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A Monte Carlo methodology for modelling ashfall hazards

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Abstract

We have developed a methodology for quantifying the probability of particular thicknesses of tephra at any given site, using Monte Carlo methods. This is a part of the development of a probabilistic volcanic hazard model (PVHM) for New Zealand, for hazards planning and insurance purposes. We use an established program (ASHFALL) to model individual eruptions, where the likely thickness of ash deposited at selected sites depends on the location of the volcano, eruptive volume, column height and ash size, and the wind conditions.

A Monte Carlo procedure allows us to simulate the variations in eruptive volume and in wind conditions by analysing repeat eruptions, each time allowing the parameters to vary randomly according to known or assumed distributions. Actual wind velocity profiles are used, with randomness included by selection of a starting date.

This method can handle the effects of multiple volcanic sources, each source with its own characteristics. We accumulate the tephra thicknesses from all sources to estimate the combined ashfall hazard, expressed as the frequency with which any given depth of tephra is likely to be deposited at selected sites. These numbers are expressed as annual probabilities or as mean return periods.

We can also use this method for obtaining an estimate of how often and how large the eruptions from a particular volcano have been. Results from sediment cores in Auckland give useful bounds for the likely total volumes erupted from Egmont Volcano (Mt. Taranaki), 280 km away, during the last 130,000 years.

Keywords: volcanic hazard; probabilistic hazard; ashfall; New Zealand; Monte Carlo

1. Introduction

The effect of airfall ash (tephra) is one of the most significant hazards from volcanic eruptions, especially to people and property some distance from the volcanic vent. Even very small thicknesses of volcanic ash can cause significant problems, in terms of disruption to communications, clean-up costs and effects on agriculture (Blong, 1984; Cronin et al., 2003). Ash thicknesses in the hundreds of millimetres present a major hazard to buildings, with less than a metre often resulting in

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complete collapse. See Spence et al. (1996) and Blong (2003) for the relation between ash thickness and the probability of collapse of different types of buildings.

Volcanic hazard assessment is often done in terms of scenario events. Plausible eruption scenarios are postulated, and their effects estimated. This is extremely valuable for planning purposes and hazard mitigation, because an effort is made to present realistic scenarios and likely effects; but for risk management purposes, such as insurance, it is desirable to have some probabilistic measure of the hazard.

Insurance companies are used to looking at earthquake risk in terms of the return period of particular intensities (MM values), or the intensity which has a particular probability in a given time, say 250 years. For volcanic ash, they would like to know the probability that a given location will have a particular thickness of volcanic ash deposited on it. From this, they could then look at the likely damage caused by this thickness of ash.

Stirling and Wilson (2002) proposed a Probabilistic Volcanic Hazard Model (PVHM) using a similar methodology to that used for earthquakes. This involved a four-step process to assess the hazard from tephra deposits:

1. Define all the volcanic sources
2. Define eruption magnitude–frequency relationships for each source
3. Calculate the tephra thickness as a function of position, relative to the volcano
4. Use these thickness distributions to develop plots of either the frequency or the probability of exceedance of thicknesses of ashfall.

The third step is much more difficult for the volcanic situation, compared to an earthquake, because the ash fallout from an eruption depends to a large extent on the wind direction, so the attenuation of thickness is not primarily a function of distance. Only for the few historic eruptions in New Zealand do we have independent information on the winds at the time, so for all the earlier eruptions the ash deposition pattern is a function of the unknown winds during the eruption. This means that we have only a small sample of the possible winds in the events from any volcano, and are very unlikely to get reliable estimates of the hazard as a function of position. For ash thickness, there is no simple analogue of a ground motion attenuation curve.

In this paper, we show how to separately account for the volcano and wind effects, using a simple model of ash falling from a volcanic plume. This lets us use our knowledge of the current wind pattern, and our best models of the volcano eruption probabilities, and apply a Monte Carlo analysis, following the development of seismic hazard and risk assessment by Monte Carlo methods of Smith (2003). The Monte Carlo approach allows uncertainties in the model to be included explicitly.

The ash thickness calculations use the computer program ASHFALL, which calculates the thickness of ash deposition at specified locations from a particular volcanic eruption with a particular wind pattern. We generate a synthetic catalogue of eruptions, using statistical distributions for eruption volume and height, together with a relationship between volume and frequency of occurrence, and use wind patterns chosen randomly from actual wind records to predict the effects of each event. Statistical analysis of the predicted ash deposits at each location, throughout the whole length of the synthetic catalogue, then yields the hazard estimates.

