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Eruption styles and volcanic hazard in the Auckland Volcanic Field, New Zealand

Sharon R. ALLEN[1] and Ian E. M. SMITH[2]

Abstract The Auckland field has been active for over 140,000 years, during this time eruptions have formed 49 small volcanoes. The magmas which have fed the field range from alkali basalt to nephelinite but the most recent eruption has been of transitional to tholeiitic basalt. Each eruption has involved a new batch of magma to produce volcanoes that are monogenetic in character. Detailed work on the erupted deposits show that the two main types of activity from the field have been magmatic and phreatomagmatic. The particular type of activity in an eruption is controlled by the water:magma ratio. In "dry" conditions, strombolian and hawaiian eruptions occur. At low water:magma ratios, phreatomagmatic eruptions are dominated by pyroclastic fall whereas at high water:magma ratios, phreatomagmatic activity is dominated by base surges. The water required for phreatomagmatic activity is ground-water or surface water. If water is excluded from the active vent and the magma supply is sufficient for continuation, then activity becomes wholly magmatic and can include the effusion of lava flows.

The available ages of Auckland's volcanoes together with the volume of material produced in each, show a trend of increasing size with decreasing time. This pattern is interpreted to mean that the Auckland volcanic field is at an early stage in its evolution and that larger eruptions can be anticipated in the future.

Key words : basalt, monogenetic volcano, eruption style, volcanic hazard

INTRODUCTION

Volcanoes were first recognised in the Auckland region in the late 1800's (Heaphy 1860; Hochstetter 1864; Shewsbury 1892). Subsequent work has focused on the morphology and distribution of the volcanoes (Firth 1930; Wong 1946; Searle 1959, 1961a, 1961c, 1962, 1964a; Kermode 1992), their petrology (Searle 1961b; Heming & Barnett 1986), geophysical studies (Hochstein & Lawton 1974; Nunns 1975; Milligan 1977; Roberts 1980; Rout 1991; Shibuya *et al.* 1992; Rout *et al.* 1993) and the hazards future eruptions may present to the Auckland urban area (Searle 1964b; Lauder 1965; Nichol 1986; Dibble *et al.* 1985; Latter 1985; Smith & Allen 1993). Detailed studies on the physical volcanology of the deposits in the field have been presented by Houghton *et al.* (1991), Bryner (1991ms) and Allen (1992ms).

The Auckland volcanic field is one of three fields of monogenetic volcanoes which comprise the Auckland intraplate volcanic province (Smith 1989). The field contains 49 small basaltic volcanoes within an area of about 360 km^2 centred on Auckland City (Fig. 1). Although the most recent eruption in the field, that of Rangitoto Island, occurred within the last 800 years there is no clear oral history or written record of volcanic activity and an understanding of the type and effects of eruptions depends on detailed studies and interpretation of volcanic deposits. It is this geological record of past eruptions which provides the basis for predicting the type of eruption and associated hazard which may be expected when the Auckland volcanic field next becomes active.

This paper is an integrated account of volcanic activity in the Auckland volcanic field. It is based on published literature and incorporates unpublished thesis material from University of Auckland and the results of ongoing research projects into the nature and origins of eruptions in the field (Smith 1992).

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[1] Department of Geology, University of Auckland, Private Rag 92019, Auckland, New Zealand.
now at Department of Geology, Monash University, Clayton, Victoria, Australia.
[2] Department of Geology, University of Auckland, Private Bag 92019, Auckland, New Zealand.

