Institute of Geological
& Nuclear Sciences
Science Report

94/23

ASHFALL –
A Computer Program for Estimating Volcanic Ash Fallout

Report and Users Guide

A.W. Hurst

1994

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Institute of Geological & Nuclear Sciences science report 94/23

Institute of Geological & Nuclear Sciences Limited
Kelburn, Wellington, New Zealand
July 1994

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RECOMMENDED BIBLIOGRAPHIC REFERENCE

A.W. Hurst. 1994: ASHFALL – A Computer Program for estimating Volcanic Ash Fallout. Report and Users Guide. Institute of Geological & Nuclear Sciences Science Report 94/23. 22 p.

A.W. Hurst. Volcano Water: Hazards & Resource Group,
Institute of Geological & Nuclear Sciences Limited, Kelburn

ISSN 1171-9184
ISBN 0-478-08814-0

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ABSTRACT

This program has been developed to enable the rapid calculation of the ashfall from a volcanic eruption. It is designed for Civil Defence use when it is feared that a damaging volcanic eruption might be about to occur, or if an eruption has actually started. It is also suitable for the estimation of volcanic hazards and for studies of past eruptions, by making it possible to calculate the ash distributions produced by a range of possible eruptions, under the various likely wind conditions.

The program calculates the likely distribution of wind-borne ash. The intention is to give timely warning of areas likely to be affected by an eruption, so that if necessary these areas can be evacuated. It is assumed that the immediate vicinity of an erupting volcano will be evacuated in any case, so the local hazards from larger particles and bombs, i.e. anything greater than a centimetre in diameter, are not considered in this program.

The program also does not consider the effect of either lahars or pyroclastic flows, which may travel considerable distances from large eruptions. Calculation of these hazards is affected by the detailed topography around the volcano, whereas ashfall calculations are little affected by topography.

The information required about the eruption is the site and time of the eruption, and the height of the eruption cloud. The height is an important parameter, as it defines the extent to which ash will be spread, and also gives an indication of the rate at which the volcano is erupting. At the start of an eruption, an estimate based on eruption column height is likely to be the best available information on the eruption rate. Wind direction and speed information are also needed. Because upper atmosphere winds are often different from the low level winds, it is essential to get a complete profile of wind versus height up to the top of the eruption column. It is also desirable to have forecasts of expected changes in the wind pattern.

The programs run on an IBM-compatible PC, and for reasonable results the minimum configuration is an 80386 with co-processor. A monochrome screen is adequate, although a colour screen makes it easier to distinguish the ash contours from other details.

INTRODUCTION

Volcanic ash is one of the major hazards to life and property from moderate to large volcanic eruptions. Even small quantities of ash can produce considerable inconvenience, with one or two millimetres having the potential to contaminate water supplies, and a few centimetres can cause disruption to agriculture and transport. A thick fall of ash can be a major hazard to life, predominantly by the collapse of buildings under the weight of ash. About 30 centimetres thickness of wet ash, or one metre thickness of dry ash, can cause structures to collapse. The area at risk of serious ashfall from a volcanic eruption depends on both the characteristics of the eruption and the winds blowing at the time. For estimates of ashfall hazard to be useful in an emergency, they must be able to be produced quickly, with easily available resources. This is what this program is intended to do.

The program ASHFALL, which calculates ash thicknesses for a given volcanic eruption and wind conditions, is based on work by G Macedonio, M T Pareschi and P Armienti of the University of Pisa, Italy (Armienti et al. 1988, Macedonio et al., 1988, 1990), related to their studies of historic eruptions, especially the A.D. 79 eruption of Vesuvius. They produced a program for accurate calculation of 3-dimensional particle diffusion in ash clouds. This program requires large 3-dimensional arrays, and multi-hour runs on a VAX computer for each particle size, and is hence quite impractical for Civil Defence operations.

Macedonio, Pareschi and Armienti (pers. comm., 1990) also wrote a simpler and quicker 2-dimensional diffusion program, in which only the horizontal diffusion of ash was considered, and in which there was only a single wind direction, although the wind speed could vary with height. ASHFALL is an adaptation and extension of this program, in which the wind strength and direction can vary with altitude, and also with time, to cope with likely real situations. Vertical diffusion of ash, which is usually less significant than horizontal diffusion, is still assumed to be zero, although much of its effect can be incorporated by increasing the horizontal diffusion coefficient. It is this simplification which makes it possible to deal only with ash at a single level above the ground surface at any stage of the running of the program. This makes large 3-dimensional arrays unnecessary, and enables ASHFALL to run on a PC.

The output of ASHFALL is a file of ash thicknesses at points on a rectangular grid. This format can be used by a number of commercially available contouring and plotting programs. ASHFALL has been set up to produce output for the SURFER package, from *Golden Software* (Golden, Colorado, USA), which includes a contour program (TOPO), and a surface plotting program (SURF).

ASHFALL PROGRAM

Theory

The program starts with a volcanic eruption column that produces a certain total weight of ash. An eruption column contains turbulent hot gases, moving much faster than the settling velocities of the particles being considered here, so that the ash will not settle out until it leaves the column. The heat of the gases makes them buoyant, and their initial upwards velocity is aided by their buoyancy until they reach an altitude (Z_{buoy}), at which their density equals that of the surrounding air. Above this height the gases are heavier than the surrounding air, so they lose momentum and the upward velocity decreases, becoming zero at the top of the column. The maximum concentration of volcanic gas and ash is at Z_{buoy}.

