FREQUENCY OF ERUPTIONS AT NEW ZEALAND VOLCANOES

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ABSTRACT

This paper reviews the nature and history of activity and the extent of risk at 14 volcanoes and volcanic centres in New Zealand and the Kermadec Islands. Mean intervals between eruptions are calculated, or estimated by extrapolation, for eight classes of eruption, represented by order of magnitude volume increases from $10^4\,\mathrm{m}^3$ to $10^{11}\,\mathrm{m}^3$ (100 km³). Expected property losses in eruptions, divided by the approximate mean intervals, allow risk to be apportioned on an annual basis. In real terms the rhyolite volcanoes, between Kawerau/Lake Rotorua and the southern end of Lake Taupo, are easily the most destructive. Annually apportioned, however, the risk is highest for an eruption of about 10⁷m³ at Mt Egmont.

Cumulative volumes erupted with time are estimated for most of the volcanoes and, where possible, average rates of magma accumulation and subsequent eruption have been estimated. This enables any shortfall between the actual volumes erupted, and the expected volumes, to be estimated, thus giving a measure of eruption potential at the present time. This varies for different volcanoes, from about 0.04 km³ up to several hundred cubic kilometres. The time elapsed since the last eruption, divided by the mean frequency for that class of eruption, gives an idea of the likelihood of further activity, although the usefulness of the results is limited by large standard deviations. In the short term, less than 100 years, an eruption of $10^7 \, \text{m}^3$ at Mt Egmont again emerges as the most likely damaging event. In the medium term, of the order of a few hundred years, an eruption of c.1 km³ in the Okataina-Rotorua area, or in the district between Lake Taupo and Rotorua, becomes probable.

The data on which the conclusions are based, together with the mean intervals accepted, and the times elapsed since the last eruptions, are given in Appendices, so that the nature of the facts, and hence a wide perspective on volcanic activity in New Zealand, can be the better appreciated. The picture is one of volcanoes dormant for long periods of time, with great destructive potential, any of which could awaken at any time.

INTRODUCTION

The frequency of eruptions, whether estimated on the basis of return period for a given size, or on the basis of annual frequency, is an essential parameter in calculating the risk for a given locality, for engineering or for any other purposes.

Risk is exposure to hazard of something vulnerable and valuable. The "something" can be people, animals, property, or any asset of economic or aesthetic value and, in attempts to formulate risk pathoratically it is appealed to referred mathematically, it is usually referred to simply as $\underline{\text{value}}$. Thus Risk has been defined (1) as Value x Vulnerability xHazard. The use of different terminology can be confusing: for example, a slightly different definition (2) is Risk = Exposure x Location x Vulnerability x Hazards, where Exposure means Value, and Location, which is implicit in the term Vulnerability in (1), is given prominence as a term on its own.

At volcanoes, hazard is usually potential rather than actual because ${\tt most}$ volcanoes are dormant for 99 percent or so of their lifetimes, although many emit volcanic gases more or less continuously, and the resulting acidic and corrosive plumes can pose hazards downwind. The frequency of eruptions is therefore the parameter that defines, usually in a very approximate way, the transition time from $% \left(\frac{1}{2}\right) =\frac{1}{2}\left(\frac{1}{2}\right)$ potential to actual hazards at a volcanoe.

Many attempts have been made to analyse periodicity of eruptions statistically. Landmark studies in this field are those by Wickman (3-8), and a parti-BULLETIN OF THE NEW ZEALAND NATIONAL SOCIETY FOR EARTHQUAKE ENGINEERING, VOL. 18, NO. 1, MARCH 1985

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cularly useful summary has recently been given by Scandone (9). The present paper does not attempt so thorough an analysis of the problem but reviews the data presently available on frequency of eruptions in New Zealand and its surrounding area, which is a first stage in the construction of meaningful risk maps. Too little is yet known of the time dependence of some major types of activity for reliable risk maps to be drawn. In particular, much more information is needed on the mechanism of the largest eruptions, and on the way in which these depend on tectonic events, and on each other. At present it seems extremely likely that there is a strong interdependence in volcanic activity in a single tectonic zone, and that this is related to major tectonic episodes. In the context of New Zealand, it is likely, but not yet proven, that major volcanic activity occurs in episodes related to changes in the pattern of tectonic stress due, perhaps, to variations in the rate at which the downgoing Pacific plate is underthrusting the overriding Indo-Australian plate. At present this rate cannot be directly measured.

Major uncertainties in the volcanic history of New Zealand are due to burial of the older volcanic deposits by younger ones, to their removal by erosion, and to uncertainties in the dating process. Carbon-14 (14C) dates can only be obtained on material less than about 60,000 years old, and there are considerable inaccuracies associated with this and other methods of rock-dating. Because of these limitations it is only feasible to study a comparatively small part of each volcano's history. Ruapehu, for example, has been active off and on for at least the last 250,000 years, but for eruptions as large as those of 1945, which were certainly significant in terms of destructive ability, it is only possible to go back 100 years or so. Only for the very largest eruptions or collapses of the cone, represented by the thick lahar (mudflow) deposits around the mountain, is it possible that a complete sample has been preserved for the whole 250,000 years of activity, and even this is doubtful.

Contrary to widely-held opinion, volcances that have not erupted for hundreds, thousands, or even tens of thousands of years, are unlikely to be extinct. Volcances typically erupt infrequently, sometimes at regular intervals, but more often apparently randomly. These short episodes are separated by long periods during which molten rock (magma) rises once more into the upper crust and gas pressure builds up beneath the sealed-off vent. A new eruption occurs when the gas pressure at the top of the magma column exceeds the strength of the overlying rocks. This may happen when a fresh batch of magma is forced up to a shallow depth under the volcanc, or when tectonic movements reduce the confining pressure on the magma allowing the dissolved gases that it contains to come rapidly out of solution, or when water comes into sudden contact with hot rock or gas causing steam explosions. In all cases, the fundamental driving force of eruptions is gas, and

the dramatic expansion that accompanies its exsolution process. Dormancy is therefore the normal state of a volcano, and no volcano can be considered extinct if the time that has elapsed since the last eruption is less than, or of the same order as the average interval between eruptions, even when this is measured in thousands or tens of thousands of years (10). Only when the elapsed time is of the order of ten times the average interval between eruptions and, coupled with this, when there have been significant changes in the tectonic stress field which caused the volcano to form where it did in the first place, can it be reasonably considered that the volcano may indeed be extinct.

On this basis the following volcanoes and volcanic fields in the Kermadec Islands, New Zealand and the outlying islands to the south are dormant rather than extinct (see figure 1): a submarine volcano c.8 kilometres north of Raoul Island; Raoul Island itself; Macauley Island-Brimstone Island (all these are in the Kermadecs); the "Rumble" group of submarine volcanoes about 250 kilometres northeast of White Island; the Bay of Islands - Kaikohe volcanic field; the Whangarei volcanic field; the Auckland volcanic field; Mayor Island; White Island; Okataina volcanic centre (includes Tarawera and Haroharo volcanoes); Rotorua caldera; Maroa volcanic centre; Taupo volcanic centre; Tongariro; Ngauruhoe; Ruapehu; and Mount Egmont.

Doubtful cases are the Timaru volcanic field, Solander Island, and the Antipodes Islands.

Insufficient is known about activity in the Kermadec Islands, other than at Raoul, or at the Rumble submarine volcanoes, Timaru, Solander Island, and the Antipodes Islands, and therefore these are not considered further in this paper. The volcanic history at the remaining 14 volcanoes and volcanic fields is discussed below, and estimates of the mean frequency of eruptions are given for successive order of magnitude increases in the volume of rock ejected, from a lower limit of 10 tm up to 10 tm (100 km).

EFFECTS OF ERUPTIONS

The main factors that determine the effects of an eruption are the volume of material ejected and the rate at which this takes place. These in turn depend partly on the chemical composition of the magma (magma is molten rock containing gases in solution), which in the New Zealand area ranges from basalt, through andesite and dacite, to rhyolite. Basalt has low viscosity and flows relatively easily: gases which come out of solution in the rising magma, as the confining pressure is decreased, are therefore able to escape readily and fail to build up the potential for large explosions. Increasing silica content in the magma leads to greatly increased viscosity. Andesite is much more viscous than basalt, and dacite than andesite, and consequently

the explosive potential of dacite is very large. The eruptions of Krakatoa in 1883 were of this type, as were those of Mont Pelée which destroyed the town of St Pierre in Martinique in 1902, Mt Lamington in Papua New Guinea in 1951, and Mount St Helens in 1980. Rhyolite, with greater silica content than dacite, and therefore still higher viscosity, has the highest explosive potential of all magmas. The sudden interaction of water with magma, hot gas, or hot rocks surrounding a magmatic intrusion introduces a further complication. Water may flash to steam, expanding many times in the process. This is the mechanism for hydrothermal, or socalled phreatic eruptions. Often these trigger underlying magmatic eruptions. Because of phreatic activity, even basaltic magmas can erupt explosively, as occurred in 1886 at Tarawera.

explosive potential of magma, whether due to internal gas pressure or to rapid interaction with water, determines how the rock is erupted. There are two principal types of erupted material, lava and pyroclastics. Lava is magma from which most of the gas has escaped: it flows relatively quietly or is extruded in the form of plugs or domes. Pyroclastics, on the other hand, represent magma which has been blown apart explothe other hand, represent sively, forming a wide range of erupted debris, from large blocks and bombs, through pumice and lapilli, down to finegrained ash and dust. Pyroclastic rock may be blasted to a great height above the volcano and be carried by the wind, finally dropping as airfall "tephra", or it may be blown sideways, often as a result of gravitational collapse of eruption columns, and be emplaced as dense ground-hugging pyroclastic flows. These are turbulent, because of continual explosive gas release from the blocks and fragments of magma contained in the flow, and because of reactions between the gases and air trapped and entrained by its very rapid movement. Pyroclastic flows usually travel between 20 and 100 metres per second: when they are sufficiently hot and their volumes are large enough, the molten fragments of rock fuse together on coming to rest, forming welded ignimbites. When these cool, they resemble dense concrete-like sheets which usually grade upwards into chaotic masses of unwelded soft pumice with scattered boulders. Small pyroclastic flows can be formed by andesite, or even basalt eruptions. The larger and more destructive ones are dacitic. Ignimbrites, whether welded or un-welded, are nearly always rhyolite.

In New Zealand, during the last million years, there have been repeated eruptions, fortunately all of them prehistoric, in which massive ignimbrite sheets, tens or hundreds of metres thick, have blanketed thousands of square kilometres and attained volumes for individual sheets of as much as several hundred cubic kilometres. Emplaced at tens, perhaps hundreds, of metres per second, these cover the landscape, transforming hills and valleys alike to an even, flat surface and destroying all life. Still larger ones have been erupted prehistorically

in the USA and elsewhere, attaining volumes of as much as 3500 cubic kilometres. These represent the ultimate volcanic phenomenon.

Primary destructive effects of volcanic eruptions, apart from lava flows and gravity-controlled pyroclastic flows, and the far larger, totally devastating ignimbrites, are due mainly to airfall tephra, and at short distances from the volcano to the impact of rocks on ballistic trajectories. Gas emission and acid rain may also prove very destructive. Table 1 shows approximate areas likely to be affected by different thicknesses of airfall tephra in eruptions of various sizes: windless conditions are assumed (that is, thickness contours are assumed to be circular about the volcano).

Secondary destructive effects of eruptions are due, above all, to lahars (mudflows) and tsunamis. Lahars may be generated in a variety of ways, by heavy rainfall washing unconsolidated tephra off steep slopes, by melting of snow and ice, by lava or pyroclastic flows entering streams, or by the direct ejection of water from crater lakes. Tsunamis (so-called tidal waves) also form in many ways: the largest, such as those at Krakatoa in 1883, by the impact of ignimbrites into the sea or large lakes (11). More detailed discussion of the effects of volcanic eruptions is outside the scope of this paper. An excellent sourcebook on the subject has recently been published (12).

VOLCANIC HISTORY OF INDIVIDUAL VOLCANOES AND VOLCANIC CENTRES

Kermadec Group - Raoul Island

Raoul is of interest from the point of view of volcanic risk only because there is a permanently manned meteorological station on the island. The volcano is frequently active and last erupted in a very minor way, in 1964. The island, which has an area of only about 30 km², is the summit of a large submerged volcano and includes at least two calderas* of about 3.5 kilometres in diameter.

The volcanic history of Raoul has been reconstructed back to about 3700 years ago (13). There are much older volcanic rocks exposed on the island, dating back to about 1.4 million years, but their relationships to individual eruptions are not clear. Offshore, about 240 kilometres to the southeast, volcanic ash has been found in deep-sea cores (14) showing that there were substantial eruptions (3-5 km³?) about 30,000 years and 130,000 years ago. However, the ash is lacking in cores further north, closer to Raoul, and it is perhaps most likely that these eruptions

^{*} Calderas are large, more or less circular areas of subsidence formed after large explosive eruptions, when the roof above a rapidlydrained magma chamber collapses.

originated from the Macauley Island-Brimstone Island volcanic centre, further south in the Kermadecs, about which very little is known.

During the last 3700 years or so, it is estimated that there have been 12 explosive eruptions at Raoul which have ejected more than about $10^8~\mathrm{m}^3$ (figure 2). Volumes are very hard to estimate, and are rough approximates only, because the small size of the island means that most of the erupted debris fell offshore. Four of these eruptions probably ejected more than $10^9~\mathrm{m}^3$ (1 km³), and one, the Fleetwood eruption about 2200 years ago, perhaps more than $10~\mathrm{km}^3$. Any eruption over about $10^8~\mathrm{m}^3$ would be destructive at the meteorological station on Raoul.

The eruptions are listed in Appendix 1, together with an estimate of their volumes. The average interval between eruptions of $\geq 10^8$ m³ works out as 327 \pm 302 years, and that between eruptions of $\geq 10^9$ m³ as 777 \pm 182 years. These means define a line which is shown extrapolated in figure 2a. However, because the single large eruption about 2200 years ago dominates the volumes erupted during the period studied, a better estimate of the volume of eruptions versus time can be found from figure 2b. The true rate probably lies between the upper and lower limits shown, that is, between about 138 and 670 years for a cumulative volume of 1 km³. At present the shortfall between the expected and actual volumes erupted lies in the range 1.5 km³ to 14 km³, and we are therefore in line, in a long-term sense, for an eruption in this range of magnitudes.

These figures, like all other average intervals and rates of eruption given in this paper, can only be taken as a rough guide to the frequency of eruptions. Where the standard deviations are approximately the same as the mean intervals, the eruptions are essentially random in their occurrence. Furthermore, the accuracy of rock-dating and estimation of volumes erupted is low.

New Zealand

Bay of Islands - Kaikohe Volcanic Field

This is a large area in Northland covering some 500 km², in which eruptions, predominantly of basalt, have occurred sporadically for at least the last 2 million years. Very little is known in detail of the eruptions, and there are few reliable dates. The most recent activity took place at the Te Puke cones near Waitangi and may be about 17,000 years old, although this date is doubtful (15). A very rough estimate of 67,000 years for the mean interval between typical eruptions (of the order of 108 m³) has been worked out from the fact that there have been about 19 such eruptions in 1.27 million years. Figure 3 shows an extrapolation of this interval by making the trend parallel to that derived for the very similar Auckland volcanic field.

Part of the area lies beneath the sea, and moderately explosive eruptions

have occurred, and may do so again, as a result of interaction of water with the basaltic magma. Most eruptions, however, have been comparatively mild. Small volumes of rhyolite have been produced, notably at Putahi near Ngawha, by chemical differentiation of the basalt. This process is capable of yielding only a small amount of rhyolite, quite different to the situation in the Taupo-Rotorua area where huge volumes of rhyolite are produced by large-scale melting of the upper crust.

Eruptions in this area are unlikely to exceed 10 ° m³ (1 km³). Some damage to buildings with flat roofs might occur when tephra thickness reaches 50 cm, especially when rain saturates the deposits. Table 1 shows that this thickness would occur within a radius of about 7 km from the vent, twice this distance perhaps with the effect of a strong wind. There are few large towns in the area, and the probability of an eruption close enough to damage Kaikohe, for example, is remote. It is, however, unlikely that this volcanic field is extinct; further eruptions, but at very infrequent intervals, may be expected. Small hydrothermal (phreatic) eruptions in the Ngawha geothermal field also take place occasionally and these could be destructive at short distances.

