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Eruption patterns in monogenetic volcanic fields

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Geomagnetic excursion captured by multiple volcanoes in a monogenetic field

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[1] Five monogenetic volcanoes within the Quaternary Auckland volcanic field are shown to have recorded a virtually identical but anomalous paleomagnetic direction (mean inclination and declination of 61.7° and 351.0°, respectively), consistent with the capture of a geomagnetic excursion. Based on documented rates of change of paleomagnetic field direction during excursions this implies that the volcanoes may have all formed within a period of only 50–100 years or less. These temporally linked volcanoes are widespread throughout the field and appear not to be structurally related. However, the general paradigm for the reawakening of monogenetic fields is that only a single new volcano or group of closely spaced vents is created, typically at intervals of several hundred years or more. Therefore, the results presented show that for any monogenetic field the impact of renewed eruptive activity may be significantly under-estimated, especially for potentially affected population centres and the siting of sensitive facilities. **Citation:** Cassidy, J. (2006), Geomagnetic excursion captured by multiple volcanoes in a monogenetic field, *Geophys. Res. Lett.*, *33*, L21310, doi:10.1029/2006GL027284.

1. Introduction

[2] A monogenetic volcanic field is the magmatic equivalent of a large long-lived composite volcano. Successive magma pulses from depth exploit new pathways to the surface, eventually creating a field of small volcanoes covering several 100 km^2 [*Connor and Conway*, 2000]. Monogenetic fields most likely result from a low magma supply rate and regional extensional stress [*Walker*, 1993]; the resulting volcanoes are short-lived and have recurrence intervals up to several thousands of years, however the spatio-temporal controls on eruptions are poorly understood [*Connor and Conway*, 2000].

[3] This poses serious challenges to hazard assessment and mitigation since both the timing and location of future volcanic events are unknown; furthermore, compared with polygenetic volcanoes, long-term eruption precursors are less likely and predictive hazard mapping less applicable. Worldwide, several cities are built on or close to active monogenetic volcanic fields, for example Auckland, Honolulu and Mexico City; so too is the proposed nuclear waste repository site at Yucca Mountain, US.

[4] The Auckland volcanic field is coincident with Auckland city (Figure 1). It comprises 49 basaltic volcanoes consisting of explosion craters, cinder cones and lava flows, all hosted within Quaternary-Miocene sediments [*Kermode*, 1992]. Unusually, the distribution of volcanoes has no obvious structural control, as observed in most basaltic fields elsewhere [e.g., *Walker*, 1993; *Connor and Conway*, 2000; *Connor et al.*, 2000]. $^{40}Ar/^{39}Ar$ dating suggests that the field may be 250 ka old, though twelve distinct eruptions are interpreted to have occurred between 15 and 35 ka based on tephra horizons in sediment cores, with a shortest interval between consecutive tephras of 400 years [*Shane and Hoverd*, 2002]. This equates to average recurrence rates of about 1 volcano per 1–5 kyr.

[5] However, three volcanoes at the southwest perimeter of the field (Puketutu, Crater Hill and Wiri) (Figure 1) record similar anomalous paleomagnetic directions, attributed to a geomagnetic excursion [*Shibuya et al.*, 1992], which suggests a much shorter time interval between these volcanoes. Such uneven rates of eruption are typical for monogenetic fields [*Conway et al.*, 1998; *Connor and Conway*, 2000], nevertheless, the average recurrence rate is a useful parameter for hazard assessment, especially when applied to small fields or vent clusters [*Conway et al.*, 1998].

[6] Using new paleomagnetic and other magnetic data, this study investigates a temporal link between five volcanoes within the Auckland volcanic field, which remarkably have all captured a geomagnetic excursion. This fortuitous magnetic record is shown to provide a high-resolution relative timing index for eruptions. The implications of this temporal link for both magmatic processes occurring deep in the melt zone and hazard assessment are discussed.

2. Geophysical Data

[7] Existing aeromagnetic data over the Auckland volcanic field [*Cassidy and Locke*, 2002] were flown at a nominal ground clearance of 430 m, a line spacing of 250 m (ENE-WSW orientation) and with an in-line sampling interval of 100 m; the International Geomagnetic Reference Field has been subtracted from the data. A long-wavelength (>5 km) regional component has also been subtracted in order to isolate residual anomalies associated with the volcanoes. Remanent and induced magnetization directions in these Auckland rocks could be expected to be similar given their late-Quaternary age, which together with the $-60°$ inclination of the geomagnetic field at this latitude would give positive residual magnetic anomalies that peak just to the north of the volcanic centres, which is the case for most volcanoes in the field. However, five volcanoes exhibit characteristic negative magnetic signatures consistent with having recorded the Auckland geomagnetic excursion – the three already known [*Shibuya et al.*, 1992], plus Mt Richmond and Taylor Hill (Figures 1 and 2) which had not previously

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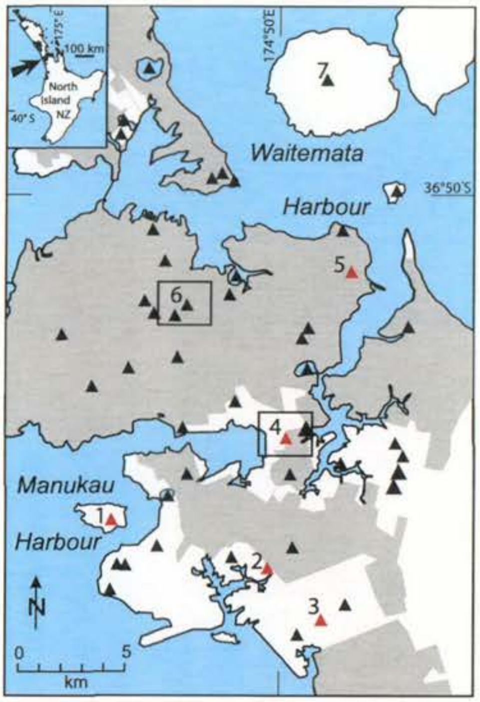

Figure 1. Location of volcanoes (triangles) within the Auckland volcanic field and Auckland city (shaded grey). Red triangles denote volcanoes discussed in text: 1, Puketutu (PT); 2, Crater Hill (CH); 3, Wiri (W); 4, Mt Richmond (MR); 5, Taylor Hill (TH). Other volcanoes referred to: 6, Mt Hobson; 7, Rangitoto. Inset: North Island, New Zealand, location of Auckland arrowed. Inset boxes show areas covered by Figure 2.

been identified from paleomagnetic studies. These aeromagnetic data are especially valuable where outcrop is limited and also demonstrate that the anomalous magnetization is a bulk parameter, implying that volcano lifetimes are much shorter than the duration of the anomalous paleomagnetic field.

