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Magnitude production imbalances and the present seismogenicity state of the San Andreas Fault system

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ABSTRACT

Seismicity of the San Andreas Fault system, between 21°N–40.2°N and 105°W–125°W, is subjected to the piecewise gradient analysis in order to assess the present magnitude production balance of that seismogenic system and its possible implications. The analysis is based on a technique applied to a global seismicity dataset of earthquakes in the magnitude range 6.1–9.0 for the period 1973–2003 that suggests that temporal imbalances in the production of different magnitudes generated within a seismogenic system exhibiting departures from linearity in the Gutenberg–Richter Law may be symptomatic of an imminent, significant magnitude event. The approach uses a variant of the traditional b-value plot, which tracks through time any changes in piecewise gradients within subsets of the magnitude–frequency statistics. Obvious offsets from the usual straight line fit are taken as an indication of a deficit in magnitude production that will eventually be supplied to restore linearity, the timing of which can be informed by regular analysis of the relative production of different magnitude classes. This study shows that, in the recent past, an emergent pattern of magnitude output imbalance, seismicity acceleration and then relative quiescence has preceded all of the more significant events, magnitude >6.5, within the defined San Andreas Fault system. In 2010, two earthquakes of magnitude >6.5 occurred in quick succession, which is a pattern not previously seen. The overall piecewise gradient analysis technique suggests that the system appears poised to release an event of magnitude >7.5.

1. Introduction

The ability to predict the behaviour of a system governed by stated physical laws is the ultimate test of any scientific theory (Ben-Manahem, 1995), the holy grail of seismology (Bakun et al., 2005). Earthquake prediction studies continue to be pursued in the hope of recognising evidence of impending major or great shocks on a time-scale that would allow realistic, useful, mitigating action.

The devastating effects, with surface rupture, of the 1906 California earthquake, with a magnitude close to 8, and an understanding that events of that size belong to a class of events with potential for recurrence on the San Andreas Fault system (SAFS), have contributed to making that fault system one of the most intensely studied on Earth (Becker et al., 2005). It is the primary boundary fault between the Pacific and North American plates (Grant and Lettis, 2002) and one of the few continental transform faults (Fowler, 1990). Usually, focus has been placed on certain subsections of the system in the hope of deriving a better system-wide understanding (Bakun and Lindh, 1985), with journals dedicating special issues to research dealing with any section of the SAFS (e.g. Grant and Lettis, 2002). The Parkfield segment of the SAFS, with its perceived stable recurrence of significant events in recent decades, is among the most densely instrumented fault segments anywhere, and the Parkfield prediction experiment the best-known forecast associated with the San Andreas Fault system (Bakun and Lindh, 1985; Bakun et al., 2005; Lindh et al., 1979). An analysis of activity within the Parkfield segment led to the projection that a significant magnitude earthquake would occur within the segment during the period 1988 to 1993 (Lindh et al., 1979). There was no significant magnitude event in the fault segment during the defined period. Further analysis gave reason to believe that the expected event had been delayed and would take place in 2002 (Toppozada et al., 2002 and references therein). Again, the event failed to occur, as anticipated and did not occur until September 2004 (Langbein et al., 2005).

Most studies on the SAFS are restricted to the known on land mapped fault segments (see e.g. Becker et al., 2005). The present study, however, takes a broader perspective, and analyses the dataset

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of all earthquakes of magnitude 4.6 and greater within the area 21°N–40.2°N and 105°W–125°W. For present purposes, the seismogenic segments within this zone will be referred to collectively as the SAFS. The northern limit was chosen to exclude the Mendocino Triple Junction which is considered to mark the end of the SAFS in the north (Cox and Hart, 1986). At its southeast end, the system merges more gradually with the set of transform faults of the northern end of the East Pacific rise (Fowler, 1990) underlying the Gulf of California and, at that end, the geographic limit of the SAFS was here chosen generously in an attempt to include all interacting seismogenic faults (Keilis-Borok et al., 2001, Keilis-Borok, 1994), which may be involved in the system. The present analysis technique produces temporal plots of trends of relative magnitude production along the whole of the SAFS since 1973. The approach uses a variant of the traditional Gutenberg and Richter (1944) *b*-value plot and tracks changes in subset piecewise gradients within the magnitude–frequency statistics (Latchman et al., 2008). Marked offsets from linearity are taken to be an indication of deficits in magnitude production that are likely to be supplied, sooner rather than later, so that the statistical counts regress to restore linearity. Patterns observed through time together with current disparities in magnitude production on the SAFS, indicated by this piecewise gradient technique, are used to anticipate an increased short-term likelihood of a significant new high magnitude event within the SAFS.