Whangarei Volcanic Field

Activity in this area, which includes the city of Whangarei and covers in all some 350 km², is very similar to that in the Bay of Islands-Kaikohe district. The most recent activity, however, seems to have occurred about 34,000 years ago, in the Kamo area. This is twice as old as the supposed date for the latest Bay of Islands eruption, but is still a short time ago compared to the very long average interval between eruptions. This, deduced from the fact that there have been approximately 14 such eruptions (of c.10 m³) in the past 2.3 million years, is about 166,000 years (15); see figure 3 where the trend centred on this interval is again drawn parallel to Auckland. Like the Bay of Islands-Kaikohe field, the largest eruption to be expected will probably be about 1 km³. The potential for damage is, however, greater than in the former area, since an eruption could well occur in or near Whangarei City. The predominantly basaltic eruptions will be explosive, as in the past, if water is involved: most, however, will proceed comparatively quietly with the emission of lava flows.

Auckland Volcanic Field

It is unfortunate that the largest city in the country corresponds so closely to the extent of this volcanic field. Older volcanic cones lie to the south, in the area of the Bombay Hills, and are probably extinct. The Auckland field itself covers about 650 km², and extends from north of Takapuna to near Manurewa (16, 17). Like Bay of Islands-Kaikohe and Whangarei, activity is basaltic, more completely so in fact than either of the

other two districts, and has produced more lava than tephra. The presence of the sea over much of the field, however, means that many of the past eruptions have been moderately explosive, and similar activity is expected in the future. Although the largest single eruption ever likely to occur in the Auckland field will be of the order of 1 km³, as in the Bay of Islands and Whangarei districts, the potential hazards are very much greater than in either of these areas, because the field is built up and densely inhabited except for that part of it which lies beneath the sea. Eruptions in shallow water will be explosive, although the comparatively small volumes of magma involved will limit the destructive effects (Table 1). Small tsunamis may well be generated, and these are also likely to cause damage.

In assessing the frequency of eruptions in the Auckland field, a major difficulty has been the fact that many centres have erupted, each usually in a single cycle of activity, and usually with only a small volume of tephra. Accordingly, the products of different centres seldom overlap, and their relative ages are therefore hard to assess. Also, few absolute ages have been obtained by 14°C or other means, for the Auckland rocks. As in the Bay of Islands-Kaikohe and Whangarei fields, most cones in the Auckland field have been active only in a single eruptive cycle, which may last perhaps a few years to several tens of years, after which they become extinct. Rangitoto may be an exception. This centre has produced by far the greatest volume of lava and ejecta in the Auckland area (Appendix 1: figure 3).

Although the evidence is sparse, most eruptions seem to take place in cycles of activity lasting for a few hundred to perhaps 1500 years, during which many centres may be active (17). Rangitoto last erupted only about 250 years ago, and began erupting some 500 years before that. Although there has been no activity there in historic times, this short interlude may represent only a pause in the "present" or "Rangitoto" cycle of activity. It is clear from figure 3b that if a resurgence of activity were to take place today it would be grouped in with this "present" cycle which began about 750 years ago. As the volume of lava extruded to form Rangitoto has already been so much greater than in previous cycles of activity, any continuance of the present cycle is unlikely to involve eruptions bigger than about 10 8 m³.

In figure 3a the mean intervals between eruptions, determined from the groupings and estimated ages given in Appendix 1, are given for events yielding $\geq 10^8$ m³ and $\geq 10^9$ m³, and are shown extra-polated for smaller eruptions. Mote that in this context "eruptions" means "eruptive cycles": there is no evidence to indicate the periodicity of eruptions within a single cycle. Hence little can be said of the probability of the next (comparatively minor?) eruption in the present "Rangitoto" cycle, beyond saying that an eruption up to the order of 10^8 m³ is entirely likely, more so in fact than

it would be <u>between</u> eruptive cycles, and that it will probably take place at or near Rangitoto rather than in some totally different part of the Auckland volcanic field.

Mayor Island

Mayor Island, with an area of about 15 km², is the summit of a submerged rhyolitic volcano in the western Bay of Plenty. It is surmounted by a caldera about 3 km in diameter. A long period of submarine eruptions had built up the cone to above sea level by about 42,000 years ago, when the products of a major eruption in the Okataina volcanic centre (see below) were deposited on the island. Since then it is estimated that there have been 11 eruptive episodes of $\geq c.10^7$ m³, of which three have exceeded about 10^9 m³ (19, 19): from this, approximate mean intervals between eruptions can be calculated, and are shown in figure 4a. The eruptions are listed with their estimated dates in Appendix 1, and are also shown in figure 4b, where the smaller eruptions ($\geq 10^8$ m³) are arrowed.

It is clear that activity has been episodic, with a period of intermittent voluminous eruptions between about 10,000 and 6000 years ago. How this period relates to previous episodes at the volcano, and hence to future ones, is not clear. More work is required, and it would be especially desirable to obtain some marine cores downwind of the island: from this it is likely that a reliable chronology of eruptions could be built up.

Although Mayor Island has no permanent inhabitants, it represents a high degree of volcanic risk. Past eruptions have been entirely of rhyolite, and hence very explosive. Large pyroclastic flows impacting into the sea commonly give rise to tsunamis (11), and these could devastate a large part of the Bay of Plenty and Coromandel coastline. Furthermore, Auckland lies downwind of the island, insofar as the upper altitude winds are concerned (low altitude winds blow in the opposite direction, from west to east), and could receive a significant amount of ashfall in a very large eruption. It is not known whether Mayor Island has the potential for eruptions as large as 100 km³, but any rhyolitic volcano should be suspected of having such a potential unless evidence can be found to the contrary.

White Island

White Island, in the eastern Bay of Plenty, is an andesitic to dacitic volcano almost entirely submerged. A large crater open to the east lies only just above sea level, and smaller craters within this overall depression extend down well below sea level. The island is small, no more than about 3 km². Its highest peak, 321 m, directly overlooks the crater and has a very steep headwall composed of rock much weakened by fumarolic alteration. A system of arcuate faults, parallel to the crater tim, passes behind the peak on the side away from the crater. This very unstable situation leads to massive rock-

falls from the inner crater walls. One such, in 1914, blocked vents on the crater floor, causing gas pressure to build up. Resulting explosions mobilised debris and generated a lahar (mudflow) which overwhelmed the sulphur works and killed everyone on the island. Similar events are likely in the future. Nowadays there are no residents on White Island and, except in very large eruptions, risk is limited to occasional visits by scientists, tourists, fishermen or muttonbirders.

Large eruptions are, however, possible, up to a maximum of perhaps 1 km³. In such an event, subsidence or large explosions beneath the crater floor could conceivably allow seawater access to the present deep vents. If this were to happen suddenly, tsunamis might be generated which would be destructive on the Bay of Plenty coast. However, calculations suggest that a large volume of water would need to come into very rapid contact with the near surface magma beneath the vents for this to happen, and that this would be most unlikely to occur (20). The risk of tsunamis from White Island is therefore considered to be much less than at Mayor Island.

The volcanic history of White Island has been elucidated back to about 15,500 years before the present, by comparing the record of eruptions on the island (21) with marine cores obtained within a distance of about 70 km (22). There have been seven eruptions during this period which have deposited a significant amount of ash in the marine cores: these, at a guess, have each ejected more than about $10^7 \, \mathrm{m}^3$. The latest eruption, which began in December 1976 and ended in January 1981, may rank with these seven previous events in terms of volume ejected. Two eruptions about 4200 and 9000 years ago (22) were substantially larger ($\geq 10^{8} \text{m}^{3}$?), and are tentatively correlated with the eruptions which formed the west and east parts, respectively, of the main crater depression at White Island (21). It is likely that eruptions of this size gave rise to minor ashfall on the mainland, and small to moderate tsunamis may have been generated.

Eruptions are listed in Appendix 1, and are shown on figure 5. From the relationship in figure 5b it is clear that there is a regularity in the volume produced with time. This suggests, in spite of the latest eruption in 1976, that the volcano currently has a potential for eruption of something like 4 x $10^7 \, \mathrm{m}^3$. Estimates of volume are, however, very sketchy, and are certainly no better than rough order of magnitude approximations.

Okataina Volcanic Centre

The Okataina volcanic centre is a complex structure of overlapping calderas and associated rift zones, lying between Lakes Okataina, Rotoiti, Rotoma, Rerewhakaaitu, Rotomahana and Tarawera, in the area between Rotorua and Kawerau. It includes the two volcanoes Tarawera and Haroharo, and is dominantly a rhyolitic centre, although small volumes of basalt have been

erupted there also, as in 1886 in the Tarawera eruption. The volcanic history of the centre has been closely studied back to about 42,000 years ago, the time marked by a large eruption, the Rotoiti Breccia and associated Rotoehu Ash (see Appendix 1) in the north of the area. For the largest eruptions (\ge c.150 km³), the chronology has been established back to about 230,000 years, the date of the first eruption which can be traced definitely to the Okataina centre (23).

Very large eruptions, with volumes of the order of $150-300~\mathrm{km}^3$ were erupted from the centre between 230,000 and 150,000 years ago, as welded ignimbrites. These dominate the record of eruptions (figure 6b). Since 150,000 y BP, activity has greatly declined, although these have been two large unwelded ignimbrites, at about 42,000 and 33,000 years ago. All other eruptions during this period have been of no more than about 20 km³. This is still a large figure (the great Krakatoa cruption of 1992 printed about 20 km³). eruption of 1883 ejected about 18 km3), but it is insignificant compared to former eruptions. Note that the largest historic eruption in New Zealand, the Tarawera eruption of 1886, is barely visible on the scale of figure 6b. This event, which had a traumatic effect on the Rotorua district, killing over 150 people, was similar in size to the eruption of Mount St Helens, Washington, USA in 1980. This serves to highlight the tremendous potential for destruction that exists here and elsewhere in New Zealand.

A major difficulty in assessing the probability of future eruptions, which is common to all centres that erupt rhyolitic ignimbrites, arises from the very long intervals which typically separate the largest eruptions. In order to project a reliable trend forward, a long history of past activity must be known. However, the older deposits are often ero-ded and are usually overlain by younger ones, so that realising this aim is almost always very difficult. Furthermore, the rate at which eruptions have taken place, the volume/time relationship illustrated in figure 6b, has not remained constant. Overall trend lines showing this relationship can be fitted to groups of eruptions, as has been done in figure 6b. From this, it is clear that the rates fluctuate considerably. At present it seems likely that a shortfall of some 50 km³ exists at Okataina between the volume actually erupted and the volume predicted by the extrapolation of the trend given by eruptions over the past 15 000 years tions over the past 15,000 years or so.

Average intervals calculated from all known eruptions at Okataina of $\geq 75~\mathrm{km}^3$, and for all smaller eruptions over the past 42,000 years, are plotted in figure 6a. This clearly shows the existence of two quite different trends, and there is the hint of a third, for the very largest eruptions. This suggests that different mechanisms operate for the eruptions above and below about 9 km³ in volume.

Eruptions like that of Tarawera in 1886, in the volume range 1-5 km³, would be destructive close to the volcano.

Those of 10 km 3 or so would cause damage at Kawerau and Rotorua: large lahars would probably form in the river valleys, and pyroclastic flows would travel considerable distances. Eruptions of the order of 100 km 3 would be destructive over a large part of the North Island. Volcanic risk is potentially, therefore, very great at Okataina, as it is at all the rhyolite volcances in the country.

Eruptions at Okataina tend to occur along two rift zones. One is the wellknown Waimangu-Rotomahana-Tarawera rift in the south of the volcanic centre. can be traced further northeast as a zone of weakness at least as far as Kawerau and Mt Edgecumbe. Mt Edgecumbe represents the extrusion of a large volume of degassed magma some 8000 to 10,000 years ago, probably related to one of the tephra eruptions in the Okataina centre proper (see Appendix 1). The other rift system parallels the Tarawera rift to the north, and includes the dormant Haroharo volcano and several subsidiary centres between Lake Okareka and Lake Rotoma. In addition it has been suggested that there is a substantial magma body, of the order of 300 km³ dense rock volume, near the eastern end of Lake Tarawera (24), between the two rift zones. If confirmed, it is likely that future large eruptions will take place in this area.

Figure 7 shows how volcanic activity in the Okataina centre has been split between the two rift systems. The volumes erupted on the Tarawera rift have been far greater than at Haroharo because of the three large ignimbrites erupted before about 150,000 years ago. The rate of eruptions (figure 7b) has fluctuated greatly, but from the average intervals (figure 7a) there is no evidence to suggest anything but an overall straight line relationship. Volumes erupted at Haroharo have been greater during the past 50,000 years than at Tarawera and the rates have also fluctuated greatly. The average intervals between eruptions on the Haroharo rift system (figure 7a) show the same two trends that can be seen for Okataina as a whole (figure 6a). At present the shortfall at Tarawera seems to be of the order of 40 km³, and at Haroharo about 80 km³, although there is some doubt about how the trend lines should be drawn.

Numerous very large ignimbrites were erupted from the central volcanic region before 250,000 years ago. Many have not yet been traced to their origin, and it is possible that some were erupted from the Okataina volcanic centre. These ignimbrites of unknown origin are discussed below under the Maroa volcanic centre and are illustrated on figure 9 (see also Appendix 1).

Rotorua Caldera

Rotorua caldera was probably formed by subsidence after the eruption of the Mamaku ignimbrite about 140,000 years ago (the youngest of the major welded ignimbrites). Previous activity, if any, is unknown and subsequent eruptions (see figure 6b) have been insignificant in volumetric terms. The lava dome of Ngongotaha (c.10 km³?) was extruded (23) at some unknown date between the Mamaku ignimbrite eruption and the Rotoiti eruption from Okataina about 42,000 years ago. There was at least one lesser eruption (of the order of 1 km³) between 42,000 and 13,800 years ago. These rough dates allow a crude approximation of average intervals to be made, and suggest a return period of the order of 70,000 years for eruptions \geq 10 km³, and about 47,000 years for eruptions of \geq 1 km³. This trend is shown in figure 6a.

Rotorua caldera may be a "one shot" caldera in which no further ignimbrite eruption of the scale of the Mamaku ignimbrite will occur again. However it is the youngest of all the rhyolite centres except Mayor Island, and it is equally possible that a series of major rhyolite eruptions will take place there in the future. Volcanic risk is high because of the presence of Rotorua City, and damage would probably be severe in any eruption of 1 km³ or above.

Maroa Volcanic Centre

The Maroa volcanic centre as defined (25) lies south of the Waikato River between Orakeikorako and Atiamuri. It is a cluster of rhyolite domes within an area about 15 km in diameter, lying within a larger, roughly circular area, slightly elongated in the east-west direction, which is about 45 km in maximum diameter. This larger area, or outer ring structure, is defined by rhyolite domes near Whakamaru and Mokai in the west, Oruanui and Kaimanawa in the south and Horohoro and the Waiotapu area in the north; to the east it is bounded by the Kaingaroa Fault. Dacite domes, as well as rhyolite ones, are found near Waiotapu, and minor basalts are exposed near Whakamaru. The whole area is one of subsidence, cut by northeast trending faults which separate uplifted blocks such as Haroharo and Paeroa from sinking grabens such as the Guthrie, Ngakuru and Waikite valleys. For the purposes of the present discussion the Maroa volcanic centre is taken to include the outer ring structure. It is bounded by the Rotorua caldera and the Okataina volcanic centre to the north and northeast, and by the Taupo volcanic centre to the

Very large welded ignimbrites have been erupted intermittently from the Maroa volcanic centre, possibly from near Mangakino, over a period of at least 900,000 years, from c.1.05 million y to 150,000 years, from closs million years with tephra found in marine cores at distances of up to 2000 km from the North Island (14, 33). There is still considerable doubt both as to the source and the number of individual ignimbrite eruptions, and there are anomalies in the dates which have been found. The volumes are huge and can only be approximately estimated. In spite of all these uncertainties, however, a broad picture of the volcanic

activity at Maroa can be obtained (figure 8b). Uncertainties, marked by the cumulative volumes shown as maximum and minimum in the figure, make it impossible to estimate whether the rate has remained constant up to about 150,000 years ago, or declined during the last 280,000 years. Either way, unless the centre is extinct, which is possible but unlikely, it would seem that a substantial shortfall exists, of at least 100 km³ and possibly of as much as 700-900 km³, between the volume actually erupted and the volume expected on the basis of the time elapsed. These estimates, however, are very approximate.

