28 June 2012

Final Report on Project 08/TVH564:
Physical and statistical models for the seismological properties and a temporal evolution of earthquake sequences (swarms) in the Central Volcanic Region, New Zealand

Layman's Abstract

We have investigated earthquake sequences (swarms) in the Central Volcanic Region (CVR), NZ. A new CURATE method was developed to systematically identify these sequences by comparing observed seismicity rates to an average rate. This new method differs from other clustering techniques in that it does not make assumptions about physical processes or the idea that earthquakes are caused by preceding seismicity. The CURATE method allowed us to investigate correlations between sequence parameters (duration, area, number of events, and largest magnitude) and to study temporal evolution of individual sequences. We have found that swarm sequences have a few unique time patterns that are distinct from mainshock-aftershock behavior. These insights along with further investigations may facilitate future forecasting of swarm sequences as they develop. There are a variety of potential applications for investigations of physical process and hazard assessment. In particular the CURATE method will be a good tool for identifying rate changes and sequences at a range of local and regional scales by providing a context in which to judge 'normal' and 'anomalous' behavior, allowing objective investigations of swarm parameters and swarm types that may lead to advances in swarm models and regional earthquake forecast models.

Introduction

The major accomplishment of this project is the development of a new method to identify earthquake sequences. This method differs from other methods in that it does not rely on assumptions about physical processes or the idea that earthquakes are caused by preceding seismicity. The freedom from physical causality assumptions allows us to categorize swarm sequence more systematically. The attached paper details the method and compares it to standard clustering and declustering techniques.

This method goes a long way towards giving seismologists quantitative tools to investigate earthquake sequences parameters (especially swarms). We think this tool will be useful in cataloging sequence activity and with further development and use may be useful for forecasting sequences as well. Though using it for forecasting is not possible at this time it can be used now to identify anomalous behavior. The CURATE method has a variety of potential applications for investigation of physical processes and hazard assessment. A few examples of our initial investigations using this method are given below.

We have undertaken testing of the main parameters of identified sequences including duration, largest magnitude, number of earthquakes, and area. There is no strong overall correlation between any of these key parameters. There is some indication that these parameters may be slightly better correlated than in mainshock-aftershock dominated catalogs but this conclusion needs further testing.

Time of occurrence of the largest magnitude

To investigate the position in time of the largest magnitude event, M_{max}, we first normalize the time of the sequences, with the beginning of the sequence set to zero and the end set to one. This allows us to make a relative comparison between sequences of different durations. The cumulative distribution function of the position in time of M_{max} is shown for 163 sequences from the CVR with a minimum number (N_{min}) of four earthquakes (figure 1). The normalization of duration requires each sequence to have an earthquake at t=0 and t=1, which increases the probability of observing the largest earthquake at those times. If the distribution of M_{max} were actually uniform in time, the fraction of sequences at t=0 and t=1 would each be approximately 1/(2 N_{min}). For N_{min}=4, this is 1/8 or 12%. This is a good approximation of the observed effect in figure 1. Despite this artifact there is still a clear probability increase above this value in the first ten-percent of a sequence (by duration). After the initial increase, the cumulative probability becomes approximately linear with a shallower slope, implying a nearly uniform distribution over the rest of the duration. This is a simple way to visualize our basic understanding about types of earthquake sequences. If the largest magnitude earthquake does not occur early in the sequence we generally assume that earthquakes in the sequence will be relatively similar in magnitude [*Mogi*, 1963]. This leads to the conclusion that the where the largest earthquake does not occur early in the sequence it is unlikely to be the dominant driver of sequence. The nearly uniform distribution will provide us with a quantitative way to calculate the likelihood of early large events causing the sequence.