Given the total volume (V) of the eruption, and the height of the eruption cloud, the ash distribution with height (V'(z)), is assumed to follow the Suzuki distribution

$$V'(z) = kV(1-z/Z)e^{-A(1-z/Z)}$$

where Z is the height of the eruption cloud, and
k is a constant of integration, a function of A

The Suzuki constant A defines the relationship between Z and Z_{buoy}. A typical value of 5 (Macedonio et al., 1988) means that $Z_{buoy} = 0.8Z$, i.e. the highest ash concentration is found at 80% of Z. The amount of ash leaving the column at any height is assumed to be proportional to the concentration at that height. This is the case if the eruption column continues for a considerable period, or decays slowly.

If the eruption column collapses, a pyroclastic flow will produce a quite different hazard situation, which is much more dependent on topography. The program described here is appropriate for any ashfall situation in which the horizontal distance travelled by the ash as a direct result of volcanic processes, such as pyroclastic flows, is small compared to the distance the ash is carried by wind. This program can be used for the calculating the far-field distribution of a co-ignimbrite ash produced by a pyroclastic flow becoming buoyant, based on the mechanism that appears to have occurred at Mt St Helens on 18 May 1980 (Sparks et al., 1986).

From the ash distribution in the column for each eruptive event, the ashfall distribution is obtained by tracing how the ash falling out of the column is influenced by wind. The outwards initial velocity of the ash, as the upper parts of the column spread out, is not explicitly calculated, but is effectively incorporated in the horizontal diffusion coefficient. Volcanic ejecta size varies from fine dust up to blocks. For this program, all material with a similar settling velocity is classed together, and the trajectory of each class of ash is calculated separately. During the time that ash particles fall by one vertical step, their horizontal position will change, depending on the wind at the time. At each step, the current positions are calculated for the particles which originally started from each level in the eruption column. Once a class of particles reach ground level, their distribution is calculated, based on a horizontal diffusion coefficient, and the time since they left the eruption column. The ash thicknesses are calculated for all the points in a rectangular grid. When the thicknesses of all the settling velocity classes for all the eruptive events have been added, then this grid file has the total ash thicknesses at these points.

Program Operation

Procedure START establishes all the files needed for input and output, sets to zero as much of the temporary file D:TEMP.DAT as is needed, and reads the constant section of the .VOL file. Then ERUPTION reads each eruption as a separate event. Each eruption is assumed to produce an instantaneous eruption column. The input data includes the total volume of the eruption, and the height of the eruption cloud, from which procedure SUZUKI is used to calculate the ash distribution with height. When the quantity of ash landed in each area has been calculated as described below, these quantities are added to the values stored in TEMP.DAT. When the end of the *.VOL file is reached, then the thicknesses in TEMP.DAT are copied into the output *.GRD file, with an appropriate header.

Each eruptive event has its own distribution of particle settling speeds, and each size of particles must be analyzed separately. The important parameter here is TIMESTEP, the time in seconds in which the particles fall by DZ. For each particle size, each call of procedure DRIFT represents the falling of the particles by DZ, in other words, a time interval of TIMESTEP. For example, if DZ is 1 km, and the settling velocity is 2.0 m/sec, then TIMESTEP is 500 seconds. To allow for changes in wind velocity and direction, the wind file is checked (Procedure WINDIN) at every step. The wind velocity and direction at any time is estimated by linear interpolation between the wind profile before and the wind profile after that time. As the particles settle, those that have reached the ground are eliminated from later steps of the wind movement routines.
The positions calculated by DRIFT are the "centre of gravity" of ash of each settling velocity, released at each height. The horizontal diffusion coefficient, and the fall time (initial height/settling velocity) give the characteristic width of the gaussian distribution for ash with that fall time, and settling velocity. From these two parameters, the complete distribution of ash with those initial characteristics can be calculated. By summing the distributions of ash for all initial heights and all settling velocities, the complete distribution is obtained.

This program does not include the effects of vertical diffusion of ash, but increasing the value of the horizontal diffusion coefficient will tend to compensate for this. Another minor effect that has not been allowed for is that settling velocity increases with height, because of the lower air density ($V_S \propto e^{0.024z}$, where z is height in km, Macedonio et al., 1988). This factor can be introduced, if desired, by increasing the z steps by this factor, giving larger steps at higher altitudes, but this is not done in the current version of the program.

The output of ASHFALL is a two-dimensional grid of ash thicknesses (a *.GRD file). The SURFER plotting package is then used to produce contour maps (program TOPO), or "3-D" diagrams (program SURF), on the screen or on a printer.

Program Parameters

The program ASHFALL.EXE calculates the expected thickness of ashfall as a function of position. The ash distribution depends on both Volcanic and Meteorological factors.

Volcanic Factors

1) Eruption column position and height
2) Total erupted mass
3) Fraction of ash of different sizes (and hence settling velocities)

Meteorological Factors

4) Wind direction and velocity at each level between ground level and the top of the column, and variation of this with time and space.

The ease with which these factors can be estimated will now be considered.

1) Eruption column position and height

If a volcanic eruption is occurring, the position and height of the eruption column are the parameters which can most easily be observed, either from the ground, from aircraft, or from satellites. Once an eruption column has developed it may be difficult to see its maximum height from the ground. If only the height of the bottom of the spreading-out cloud that develops from the column can be estimated, then this should be doubled to give a rough figure for the total height. The bottom of the Mt St Helens Cloud III of Sparks et al. (1986), was at a height of 10 km, and the cloud extended to 25 km.

If the eruption has not yet started, or seems to be increasing in intensity, then the final eruption column height will have to be estimated from the knowledge of previous eruption sizes.