Very little is known of the chronology of smaller eruptions at Maroa. A rough estimate of about 10,000 years for the average interval between eruptions of the order of 10⁸ m³ (34) has been used in figure 8a to define the average volume versus time relationship. The trend marked A was used in a previous study (35). That marked B has been adjusted to give a better fit to the data presented here for the largest eruptions.

It is clear from the record preserved in the deep sea cores (33) that large eruptions have occurred intermittently in the North Island for at least the last 3.7 million years. Many of the older ones, before about 1 million years ago, probably originated in the Coromandel district, which was active before the Taupo volcanic zone. The exact source of these ignimbrites is unknown, and it is only those that have taken place since c.1.05 million years ago that can be traced definitely to the Maroa or Mangakino centres or their surroundings (figure 8b and Appendix 1). In order to examine the overall way in which the rate of eruptions has changed with time, an estimate of volumes and dates has been plotted in figure 9 (see also Appendix 1). All rhyolite eruptions are shown, including those from the Okataina, Taupo and Rotorua centres, as well as those which can be definitely traced to Maroa/Mangakino and those whose source is unknown. The average intervals versus volumes are shown in figure 9a, and on figure 9b the cumulative volumes erupted, from which a steady increase in the rate of eruption can be clearly seen. This began about 1.5 million years ago and climaxed about 300,000 years ago. It has declined quite markedly over the last 200,000 years. These changes in rate are plotted separately on figure 10. Extrapolation of the trends into the future is dificult, but it is clear that the rate remains high, probably of the order of 1 km³/300-500 years.

Any eruption of more than 1 km³ or so in the Maroa area would cause damage to forests and farmland. The larger eruptions would be highly destructive. Lahars would probably be generated in the Waikato River and would cause extensive damage to dams, power plants and towns downstream.

Taupo Volcanic Centre

The Taupo volcanic centre, which abuts the Maroa centre to the north and the andesitic Tongariro centre to the south, consists of a large area of subsidence, 30 to 35 km in diameter now largely covered by Lake Taupo, and probably includes several overlapping calderas. It is cut by a number of prominent northeast-southwest trending faults, along which many of the rhyolite intrusions are aligned. There are minor basalt extrusions close to several of the faults and one andesite extrusion on the fault-bounded eastern margin. Tauhara, east of Taupo borough, and a small dome further southwest, are composed of dacite.

The volcanic history of the centre has been studied in detail back to the Rotoiti eruption from Okataina about 42,000 years ago (36-40). During this time there have been about 16 explosive rhyolite eruptions from the Taupo centre, two of which have erupted ≥ about 100 km³. The latest of these, the Taupo pumice eruption about 1800 years ago (36,39) has to a great extent determined the landforms in the central North Island. Most present river valleys are cut in terraces of Taupo pumice which were emplaced by massive lahars and floods following the eruption. Some large lahars were generated by pyroclastic flows (unwelded ignimbrites) impacting into river valleys. Taumarunui is built on ignimbrite debris of this kind and Wanganui City on lahar terraces formed as a result of this eruption. About 20,000 years ago there was a still larger eruption, the Kawakawa or Oruanui unwelded ignimbrite and associated tephra (see Appendix 1). Most eruptions, however, during the past 40,000 years have been comparatively small, typically of 1 to

It is likely that at least three major welded ignimbrite eruptions originated in the Taupo volcanic centre between about 320,000 and 215,000 years ago. If this interpretation is correct, the Taupo centre is somewhat older than Okataina (230,000 years?), but much younger than Mangakino/Maroa (1.1 million years?). Eruptions are listed with their dates and estimated volumes in Appendix 1, and average intervals and cumulative volumes are shown on figure 11. There is little evidence to suggest the current rate of eruption (figure 11b) because the record is entirely dominated by the gigantic eruptions about 320,000 years ago. On the basis of activity during the last 40,000 years it has been suggested (40) that no large eruption will take place at Taupo for 10,000 years or so, although there could well be small eruptions of less than about 5 km³. A similar calculation for Okataina suggested a shortfall at present of about 16 km³, compared with my estimate (see above) of about 50 km³. Uncertainties in the dates and source vents of the earlier eruptions, and especially in the volumes emitted (see 40 for a thorough study of this problem) mean that estimates of future eruptions are inevitably imprecise.

Tongariro Volcanic Centre

The Tongariro volcanic centre includes the two large andesitic massifs of Tongariro and Ruapehu, and the smaller cone Ngauruhoe. It also includes older andesite volcanoes which are now probably extinct, such as Tihia, Kakaramea and Pihanga. The centre lies south of Lake Taupo and marks the southern extension of the Taupo volcanic zone. The present active vents are aligned along a north northeast trending zone which continues beyond Tongariro, to the northeast of Lake Rotoaira where a number of small explosion craters have formed. Lake Rotopounamu fills the largest of these. Eruptions are possible in the future anywhere along this zone, from a short distance southwest of Turangi to just south of Ohakune, where there are also explosion craters which formed comparatively recently. A description of the three presently active or potentially active volcanoes - Tongariro, Ngauruhoe and Ruapehu - follows.

The oldest of the three is This is a complex andesite Tongariro: volcano with many craters, some containing lakes, and some still fumarolic. Activity probably started here half a million years or so ago, and during its long life there have been several moderately large explosive eruptions. The largest which have been recognised, for example the Mangamate eruptions about 8000 years ago (41) probably amounted to 3-4 km³ or so, and somewhat resembled the 1980 Mount St Helens eruption in scale. The largest which is considered ever likely to occur at Tongariro would be of the order of 10 $\rm km^3$. Such an eruption would generate lahars and spread ash over a wide area, but damage would be limited as the area is not densely populated, and only Turangi, among the larger towns in the district, would be affected. Power lines and communications would be cut, and widespread contamination of rivers and lakes by lahars and airfall tephra would cause damage and disrupt the Tongariro power scheme.

Little detailed work has been done on the past eruptions of Tongariro and in particular, little is known of the sequence of lahars that built up the extensive ring-plain around the volcano. In considering eruptions of ≥ 1 km³, it is necessary to include Ngauruhoe with Tongariro as Ngauruhoe is really only a parasitic cone on the Tongariro structure. The marked activity associated with the birth of the present Ngauruhoe cone about 2500 years ago, and the earlier Mangamate eruption about 8000 years ago, suggests that a typical interval between eruptions of c.1 km³ is about 5500 years. Small historic eruptions in the 19th century, between 1855 and 1896, and a possible small eruption in 1926, define a rough periodicity of about 24 years for eruption of the order of 105 m³ (see Appendix 1). The trend given by these values is marked on figure 12a. The cumulative volumes erupted over the past 12,000 years at Tongariro and Ngauruhoe are shown on figure 12b. There is insufficient information to project a reliable trend forward as a basis for estimating future activity,

but a shortfall of the order of 4.5 $\mbox{km}^{\,3}$ seems likely.

Ngauruhoe: As mentioned above, Ngauruhoe is really only a parasitic feature on the flank of Tongariro. The present cone began to form only about 2500 years ago. A previous, much larger cone on or near the same site is inferred from the remnants of glacial valleys to have existed at the end of the Ice Age, from perhaps 30,000 to around 10,000 years ago. It is likely that this cone was destroyed in the Mangamate series of eruptions about 8000 years ago (see Tongariro above).

There have been many historic eruptions at Ngauruhoe (see Appendix 1). Three of these, in 1870, 1949 and 1954, produced lava flows. The 1870 and 1954 eruptions produced volumes of the order of 10⁷ m³, as also did the February 1975 eruption, which was the last substantial event to have taken place at Ngauruhoe. The 1949 lava eruptions and the 1974 January ash eruptions are thought to have each produced approximately 10⁶ m³. All other historic eruptions appear to have been smaller. Average intervals are shown in figure 12a.

The largest likely eruption at Ngauruhoe would be of about 1 km³. Damage would be limited to a small area which might include Whakapapa village. Trampers and people in the vicinity of the mountain would be at risk, and there might be disruption of power lines and communications on the Desert Road. Apart from this, the risk arising from eruptions at Ngauruhoe is slight.

Ruapehu: Like Tongariro, Ruapehu is a large complex andesitic volcano. Its summit plateau is made up of several extinct craters, and the present active crater contains a lake which is kept heated by constant fumarolic activity. The volume of the lake fluctuates somewhat but is generally close to 10⁷ m³. Because it lies at an altitude of about 2530 m and several major rivers rise on Ruapehu, the lake-filled crater dominates much of the surrounding district and represents a high degree of volcanic risk.

Eruptions have been going on intermittently at Ruapehu for at least the last 250,000 years, but the bulk of the mountain is less than 100,000 years old, and all the upper part formed less than 50,000 years ago (42). An extensive ring-plain around the mountain was formed, as at Tongariro, by repeated lahars from the upper slopes. Some were extremely large (c.108 m³?) and huge boulders carried by lahars were deposited in the Rangitikei valley as far away as Mangaweka and Ohingaiti, at a distance of about 80 km from Ruapehu. On the other side of the mountain large laharic boulders were carried nearly as far as Taumarunui.

Only a very rough chronology can be pieced together for these major lahars (43), which probably accompanied largescale collapses of parts of the cone. It is unclear whether all of them were accompanied by eruptions. What information

is available is given in Appendix 1 and is plotted on figure 13b. Smaller lahars, which are still an order of magnitude larger than any that have happened in historic times, are recorded by deposits laid down by the Whangaehu River, which drains Crater Lake. There are only two such deposits above the marker bed laid down by the Taupo pumice eruption about 1800 years ago, and they have been dated (44) at 756 ± 56 and 407 ± 70 years BP. These are shown on figure 13c. It is likely, if such lahars were to occur again, that they would represent the explosive ejection of all the water at present in Crater Lake, or the sudden catastrophic collapse of the southeast wall impounding the lake, with rapid release of all the water. In the former case there would be devastating lahars on all sides of the mountain: these would affect not only the upper Whakapapa skifield but Iwikau and Whakapapa villages also (Top O' The Bruce and the Chateau). In the latter case all the water would be channelled down the Whangaehu River, and the resulting lahars would cut the main electricity transmission lines and the Desert Road, and would inundate Wajouru.

During historic times, smaller lahars (c.10 6 m 3), amounting to a tenth or so of the volume of Crater Lake, have several times caused damage on and around the mountain (45). Such events took place in 1861, 1895, 1925, 1969 and 1975 and are shown on a reduced scale in figure 13d. The mean interval between these is about 23 \pm 11 years. Numerous smaller lahars occur in the Whangaehu River at intervals of a few years. These are not destructive.

Little is known of the dates of tephra and lava eruptions at Ruapehu. There was a major eruption or series of eruptions which produced the Rangataua lava flows (\geq c.10° m³:42) and the Okupata Tephra (108-10° m³:41) between about 8000 and 13,000 years ago. This eruptive episode almost certainly corresponds to the latest large lahar (figure 13b), the Muri-motu lahar which laid down the large mounds near the bottom of the Chateau Road. During historic times there have been two occasions, in 1861 and 1945, when lava was present at the surface in Crater Lake and notable eruptions took place. Many phreatic eruptions have been recorded throughout the historic period (45: see Appendix 1). These have a mean periodicity of about 2.5 years. Estimates of the mean intervals for eruptions are shown on figure 13a. The largest likely eruption at Ruapehu would be of the order of 10 km³ (about twice the 1980 Mount St Helens eruption) and, as can be seen from the figure, the frequency of such an event is very low. The present shortfall, based on the record of past lahars, seems to be about 0.06 km³.

Mt Egmont

Dominating Taranaki, the isolated andesitic volcano Mt Egmont is thought by many to be extinct but is certainly only dormant. It last erupted in a comparatively minor way about 1755 AD. Somewhat larger eruptions took place about

100 years earlier. Previous eruptions back to about 25,000 years have been intensively studied, and for the largest lahars a rough chronology has been worked out for the last 50,000 years (46, 47).

The mountain is surrounded by laharic ring-plains more extensive than those at Ruapehu or Tongariro. These have also formed by large scale collapses (sector collapses) of the cone. The largest, which was probably triggered by a major explosive eruption, occurred about 23,000 years ago and attained a volume of 12 to 15 km³ (see Pungarehu lahars, Appendix 1), covering large areas at the western foot of the volcano. Such lahars, although hopefully on a smaller scale, are likely to occur again. The present summit, formed by a lava dome intruded 300 years or so ago, is greatly oversteepened and liable to collapse. Future eruptions would be very likely to cause this to happen.

The largest likely eruption at Mt Egmont would be of the order of 10 ${\rm km}^{\,3}$ and would devastate a large part of Taranaki. However, the periodicity inferred by extrapolating the data in figure 14a suggests that such an event occurs only once in 140,000 years or so. This is probably longer than the time elapsed since Mt Egmont began erupting (50-70,000 years ago?), and as one such event (the Pungarehu lahars) has already occurred it is unlikely that eruptions in the near future will attain this volume. Smaller eruptions, of 1 $\rm km^3$ or so, are estimated to have a typical return period of the order of 12,000 years. Such events, and still smaller ones also, would generate lahars and cause damage over a substantial area. Towns such as Inglewood would be affected (48), and ashfall would affect grazing and water supplies over most of the region. Because of the steepness of the cone and the way in which it looms over the landscape, even quite small eruptions, of the order of 10⁷ m³, would be liable to generate lahars which would be destructive in river valleys around the mountain.

Estimated cumulative volumes are plotted against time in figure 14b. The volume emission rate has remained approximately constant, at about 1 km³/5900 years, since the Pungarehu eruption c.23,000 years ago. A shortfall of the order of 0.35 km³ appears to exist at present. On the basis of average intervals between eruptions (figure 14a) a smaller eruption, of the order of 10⁷-10⁸ m³ would seem more likely. At all events it is abundantly clear that the volcano is dormant rather than extinct.

QUANTITATIVE VOLCANIC RISK AND FREQUENCY OF ERUPTIONS

In a previous study (35) estimates were made of the total losses expected in eruptions at all the volcanoes discussed above. Naturally these are dominated by the largest eruption expected for each volcano. Neglecting Raoul Island, figures range from \$10 million to \$3000 million for the andesites, \$35 million to \$3100 million for the basalts, and

\$14,000 million to \$25,000 million for the rhyolites. The upper limit for a single rhyolite eruption is therefore broadly equivalent to the total external and internal deficit which at present burdens the nation's economy!

Clearly, however, it does not make much sense to regard the rhyolite volcanoes as the source of the greatest short-term threat, short-term in this sense being anything less than 500 or 1000 years. Some allowance must be made for the mean frequency of eruptions. A simple way of combining the two sets of data, the risk on the one hand, and the mean frequency on the other, is to apportion the risk on an annual basis, by dividing the amounts at risk in each magnitude range at each volcano by the mean interval between eruptions. The mean intervals accepted and used for this purpose are listed in Appendix II.

Risk calculated on an annual basis in this way ranges from about \$700 to \$3 million for the andesites, \$400 to \$400,000 for the basalts, and \$200,000 to \$1.25 million for the rhyolites (neglecting Raoul Island, as before, where the values at risk are very low). Apportioned annually, the greatest risk for the andesites stems from Mt Egmont, for the basalts, from Auckland, and for the rhyolites, from Okataina. In the country as a whole, by far the greatest volcanic risk, on an annually apportioned basis, is due to Mt Egmont, with Okataina a poor second.

This is all the more significant when it turns out that the greatest annually apportioned risk for Okataina is for the largest eruption class (100 km³) while for Mt Egmont it is for an eruption of only 10⁷ m³, a size that has a high degree of probability of occurrence. Larger and more damaging eruptions at Mt Egmont, when considered on an annual risk basis, amount to much less because of the proportionately much longer intervals that separate the large andesite eruptions compared to those at the rhyolite volcanoes. Ruapehu, which is second to Mt Egmont among the andesites in terms of annual risk, similarly reaches its highest risk value for a comparatively small eruption, in this case 10 ⁶ m³ only, an order of magnitude smaller than Mt Egmont. All other volcanoes have both their actual and annually apportioned risk at a maximum for their largest eruptions, except Raoul Island where the values at risk are so close to the volcano that peak loss, apportioned annually, is reached for 10 mm eruptions.