[8] Magnetic mapping can very rarely be used to locate rocks that have recorded excursions; the only comparable examples are from mid-ocean ridges [*Roberts and Lewin-Harris*, 2000]. This approach is successful here because the volcanoes were short-lived and have high natural remanent magnetization (NRM mean values typically 2–10 A/m) which contrasts with their non-magnetic host rocks, even though the paleomagnetic field during eruptions appears to have been anomalously low [*Mochizuki et al.*, 2006]. Konigsberger ratios (ratio of remanent to induced magnetization) are also high (typically 3–7).

[9] Characteristic paleomagnetic directions for all five volcanoes were determined by thermal demagnetization of samples of basalt lava and welded scoria using standard techniques [e.g., *Tauxe*, 2002]. Sample sites consist of either a single flow unit or scoria cone at which 5–9 core samples were drilled and oriented by sun compass or geographical sighting; 2–3 sites were sampled per volcano. Laboratory measurements were carried out using a Magnetic Measurements Thermal Demagnetiser and Molspin spinner magnetometer, with temperature steps of 50°C up to 500°C, and 25°C steps subsequently. Samples characteristically exhibit high stability during progressive stepwise demagnetization, after any component of viscous magnetization is removed (usually by 200°C), with blocking temperatures typically in the range 400–500°C. These results are consistent with rock magnetic properties for Auckland basalts (including Crater Hill and Wiri samples) reported previously [*Mochizuki et al.*, 2006], which show a range of magnetic characteristics indicative of titanium-poor to titanium-rich titanomagnetite carriers, though with single-domain behaviour dominant. Principal component analysis of vector demagnetization plots shows that the samples have predominantly single-component magnetizations which can be interpreted as the primary magnetization directions acquired during cooling. These primary directions are well-determined for all sites within each volcano (Figures 3a and 3b and Table 1).

[10] Primary directions for Puketutu, Crater Hill and Wiri confirm earlier results based on alternating field demagnetization techniques [*Shibuya et al.*, 1992]. Site mean directions within each volcano (Figure 3c), and mean directions for each of the five volcanoes (Figure 3d and Table 2),

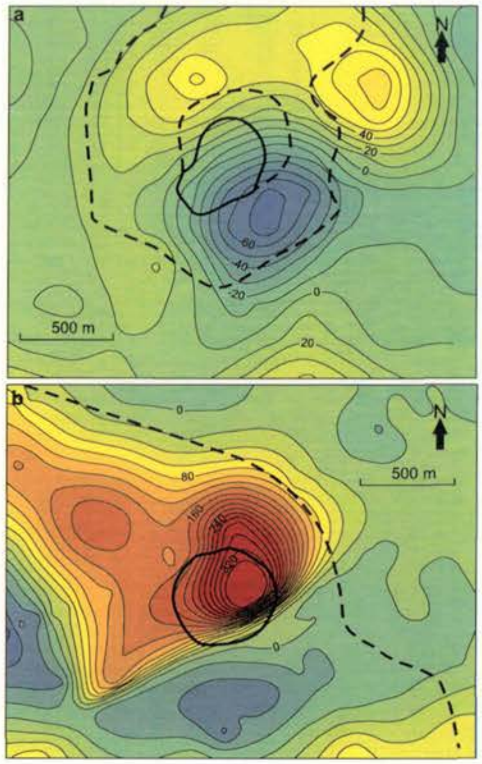

Figure 2. Example of contrasting residual aeromagnetic anomalies over Auckland volcanoes, for areas boxed in Figure 1: (a) Mt Richmond volcano and (b) Mt Hobson volcano. Contour intervals 10 nT (Figure 2a) and 20 nT (Figure 2b). Heavy solid and dashed lines denote boundaries of scoria cones and tuff deposits, respectively; sedimentary rocks occur elsewhere (thin deposits from nearby volcanoes excluded for simplicity). Mt Richmond volcano shows a negative anomaly due to capture of a geomagnetic excursion and Mt Hobson volcano shows a positive anomaly due to a normal direction of magnetization. The high amplitude anomaly west of Mt Hobson is caused by lava flows below tuff deposits.

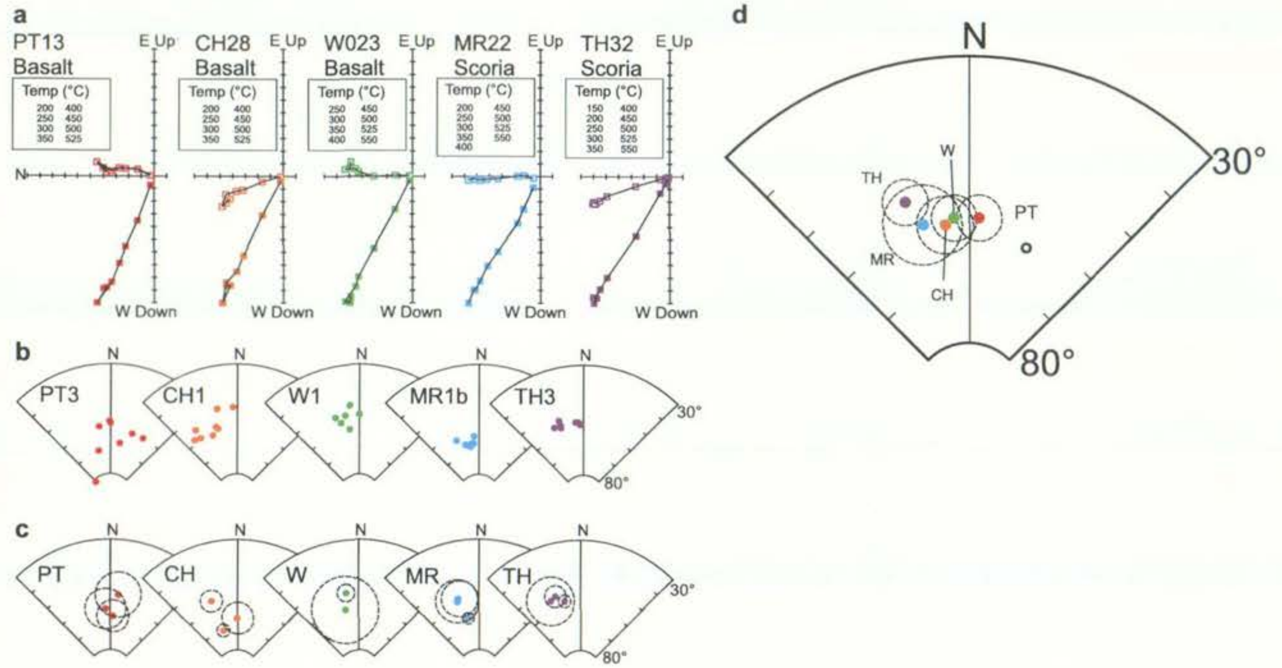

Figure 3. Paleomagnetic data for volcanoes recording the Auckland geomagnetic excursion. (a) Orthogonal vector plots of relative magnetic intensity for thermal demagnetization of selected samples; open (closed) symbols denote horizontal (vertical) plane. Equal-area lower-hemisphere stereo plots: (b) characteristic magnetization directions of samples (after demagnetization) from selected sites; (c) mean characteristic magnetization directions for all sites showing α_{95} values (cone of 95% confidence) as dashed circles; (d) mean characteristic magnetization directions for each volcano (colours as Figures 3a–3c) with α_{95} circles. Present-day field direction (upwards inclination) shown as open circle. Previously published mean site directions [*Shibuya et al.*, 1992] for PT, CH and W (1, 3 and 4 sites, respectively) are included in the volcano mean calculations. Overall mean inclination and declination is 61.7° and 351.0°, respectively; corresponding VGP is 9.8°N, 168.1°E (α_{95} = 6°).

cluster tightly around one of the three previously reported excursion directions [*Shibuya et al.*, 1992]. Mean inclinations and declinations for the five volcanoes range over 5° and 20°(cf. Table 2) respectively, though there is no statistically significant difference in inclinations (overall mean inclination/declination of 61.7°/351.0°, α_{95} = 6°). The concordance of these paleomagnetic directions implies that the five volcanoes erupted over the same short period of time – the question is, how short?