2) Total erupted mass

It has been observed that the column height (Z) is positively correlated with both the rate of eruption, and the total size of the eruption. Carey & Sigurdsson (1989) suggested that for Plinian eruptions of a wide range of sizes, there was a close relationship between the maximum sustained height of the eruption column and the total erupted mass (M). Their relationship was

$$\log_{10}M = (Z+60.5)/7.18 \qquad \text{M in kg, Z in km.}$$

The relation above can be used to make an estimate of the size of an eruption from the column height if an eruption has started. For example, a column height of 30 km would suggest a total mass of about $4*10^{12}$ kg, or an ash volume of 5 km^3, using a typical ash density of 800 kg/m^3.

The alternative is to use the size of previous eruptions as a guide to a likely total mass, remembering that most volcanoes produce eruptions of a range of sizes. Note also that this program gives ash thicknesses for the ash based on in its freshly fallen state, which is most relevant for hazard and Civil Defence purposes. If eruption size is based on estimates of previous eruption volumes based on DRE (Dense Rock Equivalent) volumes, then these should be doubled, as the ash density is about half of the rock density.

3) Ash size distribution

The ash size distribution is not likely to be known until the ash has landed, which is obviously too late to be useful. Therefore in any practical case, an ash size distribution derived from previous eruptions of the same volcano, or other eruptions with similar characteristics, will have to be used.

Once ash particles leave the eruption column and start falling, their settling velocity will very soon reach the terminal velocity, at which the drag force equals the gravitational force. The terminal velocity of ash particles increases with particle size and density, but cannot be calculated by a simple formula in the range of interest for volcanic ash studies. Walker et al. (1971) found that modelling ash fragments as cylinders gave good agreement with laboratory measurements, and their results for these are given in Fig 1.

Woods and Bursik (1991) summarised the particle sizes distributions from a number of volcanic eruptions. Fig 2 shows some of their cumulative grain-size distributions, and further examples and references are included in their paper. From this information a reasonable distribution of grain sizes can be selected for an eruption. Macedonio et al. (1988) assumed that 20% of the material was lithics, with a specific gravity of about 2.6, and the remainder was lighter particles, with a density of about half that. Using the selected proportions of particle sizes and densities, Fig 1 can be used to calculate the settling velocity of each class of particles, for producing the total settling velocity distribution.

As a starting point, the distribution used in the sample file (EX401), by smoothing the ash distribution from the Vesuvius eruption of A.D. 79 (Macedonio et al., 1990), should give a reasonable estimate of the ashfall from eruptions of volumes from 0.1 to 10 km^3. At large distances, the ash distribution is dominated by fine grained ash. Studies of this at Mt St Helens and elsewhere (Carey & Sigurdsson, 1982, Lane et al. 1993) show that fine volcanic ash often tends to form loosely-bound aggregates, with a settling velocity about 0.3 - 0.6 m/sec, so that this is effectively the lower bound for settling velocity.

4) Wind direction & velocity

The initial estimates of meteorological conditions would normally be obtained from the New Zealand Meteorological Service ionosondes. Currently the upper wind profiles are measured daily at Kaitaia, New Plymouth, Gisborne, and Paraparaumu. These profiles generally cover heights up to about 20 km. In an emergency situation, it is likely that doppler radar systems for wind measurement could be deployed near the area of the eruption to provide better local wind information.

Note that the current version of the program incorporates the variation of wind velocity with time, but does not yet allow for variation of wind velocity over the area of interest.

The only other parameter that might need to be varied is the horizontal diffusion coefficient, Cdiff. Macedonio et al. (1988,1990) used 3000 m^2/sec in their 3-dimensional model. The use of 6000 m^2/sec in a 2-dimensional model with no vertical diffusion seems to give similar results. For modelling possible eruptions, it can be advantageous to use 12000 m^2/sec to give a broader distribution to reduce the likelihood that reliance will be placed on the fine detail of the result.

PROGRAM USE

Hardware Requirements

To run the ASHFALL program, an IBM-compatible PC computer with DOS 3.3 or later is required. A 80386 (with co-processor) or 80486 processor is preferable, but slower machines with an appropriate co-processor can also be used. The machine should have sufficient memory for a RAM-Disk of about 512 Kbytes to be set up as the D: drive to hold a large temporary file. A hard disk can be used for this, but the program will take longer to run. The time taken to do calculations can depend critically on the setting up of the PC, so that it is worth experimenting if the program is running slower than expected.

Software Requirements

The program file ASHFALL.EXE is executable in its current state. If any alterations are needed, they have to be made to ASHFALL.PAS, and a new ASHFALL.EXE file produced with a TurboPascal compiler. A text Editor, such as the EDIT of DOS 5.0, is needed to alter the *.VOL and *.WIN files.

The display and plotting of ash thicknesses is done by the SURFER package, from *Golden Software*, although other plotting packages can be used. The *.GRD file has header lines which are used by SURFER to identify the area being plotted, and these might have to be changed for other plotting routines.

Input Files

All the input information is read from two input files, the volcano file (*.VOL) with initial setup information and eruption parameters, and the wind file (*.WIN) with information on wind velocity and direction. The information required is as shown in the next two sections.

All data must be as shown, with free format on lines, and comments to right of data.

Volcano file (*.VOL)

A: Constant Section (Once only at start of file)

XI, YI, XF, YF	Coordinates of initial and final X (East-West) and Y (North-South) values, NZMG (New Zealand Map Grid) values (m)
DX, DZ, CDIFF, ASUZ	X and Z steps (m), Horizontal diffusion coefficient (m^2/sec), and Suzuki constant (5 is usual).