A measure of "likelihood" of eruptions is given in figure 15, assuming that eruptions are not a random process and that a volcano carries the "memory" of past events. This assumption is likely to be correct, since refilling of magma chambers, accumulation of gas pressure, and similar processes must to a large extent determine the time of eruptions. For each volcano the time elapsed since the last eruption in each magnitude class is divided by the mean interval between eruptions (Appendix II) and the results are plotted. Values below 1 indicate that

the time elapsed since the last eruption is less than the mean interval for that magnitude range. This serves to highlight those volcanoes and eruption sizes which are, in terms of the mean interval, "overdue". It is important to realise, however, that the large standard deviations on most intervals mean eruptions may still occur below the level 1, and equally that those volcanoes showing high values of "likelihood" may not necessarily be the first to erupt.

FUTURE ERUPTIONS: EVIDENCE FOR MAGMA BODIES

Although basaltic magmas can rise rapidly to the surface from beneath the Earth's crust, andesitic-dacitic, and rhyolitic magmas accumulate in reservoirs within the crust and remain there for long periods before eruption. These reservoirs are not totally, or even mostly, filled with molten rock, but with partial melts which typically amount to 20-30 percent of the total rock volume (40).

In New Zealand where the source region for large rhyolite eruptions is large and ill-defined, including all the central North Island from the north of Lake Rotorua to the south of Lake Taupo, it is a matter of urgency to locate underground sources of magma which might give rise to future large eruptions.

In this respect, a knowledge of the history of past eruptions is very helpful. Eruptions have occurred repeatedly along the Haroharo and Tarawera rift systems at Okataina and from the Horomatangi Reef (see figure 1) in Lake Taupo. Others have taken place at long intervals in the Maroa, Mangakino and Kapenga volcanic centres (figure 1) but in general so long ago that few can be traced to their individual source vents (32); still others have occurred at scattered vents throughout the area, now marked by rhyolite lava domes; and in a few cases individual tephra layers can be traced back to particular lava domes (37).

Geophysical evidence, such as the attenuation of S-waves (transverse waves) propagated by earthquakes, or the occurrence of volcanic earthquakes or volcanic tremor (a more or less continuous vibration recorded on seismograms) can point to the existence of partially molten bodies within the crust. In favourable circumstances, with enough recording instruments, it may be possible to delimit the boundaries of such bodies. This has been done on a small scale in the Tongariro National Park (49).

An analysis of gravity and magnetic measurements suggests that a large magma body, with about 300 km³ of partial melt, exists at shallow depth beneath the eastern end of Lake Tarawera (24). Another substantial magma body may underlie the Guthrie-Ngakuru area since a swarm of apparently volcanic earthquakes took place there in May 1983. This is the area previously identified as the Kapenga volcanic centre (24, 32). A third source of magma is inferred, on seismological

grounds, to lie along the line of the Ngangiho Fault (see figure 1) which cuts both the Taupo and Maroa volcanic centres. These are the only places within the area liable to rhyolite eruptions where evidence has been found up to the present time of the existence of magma bodies.

CONCLUSIONS

In assessing volcanic risk, a major practical difficulty lies in the very long intervals, often thousands or tens of thousands of years, between the largest, most damaging eruptions. This is accentuated by the fact that in New Zealand, which is famous for its rhyolite ignimbrite eruptions, activity has been on such a gigantic scale that much of the evidence concerning eruptions in the present cycle of activity, which is it vital to assess in order to forecast future activity, lies buried and inaccessible beneath later deposits.

In the short term, 100 years or less, the greatest volcanic risk in New Zealand lies in moderate eruptions at Mt Egmont of the scale that have occurred many times in the past. In the medium term, say 100-200 years, a destructive eruption of 1 km³ or thereabouts at Raoul Island becomes a likely event. In the long term, very large rhyolite eruptions at Okataina or Maroa/Kapenga are increasingly likely, and these may well take place from magma bodies inferred to underlie the east end of Lake Tarawera, and the Guthrie graben (Kapenga volcanic centre). No systematic search for magma bodies has yet been undertaken, and there are likely to be other sources of underground magma in the central volcanic district. One such probably lies along the line of the Ngangiho Fault.

By plotting cumulative volumes erupted against time, it is possible to estimate the current potential for eruptions at many of the volcanoes. This is expressed on the diagrams as a shortfall between the volumes actually erupted and those estimated by extrapolating past rates of eruption to the present time. The current potentials are roughly as follows: Raoul Island 1.5-14 km³; Auckland 0.1 km³ likely in the present (unfinished?) episode of activity; White Island c.0.04 km³; Okataina c.50 km³; Maroa 100-900 km³ unless the centre is extinctm, which is possible but unlikely; Tongariro (including Ngauruhoe) c.4.5 km³; Ruapehu 0.06 km³; and Mt Egmont c.0.35 km³. There is insufficient information to project a reliable trend for Mayor Island, Rotoroa Caldera, Taupo, or for Ngauruhoe on its own in spite of the large volume of data on small eruptions. However, the potential at Taupo is probably less than about 5 km³. At Ruapehu it is uncertain whether the large lahars are all eruption-related and the estimate may therefore be unreliable.

Quantitative estimates of volcanic risk expressed as property losses, excluding casualties, amount to about \$3000 million for the largest basalt and ande-

site eruptions, and to about \$25,000 million for the largest rhyolite eruption. These have been normalised to correct for differences in the mean frequency of eruptions, and are expressed as annually apportioned risks. For an individual volcano expected losses, annually apportioned reach \$3 million for the andesites (Mt Egmont), \$1.25 million for the rhyolites (Okataina), and \$400,000 for the basalts (Auckland). The greatest losses in an individual eruption, spread annually, are for about \$2.2 million (Mt Egmont, 107 m³ erupted), and \$620,000 (Okataina, 100 km³ erupted).

A measure of likelihood of eruptions is obtained by dividing the time since the last eruption by the mean frequency of eruptions. For those that could be significant in terms of damage (≥10⁷ m³), the greatest short-term likelihood exists for an eruption of about 10⁷ at Mt Egmont, which coincidentally is also the eruption for which apportioned annual risk is highest. The mean frequency of such an event is less than 100 years. In the medium term an eruption of about 1 km³ at Raoul Island, with a mean frequency of about 800 years, is considered probable. In the longer term, eruptions of the order of 100 km³ appear likely in the Maroa area and at Okataina. These have mean frequencies of about 100,000 years and 25,000 years respectively. There is, however, a possibility that the Maroa centre may be extinct.

Further work is needed to obtain a better estimate of the dates of past lahars at Tongariro and Ruapehu. This is crucial in assessing volcanic risk. So too is the need for a better understanding of the timing, sources, volumes and degree of interdependence of the large rhyolite eruptions. More data are urgently needed on the history of eruptions at Mayor Island, and could best be obtained by marine coring downwind of the island. Finally, a major integrated effort is required to locate any large magma bodies that may exist within the crust from southern Lake Taupo to north of Rotorua.

ACKNOWLEDGEMENTS

Among his many colleagues who have contributed ideas towards this paper, the author wishes to thank especially J W Cole, P C Froggatt, B F Houghton, E F Lloyd, V E Neall and C J N Wilson. The publication of this paper is subject to the approval of the Director, Geophysics Division, DSIR. Thanks are also due to S R Hicks for help with some of the diagrams.

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FIGURE CAPTIONS

Locality Map: 1:3,200,000, North Island, New Zealand, with insets, 1:2,000,000, Figure 1 central volcanic region and 1:25,000,000, the Kermadec-New Zealand region. Squares represent basaltic volcanic fields, and circles rhyolitic volcanic centres. Asterisks are volcanoes, and filled circles are towns. Dashed ovals on the insert are volcanic centres, and dashed lines are faults. Abbreviations are as follows:

```
Antipodes Islands
AΤ
AVF
         Auckland volcanic field
BOI-KVF
         Bay of Islands-Kaikohe volcanic field
         Cambridge
E
         Mt Egmont
H
         Haroharo
HR
         Horomatangi Reef
K
         Kawerau
         Kapenga volcanic centre: the faults cutting it mark the Ngakuru-Guthrie
KA
         graben (inner ring = approximate location of magma body)
М
         Mangakino (town: volcanic centre shown as dashed oval)
ΜI
         Mayor Island
MI-BI
         Macauley Island-Brimstone Island
MU
         Murupara
MVC
         Maroa volcanic centre (inner ring on inset): outer ring = associated
         rhyolite extrusions
N
         Ngauruhoe
NF
         Ngangiho Fault
OVC
         Okataina volcanic centre (the faults cutting it mark the Haroharo and
         Tarawera rift zones)
         Ruapehu (on inset, 1:2,000,000 = Rotorua)
R
RC
         Rotorua caldera
RI
         Raoul Island
RSV
         Rumble submarine volcanoes
SI
         Solander Island
         Tongariro (on inset, 1:2,000,000 = Tarawera)
Т
ΤА
         Taupo
То
         Tokoroa
TM
         Timaru
וזיד
         Turangi
         Taupo volcanic centre
```

Figure 2 Raoul Island

ጥህር W

WI

WVF

Whakatane

White Island

Whangarei volcanic field

- Log-log plot of mean intervals between eruptions. Filled circles are cala) culated values, and asterisks their corresponding standard deviations.
- h) Cumulative volume erupted versus time, to which lines defining two possible average rates of eruption have been fitted. These indicate a current shortfall in the volume erupted (that is, an eruption potential) of between about 1.5 and 14 km3.

Auckland volcanic field Figure 3

- Log-log plot of mean intervals between eruptions. Filled circles are calculated values, and asterisks their corresponding standard deviations. Unfilled circles are rough estimates for the Whangarei and Bay of Island-Kaikohe volcanic fields, for which the trends have been drawn arbitrarily parallel to that for Auckland.
- Cumulative volume erupted versus time (Auckland volcanic field only), to b) which an average rate of eruption trend has been fitted. Note that there is no evidence for the frequency of eruptions within an eruption cycle, and that it is unlikely that the current cycle has ended.

Figure 4 Mayor Island

- a) Log-log plot of mean intervals between eruptions. Unfilled circles are rough estimates only.
- b) Cumulative volume erupted versus time. Activity has been episodic, and there is insufficient evidence for an average rate of eruption to be determined. Heavy arrows mark eruptions of about 10⁷ m³. These are too small to show as steps on the diagram.

Figure 5 White Island

- a) Log-log plot of mean intervals between eruptions. Filled circles are calculated values, and asterisks their corresponding standard deviations. The unfilled circle is a rough estimate. The line marked A was used in the quantitative risk survey referred to (35). That marked B is a better fit to the data and yields the values given in Appendix II.
- b) Cumulative volume erupted versus time. The average rate of eruption is shown by the line which suggests that there is a current shortfall in the volume erupted (that is, an eruption potential) of about 5×10^7 m³.

Figure 6 Okataina volcanic centre and Rotorua caldera

- a) Log-log plot of mean intervals between eruptions. Filled circles are calculated values, and asterisks their corresponding standard deviations. The values seem to lie on three linear segments with slope changes at about 9.1 x 10^9 m³ and 1.1 x 10^{11} m³. The unfilled circles are rough estimates for the Rotorua caldera.
- b) Cumulative volumes erupted with time for the Okataina volcanic centre and Rotorua caldera. The Okataina data suggest several changes in the average rate of eruption. The latest trend, beginning about 14,000 years ago, suggests a current shortfall (that is, an eruption potential) of about 50 km³. The Rotorua data are insufficient to estimate the average rate of eruption.

Figure 7 Tarawera and Haroharo

In this figure the data for the Okataina volcanic centre are subdivided to give results for the two principal rift systems of the centre, the Tarawera and the Haroharo rifts.

- a) Log-log plot of mean intervals between eruptions. Filled circles are calculated values and asterisks their corresponding standard deviations. Unfilled circles are rough estimates. The values for Haroharo define two trends, with a change in slope at about $10^{10}~\rm{m}^3$. The Tarawera data are less complete, but appear to fit a single trend (the lowest value has large standard deviations).
- b) Cumulative volume erupted versus time. The data for both Tarawera and Haroharo suggest several changes in the average rate of eruption. Current shortfalls (that is, eruption potentials) may be about 80 km³ at Haroharo and about 40 km³ at Tarawera. However the lines are not well defined and it would be possible to draw a trend line for Haroharo which would give a shortfall of about 20 km³.

Figure 8 Maroa volcanic centre

The Maroa volcanic centre is taken to include the Mangakino and Kapenga volcanic centres. On this figure only those ignimbrites that can be definitely traced to sources within this area are included. Others are shown on figure 9.

- a) Log-log plot of mean intervals between eruptions. Filled circles are calculated values and asterisks their corresponding standard deviations. Unfilled circles are rough estimates. Line A was used in the quantitative risk survey referred to (35). Line B gives a better fit to the recalculated values at the high end and yields the values given in Appendix II.
- b) Cumulative volume erupted versus time. Uncertainty over which ignimbrites originated from the Maroa/Mangakino/Kapenga area is the reason for the two cumulative totals shown. Average rates of eruption fitted to these range from 1 km 3 /182 years to 1 km 3 /1333 years, and suggest current shortfalls in the volume erupted (that is, an eruption potential) of between 900 km 3 and 125 km 3 respectively.

- Figure 9 All known rhyolite eruptions (all sources, including Okataina, Rotorua, Maroa/Mangakino/Kapenga, and Taupo, and unknown sources in the North Island).
 - a) Log-log plot of mean intervals between eruptions. Filled circles are calculated values, and asterisks their standard deviations (envelope outlined). Unfilled circle is a single value. Wavy lines mark discontinuities in the data. Above the wavy line marked 1, mean intervals were calculated over the past 3.7 million years; between those marked 1 and 2, the period considered was the past 1.3 million years; and below 2, it was the past 42,000 years. The vertical discontinuity marked A may therefore be suspect, whereas that marked B is probably real. This implies a different mechanism for eruptions between about 20 km³ and 575 km³, the point which marks the abrupt change in slope at the upper end of the diagram, from both smaller and larger eruptions.
 - b) Cumulative volume erupted versus time. Many changes have taken place in the average rate of eruption. An interpretation of these is given by the straight lines fitted to the step function. The figures are years needed to accumulate 1 $\rm km^3$, the eruptions taking place intermittently and with large volumes.
- Figure 10 Rate of eruption of rhyolite versus time during the past 4 million years. The data plotted are the rates of accumulation of 1 km³ shown on figure 9b. The rate reached a peak about 325,000 years ago of about 1 km³/125 years. It has since declined, but remains high at approximately 1 km³/300-500 years. An overall period of about 2.5 million years is suggested by the data.

Figure 11 Taupo volcanic centre

- a) Log-log plot of mean intervals between eruptions. Filled circles are calculated values, and asterisks their corresponding standard deviations. The unfilled circle is a rough estimate based on a single observation. Two trends are indicated by the data with a change in slope at about 1.55 x $10^{10} \rm m^3$.
- b) Cumulative volume erupted versus time. The large volumes erupted before 200,000 years ago make it hard to assess a reliable rate of eruption for this centre. The long period of quiescence c.215,000 years ago covers a period which has not been well studied at Taupo, and may be suspect.

Figure 12 <u>Tongariro and Ngauruhoe</u>

- a) Log-log plot of mean intervals between eruptions. Filled circles are calculated values and asterisks their corresponding standard deviations. Two plots are shown: the line marked Tongariro includes eruptions at Ngauruhoe of $\geq 10^8$ m³. The line marked Ngauruhoe is based on data for eruptions of $\geq 10^7$ m³ at Ngauruhoe only.
- b) Cumulative volume erupted versus time: Tongariro and Ngauruhoe combined. The data are imprecise but suggest an average rate of eruption of 1 $\rm km^3$ in about 2090 years, and a current shortfall (that is, an eruption potential) of about 4.6 $\rm km^3$.
- c) Cumulative volume erupted versus time: Tongariro since 1850 AD. Data very approximate.

