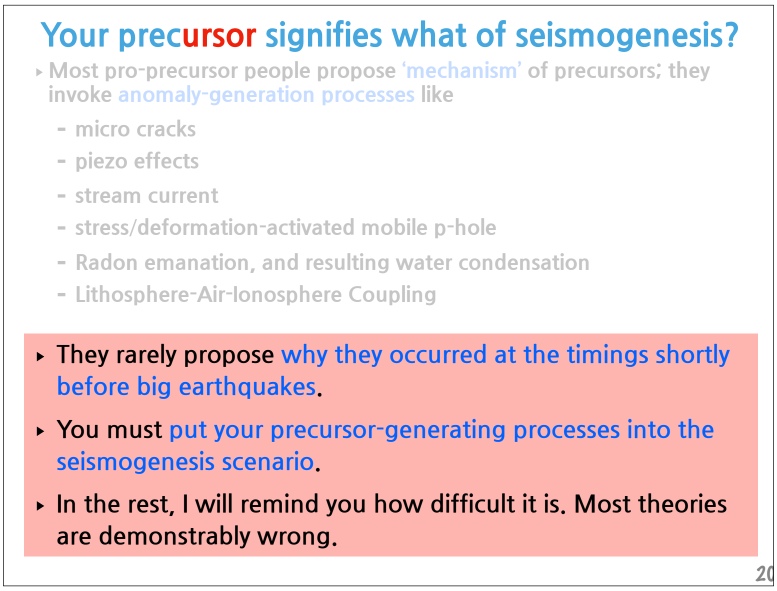
So, chapter 1 begins. Precursor signifies what of seismogenesis? You know, it's precursor of earthquake, so must be signifying something of seismogenesis. (11)



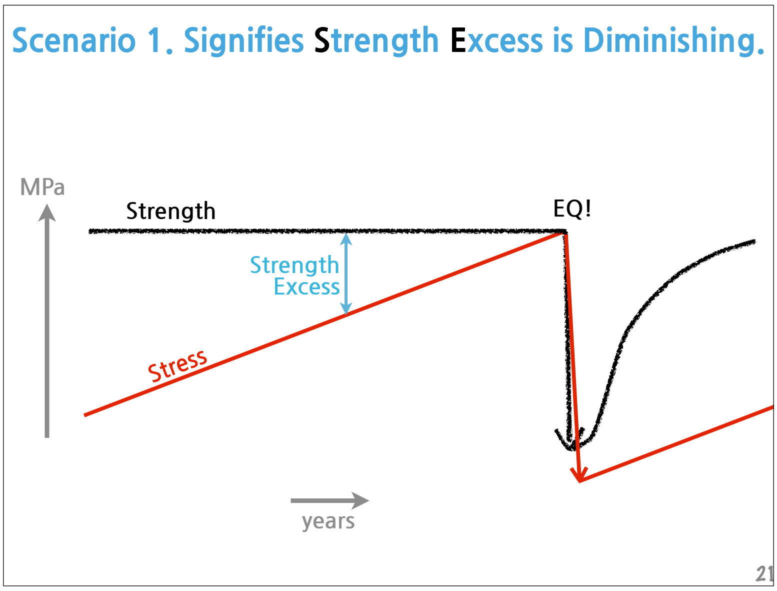
People, especially believers, talk about mechanisms of their precursors. Like micro-cracking, piezos, p-hole, Radon… (9)



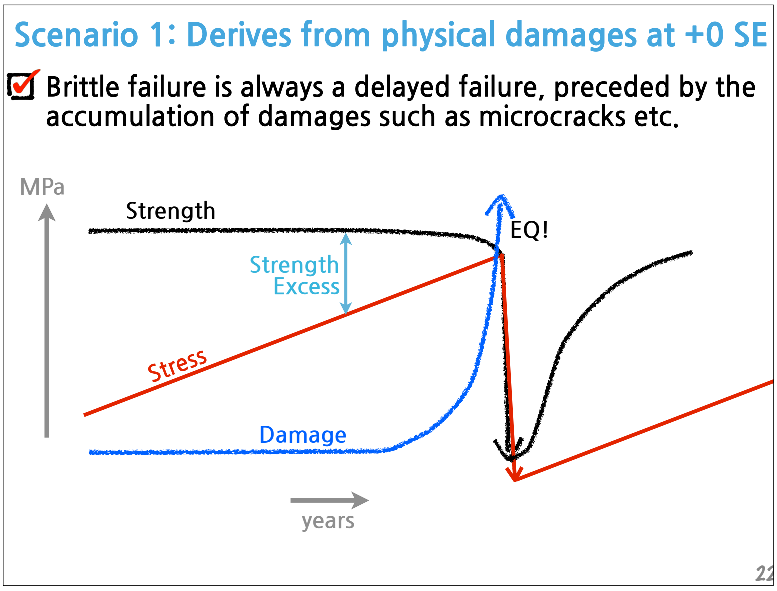
But, sorry, that's not the most pertinent point. We study pre-cursor of earthquake. You must explain why your processes occur just before the earthquakes. Why are they precursory? (12)



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)

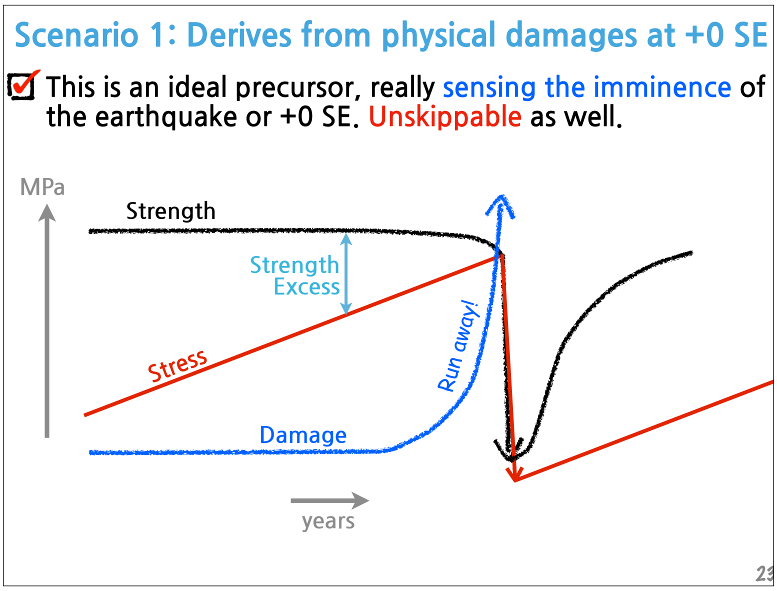


Scenario 1 is very easy. You know, the Reid's earthquake cycle. Stress slowly increases due to tectonic loading, and eventually reaches the strength of the fault, and an earthquake occurs. A brittle failure. (13)



