EARTH SCIENCE

Is earthquake rupture deterministic?

Arising from: E. L. Olson & R. M. Allen *Nature* 438, 212-215 (2005)

It is essential in an earthquake early-warning system to be able rapidly to determine the size and location of an earthquake. Olson and Allen[1] claim that the size of large earthquakes (magnitude (M) greater than 5.5) can be estimated from the seismic energy radiated during the first several seconds of fault rupture, implying that the earthquake process is deterministic. But here we analyse waveform data from more than 50 events ($M \geqslant 6.0$) recorded by the Japanese Hi-net seismic network and find no evidence that earthquake magnitude can be estimated before the rupture has completed. This bears on the difficult problem of understanding the physics of the earthquake process[2].

Investigations[1,3] of seismic energy radiated during the initial fault rupture have suggested that the earthquake process may be deterministic, as these data apparently provide an estimate of the size of the event. The method of analysis was to find a velocity spectral peak in the first several seconds of P-wave seismic data. A peak indicates that there is a predominant period, τ_p^{max}, in the seismogram, which was found to scale with earthquake magnitude, suggesting that the magnitude of larger earthquakes can be estimated before rupture has completed[1,3]. For events smaller than about $M = 6.0$, several seconds of P-wave data contain almost the entire history of rupture, and conventional models of the earthquake process[4,5] predict that the spectral peak will scale with magnitude, as is observed[3,6].

For events of magnitude $M \geqslant 6.0$, however, the claim by Olson and Allen that a spectral peak from a short — compared with rupture duration — time series predicts the earthquake's magnitude has necessarily resulted in speculation about the initiation process and the physical state of the fault. The authors suggest[1] that an earthquake develops into a large event if fault slip at the onset of rupture provides enough energy for continued propagation across fault heterogeneities, which could inhibit rupture and thereby result in a smaller event. This large slip would cause a velocity peak in the initial P-waveform data and would scale with earthquake size. It is not clear, however, what mechanism controls the information transfer between the heterogeneities across tens to hundreds of kilometres of fault zone and the initial slip. Also, waveform data have been used to model the fault slip[7] and the largest amount of slip does not necessarily coincide with the location of the initial rupture.

A high-quality seismic network (Hi-net), comprising some 700 stations that have seismometers set in boreholes at depths of more than 100 metres, was installed in Japan after the 1995 Kobe earthquake. In an earthquake-prone country, the ability to predict an earthquake's size ($M > 6.0$) from initial P-wave data would be invaluable in an earthquake-warning system[8], as not only could the hypocentre be located from the P-wave arrival times[8,9], but the (eventual) size could also be quickly estimated.

We analysed Hi-net data for 52 Japanese earthquakes with a magnitude range of $6.0 \leqslant M \leqslant 8.0$, as determined by the Japan Meteorological Agency[10]. For each event, and using the same method of analysis as Olson and Allen[1], we calculated the predominant period, τ_p, in the velocity spectrum of the P-wave arrival data from the five stations closest to the earthquake and then found the maximum value, τ_p^{max}; these values were then averaged (Fig. 1). No trend is evident in Fig. 1 as the correlation coefficient is not statistically significant and the probability of a chance occurrence is high. Our results show that the eventual size of Japanese earthquakes in this magnitude range cannot be determined from

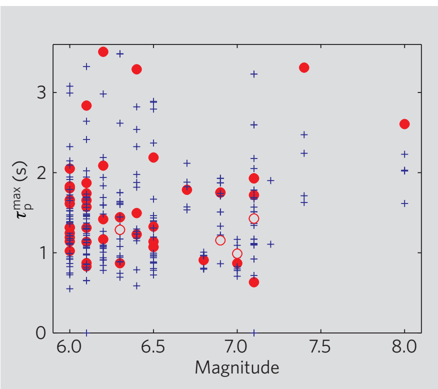

Figure 1 | Plot of τ_p^{max}, the peak value of the predominant period in P-wave arrival data, versus magnitude for large ($M > 6.0$) earthquakes recorded by the Hi-net seismic array in Japan. Filled circles show the mean values of τ_p^{max} that were estimated from the five stations (cross symbols) that were closest to the epicentre of each earthquake. Regression analysis gives a correlation coefficient ($r = 0.16$) that is not statistically significant and has a high probability ($P = 0.26$) of occurring by chance from a random distribution. Open circles are values from the four earthquakes used in Fig. 2. The Hi-net array has an inter-station spacing of 20–25 km and employs three-component seismometers; however, only the vertical component is used in this instance.