2. Program ASHFALL

ASHFALL is based on the 2-D and 3-D diffusion programs developed at the University of Pisa (Armienti et al., 1988, Macedonio et al., 1988, 1990). An eruption event is assumed to instantaneously produce a vertical distribution of ash above the volcanic vent, with most of the ash concentrated in the upper portion, according to the Suzuki (1983) distribution. Then the ash is moved by the wind as it falls under gravity. Long eruptions are modelled as a series of sub-events.

ASHFALL allows wind velocity and direction to vary with level and time. It can easily be extended so the wind varies with location also, but this is not done in the current version. Each size of ash is analysed separately, which allows the calculations to be made simpler by using the time in which that size of ash falls by one vertical interval (often 1000 m), as the time step. The landing point of a particular size of ash that is calculated by this method is actually the centre of a distribution, whose width is proportional to the horizontal diffusion coefficient. This method does not allow the direct incorporation of vertical diffusion, but it has been found that increasing the value of the horizontal diffusion coefficient gives ash distributions that adequately agree with observed values. The initial calibration of ASHFALL was done with matching the Vesuvius 79 A.D. eruption (Hurst, 1994). More recently we have been able to get a good agreement with the observed ash distribution from the 1995 and 1996 Ruapehu eruptions (Hurst and Turner, 1999), which were of the order of 0.01 km^3 (Fig 1).

The Monte Carlo method can be used with any method of calculating the thickness of ash at different locations. However, because the ash distribution has to be calculated for a large number of eruptions, it is desirable to use a simple, fast program like ASHFALL, rather than a full atmospheric model which would take much longer.

3. Forward eruption modelling—Taupo Volcanic Zone

The Taupo Volcanic Zone of New Zealand contains both andesitic stratovolcanoes, built by comparatively frequent small eruptions, and predominantly rhyolitic calderas, which can produce much larger eruptions at greater intervals (Cole, 1979; Wilson et al., 1984). As an initial demonstration of the technique, we used ASHFALL to model ash deposition from the three centres for which we have the best information about their eruptive history: the andesite volcano Ruapehu, and the mainly rhyolitic Taupo and Okataina volcanic centres. Any estimates of the overall ash hazard in the Taupo Volcanic Zone would require good estimates of the eruption history of all the significant volcanic centres, so the results we derive from these three sources should be viewed as an example of how the technique works, rather than an estimate of the actual hazard.

3.1. Eruption frequency and volume

3.1.1. Ruapehu

This is a stratovolcano with a crater lake which has eruptions ranging from frequent very small ones, up to

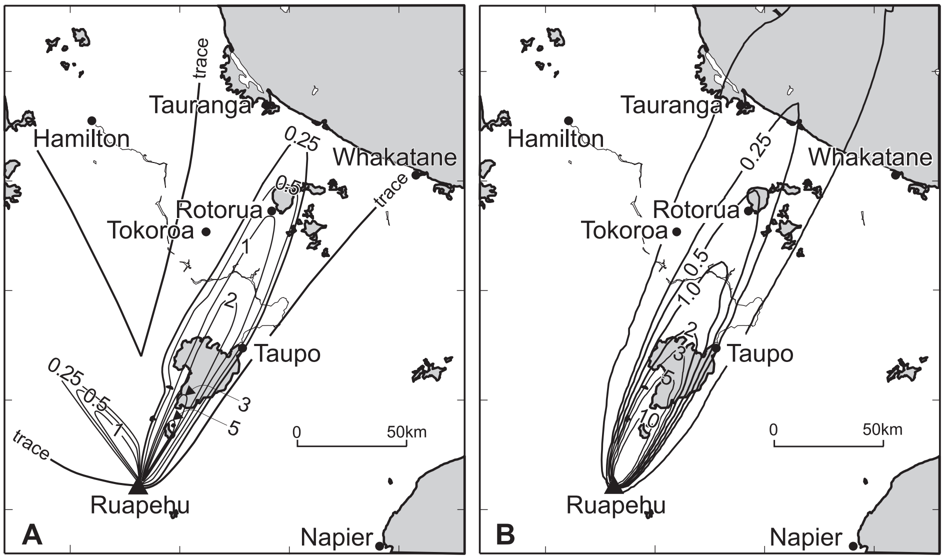

Fig. 1. (A) Isopach map with thickness in millimetres of the 17 June 1996 tephra from Ruapehu (from Cronin et al., 2003). (B) Isopach map with thickness in millimetres based on ASHFALL model for the 17 June 1996 tephra from Ruapehu, using actual wind measurements, a 7-km-high eruption column, and a total volume of 0.012 km^3 (from Hurst and Turner, 1999).