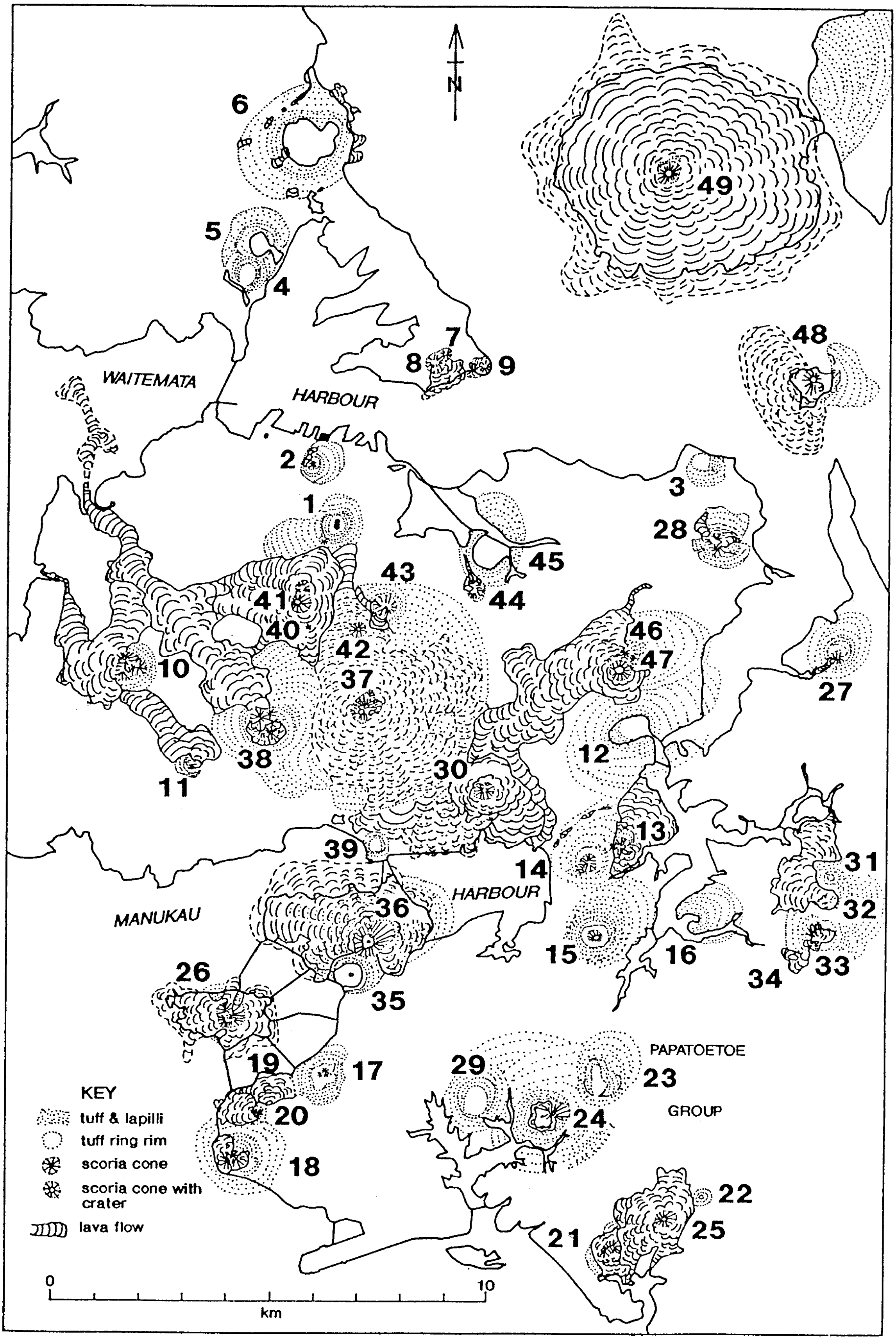

Fig. 1 The Auckland volcanic field showing the distribution of eruption centres. Numbers refer to volcanic centres named in tables 2 and 3.

Volcanoes in the Auckland volcanic field have all erupted magma within a narrow compositional range; individual centres show rock compositions which range from alkali basalt to basanite and in some cases to nephelinite or rarely from transitional basalt to olivine tholeiite. Although these differences are significant in petrological terms they play an insignificant role in determining the physical eruption processes. Two factors have been found to be important in controlling the character of eruptions in the Auckland volcanic field. The first of these is magma/water interaction, the second is the evolution of magmatic gas.

ERUPTION STYLES IN THE AUCKLAND VOLCANIC FIELD

The general model for eruptions in the Auckland volcanic field is that discrete batches of mantle derived basaltic magma have erupted to produce each of the recognised eruption centres; this is implicit in the appellation monogenetic. The specific style of a particular eruption sequence is determined by the rate of magma supply and its gas content and by the availability of external water to the magma fragmentation surface. The ratio of external water to magma controls whether the eruption is dominated by 'dry' (Hawaiian to Strombolian) or 'wet' (phreato-magmatic) conditions although in practice there is a continuous spectrum between dry and wet end member eruption types (Fig. 2). Phreatomagmatic and magmatic activity alternates from the same vent depending on the supply of water.

Table 1 summarises the types of deposits found in the volcanic centres of Auckland. Most centres show evidence of an early phreatomagmatic phase although in some cases the tuff has been completely covered by later deposits of scoria or lava. If the eruption continued once the water source was depleted then dry eruptions produced scoria cones and in many cases, lava flows. In total 71% of the volcanoes within the Auckland volcanic field show evidence of phreatomagmatic activity, 77% have evidence of Hawaiian to Strombolian activity and 61% have evidence of lava flows.

