

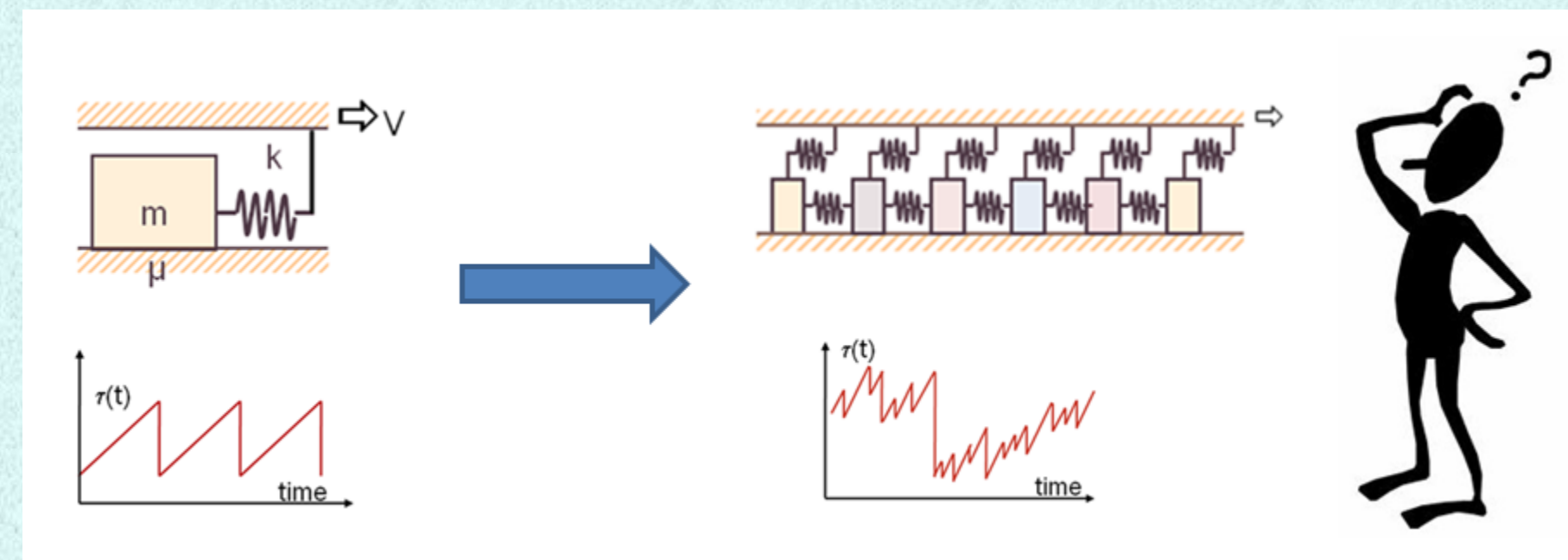
Physics-based simulation of spatiotemporal patterns of earthquake preparation in the Nankai mega-thrust

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Introduction

The characteristic earthquake hypothesis, based on the elastic rebound theory, justifies a time and size predictable model for earthquake occurrence. However, the complex situation of real fault systems may lead to a more chaotic and (almost) unpredictable behaviour, often referred to as a manifestation of self organized criticality.



Even if they cannot substitute the information contained in a good historical catalog, physics-based earthquake simulators have become popular in the recent literature, and their application has been justified by a number of reasons. In particular, earthquake simulators can provide interesting information on which renewal models can better describe the recurrence statistics, and how this is affected by features as local fault geometry and kinematics. In the latest decade new and more complex physics-based simulators have been developed and have acquired a growing interest as a tool for the comprehension and testing of seismic process models.

Algorithm adopted in our earthquake simulator

Here we introduce a new generation earthquake simulation algorithm and its potentiality for modelling both short- and long-term spatiotemporal process of strong earthquakes preparation. A specific seismogenic structure is modelled by quadrilateral faults constituted by thousands of cells of few kilometres size each. The physical model on which the latest version of our simulation algorithm is based includes, besides tectonic stress loading and static stress transfer as in the previous versions, also the Rate & State constitutive law. The simulator code can be run on a relatively modest computer and is capable of simulating thousands years of seismic activity producing catalogs of tens of thousands events in a wide range of magnitudes. The resulting synthetic catalogs exhibit typical magnitude, space and time features, which are comparable with those of real observations.