3. Discussion

[11] The Auckland event appears to correlate with the Mono Lake excursion (age ~29 ka) [*Benson et al.*, 2003], given the K-Ar date of 27 ± 5 ka for Wiri [*Mochizuki et al.*, 2004] and ^{14}C date of 29.7 ± 2 ka for Crater Hill [*Grant-Taylor and Rafter*, 1971], though correlation with the Laschamp excursion (age ~40 ka) [*Guillou et al.*, 2004] cannot be discounted entirely. Both these well-documented excursions are generally agreed to have inclination anomalies with durations of about 1,500 years [e.g., *Laj et al.*, 2000; *Teanby et al.*, 2002; *Benson et al.*, 2003]. Given the similarity of paleodirections for the five Auckland volcanoes and the rarity and short duration of excursions, it seems highly unlikely that more than one excursion event has been recorded. Of course this possibility cannot entirely be ruled out and requires high resolution dating studies to resolve.

[12] Therefore, an average recurrence interval of 300 years (based on the assumed total time span of 1500 years discussed above) for these five volcanoes is indicated. However, the spread of paleodirections is only a fraction of the total excursion path, implying that recurrence intervals are significantly less. Applying normal rates of secular variation to the excursion path, of ~0.01°/yr and ~0.03°/yr for inclination and declination, respectively, as shown by normal secular variation data from New Zealand [*Turner and Lillis*, 1994], gives a total time span of about 1000 years (based on the ranges and uncertainties of paleodirections). Hence a recurrence interval of only 200 years would be estimated.

[13] Rates of change of paleofield direction during excursions are likely to be higher than during normal secular variation since they are controlled by more dynamic processes, although the directional behaviour of geomagnetic excursions is not well established [*Gubbins*, 1999]. Some of the best-documented examples show rates of about 0.1°–0.2°/yr for inclination [e.g., *Coe and Liddicoat*, 1994; *Laj et al.*, 2000; *Teanby et al.*, 2002]. Using these rates gives a total time period of 50–100 years for the five volcanoes (equivalent to the 10° uncertainty envelope of inclinations). The same result is obtained using the observed overall change in paleomagnetic direction (about 20°) and a recent estimate of directional rates of change [*Laj et al.*, 2006] of about 0.2°/yr, based on several different excursion records. It is conceivable that the virtual geomagnetic pole (VGP) paused in a preferred location, in particular northern Australia, as has been noted during transitional states

Table 1. Site Mean Paleomagnetic Directions[a]

Site	Grid Ref.	n/N	Dec., deg	Inc., deg	α_{95}, deg	k	VGP_{lat}, deg	VGP_{long}, deg
CH1	734667	8/8	339.9	59.2	4.6	145	10.9	159.2
CH2	731666	7/8	0.3	68.2	7.0	76	1.7	175.0
CH3	733668	7/7	340.6	71.6	2.6	522	−4.7	164.1
MR1a	740726	4/5	344.4	59.7	8.8	110	11.2	162.8
MR1b	740726	7/7	348.2	67.2	2.2	746	2.4	167.3
MR2	742728	6/6	344.0	58.7	7.8	74	12.3	162.2
PT1	655649	5/6	6.2	58.0	10.1	58	14.3	179.8
PT2	667697	7/8	355.5	64.1	8.6	50	7.1	171.7
PT3	656693	8/8	3.2	66.7	7.3	59	3.8	176.9
TH1	770803	9/9	340.7	57.2	5.3	96	13.2	159.3
TH2	773802	7/7	337.4	58.3	11.3	29	11.4	157.1
TH3	772802	7/7	346.8	58.7	3.2	356	11.9	164.7
W1	757651	6/7	350.8	56.8	3.8	307	15.2	167.3
W2	757653	4/7	348.1	64.4	15.5	36	6.2	166.6

[a]Site labels are given in caption to Figure 1. Grid ref. refers to New Zealand Map Series 260 sheet R11 1:50,000. n/N, number of samples yielding result (n) as a subset of total number of samples (N). Dec. and Inc., mean declination and mean inclination. α_{95}, cone of 95% confidence. k, Fisher precision parameter. VGP_{lat} and VGP_{long} are corresponding virtual geomagnetic pole latitude and longitude for sites at five volcanoes.

[*Singer et al.*, 2005]; this may have slowed the rate of change during that time (which would result in an underestimation of recurrence interval). However, the VGP of the Auckland excursion falls well outside this region and the continuous sediment and igneous records of recent excursions do not indicate this morphology [e.g., *Coe and Liddicoat*, 1994; *Laj et al.*, 2000; *Teanby et al.*, 2002].

[14] The resulting estimate of an average recurrence interval of 10–20 years for the five volcanoes (based on the estimated total time period of 50–100 years) is extraordinarily short and raises the possibility that some eruptions were actually contemporaneous, given that most paleodirections are insignificantly different. Contemporaneous eruptions in monogenetic volcanic fields elsewhere invariably occur from adjacent vents (up to a few km apart) with some structural linkage, such as a fissure [*Connor and Conway*, 2000]. The only other reported example from a comparable basaltic field, where several volcanoes have recorded intermediate paleodirections linked to excursions, occurs in West Eifel, Germany [*Schnepp and Hradetzky*, 1994]. Uncertainty in the age of this event (510 ± 30 ka) precludes confirmation that only a single excursion event was recorded; in the Auckland case, the recorded excursion event is very recent, hence better constrained, and with tighter clustering of paleodirections. In both cases, the temporally linked volcanoes are widespread over the whole field (Figure 1) and in Auckland they appear not to be structurally related.

4. Implications and Conclusions

[15] Given the likely rapid ascent rate of magma [*Walker*, 1993; *Johnston et al.*, 1997], these results imply that magma overpressure was concurrent throughout the reservoir. If rupture of the overlying roof had initiated at some point in a contiguous reservoir, it might be expected that pressure would reduce elsewhere, resulting in the development of a single conduit to the surface. This observation therefore could suggest a lack of melt interconnectivity in the source reservoir [cf. *Canon-Tapia and Walker*, 2004]. Alternatively, a transient increase in regional extension rate could have initiated relatively rapid decompression melting across the source region, coupled with fracturing in the overlying lithosphere.