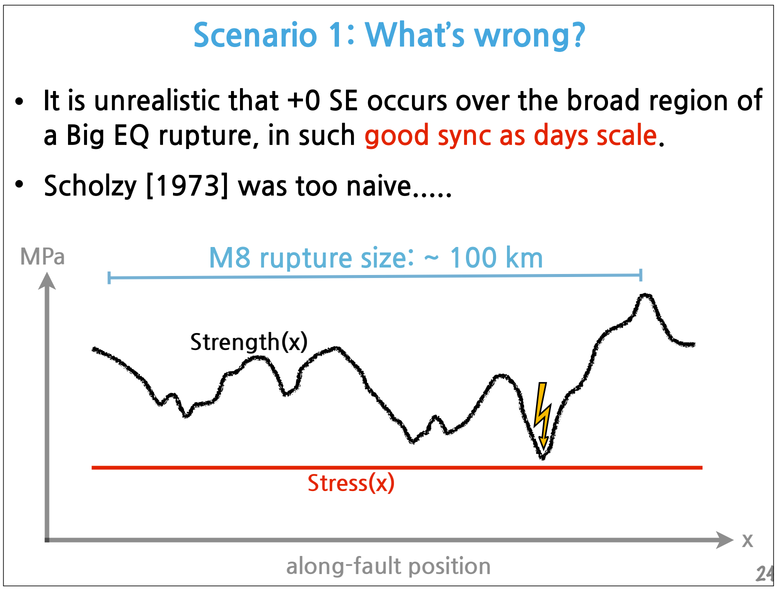
But, the real world is more interesting. Any brittle failure is a delayed failure, and hence, is necessarily preceded by microscopic damage. Lots of them.

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)



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)



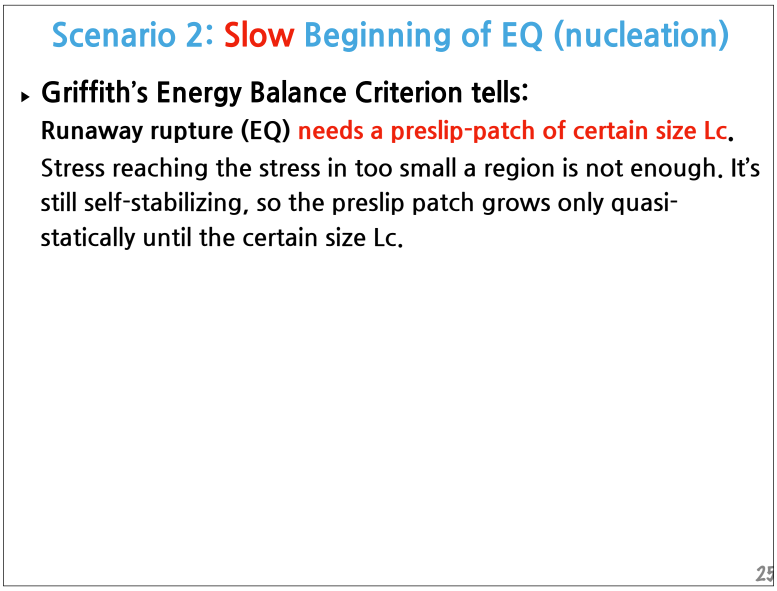
However, as you know, the precursor fever of 70s ended miserably. Many earthquakes occurred without signals from those damage. What's wrong?

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.

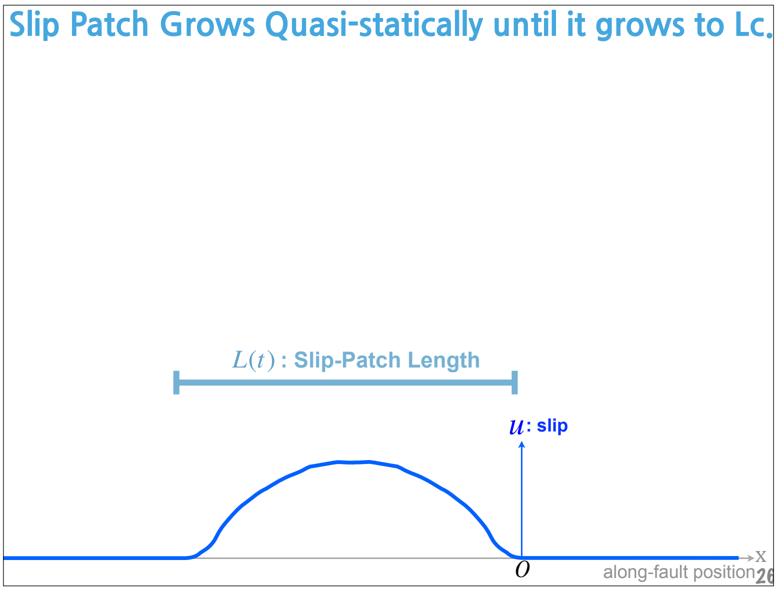
An implicit assumption behind this type of theory is that nearly-zero strength excess is achieved over a broad region along the fault, in such good synchronization of days scale, emitting loud short-term precursors, warning a big earthquake.

Given the heterogeneity of faults, you better forget such an unrealistic scenario. (50)

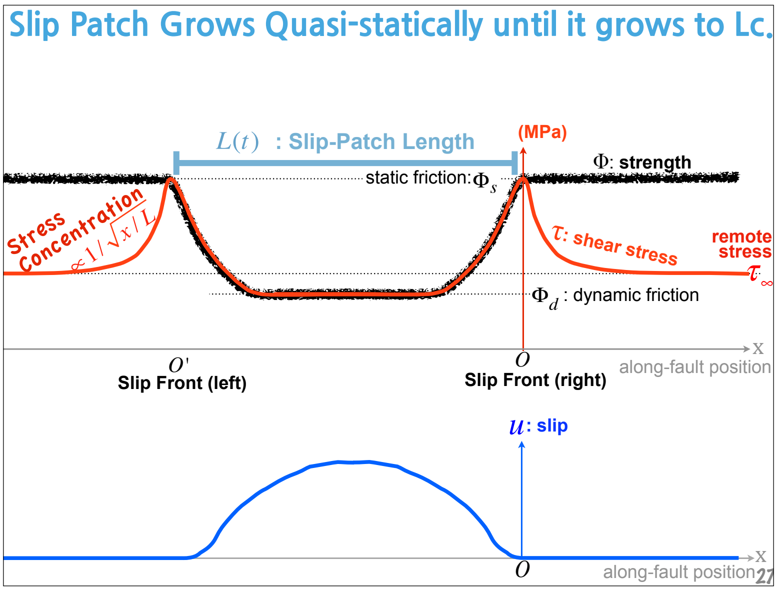


Now, we move to another beautiful scenario called nucleation. The point is, nucleation is the slow initiation of an earthquake, and it occurs only in a limited portion of the big fault that will bump soon.