The Nankai Mega Thrust

In this study we apply the simulator code to a physical model of the Nankai mega thrust, a well-known seismic structure 650 km long, aligned with the Pacific Ocean coast of Southern Japan, which generated several earthquakes of magnitude larger than 8.0 in the last 13 centuries (Table 1). This structure is typically modelled as subdivided in five main segments characterized by different slip-rates, which can rupture separately from or simultaneously with each other (Figure 1).

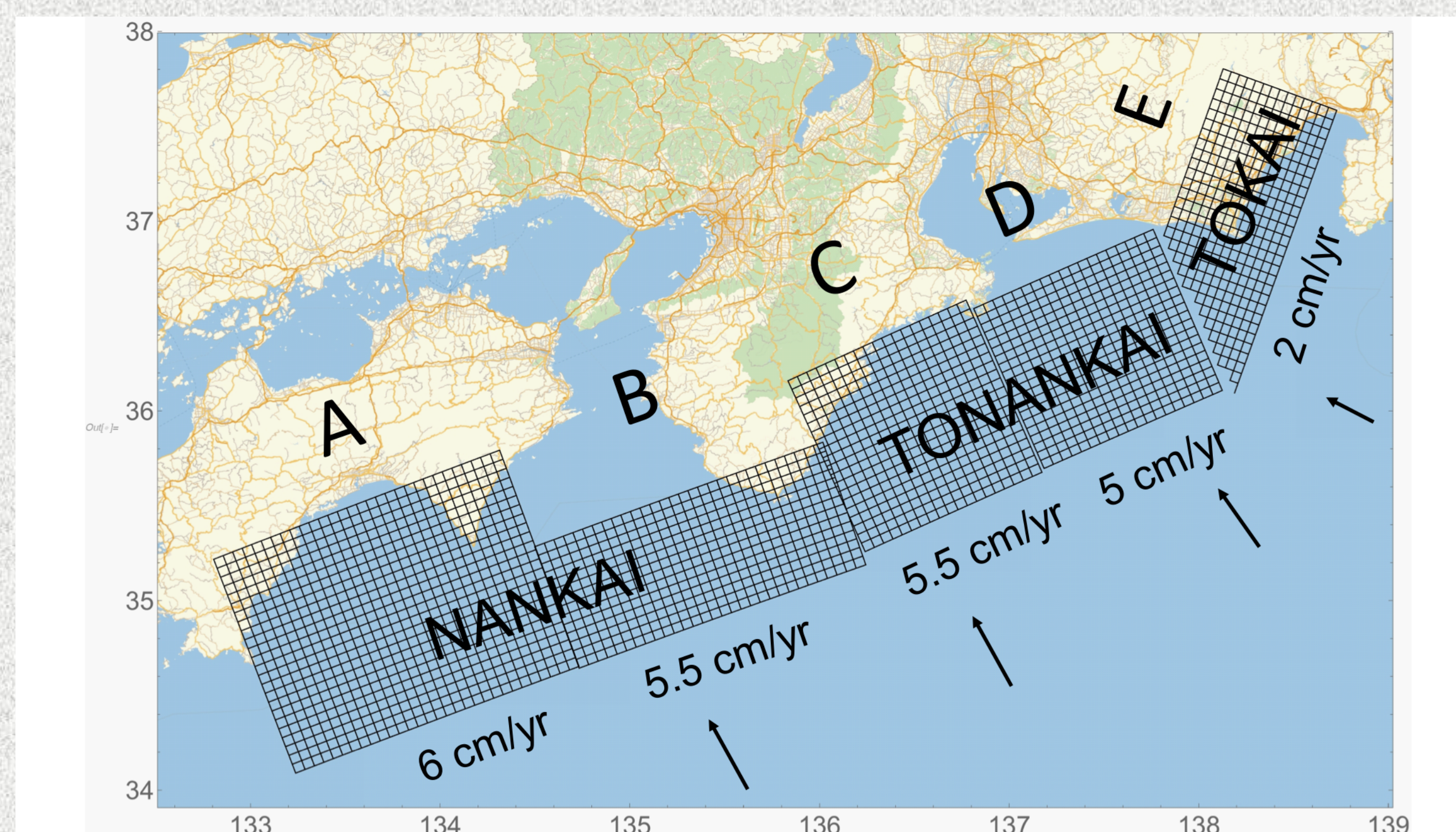


Fig. 1
Simplified model of the Nankai mega thrust. The seismogenic structure is modelled by quadrilateral faults, each of which composed by square cells of 5 km x 5 km.