Wet Eruptions

If significant water is present at the eruption site, magma/water interaction (water:magma≧0.3, Wohletz 1983) results in phreatomagmatic explosions which generate a vertical eruption column together with base surges. With time, surge and air fall tephra deposits form a tuff ring surrounding a broad central crater. As Table 1 shows, phreatomagmatic deposits are found in many of Auckland's volcanoes and detailed mapping has shown that in general these occur early in the eruption sequence and have dominated the eruptive

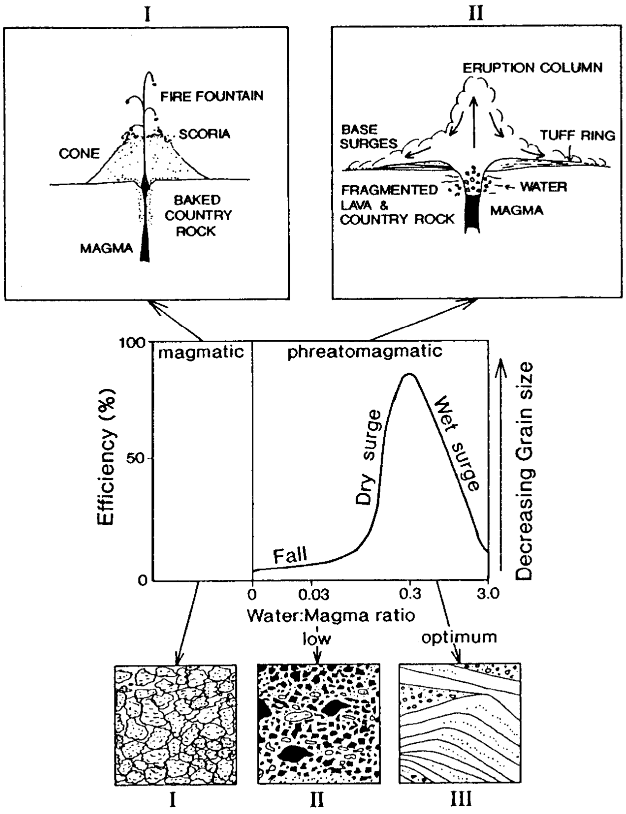

Fig. 2 Eruption styles in the Auckland volcanic field. The upper part of the diagram illustrates the two dominant eruption types in the Auckland volcanic field:

Type I - eruptions of Strombolian or Hawaiian activity. Explosive processes are dominated by rupturing gas bubbles within the magma. The characteristic deposit is scoria (I in the lower part of the diagram), which falls to form a cone.

Type II - phreatomagmatic eruptions. Explosions result from interaction between hot magma and water. An explosion crater is formed as the country rock is fragmented and caught up in the eruption column along with fragmented magma. High concentration flows of steam, fragmented rock flow out from the vent as base surges depositing material around the vent to build a tuff ring.

The lower part of the diagram is a plot of eruption mechanics plot modified from Wohletz (1983). The efficiency of the phreatomagmatic eruption is dependent on the water:magma ratio. At low water:magma ratios, the eruption is dominated by coarse grained fall deposits (II). The clasts representing the phreatic component of the eruption are dominated by blocky, dense basalt and country rock. The clasts representing the magmatic component are ragged and vesicular. As the water:magma ratio increases the efficiency of phreatomagmatic explosions increases and grain size decreases. Base surges are formed, transporting material away from the vent. Deposits left by the surges are fine grained and dune-bedded (III).

Table 1 A summary of the types of eruptive deposit exposed in the Auckland Volcanoes T = Tuff, C = Scoria, L = Lava (updated from Firth 1930; Searle 1959, 1961a, 1961c, 1964a, 1964b, Kermode 1991).

T	TC	TCL	TCLT	C	CL
Ash Hill	Mangere Lagoon	Hampton Park	Pupuke	Mt Cambria	Little Rangitoto
Hopua	Waitomokia	McLennan Hills		Te Pouhawaiki	Matakarua
Kohuora	Robertson Hill	Albert Park		Mt St John	Mt Eden
Onepoto	Mt Richmond	Domain		Purchas Hill	Mt Mangere
Orakei		Green Hill			Mt Smart
Panmure		Wiri Mt			Mt Victoria
Pukaki		Maungataketake			One Tree Hill
Pukekiwiriki		Motukorea			Pukeiti
St Heliers		Mt Albert			Rangitoto
Styaks Swamp		Mt Hobson			Otuataua
Tank Farm		Mt Roskill			
		Mt Wellington			
		Otara Hill			
		Pigeon Mt			
		Puketutu			
		Taylors Hill			
		Three Kings			
		North Head			
		Crater Hill			

activity until the water source has become depleted, the vent area sealed or the magma supply exhausted. The details of eruptive phases depend on the particular magma:water ratio (Sheridan & Wohletz 1983; Wohletz & Sheridan 1983). At high water:magma ratios, activity is dominated by the production of a vertical eruption column and the development of base surges. The corresponding deposits are relatively fine grained planar to cross bedded lapilli and ash beds. At low water:magma ratios, activity is dominated by phreatomagmatic fall, where cooled magma is ejected as blocks and lapilli following short ballistic trajectories to form deposits of relatively coarse grained, massive, unsorted lapilli stone and block breccia. In Auckland phreatomagmatic deposits are restricted to within 1 to 3 km from the vent.