B: Eruption Section (Any number of these can be included)

Ehr, X, Y, Zmax, Totvol	Eruption time (hrs), NZMG coordinates of eruption (m), height of eruption column (m), and eruption volume, (km^3)
NJ	Number of size (and hence settling velocity) groups used.
VJ[j],NVJ[j]	j'th settling velocity, and % of ash which has this velocity. One pair of readings per line

A sample volcano file, EX401.VOL, used to derive Fig 5, is listed in the Appendix. This is a single eruption; for a multi-stage eruption the section from line 3 onwards would be repeated with increasing values of Ehr. On a 33 MHz 80486 PC, this example took 45 seconds from the start until the complete contours and base map were displayed on the screen.

Wind file (*.WIN)

The wind file must contain wind values for the whole time ash is in the air, i.e. from before the time of the first eruption until all the ash has landed, which may be 12 or more hours after the last eruption.

Whr, NW, DZ, WX, WY	Wind Time (hrs), Number of levels at which wind direction and speed are given, Vertical Step (for checking purposes), and coordinates of Wind Profile. Space interpolation of Wind is yet to be implemented.
VENTO[j],VENTD[j]	Wind velocity and direction at j'th level. Velocity in m/s, direction in degrees. One pair of readings per line.

The wind file example in the Appendix (EX401.WIN) was also used to derive Fig 5. In this case the wind does not change with time, so the starting and finishing wind information is the same.

Running ASHFALL

The file ASH.BAT automates the operation of this program, running the complete process of calculating the ash distribution, displaying the ash distribution on the screen and plotting it on the contour map.

ASH *file1* will use input files *file1*.VOL and *file1*.WIN.

or ASH *file1 file2* will use input files *file1*.VOL and *file2*.WIN. This enables standard "eruption" and "wind" files to be tried in any combination, providing the *file1*.VOL and *file2*.WIN files have the same vertical interval.

In either case, the output file will be *file1*.GRD.

To calculate the grid file of ash thicknesses without displaying or plotting it, type ASHFALL *file1*, or ASHFALL *file1 file2*.

Typing ASHFALL with no filename will put it into prompt mode, in which the program prompts for input file names, and offers the opportunity to alter seven parameters before running the ash thickness calculation. These parameters are Zmax, Totvol and CDIFF and the four parameters (XI,XF,YI,YF) that define the boundary of the area of interest. This enables rapid testing of alternative models.

ASHFALL Output & SURFER Package

The output grid file (*.GRD) from the ASHFALL programme includes a header, which defines the X and Y directions based on the NZMG grid. The TOPO programme of the SURFER package uses the command file ASHFALL.CMD to make screen and hard-copy plots of the ashfall maps. The command file can be altered using the STORE command in TOPO or by direct editing of the command file, so as to suit the screen and plotter configuration being used. Files with the extension .LVL are used to select the contours to plot, while files such as TOWNS.PST and TOWNS.DAT are used to put cultural background on the plots.

Files with the extension .BLN file provide background information to display and plot. BASEMAP.BLN produces a map of the outline of the North Island of New Zealand with major rivers and lakes. The command file can also include a .PST file of labelled data points, the default of which is TOWNS.DAT, showing cities and major towns near the main volcanoes.

Other options are available for these files, including ROAD.BLN and RAIL.BLN. Unfortunately, the current version of SURFER (V4.1.5) only uses one colour for .BLN files, making it difficult to use colour displays effectively. If plotting to a colour plotter, this can be overcome by appending a number of runs of TOPO, each with a different .BLN file, and each plotted in a different colour.

Examples

A/. Figures 3 and 4 compare the results of ASHFALL with results published by Macedonio et al. (1990). In both cases the maximum height of the eruption column is 16 km. The summer mean wind for the area around Vesuvius, used for Fig 3, varies between a light wind (7-8 m/sec) of average direction 340° (N 20°W) at ground level, to a moderate (28 m/sec) westerly (270°) wind at a height of 10 km. Above 10 km, the wind velocity typically decreases, and there are further changes in direction, but the westerly direction is maintained as far as 16 km, the greatest height of concern. The mean winter wind, on the other hand, has a fairly similar velocity profile, but the direction is exactly westerly at all heights. This gives the much narrower pattern shown in Fig 4. The differences between the ashfall patterns produced by ASHFALL, and those produced by the 3-dimensional diffusion equation are much smaller than are likely to be produced by uncertainties in the eruption volume and column height, or in the wind pattern, so this simple model is therefore quite adequate for the purpose of rapid estimation of ash patterns.

B/. Fig 5. Eruption from Blue Lake, Tongariro producing a total ashfall of 1 km^3 (10^9 m^3) with wind from west of south.

This represents a large eruption from Tongariro, and also gives a rough upper bound for an eruption from Ngauruhoe. The total volume of this eruption is comparable with the eruption or eruptions that produced the Poutu ash (Topping, 1973). The eruption column is 12 km high, and the wind pattern is based on that of 11 February 1992.

The 100 mm ash contour extends for 110 km, and has a maximum width of 24 km, compared to the empirical formula of Latter (1990a,b), which gave an extension of 135 km, and a maximum width of 15 km. This difference reflects a more realistic wind pattern (i.e. some variation in direction with altitude) in the present model, and also represents the effect of the high horizontal diffusion coefficient used in this model, which partly represents the uncertainty in the wind.

C/. Fig 6. Eruption from Lake Taupo (Horomatangi Reef), producing a total ashfall of 5 km^3 with wind varying from north-westerly at low elevations to south-westerly at higher levels. The ash sizes are based on the Hatepe eruptions of about 1800 years ago (Woods and Bursik (1991).

