EQC-TVH 2-8 Scaling law and repeat times for Ruapehu volcanic events

A.D. Jolly S. Sherburn

GNS Science Consultancy Report 2009/20
February 2009

CONFIDENTIAL

BIBLIOGRAPHIC REFERENCE

Jolly, A.D.; Sherburn, S. 2009. EQC-TVH 2-8 Scaling law and repeat times for Ruapehu volcanic events, *GNS Science Consultancy Report* 2009/20. 18p.

CONTENTS

FIGURES

TABLES

EXECUTIVE SUMMARY

We have completed a study of the scaling laws of earthquakes at Ruapehu volcano using volcanic earthquakes recorded by GeoNet for the period 2000 to 2007. We examined the frequency-size distribution for these volcanic earthquakes and obtain a *b*-value of 1.0. The frequency-size distribution appears to follow closely a power law over the magnitude range 1.0-3.2 M_L. Based on these data we also obtain a recurrence time for earthquakes > 3.0 M_L of about 2.5 years assuming a Poisson process and power law scaling. This important magnitude threshold has been shown to be about the minimum for surface expressions of volcanic activity. We also examined the inter-event times for the same group of earthquakes and find that the probability of an earthquake is much higher than normal if an earthquake has occurred within the previous 10 days. We find that volcanic earthquakes at Ruapehu have highly variable durations with one subset of earthquakes having short durations (associated with a classical long-period source process), and longer duration earthquakes (some lasting several hours) which include post-event tremor or volcanic earthquakes embedded within a tremor episode. Examination of the long duration pulses using a duration-size distribution method shows that the volcanic earthquakes obey a power law distribution, while the tremor obeys an exponential law. Our results can be used to inform the decision making process regarding the time-varying volcanic hazards at Ruapehu volcano.

INTRODUCTION

Efforts to assess hazards from volcanic eruptions are hindered by an incomplete understanding of scaling relationships in volcanic systems and the physical mechanisms behind those scaling laws. Global analyses show that volcanic eruption sizes obey power law scaling over several orders of magnitude [S*imkin*, 1993], while volcanic tremor amplitude follows an exponential scaling law [*Benoit et al.*, 2003].

At Ruapehu volcano, volcanic earthquakes, having local magnitudes greater than about 3.0, are strongly linked with volcanic eruptions. Smaller volcanic earthquakes also occur, but these events have no obvious surface expression, and may indicate non eruptive conditions or unobserved sub-aqueous eruptive activity within Ruapehu Crater Lake. Volcanic earthquake activity is also swarm-like in character, with the occurrence of an event increasing the likelihood of further activity.

Our objective is to develop conceptual models of volcanic earthquake activity and to use these models to assess the likelihood of eruptive activity in a probabilistic way. This analysis will provide a basis for estimating risks in the near volcano environment based on long term event probabilities and will improve risk assessment in the immediate aftermath of a volcanic eruption.

DATA AND METHODS

For our analysis, we used volcanic earthquakes recorded by GeoNet for the period 2000 to 2007. In the initial evaluation, we found that the observed events had a wide range in event duration (Figure 1). A large number of events had relatively short event durations (< 50 s) while other events had longer durations (>> 1 minute). It is likely that the shorter duration events are classical long-period earthquakes while the longer duration events promote some tremor excitation. This mixture of event types is a consequence of analyst interpretation for the catalogue which included all earthquakes within 5 km of the crater lake and which had dominant 2 Hz frequencies and/or indistinct earthquake phases. The events with the longest durations include the 4 October 2006 sub-aqueous eruption and the 25 September 2007 phreatic eruption which had durations of about ~ 250 seconds. Because the earthquakes at Ruapehu contain features of both classic long-period earthquakes and extended tremor-like events (tremor bursts), their scaling process may be examined using either discrete event or continuous process methods.

We approached our scaling analysis by using two separate tools. Firstly, we used the frequency-size distribution (FSD) given by the *Gutenberg and Richter* [1954] relation

$$LogN = a - bM, \quad (1)$$

where the frequency of occurrence N is related to the earthquake size M via a parameter describing the slope b of the frequency-magnitude relation, which is useful in analyzing scaling of discrete earthquake events, and a is the productivity of the data. Secondly, the duration-size distribution (DSD) [*Aki and Koyanagi*, 1981; *Benoit et al.*, 2003] is a useful way of describing scaling of phenomena having extended durations like volcanic tremor. *Benoit et al.* [2003] used an exponential law of the form

$$d(D_R) = d_t \exp(-\lambda D_R), \qquad (2)$$

where d is the duration of the signal ≥ the amplitude as given by the reduced displacement, D_R, d_t is the total duration of the given event, and the slope of the distribution is given by λ.

For the FSD data we also examined earthquake inter-event times. We evaluated the time between given earthquakes at a lower time resolution of 1 day. We filtered the data by including increasing magnitude data sub-sets to examine the effects of magnitude. We also applied the inter-event time analysis to an earlier unpublished data set compiled by former DSIR geophysicist John Latter.

RESULTS

Scaling

FSD

Examining the FSD we obtain a *b*-value of 0.993 +/- 0.05 for volcanic earthquakes from 2000-2007 (Figure 2). The magnitude of completeness for this calculation is 1.0. The fit of the data to a power law relation is quite good over the 2 orders of magnitude observed in our data set. We can also obtain a recurrence time for the given data set using the equation [*Weimer and Wyss*, 1997]:

$$T_r = \Delta T / 10^{(a-bM)}, \qquad (3)$$

where ΔT is the recording period of the catalogue. Given ΔT = 6.6, a=3.4, b=0.99 and a magnitude of 3.0, we obtain T_r ~ 2.5 years assuming a Poisson process and scale invariance of the distribution. This means an earthquake having M_L greater than or equal to 3.0 is expected every 2.5 years assuming a Poisson process (implying independence of individual earthquakes) governed by power law earthquake scaling. An important caveat must be stated with this calculation. If the process governing the scaling of volcanic earthquakes at Ruapehu is not scale invariant above some relevant magnitude (i.e. too few earthquakes above magnitude 3) then the observed recurrence time will not accurately reflect expected earthquake frequency.