a maximum size of about 0.1 km^3 (Houghton et al., 1987). The data available to develop a frequency–volume relationship are very minimal:

- Two eruptions in the past 10 years, with volumes exceeding 0.001 km^3.
- Two eruptions in the past 100 years, with volumes exceeding 0.025 km^3.
- Two eruptions in the last 15,000 years, with volumes exceeding 0.3 km^3.

These data (Fig 2) allow us to fit a truncated exponential frequency–volume relationship (as used by Stirling and Wilson, 2002) of the form:

$$N = 10^{a-b\log V} \qquad V<V_{\max} \tag{1}$$

$$N = 0 \qquad V>V_{\max}$$

For parameter b, we find a value of 1.25 by least squares. Eq. (1) is similar to that used in seismicity studies (with log V replacing the magnitude), and for such studies it is normal to use the maximum likelihood estimate for b, rather than a determination by least squares (e.g. Aki, 1965); but in this case the data are so sparse, and they correspond to such different time scales, that a least squares estimation is adequate.

Eq. (1) defines a frequency distribution for events, but what is needed is the cumulative distribution, and for this we use the value of b (1.25) with the three detection thresholds given above, for the three periods of observation. This is the technique used by Stirling and Wilson (2002) for Taupo and Okataina. Combining the three observations of rate of occurrence, we obtain a cumulative distribution of the form:

$$N(V) = N_0\left(10^{-b\log V} - 10^{-b\log V_{\max}}\right) \tag{2}$$

$V_{\max}$ is the maximum eruption volume. We have chosen this to be 1 km^3, which is three times the largest known eruption. N_0 relates to the frequency of eruptions of volume greater than that at which log V is equal to zero, i.e. 1 km^3 which is fortuitously the same as $V_{\max}$. N_0 should therefore be interpreted as the annual frequency of eruptions greater than 1 km^3 that would occur if $V_{\max}$ were infinite. N_0 takes a value of 4.5×10^{-5}. This curve is shown in Fig. 2, with the three contributing data points.

For the purposes of estimating ashfall thickness, we chose a threshold eruption volume of 0.01 km^3. For this volume, the annual frequency of exceedance is 0.0142.

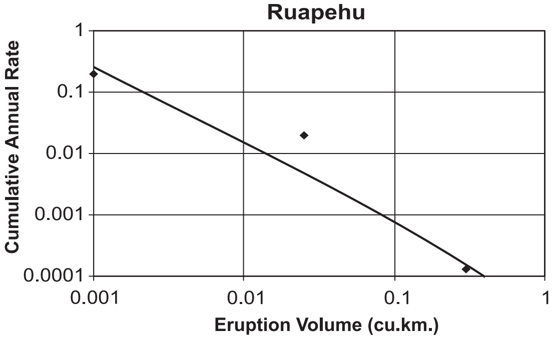

Fig. 2. Cumulative eruption frequency vs. eruption volume plot for Ruapehu, based on Stirling and Wilson (2002).

3.1.2. Taupo

Most of this volcanic centre is occupied by Lake Taupo. The last recorded eruption from this centre was about 1800 years ago, and included a large plinian eruption, producing a total of about 100 km^3 of pumice and ash, and later in the sequence a large pyroclastic flow, which travelled at least 90 km (Wilson et al., 1984). Stirling and Wilson (2002) list 21 eruptions in the last 7500 years, a record which is apparently complete above a volume of 0.01 km^3. They also list some earlier events, and consider that for the last 22,600 years the record is complete above 1 km^3. There are five events greater than this threshold.

We have taken the 7500-year record and fitted to it a distribution of the form of Eq. (1) above (Fig 3). The square symbol represents the Oruanui eruption of 22,600 years ago, plotted at an annual frequency of 1/22,600. This eruption had a volume of 760 km^3. The broken line represents a fit to the 7500 years data, with a maximum eruption volume of 1500 applied. While this does not fit the Oruanui point exactly, it is not inconsistent with it, for the periodicity of such eruptions, from only one occurrence, is highly uncertain. For Eq. (1), then, the parameters are: b=0.30, $V_{\max}$=1500 km^3.