Features of the synthetic catalogue

We ran the simulator for 3,000 yrs including a warm up period of 1,000 yrs. The 2,000 yrs output synthetic catalogue contains 9,635 events of magnitude ranging from 5.6 (earthquakes rupturing only two cells) to 8.48 (an earthquake rupturing 1,838 cells of segments A-D). Table 2 displays some of the main features of the synthetic catalogue and Figure 2 shows its magnitude distribution.

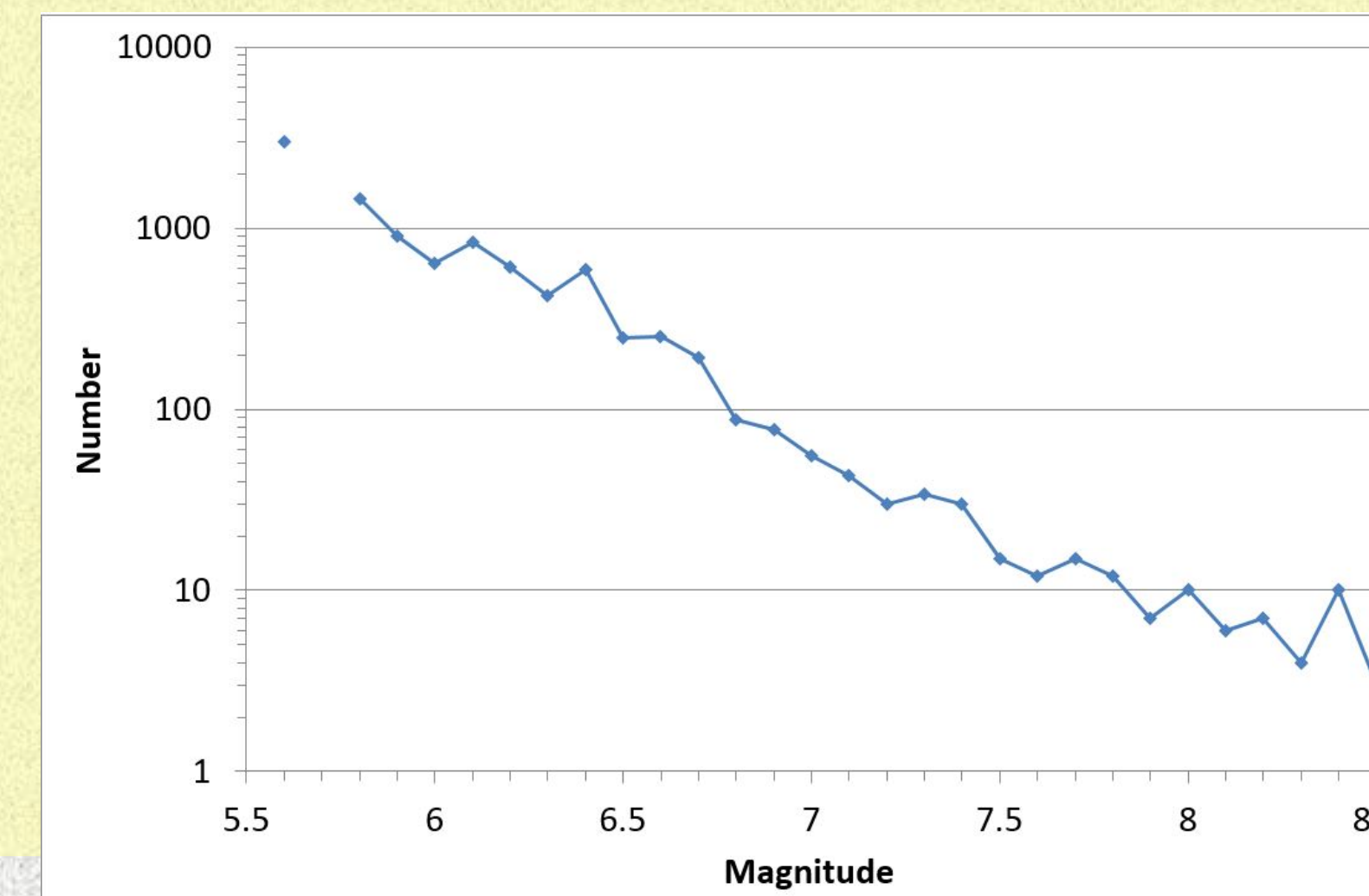
Table 2

Features of the 2,000 yr synthetic catalog

Number of earthquakes of $M \geq 6.0$	4,182
Number of earthquakes of $M \geq 8.0$	40
Maximum likelihood b-value ($M \geq 5.6$)	1.08
Largest magnitude	8.48
Annual seismic moment M_0 ($M \geq 4.0$)	$1.51E+20$ Nm/yr
Number of earthquakes of $M \geq 8.0$ rupturing only one segment	7
Number of earthquakes of $M \geq 8.0$ rupturing at least two segments	26

Fig. 2

Frequency magnitude distribution of the 2,000 yr synthetic catalog



The stress history on the seismogenic structure

As the simulator algorithm allows computing the stress on all the cells constituting the seismic structure adopted in the model, we may build up the stress history on each cell and display it in a sort of animation (Figure 3).

Fig. 3 Stress time history on the Nankai seismogenic structure for the first 76 years