DSD

In examining the DSD of Ruapehu volcano, we are limited to longer duration events or alternatively multiple events within tremor. We have examined the DSD for longer duration earthquakes and focus specifically on the 4 October 2006 and 25 September 2007 events. For our analysis, we calculate the DSD using the reduced displacement. This measure has the advantage in that it corrects for station distance and can thus be compared between several stations at the volcano or even between tremor occurring at separate volcanoes. We use the formulation of reduced displacement for body waves e.g. [*Benoit et al.*, 2003] of the form

$$Dr = \frac{ArM}{2\sqrt{2}}, \qquad (4)$$

where *A* is the maximum amplitude of the waveform, *r* is the geometrical spreading correction, and *M* is the system magnification. We calculate D_R for 6 second windows in the frequency band (0.5 to 10 Hz) obtaining a distribution over an event waveform envelope (Equation 4). Our selection of 0.5-10 Hz follows from Benoit et al. [2003] while the selection of a six second window is arbitrary but fits with order of magnitude time scaling of D_R measurements (i.e. we compute 6 s, 60 s and 600 s D_R windows (analysis not shown)). We then examine the DSD (Equation 2) over windows of sufficient total duration. We find that the D_R values obtained for the two eruptions are in line with worldwide observations at volcanoes. The values obtained at station DRZ are somewhat higher than those obtained at more distant stations (FWVZ, WPVZ) probably due to the closer station residing in the near-field and hence not behaving according to a $1/r^2$ geometrical decay approximation. We anticipate that the more distant stations provide a more robust absolute D_R value which can be compared to volcanoes worldwide (Table 1). The calculated results for FWVZ and WPVZ are consistent with those obtained by *Sherburn et al.* [1999] for the 1995-1996 eruption sequence. The details of the post eruption tremor cannot be seen with greater distance from the volcano. To determine if the tremor scaling obeys an exponential or power law relation, station DRZ (< 1 km) provides more information than more distant stations, even though D_R values are probably not absolutely correct (Figures 3-6).

Table 1 Reduced displacement for recent eruptive events.

	4 October 2006	25 September 2007
DRZ	24.75	No data
FWVZ	7.01	10.44
WPVZ	12.60	18.62

To examine the DSD for the 2006 and 2007 eruptions, we used a moving window analysis and the 6 second reduced displacement data. We tried several DSD total duration windows in our analysis and found that moving windows with 400x6 second sampling (i.e. 40 minute windows with no overlap) produced robust observational results. Results with longer or shorter windows were similar, however. For each window, we regressed the DSD observations using a weighted least-squares assuming both an exponential and power law distribution (Figures 3-4). We used R^2 as the test statistic to determine which distribution fits the observations better. For the 4 October sub-aqueous eruption, the amplitude data followed a power law, while the post eruption tremor fitted the exponential law better (Figure 3, 4, 5). Post eruption volcanic earthquakes are also observed (arrows in Figure 3 and 4) and tend to follow a power law distribution. The 25 September eruption (Figure 6) was not recorded completely on station DRZ due to station failure caused by the eruption. The more distant stations (FWVZ and WPVZ) do not record the weak post eruption tremor strongly enough to be observed on the wide band reduced displacement measurements. Regardless, the eruption favours a power law over an exponential law (Figure 6) for station FWVZ.

Earthquake inter-event times

We examined earthquake inter-event times [e.g. Hurst et al., 2008] to determine if the occurrence of a given earthquake increased the likelihood of additional earthquakes. For the analysis we examined all Ruapehu volcanic earthquakes in the GeoNet CUSP catalogue since 2000 and determined the time between events by grouping the inter-event data into 1 day bins. For this catalogue period, there is a strong swarm from April to May 2003. To test the effect of this swarm on inter-event times, we examine the total data set and then the data set excluding the 2003 swarm (Figure 7). Results show that there is strong clustering at earthquake inter-event times shorter than 10 days. The strongest clustering is at an interval of one day or shorter with some clustering persisting to ~10 days. Beyond 10 days all inter-event times are equally likely so there is no clustering. The observations occur in both the complete data set and the de-clustered data set.

Because larger magnitudes accompany eruptions and the period 2000 – 2007 has few eruption and few large volcanic earthquakes, an unpublished list of volcanic earthquakes (M>=3) compiled by John Latter for 1971 – 1990 was used to study larger events. The same procedure was applied and the same short-term clustering seen for smaller events for 2000 – 2007 is also apparent in the older, larger data set (Figure 8). Of 44 inter-event times 21 are <= 10 days (almost 50%) and 11 (25%) are <= 1 day. The older unpublished data also identifies which events accompanied eruptions. If we consider only eruptions (Figure 9) the data set is much smaller but 5 of 14 data points are <= 1 day (1/3) and 8 of 14 are <= 10 days (more than 50%). These results suggest that there is significant clustering of volcanic earthquakes for periods less than 10 days. This clustering is most obvious for periods <= 1 day, but persists to about 10 days, beyond 10 days there is no obvious clustering.