This shows the effects of a moderate-sized large eruption from a vent near Horomatangi Reefs, moderate-sized compared with what is possible at this centre, at a time when westerly winds are blowing. The maximum column height is 18 km, and the wind pattern is that of 14 February 1992. The double-lobed pattern is the result of different wind directions at different levels. The wind at 1 km elevation was 23 m/sec from 320°, while that at 14 km was 37 m/sec from 245°. Even more widely and irregularly dispersed patterns can occur if the wind changes during the eruption, or while ash is still in the atmosphere.

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APPENDIX

Sample Volcano File EX401.VOL

2700000.	2850000.	6200000.	6400000.	XI	XF	YI	YF	
500.	1000.	12000.	4.	DX	DZ	Cdiff	Asuz	
0.	2737000.	6224000.	10000. 1.0	Her	X	Y	Zmax	Totvol
15		Number of Ash sizes						
0.4	.03	Settling Velocity & Fraction with Velocity						
0.5	.04							
0.6	.05							
0.8	.05							
1.0	.06							
1.2	.06							
1.4	.06							
1.7	.07							
2.0	.08							
2.4	.12							
3.0	.08							
4.0	.11							
5.0	.07							
7.0	.04							
9.0	.08							

Sample Wind File EX401.WIN

```
 0      19          1000   6500   2700   Whr    NW    DZ    WX    WY
 5.     210                              Velocity, Direction  (NW lines)
12.     205
14.     210
16.     225
17.     215
19.     205
20.     205
22.     200
23.     200
25.     200
28.     195
31.     190
33.     190
30.     200
28.     210
24.     205
20.     200
16.     195
13.     190
99.      19         1000   6500   2700   Whr = 99, Final Wind Profile
 5.     210
12.     205
14.     210
16.     225
17.     215
19.     205
20.     205
22.     200
23.     200
25.     200
28.     195
31.     190
33.     190
30.     200
28.     210
24.     205
20.     200
16.     195
13.     190
```

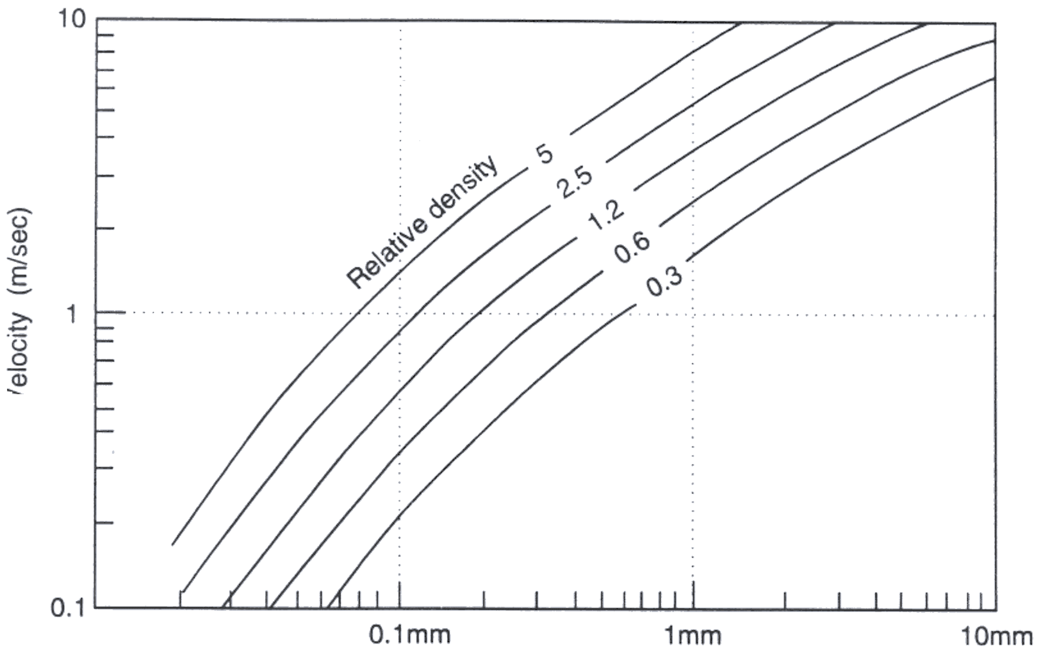

Fig 1. Settling (terminal) velocities of volcanic ash of various sizes, based on results for cylinders by Walker et al. (1971)