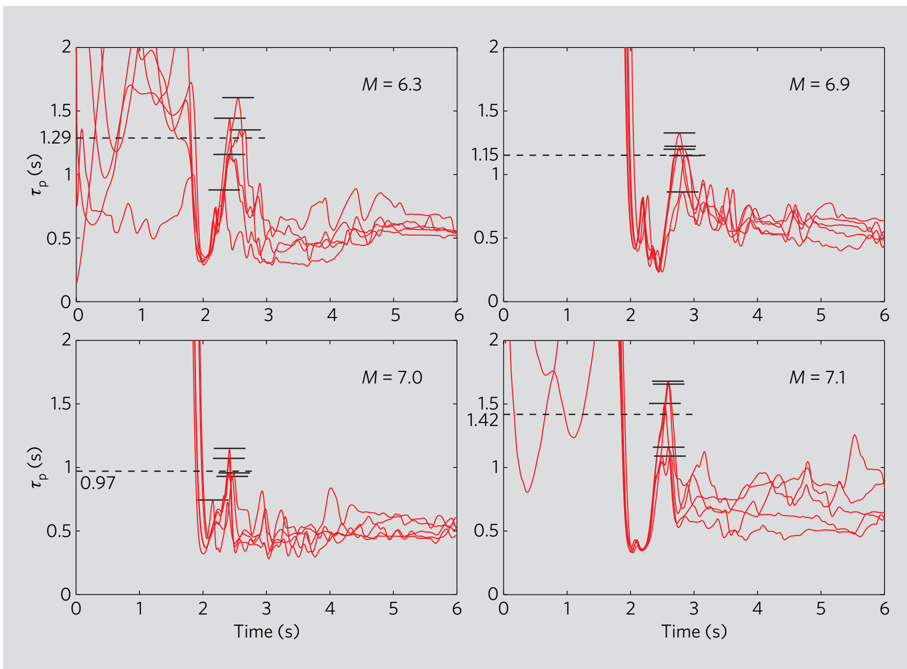

Figure 2 | Time history of τ_p analysis, the predominant period of P-wave arrival data, for four earthquakes in the magnitude (M) range of 6.3 to 7.1. The five traces for each event are from the five stations that were nearest to the epicentre. A solid horizontal bar is centred over the position of the τ_p^{max} peak for each station and the dashed line is the average of these peak values (open circles in Fig. 1). The P-wave arrival here is always at 2 s and the background noise in the seismogram may produce large values of τ_p before the arrival of the seismic energy.

just several seconds of P-wave data, a position that disagrees with Olson and Allen[1].

Closer inspection of Olson and Allen's plot of τ_p^{max} versus magnitude (Fig. 3 in ref. 1) reveals a distinct break in the linear trend of the data at about $M = 5.5$. Below this magnitude, a scaling is observed but, as already noted, such scaling is expected from conventional seismic theory. Above $M = 5.5$, scaling is less evident[1], but neither the correlation coefficient nor the statistical significance was calculated by the authors for these larger events. We calculate the correlation $r = 0.34$ for this section of the trend, with a probability of 0.074 of chance occurrence; these values therefore represent a case of borderline statistical significance and should be viewed with caution, particularly given the important implications. The larger sample used here (about 2.3 times the size of that of Olson and Allen[1]) reveals no trend and hence we cannot support the claim that the first several seconds of rupture energy can be used to estimate the eventual size of a large earthquake.

The individual station estimates of τ_p for four larger earthquakes (Fig. 2) are also evidence for the poor predictability of τ_p^{max} analysis. The results from station to station are generally consistent for τ_p^{max}, but no systematic increase in τ_p^{max} with earthquake size, nor the time at which it occurs, is found for any of these events.