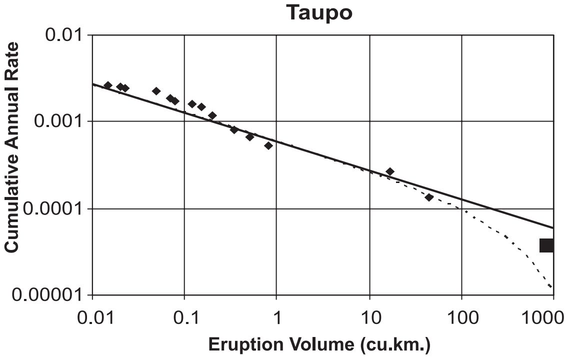

Fig. 3. Cumulative eruption frequency vs. eruption volume plot for Taupo Caldera, based on Stirling and Wilson (2002).

3.1.3. Okataina

Okataina is another caldera volcanic centre which has produced very large eruptions in the past (Wilson et al., 1984). The most recent eruption was the Tarawera eruption of 1886, which was not a typical rhyolitic eruption, but involved a basaltic magma. The eruption started from the preexisting Tarawera rhyolite dome, producing an ash column with a height estimated at 28 km (Walker et al., 1984), and then extended into Lake Rotomahana. The eruption from this area was much more violent, because of the interaction of water, and deposited a thick layer of Rotomahana mud on surrounding areas. The whole eruption of about 2 km^3 lasted only a few hours during the morning of 10 June 1886.

Stirling and Wilson (2002) presented eruption data from Okataina which indicate a very different frequency distribution for eruption volumes from that for Taupo. In particular, there is a falloff in frequency for eruptions smaller than about 5 km^3, which Stirling and Wilson (2002) interpret to be real. The data comprise 11 eruptions in the last 25,000 years, a record which Stirling and Wilson consider to be complete over 0.5 km^3, and there was an earlier event (Rotoiti) of volume 30–100 km^3, 64,000 years ago. The Rotoiti event is represented as the square symbol in Fig 4, which shows the cumulative distribution and the distribution function that we have chosen. This function is of the form:

$$N(V) = \frac{p}{1 + \left(\frac{V}{q}\right)^r} \qquad (3)$$

We present no theoretical basis for this function. Justification for its use is simply that it appears to fit the data. Values found for the three parameters were: $p = 0.00043$; $q = 12.0$; $r = 2.0$.

The ease with which a different model can be implemented is an important point here. The Monte Carlo forward modelling procedure is not limited to traditional distributions of the form of Eq. (2).

3.2. Column height

The total erupted volume is only one parameter of an eruption. For assessing tephra hazard, we need to know more details, especially the column height and the ash size distribution.

The greater the column height, the longer the ash particles take to fall to the ground, and hence they will generally be distributed further by the wind. This is particularly the case when ash is erupted to above about 10 km, where the stronger stratospheric winds are found. Virtually no volcanoes have enough observed eruptions to give an accurate estimate of the expected distribution of column height in eruptions. Therefore, the best available method to estimate the column height is to use the relationship between eruption mass and column height that Carey and Sigurdsson (1989) derived from 45 Plinian eruptions

$$H = -60.5214 + 7.176 \log M \qquad (4)$$

where the height H is in km and mass M in kg. For the Monte Carlo analysis, we then randomise this height by replacing H by a random number which has a Normal distribution. This distribution has a mean H as determined by Eq. (4) and a standard deviation equal

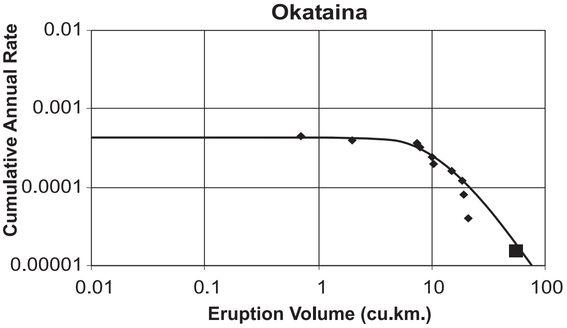

Fig. 4. Cumulative eruption frequency vs. eruption volume plot for Okataina Caldera, based on Stirling and Wilson (2002).

to the smaller of 5 km and one quarter of H. This formulation was considered to be a plausible representation of the uncertainty in H.