DISCUSSION AND CONCLUSIONS

This research points to several features of scaling at Ruapehu volcano. The FSD data show that volcanic seismicity for the period April 2000 to November 2007 follow a power law distribution having b = 1. This result is interesting given that most volcanic systems have earthquakes which have higher b-values (usually greater than 1.5) [*Wiemer and McNutt*, 1996]. Our preliminary DSD results show that the seismic envelopes of volcanic earthquakes also tend to follow a power law distribution while the tremor tends to follow an exponential law. *Benoit et al.* [2003] showed that the DSD for different types of tremor tended to follow an exponential law and suggested that this implied a scale-bound process. Our DSD results suggest that discrete volcanic earthquakes at Ruapehu may not reveal a bounded upper limit in size which is reflected in the DSD results. While earthquake coda decay is generally observed to follow an exponential process, we surmise that the volcanic earthquake generation process at Ruapehu is not scale bound for the observed range of earthquakes.

Our results offer some practical application to understanding hazards at Ruapehu volcano. The present study suggests that potential eruptive activity, associated with volcanic earthquakes larger than magnitude 3, has a recurrence time of ~2.5 years assuming a power law relation and that M_L 3.0 or larger earthquakes accompany surface activity. We find, however, that the probability of a volcanic earthquake increases for about 10 days if a volcanic earthquake has already occurred. Likewise, there is a 0.5 probability of a volcanic eruption within 10 days of a previous eruption.

We surmise that a Poisson process can be used to describe volcanic earthquakes at Ruapehu for time-scales longer than 10 days, but that non-Poisson processes increase the likelihood of activity over shorter time periods.

REFERENCES

Aki, K. and Koyanagi, R. Deep volcanic tremor and Magma Ascent Mechanism under Kilauea, Hawaii, *J. Geophys. Res.*, 86,B8,7095-7109, 1981.

Benoit, J.P., McNutt, S.R. and Barboza, V. The duration-amplitude distribution of volcanic tremor, *J Geophys. Res.* , *108*(B3), 2146, doi:10.1029/2001JB001520. vol, num, 2003.

Gutenberg, B. and Richter, C.F. Magnitude and energy of earthquakes, *Ann. Geophys*., 9,1-15, 1954.

Hurst, T., Bannister, S., Robinson, R. and Scott, B. Characteristics of three recent earthquake sequences in the Taupo Volcanic Zone, New Zealand, Tectonophysics, 452, 17-28, 2008.

McNutt, S.R. Volcanic tremor amplitude correlated with eruption explosivity and its potential use in determining ash hazards to aviation, *USGS Bull*., 2047, 377-385, 1994.

McNutt, S.R., Tytgat, G.C. and Power, J.A. Preliminary analysis of volcanic tremor associated with volcanic eruptions of Crater Peak, Mount Spurr volcano, Alaska, in *USGS Bull, 2139* The 1992 eruptions of Crater Peak vent, Mount Spurr volcano, Alaska T.E.C. Keith, ed. 161-177, 1995.

Simkin, T. Terrestrial volcanism in space and time, *Ann. Rev. of Earth and Planet. Sci.*, 21, 427-452, 1993.

Sherburn, S. Characteristics of earthquake sequences in the Central Volcanic Region, New Zealand. *New Zealand Journal of Geology and Geophysics*, 35: 57-68, 1992.

Sherburn, S., Bryan, C.J., Hurst, A.W., Latter, J.H. and Scott, B.J. Seismicity of Ruapehu volcano, New Zealand, 1971-1996: A review, *J. Volcan. Geotherm. Res.*, 88, 255-278, 1999.

Wiemer, S. and Wyss, M. Mapping the frequency-magnitude distribution in asperities: An improved technique for calculating recurrence times, *J. Geophys. Res*., 102, 15115-15128, 1997.