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)

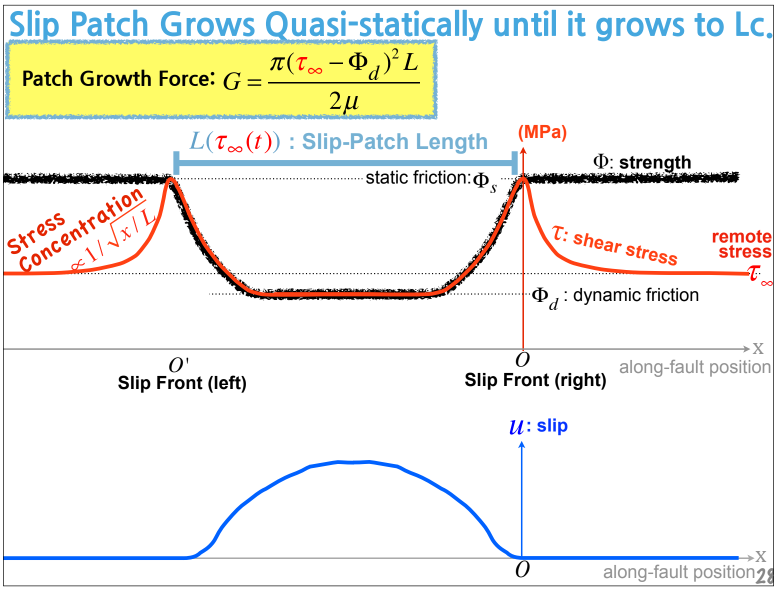


Here, this blue curve is the slip profile along the fault. Only this part, length L, has slipped and released the stress, down to the dynamic friction. Let’s see the stress. (9).



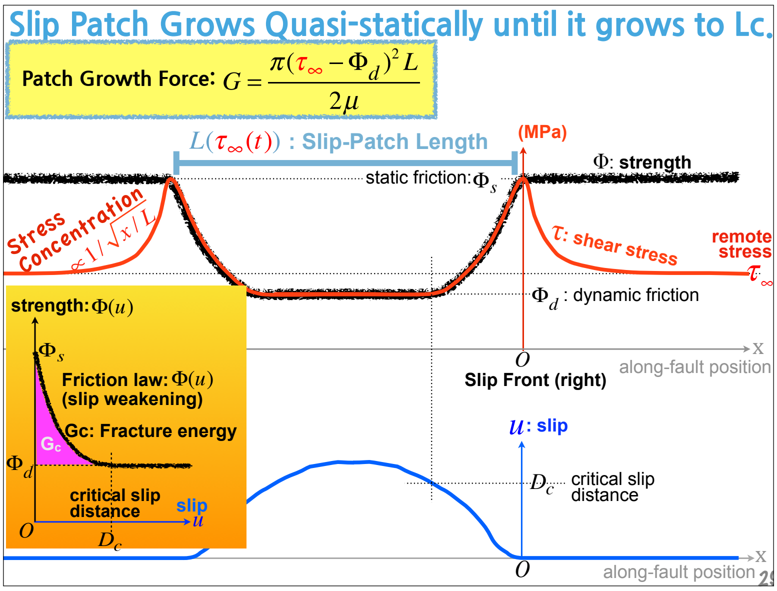
This red curve is the stress profile, and the dynamic friction is here, the low level. Outside the patch, the fault is still locked by the static friction. This creates the stress concentration around the patch front, due to elasticity.

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)

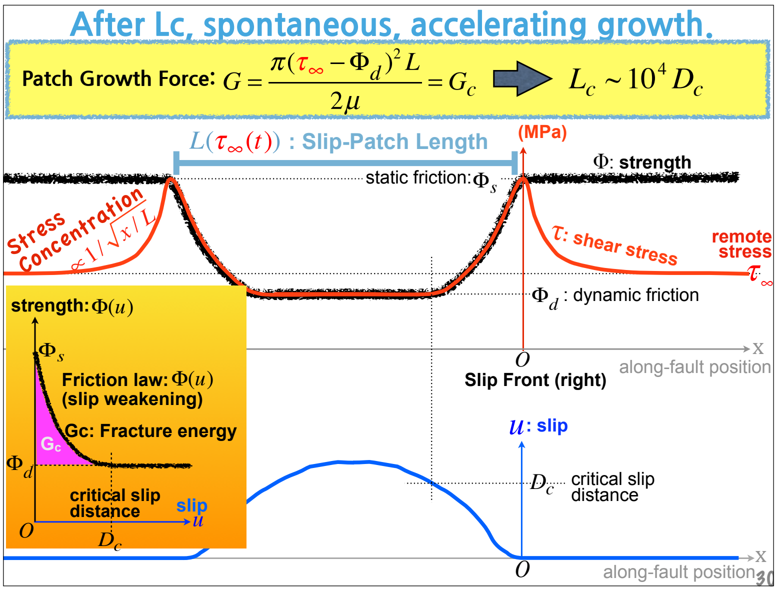


The elastic energy available for patch extension is this G, in the yellow banner. G is proportional to the patch length L. When G is still less than a fault property called fracture energy Gc, the elastic energy released by the advancement of the patch front is less than the frictional loss Gc, so the 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_infinity. So, this is a very slow process.

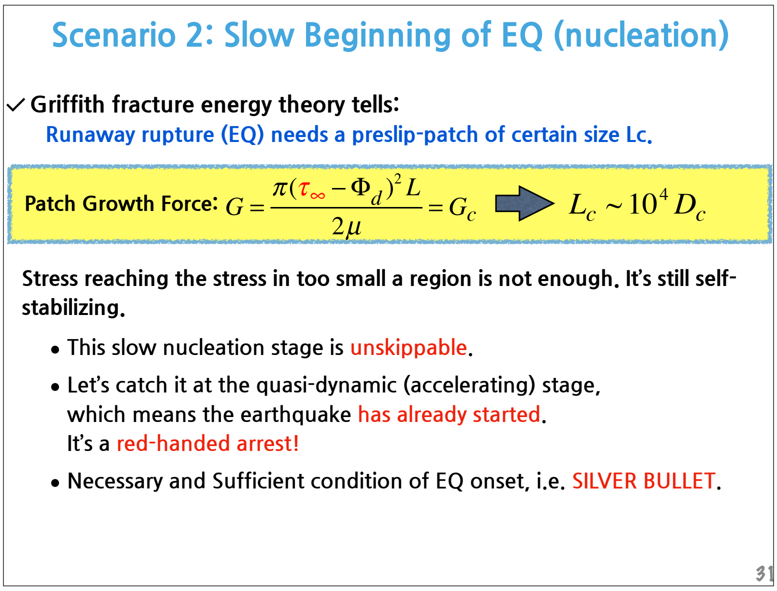
However, one day, L becomes large enough so that G reaches Gc, then, growth becomes spontaneous. (40)