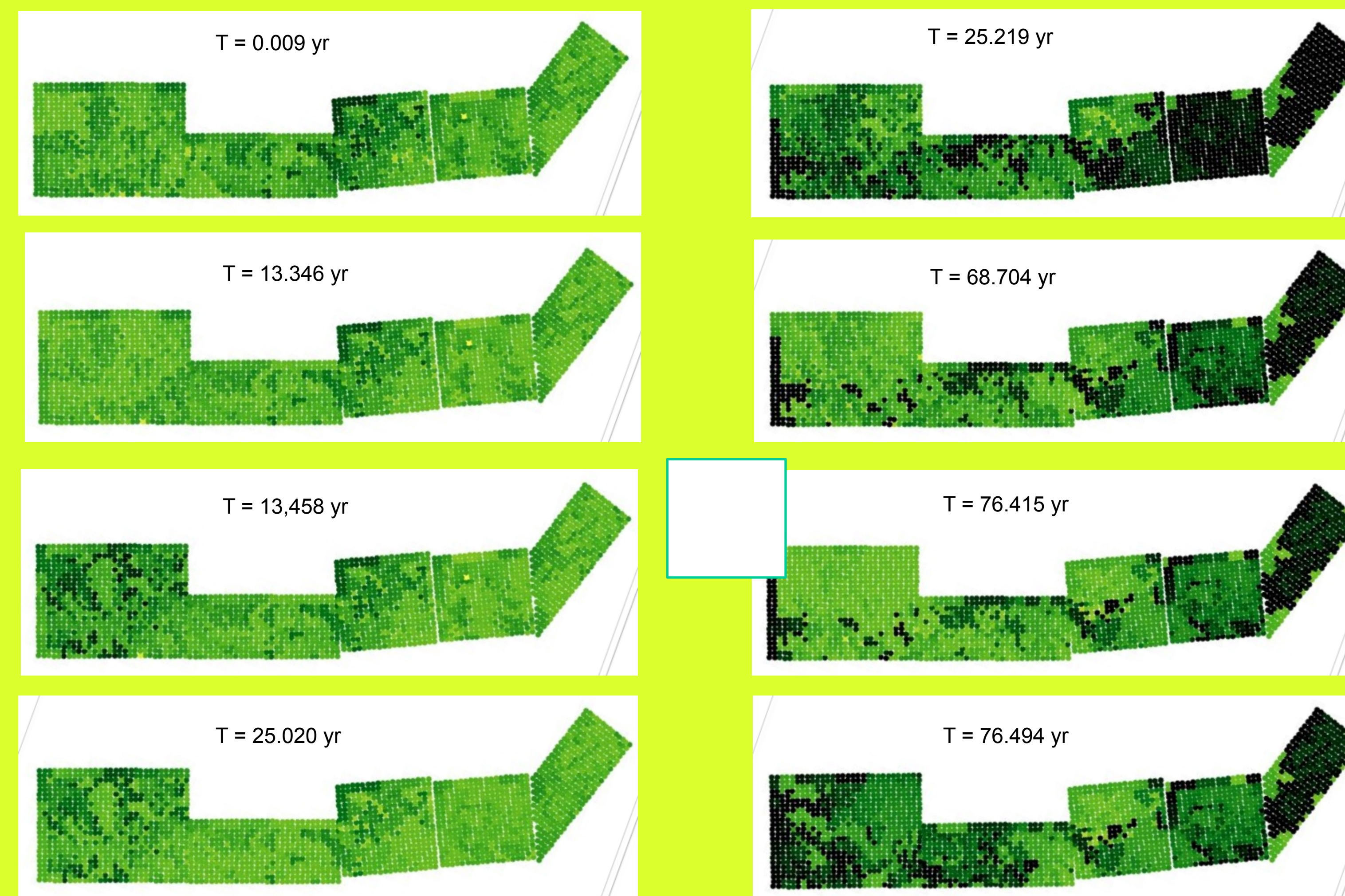


Table 1

List of observed or argued mega-earthquakes that ruptured two or more segments of the Nankai mega-thrust. (From Parsons et al., GJI 2012)

Year	Segments
684	AB or ABCD or ABCDE
887	AB or ABC
1096	CD or CDE
1099	AB
1361	AB or ABCD or ABCDE
1498	CDE or ABCDE
1605	ABCD
1707	ABCDE
1854	CDE
1854	AB
1944	CD
1946	AB

Link to the full animation of the above 2,000 yr stress time history (smartphone viewable)



Link to a zip archive of Wolfram CDF interactive visualiser of the same history (needs free Wolfram Player)