FIGURES

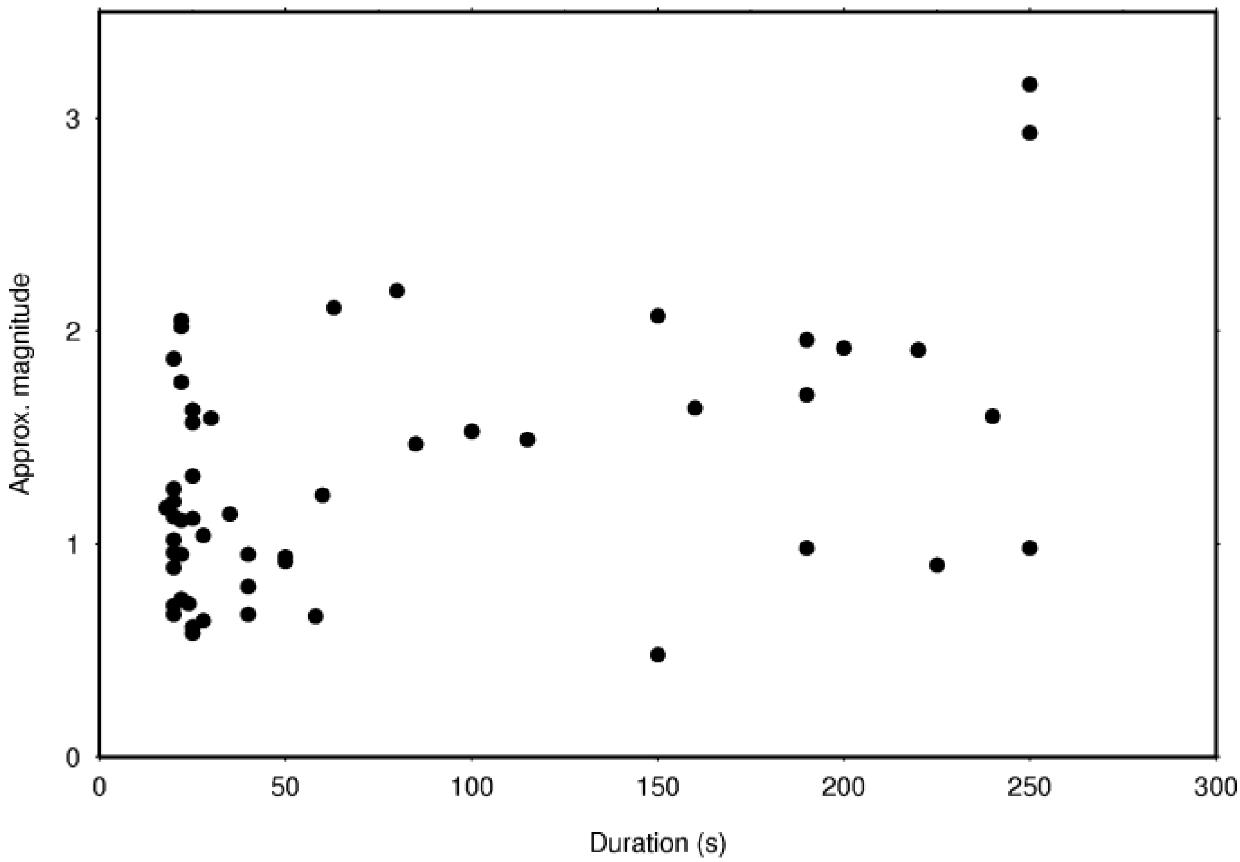

Figure 1 Duration of volcanic earthquakes vs magnitude at Ruapehu.

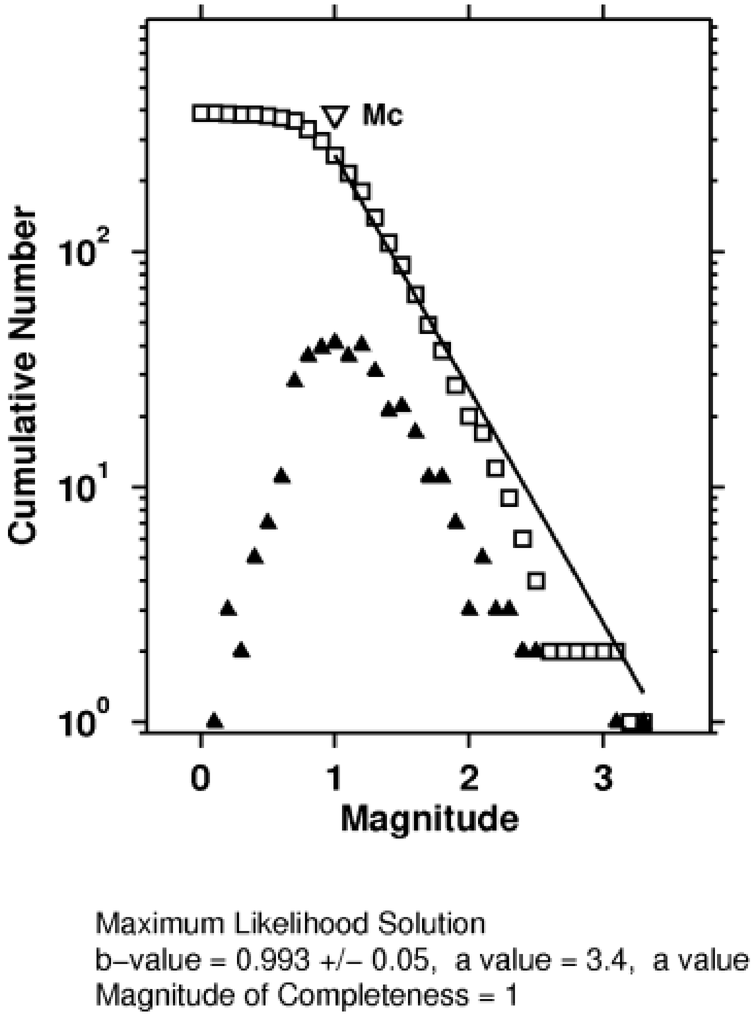

Figure 2 Frequency-size distribution of volcanic earthquakes at Ruapehu.