[16] The five volcanoes are small to medium in size with a total volume of primary material ($\sim$0.1 km^3) comparable to that typical of the larger, more recent Auckland volcanoes [*Allen and Smith*, 1994], hence no change in magma flux is implied. In contrast, the youngest volcano, Rangitoto (age 620 ± 70 yr) [*Kermode*, 1992] erupted singularly, producing a volume of material equal to the sum of all the other volcanoes in the field [*Allen and Smith*, 1994]. Melt accumulation and the dynamics of rupture in the magma reservoir has therefore varied considerably over a relatively short timescale ($\sim$30 ky).

[17] Multiple eruptions in monogenetic fields as described here appear to be extremely rare. Identifying such multiple eruptions in the geological record is difficult because of the limited resolution of dating methods and lack of stratigraphic overlap of small volcanoes; it is arguable that these events are more common than is generally supposed. One way of looking for multiple volcanoes in very young fields like Auckland might be a combination of precise $^{40}Ar/^{39}Ar$ dating and magnetic paleodeclination studies. Spatio-temporal clusters of vents within monogenetic fields have been recognized elsewhere, but only at much broader temporal scales [e.g., *Connor and Hill*, 1995; *Conway et al.*, 1998]. Current age data for the

Table 2. Volcano Mean Paleomagnetic Directions[a]

Volcano	Sites	Dec., deg	Inc., deg	α_{95}, deg	k	VGP_{lat}, deg	VGP_{long}, deg
Crater Hill	6	351.6	63.2	4.9	156	8.0	168.8
Mt Richmond	3	345.3	61.9	7.3	290	8.9	164.0
Puketutu	4	3.0	62.2	4.0	358	9.6	177.0
Taylor Hill	3	341.6	58.4	4.2	880	12.2	160.3
Wiri	6	354.5	61.6	2.3	214	10.2	171.0

[a]Dec. and Inc., mean declination and mean inclination. α_{95}, cone of 95% confidence. k, Fisher precision parameter. VGP_{lat} and VGP_{long} are corresponding mean virtual geomagnetic pole latitude and longitude for each of the five volcanoes. Table includes previously published data from other sites within the volcanoes [*Shibuya et al.*, 1992], additional to those listed in Table 1.

Auckland field are very poor [*Allen and Smith*, 1994; *Shane and Hoverd*, 2002] and corresponding paleomagnetic data are incomplete [*Shibuya et al.*, 1992], therefore few conclusions can be drawn from these data regarding the relative timing of eruptions in Auckland. These new paleomagnetic data have thus provided a relative timing index of exceptionally high sensitivity. These five volcanoes also potentially provide an unusual temporal snapshot of spatial variations in magma chemistry within a single magma reservoir, allowing synchronous partial melt variations to be studied.

[18] Probabilistic approaches to hazard assessment in monogenetic fields usually involve estimates of the likelihood of the next single eruption, assuming that a new eruptive episode is an independent event resulting in a single volcanic centre [e.g., *Connor and Hill*, 1995; *Conway et al.*, 1998; *Connor et al.*, 2000]. Whilst account is taken of broad spatio-temporal clustering of vents in large fields, as at Yucca Mountain [*Connor et al.*, 2000] and elsewhere [*Conway et al.*, 1998], none of these statistical models envisage several volcanoes occurring within a very short, or contemporaneous, timeframe.

[19] The likelihood of such events therefore needs to be considered in risk assessment and volcano monitoring. In this scenario, although the average recurrence rate of such *events* (and probability of next eruption) for a field would be less than that assuming single volcano events, the impact of events would obviously be greater, due to the increased extent and compounding of volcanic effects. Since there are very limited data on multiple eruptions in other monogenetic fields, it would perhaps be premature to develop widely applicable statistical models which take this into account. For the case of Auckland however, a city of over 1 million people, volcanic impact assessments to date have assumed that renewed activity will result in at most two new volcanoes or in a group of closely spaced vents [*Johnston et al.*, 1997; *Magill and Blong*, 2005; *Magill et al.*, 2005] and hence may significantly underestimate the possible impact associated with future volcanic events.

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Final Report

Research Project 03/491: Eruption patterns in monogenetic volcanic fields

General abstract

How often do new volcanoes erupt in volcanic fields such as Auckland? Geophysical research has shown that five volcanoes, geographically spread throughout the Auckland volcanic field, may have erupted at the same time. These volcanoes are Puketutu, Crater Hill, Wiri, Mt Richmond and Taylor Hill. This multiple volcanic event, which occurred about 30,000 or more years ago, has been recognized from magnetic measurements on volcanic rocks which have recorded an unusual perturbation of the Earths magnetic field. The first high-precision radiometric dating of the Auckland volcanoes is currently being undertaken to confirm the date of this event and to provide other dating information crucial for understanding the timing of eruptions in Auckland. Planning for the re-awakening of volcanic fields such as Auckland has not previously envisaged the possibility of contemporaneous eruptions from several widespread volcanoes. The results of this research identify that the possibility of such a scenario needs to be considered in hazard assessment and mitigation planning for Auckland City and also have important implications for cities elsewhere in similar settings.

Technical abstract

Five monogenetic volcanoes within the Quaternary Auckland volcanic field are shown to have recorded a virtually identical but anomalous paleomagnetic direction (mean inclination and declination of 61.7° and 351.0°, respectively), consistent with the capture of a geomagnetic excursion. The volcanic rocks also record that the paleointensity of the geomagnetic field was 8 – 21 μT, i.e. on average about 20% of normal values, thus confirming the occurrence of an excursion event. High-precision ^{40}Ar - ^{39}Ar dating of these volcanoes appears to confirm that a single excursion event has been recorded by the volcanic rocks, though the exact age of the event is currently subject to confirmation. Based on documented rates of change of paleomagnetic field direction during excursions, the narrow spread of directions implies that the volcanoes may have all formed within a period of only 50-100 years and possibly erupted contemporaneously. These temporally linked volcanoes are widespread throughout the Auckland volcanic field and appear not to be structurally related. Hence these results provide the first clear evidence for widespread multiple eruptions in the Auckland field and by analogy for multiple eruptions in any other similar monogenetic volcanic field. This finding challenges conventional risk calculations for monogenetic fields such as Auckland since the general paradigm for their reawakening is that only a single new volcano or group of closely spaced vents is created, typically at intervals of several hundred years or more. The work therefore has critical importance to volcanic hazard assessment in Auckland, and also elsewhere, since the impact of renewed eruptive activity could be significantly under-estimated.

Purpose of project

To provide new information on the relative timing and possible coincidence of eruptions within the Auckland Volcanic Field, factors critical to accurate hazard assessment.