The fracture energy Gc 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. Gc 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 Dc. (23-)

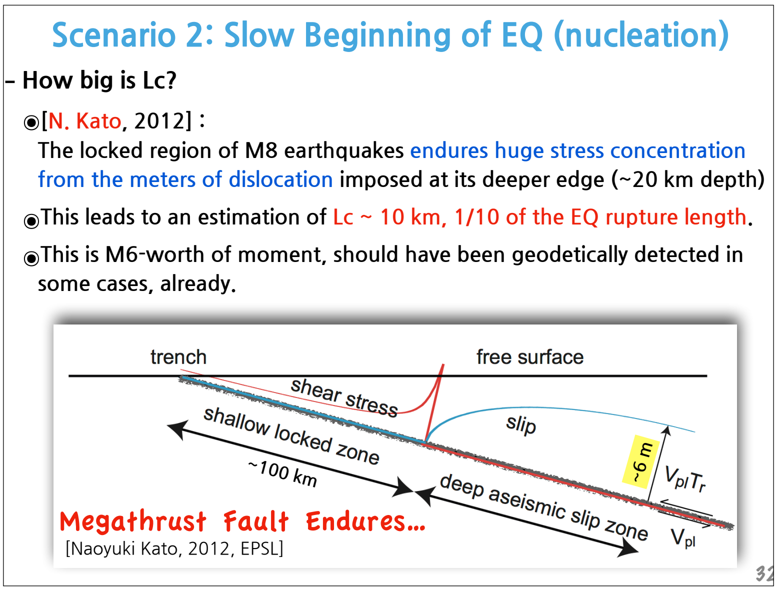


Once the patch has reached Lc, or G has reached Gc, the rest is spontaneous. I mean, the patch grows in an accelerating way due to the positive feedback through the even broader stress concentration as the patch grows further. It does not need help from further tectonic loading. Eventually it becomes 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 Lc, given by the yellow-banner energy balance. With typical stress drop, rigidity and stuff, it is about 10 thoudand times the Dc. (36)



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.

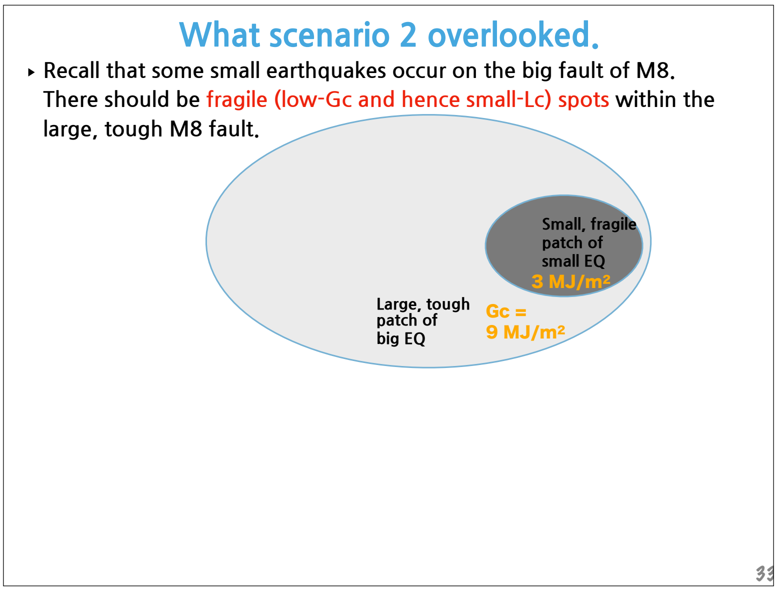
So, how big is Lc? Is it a detectable size? (18)



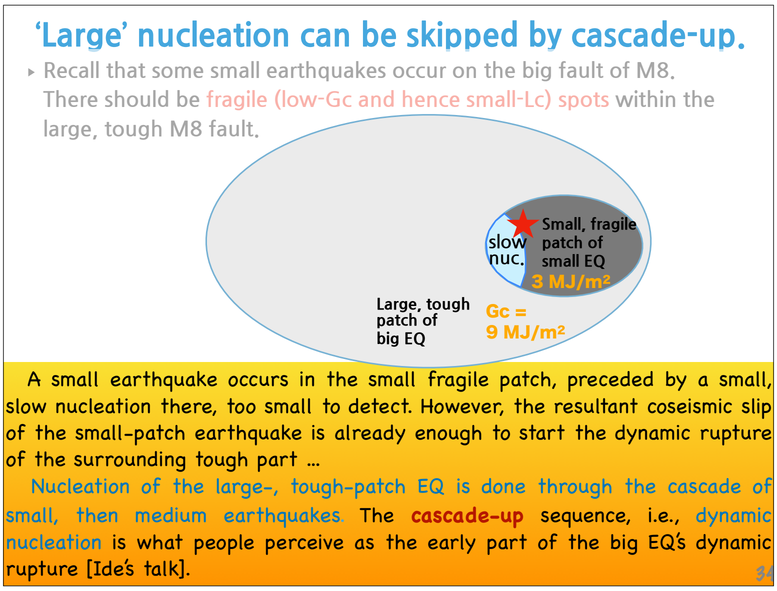
How big is Lc for natural faults? Naoyuki Kato has solved this long-standing problem by a very simple argument. He was like, hey, locked part of M8 megathrust fault endures the huge stress concentration from meters of dislocation, on the creeping down-dip extension. Gc must be big!

So, Lc 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.