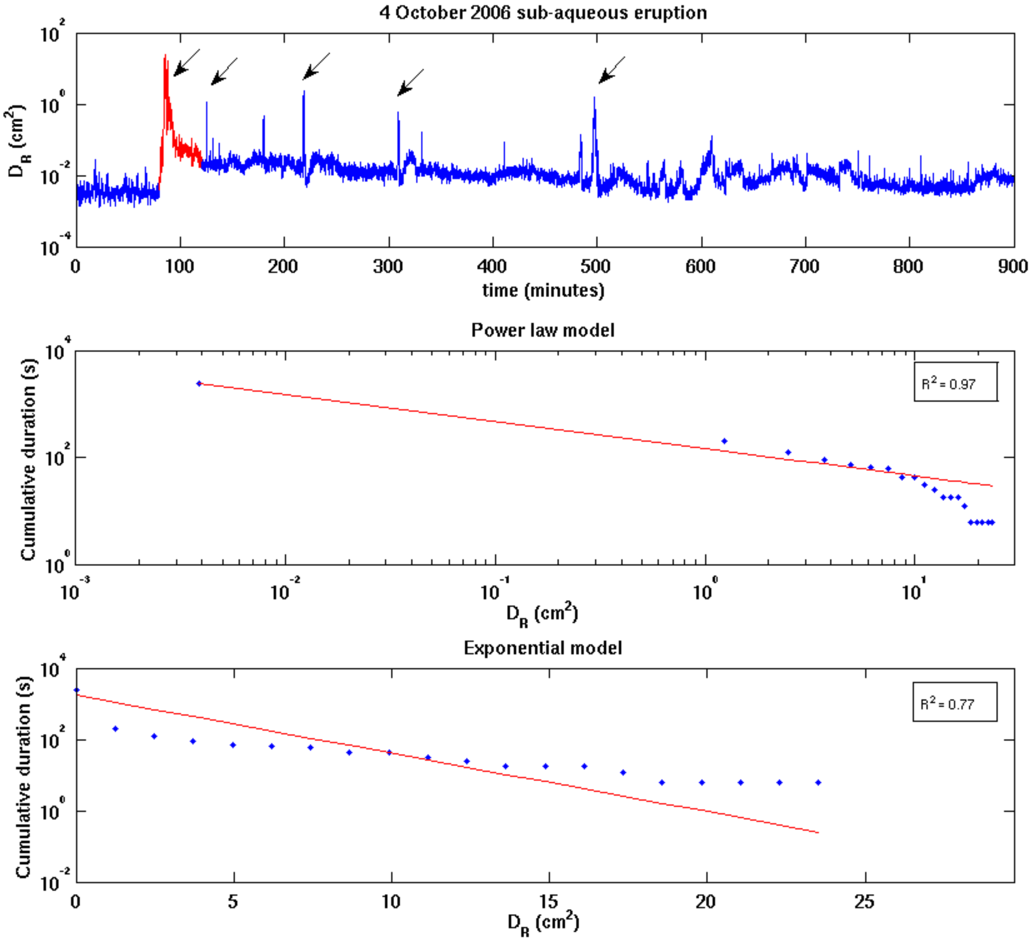

Figure 3 The 4 October 2006 sub-aqueous eruption recorded at station DRZ (top-red) and example weighted least-squares regressions for power law (middle) and exponential law (bottom). Goodness of fit is given by R^2. Arrows indicate measured volcanic events within post-eruption tremor.

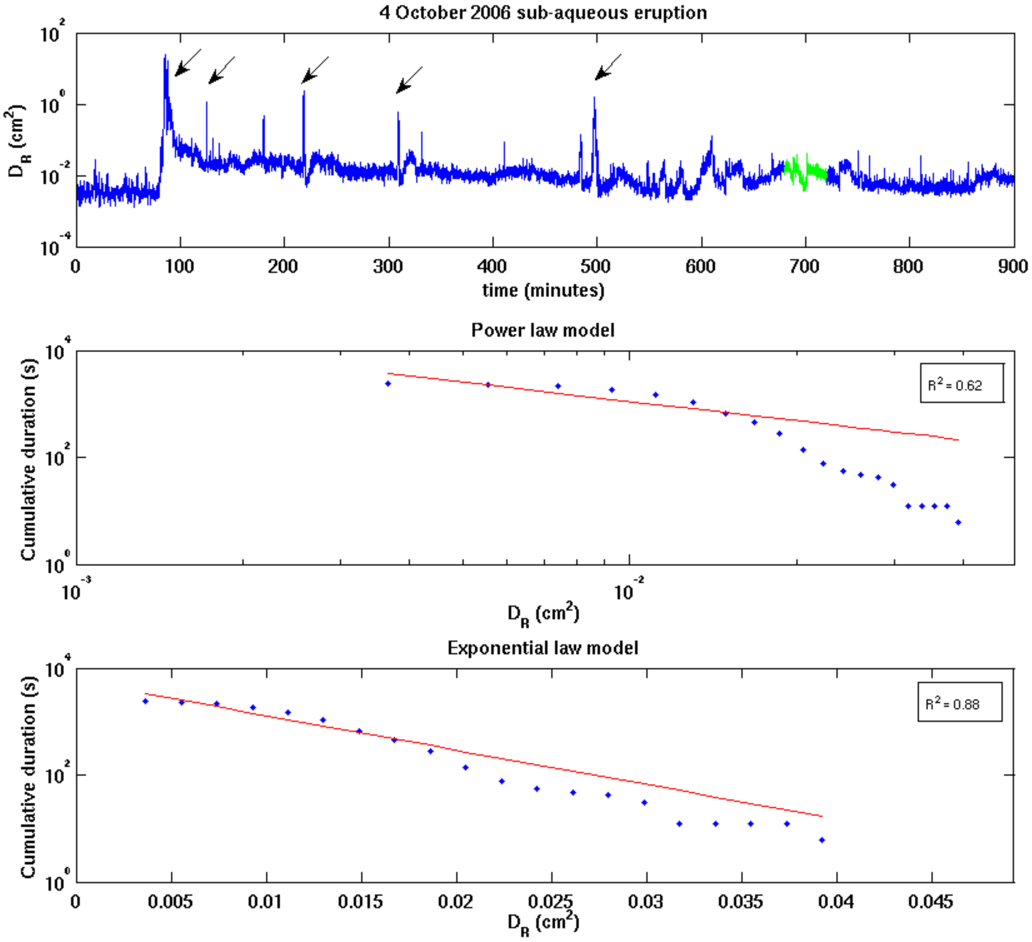

Figure 4 The 4 October 2006 post-eruption tremor (top-green) and example weighted least-squares regressions for power law (middle) and exponential law (bottom). Goodness of fit is given by R^2. Arrows as in Figure 3.