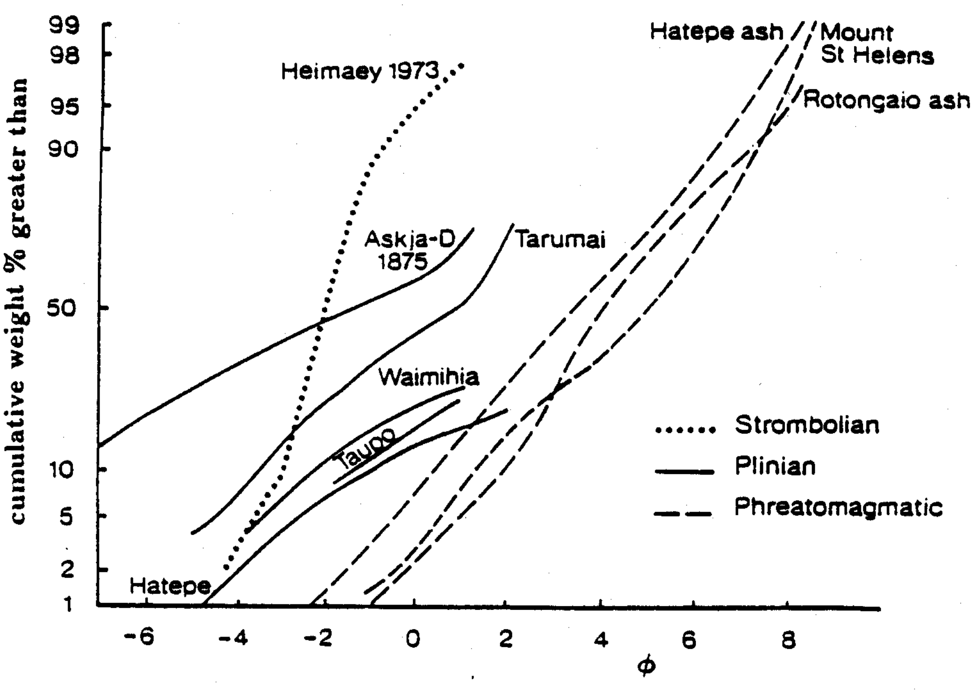

Fig 2. Cumulative grain-size distributions from several eruptions where $\varphi = -\log_2$(diameter in mm.), from Woods and Bursik (1991)

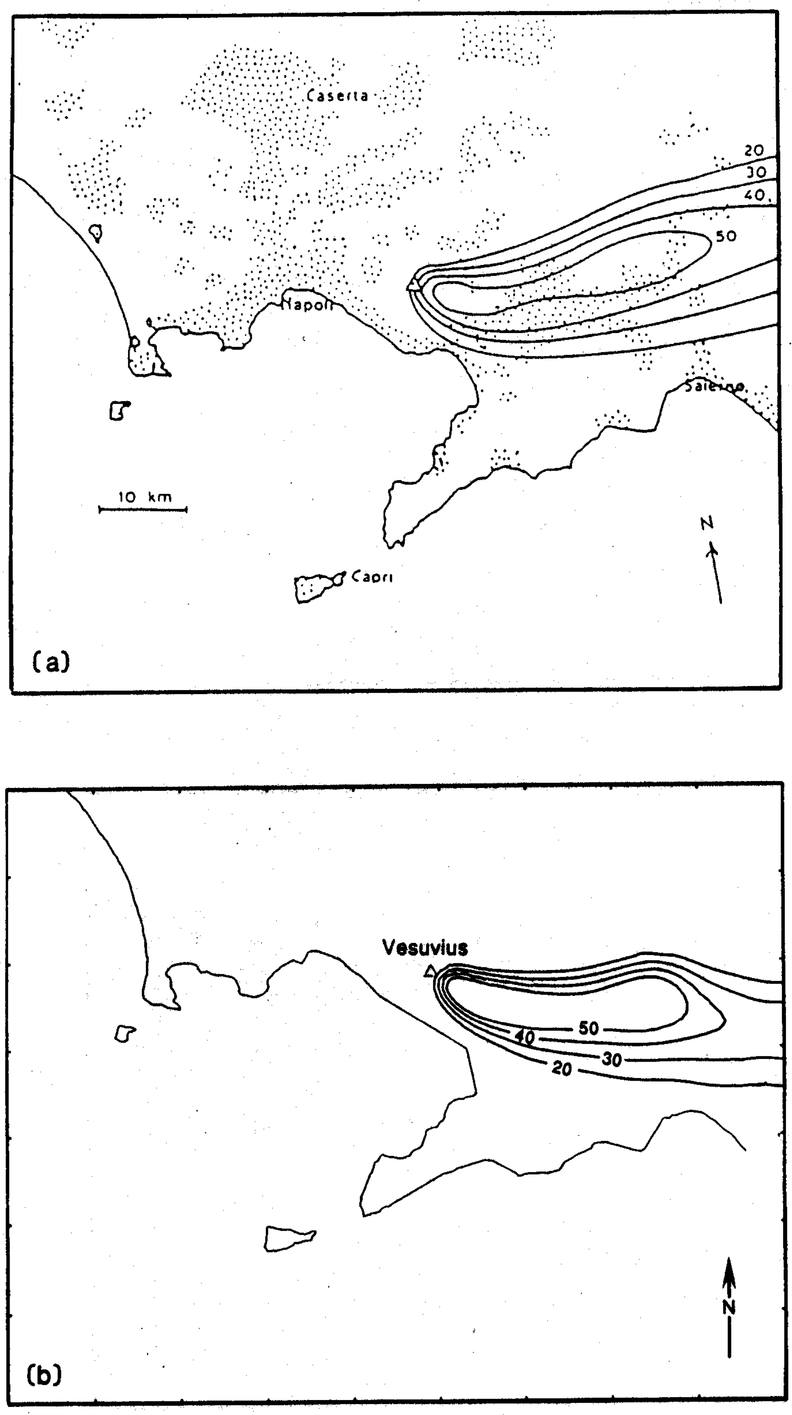

Fig 3. Ashfall from Vesuvius eruption, column height of 16 km, summer mean wind.
(a) Results of Macedonio et al. (1990), with contours in kg/m^{-2}
(c) Results from ASHFALL, with total mass adjusted to give similar ashfall contours

