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A test of the precursory accelerating moment release model on some recent New Zealand earthquakes

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SUMMARY

The proposal that the moment release rate increases in a systematic way in a large region around a forthcoming large earthquake is tested using three recent, large New Zealand events. The three events, 1993–1995, magnitudes 6.7–7.0, occurred in varied tectonic settings. For all three events, a circular precursory region can be found such that the moment release rate of the included seismicity is modelled significantly better by the proposed accelerating model than by a linear moment release model, although in one case the result is dubious. The 'best' such regions have radii from 122 to 167 km, roughly in accord with previous observations world-wide, but are offset by 50–60 km from the associated main shock epicentre. A grid-search procedure is used to test whether these three earthquakes could have been forecast using the accelerating moment release model. For two of the earthquakes the result is positive in terms of location, but the main shock times are only loosely constrained.

Key words: earthquake prediction, New Zealand, seismicity.

INTRODUCTION

In recent years there has been a trend towards the view that large earthquakes are inherently unpredictable (e.g. Geller *et al.* 1997). Support for this view comes from proposals that the Earth's crust is perpetually in a state of self-organized criticality (Bak & Tang 1989; Ito & Matsuzaki 1990). In such a scaleless state, the generation of a large earthquake is just a matter of chance; that is, a small event can cascade into a large one depending on more-or-less random, and generally unobservable, factors. However, another view is that in a given fault network there are distinctive large defining events that serve to move the crust well away from the critical state (e.g. Bowman *et al.* 1998). Such an event can only occur when there are long-range correlations in stress, as is expected in the critical state. Afterwards, the crust moves to reorganize itself over time and the background seismicity evolves in a characteristic way. Once the critical state is again achieved the next defining event can occur.

Assuming the latter view to be correct, it is possible to derive mathematical models of the evolving seismicity prior to a large defining event. These models predict that relevant measures of the seismicity will show a power-law increase with time, until the critical point is reached. By fitting a model to the observed seismicity before the critical point is reached, an estimate of the critical time could be provided. In this report this potential forecasting method is referred to as the AMR method (for Accelerating Moment Release).

There have been several studies of the AMR, or 'time-to-failure', forecasting model in recent years, exemplified by the case of the Loma Prieta earthquake in California (Bufe & Varnes 1993). Jaumé & Sykes (1999) give a review of these studies, both in the real world and in computer models of seismicity. In this study the results of testing the AMR method using three recent, large New Zealand earthquakes are presented (see also Robinson 1997). The results are somewhat mixed, with clear support for the model in two cases, but with unresolved questions about several aspects of applying the method to real-world data, with all its quirks and susceptibility to different interpretations. Other work in progress in New Zealand (Vere-Jones *et al.* in preparation) offers the prospect of improved methods of fitting theoretical models to real data, and the application of those methods to New Zealand data will be undertaken in the future.

MATHEMATICAL MODELS AND FITTING PROCEDURES

There are two mathematical models of precursory accelerating seismicity. The first, introduced by Varnes (1989), is

$$\Sigma M_{\mathrm{o}}^{\alpha}(t) = A + B(tf - t)^{m}, \tag{1}$$

where t is time, tf is the time at which the critical state is reached, M_{o} is the seismic moment, and A, B and m are constants to be determined from the data (along with tf). α is a chosen constant, usually 0.5 as used here. In the case where faults in the network are arranged in a hierarchical manner, eq. (1) can be shown to be decorated with log-periodic oscillations (Saleur *et al.* 1996):

$$\Sigma M_{\mathrm{o}}^{\alpha}(t) = A + B(tf - t)^{m}[1 + C\cos(\phi + 2\pi\log(tf - t)/\log\lambda] \,, \tag{2}$$

where C, λ, and ϕ are additional constants. Because of the fact that these log-periodic decorations are often not evident in real-world examples (Jaumé & Sykes, 1999), the extra complexity involved in fitting eq. (2) to the data, and the suspicion that the three additional parameters merely serve to 'fit the noise', only eq. (1) is used in this report, except in one case.

Despite the fact that the observed data in eq. (1) are cumulative quantities, it is common to use standard non-linear least-squares methods to fit the model to the data, and this is the approach adopted here. [Vere-Jones, Robinson & Wenzheng (in preparation) present statistically preferable procedures and discuss why the parameter A is ill-defined.] The Levenburg–Marquardt method, as presented in Press *et al.* (1992; pp 675–683), is used. In some studies the value of A is used to estimate the magnitude of the final defining event, but that is not done here—only tf is of concern.

New Zealand Data

New Zealand lies on the boundary between the Pacific and Australian plates, and earthquakes occur not only at crustal depths but also deeper, in the subducted Pacific plate (northern New Zealand) and in the subducted Australian plate (far south). Between the two subduction zones is a region of continental-type collision resulting in the Southern Alps and the major Alpine fault. Overviews of the seismicity and tectonics of New Zealand can be found in Anderson & Webb (1994) and Walcott (1978).