Figure 13 Ruapehu

- a) Log-log plot of mean intervals between eruptions. Filled circles are calculated values, and asterisks their corresponding standard deviations.
- b) Cumulative volume of lahars versus time during the past 250,000 years, or approximately during the lift of the volcano. The steps represent only large lahars (sector collapses): there are no data available on lava or tephra eruptions apart from the Rangataua lavas and Okupata tephra, shown arrowed, which probably occurred at about the same time as the Murimotu lahars. The rate of production of lahars at Ruapehu is approximately 1 km $^3/600,000$ years: on this basis there is a current shortfall (lahar potential) of about 6 x $10^7 \ \mathrm{m}^3$. There may be no physical reason for any regularity in the production of lahars since some may not be eruption-related. Hence this estimate is very doubtful.
- c) Represents cumulative volume versus time of lahars in the Whangaehu valley since the Taupo pumice (arrowed) at about 1800 y BP.

Figure 13 d) Represents cumulative volume versus time of eruptions (both phreatic and magmatic) since 1861 AD.

Figure 14 Mt Egmont

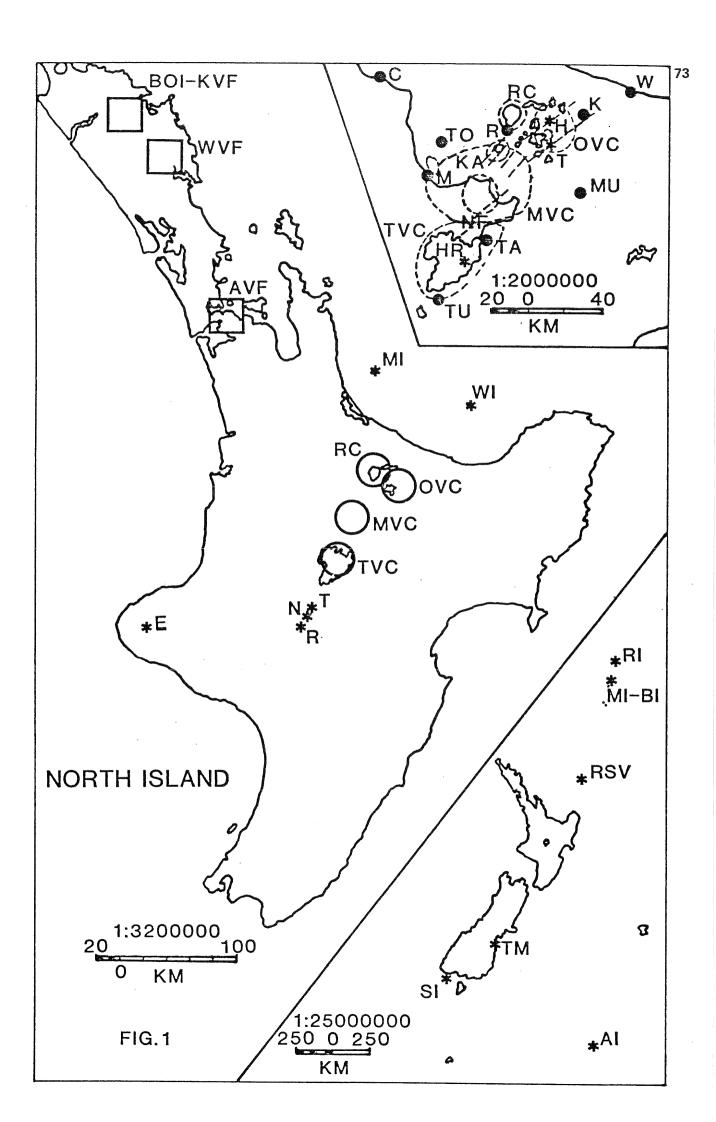
- a) Log-log plot of mean intervals between eruptions and lahars combined. Filled circles are calculated values and asterisks their corresponding standard deviations. Events at the low end are small debris flows, and those at the high end are large sector collapses of the cone. Events define two trends, which intersect at 8.3 x 10 6 m³.
- b) Cumulative volume of lahars and eruptions versus time. A steady rate of 1 km³/c.5840 years is apparent since the major cone collapse represented by the Pungarehu lahars about 23,000 years ago.

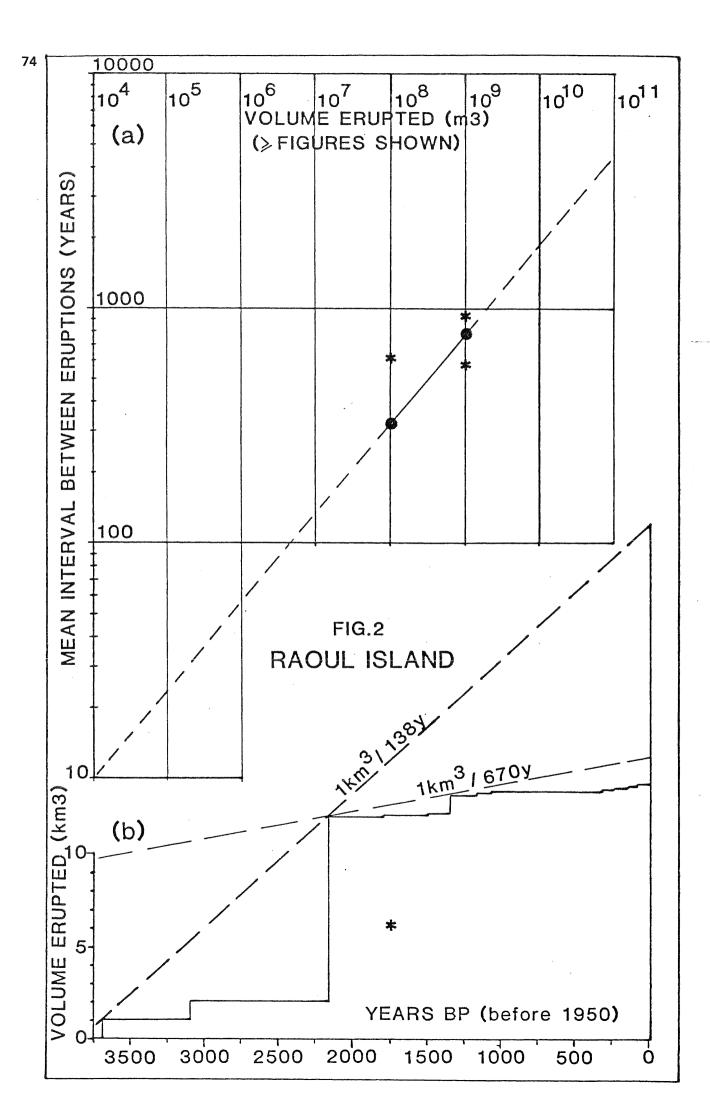
Figure 15 Likelihood of eruption

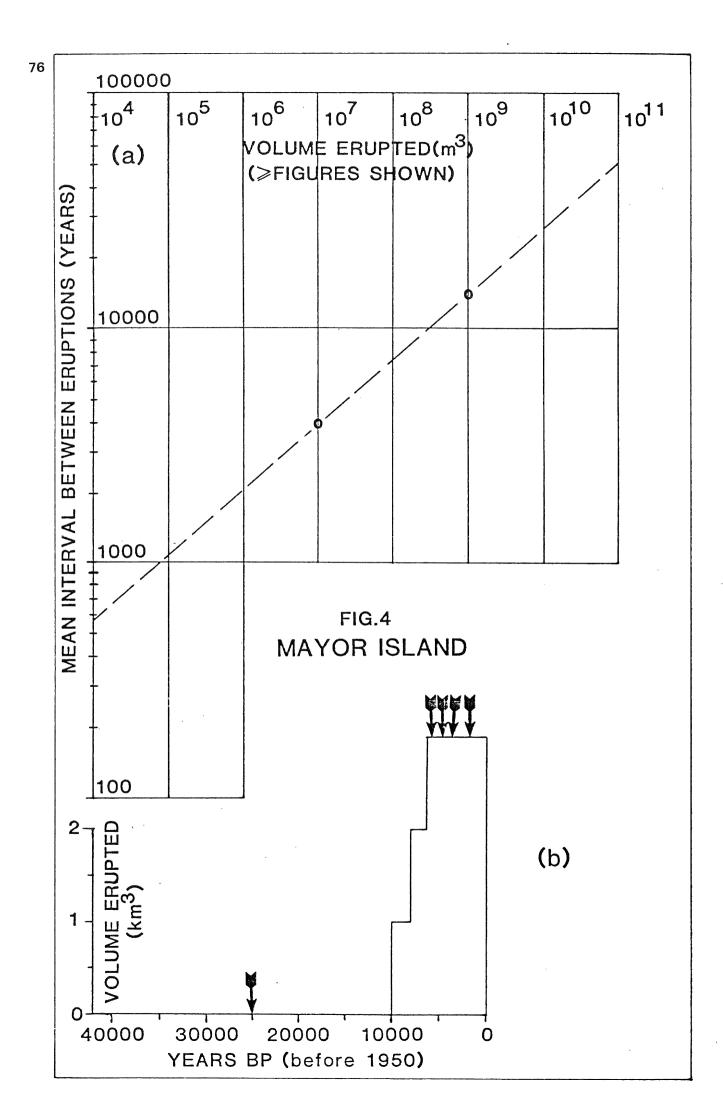
a) and b)

The figure shows the time since the last eruption or eruption-related event for a given magnitude class at a given volcano, divided by the mean frequency (see Appendix II) for the same magnitude class and volcano. Filled circles are well-determined values, and open ones are approximate values. Values below 1 represent elapsed times since the last eruption which are shorter than the mean intervals. The higher above the line representing 1, the more likely eruptions are to occur. For significant eruptions in terms of risk (those of $\geq 10^6~\text{m}^3$) Maroa, Mt Egmont ($\geq 10^7~\text{m}^3$), Taupo ($\geq 10^7~\text{m}^3$), Raoul Island ($\geq 10^9~\text{m}^3$) and Okataina and Rotorua (both $\geq 10^{11}~\text{m}^3$) emerge as the most likely events. Note that the mean frequencies of these eruptions are all greater than 500 years, except for Mt Egmont for which the mean frequencies of $10^6~\text{m}^3$ and $10^7~\text{m}^3$ eruptions are both less than 100 years (see Appendix II).

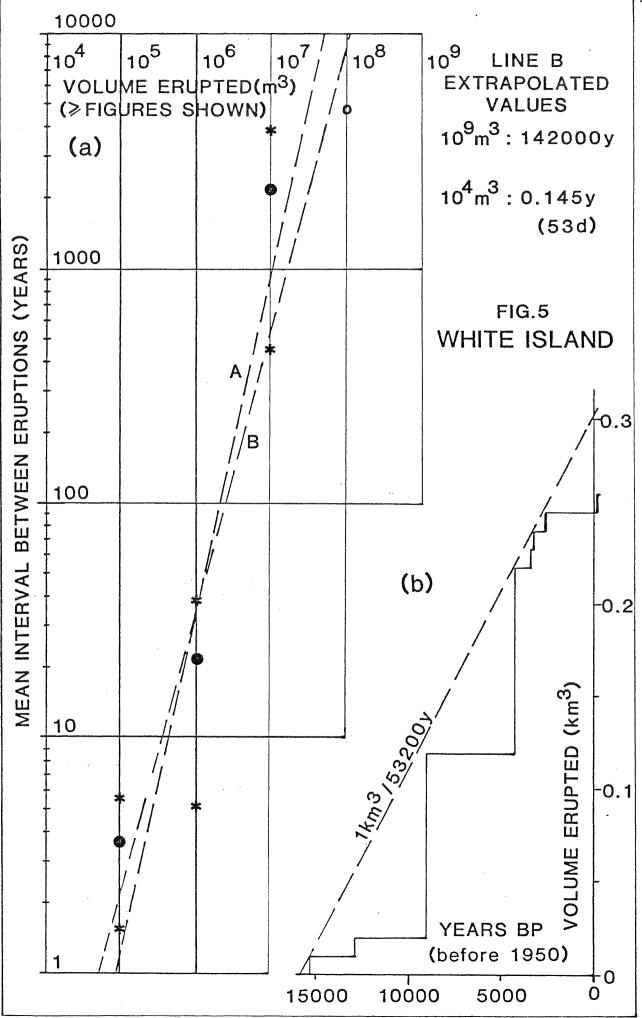
The figure is in two parts: 15a) shows data for Mayor Island, White Island, Okataina, Rotorua, Maroa, Taupo and Ruapehu; 15b) shows data for Raoul Island, Bay of Islands-Kaikohe, Whangarei, Auckland, Tongariro, Ngauruhoe and Mt Egmont.