3.3. Mass flux and duration

The mass flux is necessary only so we know how long the eruption takes, and can take account of wind changes during this time. We determine the mass flux from the column height, using the relationship from Woods (1998):

$$H = 0.19F^{0.269}$$

where F is in kg s^{-1}.

The duration is then determined using the relationship:

$$Duration = \frac{Mass}{Flux} \tag{5}$$

which was randomised using a lognormal distribution with mean equal to the duration as determined from Eq. (5). The lognormal distribution has the property that it extends from zero to very large values, though probabilities are very small at the extremes. This allows for a wide distribution of duration values. It was necessary to choose a standard deviation for the lognormal distribution; we used the common assumption that the standard error is equal to the mean. We examined the sensitivity of the results to our choice of the lognormal distribution by using instead a much more peaked duration distribution, a Normal distribution with a standard deviation one quarter of the mean. It made virtually no difference to the final ash distribution, implying that the choice of distribution was not critical.

3.4. Ash size distribution

The ash size distribution is also important in determining the volcanic hazard, since ash particles fall at rates depending on their size, and hence travel different distances.

With limited direct information, we had to use available measurements to get a reasonable distribution of ash sizes. For Ruapehu, we used an ash distribution based on the A.D. 79 eruption of Vesuvius, as originally used by Macedonio et al. (1988), but with less fine ash corresponding to less violent eruptions. For Taupo and Okataina, we used an ash distribution based on the results of Walker (1981) for the Hatepe eruption, with a source in Lake Taupo. Walker concluded that this had a total volume of 7 km^3, using the crystal concentration method to estimate the amount of widely distributed fine ash.

The hazard estimates are most sensitive to the quantities of coarser material, say larger than 0.5 mm, which makes up much of the thicker deposits near the vent. Hazard assessments should ideally be based on whole-deposit grain-size volumes, as produced by Walker (1981) for classes greater than 0.5 mm for the Hatepe eruption. However, if this information is not available, volumes based on actual ash thickness measurements will provide a good estimate of the volume of coarse ash. This contributes nearly all the hazard, as over the region where there is enough ash thickness to be a significant hazard, most of the ash will be coarse (say >0.5 mm), and the unknown quantity of fine ash makes little addition to the thickness. In other words, the difficulty of calculating the total volume of a large explosive eruption, because most of the fine ash is very widely distributed, often out to sea, and cannot be mapped, is not actually a problem for the assessment of the ash hazard for places within a few hundred kilometres of the volcano.

Most measured ash distributions use wide size classes, often with a factor of two in ash size. If we used only a few ash sizes in ASHFALL, there would be a large percentage of certain ash sizes (and hence fall velocities), producing a very “lumpy” ash distribution. Therefore, an interpolated plot of ash sizes is produced from any initial ash size distribution. From this, we calculate closely spaced size classes with no more than a few percentage points in any particular size class. Normally about 25–40 ash size classes are used to provide a smooth distribution. The final ash distributions used for Ruapehu and Taupo/Okataina are shown in Fig. 5.

Although ash thicknesses give a basic indication of how big a problem volcanic ash might be, for some purposes ash size may be an important factor. For instance if one is concerned with very fine ash penetrating equipment, one could include only the percentages of very fine ash to get the distribution of material less than a certain size. Also the effect of a certain ash thickness is dependent on state after it

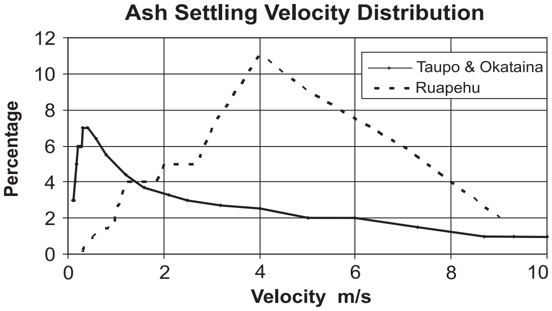

Fig. 5. Ash settling velocity distribution used for Ruapehu, based on Vesuvius 79 A.D. eruption (Macedonio et al., 1990), and for Taupo and Okataina, based on Hatepe eruption (Walker, 1981).

falls, especially whether it has absorbed moisture and/or been compressed.