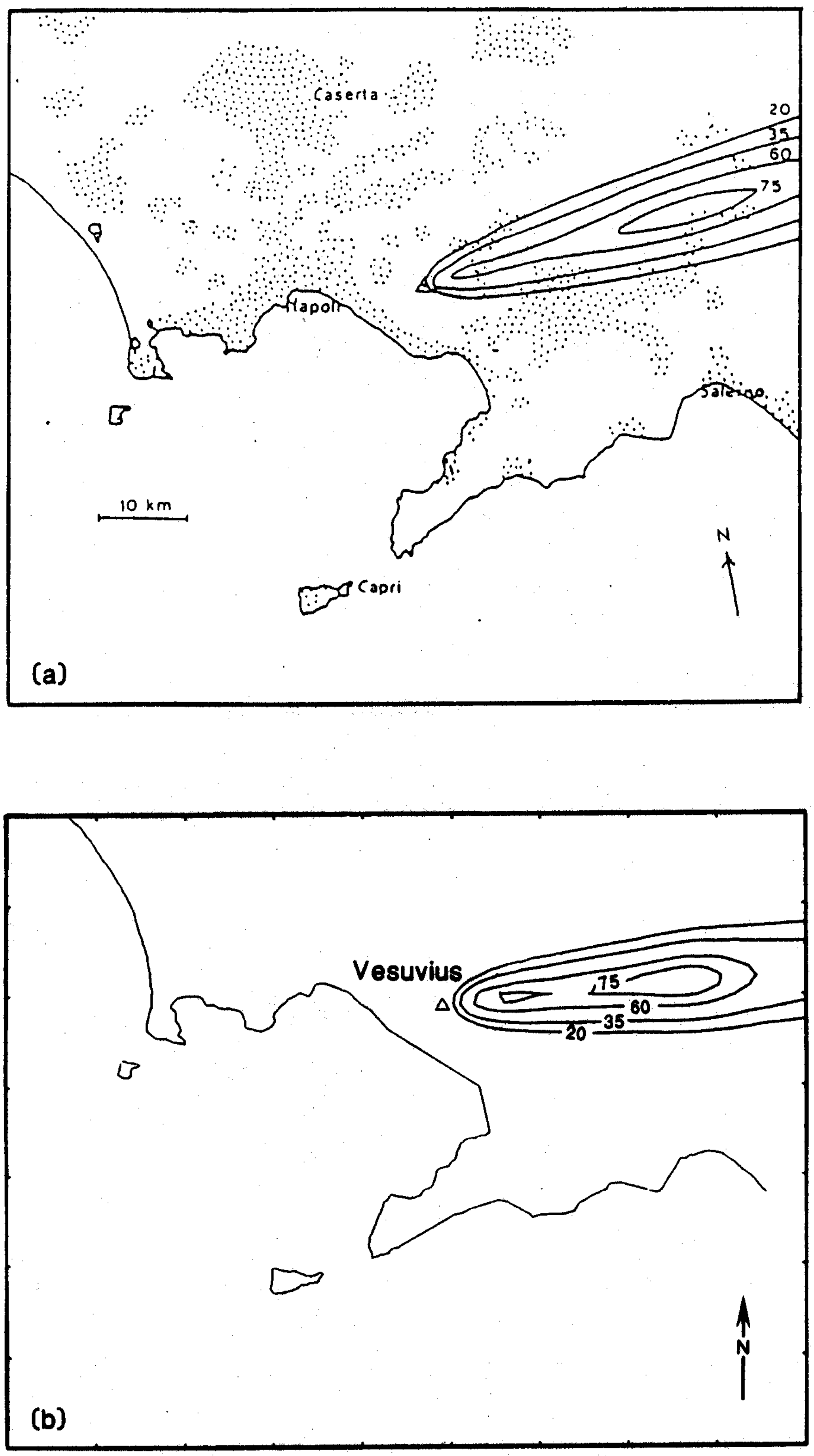

Fig 4. Ashfall from Vesuvius eruption, column height of 16 km, autumn-winter-spring mean wind.
(a) Results of Macedonio et al. (1990), with contours in kg/m^{-2}.
(c) Results from ASHFALL, with total mass adjusted to give similar ashfall contours.