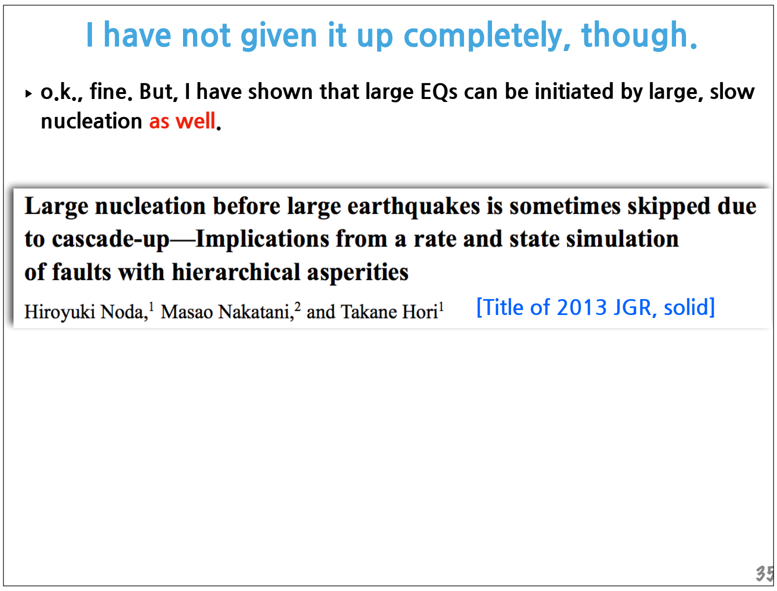
What was wrong with this beautiful nucleation scenario? (41)



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)

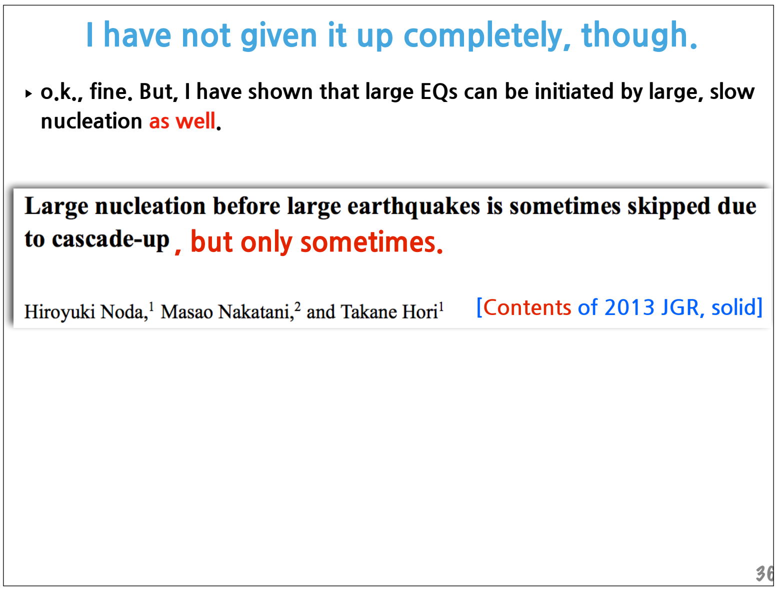


In such fragile, low-Gc spots, Lc is small, so a small earthquake nucleates in secret and then bumps. Now, the coseismic slip patch of the small earthquake is already large enough to overcome the higher Gc around. This is the bloody cascade-up scenario, which crushed all our dreams. Dr. Ide will talk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



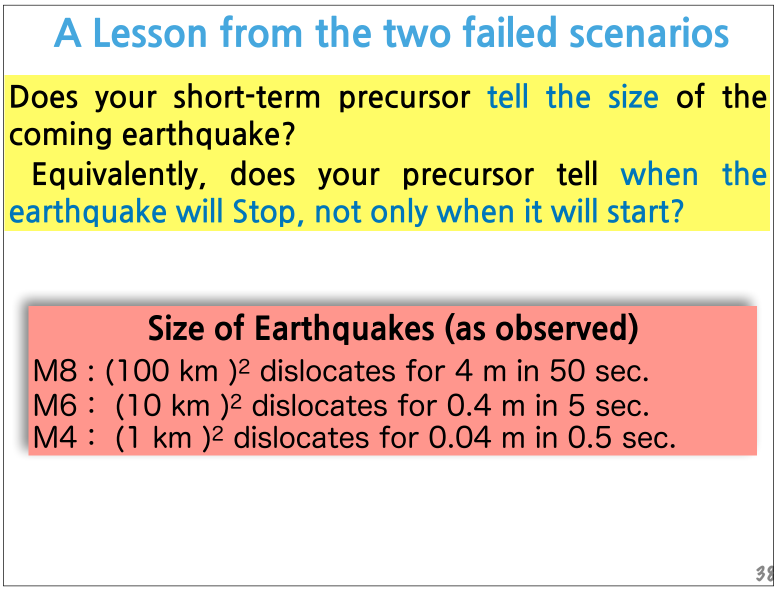
However, the nucleation theory is too good to give up completely. So, I wrote a paper like this. Here's the official title. Reads, "Large nucleation before large earthquakes is sometimes skipped due to cascade-up."

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



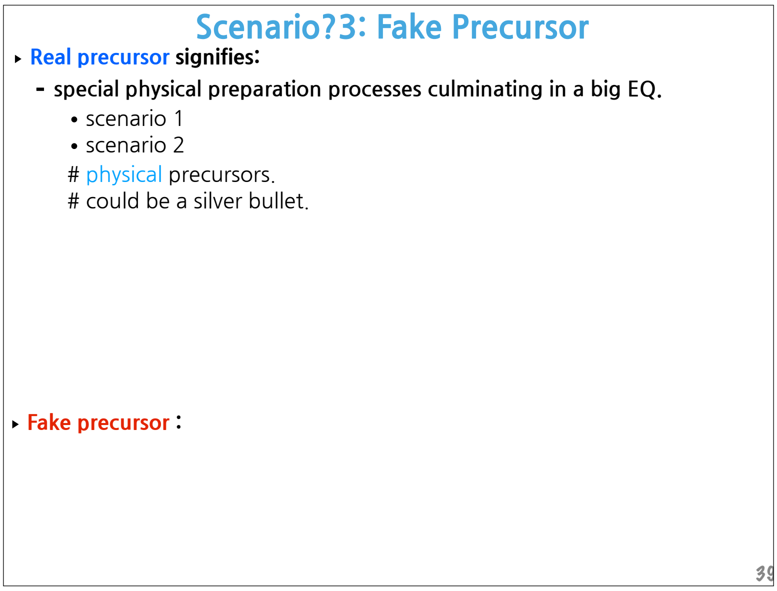
this paper rather emphasizes the opposite. “But only sometimes.” (4)

haha, futile? (2)