3.5. Wind conditions

The wind information available was twice-daily wind forecasts for Ruapehu and White Island, provided by the Meteorological Service of New Zealand (MetService), based on rawinsonde data. This was available for a period of almost 3 years in 2000–2002 for the two locations, Ruapehu and White Island. For Okataina, we took a mean between the White Island and Ruapehu forecasts, whereas Taupo was taken by combining 75% Ruapehu to 25% White Island. Some editing was required to cope with rapid changes in direction, as sometimes occurred. We did this by interpolating extra readings into the files, so the wind direction at any level did not change more than 100° between successive forecasts. This was to avoid problems with the ambiguity of which way the wind was changing if it changed to a nearly opposite direction between two forecasts. (In this area, changes between southerly and northerly winds nearly always are via a westerly wind, rather than an easterly one, Richard Turner, NIWA, personal communication.) It would be preferable in the future to extend the wind patterns to a considerably longer period, to cover a number of “El Nino”–“La Nina” cycles to give a better estimate of average winds.

The procedure for randomising wind data recognised that it was important to use actual variation with height, and actual variation from day to day, so it was not appropriate to choose random values of the velocity and direction. Rather, we took the 3 years' data and chose a *random starting date*, i.e. a rectangular distribution extending over the 3 years. This met the criteria of a realistic representation of the velocity and direction profiles, together with the diurnal and other wind changes likely to occur during a long eruption, while still sampling all the annual variation.

3.6. Monte Carlo procedure

The procedure was as follows. For each volcano in turn, we determined the number of eruptions there would be from the total length of the Monte Carlo run, typically 1,000,000 years, using Eq. (2) (Ruapehu and Taupo) or Eq. (3) (Okataina), then for each eruption we chose a volume randomly from the appropriate distribution (Eq. (2) or Eq. (3)). For this sized eruption, we then selected the height and duration, introducing further random variation as described above. Fixed ash size distributions were used, as at present we have too little information to develop a distribution of ash sizes for the different volcanoes, whether as a function of eruption size or not. Finally, a random starting date was selected from which the wind information was obtained.

By running ASHFALL many times, each with randomly selected parameters as described above, we have taken many samples from the combined parameters for determining ash thickness, and it is simply a question of accumulating statistics at each site. After some experimentation, we chose a run length of 1,000,000 years, and accumulated counts of the number of times selected ash thicknesses were

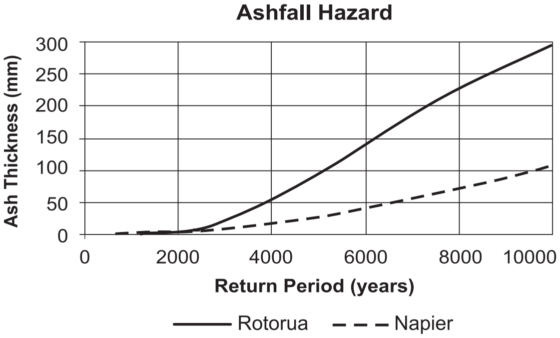

Fig. 6. Return period as a function of ash thickness for the combined effects of Ruapehu, Taupo and Okataina eruptions at the cities of Rotorua and Napier.

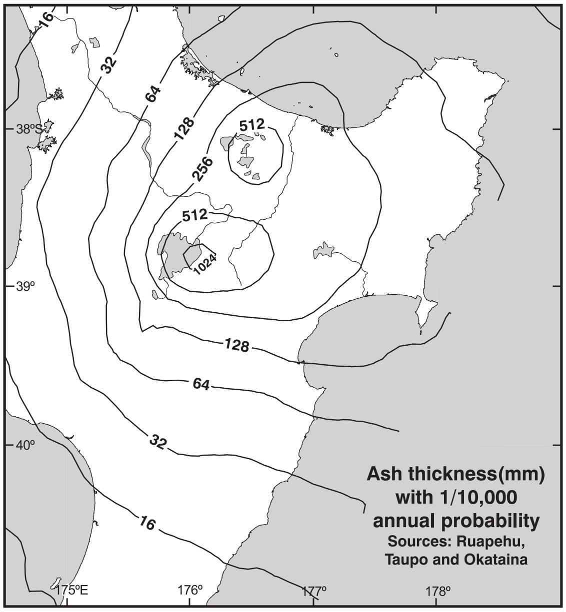

Fig. 7. Ash thicknesses with a 10,000-year return period based on eruptions from Ruapehu, Taupo and Okataina.

equalled or exceeded at a grid of sites covering much of the North Island. Two alternative ways of showing these results are to plot the return period of different ash thicknesses at particular sites (Fig 6), or to plot contours of the ash thicknesses with a particular return period, such as 10,000 years (Fig 7).