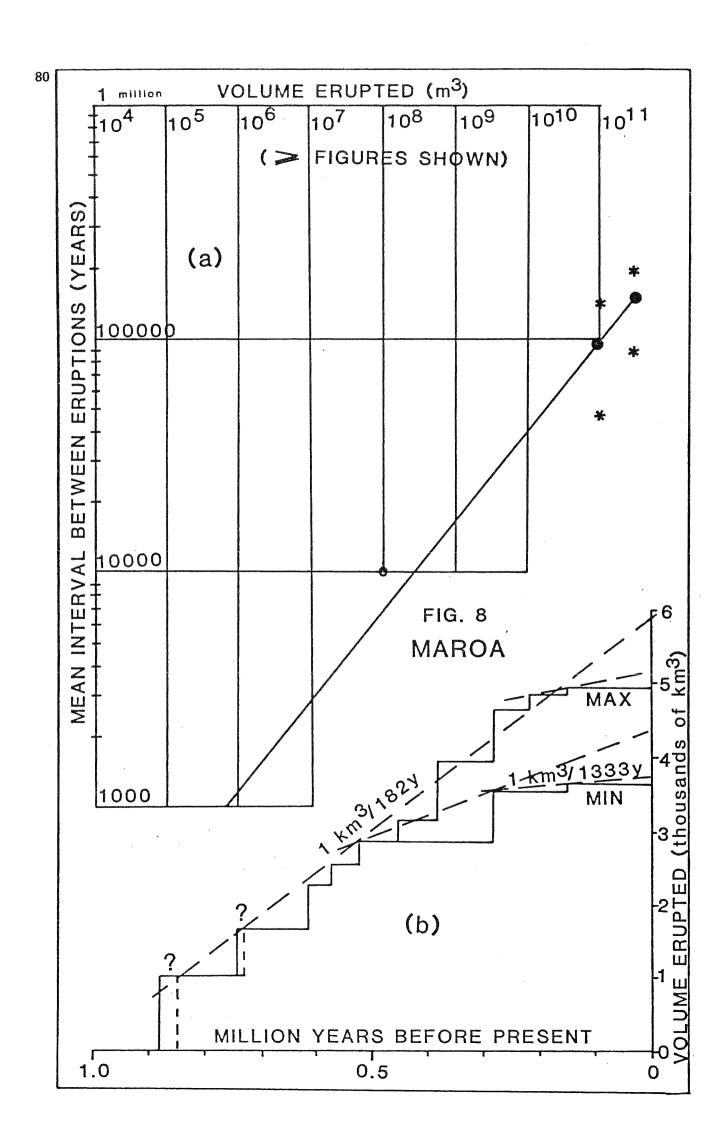












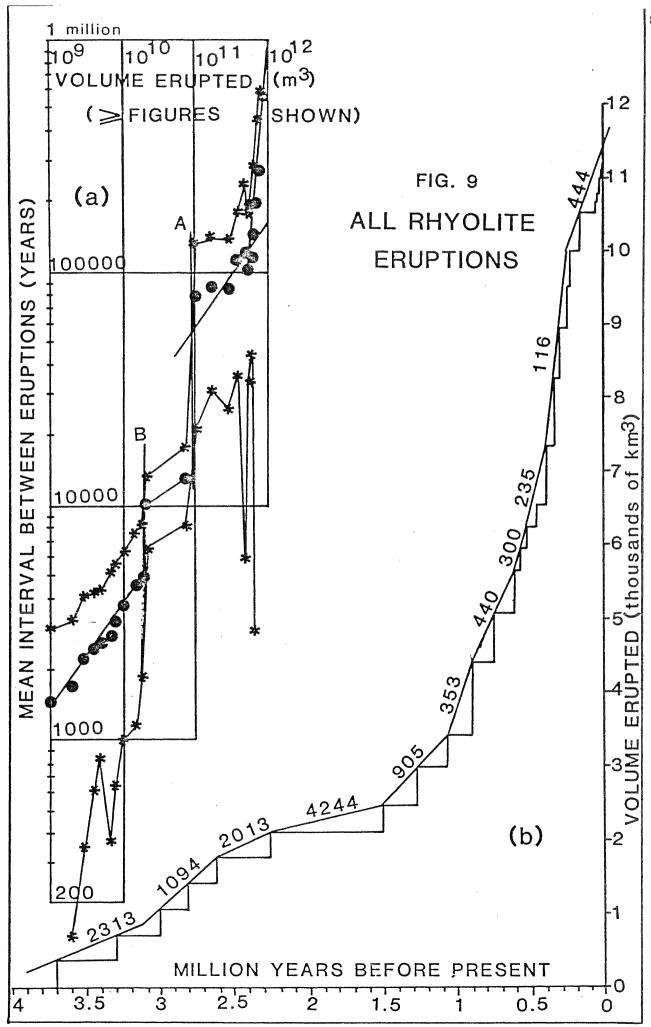
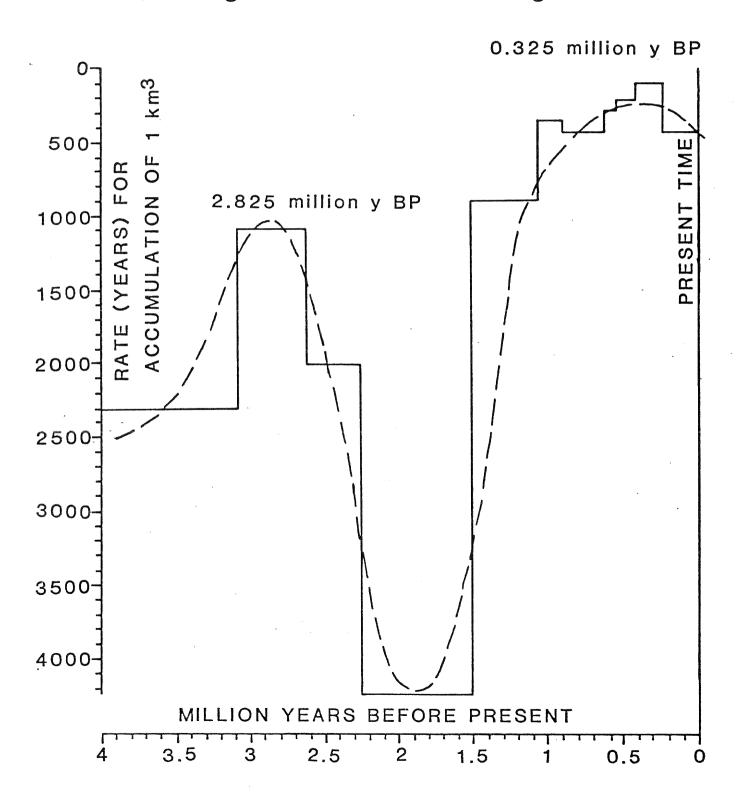
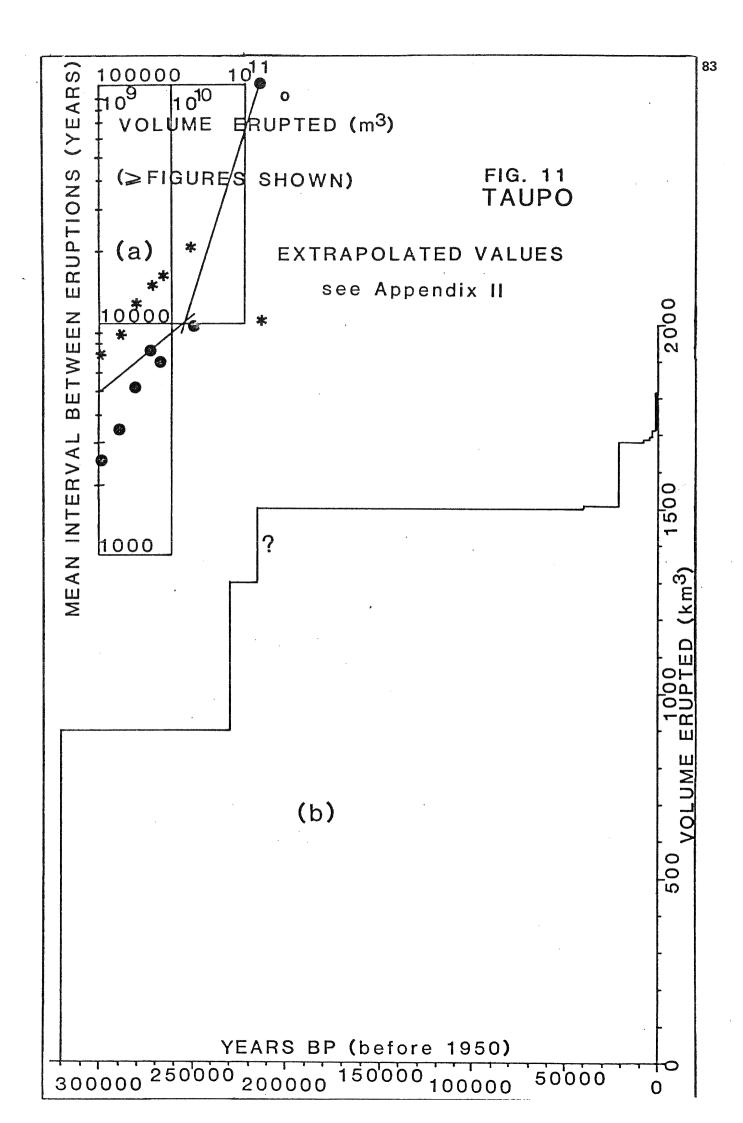


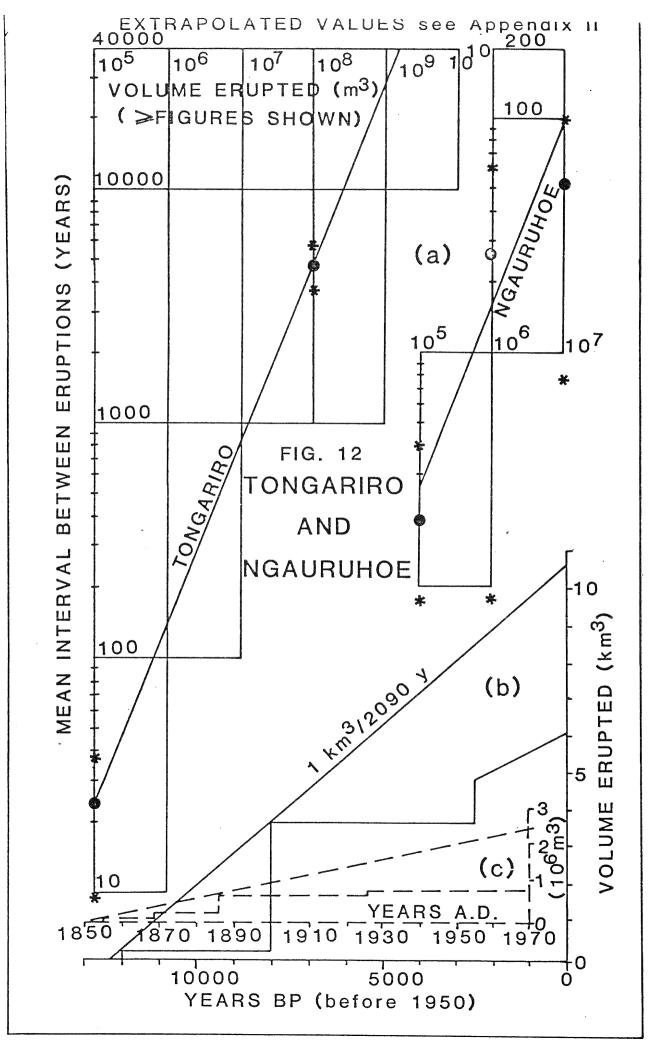
FIG. 10

RATE OF ERUPTION OF RHYOLITES

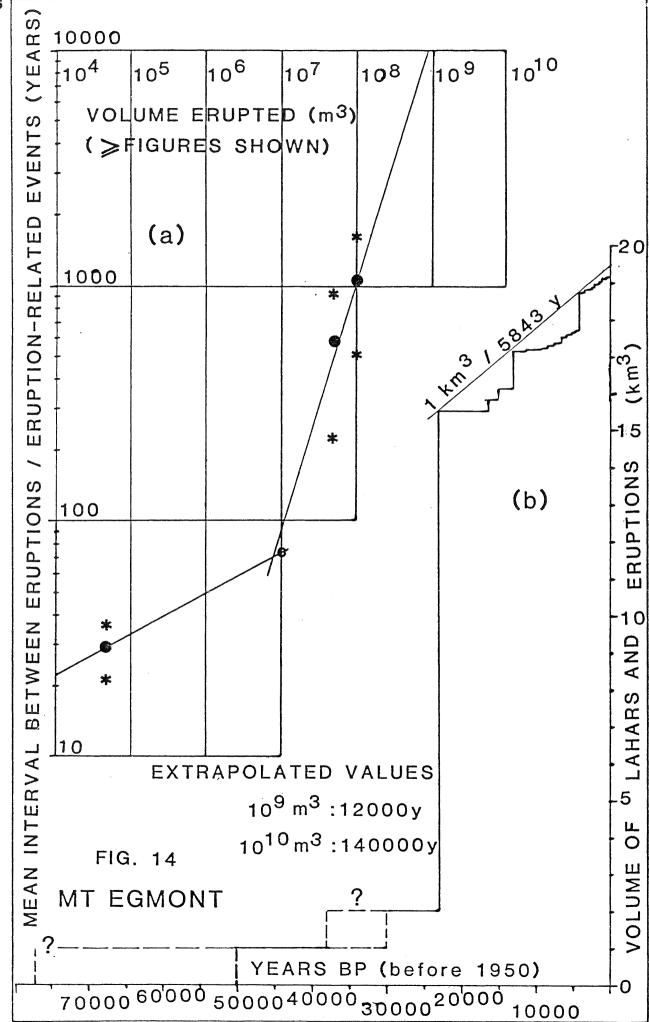
(average rates taken from Fig. 9b)

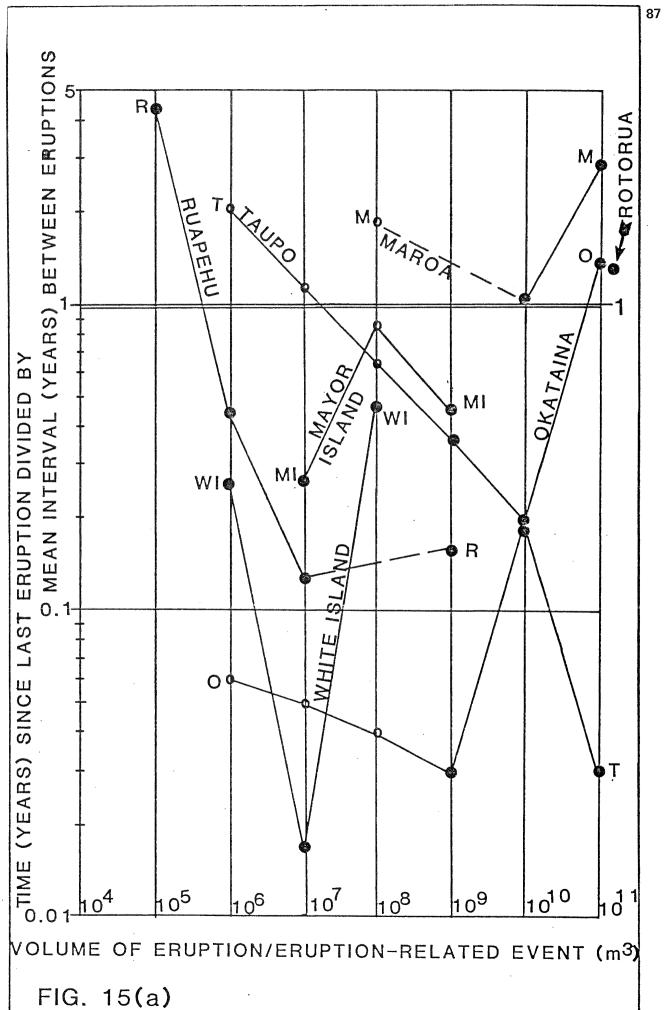


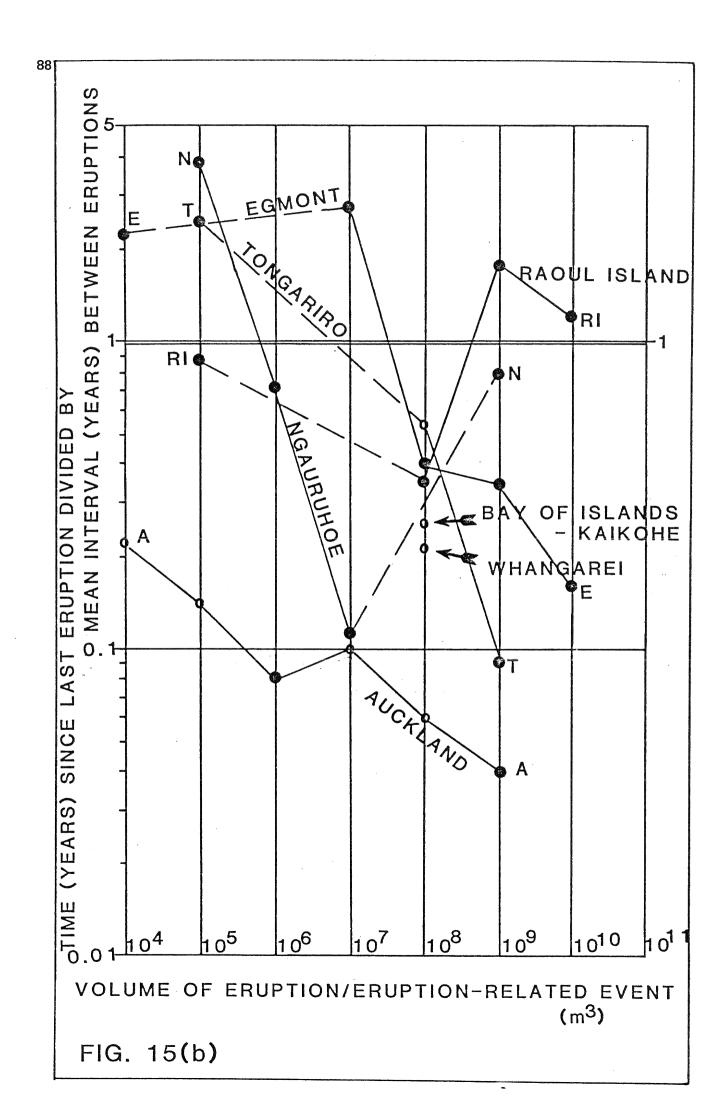












APPENDIX I

LIST OF ERUPTIONS, DATES, AND ESTIMATED VOLUMES.

Dates of eruptions are given in years "before present" (BP): following normal usage, "present" is taken as 1950: add 35 years, therefore, to give the elapsed time up to 1985.

RAOUL IS. (Ref. 13)

Activity in last 3700 years

Eruption	Estimated Volume (m³) **	Years BP (1950)	Interval (years)			
			≥10 ⁵ m ³	≧10 ⁸ m ³	≥10 ⁹ m ³	
1964 Breccia*	10 ⁵	-14	94			
1870 Breccia	10 ⁸	80		56		
Smith Breccia	10 ⁸	136		94		
Sentinel & Tui Breccias	10 ⁸	230		90		
Rangitahua Tephra	10 ⁸	320		c.755		
Expedition Breccia	10 ⁸	c.1075±75		c.125		
Pukekohu Breccia	108	c.1200		c.150		
Green Lake Tephra	10 ⁹	c.1350		c.150	c.810	
Rayner Tephra	108	c.1500		c.300		
Judith Tephra	108	c.1800		c.360		
Fleetwood Tephra	1010	c.2160		c.940	c.940	
Oneraki Tephra	10 ⁹	c.3100		c.580	c.580	
Matatirohia Tephra	10 ⁹	c.3680				
М	ean intervals	5		327±302 (n=11)	777±182 (n=3)	
			(record			

(record incomplete)

- * Eruptions designated "Breccia" were largely or entirely phreatic, i.e. the result of interaction with water. Those designated "Tephra" were predominantly magmatic.
- ** Volumes given are "fresh-fallen", i.e. as they actually appear in an eruption. These volumes are expanded in the process of gas release, by a factor which is usually close to 2, from dense rock equivalent volumes, which are approximately the volumes of the magma before eruption.