There are no wide spread airfall ash deposits from phreatomagmatic eruptions in the Auckland volcanic field. This is due to two factors; firstly, large volumes of fine material are unlikely to have been produced in these basaltic eruptions and secondly such fine material that was deposited would have been rapidly dispersed by surface erosion.

Because sea levels during past eruptions in the Auckland volcanic field were lower than at present (Gibb 1986; Chappell 1975 & 1983; Chappell & Shackleton 1986; Chappell *et al.* 1990) and most eruptions occurred above sea level, sea water was probably not a factor in most of the volcanic activity. The only known volcano to initially erupt below sea level was Rangitoto. Potential sources of the water for phreatomagmatic activity are rivers, aquifers and wet surfical sediments. The main source of water is thought to have been surface water, aquifers within underlying Permian-Mesozoic and Miocene sediments and in deposits of Plio-Pleistocene alluvium (Rout *et al.* 1993).

Dry Eruptions

In "dry" conditions characterised by actively vesiculating magma, eruptions are Strombolian to Hawaiian in style. Variations within this spectrum, and in intensity, are controlled by rate of magma supply and magmatic gas content. The deposits of this magmatic activity are lapilli tuffs together with bomb and block breccias; collectively, these are commonly referred to as scoria. Scoria deposits are typically well sorted on a small scale and form continuous vertical sequences showing wide grain size variations reflecting variations in the eruption intensity. With time, accumulations of scoria form the steep sided cones with well developed summit craters which are a feature of the Auckland landscape.

Lava Flows

Once dry magmatic eruptions have become established, lava flows may become part of the eruption sequences. Lava flows originate either as lava effusions directly from a vent or as rootless flows where high rates of Hawaiian-type fire fountaining deposit hot magma fragments which recombine to form a flow. Flow producing vents are most commonly situated at the base of scoria cones but also occur within the main crater of breached cones. In this latter case breaching appears to have occurred in response to the pressure of magma welling up in the crater.

Lava flows in the Auckland volcanic field are pahoehoe with subordinate aa type; they show considerable variation in length and thickness (Table 2). Significant thicknesses (30-50 m) of flows have been built up in the Ellerslie area by eruptions from One Tree Hill and Mount Wellington volcanoes. The longest flow in the field is the Meola Reef flow from Three Kings volcano and the greatest single effusion of lava is the Rangitoto lava field.

MAGNITUDE OF ERUPTIONS

The volume of the deposits from eruptive centres in the Auckland volcanic field has been used to determine the magnitude of eruptions. Table 2 is a compilation of data on the dimensions and volumes of scoria cones, tuff deposits and lava flows. Volume calculations are based on thickness and areal extent of deposits from field investigations and limited borehole data. In total there has been 0.207 km^3 of scoria, 0.459 km^3 of tuff and 3.505 km^3 of lava erupted. This total volume of 4.1 km^3 equates to 3.41 km^3 of magma in Dense Rock Equivalents (DRE).

Thirty three of the 49 volcanic centres have volumes (DRE) less than 0.01 km^3, four centres have volumes between 0.01 - 0.02 km^3, five centres have volumes between 0.02 - 0.05 km^3, six centres have volumes between 0.05 - 0.35 km^3 and one centre (Rangitoto) has a volume of 2.02 km^3. Thus, Rangitoto represents 59% of the total magma erupted in the field. A comparison of the eruptive volume of deposits with time shows that the 7 largest eruptions have occurred within the last 20,000 years (Fig. 3). A consistent interpretation of this trend is that the size of eruptions in the Auckland volcanic field is increasing. Although the trend appears consistent there is no simple relationship to enable prediction of the magnitude of the next eruption in Auckland or to estimate when it will occur.

