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Devil's Staircase of Earthquake Occurrence: Implications for Seismic Hazard in Australia and New Zealand

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The temporal clustering of large surface faulting earthquakes that has been observed in the western part of Australia has been elegantly explained by the Devil's Staircase fractal model of fault behaviour. Although the only available paleoseismic observations in eastern Australia are from the Lake Edgar fault in Tasmania, it seems likely that the Devil's Staircase also describes large surface faulting occurrence in Eastern Australia and more generally worldwide.

Paleoseismic Observations of Surface Faulting Recurrence in Australia

Clark et al. (2012, 2014) showed that large surface faulting earthquakes in Australia are clustered within relatively short time periods that are separated by longer and variable intervals of quiescence. Figure 1 shows the time sequences of large earthquakes on a set of faults in Australia in the past million years inferred from paleoseismic studies. Most of these faults are in Western Australia and it is remarkable that earthquakes have occurred on three of these faults in historical time. Before now, the most recent period of activity was about 10,000 years ago. Few observations of this kind are available in other stable continental regions of the world analogous to Australia.

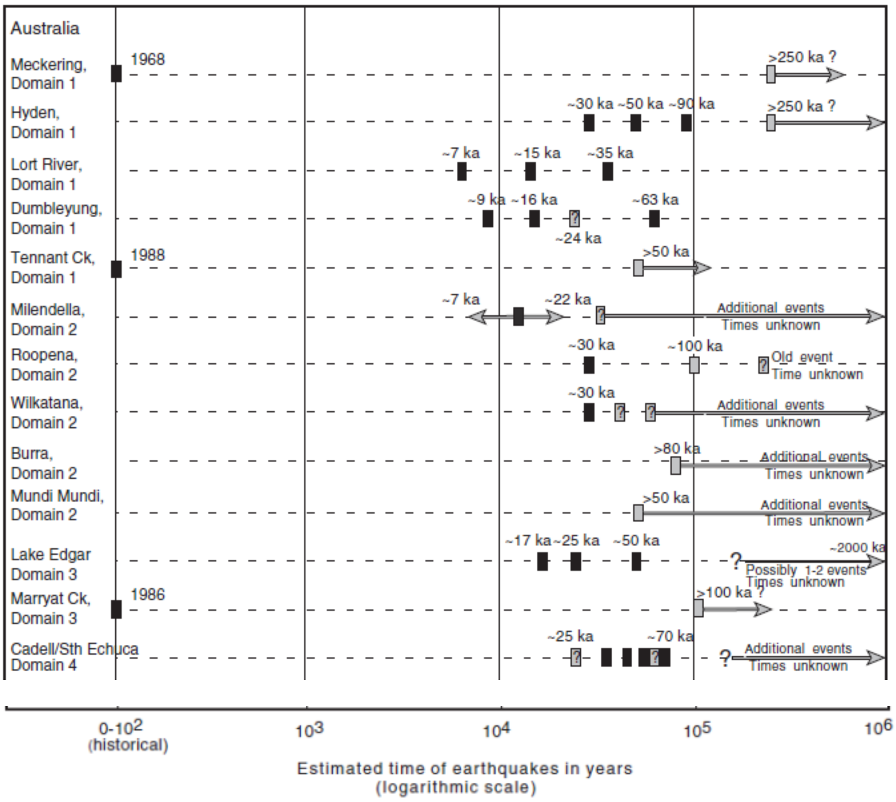

Figure 1. Occurrence of surface faulting earthquakes on individual faults in the past million years. Source: Clark et al. (2012).

The Devil’s Staircase in Global Earthquake Catalogues

Clark et al. (2012) proposed the earthquake recurrence model shown in Figure 2 in which clusters of several earthquakes are separated by long intervals of seismic quiescence. Chen et al (2020) have shown that this irregular earthquake recurrence can be described mathematically by the “Devil’s Staircase” (Mandelbrot, 1982; Turcotte, 1997). The Devil’s Staircase is a fractal property of complex dynamic systems. The Devil’s Staircase is commonly found in nature, and fractal properties are scale invariant, and so they are observed on all scales. Fractal systems are characterized by self-organised criticality, in which large interactive systems self-organize into a critical state in which small perturbations result in chain reactions that can affect any number of elements within the system (Winslow, 1997).