The timing of the largest earthquake in a sequence is important not only for emergency managers, but may also have implications for the analyses of physical processes. The higher probability for M_{max} to occur in the first 10% of the sequence is unsurprising since our catalog includes some mainshock-aftershock and foreshockmainshock-aftershock sequences which necessarily have the mainshock early. To see if mainshock-aftershock sequences are the sole cause of this discrepancy, we examine sequences which fit the following criteria: a magnitude separation of at least 0.5 between the largest and second largest earthquakes [*Bath*, 1965; *Sherburn*, 1992] and the largest earthquake happening within the first third of the earthquakes in a sequence. There are seven such sequences in our whole catalog, and three of those sequences have at least ten earthquakes. These seven sequences are not enough to explain the 20% probability of a very early M_{max} or the nearly 40% probability of it occurring during the first tenth of the sequence. A similar inclination for M_{max} to occur early in the sequence was observed by Vidale and Shearer [2006] in their study of seismic bursts. It may be explained by the ability of all earthquakes to trigger other earthquakes. It makes sense that if the largest earthquake does not drive the sequence but there are multiple earthquakes of similar magnitude, the probability of observing the largest earthquake at any point in the sequence will be partially dependent on the percent of earthquakes which occur over the same time. Figure 1 shows that even if we were able to estimate the duration of a sequence, the probability of having an earthquake as large as or larger than those already observed remains almost constant until the sequence is over. We intend that this finding will go in a future paper focused more on physical mechanisms and forecasting of swarm sequences.

Regional Application

In addition to using the CURATE method on the whole CVR catalog we have undertaken the testing of several specific areas where sequences occur. Here we show examples of how regional sequence catalogs might be used. We present initial observations and potential applications of the CURATE method around the Waiouru, Ruahpehu (including Erua/Raurimu fault), Lake Taupo, and Wanganui regions (fig. 2).

While Wanganui is not within the volcanic zone, its position south of the Taranaki-Ruapehu line, its known propensity for swarms, and its spatial proximity to slow-slip events around Kapiti and Manawatu make it an interesting place to analyze. Triggering and seismicity related to slow-slip events in New Zealand has been recognized as an increase in very low magnitude earthquakes [*Delahaye et al.*, 2009]. The CURATE technique will allow us to see if there are broad scale changes in larger magnitude events. Note in Figure 3 that while the cumulative number of events at Wanganui looks more steady than the other three regions the CURATE shows substantial fluctuations indicating that the temporal clustering is changing on short time scales that are not visible through the background rate. These fluctuations could be compared to the timing of slow-slip or other tectonic processes. Understanding how slow-slip events affect the crust may help us interpret the complete volcanic cycle.

The Waiouru and Raurimu Fault (Erua) earthquake clusters, to the East and West of Ruapehu respectively, have both been cited as potential areas that show stress changes associated with volcanic activity at Ruapehu (Hurst and McGinty, 1999; Hayes et. al., 2004). While there is only one major eruptive episode (two eruptions) during the recorded earthquake catalog it is worth comparing these two locations to know the possible or expected behavior for future activity. Figure 2 shows the CURATE plots for all four subset areas. Both the Ruapehu and Waiouru regions have the biggest CURATE increase in 1997, following eruptive activity. However figure 3 shows that there was spatial-temporal clustering at Ruapehu preceding the eruptive activity while that at

Waiouru all follows the main eruptions. This may be specific to the direction or location of magmatic intrusion during the 1995-1996 eruptions. It might also indicate that the Waiouru zone is unlikely to be as useful for monitoring as the Raurimu fault. It is interesting to note that the Lake Taupo and Wanganui regions also have increases in activity following the eruptions. Although the increase continues in time after activity settles down at Waiouru and Ruapehu/Raurimu regions, and it is not dominant feature in either of these catalogs, it may indicate that there are broad scale changes in the subduction zone which causes widespread activity (stress re-adjustment) following the eruptions.

Another possible monitoring application would be to use the CURATE plots to look for simultaneous upticks in activity in these areas around Ruapehu. These observations can be made without the CURATE method, but the use of the method facilitates such applications and provides a standardized quantitative element that is often absent in studies of earthquake swarms.

Lake Taupo can be seen to exhibit an entirely different behavior with low overall seismicity rates (figs. 2 and 3). Large events dominate this low background environment. These swarms do not tend to have as many events or as high a rate as other locations in the CVR, so they do not show up in the large scale sequence study. Using subset data like this (especially in areas where a lower magnitude of completeness is possible) may allow us to study regions in more detail. A detailed small scale application of the CURATE method could be linked with GPS or gas measurement data.