2. Piecewise gradient technique

The original Gutenberg–Richter law (Gutenberg and Richter, 1944) depicts the earthquake magnitude–frequency relation in terms of the logarithm of the cumulative number of events equalling or exceeding a given magnitude, to which a single straight line with slope *b* is fitted. The estimation of the overall *b*-value for a particular dataset can be done in a number of ways, but the data transformations implicit in such procedures inevitably tend to obscure, or obliterate completely, any internal structuring or temporal variations within the magnitude–frequency distribution, which could be informative as to future behaviour. These can be explored by representing the underlying power law distribution in terms of a temporally-partitioned piecewise gradient, rather than a single, time-integrated best-fit straight line. The observation that the *b*-value need not remain constant over different magnitude ranges has led to the suggestion that it is sometimes more appropriate to plot the raw data, rather than fitting the data with a straight line uncritically, when such a fit may not be warranted (Ziv et al., 2003).

An alternative, and usually neglected, approach avoids this filtering transformation by plotting discrete numbers of events within specified magnitude bins. The relative contributions at different magnitude levels can then be examined by fitting local piecewise gradients (denoted here as b^*) across sub-sections of the data, for any specific magnitude ranges of interest. Latchman et al. (2008) put it algebraically as follows: in a b^*-value plot at a given time T_m from the onset of monitoring, the gradient of any line-segment, b^*_m, would change with the passage of time such that, if t_1 and t_2 are the assumed stable average recurrence intervals for adjacent magnitude bins, and if i is the width of each magnitude bin:

$$b^*_m = \left(\frac{\log \frac{T_m}{t_1} - \log \frac{T_m}{t_2}}{i} \right) \tag{1}$$

$$b^*_m \xrightarrow{T_m \to n_{t_1}^{t_2}} b$$

where n = 1, 2, 3. . . . . . . .and represents multiples of the recurrence interval

This may be rewritten as:

$$b*_m = \left(\frac{\log \lambda_1 T_m - \log \lambda_2 T_m}{i} \right) \tag{2}$$

where $\lambda = 1/t$.

While this method also tends to overall linearity with plentiful data, it is particularly suitable for detecting temporal shifts in the relative numbers of events produced at different magnitudes, and tracked as changes in individual b^* gradients (see Fig. 1).

Transitory offsets from expected b^* linearity were used to infer when larger events were imminent in two successful alerts for damaging earthquakes on a fault system near Tobago, West Indies (Latchman et al., 2008; Morgan et al., 1988). Other workers have also noted that tracking ratios of significant magnitude events in different ranges might be valuable in identifying times of increased probability for the largest earthquakes (Keilis-Borok and Rotwain, 1990). The technique was formalised, and expanded to include daily tracking of the gradients of the individual sections comprising the b^*-value plot, then applied to the Earth as a whole, which may be considered the ultimate seismogenic zone (Yegulalp and Kuo, 1974) based on the hierarchical fault system model of (Keilis-Borok et al., 2001; Keilis-Borok, 1994). Global data from 1973 onwards—scrutinised prior to the occurrence of the 2004 and 2005 Sumatran mega-events—exhibited magnitude occurrence imbalances and seismicity accelerations which were interpreted as possibly precursory to an imminent great earthquake, with anticipated magnitude higher than 8.5 (Latchman et al., 2008). The subsequent 2004/12/26 Sumatra–Andaman earthquake had a magnitude of 9 M_ω (NEIC, 2009). Following that event, the global data piecewise b^* plots remained inconsistent with balanced magnitude production, indicating another large earthquake was likely in the short term, again exceeding magnitude 8.5; the magnitude 8.6 M_ω (NEIC, 2009) Simeulue-Nias earthquake occurred on 2005/03/28. Latchman et al. (2008) demonstrated that persistent magnitude output trends in the global seismogenic system were sufficiently low probability phenomena to view their occurrence as having significance and showed that persistent trends are precursory to significant magnitude events and could even be used to recognise the imminence of mega-events. Kossobokov (2006) also demonstrated that the precursory activation zone to the largest events appears global in extent. In addition, the observation has been found to be applicable in a small scale fault zone (Morgan et al., 1988) suggesting that the phenomenon may be scale independent. In this context, the technique may be applied to a regional fault system to seek out trends associated with moderate and

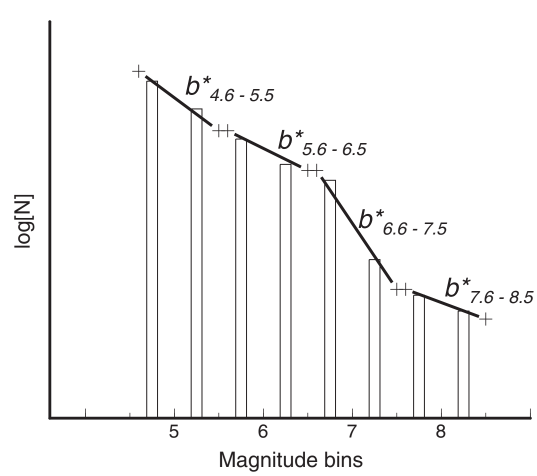

Fig. 1. Generalised graph shows the sections comprising the b^*-value plot with piecewise section gradients labelled. (n.b. log[N] is simple count of events in magnitude bins, not cumulative count as in conventional G–R relation).