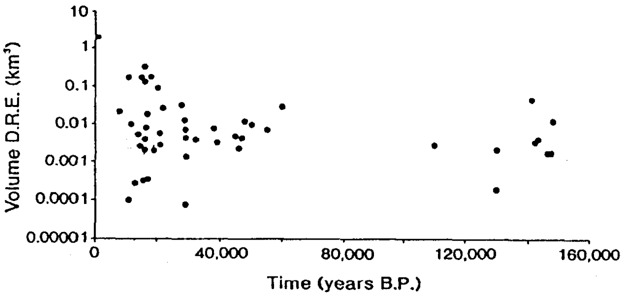

Fig. 3 Relationship between volume of deposits and time. Volume and relative age data are taken from Tables 2 and 3.

TIME/SPACE RELATIONSHIPS

Age

Many of the Auckland volcanoes considered by Searle (1964a) to be in the older age bracket have not been dated but there are at least approximate ages for most of the younger volcanoes in the central part of the field. Various techniques have been used to date the Auckland centres; radiometric, thermoluminescence, methanol dating, magnetic declination and morphology. Few volcanoes have consistent dates from more than one technique and some have not been dated at all. Each method has limitations. Carbon-14 dating is limited by two factors; firstly, by the upper age limit of about 40,000 years for the available dates and secondly, by contamination. Potassium-Argon dating (T. Itaya unpublished data) has produced unreliable results because of an apparent excess radiogenic argon problem (MacDougall *et al.* 1971). Thermoluminescence dating (Wood 1991ms) has produced consistent results for several of the younger centres and has also given the upper age limit of the field. Assigning the volcanoes to an age order is difficult because of the small number of dates and of inaccurate and conflicting data. A compilation of available dates in proposed eruption sequence in given in Table 3. It is important to note that for a significant number of Auckland's volcanoes there is no firm age data and the relative time ordering of volcanoes given in Table 3 and used in Fig. 3 is provisional.

Frequency

Of the 49 eruptions in the Auckland field, 20 have occurred within the last 20,000 years and of these, 18 were between 20,000 and 10,000 years ago. By comparison there were 20 eruptions between 20,000 and 100,000 years ago, and about 9 eruptions greater than 100,000 years ago. Although these figures indicate that there has been a dramatic increase in the number of eruptions in recent times, they are not detailed enough to allow eruption frequencies to be estimated. Attempts at frequency analysis have been made by earlier workers. Searle (1964b) calculated a 2% probability of an eruption per century using a younger upper age limit of 60,000 years for the field. Nichol (1986) estimated an 8% probability of an eruption per century using an older upper age limit for the volcanoes. Latter (1985) estimated an average time interval of 8,000 years between eruptions with volumes from 0.1 km^3 to 1 km^3 and an average interval of 13,500 years between eruptions of greater than 1 km^3.

Although petrological work on the Auckland volcanoes indicates that each eruption has involved a discrete batch of magma there is evidence from the Papatoetoe group of centres in the southern

Table 2 Dimensions and volume estimates of erupted products from the Auckland Volcanic Centres. a Cone height in metres above present sea level from Searle (1964a), Firth (1930). b Estimation of cone height above the pre-volcanic terrain (metres). Estimates of cone and tuff height are based on surrounding topography, outcrops and bore hole data. c Basal area of the cone x $10^4 m^2$. Area estimates of cones, explosion craters, tuff deposits and lava flows of height have been calculated from aerial photographs, diagrams in Searle (1964a), and the DSIR industrial series maps Kermode (1966, 1968, 1969, 1975, 1978, 1986); Kermode and Searle (1966). d Cone volume x $10^6 m^3$. e Method of calculation for scoria cone volume (see below). f Tuff cone height (metres above sea level). g Tuff height above pre-volcanic ground (m) from Searle (1964a), Firth (1930). h Area of the explosion crater x $10^4 m^2$. i Estimated area covered by tuff and ash x $10^4 m^2$. j Tuff and ash volume x $10^6 m^3$. k Method of calculation for tuff and ash volume (see below). l Maximum distance travelled by the lava flow from the vent (meters). m Average thickness of the lava flow (meters). n Approximate area covered by the lava flow x $10^4 m^2$. o Lava volume (average thickness times area) x $10^6 m^3$. p Total volume of eruptive products for each centre x 10^6 m^3. q Total volume of eruptive products for each centre in Dense Rock Equivalents (DRE). DRE are estimated as; tuff 30%, scoria 80%, and lava 95%. Exceptions to this are Pupuke tuff which has an exceptionally high percentage of cognate basalt in the tuff ring and DRE is estimated as 60 percent and lava flows from Rangitoto which are exceptionally scoriaceous and are taken as 85% DRE.