Haroharo Region

We have used the overall sequence catalog produced by the CURATE method to look at sequences around the Haroharo area. Our method identifies three sequences of more than fifty earthquakes from 1997 through 1998. The three sequences occur on either side of Lake Tarawera. One of the 1998 sequences was described by Hurst et al. [2008]. While there were not three component stations at the time of these swarms we have carried out a calculation of seismic velocity ratios (Vp/Vs) around the swarms (fig. 4) using phase picks in the Geonet catalog. This initial investigation show possible changes in the Vp/Vs ratio at individual stations following the first swarm onset. Changes in Vp/Vs may indicate fluid signatures (slower S-wave velocities) and recent studies have suggested they may also be indicative of pressurized gases (Unglert et. al. 2011, and references therein). While we see some changes in Vp/Vs ratios at the time of this swarm we need to test for significance and may require additional phase picks and further investigation.

Possible Fluid Diffusion

We have also looked at a few larger sequences in the CVR for any evidence of fluid diffusion patterns. While initial testing has not revealed any obvious patterns, we are continuing a more detailed study and new studies around the L'aquila region in Italy suggest it may be possible for parts of a sequence to exhibit a fluid diffusion signature while another geographic portion in the same sequence behaves differently [*Malagnini et al.*, 2012]. Hainzl and Fischer [2002] proposed using probability density of inter-event times as a way to look for fluid signatures. Hurst et al. [2008] plotted inter-event time distributions after Hainzl and Fischer [2002] but found that only one of three studied TVZ sequences matched the expected distribution; however some sequences lacked enough data to perform the analysis.

Temporal Evolution

Despite the lack of obvious fluid diffusion signatures our attempts to find them led us to one of the most interesting discoveries in the project. Because the probability density calculation requires a large amount of data it is not suitable for use with the high magnitude of completeness in the TVZ. We decided to use inter-event times in a different way. For each individual sequence we plot the average inter-event time at the time of each earthquake in the sequence. This shows general trends in rate and although it cannot be applied to very small sequences (~ten events or less) it can be used on much smaller sequences than the probability density method. Looking at these average inter-event times we discovered three distinct patterns (fig. 5). One corresponds to mainshock-aftershock behavior, but the other two have not been documented before. There is a fourth group of sequences which do not demonstrate a specific pattern at all. The variety of patterns also confirms that many different processes may cause swarm sequences. Swarms are often thought to have little to no specific temporal development, which makes them difficult to forecast. If these observed patterns in rate are real, then they may show for the first time that there may be forecastable elements to some swarm sequences. Using this technique may allow us to better categorize different types of swarm behavior.

This work has given us the tools to investigate sequence occurrence and physical process more thoroughly. Initial analysis of the sequence data in the CVR has already revealed several potentially new swarm characteristics. We are continuing our investigation of swarms and other sequences in the CVR and throughout New Zealand. We would like to thank EQC for their funding of this work. The thesis containing our ongoing work will be submitted in the next twelve months and a copy will be provided to EQC.