It would be particularly advantageous if the magnitude of a large ($M > 6.0$) earthquake could be estimated from just several seconds of P-wave data, because a real-time warning could then be issued before the later arrival of the highly destructive S waves. However, our τ_p^{max} analysis of Hi-net data does not seem to provide this information in advance.

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Olson & Allen reply

Replying to: P. Rydelek & S. Horiuchi *Nature* 442, doi:10.1038/nature04963 (2006)

Rydelek and Horiuchi[1] present an analysis of earthquakes in Japan whose magnitudes (M) ranged from 6.0 to 8.0. They determine τ_p^{max}, the peak predominant period for P-wave arrival, for the five nearest Hi-net seismic-network stations and plot the event-averaged τ_p^{max} versus magnitude. They find no statistically significant trend in their data.

The scaling relation between τ_p^{max} and magnitude that we presented[2] was derived for earthquakes with magnitudes ranging from 3.0 to 8.3. In the analysis of Rydelek and Horiuchi[1], all but two of the events are in the magnitude range of 6.0 to 7.1. When a large magnitude range is used, the scaling relation is clear, as shown in Fig. 3a of ref. 2. However, there is also scatter in the magnitude of events with the same τ_p^{max} observation. The full range of variability in the event-averaged τ_p^{max} that we observed is ±1 magnitude unit. Given the narrow magnitude range used by Rydelek and Horiuchi[1], and the variability in τ_p^{max} observations as noted by us, it is not possible — and, indeed, we do not expect — to observe a significant trend. Rydelek and Horiuchi[1] cannot therefore call into question the existence of a scaling relation between τ_p^{max} and magnitude based on their data set. The uncertainty in their event-averaged τ_p^{max} observations[1] is also increased by their use of only five stations per event; we used all available data within 100 km of each event, which is an average of 26 stations per event.

Our interpretation that earthquake rupture is deterministic is based on the observation that the magnitude can be estimated before rupture is complete. Rydelek and Horiuchi[1] have explained that their rationale for using only $M \geq 6.0$ events is that the rupture duration for events of $M = 6.0$ is about 4 s, claiming that our τ_p analysis uses 4 s of data, and therefore that only events with $M \geq 6.0$ can be used to determine whether rupture is deterministic (P. Rydelek and S. Horiuchi, personal communication).

Our τ_p analysis does not use 4 s of data: it uses a maximum of 4 s of data. The actual amount of data used is shown in Fig. 3b of ref. 2, which plots the delay time, τ_d, at which τ_p^{max} is observed with respect to the P-wave trigger, together with the typical rupture duration. For all events that plot below the rupture-duration line, the magnitude can be estimated before rupture cessation, suggesting a deterministic process. This is the case for 58 of the 72 earthquakes in our study. These 'deterministic' events have a magnitude range of $3.3 \leq M \leq 8.3$ and include all events with $M \geq 4.0$.

Rydelek and Horiuchi[1] also point out a "break" in the linear trend in τ_p^{max} at $M = 5.5$. This is a visual artefact resulting from the criteria used to select the data set. The apparent break results from the fact that all available earthquakes from southern California were combined with $M \geq 6.0$ events from other regions around the world. This resulted in fewer events in the $5.5 \leq M \leq 6.0$ range. It should also be noted that the uncertainty in a magnitude estimate derived from a τ_p^{max} scaling relation for a specific region, California for example, is lower than when combining observations from a global data set.

Our interpretation for the observed scaling relation is that a stronger initiation will lead to a rupture that is statistically more likely to propagate further across a heterogeneous fault plane. This has been suggested previously[3-5] and does not require the largest amount of slip to be at the hypocentre. Although the hypothesis is controversial[6,7], another study[8] shows that the region of largest slip is statistically near the hypocentre, implying that the location of rupture initiation and peak slip are not independent of one another.

Beyond its implications for the physics of earthquake rupture, rapid magnitude determination can also be used in earthquake-warning systems to provide seconds to tens of seconds of warning before the onset of severe ground-shaking[9,10]. The Japan Meteorological Agency currently operates an early-warning system that estimates the location and magnitude of an earthquake using P-wave arrivals[11]. Starting in June 2006, any organization can apply to receive early warnings of earthquakes.

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