AUCKLAND VOLCANIC FIELD (Ref. 16, 17)

Activity in last 42 000 years

Eruption		Estimated Volume (m³)	Years BP (1950)	≧10 ⁷ m ³	Interval (years) ≧10 ⁸ m ³	≥10 ⁹ m ³
Rangitoto		6x10 ⁹	225-750 (500, say)		c.8850	c.8850
Mt Wellington Mt Smart One Tree Hill? Mt Eden? Mt Hobson? Mt St John? Orakei? Little Rangitoto? Browns Is.?)))))))	10 ⁹	9300-9400 (9350, say)		c.8930	c.18 150
Mangere		108	18 280(±265)		c.9220	
Panmure Basin? Taylors Hill? Pigeon Hill?))	10 ⁷	c.21 000	c.6500		
Three Kings Mt Cecilia Styaks Swamp Otara Green Hill Wiri McLaughlins Hill Ash Hill Mt Roskill)))))))))	10 ⁹	26 910(±190) to 28 300(±690) (27 500, say)	,	c.7500?	
Mt Albert Complex		10 ⁸	30 000-40 000 (35 000, say)		c.6750?	
Ihumatao Hopua? Mangere Lagoon? Puketutu? Waitomokia? Pukeiti? Otuataua?)	10 ⁸	41 750(±700)			

Mean intervals -- 8250±1070 (13500±657 (n=5) (n=2) (record incomplete)

MAYOR ISLAND (Ref. 18, 19)

Activity in last 42 000 years

Eruption	Estimated Volume	Years BP (1950)	Interval (years)		
	(m³)	(1330)	≥10 ⁷ m ³	≥10 ⁹ m ³	
Tarewakoura	10 ⁷ (10 ⁷	1500-1000? c.2000?	c.500 c.2000		
Te Parita ring fracture	(10 ⁷ (10 ⁷	c.4000? c.6000?	c.2000 c.350		
Tuhua Tephra (2 episodes) & Panui	10 ⁹	6340±190	1660	1660	
Unnamed (2 episodes)	10 ⁹	8000±70	c.2000	c.2000	
" (2 episodes)	10 ⁹	c.10 000?	c.15 000		
u	107	c.25 000?			
Ме	an intervals		3357±5157 (n=7)	1830±240 (n=2)	

Data inadequate: better estimate from 11 episodes $\ge 10^7 \text{m}^3$ in 42 000 y (1:3818 y), and 3 episodes $\ge 10^9 \text{m}^3$ (1:14 000 y).

WHITE IS. (Ref. 21, 22)

a) Activity in period 1946-1984 A.D.

		Date	≧10 ⁵	≧10 ⁶
Christmas Crater	107	1976 Dec 18 (to 1981 Jan)	5.5	10.1
1971 Crater	10 ⁵	1971 Jul 19	3.5	
Rudolf Gilliver Big John) 1.7x10 ⁶ 10 ⁵	1968 late Jan 1966 Nov 21 1962 Dec	1.2 3.9 5.0	33.6 (see b))
	10 ⁵	1957 Dec?	2.75?	
	10 ⁵	1955 Mar?	8.3?	
Noisy Nellie	105	1946 Dec?		

b) Activity in period 1914-1934 A.D. (intervening period 1934-1946 uncertain)

			Date	≧10 ⁵	≧10 ⁶
1933 crater		10 ⁶	1933 Apr 2	4.6	
new vents		10 ⁵	1928 Sep 1	2	
new fumarole eruption)	(minor	105	1926	2	
new vent		10 ⁵	1924	2	
new vent		105	1922		
		Mean intervals (combining a) and		3.61±2.04 (n=11)	21.86±16.66 (n=2)

c) Activity in last 15 500 years (≥c.10⁷m³)

		Years BP (1950)	≧10 ⁷ m³	≥10 ⁸ m ³
Christmas Crater	107	-26	c.2525	,
Marine core J94	107	c.2500	c.650	
и и и	10 ⁷	c.3150	c.180	
n n	10 ⁷	c.3330	c.870	
Marine core to NNE (W sub-crater?)	108	c.4200	c.4800	c.4800
Marine core to NNE (E sub-crater?)	108	c.9000	c.3860	
Marine core J94	107	c.12 860	c.2440	
" " Ј98	107	c.15 300		
	Mean intervals		2189±1729 (n=7)	(c.4800) (n=1)

OKATAINA (Ref. 23)

a) Activity in last 42 000 years (* = Basalt: remainder = Rhyolite, except ** = Dacite). (Ø includes unwelded ignimbrite)

Eruption	Source	Estimated Volume (m³)	Years BP (1950)	≧10 ⁹ m³	Interval (years) ≥10 ¹⁰ m ³	≤10 ¹¹ m³
1886 A.D.*	Tarawera	2-5x10 ⁹	64	c.700		
Kaharoa	***	7½x10 ⁹	c.800	c.3200	c.4700	
Rotokawau*	NW Okataina	7x10 ⁸	c.4000	c.1500		
Whakatane	Haroharo	1.9x10 ¹⁰	c.5500	c.2000	c.2000	
Mamaku	11	2.1x10 ¹⁰	c.7500	c.1500	c.1500	
Rotoma	**	1.5x10 ¹⁰	c.9000	c.2000	c.2000	
Waiohau	Tarawera	1.9x10 ¹⁰	c.11 000	c.2800	c.2800	
Rotorua	Haroharo	8x10 ⁹	c.13 800	c.1200	c.1200	
Rerewhakaaitu	Tarawera	8x10 ⁹	c.15 000	c.2000	c.2000	
Okareka	п	1x10 ¹⁰	c.17 000	c.2000	c.2000	
Te Rere	Haroharo	1x10 ¹⁰	c.19 000	c.7000	c.7000	
ø Omataroa**) + Awakeri)	")	2x10 ¹⁰	c.26 000	c.7000	c.7000	
<pre>ø Mangaone +) Hauparu**) + Te Mahoe**) + Maketu**)</pre>	**	7.5x10 ¹⁰	c.33 000	c.3000	c.9000	c.9000
Ngamotu**) + Tahuna**)	Tarawera	2x10 ⁹	c.36 000	c.6000		
ø Rotoiti +) Rotoehu)	Haroharo	1x10 ¹¹	c.42 000			
	Me	an intervals	:	2993±2114	3745±2726	(c.9000)

2993±2114 3745±2726 (c.9000) (n=14) (n=11) (n=1)

b) Activity in last 230 000 years (≥c.10¹¹m³)

					≥10 ¹¹ m ³
Mangaone etc	Haroharo	7.5x10 ¹⁰	c.33	000	c.9000
Rotoiti + Rotoehu	11	1x10 ¹¹	c.42	000	c.103 000
2- Kaingaroa	Tarawera	1x10 ¹¹ ?	c.145	000	c.10 000
Ignimbrite 1—Kaingaroa	"	1x10 ¹¹ ?	c.155	000	c.45 000
Ignimbrite Matahina Ignimbrite	n	3x10 ¹¹ ?	c.200	000	c.15 000
Onuku-Pokopoko Ignimbrite	Haroharo	1-2x10 ¹¹ ?	c.215	000	c.15 000
Quartz-biotite Ignimbrite	Tarawera	2x10 ¹¹ ?	c.230 -250		
	Me	an interval			32833±36870 (n=6)

ROTORUA CALDERA (Ref. 23)

Mamaku Ignimbrite 2x10¹¹? c.140 000 (and lesser eruptions, see text).

MAROA-MANGAKINO VOLCANIC CENTRES (Ref. 14, 25-33)

a) Activity in last 50 000 years

Puketarata (Maroa) 10⁸ c.12 500

Bulk of Maroa lava domes 10⁸-10⁹? c.30 000-40 000

Earthquake Flat Breccia 10¹⁰? c.40 000-50 000 (probably c.42 000)

b) Activity in last 1 million years (≥c.1.5x10¹¹m³: record incomplete)

			≥10 ¹	¹ m ³
Biotite Ignimbrite	3-4x10 ¹¹ ?	c.280 000	c.100	000
Rangitawa Pumice + Waiora Formation? (thi (source doubtful) Ign	4x10 ¹¹ ? s, or the ne imbrite, pro	c.380 000 ext, probably equi bbably from Kapend	c.70 ivalent to ga (32))	
Waiomio pumiceous sediments? (source doubtful)	1-2x10 ¹¹ ?	c.450 000	c.70	000
Rocky Hill Ignimbrite (= Upper Marshall Ignim. = Upper Ahuroa Ignim.?) (incl. Waitapu pumiceous sediments?)	1-2x10 ¹¹ ? (source Man	c.520 000 ngakino (32))	c.50	000
Lower Marshall Ignim. = Lower Ahuroa " ? (incl. Kaukatea Ash ?)	1-2x10 ¹¹ ?	c.570 000	c.40	000
<pre>Upper Waipari Ignim.? (incl. Potaka Pumice?) = marine core layer C?(14)</pre>		c.610 000 ording to (32) Ahu y BP from Mangak		000
Ongatiti Ignimbrite = Lower Waipari Ignim.? and ?Rahopaka & ?Te Weta Ignimbrite? (incl. Rewa pumice?) = marine core layer B?(14)	÷	:.730 000-740 000	c.110 -150	
Kidnapper Tuff-Mangapipi Ash (? = Ngaroma/Lower and Middle Rangitoto Ignim.?) = marine core layer A?(14)	5x10 ¹¹ ?	c.850 000- 880 000	c.160 -210	
Ridge Ash-Pakihikura Ash (Tikorangi Ignimbrite?)	2x10 ¹¹ ?	c.1040 000- 1060 000 ngakino (32))		

Mean interval

96250±48606 (n=8)

c) Previous Ignimbrites < 4 million years old (≥c.1.5x10¹¹m³: sources unknown: record very incomplete)

				,		·			≥1	.0 ¹¹ m ³		
Mangah	ou As	sh			2-3x10 ¹¹ ?	c.1.26	million	У	0.24	million	у	
Ohinga	iti <i>P</i>	Ash			1-2x10 ¹¹ ?	c.1.50	**	"	0.75	n ·	11	
Marine	core	e M ₁ A	sh	(33)	1-2x10 ¹¹ ?	c.2.25	n	"	0.37	10	**	
Spoone core G				ne	1-2x10 ¹¹ ?	c.2.62	11	11	c.0.2	11	"	
Marine	core	e Ga	ash	(33)	1-2x10 ¹¹ ?	c.2.8	**	"	c.0.2	11	**	
**	Ħ	Ga ₂	Ħ	(33)	1-2x10 ¹¹ ?	c.3.0	11	11	c.0.3	u	".	
**	, 11	Ga ₁	**	(33)	1-2x10 ¹¹ ?	c.3.3	п	"	c.0.4	ŧi	n	
11	**	G ₁		(33)	1-2x10 ¹¹ ?	c.3.7	11	"				
					Mean interv	al		C	.35±0.19	million (n=7)	u A	ears

TAUPO VOLCANIC CENTRE (Ref. 14, 33, 36-40)

a) Activity in last 42 000 years (\$\phi\$ includes unwelded Ignimbrite)

Eruption	Estimated Volume	Years BP (1950)		Interval (years)	
	(m³)	-	≧10 ⁹ m ³	≥10 ¹⁰ m ³	≥10 ¹¹ m ³
∅ Taupo Pumice	1x10 ¹¹	c.1800	c.400	c.1600	c.18 700
Mapara	2x10 ⁹	c.2200	c.600		
Whakaipo	2x10 ⁹	c.2800	c.600		
ø Waimihia	1.9x10 ¹⁰	c.3400	c.1250	c.17 100	
Hinemaiaia	3x10 ⁹	c.4650	c.720		
Motutere	1x10 ⁹	c.5370	c.3430		
Opepe	4×10 ⁹	c.8800	c.400		
Poronui	3x10 ⁹	c.9200	c.600		
Papanetu	1×10 ⁹	c.9800	c.110		
Karapiti	5x10 ⁹	c.9910	c.10 590		

Kawakawa (Oruanui)	1.7x10 ¹¹	c.20 500	c.300	c.500	
Poihipi		1×10 ⁹	c.20 800	c.200		
Okaia		7x10 ⁹	c.21 000	c.17 000		
Tihoi		5×10 ⁹	c.38 000	c.1000		
Waihora		1x10 ⁹	c.39 000	c.1000		
Otake		2x10 ⁹	c.40 000			
	Mea	n intervals			6400±9283 (n=3)	(c.18 700) (n=1)
	(over pas	t 10 000 yea	rs only)	(901±997 (n=9)	9350±10960 (n=2)))

b) Activity in last 320 000 years (≥10¹¹m³)

			≧10 ⁻	11 _m 3 · · · · ·
Taupo Pumice	1×10 ¹¹	c.1800	c.18	700
Kawakawa (Oruanui)	1.7x10 ¹¹	c.20 500	c.194	500
Rautawiri Ignimbrite (possibly from Maroa)	2x10 ¹¹ ?	c.215 000	c.15	000
Mt Curl Tephra (? = marine core layer D(14))	2-3x10 ¹¹ ?	c.230 000	c.90	000
Whakamaru Ignimbrite? = Rangitaiki " = Te Whaiti " (? = Wairakei ")	~ 4-5x10 ¹¹ ?	c.320 000		
(N.B. Correlation of indis doubtful.)	dividual ignim	brites with	offshore marine	cores

Mean interval

79550±84048 (n=4)

TONGARIRO (Ref. 41, 45)

a) Activity in period 1850-1984 A.D.

			Interval (years)	
			≥10 ⁵ m ³	
Red Crater	10 ⁵	1926 Apr	40	
Upper Te Mari	105-106	1886 Jun- 1896 Nov	17	
и и п	105	1869	14	
Red Crater	105	1855-1859		
	Mean interval		23.7±14.2 (n=3)	

b) Activity in last 12 500 years ($\ge 10^8 \text{m}^3$) Ngauruhoe included with Tongariro

			≥10 ⁸ m ³	$\geq 10^9 \text{ m}^3$
Mangatawai tephra (birth of present Ngauruhoe cone) + activity at North Crater	1.2x10 ⁹	c.2500	c.5500	c.5500
Mangamate tephra (including Poutu, Pahoka & Te Rato tephras)	3.5x10 ⁹	c.8000	c.4000	
Rotoaira Lapilli	2×10 ⁸	c.12 000	** **********************************	
	Mean intervals		4750±1061	(c.5500)

(n=2)

NGAURUHOE (Ref. 45)
Activity in period 1839-1984 A.D.

			≧10 ⁵ m ³	≧10 ⁶ m ³	≥10 ⁷ m³
	10 ⁵	1975 May 12	0.22		
	107	1975 Feb 19	0.90	1.075	20.805
	10 ⁵ -10 ⁶	1974 Mar 28	0.175		
	10 ⁶	1974 Jan 23	0.11	19.73	
	10 ⁵	1973 Dec 15	0.37		
	10 ⁵	1973 Aug 2	0.23		
	10 ⁵	1973 May 11	0.35		
	10 ⁵	1973 Jan 2	0.68		•
	10 ⁵	1972 Apr 29	2.79		
	105	1969 Jul 16	0.59		
	105	1968 Dec 14	0.41		
	10 ⁵	1968 Jul 19	9.13		,
	10 ⁵	1959 Jun 1	0.57		
	10 ⁵	1958 Nov 5	2.8		
	10 ⁵	1956 Jan	1.7		
Lava eruption	107	1954 May	1.6	5.3	84.1
	10 ⁵	1952 Nov	1.5		
	10 ⁵	1951 May	0.9		
	10 ⁵	1950 Jun 16	1.3		
Lava eruption	· 10 ⁶	1949 Feb	0.4	78.75	
	105	1948 Sep	0.4		
	105	1948 Apr	7.6		
	105	1940 Sep	1.1		
	10 ⁵	1939 Aug	2.6		
	105	1937 Jan	2.1		
	105	1934 Dec	0.5		

105	1934 Jun	3.1
105	1931 May	0.25
105	1931 Feb	2.6
10 ⁵	1928 Jul	0.3
10 ⁵	1928 Mar	1.3
10 ⁵	1926 Dec	0.7
10 ⁵	1926 Apr	0.5
10 ⁵	1925 Nov	1.1
10 ⁵	1924 Oct	0.4
10 ⁵	1924 May	0.3
10 ⁵	1924 Jan	6.3
10 ⁵	1917 Oct	3.1
105	1914 Sep	1.3
10 ⁵	1913 May	0.4
105	1913 Jan	2.0
10 ⁵	1911 Jan	0.3
10 ⁵	1910 Oct	0.75
10 ⁵	1910 Jan	0.5
105	1909 Jul	0.3
10 ⁵	1909 Mar	1.4
10 ⁵	1907 Nov	0.5
10 ⁵	1907 May	0.25
105	1907 Feb	0.9
105	1906 Mar	1.3
10 ⁵	1904 Nov 22	6.8
105	1898 Jan	1
10 ⁵	1897	5
10 ⁵	1892 Nov	0.75

	105	1892 Feb	3.8
	105	1888 Apr	5.0
	105	1883 Apr	1.75
	105	1881 Jul 6	3
	10 ⁵	1878 2 ^d half	3
	105	1875 2 ^d half	5.3
Lava eruption	107	1870 Apr	0.7
	105	1869 Aug	4.75
	105	1864 Dec	0.7
	105	1864 Apr	1.25
	105	1863 Dec	1.0
	10 ⁵	1862 Jan	3.1
	10 ⁵	1859 Dec	2.8
	105	1857 Feb	2
	10 ⁵	1855	10
	10 ⁵	1845 Jan	0.25
	105	1844 Oct	3
	10 ⁵	1841	2
	10 ⁵	1839 Feb	

Mean intervals

^{1.92±2.12 26.2±35.9 52.5±44.8} (n=72) (n=4) (n=2)

 $\underline{\text{RUAPEHU}}$ (Ref. 41-45) * = accompanied by major lahar

a) Activity in period 1861-1984 A.D.