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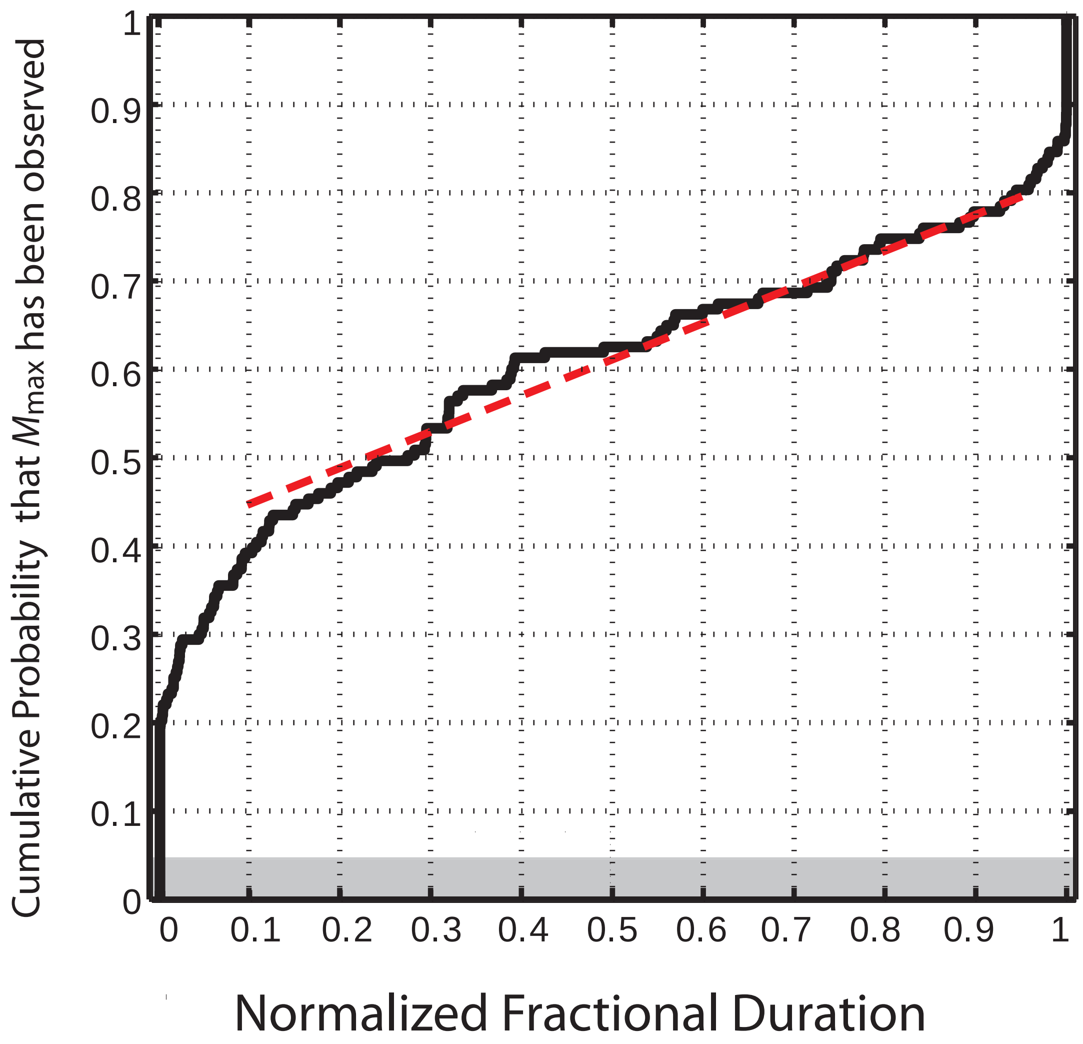

Figure 1. Cumulative distribution function of the fraction of the duration that has occurred at the time of the largest magnitude earthquake (Mmax) for 163 sequences with at least four earthquakes. The dotted line is for comparison to a straight line fit only. The gray box indicates the percent of sequences which are classified as mainshock-aftershock sequences.