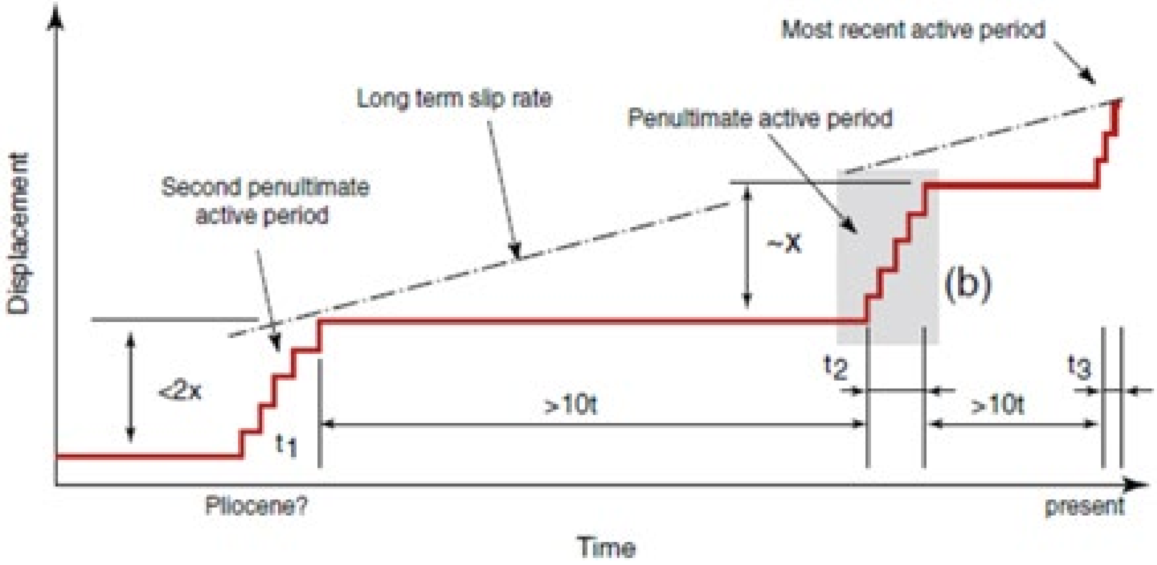

Figure 2. Schematic model of earthquake recurrence on a fault in Australia. Source: Clark et al. (2012)

Chen et al. (2020) fit the interevent time data with probability models using the maximum likelihood method to a set of earthquake catalogues, one of which is shown on the left of Figure 3. They tested five probability models (Poisson, gamma, Weibull, lognormal, and Brownian passage time [BPT]). The Poisson model assumes that, although the mean interval between events is known for a sequence, the exact occurrence time of each event is random. The interevent-time distribution of such a sequence follows an exponential distribution. The Poisson model is a simple one-parameter model commonly used in seismic hazard analysis, and is a special case of the more generalized gamma and Weibull distributions. Both the gamma and Weibull models fit the data for earthquakes of magnitude 6 and larger better than the Poisson model, whereas the lognormal and BPT models fit worse, as shown on the right of Figure 3.

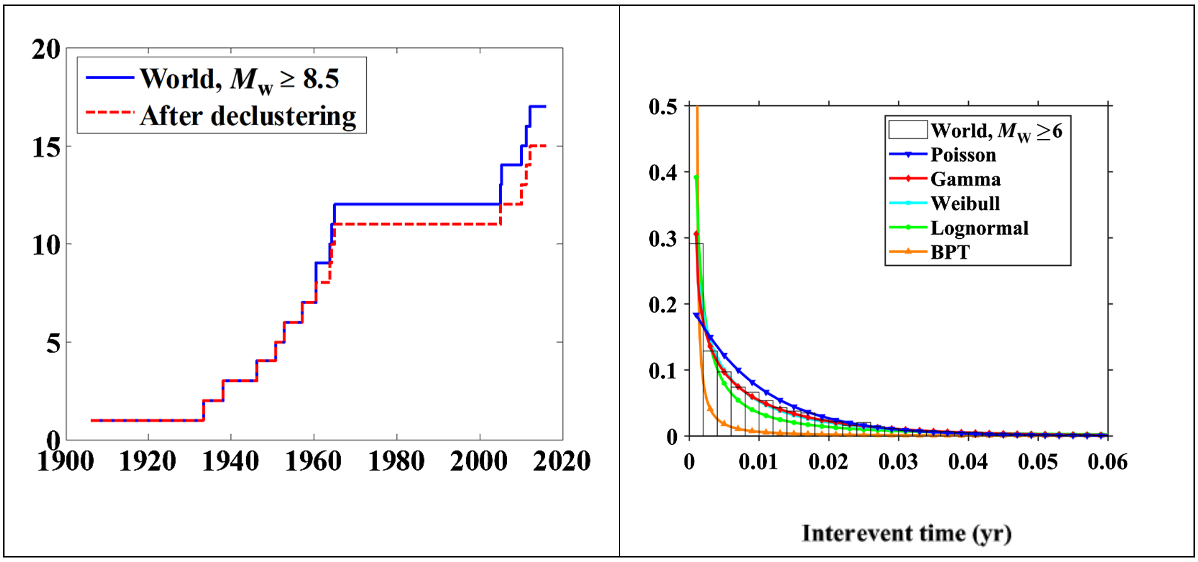

Figure 3. Left: Cumulative number of earthquakes in the world with magnitudes 8.5 or larger since 1900; declustering indicates the removal of dependent events (aftershocks). Right: Comparison of the relative frequency histograms (rectangular columns) of the distribution of interevent times with probabilities predicted by five probability models (curves) for all earthquakes in the world with magnitude 6 or larger. Source: Chen et al. (2020).