The region of seismicity studied here is from 36°S to 47°S, and 164°E to 177°W, except that events in the Taupo Volcanic Zone, and the relatively aseismic region to its northwest, are excluded (Fig. 1). Previous experience (Robinson 1997) has shown that the numerous swarms associated with volcanic activity in that region are not in accord with the AMR model. All hypocentre data used are taken directly from the master catalogue of the New Zealand Seismological Observatory 1964–1998. Aftershocks are removed since they seem to be more closely related to a very localized stress redistribution closely associated with the main shock and not to be part of the more widespread fault network evolution. In any case, because of the magnitude threshold of 5.0 (see below) there are not many to remove. Only 'shallow' earthquakes, those with depths of 40 km or less, are considered; this is the apparent maximum depth of close interaction between subducted and over-riding plates in New Zealand. Only events of magnitude 5.0 or more are used. Jaumé & Sykes (1999) report several studies that find that events more than 2 magnitude units below the main shock do not participate in the AMR pattern. The three New Zealand main shocks considered here (see below) range from magnitude 6.7 to 7.0. The New Zealand catalogue should be complete for the region and period used at least to magnitude 5.0. Magnitudes in the New Zealand catalogue are M_{L} (local magnitude); they are converted to moment using

$$\log M_{\mathrm{o}} = 1.5M_{\mathrm{L}} + 9.05 \,, \tag{3}$$

where M_{o} is in newton metres (Kanamori 1977).

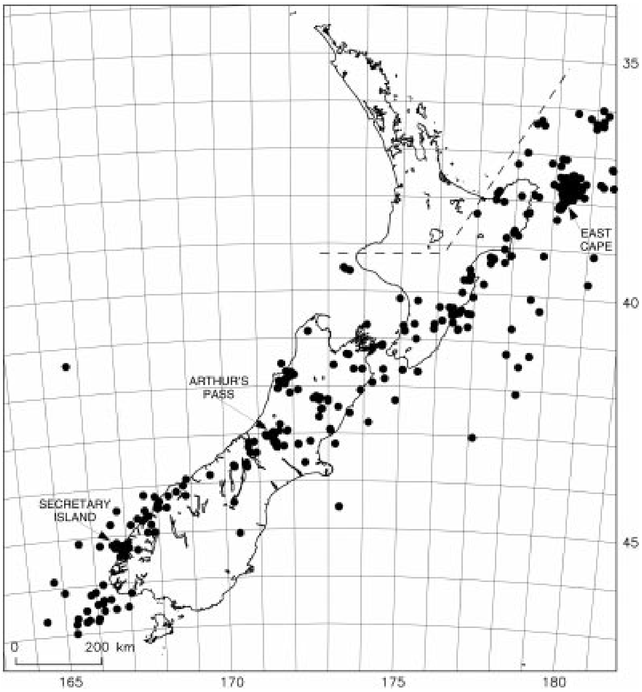

Figure 1. The New Zealand region, and shallow (depth <40 km) earthquakes of magnitude 5.0 or more, 1964–1998, as used in this study except that aftershocks have not been removed. The dashed lines show the south and east boundaries of the Taupo Volcanic Zone: seismicity to the north and west is not considered here. The three large, recent New Zealand earthquakes studied in this report are indicated on the figure.

TESTS ON THREE EARTHQUAKES

The three largest, shallow, New Zealand earthquakes since 1990 are considered here. The tests applied are as follows. (1) Given the position and time of the main shock, is the preceding seismicity consistent with eq. (1)? (2) Could a search for regions of accelerating moment release have identified the positions and times of the events beforehand?

First, test 1 is carried out for each individual event; this requires knowledge of the size of a precursory region appropriate for the event's magnitude. The second test is applied to all three events together via a grid-search procedure described in more detail below. The relation between the main shock magnitude and radius R of a circular precursory region is taken from Fig. 5 of Jaumé & Sykes (1999):

$$\log R = -0.2 + 0.36M \,, \tag{4}$$

where M is equated to M_{L} and R is in kilometres. Because there is a wide scatter in the observations of R versus M, a search is done to find the best result for radii within ± 25 per cent of the R from eq. (4), in steps of 5 per cent. The search also includes possible offsets of the region centre from the epicentre in the N, S, E, and W directions of 0°–0.5°, in steps of 0.1°. There are, then, 1331 possible combinations of R and region centre (11×11 for offset $\times$ 11 for R). Here the 'best result' means that with the lowest ratio of (rms error using eq. 1) to (rms error using a linear fit), as in Bowman *et al.* (1998).

To satisfy test 1, two things are required: first that the best model have $m < 1$ (accelerating pattern, not decelerating); and second that the variance for the best model be less than half of the variance for a straight-line fit to the data (steady accumulation of moment). The second criterion is rather arbitrary, but standard statistical tests cannot be applied to cumulative data.

The East Cape earthquake, 1995 February 5

This event, magnitude 7.0, is the largest New Zealand event since 1942. It was located 85 km off the northeast coast of the North Island, 37.65°S, 179.49°E, at a nominal depth of 12 km. It was a normal faulting event near the axis of the Hikurangi Trough, where subduction of the Pacific plate commences. A region radius of 209 km is suggested by eq. (4).

For test 1, the best model (variance ratio 0.23; Fig. 2a) is for a region of 167 km radius centred at 37.15°S, 179.24°E, 60 km NNW of the epicentre. So test 1 is satisfied. In this case there appear to be oscillations of the data about the best model which might be explained by eq. (2) (but see below).