4. Inverse modelling, Mt. Taranaki (Egmont Volcano)

The last eruption of this 2518-m-high andesitic stratovolcano was about 250 years ago (Druce, 1966). It represents a major hazard to the surrounding area, because it has a history of major cone collapses, as well as ash eruptions, pyroclastic flows, and lahars which covered the surrounding areas. Alloway et al. (1995) concluded that at least 76 tephra events with over 10^7 m^3 of material had occurred in the last 28,000 years. As part of any hazard assessment, one would like to know the average rate at which material has been erupted from this volcano, but the complex volcanic history has made this very difficult, with most nearby sections complicated by cone collapses and pyroclastic flows.

Tephra from Egmont eruptions has been found over a wide area (Lowe, 1988). Recently, a core has been drilled in an old lakebed at Onepoto in the Auckland area, 280 km NNE of Mt. Taranaki, with an approximate bottom date of 130,000 years (Shane and Hoverd, 2002). As well as ash layers from local Auckland volcanoes, and various Taupo Volcanic Zone volcanoes, it showed 40 ash layers that could be identified as coming from Mt. Taranaki. Most of these were only 1–2 mm thick, but the thickest was 20 mm thick, and two others were nearly 10 mm thick. This extended the record of Taranaki eruptions obtained in the Pukaki Crater, about 30 km south of Onepoto (Sandiford et al., 2001).

Inverse modelling involves using the ash deposits from this drill-hole to estimate the volume of tephra erupted from Mt. Taranaki in the last 130,000 years. The main unknown is the wind pattern, which may have been different from present-day winds during this period, because of different climatic regimes. For much of the last 130,000 years, particularly between 18,000 years B.P. and 80,000 years B.P., the climate in New Zealand was variable, fluctuating between interglacial and glacial conditions, and often significantly colder than it is now, as recorded in the Vostok Ice Cores (Petit et al., 1999). It has been suggested (Alloway et al., 1992) that this corresponded to a significantly altered wind pattern over New Zealand. With the uncertainty over wind conditions, this study should be regarded primarily as a test of the technique.

Wind values are measured twice daily above New Plymouth, just north of the volcano, and a 3-year record (2000–2002) was used to produce our simulated wind file. Taking the form of the eruption–frequency relationship from Ruapehu, as the most similar available record, we then tried different coefficients to see whether we could match the ash layers observed. The main parameter to match is the total ash thickness, which will be dominated by the large eruptions, and is proportional to the total tephra volume produced. We also tried to match the number of ash layers, to get an indication whether we had a realistic eruption–frequency relationship. The description of the ash layers has categories <1, 1, 1–2, 2 mm and greater thicknesses. Plotting the cumulative number of layers thicker than each of these sizes (line Onepoto in Fig 8) showed the curve bends down for ash layers of 1 mm or thinner, suggesting that only

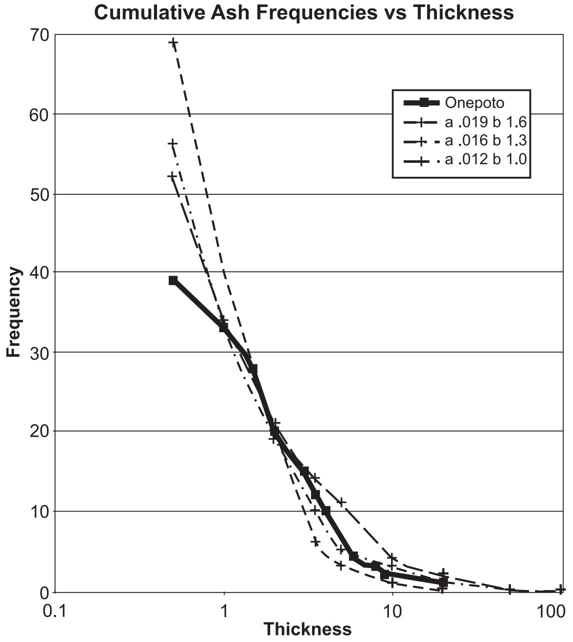

Fig. 8. Comparison of observed cumulative thickness frequency for Taranaki tephra in Onepoto core with Monte Carlo simulations using ASHFALL.