A statistical tool for hazard forecast

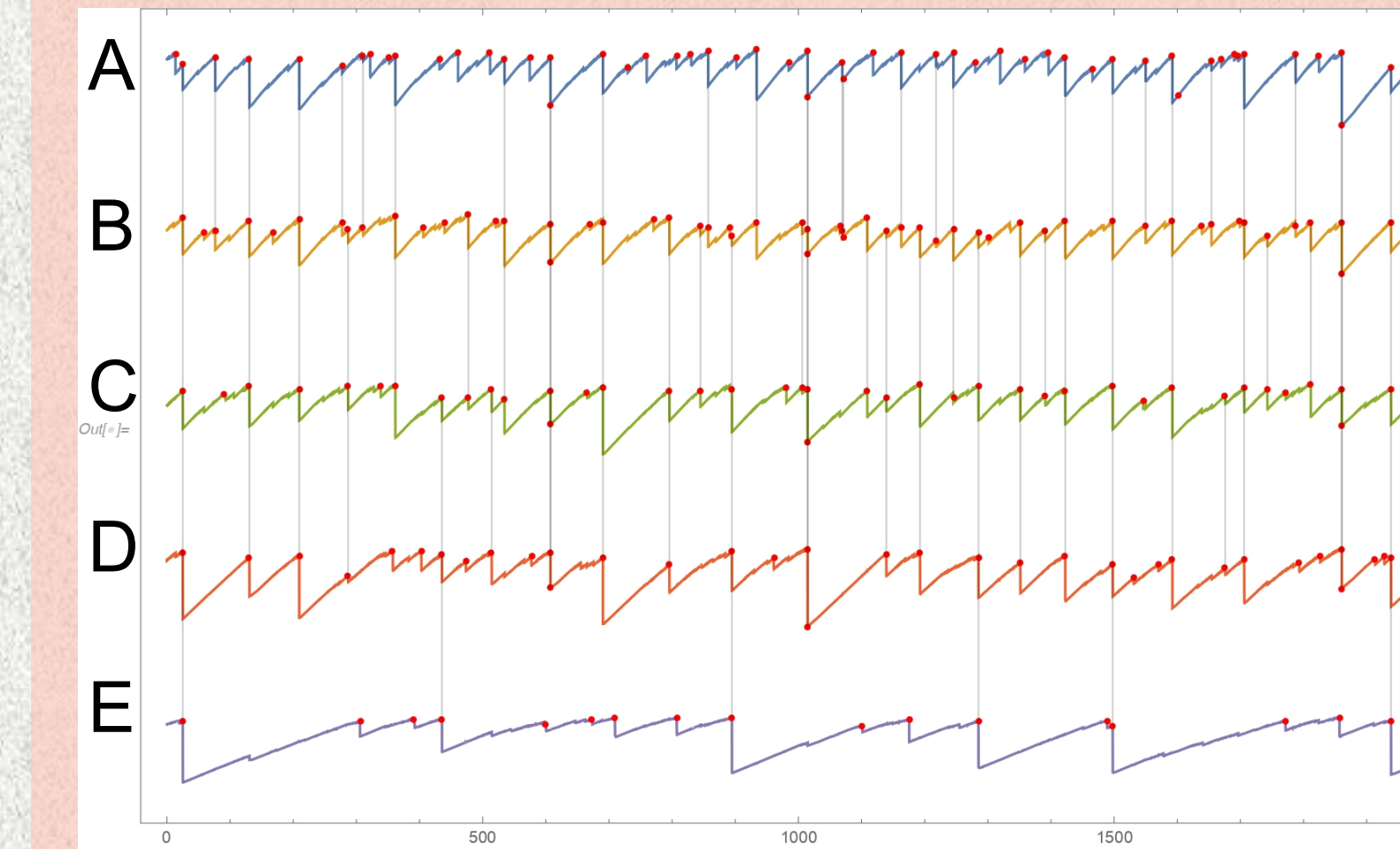


Fig. 4

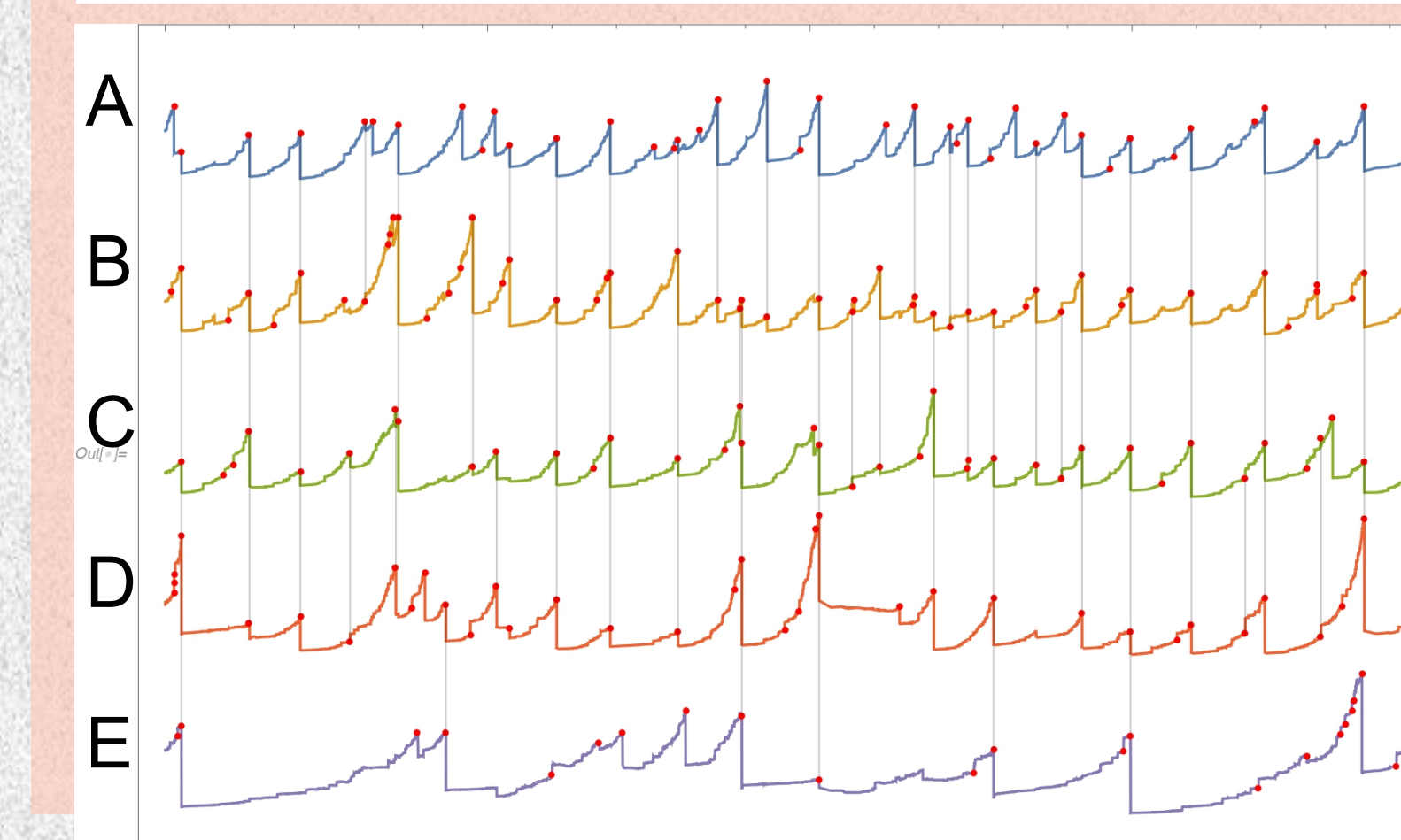
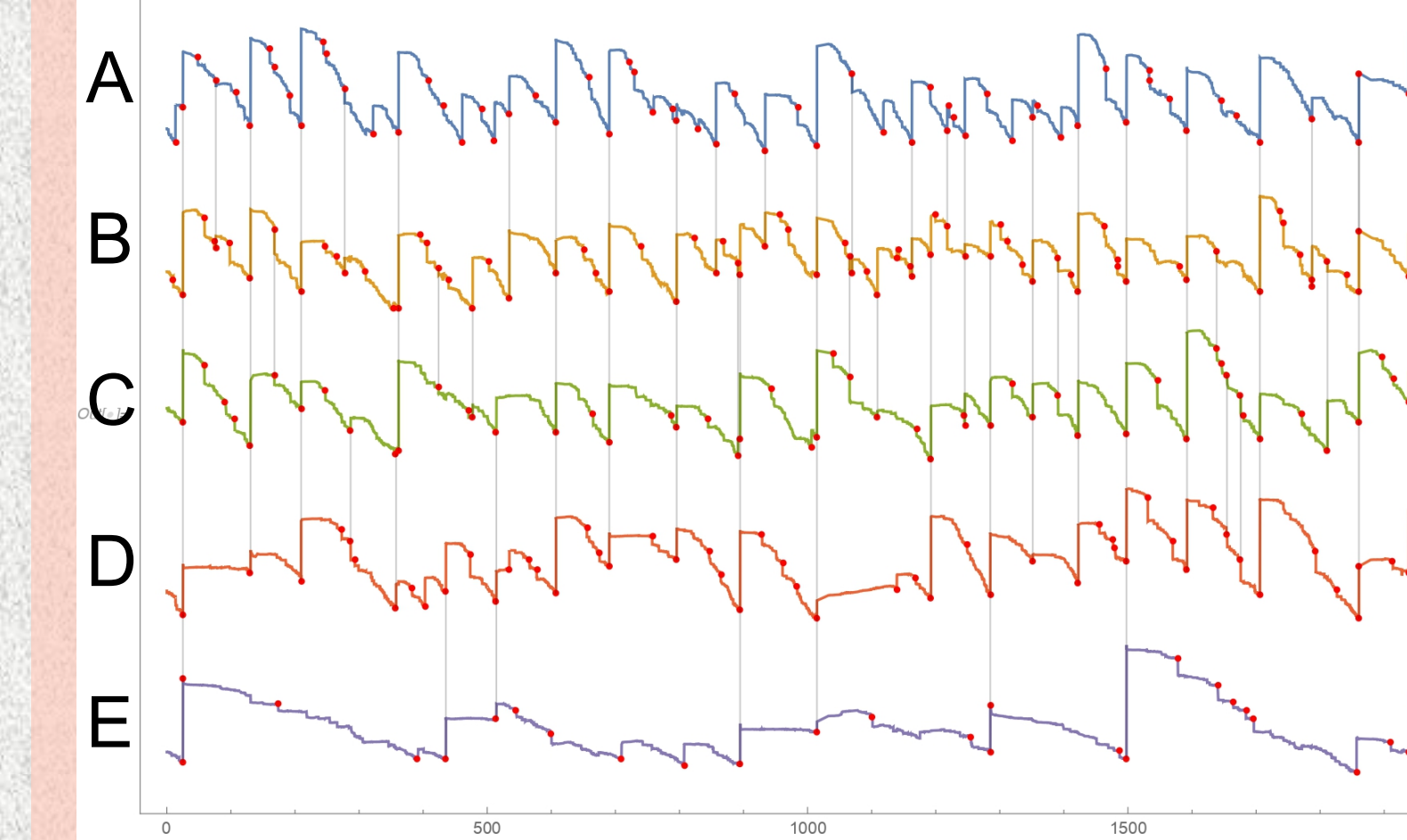
The top panel to the left shows (in a normalized scale) the time history of the average stress computed on all the cells of each segment from A to E in a time span of 2,000 yrs. Vertical bars indicate the occurrence time of earthquakes whose ruptures modified significantly the stress of more than one segment.