The Arthur's Pass earthquake, 1994 June 18

This event, 43.01°S, 171.46°E, magnitude 6.7, was the largest of a regional cluster of moderate-magnitude events in the central South Island from 1984 to 1995. It was a thrust event within a broad region of deformation east of the Alpine fault. A region radius of 163 km is suggested by eq. (4).

For test 1, the best model (variance ratio 0.02; Fig. 2b) is for a region of 139 km radius centred at 43.11°S, 170.78°E, 56 km SSW of the epicentre. So test 1 is satisfied. In this case there do not appear to be log-periodic oscillations of the data about the best model.

The Secretary Island earthquake, 1993 August 10

This event, 45.21°S, 166.71°E, magnitude 6.7, was a shallow subduction thrust event just off the southwest coast of the South Island (Fiordland). A region radius of 163 km is suggested by eq. (4).

For test 1, the best model (variance ratio 0.09; Fig. 2c) is for a region of 122 km radius centred at 45.21°S, 166.00°E, 56 km west of the epicentre. So test 1 is satisfied. In this case there do not appear to be log-periodic oscillations of the data about the best model.

Remarks on test 1

Although all three events satisfied test 1 there are differences in detail. The East Cape event had the highest (i.e. poorest) variance ratio, which can be interpreted as being due to strong oscillations of the data about the best model. At first sight it seems that eq. (2) would do a better job of fitting the data, but attempts to do so produce negligible improvements in the rms error which are not significant given the extra three parameters. Eq. (2) can fit some intervals of the data better but at the expense of worsening the fit for other intervals, with the result that the best fit is not much different from that for eq. (1).

The results for the Secretary Island earthquake meet the criteria for test 1 but are probably the least convincing. Except for the last event before the main shock, the data can be well modelled by a linear increase with time.

Because the main shocks, which are of course large, are included in the data to be fit, and because the data end there,

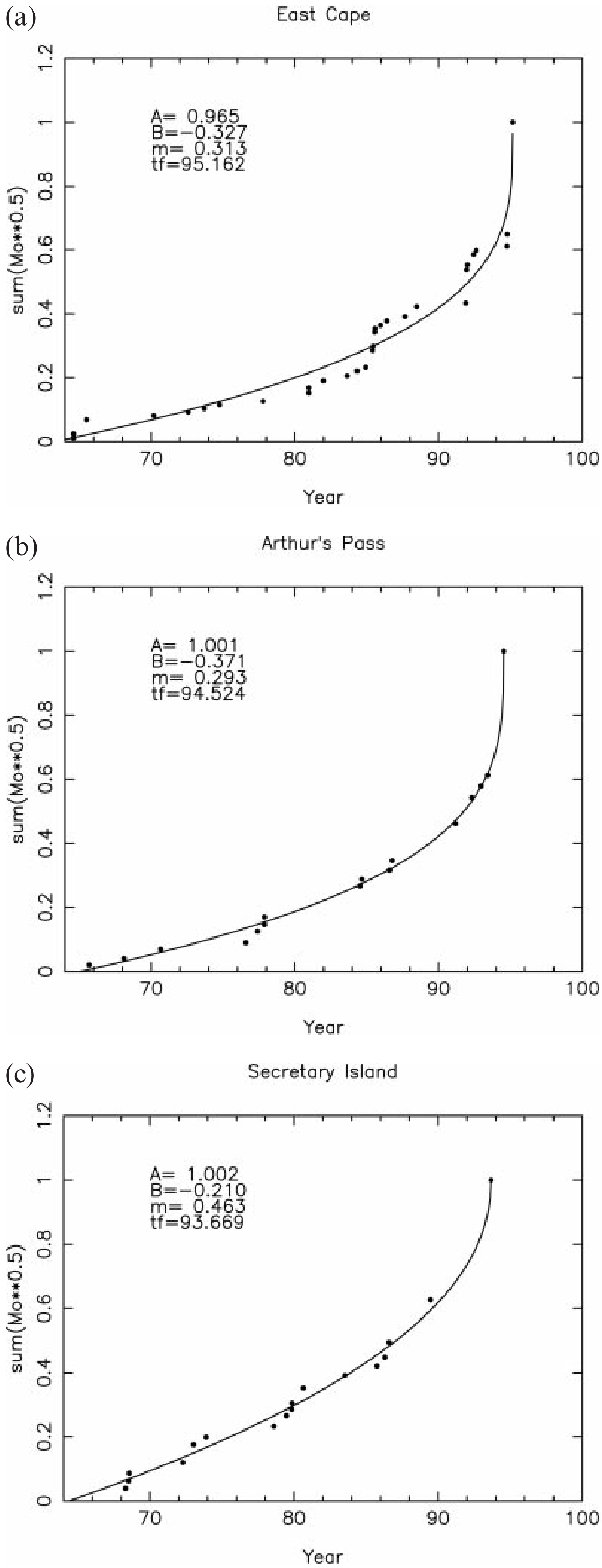

Figure 2. Best fits of eq. (1) to seismicity near three large, recent New Zealand earthquakes. For (a) the East Cape Earthquake, (b) the Arthur's Pass earthquake, and (c) the Secretary Island earthquake.