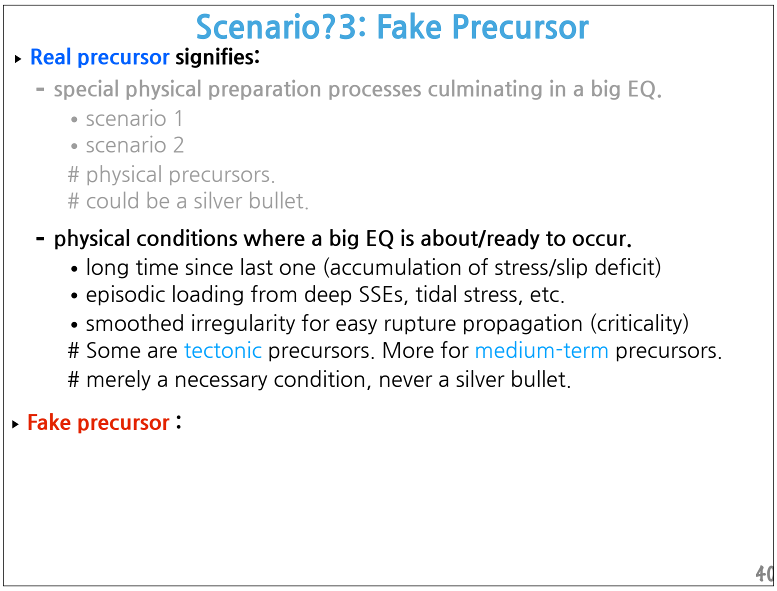
Well, a remark. In a sense, the two scenarios failed for the same reason.
You know, they may tell when the earthquake will start, but they do not tell when the earthquake will stop.

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

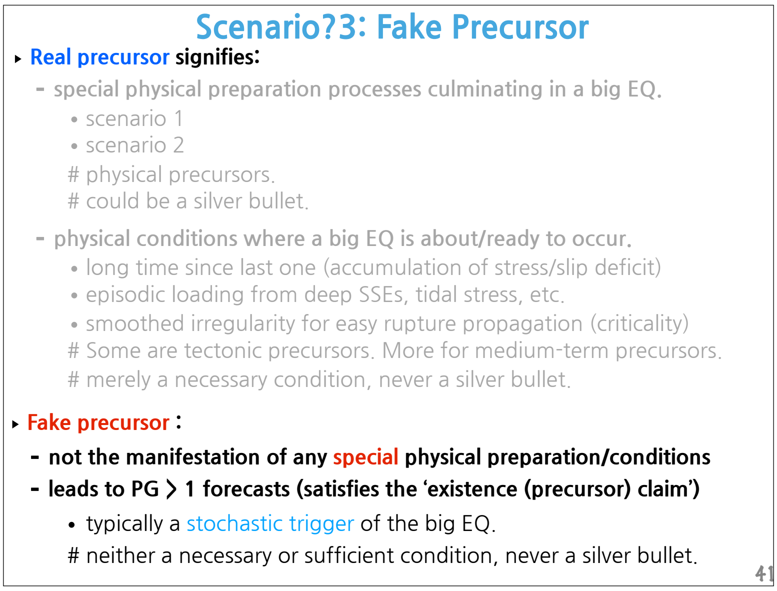


Now I lecture the last topic, which is a real brain twister.

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)

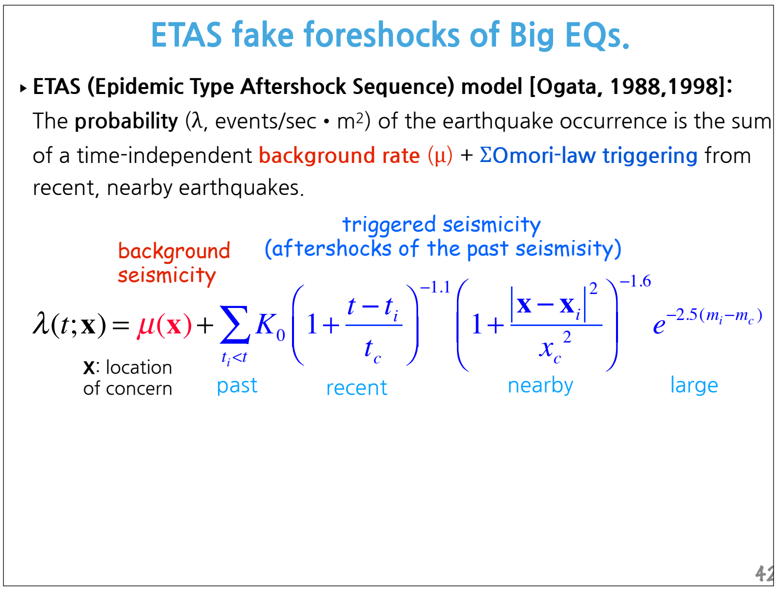


Also, so-called tectonic precursors, typically signifying the regional stress level is high, are real precursors. But, these scenarios are more for medium-term precursors. So, I don't dig in. They signify merely necessary conditions, and hence never make a silver bullet. (17)



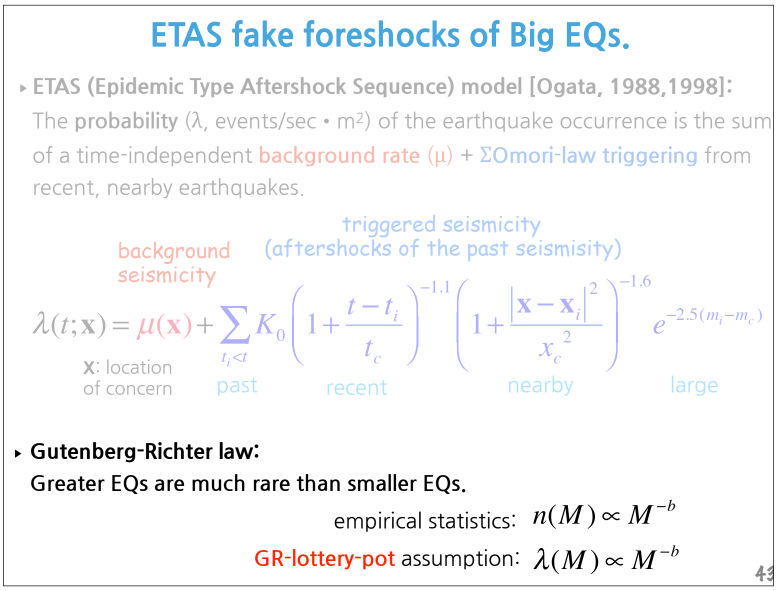
Now, fake precursor. The brain-twister.