Methods of calculating the volume of erupted material

1: if the area of the explosion crater was known, tuff volume was calculated by the formula

$$Tuff\ volume = \frac{1}{3}\pi r^2 h - [\pi r_c^2 h_t + \frac{1}{3}\pi r_c^2 (h - h_t)]$$

where r = radius of the tuff deposits + explosion crater
r_c = radius of explosion crater
h = estimated height of the deposits at the centre of the crater by extrapolation
h_t = height of the tuff ring.

2: by calculating the volume of country rock removed in the explosion crater from geophysical information (Nunns (1975)-Onepoto Basin, Orakei Basin; MoW in Nunns (1975)-Hopua; Milligan (1977)-Rangitoto). In addition 30% was added to allow for the magmatic content. In comparison, volume of tuff and ash calculated for Onepoto Basin by method 1 is 11.7 x $10^6 m^3$.

3: based on the equation given in method 1, with the addition of a tuff base where erosion eliminated distal tuff deposits.

4: where limited data was available, by the formula $\frac{1}{3}\pi r^2 h$.

		a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q
1	Domain	75	55	~1.5	0.28	1	75	30	~ 23	180	19.33	1	670	13.4	~47	6.3	26.41	12.16
2	Albert Park	30	40	0.5	0.07	1	16.8		?	70	3.92	4		19.65	3	0.59	4.58	1.79
3	St Heliers						45	25	~ 10	65	5.87	1					5.87	1.76
4	Onepoto Basin						25	13	16±2	240	13	2					13	3.9
5	Tank Farm						25	13	22±2	240	11.64	1					11.64	3.49
6	Lake Pupuke						15	9	110	1018	33.96	1	>1460	8	330	26.4	60.36	45.46
7	Mt Cambria	35	25	3±2	0.25	1											0.25	0.2
8	Mt Victoria	81	63	7±2	1.47	1							590	~ 10	10	~ 1	2.47	2.13
9	North Head	65	72	>10	2.67	1	53	60	?	>10	2	4			~ 1	0.03	4.7	2.76
10	Mt Albert	148	78	22±3	5.72	1		~ 5		100	1.67	4	3250	8.3	295	24.99	31.88	28.34
11	Mt Roskill	109	52	7.8±0.5	1.36	1		~ 3		7.8	0.08	4	2445	~ 3.8	165	~ 6.27	7.71	7.07
12	Panmure Basin						18	18	52±2	314	30.68	3					30.68	9.20
13	McLennan Hills	50	30	11±5	1.1	1				?	?		1675	~ 5	220	~ 11	12.10	11.33
14	Mt Richmond	50	32	17±2	1.81	1	~28	10	11±2	240	8.98	1					10.79	4.14
15	Roberston Hill	78	60	6±2	1.20	1	~23	5	28±2	240	4.43	1					5.63	2.29
16	Pukekiwiriki								~ 26	187	15.70	1					15.70	4.71
17	Waitomokia	30	27	6±2	0.54	1			31±2	180	9.64	1					10.18	3.32
18	Maungataketake	76	77	17±2	4.36	1	15	16	?	1365	7.20	4	525	~ 5	40.6	~ 2.03	13.59	7.58
19	Pukeiti	30	27	1.4±1	0.13	1							740	~ 6.7	57.8	~ 3.87	4.00	3.78
20	Otuataua	64	61	5±2	1.02	1							940	~ 8	45.3	~ 3.62	4.64	4.26
21	Matakarua	73	63	9±2	1.89	1							>675	7.2	82.5	5.94	7.83	7.16
22	Ash Hill						28	8	0.64±.1	3.22	0.25	2					0.25	0.08
23	Kohuora						30	27	~ 10	50	4.71	1					4.71	1.41
24	Crater Hill	30	27	7±2	3.82	2	37	34	56	203	22.4	1	609		37.4	~2.62	28.84	12.27
25	Wiri Mountain	91	81	16±2	4.32	1	2	12	~ 10	?	~ 0.40	4	1312	8.6	330	28.38	33.10	30.54
26	Puketutu	55	76	35±2	14	2	9	30	?	143	14.30	4	1437	6.8	160	10.88	39.18	25.83
27	Pigeon Mountain	55	31	10±2	1.06	2		~10		190	~6.33	4	700	3	4.7	0.14	7.53	2.88
28	Taylors Hill	57	45	13±2	1.95	1		6.7		100	~ 2.23	4	825	5.4	9.50	0.51	4.69	2.71
29	Pukaki						30	27.3	33±2	195	19	1					19.00	5.7
30	Mt Smart	87	77	13±3	3.81	2							1750	22.5	398	89.55	93.36	88.12
31	Styaks Swamp						23	9.1	6±1	36	1.17	1					1.17	0.36
32	Green Hill	79	65	11±2	3.30	2	18	~ 3	18	154	1.71	1	2125	6.9	224	15.46	20.47	17.84
33	Otara Hill	97.5	83	16±3	4.43	1		~ 3		53	0.53	4	525	7.3	60	4.38	9.34	7.86
34	Hampton Park	35	19	1.3±0.5	0.08	1							690	~ 6.5	31	~ 2.1	2.18	2.06
35	Mangere Lagoon	9	30	~ 1	0.1	1	7.5	28.5	23±2	73	6.46	1					6.56	2.02
36	Mt Mangere	107	128	42±3	21.50	2							3575	31	535	165.85	187.35	174.76
37	One Tree Hill	183	148	28±1	24.87	2							3575	28.4	1146	325.46	350.33	329.08
38	Three Kings	87	45	26±3	12	2	86	20	97	1194	89.35	1	9500	20.8	480	99.84	201.19	131.25
39	Hopua						2	22	0.5±0.2	28	12.83	2					12.83	3.85
40	Te Pouhawaiki	?		3	~ 0.4												0.4	0.32
41	Mt Eden	196	146	27±3	21.73	2							3025	23.4	693	162.16	183.89	171.44
42	Mt St John	126	54	9±2	2.21	2		3		280	2.80	4					5.01	2.61
43	Mt Hobson	143	76	14±2	5.07	2		~ 3	?	280	2.80	4	750	~ 5	5	~ .25	8.12	5.13
44	Little Rangitoto	75	13	4	0.17	1							270	~ 10	1.5	0.15	0.32	0.28
45	Orakei Basin								55±3	330	32.5	2					32.5	9.75
46	Purchas Hill	30	10	~ 4	0.13	1											0.13	0.10
47	Mt Wellington	160	137	23±5	20.91	2		4.6		600	9.2	4	4750	23.7	675	159.98	190.09	171.47
48	Motukorea	68	73	16	3.89	1	38	48	~ 113	314	44.22	1	880	6.6	75	4.95	53.06	21.08
49	Rangitoto	260	274	37±2	33.79	1		0.9	~ 960		19.16		3700		2587	2341.21	23894.16	2022.81
	Totals				207.41						459.65					3505.41	4172.47	3410.03