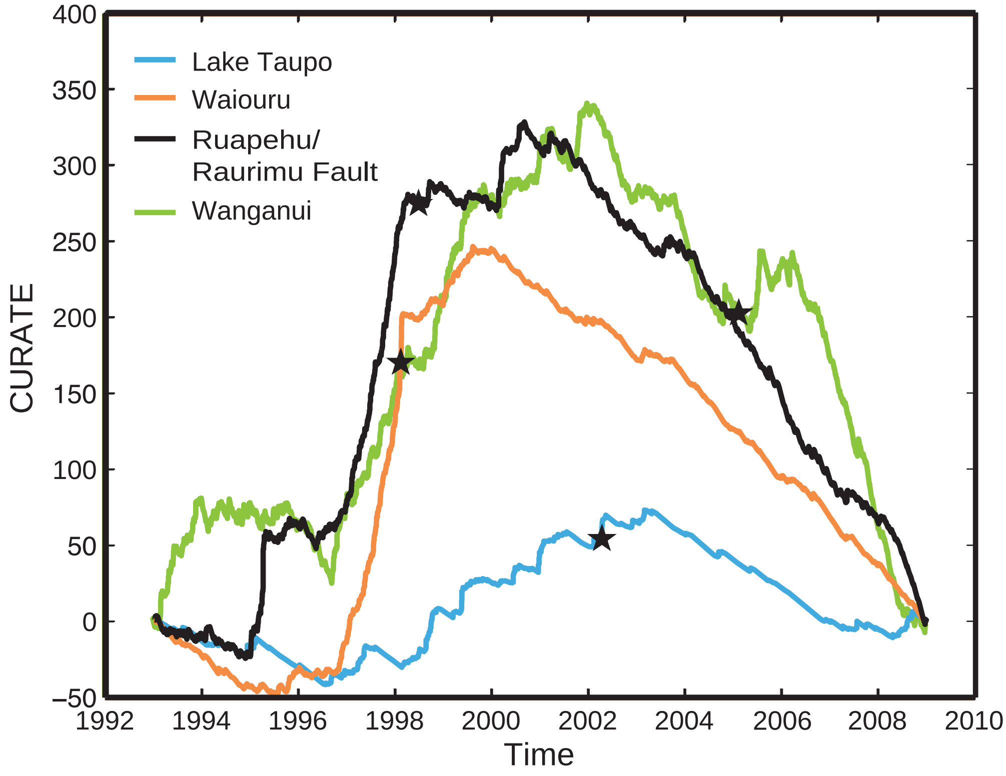

Figure 2. CURATE plots for regions in New Zealand. Black stars indicate the largest magnitude earthquake in each regional catalog. Note that three regions, Waiouru, Ruapehu, Wanganui, showed similar increases in rate during 1997-1998, suggesting a common causal relation throughout the central North Island.