it is likely that a model with an upward curvature will do better than a linear model. The tests have been repeated after exclusion of the main shock, more in line with the procedure of Bowman *et al.* (1998), but I feel that the purpose of test 1—to see if eq. (1) describes the moment release better than a linear model—is better served by keeping the main shock in the data. I believe that eq. (1) should apply to the main shock as well as to the precursory activity. In any case, the results from test 1 when the main shocks are excluded are similar to the results when they are included (Table 1), in that a precursory region can be found within which the data are consistent with eq. (1), although the improvement in variance ratio is, as expected, smaller. The biggest change is in the centre of the best precursory region for the East Cape event. Note that in test 2, below, only pre-main shock data are used.

The values of the parameter m found for the East Cape and Arthur's Pass events (Fig. 2) are close to 0.3, a value sometimes quoted as 'typical' (Bufe & Varnes 1993). The value for the Secretary Island event is somewhat higher, again reflecting the less pronounced curvature in the accumulated moment curve.

For all three events, the 'best' region is found to be offset from the epicentre by about 50–60 km, and the radius is found to be less than that predicted by eq. (4). For the Arthur's Pass and Secretary Island events the offset and radius serve to remove some nearby events of magnitude similar to the main shock which would destroy the upward curvature needed for eq. (1) to do better than a linear fit. This problem of overlapping main shock events has been recognized and discussed in Brehm & Braile (1998) and Huang *et al.* (1998); it needs to be investigated in more detail, as does the more general question of the applicability of the AMR model to main shocks smaller than the 'defining' event for a given fault network

Given the uncertainties in magnitude determination, it is unlikely that the systematically lower optimum radius found here, compared with that from eq. (4), is significant. The use of Harvard moment magnitudes for the three main shocks increases the discrepancy with eq. (4) ($M_w = 7.1$, 6.7, 6.9 compared with $M_L = 7.0$, 6.7, 6.7).

Test 2

For this test it is necessary to develop a grid-search procedure. The idea is to generate a set of equally spaced grid points throughout New Zealand (except for the Taupo Volcanic Zone and the region to its northwest) and look at the seismicity within circular regions centred at those grid points. The grid used (Fig. 3) has a spacing of 10 km, with an 'origin' at 41.0°S, 175.0°E. The search is made for radii appropriate for 'roundish' main shock magnitudes (6.50, 6.75, 7.00, and 7.25; radii = 138, 170, 209, 257 km using eq. 4), and for end dates of 1993, 1994, 1995 January 1. A grid point is marked as 'positive' if: (1) the application of eq. (1) predicts a tf greater than the time of the last data point but less than the time of the last data point $+5$ years; (2) the variance of the eq. (1) model is less than half of the variance of a linear fit model; (3) there are at least 10 data points. Note that the fitting procedure is able to find a model that interprets an event that has already happened as the main shock, if the data demand it, by assuming that the seismicity after a main shock is a mirror of that before.

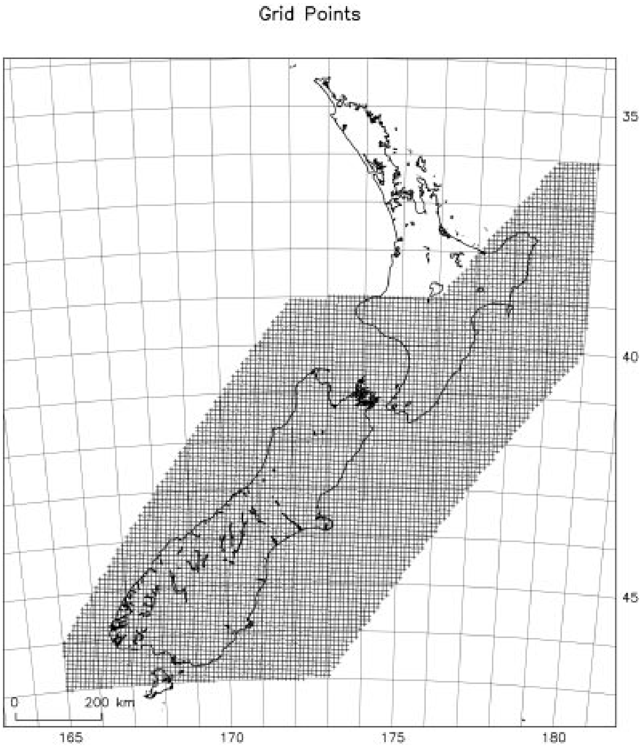

Figure 3. The grid points used as centres of potential precursory regions.

It is difficult to know how to specify a 'success' for test 2. In fact, the test can be regarded as a first attempt to formulate the criteria for a success; this formulation can then be used in real-time testing in the future using the probabalistic methodology developed by Evison & Rhoades (1993). Maps of positive grid points for the three cut-off dates (Figs 4, 5 and 6) are

Table 1. Comparison of test 1 results with the main shock included and excluded.