Table 3 Dates of the volcanoes in the Auckland volcanic field in relative age order. Dating method C-14=radiogenic carbon dating, K-Ar=radiogenic Potassium Argon dating, Therm=Thermoluminescance, Geomorph=Geomorphology, mag.dec.=magnetic declination, BH=Bore Hole data, O=old, M=middle, Y=young (Searle 1964) Ref=References: 1. Grant-Taylo & Rafter (1971); 2. Polach *et al.* (1969); 3. Grant-Taylor & Rafter (1963); 4. Macdougall *et al.* (1969); 5. Stipp & Thompson (1971); 6. Phillips (1989ms); 7. Fergusson & Rafter (1959); 8. Brothers & Golson (1959); 9. Itaya *et al.* (unpublished data); 10. Robertson (1983ms); 11. Searle (1961a); 12. Searle (1959); 13. Wood (1991ms); 14. Stipp (1968ms); 15. Searle (1962); 16. Bryner (1991ms); 17. Sameshima (1990); 18. Searle (1965); 19. Latter (1990); 20. Kermode (1992).

Volcano	**C-14**	**K-Ar**	**Therm**	**Geomorph**	**Ref**
1 Domain		148 000±10 000		O	4
2 Albert Park				O	
3 St Heliers				O	
4 Onepoto	> 42 000			M	3
5 Tank Farm				M	
6 Pupuke	> 42 000	178 000±9000	141 000±10000	M	4,7,13
7 Mt Cambria				M	
8 Mt Victoria				M	
9 North Head				M	
10 Mt Albert	> 30 000	129 000±4000		> Mt Roskill	3,4,
				> Mt Eden	7,11
11 Mt Roskill				> Three Kings	
12 Panmure Basin	25 700±440				3,7,
	28 000±100	189 000±600		M>McLennans	14,15
13 McLennan Hills	26 900±190	40 000±19000	48 800±2400	M=Mt Richmond	2,4,13
14 Mt Richmond					
15 Robertson Hill					
16 Pukekiwiriki				M>Styaks Swamp	
17 Waitomokia				M>Pukeiti	12
18 Maungataketake	29 000±1500				3,4,
	31 000±1000				7,13,
	36 600±2100				4,2,
	41 750±700				19
	43 000±1400	74 000±15000	38 000±1900	M>22 000	
19 Pukeiti		32 000±6000		M>Otuataua	4,12
20 Otuataua		29 000±10000		M	4
21 Matakarua		110 000±40000		M	9
22 Ash Hill					
23 Kohuora	29 000±700			M>Crater Hill	1,11
24 Crater Hill	29 700±2000	60 000±30000		M>22 000	1,9
25 Wiri Mountain	24 770±500				
	25 370±350				1,4,11
	28 300±690	33 000±6000		M<McLaughlins	2,19
26 Puketutu			22 000±3300		13
27 Pigeon Mt				M	
28 Taylors Hill				M	
29 Pukaki					
30 Mt Smart				> One Tree Hill?	
				>Mt Wellington	15
31 Styaks Swamp				M	
32 Green Hill	Methanol Dating 17 000±8000			M	17
33 Otara Hill				M	
34 Hampton Park					
35 Mangere Lagoon				> Mt Mangere	
36 Mt Mangere	18 280±265				
	27 800±1600	120 000±30000		< Mt Smart	1,9,20
37 One Tree Hill		16 500±1360	20 000±2250	M>Three Kings	6,13
38 Three Kings	21 000±800				
28 000±800	117 000±1200			M>Mt Eden	3,7,18
39 Hopua Basin				<One Tree Hill	B.H.
40 Te Pouhawaiki					
41 Mt Eden		154 000±4000	14 000±1220		
		16 200±2000		M	6,13
42 Mt St John					
43 Mt Hobson					
44 Orakei Basin					
45 Little Rangitoto					
46 Purchas Hill					
47 Mt Wellington	9000±160				
9210±80					2,4,
9390±95	57 000±7000	11700±1400		Y	7,13
48 Motukorea				7-9000	16
49 Rangitoto	750±50				
770±50	146 000±12000	530±50			3,6,7,
		659±80		Mag. dec.	8,10,13
				450±120 -950±170	14