The variation of the interevent times can be measured by the coefficient of variation (COV), or aperiodicity, which is defined by the ratio of the standard deviation of interevent times to the mean of interevent times (Salditch et al., 2019). For a sequence generated by a Poisson process, the COV value is 1. To measure the deviation from the Poisson model, Chen et al. (2020) use a normalized COV, called the burstiness parameter B (Goh and Barabási, 2008), whose value ranges from –1 to 1. B of –1 corresponds to a perfectly periodic sequence with a COV of 0; B of 1 corresponds to the most bursty sequence with infinite COV, and B of 0 corresponds to a sequence produced by an ideal Poisson process a COV of 1. Thus, a sequence is “bursty” when $0 < B < 1$ (Fig. 4b) and quasiperiodic (the opposite of “bursty”) when $-1 < B < 0$ (Fig. 4c).

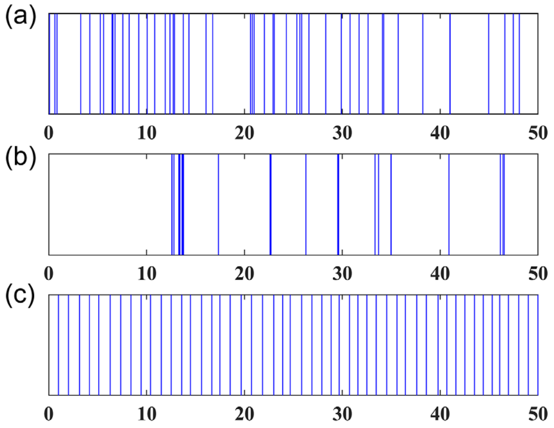

Figure 4. (a) A sequence of events generated by a Poisson model. (b) A bursty sequence generated by the Weibull interevent-time. (c) A quasiperiodic sequence generated by the Gaussian interevent-time distribution. Source: Chen et al. (2020).

Implications of the Devil's Staircase for Seismic Hazard Analysis in Australia and New Zealand

The Devil's Staircase pattern of large earthquakes has important implications for earthquake hazard assessment. The mean recurrence time, a key parameter in seismic hazard analysis, can vary significantly depending on which part of the sequence the catalogue represents. This can be important in hazard assessment, because catalogues for large earthquakes are often too short to reflect their complete temporal pattern, and it is difficult to know whether the few events in a catalogue occurred within an earthquake cluster or spanned both clusters and quiescent intervals. Consequently, an event may not be "overdue" just because the time since the previous event exceeds a "mean recurrence time" based on an incomplete catalogue.

The Poisson model is a time-independent model in which each event in the sequence is independent of other events. However, Devil's Staircase behaviour indicates that most earthquake sequences, especially when dependent events are not excluded, are burstier than a Poisson sequence and may be better fit by the gamma or Weibull distributions. The conditional probability of another large earthquake for both the gamma and Weibull models is higher than that of the Poisson model soon after a large earthquake.

This concept underlies the earthquake forecast for Central New Zealand developed by an international review panel convened by GNS Science in 2018 and published by Geonet (2018). This forecast relies in part on transfer of stress from the northeast coast of the South Island to the southeast coast of the North Island following recent earthquake activity in the region, notably the Mw 7.8 Kaikoura earthquake of 2016 which occurred off the northeast coast of the South Island. Risk Frontiers has implemented this time-dependent earthquake hazard model in our recent update of QuakeNZ. Earthquake clusters involving stress transfer are ubiquitous and have occurred recently on the Sumatra subduction zone (2004 – 2008) and along the North Anatolia fault in Turkey (1939 – 1999).

Given the pervasive occurrence of fractal phenomena in geology (Turcotte, 1997) and the identification by Chen et al. (2020) of Devil's Staircase recurrence behaviour in a wide variety of earthquake catalogues, it is likely that this is a general feature of earthquake occurrence.

Temporal Clustering of Very Large Subduction Earthquakes

The left side Figure 3 reflects two clusters of very large subduction earthquakes. The first occurred in the middle of last century and included the 1952 Mw 9.0 Kamchatka earthquake, the 1960 Mw 9.5 Chile earthquake and the Mw 9.2 Alaska earthquake. The second cluster began with the occurrence of the Mw 9.15 Sumatra earthquake of 26 December 2004 and continued with the Mw 8.8 Chile earthquake on 27 February 2010 and the Mw 9.0 Tohoku earthquake on 11 March 2011. The usual approach to assessing the significance of this apparent clustering is to test statistically the hypothesis that the global earthquake catalogue is well explained by a Poisson process. Risk Frontiers analysed the power of such tests to detect non-Poissonian features, and showed that the low frequency of large events and the brevity of our earthquake catalogues reduce the power of the statistical tests and render them unable to provide an unequivocal answer to this question (Dimer de Oliveira, 2012). This conclusion is consistent with the Devil's Staircase behaviour shown in Figure 3.

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