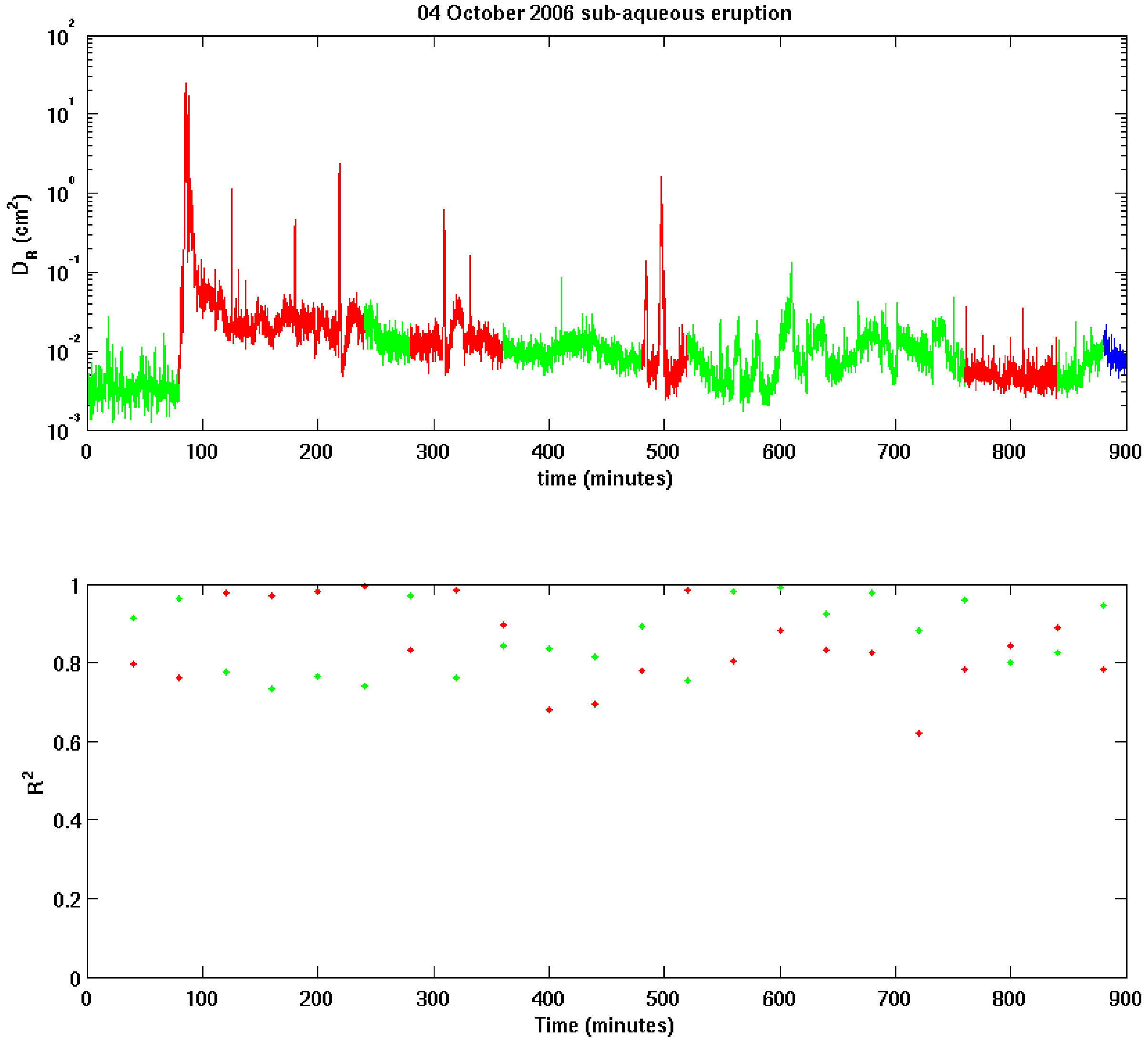

Figure 5 Reduced displacement for 4 October 2006 subaqueous eruption (top) using station DRZ. Red segments have DSD regressions which follow a power law while green segments follow an exponential law relation based on R^2 test statistic (bottom). Regressions were calculated as in Figure 3 and 4 above.