Rationale of project

The question of how often new volcanoes form in monogenetic volcanic fields, such as the Auckland volcanic field (AVF), is a critical factor in hazard assessment and mitigation planning. An accurate quantification of eruption hazard in volcanic fields requires a knowledge of the frequency of occurrence of eruptions (or 'return-time'), eruption duration and spatio-temporal eruption patterns. However, the lack of reliable age data[1] for Auckland's volcanoes, which have intrinsic uncertainties of at least thousands of years, has been a major limitation in understanding the nature of past activity and hence in assessing future risk.

The Auckland Regional Council *Contingency Plan for the Auckland Volcanic Field*[2] states that "a future eruption will involve *a* new volcano" (P4) and that "it is expected that any vents in a multi-vent episode will be in relatively close proximity" (P6). This conservative approach reflects a general paradigm for the behaviour of monogenetic fields such as Auckland[3] and elsewhere[4]. However, early paleomagnetic data[5], which perhaps had not been fully appreciated, showed that three volcanoes (Crater Hill, Wiri and Puketutu) have recorded a rare geomagnetic excursion and therefore that they may be temporally linked. New paleomagnetic and age data were deemed to have the potential to make a significant contribution to this question.

Objectives of project

- To determine the relative timing of eruptions at several distinct volcanic centres and establish if multiple centres were contemporaneously active.
- To determine the spatial extent of contemporaneous activity and investigate if there are any structural or other relationships between such centres.
- To identify which global geomagnetic excursion event has been recorded by the Auckland volcanics and determining an absolute age for the rocks that record it.
- To estimate the duration of eruptive activity in volcanoes of the AVF.
- To identify any significant relationships between timing, volumes, spatial distribution and related factors which better define the patterns and nature of volcanic activity in the AVF.

Methodology

The two key methodologies of the project were:

- *Paleomagnetic measurements* to investigate the magnetic signatures of the Auckland volcanic rocks. Any rocks that have recorded a geomagnetic excursion may carry novel information about the relative timing of events and potentially offer a relative timing index of far greater sensitivity than conventional dating.

- *Precise ^{40}Ar - ^{39}Ar dating* of volcanic rocks. This should provide the first definitive dates for any of Auckland's volcanoes and establish the date of the geomagnetic excursion. This will enable data on the same excursion from studies elsewhere to be applied to the Auckland case and help advance our understanding of eruption patterns.

Analysis of existing geophysical data

A detailed analysis of existing aeromagnetic data[6] over Auckland was carried out and identified for the first time a number of volcanoes which had anomalous magnetic signatures which appeared similar to those known to have recorded the geomagnetic excursion. These volcanoes were Taylor Hill (tentatively identified in the original proposal), Mt St John, Mt Richmond and Kohuora. Kohuora volcano is a tuff ring with no basalt outcrops, therefore a ground-based magnetometer survey was carried out to investigate its magnetic anomaly. This survey proved that the volcano is in fact normally magnetized, so the volcano was eliminated from the study.

Existing and new paleomagnetic data from the Auckland volcanoes were analysed and their suitability for further paleodirection and new paleointensity measurements were assessed and discussed with overseas collaborators.

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A comprehensive sampling plan (insofar as outcrop allowed) for the three newly identified target volcanoes was devised; also, repeat sampling was planned for the three volcanoes originally identified as anomalous. Permissions were secured to access and collect samples at all these volcanoes. The sampling sites included active commercial quarries, Auckland City reserves and works, and a private housing cooperative. Having a range of different sampling sites from each of the different volcanoes is very important for statistical purposes and fortunately a number of new in-situ outcrops (some hidden or previously unknown) at these volcanoes were able to be located. This allowed three good quality independent sites from each of the volcanoes to be established (except Mt St John for which only two poor quality sites exist). Sample sites consist of either a single flow unit or scoria deposit from which typically 5-9 core samples from in situ outcrops were drilled and oriented by sun compass or geographical sighting for later paleomagnetic measurements (75 cored samples in total for this project). Both basalt lava and welded scoria were sampled.

Further samples especially suitable for ^{40}Ar - ^{39}Ar dating were collected from several sites, which had not previously been sampled, from five of the volcanoes. A further two volcanoes (Hampton Park and McLennan Hills) were also sampled; these had been identified previously[5]

as giving somewhat anomalous paleodirections and it is possible that these volcanoes too are associated with the same excursion event and are therefore relevant targets to date.

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Experimental measurements were carried out at the Geomagnetism Laboratory, University of Liverpool (UK), which is a leading research centre in paleomagnetism and houses the only operational microwave paleointensity facility in the world. The microwave method has significant advantages over conventional paleointensity methods since the samples are not heated, thus minimising thermo-chemical alteration during the experiment, a common cause of failure with conventional methods.

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The results for Taylor Hill and Mt Richmond agree very closely with the previous data from Puketutu, Crater Hill, and Wiri[5]. Further re-analysed results for the latter three volcanoes are also concordant with previously published data and serve to significantly improve the statistical quality of the total data set. The results for Mt St John show that despite having an apparently anomalous ground-based magnetic signature, the samples exhibit normal paleomagnetic directions and hence this volcano is not deemed to be linked to the anomalous group of five.

Sites within *individual* volcanoes also show a generally tight grouping of directions which are statistically indistinguishable, therefore it was deduced that detailed profiling through individual volcanic successions would be unlikely to yield any useful further information about relative timing within and between volcanic centres.

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Paleointensity data are required to confirm the validity of the excursion event, since low field intensity is diagnostic of excursions, and also these data potentially provide a further timing index for eruptions. Paleointensity measurements are more difficult and lengthy to perform than directional analysis; the suitability of rock samples for intensity measurements depends on their magnetic mineralogy and cannot be predicted in the field. Prior to paleointensity measurements, the rock magnetic properties of several test samples from each site was

investigated using a Variable Field Translation Balance; these results suggested that most samples would be suitable for carrying out paleointensity measurements.

Over 120 experiments on samples from 12 sites from all five volcanoes (Puketutu, Crater Hill, Wiri, Mt Richmond and Taylor Hill) were carried out; about 30% satisfied the recommended acceptance criteria for quality (a percentage that is not unusual for such measurements). Four of five volcanoes proved suitable for this type of measurement, the exception being Wiri which gave unstable results. The results give paleointensities in the range 8 – 21 μT which clearly show that the Earths field was of low intensity (about 20-30% of normal intensity) during the eruptions i.e. consistent with an excursion event. There appears to be no significant difference between the volcanoes (at the level of statistical error), which is consistent with the notion that a single excursion event has been recorded.

These results are important in validating that an excursion has been recorded, and therefore that data from elsewhere in the world can be used as an analogue for the timing of events in Auckland. Given the similarity of the measured paleointensity values and their statistical spread, it appears that paleointensity variations recorded in the Auckland rocks are unlikely to be an effective timing index to investigate eruption sequences.

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The best-documented examples of rates of change of paleofield direction during excursions are about 0.1°- 0.2°/yr for inclination[7]. Using these rates gives a total time period for the eruption of these five volcanoes of only 50-100 years (equivalent to the 10° uncertainty envelope of inclinations). This equates to an average eruption return time of 10 – 20 years which is significantly less than any previous data or statistical estimates suggest.