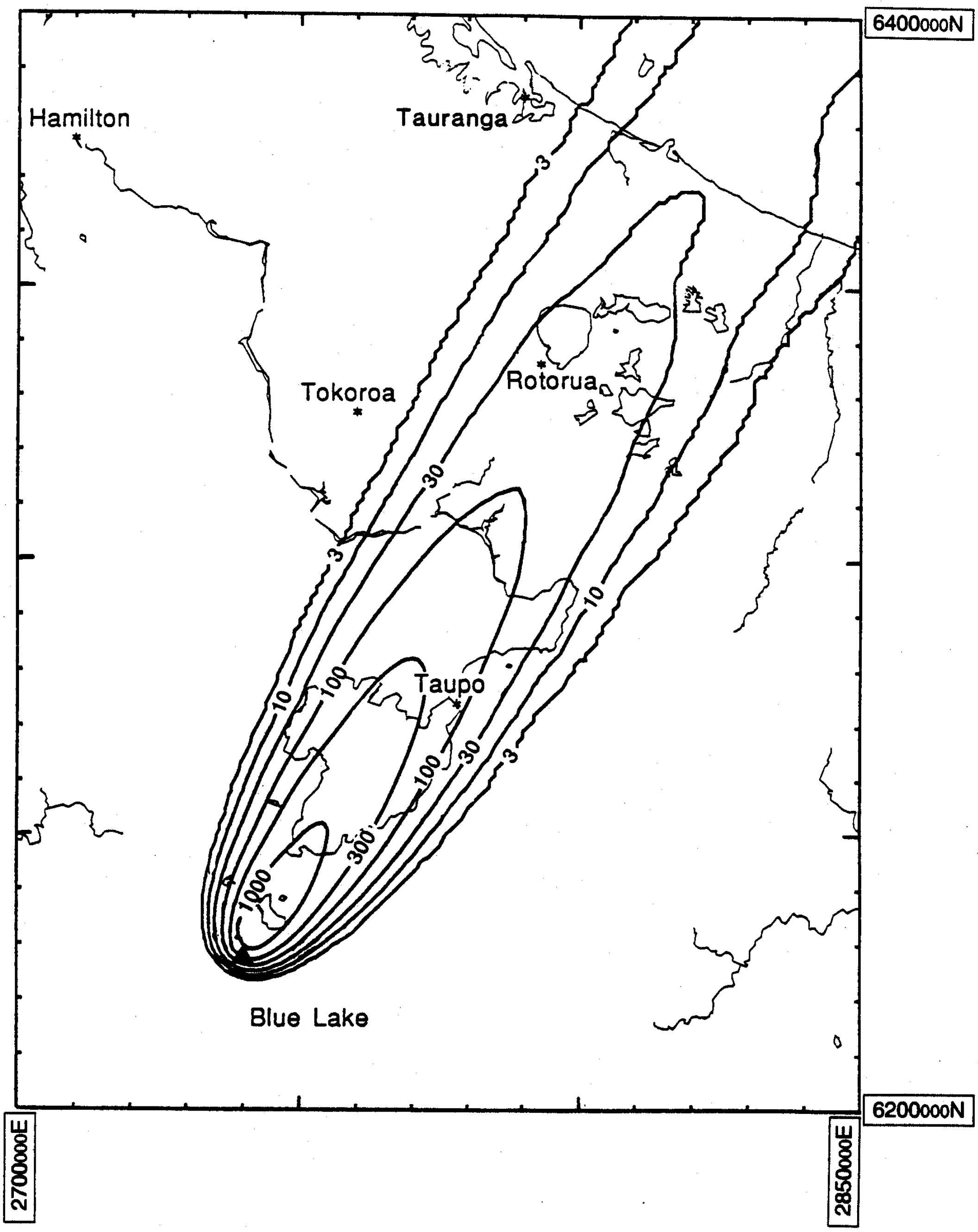

Fig 5. Contours of ashfall thickness (in mm.), for an eruption from Blue Lake, Tongariro, producing a total ashfall of 1 km^3 (10^9 m^3) with wind from west of south.

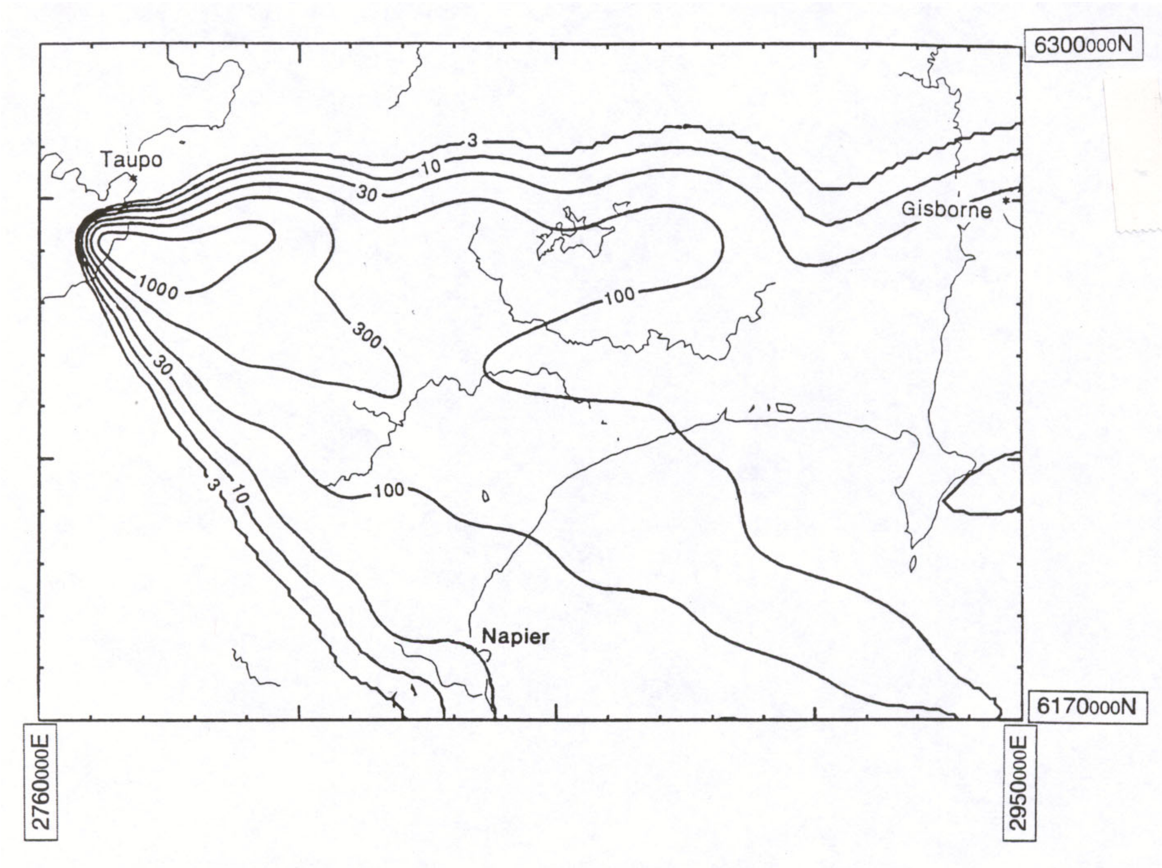

Fig 6. Contours of ashfall thickness (in mm.), for an eruption from Lake Taupo (Horomatangi Reef), producing a total ashfall of 5 km^3 with wind varying from north-westerly at low elevations to south-westerly at higher levels.