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)

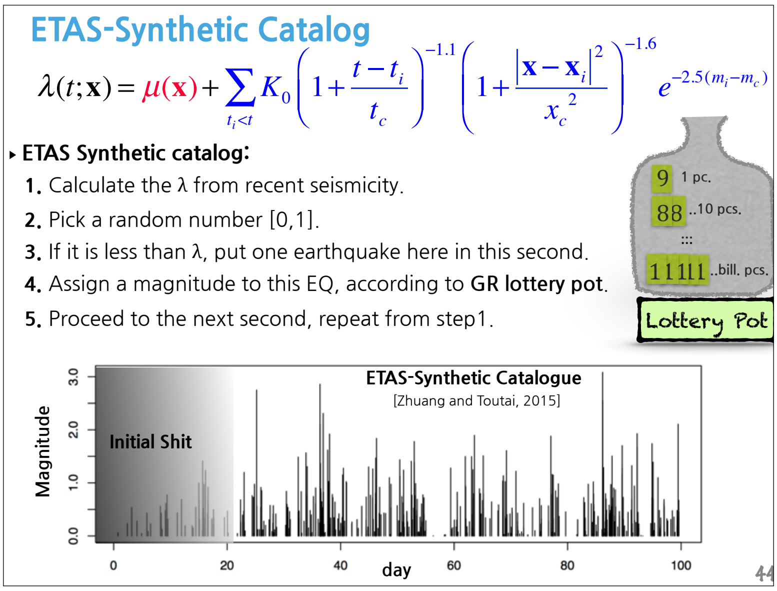


I am talking about foreshocks. We will have 4 talks about foreshocks. I prepare you for their battle in the Highland. Fake foreshocks, appearing in the ETAS synthetic catalog, is the most beautiful, pure pure example of fake precursor.

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)



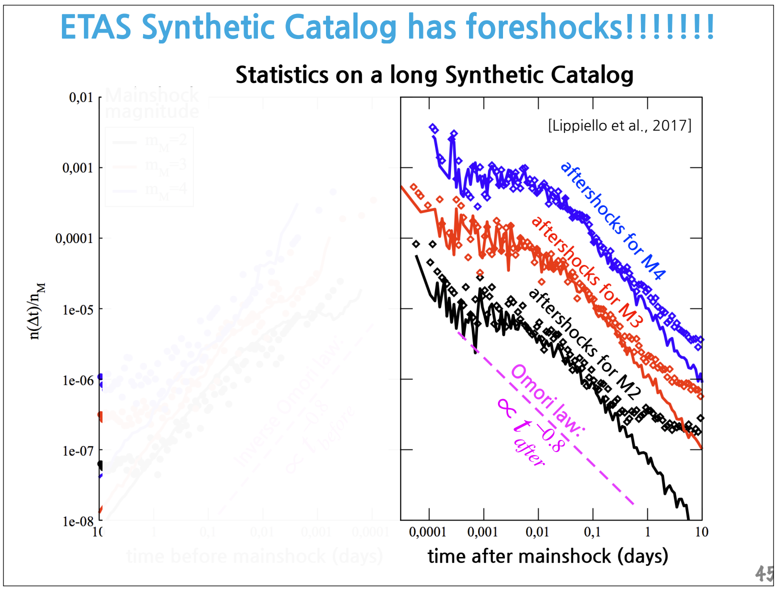
ETAS does not tell anything about the magnitude of the earthquake that will occur, so we assume the GR lottery pot. (6)



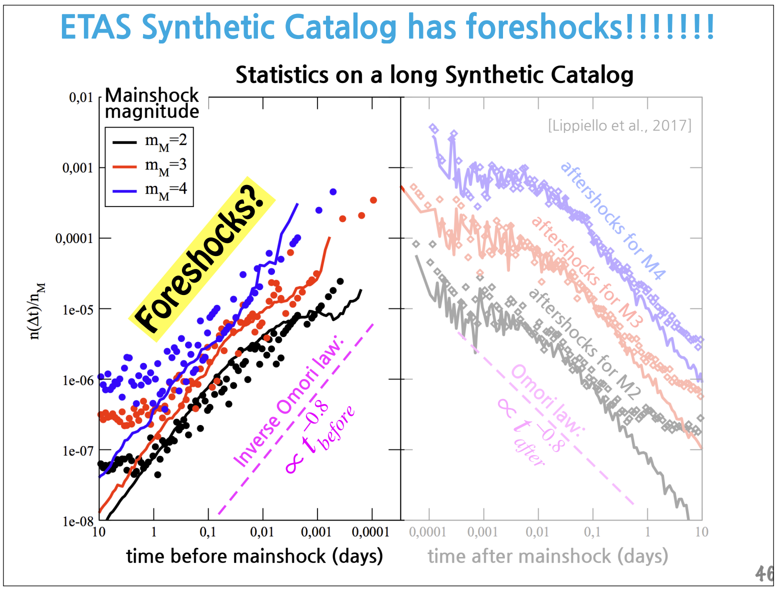
O.K. Let's forge a virtual earthquake catalog, assuming everything is random, except for the sure existence of aftershocks.

Basically, you calculate lamda, 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)

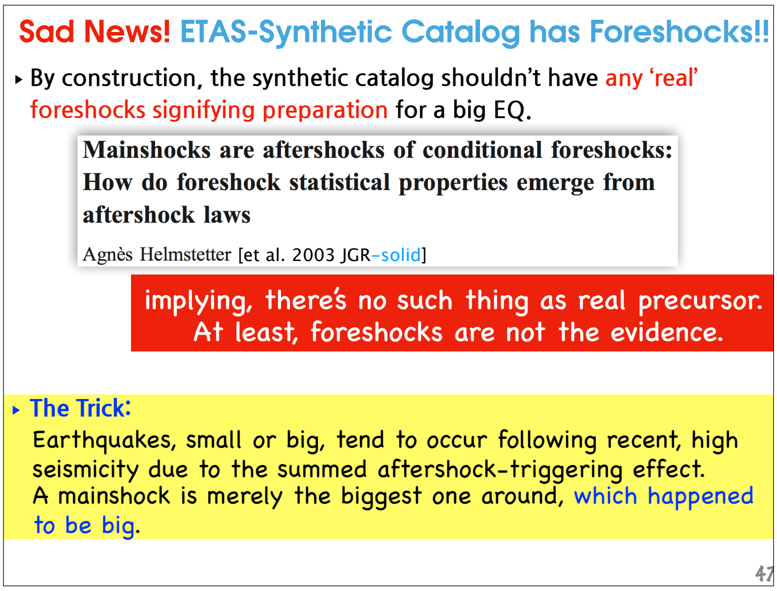


The left half of this figure shows the earthquake occurrence rate before the mainshock.