The concordance of directions between different sites within each individual volcano (and to some degree their negative aeromagnetic anomalies) also demonstrate that eruption durations at the volcanoes were short ie probably much less than hundreds of years. This result confirms existing estimates for the eruption lifetimes of Auckland's volcanoes, which is based on examples from elsewhere. The notable exception to this is Rangitoto volcano where previous paleomagnetic data[8] suggests that eruptive activity may have spanned a period of some 500 years.

The five volcanoes are small to medium in size, with a total volume of primary material (~0.1 km^3) comparable to that typical of the larger, more recent Auckland volcanoes. This implies that the multiple event did not signify the generation of a larger volume of magma than usual, but that its eruption was distributed over a much wider area. This contrasts with Rangitoto volcano for example which was the product of an unusually large magma volume, but whose eruption was concentrated at a single centre. There is no obvious geographical pattern or known structural linkage between the five volcanoes and therefore when a new eruption occurs

at a particular location in Auckland, there will be no reason to suspect any other location as a more likely site for concurrent eruptions.

^{40}Ar - ^{39}Ar dating results

This aspect of the project suffered considerable delays because my original collaborator, Dr Malcolm Pringle (formerly at the Scottish Universities Research Reactor, East Kilbride, UK) was unable to deliver any results, despite nearly three years of correspondence and a visit to his laboratory. As a consequence, critical new dates have not been able to be obtained within the timeframe of the project. However, in mid 2005 I was able to establish a new and significant collaboration with Professor Brad Singer at the Rare Gas Geochronology Laboratory, University of Wisconsin-Madison, one of the worlds leading dating laboratories. Furthermore, as a consequence of Prof Singer's new interest in the project I have also been able to negotiate very favourable laboratory charges for the ^{40}Ar - ^{39}Ar dates.

The first preliminary ^{40}Ar - ^{39}Ar dating results for pilot samples of the Auckland basalts were obtained from Prof Singer's laboratory in late 2006. These initial results need to be confirmed by more detailed dating experiments which are currently being carried out. Despite their preliminary nature, the results are very promising. Firstly, it has been commonly thought that the Auckland basalts would prove very difficult or impossible to date because of problems with excess argon. However the initial experiments appear to give stable plateau ages and Prof Singer does not consider that dating will be as problematic as first thought. If this proves correct, it will be a key breakthrough in the long-standing question of whether the Auckland volcanoes can be accurately dated using radiometric methods. It is important to acknowledge however that the method is being applied close to its intrinsic limits of resolution.

Secondly, all five volcanoes appear to give the same result within experimental error. If confirmed, this would answer one of the possible criticisms of the previous interpretations based on the paleomagetic data alone, namely that although the volcanoes all share the same anomalous paleomagnetic direction, they could be recording excursion events of very different ages. The new results suggest, as previously argued, that only one event is recorded and that therefore the five volcanoes are closely linked temporally.

In addition, samples of Pupuke volcano (one of the oldest in the field) and Mt Eden volcano (one of the youngest) have also been collected as control samples and will provide dates spanning the presumed lifetime of the Auckland field.

Conclusions

This project has made a very valuable contribution to the study of patterns of volcanic eruption in the Auckland volcanic field. It has established that five volcanoes, spread across the Auckland field and apparently structurally unrelated, were active at about the same time (at a date yet to be confirmed). Although the exact length of this episode is unknown, the estimated period of 50-100 years is very short in geological terms and raises the possibility that the eruptions were in fact contemporaneous. Only recently, and mainly as a consequence of this project, has it been more widely acknowledged that perhaps two eruption centres could develop at the same time[9]. However, this project has revealed that several volcanoes may develop during

a single episode. The possibility of such a scenario in Auckland City therefore needs to be considered in hazard assessment and mitigation planning.

This project has provided the opportunity to involve overseas collaborators who are acknowledged experts in their fields in carrying out research into the Auckland volcanic field. Most importantly, I have been successful in interesting them into continuing the work of the project beyond the tenure of the EQC grant. The EQC grant has therefore been a very valuable seed project for what will probably prove to be further key studies of the Auckland field which will undoubtedly enhance our understanding of its eruption history.

Dissemination of research findings

Publications in scientific journals (paper attached)

Cassidy, J. 2006. Geomagnetic excursion captured by multiple volcanoes in a monogenetic field. *Geophys. Res. Lett.*, 33, 21310-14.

Journal papers in preparation

Paper on the paleomagnetic intensity work incorporating results of the rock magnetic experiments, with Dr M Hill (University of Liverpool); expected publication date: late 2007

Joint paper with Prof B Singer and his team reporting the ages of the volcanoes; expected publication date: late 2007

Conferences (conference abstracts in Appendices)

"Relative timing of eruptions in the Auckland Volcanic Field, New Zealand"
International Association of Volcanology and Chemistry of the Earth's Interior, General Assembly 2004, Pucon (Chile), 14-19 November

"Contemporaneous eruptions in the Auckland Volcanic Field? Evidence from a geomagnetic excursion record"
Invited plenary speaker at Geological Society of New Zealand Annual Conference, Taupo, 6-9 December 2004

Informal talks

Scientific seminars were given at the Department of Geology, University of Auckland, the Department of Earth Sciences, University of Liverpool (UK) and at the Department of Geology and Geophysics, University of Calgary (Canada).

Media

Live radio interviews (23/01/07) on the outcomes of the project were given to Radio NZ (Checkpoint), Newstalk 1ZB (Mike Hosking) and Radio Live (Michael Laws). Concurrently, the NZ Herald carried an article on its website.

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19 March 2007

Figure 1

Location of volcanoes (triangles) within the Auckland volcanic field and Auckland City (shaded grey). Volcanoes labelled 1-5 are likely to have erupted during a single episode: 1, Puketutu (PT); 2, Crater Hill (CH); 3, Wiri (W); 4, Mt Richmond (MR); 5, Taylor Hill (TH). Other volcanoes referred to in report: 6, Kohuora; 7, Mt St John; 8, Rangitoto.