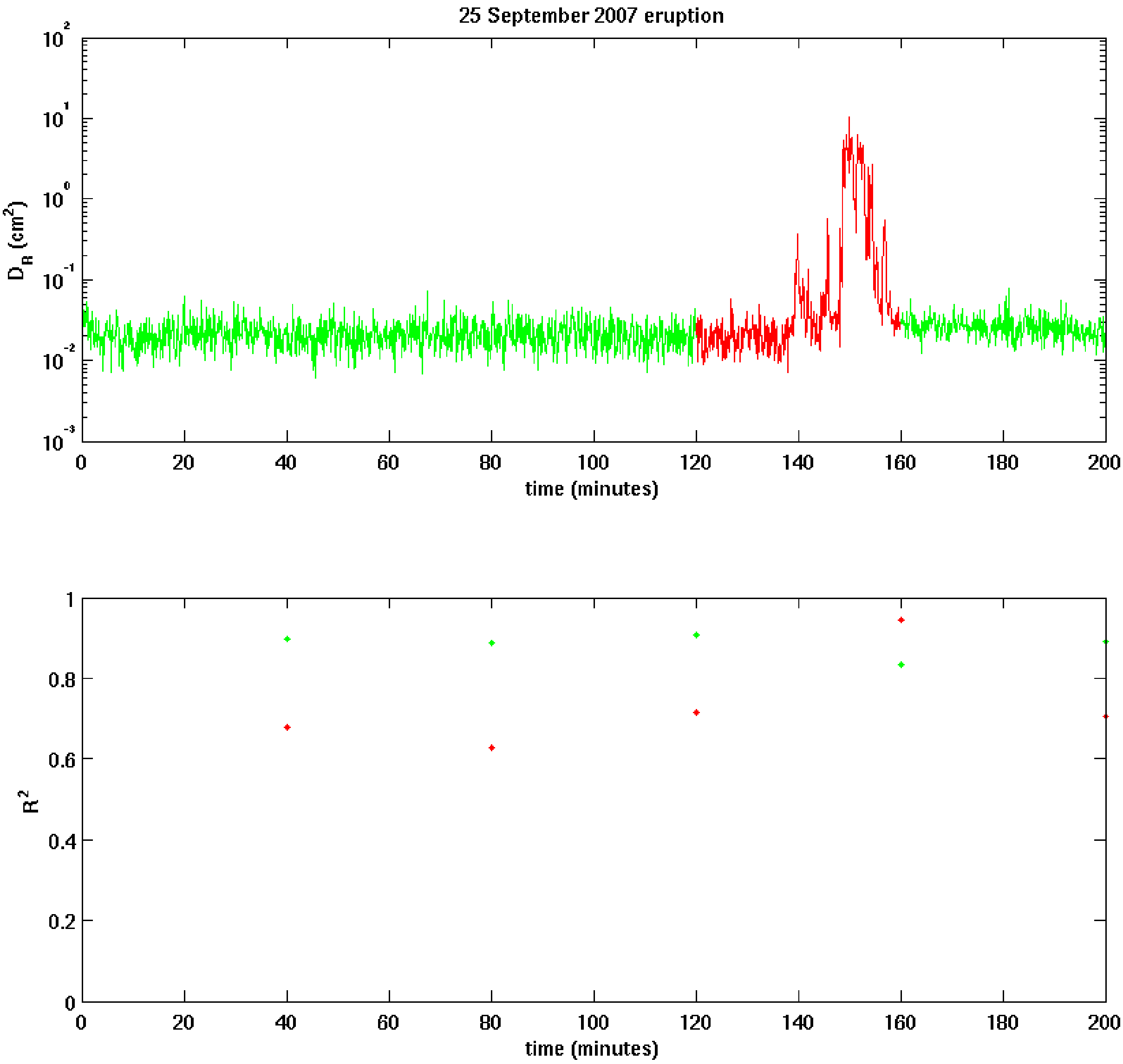

Figure 6 Reduced displacement for 25 September 2007 eruption (top) using station FWVZ. Red segments have DSD regressions which follow a power law while green segments follow an exponential law relation based on R^2 test statistic (bottom). Regressions were calculated as in Figure 3 and 4 above.

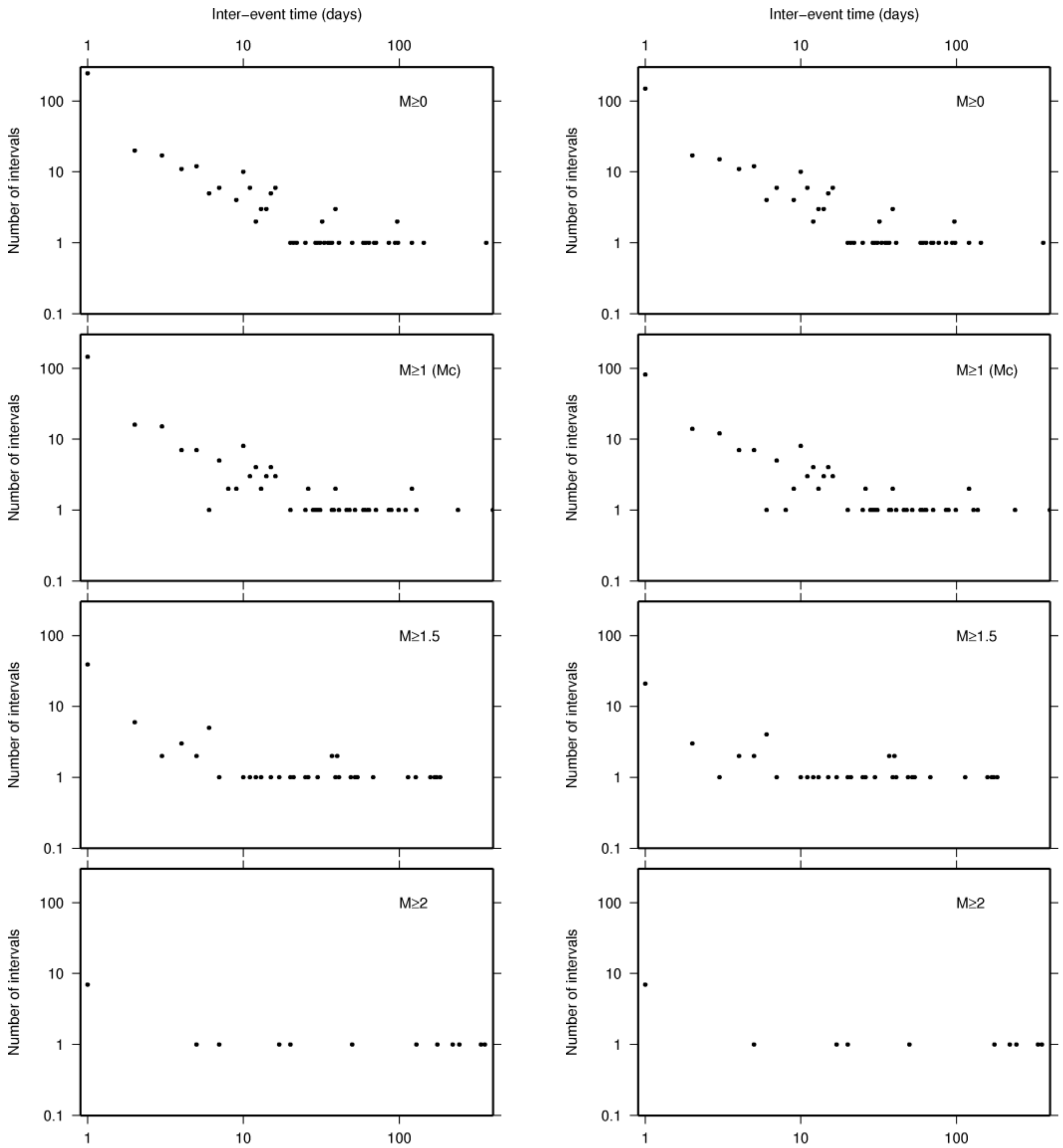

Figure 7 Inter-event times for 2000-2007 data. Inter-event times for 2000-2007 data excluding 2003 swarm.