part of the field that one magma batch has fed two volcanoes (Rout *et al.* 1993). Here, palaeomagnetic measurements on lavas from both Crater Hill and Wiri Mountain show an anomaly which has been correlated with an excursion in the earth's magnetic field about 28,000 years ago (Shibuya *et al.* 1992). Rout *et al.* (1993) show that the composition of lavas from these two centres is comparable and consistent with their belonging to a single magma batch. The evidence suggests that the eruption sequence began at Crater Hill and then broke out about 2 km away to build Wiri Mountain. This is an important discovery because it shows that some Auckland volcanoes have developed in closely spaced sequence from single magma batches which means that simple frequency models based on available dates cannot be used.

Location

The location of volcanoes in the Auckland field appears to be random. There has been no evidence for structural control from geophysical studies (Rout 1991; Nunns 1975; Milligan 1977; Roberts 1980; Russell 1976; Hochstein & Lawton 1974). None of the Auckland volcanoes has developed on the greywacke basement rocks upfaulted to the east of Rangitoto and this boundary is taken to be the eastern limit of the field.

The maximum distance between vents of consecutive eruptions based on the predicted ages is in the order of 12 km (Rangitoto to Mt Wellington; Puketutu to Wiri Mountain; Maungataketake to McLennan Hills; Panmure to Mt Albert; and Mt Albert to North Head). Whether the eruptions are totally random or spatially related is uncertain, but these distances suggest that the next eruption could occur within 12 km of Rangitoto.

DISCUSSION

The Auckland volcanic field has been active for about the last 150,000 years and has produced 4.1 km^3 of volcanic material over an area of 360 km^3. Individual volcanoes in the field are small by comparison with most volcanoes world wide. However the Pleistocene south Auckland volcanic field (Rafferty & Heming 1979) to the south of Auckland was active for about 1 million years and comprised 70 volcanoes producing approximately 20 km^3 of volcanic material over an area of 1300 km^3. The south Auckland field erupted similar magma types which showed similar eruption styles and can be regarded as an analog for the Auckland field. This could imply that the Auckland volcanic field is still in an early stage of development and that eruptions will increase in size and frequency in the future. The apparent trend of increasing size of volcanoes within the field supports this suggestion.

Because there are no detailed accounts of volcanic activity in the Auckland field the volcanic record has to be read in the deposits left by eruptions. Detailed work on only a few of the centres (Houghton *et al.* 1991; Bryner 1991ms; Allen 1992ms) has recognised three general types of eruption style controlled by availability of near surface water and rate of magma supply. The hazards from future volcanism are directly related to these eruption phenomena. Phreatomagmatic eruptions producing pyroclastic surges and wet air fall deposits are the most hazardous. However, the indications of a larger eruption in the future and uncertainty in the likely length of the present repose period mean that volcanic activity and its associated hazardous effects needs to be taken seriously in the City of Auckland.

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