some of the thinner ash layers were detected, analogous to a cumulative earthquake magnitude curve showing a detection threshold. The other curves in the diagram represent the expected cumulative numbers of ash layers, based on current winds and a range of eruption characteristics. Fig 9 shows the total ash thickness distribution from the best fitting eruption pattern. All of these thickness figures are based on the ash at its density when compacted in the lake sediments, about 1.5 Mg/m^3 (Lowe, 1988). The original rock volume (DRE) would be about 60% of this.

A good fit for most of the ash thickness range is for a b-value of 1.3 (Eqs. (1) and (2)), with values of 1.0 and 1.6 showing, respectively a surplus and deficiency of thick ash layers compared to thin ones (Fig 8). This supports our use of an exponential model with a b-value of 1.25 for Ruapehu in the preceding section, and suggests that this technique has potential for finding information about the eruption characteristics of a volcano even from only one distant site.

The total volumes of tephra produced in these models are approximately 300 km^3 (i.e. 180 km^3 DRE). This might seem large, but it is compatible with the estimate of Locke and Cassidy (1997) of 300 km^3 DRE of volcanoclastics, based mainly on topography and gravity, given that only a portion of eruptive material will be airfall ash. A major source of error is the wind pattern. If southerly winds were more common during the cold climate period than today, then fewer eruptions, with a smaller total volume, would have been required to produce the ash seen at Onepoto. In other words, if strong SSW winds were twice as frequent as today, the total tephra produced from Mt. Taranaki would only be about 150 km^3. The use of cores from other areas, such as the Waikato (Lowe, 1988), can potentially be used to at least partly reduce the effects of changes of wind pattern on volume estimates. The other main error source is the size distribution. We used a size distribution based on the A.D. 79 Vesuvius eruption (Macedonio et al., 1990), in which half of the ash particles have fall velocities in the range 0.3–0.52 m/s. More explosive eruptions, with a greater proportion of very fine ash, could affect the estimate of total eruptive volume.

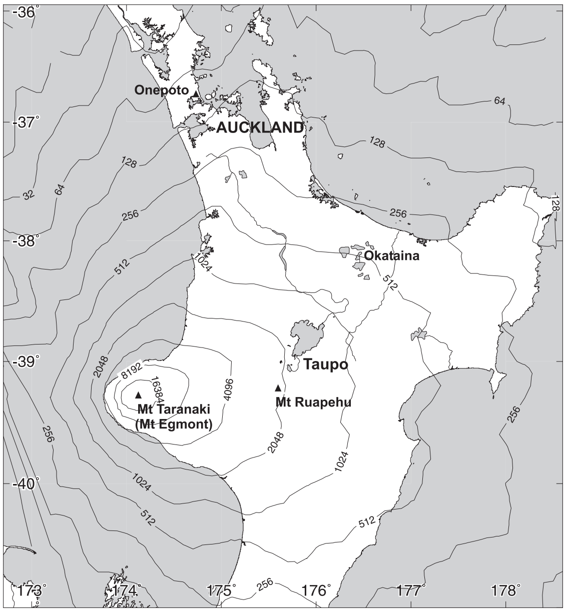

Fig. 9. Cumulative ash thicknesses in millimetres from Taranaki for the last 130,000 years, for model with a=0.012, b=1.3 (Eq. (1)).

5. Proposed developments

This study has re-emphasized that the main difficulty with probabilistic volcanic hazard assessment is quantifying the volcanic eruption history. We need reliable data on the eruption frequency distributions and ash sizes to extend this work to include all volcanic centres that pose a threat in New Zealand. As this information becomes available, we suggest that the methodology presented here offers the best technique to use limited volcanic eruption data for deriving a probabilistic volcanic hazard model, in terms of the return periods of particular thicknesses of airfall ash.

Then a further task is risk assessment: determining economic losses as a result of volcanic ash fall. This requires assessment of likely damage to typical assets, even an economic assessment of business interruption and social disruption. These topics are beyond the scope of the present study, which aims to show a practical method of assessing the tephra hazard from volcanic activity.

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