	East Cape	Arthur's Pass	Secretary Island
Variance ratio with main shock	0.23	0.02	0.09
Variance ratio without main shock	0.45	0.10	0.49
Centre latitude with main shock, degrees	−37.15	−43.11	−45.21
Centre latitude without main shock, degrees	−37.75	−43.11	−45.31
Centre longitude with main shock, degrees	179.24	170.78	166.00
Centre longitude without main shock, degrees	178.00	170.78	166.00
Region radius with main shock, km	167	139	122
Region radius without main shock, km	209	139	122

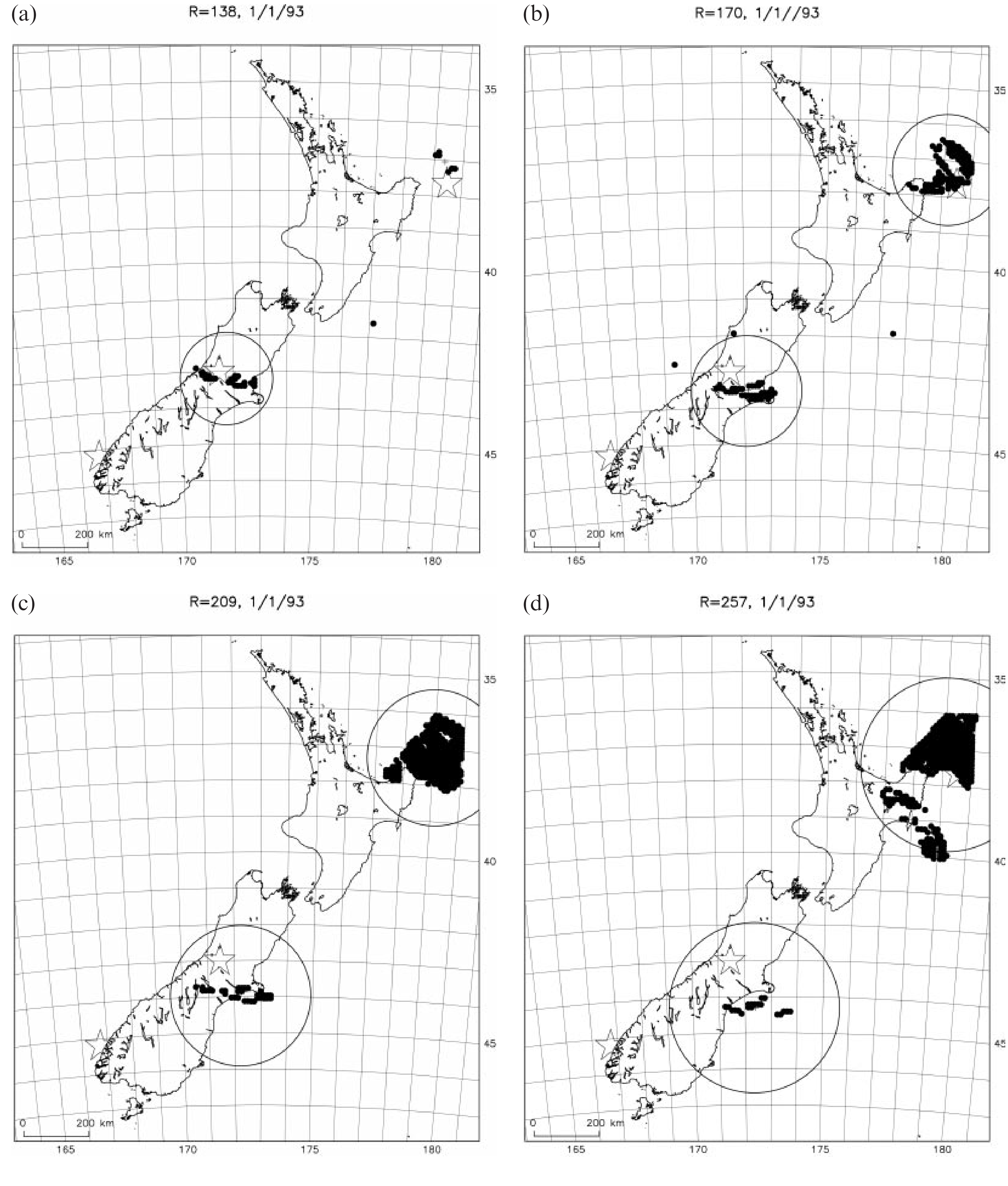

Figure 4. Positive (see text) grid points on 1993 January 1. For (a) a search radius of 138 km, (b) a search radius of 170 km, (c) a search radius of 209 km, and (d) a search radius of 257 km. The search radii correspond to main shock magnitudes of 6.50–7.25 from eq. (4). Circles have centres at the centre of clusters of positive points with a radius corresponding to the search radius.