			≥10 ⁵ m ³	Interval (years) ≧10 ⁶ m³	>107 3
			=====================================	=10 m	≧10 ⁷ m ³
	105	1978 Mar 7	0.34		
	105	1977 Nov 2	0.31		
	10 ⁵	1977 Jul 12	0.83		
	105	1976 Sep 12	1.39		
<pre>damaged Staircase) Kiosk & road bridges)</pre>	10 ⁶ *	1975 Apr 23	3.96	5.83	
,,	105	1971 May 8	1.88		
damaged Staircase) Kiosk)	10 ⁶ *	1969 Jun 22	1.2	24.2	
	10 ⁵ *	1968 Apr	1.75		
	105	1966 Jul 23	2.25		
	105	1964 Apr	4.9		
	105	1959 May 21	2.5		
	105	1956 Nov 18	2.1		
	105	1954 Oct	2.25		
	105	1952 Jul	1.3		
	105	1951 Mar 19	0.76		
	105	1950 Jun 26	0.75		
	105	1949 Sep	0.3		
	105	1949 May	1.0		
	105	1948 May 1	0.27		
	105	1948 Jan 23	0.9		
	105	1947 Feb	0.3		
	105	1946 Oct	0.5		
	105	1946 Apr	1.1		
Lava in Crater.) Ash eruptions: Chateau)	107	1945 Mar	0.4	20.2	84.1
evacuated)	10 ⁵	1944 Oct	2.2		

			105	1942 Aug	g 10	2.3		
			10 ⁵ *	1940 Ap	r	3.9		
			105	1936 Ma	У	1.4		
			105	1934 De	С	0.3		
			105	1934 Au	g 11	9.55		
			10 ⁶ *	1925 Ja	n 22	3.25	29.87	
			10 ⁵	1921 Oc	t	3.3		
			10 ⁵	1918 Ju	n 29	8.3		
			10 ⁵	1910 Fe	b 28	3.0		
			10 ⁵	1907 Fe	ь	0.9		
			10 ⁵	1906 Ma	r 15	3		
			10 ⁵ *	1903		6		
			10 ⁵	1897		2		
Large lahars			10 ⁶ *	1895 Ma	r 10	5.0	34.07	
			10 ⁵	1890 Ma	ır	0.8		
		•	10 ⁵ *	1889 Ma	чу	3.1		
			10 ⁵	1886 Ap	or	5.1		
			105	1881 Ma	ar	12		
			10 ⁵	1869		8		
?Lava in Crater in May) ?		10 ⁷ *	1861 Fe	eb 13			
		Mean	intervals			65±2.66 2 (n=44)	2.84±10.88 (84 (n=5) (n	.1) =1)

b) Activity in last 1800 years (≥10⁷m³)

								≥10 ⁷ 1	m ³
				10 ⁷	5 BP	(1945	A.D.)	84	
				10 ⁷	89	(1861	A.D.)	350	
Whangaehu	lahar	(44)		10 ⁷	439			349	
11	***	(44)		10 ⁷	788			≧1000	(to Taupo pumice)
			Mean	inter	rval			261±13 (n=3) (or 446±3) (n=4)) preferred 90

c) Activity in last 200 000 years ($\ge 10^9 \text{m}^3$)

		$\geq 10^9 \text{m}^3$
Rangataua lava flows:) Murimotu lahars: Okupata) tephra)	10° c.10 000 BP (c.8000- 12 000)	c.70 000
Taihape, lahar at 485m a.s.l.	10 ⁹ c.80 000	c.30 000
Taihape, lahar at 520m a.s.1.	10 ⁹ c.110 000	c.90 000
Taihape, lahar at 620m a.s.l.	10 ⁹ c.200 000	
Mean	interval	63333±30551

(n=3)

MT. EGMONT (Ref. 46, 47)

a) Activity in last 9000 years ($\geq 5 \times 10^{7} \text{m}^3$) * = Basalt: all others are Andesite.

Eruption	Estimated Volume	Years BP (1950)	Inter (yea	
	(m³)		$\geq 5 \times 10^7 \text{m}^3$	≧10 ⁸ m ³
Tahurangi	3-5x10 ⁷	195	165	
Burrell	1×10 ⁸	360	44	c.1440
Waiweranui-Newall	5x10 ⁷	404	162	
Okahu	107-108	566	634	
Kaupokonui	5x10 ⁷	1200	c.600	
coard tephra	10 ⁸ ?	c.1800	c.1200	c.2200
unnamed ashes	107-108	c.3000	c.300	
Lavas/lahar & Manganui*) (from Fantham's Peak))	107-108	c.3300	c.700	
Inglewood	10 ⁹ ?	c.4000	c.500	c.1000
Korito	10 ⁷ -10 ⁸	c.4500	c.500	
unnamed pumice/ash & lahar	10 ⁸ ?	c.5000	c.500	c.500
yellow pumice	10 ⁸ ?	c.5500	c.1070	c.1070
Opua lahars(major collaps ? of Fantham's Peak/ Bob's Bluff)	e))3.5x10 ⁸)	6570	400	400
Oakura (? = Middle Stent)	108?	6970	c.1030	c.1030
Lower Stent	10 ⁸ ?	c.8000	c.1000	c.1000
yellow pumice lapilli	108?	c.9000		
Me	an intervals		587±357 (n=15)	1080±560 (n=8)

b) Activity in last 38 000 years ($\geq 10^9 \text{m}^3$)

			≥10 ⁹ m³
Inglewood	10 ⁹	c.4000	c.9000
Warea lahars	1.4x10 ⁹	c.13 000	c.10 000
Pungarehu lahars	1.2-1.5x10 ¹⁰	c.23 000	c.11 000
Opunake lahars	10 ⁹	30 000-38 000 (34 400 ?)	
	Mean interva	al	10 000±1000 (n=3)

A similar result is obtained for $\ge 10^9 \text{m}^3$ by including Stratford lahars ($\ge 50\ 000\ \text{y}$ BP: c.1.5x10⁹m³): 5 episodes in c.50 000 y = 1:10 000 y.

For smaller (eruption-related?) events, an idea of the mean frequency can be obtained i) from the fact that there are 6 large Maero debris flow units (lahars), $\geq c.10^7 \text{m}^3$, above the Newall tephra (404 y BP); i.e. to 1984. A.D., 438 y, mean frequency 1:73 years, and ii) from the fact that estimates for the number of small debris flows ($\geq 5 \times 10^4 \text{m}^3$) during the last 500 years vary between 14 and 23; this gives a mean frequency of 1:29 (28.7) years.

APPENDIX II

ESTIMATE OF MEAN INTERVALS BETWEEN ERUPTIONS, AND DATES OF LATEST ERUPTIONS. Data points for mean intervals are underlined. "Eruption" includes eruption-related event, such as lahar or sector-collapse.

VOLCANO		MEAN		AL (YEARS			IONS	
(Period Considered)	≧10 ⁴	≥10 ⁵			≥10 ⁸		≧10 ¹⁰	≧10 ¹¹
RAOUL ISLAND (3700 y)	$(10\frac{1}{2})$	$(24\frac{1}{2})$	(57½)	135	327 ±302	777 ±182	1830	(4350)
Last event (years before 1985)	?	21	?	?	115	c.1400	c.2200	?
BAY OF IS KAIKOHE (1.27 million y)					± ?	(max)		
	(arbit	rarily p	ıt paral:	lel to tr	end for	Aucklan	d)	
Last event (years before 1985)	?	?		?	17000?	?		
WHANGAREI (25000)	(40000)	(65000)	(102500)	166000 ± ?)	
million y)	(arbit	rarily pu	ıt paral:	lel to tr	end for	Aucklan	d)	
Last event (years before 1985)	?	?	?	?	34000?	?		
AUCKLAND (42 000 y)	(1180)	(1900)	(3100)	5000	<u>8250</u> ±1070	13500 ±6576 (max)		
Last event (years before 1985)	?	?	260?	?	?	500?		
MAYOR ISLAND (42 000 y)	(565)	(1080)	2030	3818 ± ?	7400	14000 ± ?	26700	(50000)
Last event (years before 1985)	?	?	?	c.1000	?	6375	?	?

```
WHITE ISLAND
                                                              0.145
                                                                                               2.2
                                                                                                                                     35
                                                                                                                                                                  540
                                                                                                                                                                                              9000
                                                                                                                                                                                                                           142000
 (1914-1934 &
                                                              (53d)
                                                                                                                                                                                                                               (max)
1946-1984 A.D.
for 10<sup>5</sup> &
                                                                                                                 (best fit to data points)
10<sup>6</sup>m<sup>3</sup>.
 15500 y for
                                                                 Data points given below; -
 larger events)
                                                                                               3.61
                                                                                                                            21.86
                                                                                                                                                              2189
                                                                                                                                                                                     c.4800
                                                                                           ±2.04 ±16.66 ±1729
                                                                                                                                                                                             ± ?
                                                                                                  ?
                                                                                                                                     9
                                                                                                                                                                     9
 Last event
                                                                                                                                                                                      c.4250
  (years before
 1985)
 OKATAINA
                                                       (1010)
                                                                                  (1260) (1575) (1970) (2450)
                                                                                                                                                                                                                               3080
                                                                                                                                                                                                                                                               4563
                                                                                                                                                                                                                                                                                                24000
  (including
                                                                                                                                                                                                                                                           ±2993
 TARAWERA &
                                                           (best fit to data points given below: line changes slope at
HAROHARO
                                                         9.1x10<sup>9</sup>m<sup>3</sup> and at 1.1x10<sup>11</sup>m<sup>3</sup>). Other data points;
(42000 \text{ y for } \le 1.9 \times 10^{10} \text{ m}^3.
                                                         \geq 7 \times 10^{6} \text{m}^{3} = \frac{2993 \pm 2114}{27.5 \times 10^{9} \text{m}^{3}} = \frac{3223 \pm 2200}{37.5 \times 10^{9} \text{m}^{3}} = \frac{3745 \pm 2726}{27.5 \times 10^{9} \text{m}^{3}} = \frac{6083 \pm 5352}{27.5 \times 10^{9} \text{m}^{3}} = \frac{3745 \pm 2726}{27.5 \times 10^{9} \text{m}^{3}} = \frac{6083 \pm 5352}{27.5 \times 10^{9} \text{m}^{3}} = \frac{6083 \pm 5352}{27.5 \times 10^{9} \text{m}^{3}} = \frac{1000}{27.5 \times 10^{9}} = \frac{1000}{
 230 000 y
                                                         = 7.5 \times 10^{10} m = \frac{3745}{7300} ± 5119: \ge 7.5 \times 10^{10} m = \frac{6083}{32833} ± 5352: \ge 1.9 \times 10^{10} m = \frac{7300}{7300} ± 5119: \ge 7.5 \times 10^{10} m = \frac{32833}{32833} ± 36870: \ge 1 \times 10^{11} m = \frac{37600}{39100} ± 39100: (\ge 1.5 \times 10^{11} m = \frac{3}{30000} ± ?): (\ge 2 \times 10^{11} m = \frac{3}{30000} ± ?).
 for
\geq 7.5 \times 10^{10} \text{m}^3)
Last event
 (years before
                                                                 ?
                                                                                                   ?
                                                                                                                                     ?
                                                                                                                                                                     ?
                                                                                                                                                                                                     ?
                                                                                                                                                                                                                                       99
                                                                                                                                                                                                                                                           c.800
                                                                                                                                                                                                                                                                                            c.33000
 1985)
                                                    (6850) (10000) (14800) (21900)
 ROTORUA
                                                                                                                                                                                                                           46700
                                                                                                                                                                                         32200
                                                                                                                                                                                                                                                           70000
                                                                                                                                                                                                                                                                                            103000
(140 000 y)
                                                                                                                                                                                                                              ± ?
                                                                                                                                                                                                                                                               ± ?
Last event
                                                                 ?
                                                                                                                                    ?
                                                                                                                                                                     ?
                                                                                                                                                                                                      ?
                                                                                                                                                                                                                                       ?
                                                                                                                                                                                                                                                                                       c.140000
                                                                                                                                                                                                                                                                   ?
 (years before
 1985)
 MAROA
                                                          (200)
                                                                                           (480)
                                                                                                                        (1160)
                                                                                                                                                         (2800) (6750) (16800) 40500
                                                                                                                                                                                                                                                                                               97500
 (including
                                                                                                                                                                                                                                                                                            ±48917
MANGAKINO &
                                                         Other data points: \ge 10^8 \text{m}^3 = 10000 \pm ?: \ge 3 \times 10^{11} \text{m}^3 = 150 000 \pm 55976
KAPENGA)
 (50 000 y
 for \le 10^9 \text{m}^3.
 1.1 million y
 for \ge 10^{11} \text{m}^3)
                                                                                                  ?
Last event
                                                                 ?
                                                                                                                              ?
                                                                                                                                                                                     c.12500
                                                                                                                                                                                                                                              c.42000 c.280000
 (years before
1985)
```

TAUPO (40 000 y	(270)	(485)	(870)	(1550)	(2750)	4900	8800	60000
for ≤1.9x10 ¹⁰ m ³ . 320 000 y for ≥1x10 ¹¹ m ³)	at 1.5 ? $\geq 2 \times 10^{9} \text{ r}$ $\geq 5 \times 10^{9} \text{ r}$ $\geq 1.9 \times 10^{9} \text{ r}$	$5 \times 10^{10} \text{ m}^3$ $= 347$ $m^3 = 724$ $m^3 = 724$ $m^3 = 724$	³). Othe: <u>76</u> ± 5412 17 ± 6779	r data p : ≧3x10 ⁹ : ≧7x10 ⁹ 0935: ≧1	oints;- $m^3 = 51$ $m^3 = 64$	77 ± 6468 12 ± 9273	anges slop 3: 3: ± 84039:	e
Last event (years before 1985)	?	?	?	?	?	c.1800	c.1800	c.1800
TONGARIRO (including NGAURUHOE for $\geq 10^8 \text{m}^3$) (1850-1984 A.) for $\geq 10^5 \text{m}^3$. 12500 y for $\geq 10^8 \text{m}^3$).	(4) D.	23.7 ±14.2	138	820	4750 ±1061	28000	164000 (max)	
Last event (years before 1985)	?	59	?	?	?	c.2500	?	
	0.44 (161d)	2.63	15.75	92	(560)	(3250) (max)		
$\leq 10^7 \text{m}^3$. See	(best	fit to d	data poin	ts given	below)			
Tongariro, above, for larger events)	1.92 ±2.12	26.2 ±35.9	52.5 ±44.8				
Last event (years before 1985)	?	10	10	10	?	c.2500		
	(0.116) (42d) y	1.6	22.84 ±10.88	318	4470	63333 ±30551	(900000) (max)	
Last event (years before 1985)	?	7	10	40	?	c.10000	?	