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

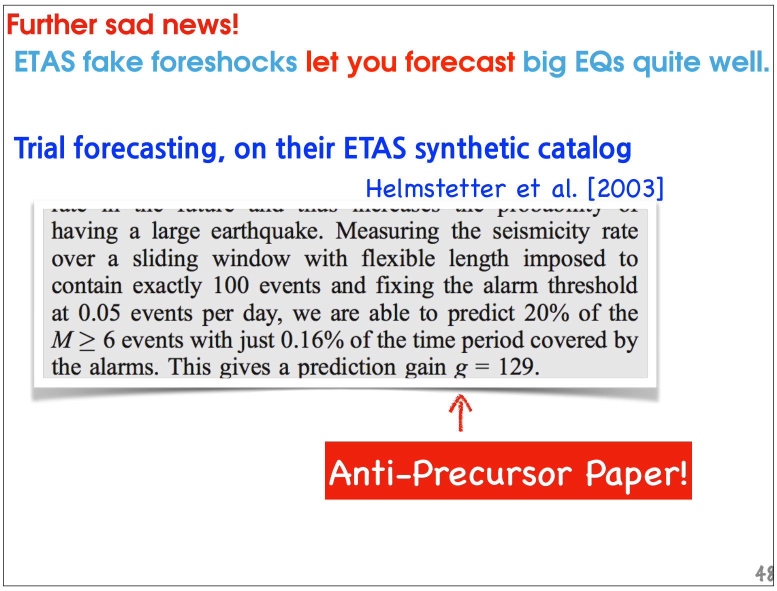
Holly cow, this is a pure pure ETAS synthetic catalog, free from any predictionist sort of mechanisms.

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



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 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+.

49

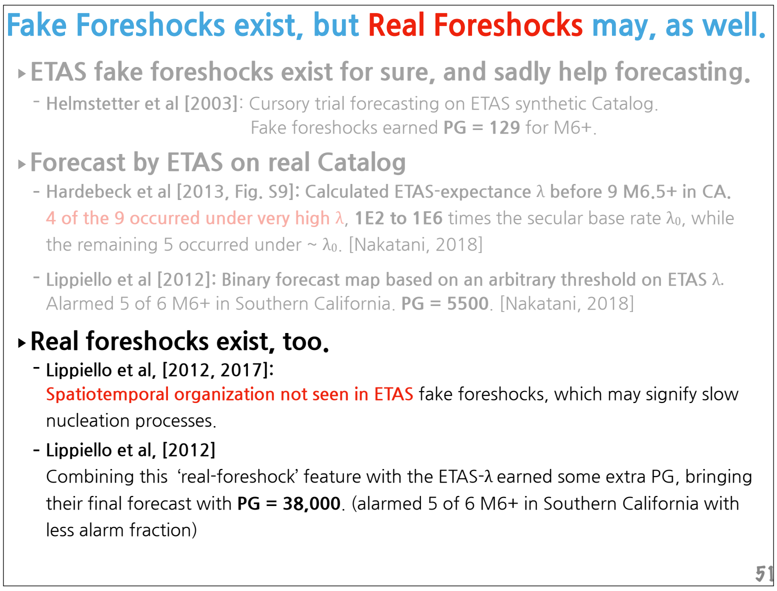
But again, make no mistake! Helmstetter's anti-precursor paper only says that foreshocks to the extent ascribable to ETAS cannot be taken as evidence for real preparation process. (10)

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

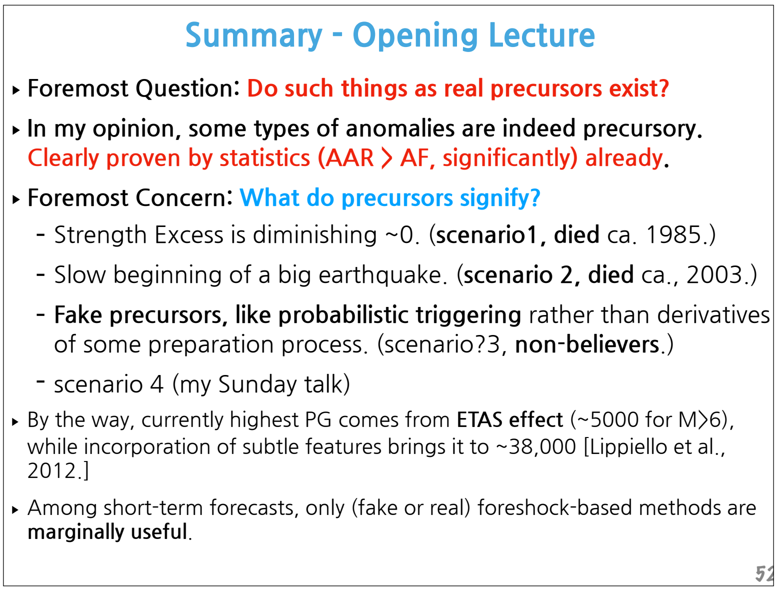
- ETAS fake foreshocks exist for sure, and sadly help forecasting.
  - Helmstetter et al [2003]: Cursory trial forecasting on ETAS synthetic Catalog.
    Fake foreshocks earned **PG = 129** for M6+.
- **Forecast by ETAS on real Catalog**
  - Hardebeck et al [2013, Fig. S9]: Calculated ETAS-expectance λ before 9 M6.5+ in CA.
    4 of the 9 occurred under very high λ, **1E2 to 1E6** times the secular base rate λ_0, while the remaining 5 occurred under ~ λ_0. [Nakatani, 2018]
  - Lippiello et al [2012]: Binary forecast map based on an arbitrary threshold on ETAS λ.
    Alarmed 5 of 6 M6+ in Southern California. **PG = 5500**. [Nakatani, 2018]

50

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



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)

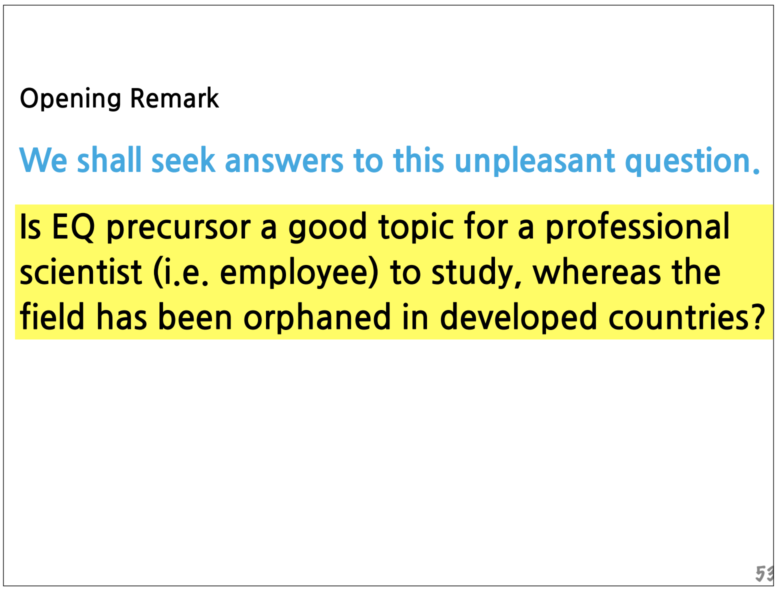


OK. Grand summary.

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)



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-)