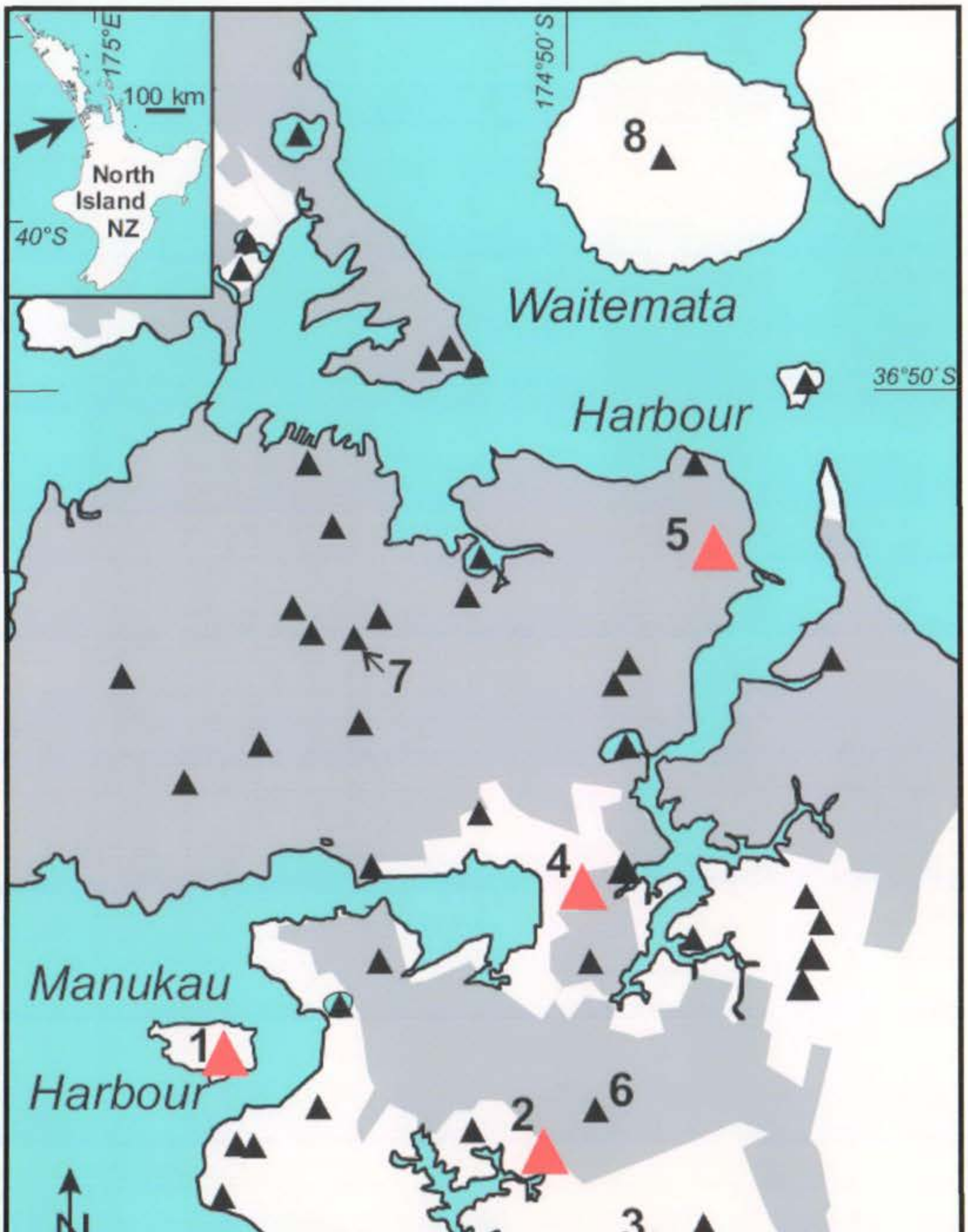
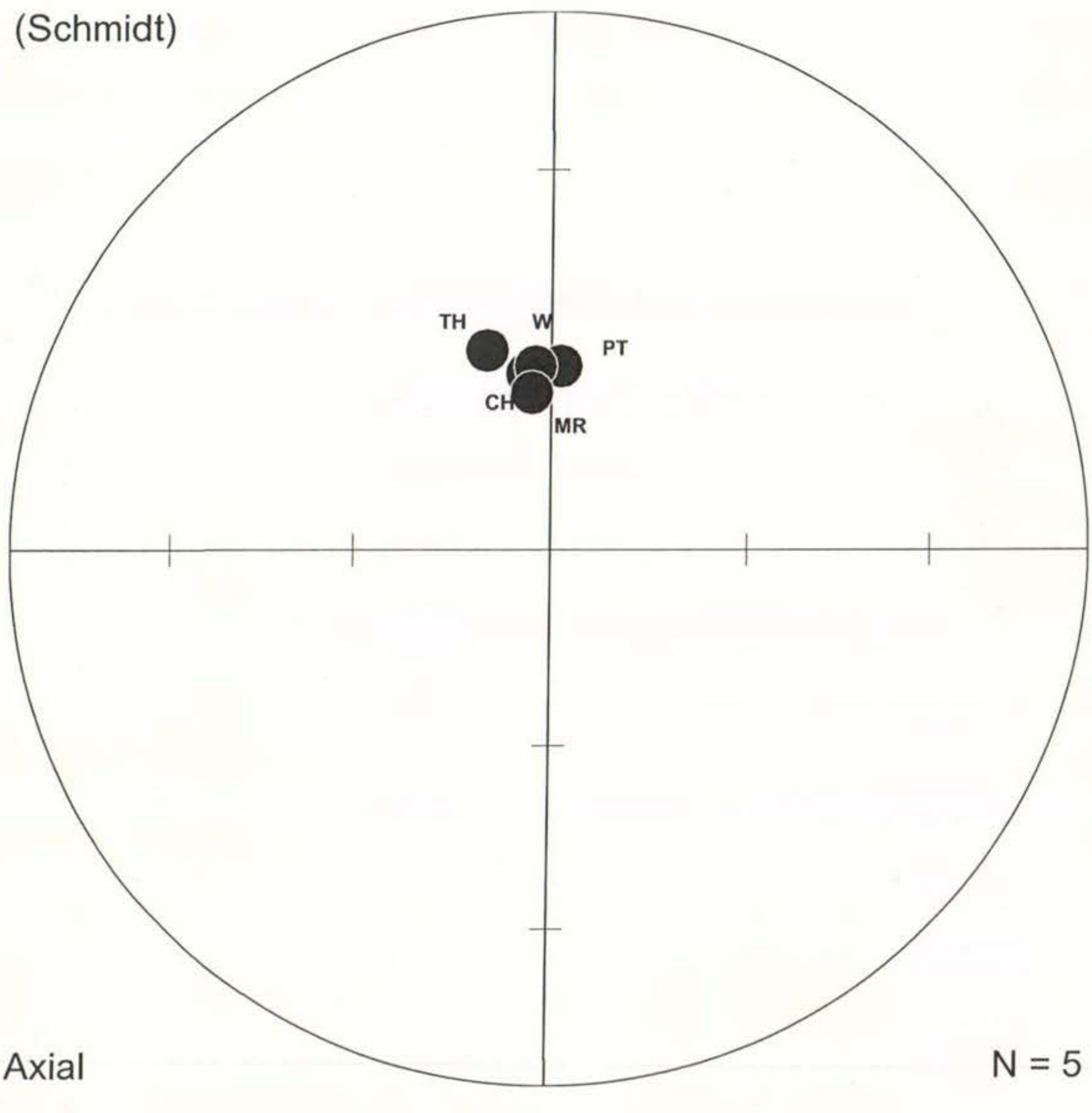


Figure 2

Equal area lower-hemisphere sterographic plot (Schmidt type) of measured paleomagnetic directions in the five related volcanoes (tick marks every 30^{o}): Puketutu (PT); 2, Crater Hill (CH); 3, Wiri (W); 4, Mt Richmond (MR); 5, Taylor Hill (TH). Sizes of circles represent confidence limits on magnetisation directions. Note that the symbols indicate downwards inclinations of directions, whereas the normal (present-day) magnetic field has upwards inclinations.