The stress increase is due mostly to tectonic loading, but also to stress transfer from the cells of a segment to the others. The average stress drops at the time of each earthquake according to the size of the rupture on the specific segment participating in the earthquake.

Mid panel: the same as in the top panel for the standard deviation of stress on the cells of each segment.

The standard deviation decreases (i.e. the stress becomes more uniform) approaching the occurrence time of earthquakes.

Bottom panel: ration between the values of the average stress and its standard deviation. This parameter increases always and only before a strong earthquake, as a possible tool forecasting large size events.

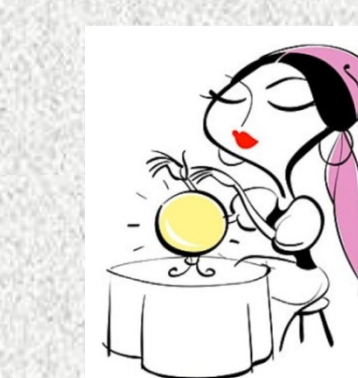


Conclusions

We applied a physics-based earthquake simulation algorithm to the seismicity of the Nankai mega-thrust fault system. The 2,000 years synthetic catalogue contains 9,635 $M \geq 5.6$ events with a maximum likelihood b-value equal to 1.08 (Table 2 and Figure 2). Moreover, the spatiotemporal pattern of large earthquakes exhibits features that are recognizable in real observations (Table 1). For instance, large earthquakes are often caused by the simultaneous ruptures of AB or CD segments, sometimes by the rupture of the four ABCD segments or even by segments ABCDE all together. We note few earthquakes of $M \geq 8.0$ caused by the rupture of one segment only.

In this study we have focused our attention on the time evolution of the stress before, during and after large earthquakes. By means of a specific interactive code, it is possible to follow the stress status of all the cells in the seismogenic system, its long-term increase due to tectonic loading, the stress drop in the cells participating in a rupture, and the stress transfer among different cells (Fig. 3).

In particular, we have quantitatively recognized that the ratio between the average stress and its standard deviation on the cells constituting a specific fault segment always increases with accelerating rate before a large rupture on a part or all of such segment, or even several joint segments (Fig. 4, bottom panel).



One view on the use of computer models for forecasts
There are many methods for predicting the future. For example, you can read horoscopes, tea leaves, tarot cards, or crystal balls. Collectively, these methods are known as "fuzzy methods." Or you can get well-researched facts into sophisticated computer models, more commonly referred to as "a complete waste of time."
(Scott Adams: The Dilbert Future)