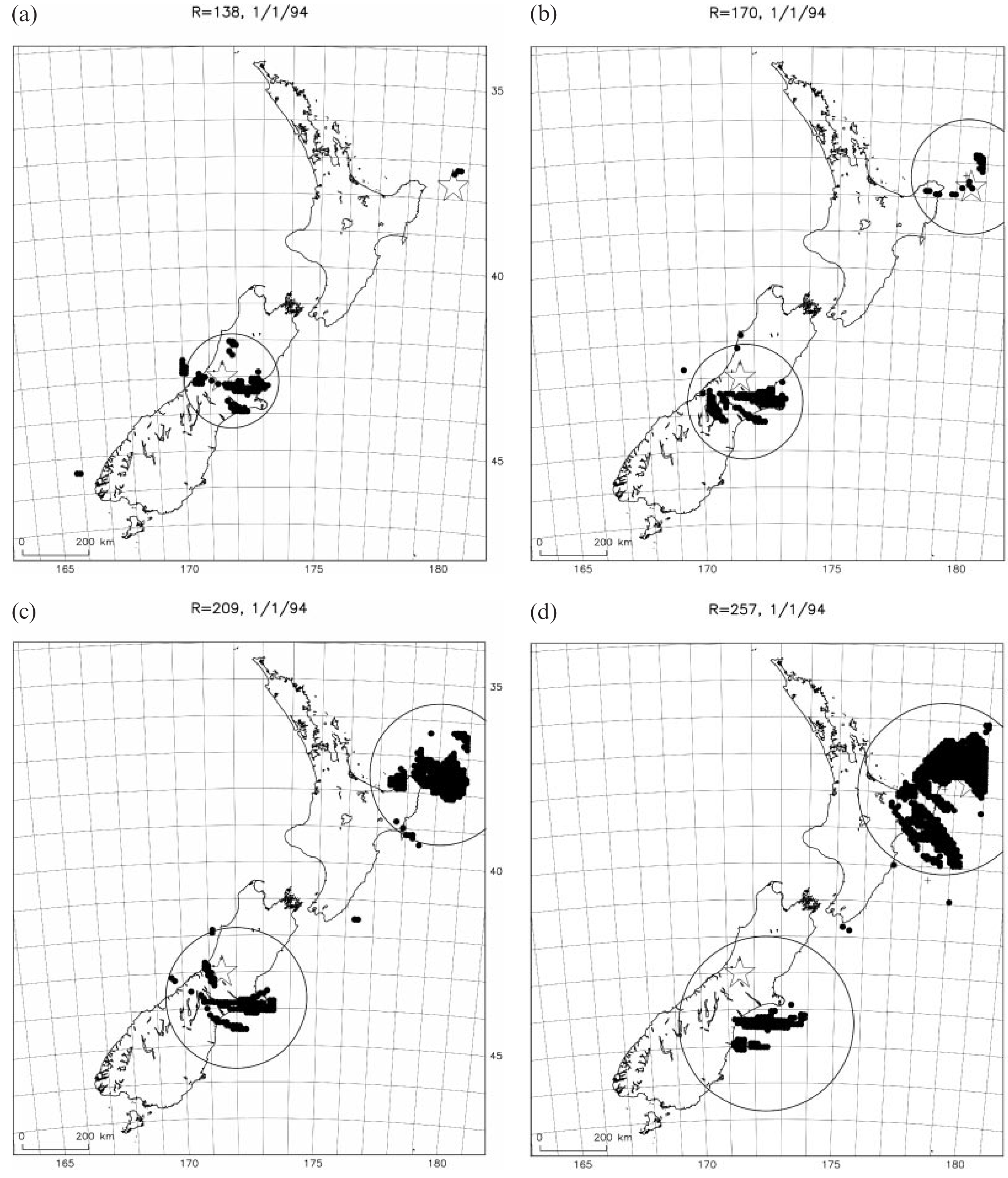

Figure 5. As Fig. 4, but for 1994 January 1.

therefore presented in order to see if any insights can be gained. In the discussion that follows a 'cluster' of positive grid points is defined as a group of 10 or more with no gap of more than 100 km.

First consider the results for the cut-off date of 1993 January 1, before any of the three test earthquakes (Fig. 4). For the smallest radius (138 km; Fig. 4a) there is a cluster of positive grid points near the Arthur's Pass event but none for the Secretary Island event, and, under the present definition, none for the East Cape event (only 6, not 10 or more points). For larger radii (Figs 4b, c and d), a cluster appears for the East Cape event, and that for the Arthur's Pass event is displaced to the southeast. The average tfs (Fig. 7) for the Arthur's Pass cluster are all within 0.5 yr of the main shock