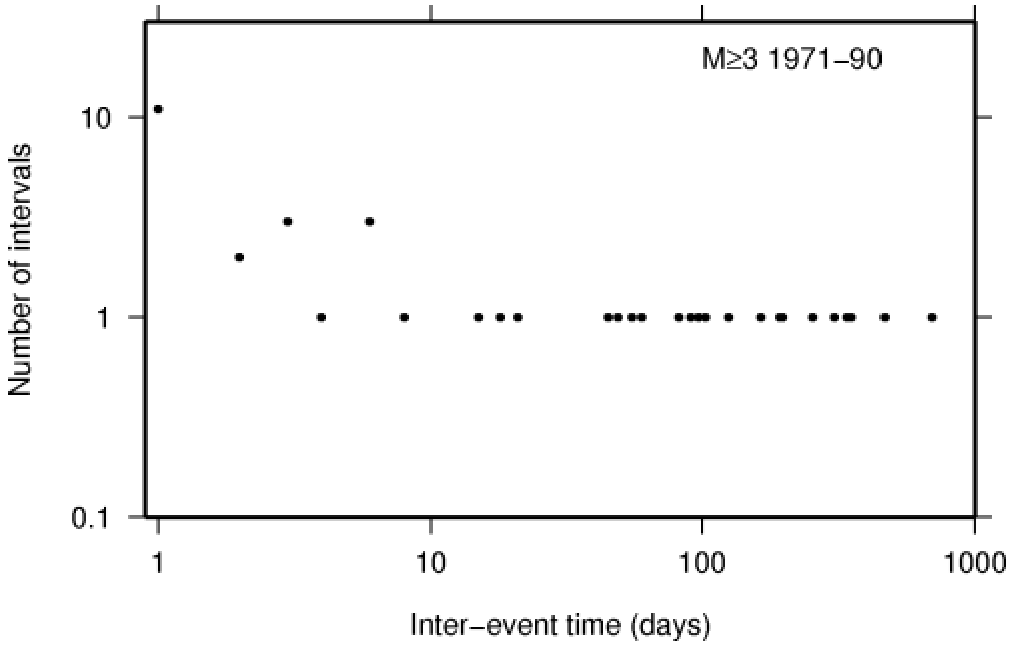

Figure 8 Inter-event time data for unpublished volcanic earthquakes for the period 1971-1990.

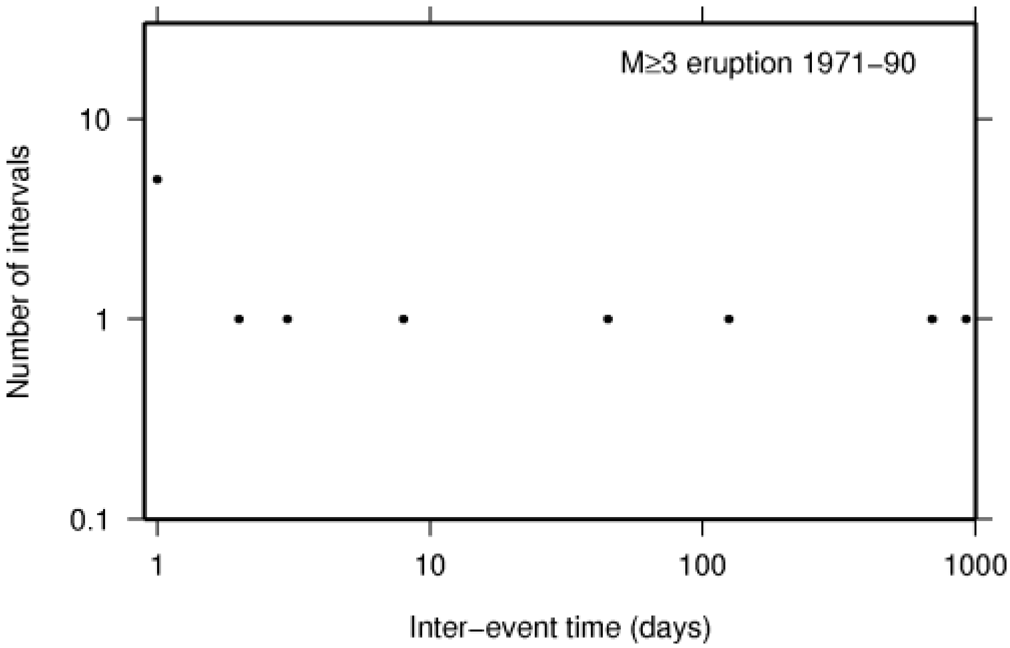

Figure 9 Inter-event data with eruptions only, including coincident seismic magnitude data.

www.gns.cri.nz

Principal Location

1 Fairway Drive
Avalon
PO Box 30368
Lower Hutt
New Zealand
T +64-4-570 1444
F +64-4-570 4600

Other Locations

Dunedin Research Centre
764 Cumberland Street
Private Bag 1930
Dunedin
New Zealand
T +64-3-477 4050
F +64-3-477 5232

Wairakei Research Centre
114 Karetoto Road
Wairakei
Private Bag 2000, Taupo
New Zealand
T +64-7-374 8211
F +64-7-374 8199

National Isotope Centre
30 Gracefield Road
PO Box 31312
Lower Hutt
New Zealand
T +64-4-570 1444
F +64-4-570 4657