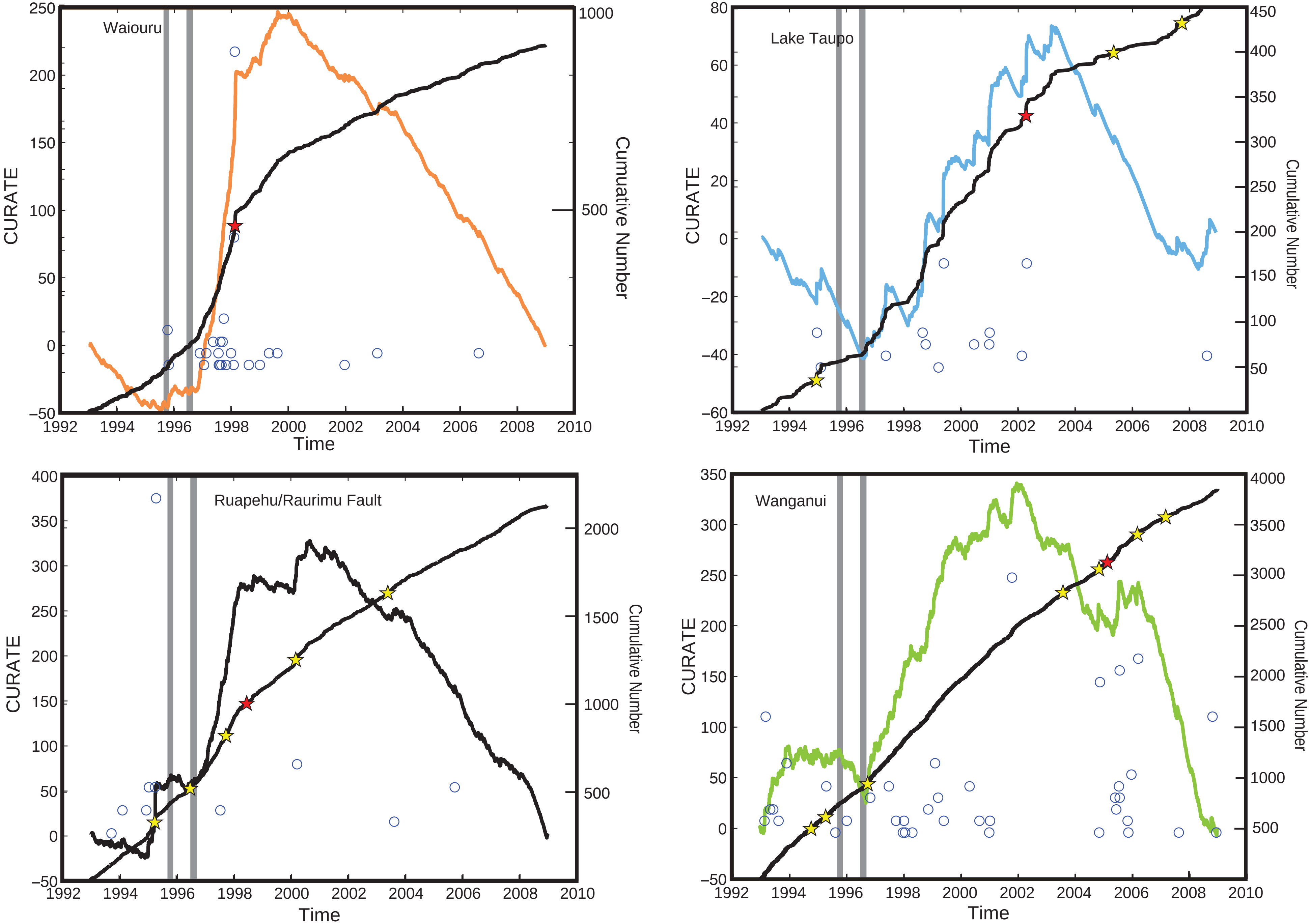

Figure 3. CURATE with cumulative number and sequences with time. Black curves in all plots show the cumulative number of events for each subset catalog. Blue circles show the time of sequences identified by the CURATE method. The CURATE and sequence identification give information that is hard to see by eye from the cumulative number plots. Shaded regions mark the time of eruptions at Ruapehu: September-October 1995, and June-August 1996. Yellow stars indicate all earthquakes >4.5, and Red stars indicate the largest earthquake in each regional catalog (also above 4.5).