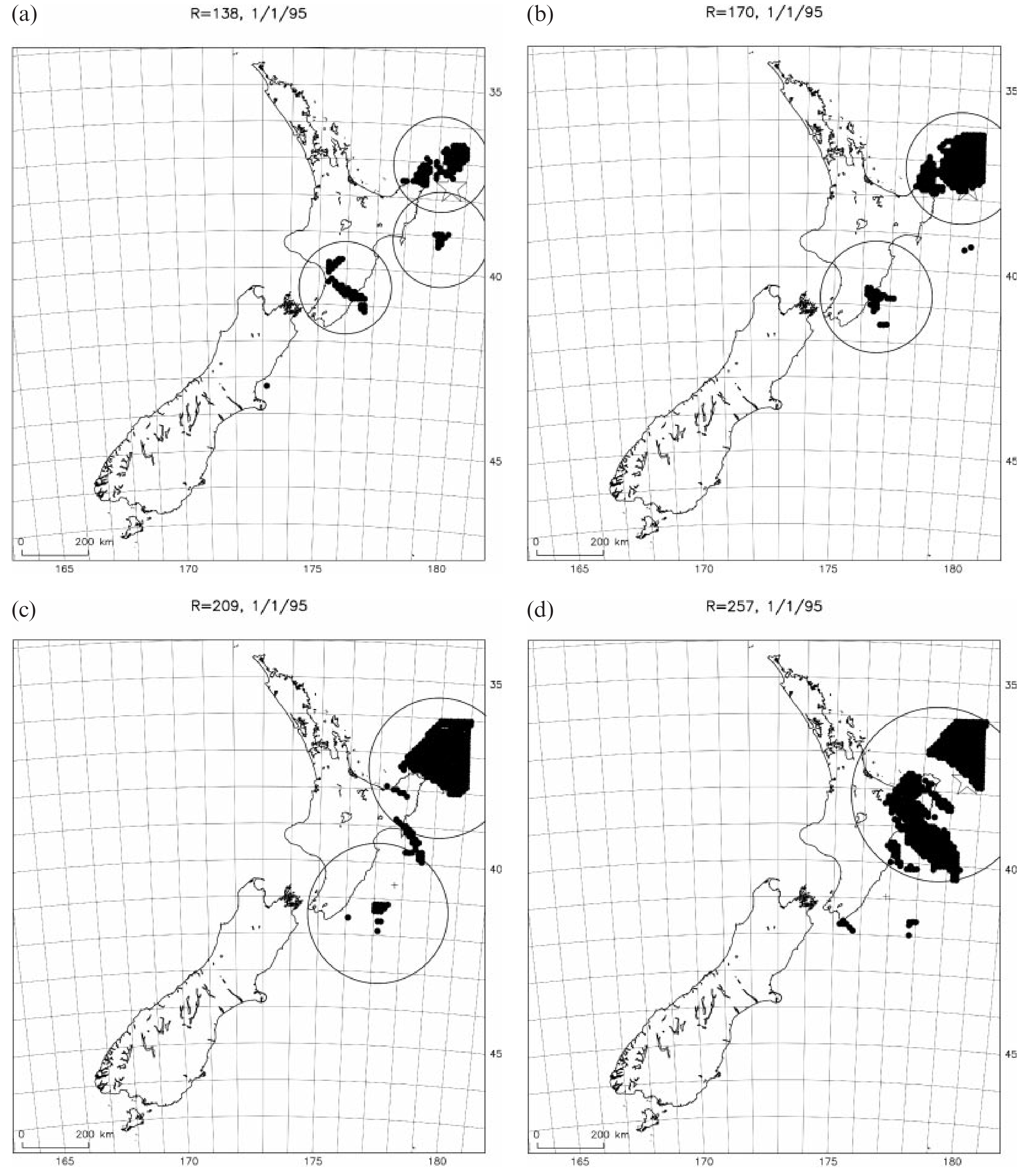

Figure 6. As Fig. 4, but for 1995 January 1.

date, but for the East Cape cluster they vary more, with that for the smallest radius (170 km) being over a year too early. If we take the 'best' radius as that with the largest number of positive grid points, normalized by area of the search, the 'best' radius for the Arthur's Pass cluster is 170 km (magnitude 6.75, $tf = 94.43$; remarkably close to the actual values of 6.7, 94.47). This cannot be done for the East Cape event because it lies near the edge of both the catalogue and the search grid, but certainly the related cluster is much better developed for the larger two radii. The average tf for the largest radius, 95.53, is closest to the actual value of 95.09. In addition to the clusters of positive grid points close to the East Cape and Arthur's Pass events there are isolated single points off the southeast North Island for two radii.

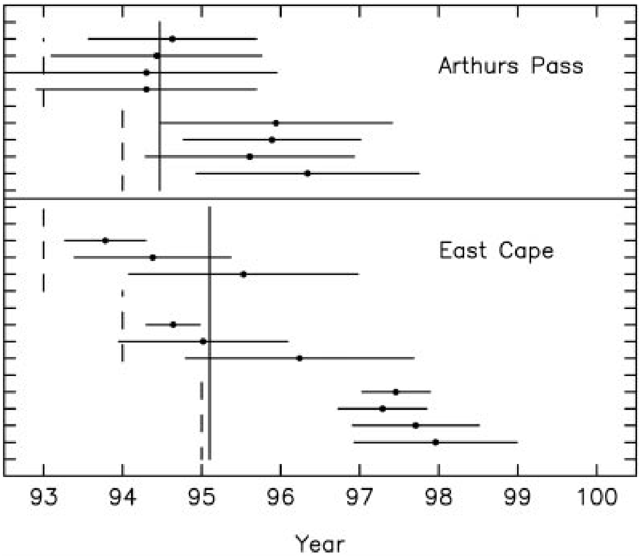

Figure 7. Average predicted tfs for clusters associated with the Arthur's Pass and East Cape earthquakes at three dates and for four region radii. Error bars are $\pm$ one standard deviation. Vertical dashed lines are the dates the predictions were made: 1993, 1994, 1995 January 1. Vertical solid lines are the dates of the two earthquakes. Within each set of results the region radius increases from top to bottom, 138, 170, 209 and 257 km, except for the 1993 and 1994 January 1 East Cape predictions for which there is no region of radius 138 km.

The results for a cut-off date of 1994 January 1 (Fig. 5), before the Arthur's Pass and East Cape events but after the Secretary Island event, are similar. Now, however, the average tf for the 'best' cluster near Arthur's Pass (again $R = 170$) is 95.89 (Fig. 7), over a year too late. The average tfs for the larger clusters near East Cape are 95.02 and 96.24, one very close and the other a year late. There are again some isolated positive grid points off the southeast North Island. Two points near the Secretary Island event, which has already happened, indicate that the fitting procedure is not interpreting that event as a main shock in these cases, but rather as a part of a continuing process towards a future event.

The results for a cut-off date of 1995 January 1 (Fig. 6), before the East Cape event but after the Secretary Island and Arthur's Pass events, show large, but disjointed (into two separate clusters for $R = 138$ km) clusters of positive grid points near the future epicentre of the East Cape earthquake, for all search radii. The average tfs (Fig. 7) are all too late, from about 2 to 3 years. In addition, the previously isolated positive grid points off the southeast North Island have now increased in number, moved inland, and formed clusters under the present definition. The tfs for these clusters are all in 1996, and there has been no large main shock in that region up to the present time.

Based on the results so far, we can tentatively set some criteria for a retrospective 'success'. First there must be at least one cluster of 10 or more positive grid points whose centre is within 1 search radius of the eventual main shock epicentre, for a search radius corresponding to a magnitude within 0.5 units of the main shock magnitude (such clusters are shown in Figs 4, 5 and 6). Second, given the variable performance as to forecasting tf, we simply say that the occurrence of such a cluster marks the beginning of a 'TIP' [time of increased probability, borrowed from the 'M8' method of forecasting (Keilis-Borok & Kossubov 1990)], which persists until the cluster disappears. Under these criteria the Secretary Island event was a failure, the Arthur's Pass and East Cape events were successes, and the outcome of the cluster off/near the southeast North Island has yet to be decided (it still exists as of 1999 January 1).

DISCUSSION AND CONCLUSIONS

The results of this study provide qualified support for the AMR model of earthquake occurrence, and show that, in retrospect, two out of three of the largest New Zealand earthquakes in the last decade could have been forecast according to the 'rules' specified above. The predicted tfs are not very reliable, however, resulting in the rather unsatisfactory situation of an open-ended TIP. Depending on how early an AMR pattern is detected, it could be many years before the event actually happens or the TIP ends without an event. Clearly, this situation needs to be improved.

The following questions also need to be answered.

(1) What is the effect of the magnitude threshold? There is some evidence that smaller earthquakes do not participate in the AMR pattern (Jaumé & Sykes 1999; Jaume, personal communication). If this is true then their use would only serve to de-emphasize any accelerating pattern. It is not clear how an increase in moment release should be expected to manifest itself—as an increase in the number of events above the magnitude threshold, as an increase in the maximum magnitude of the events, or as some combination of these. If the second process is dominant then it may provide an extra indication that the AMR process is in progress.

(2) Should search areas include events in distinct tectonic regimes? In this study the Taupo Volcanic Zone and the region to its northwest were excluded because of the frequent swarms associated with volcanic activity, which seem physically distant from the seismicity associated with plate convergence further to the east. Is a finer distinction necessary, say separating events in the strike-slip and thrust regimes along the east coast of the North Island? The numbers of events, however, may not permit this distinction. I have also restricted events in this study to be 'shallow' (less than 40 km deep). How would the inclusion of deeper events affect the results?

(3) How can the possibly overlapping critical regions for separate main shocks of similar size be resolved from one another? This problem may have prevented the grid-search procedure from detecting an AMR pattern before the Secretary Island earthquake, since there were events of similar magnitude in the Fiordland region in the previous decade. The southeast displacement of the cluster of positive grid points associated with the Arthur's Pass earthquake is another example: for search regions enclosing the Inangahua earthquake of 1968, magnitude 6.8, 130 km to the north of Arthur's Pass, the AMR pattern would be destroyed. In that case, it may be that restarting the fitting procedure after the Inangahua event would have helped.

(4) How do catalogue errors or inhomogeneities affect the results? Magnitude errors in the New Zealand catalogue undoubtedly exist due to the sometimes small number of reporting stations, especially before about 1986. When there

are only a small number of events within a search region these errors may be important, and lead to errors in the forecast of tf.

(5) Is the AMR pattern self-similar; that is, do all earthquakes count as defining main shocks with associated precursory seismicity on suitably smaller faults?

(6) What is the effect of 'sharp' criteria in various aspects of the AMR method? For example, in test 1 an AMR pattern was found for the Secretary Island event but the grid-search procedure found none. This may be because the parameters used in the grid-search procedure were not close matches to those found in test 1, and only a finer search would succeed. Moreover, the sharp criterion of an rms ratio of less than 0.5 may have played a part. Perhaps the use of fuzzy logic would be helpful.

(7) Is a circular precursory region the best choice? It may be that the tectonic 'grain' should be taken into consideration, perhaps using elliptical regions with long axes parallel to the grain.

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