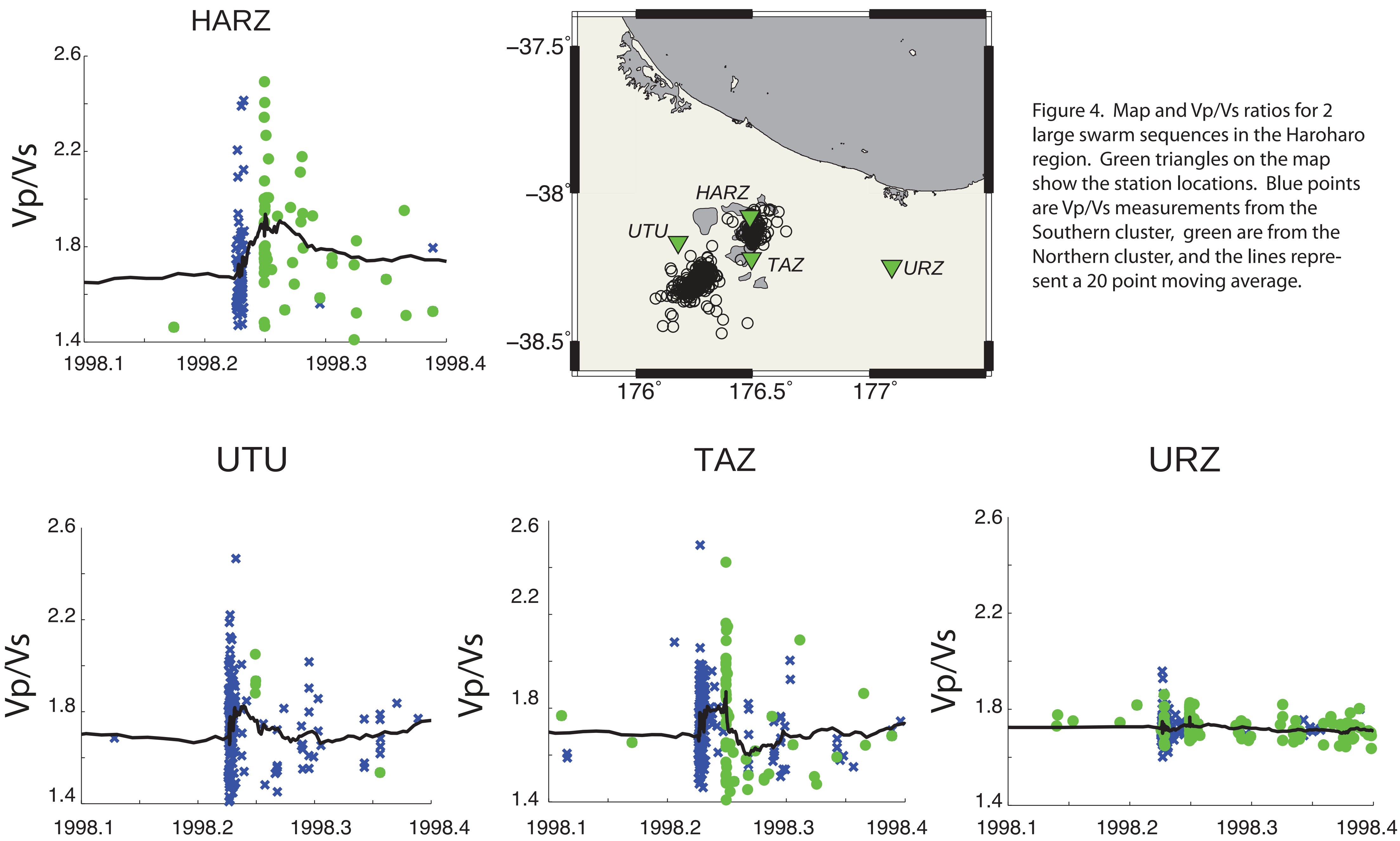

Figure 4. Map and Vp/Vs ratios for 2 large swarm sequences in the Haroharo region. Green triangles on the map show the station locations. Blue points are Vp/Vs measurements from the Southern cluster, green are from the Northern cluster, and the lines represent a 20 point moving average.

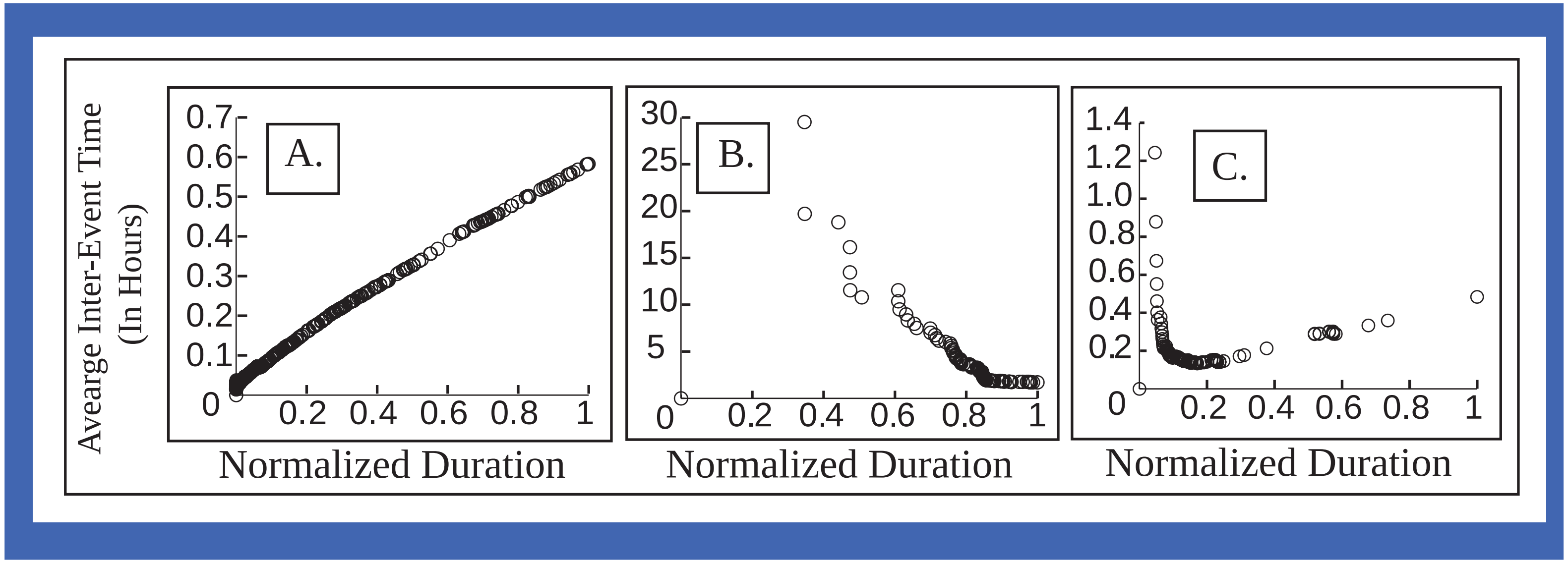

Figure 5. Three observed patterns of inter-event times. A) typical mainshock aftershock sequence. B) and C) other sequence/swarm types.