APPENDIX 1

Conference abstract

International Association of Volcanology and Chemistry of the Earth's Interior, General Assembly 2004, Pucon (Chile), 14-19 November

Relative timing of eruptions in the Auckland Volcanic Field, New Zealand

John Cassidy

Department of Geology, University of Auckland, Private Bag 92019, Auckland, NEW ZEALAND

The Auckland Volcanic Field (AVF), a late Quaternary monogenetic basaltic field containing 50 eruption centres, poses a significant risk to New Zealand's largest city. Absolute and relative ages for eruptions are poorly known making it difficult to establish patterns of eruption and recurrence intervals necessary for quantitative hazard assessment. Fortuitously, volcanoes in the AVF have recorded a geomagnetic excursion. This potentially provides a relative timing index of high sensitivity since reported rates of change of geomagnetic field direction and intensity during excursions are anomalously high. Whilst three volcanoes in the AVF have been previously documented as sharing an identical anomalous magnetisation direction, new paleomagnetic measurements combined with high-resolution aeromagnetic data, have identified at least one, and possibly two, further centres which exhibit the same anomalous direction. Preliminary paleointensity measurements for four of these volcanoes, using recently developed microwave demagnetisation techniques, yield anomalously low intensities consistent with an excursion record. Ar-Ar dating of these basalts is currently in progress in order to confirm the identification of the excursion event, currently thought to be the Laschamp. Thus a strong temporal link, even contemporaneity, is implied between these five volcanic centres which are geographically spread throughout the field, making a simple structural link between the centres unlikely. Even assuming normal rates of secular variation, the total time period for these eruptions might be only several hundred years (an estimate consistent with the reported duration of the Laschamp event), which suggests a recurrence interval much less than any currently estimated for the field.

APPENDIX 2

Conference abstract

Geological Society of New Zealand Annual Conference, Taupo, 6-9 December

Contemporaneous eruptions in the Auckland Volcanic Field? Evidence from a geomagnetic excursion record

John Cassidy

Department of Geology, University of Auckland, Private Bag 92019, Auckland, NEW ZEALAND

Absolute and relative ages for volcanoes in the Auckland Volcanic Field (AVF) are poorly known, hence patterns of eruption and eruption frequency are poorly constrained. Recurrence intervals, a key parameter in quantifying hazard assessment, have only been crudely estimated, apart from where recent drill hole data have provided better constraints based on tephra layers. Fortuitously, basalts from Auckland's volcanoes have recorded a geomagnetic excursion, which potentially provides a relative timing index of high sensitivity since rates of change of the geomagnetic field during excursions are likely to be high. Three volcanoes have previously been documented as sharing an identical anomalous magnetization direction, which has provided the only evidence which might suggest that a number of different volcanoes are closely linked in time. A further two volcanoes have been identified from aeromagnetic data as having magnetic anomalies consistent with such anomalous magnetizations. Paleomagnetic directions and intensities recorded by basalts from all five volcanoes suggest that they erupted during the same excursion event. The age of this event is currently unknown but Ar-Ar dating of these basalts is currently underway. Thus a strong temporal link, perhaps contemporaneity, is implied for these widely separated volcanoes which appear to have no structural relationship within the field. Even assuming normal rates of secular variation, the total time period for these eruptions might be only several hundred years suggesting a recurrence interval much less than any currently estimated for the field and therefore having important consequences for hazard assessment.

Final Report

Research Project 03/491: Eruption patterns in monogenetic volcanic fields

General abstract

How often do new volcanoes erupt in volcanic fields such as Auckland? Geophysical research has shown that five volcanoes, geographically spread throughout the Auckland volcanic field, may have erupted at the same time. These volcanoes are Puketutu, Crater Hill, Wiri, Mt Richmond and Taylor Hill. This multiple volcanic event, which occurred about 30,000 or more years ago, has been recognized from magnetic measurements on volcanic rocks which have recorded an unusual perturbation of the Earths magnetic field. The first high-precision radiometric dating of the Auckland volcanoes is currently being undertaken to confirm the date of this event and to provide other dating information crucial for understanding the timing of eruptions in Auckland. Planning for the re-awakening of volcanic fields such as Auckland has not previously envisaged the possibility of contemporaneous eruptions from several widespread volcanoes. The results of this research identify that the possibility of such a scenario needs to be considered in hazard assessment and mitigation planning for Auckland City and also have important implications for cities elsewhere in similar settings.

Technical abstract

Five monogenetic volcanoes within the Quaternary Auckland volcanic field are shown to have recorded a virtually identical but anomalous paleomagnetic direction (mean inclination and declination of 61.7° and 351.0°, respectively), consistent with the capture of a geomagnetic excursion. The volcanic rocks also record that the paleointensity of the geomagnetic field was $8 - 21$ μT, i.e. on average about 20% of normal values, thus confirming the occurrence of an excursion event. High-precision ^{40}Ar - ^{39}Ar dating of these volcanoes appears to confirm that a single excursion event has been recorded by the volcanic rocks, though the exact age of the event is currently subject to confirmation. Based on documented rates of change of paleomagnetic field direction during excursions, the narrow spread of directions implies that the volcanoes may have all formed within a period of only 50-100 years and possibly erupted contemporaneously. These temporally linked volcanoes are widespread throughout the Auckland volcanic field and appear not to be structurally related. Hence these results provide the first clear evidence for widespread multiple eruptions in the Auckland field and by analogy for multiple eruptions in any other similar monogenetic volcanic field. This finding challenges conventional risk calculations for monogenetic fields such as Auckland since the general paradigm for their reawakening is that only a single new volcano or group of closely spaced vents is created, typically at intervals of several hundred years or more. The work therefore has critical importance to volcanic hazard assessment in Auckland, and also elsewhere, since the impact of renewed eruptive activity could be significantly under-estimated.

Purpose of project

To provide new information on the relative timing and possible coincidence of eruptions within the Auckland Volcanic Field, factors critical to accurate hazard assessment.

Rationale of project

The question of how often new volcanoes form in monogenetic volcanic fields, such as the Auckland volcanic field (AVF), is a critical factor in hazard assessment and mitigation planning. An accurate quantification of eruption hazard in volcanic fields requires a knowledge of the frequency of occurrence of eruptions (or 'return-time'), eruption duration and spatio-temporal eruption patterns. However, the lack of reliable age data[1] for Auckland's volcanoes, which have intrinsic uncertainties of at least thousands of years, has been a major limitation in understanding the nature of past activity and hence in assessing future risk.

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- To determine the relative timing of eruptions at several distinct volcanic centres and establish if multiple centres were contemporaneously active.
- To determine the spatial extent of contemporaneous activity and investigate if there are any structural or other relationships between such centres.
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The first preliminary ^{40}Ar - ^{39}Ar dating results for pilot samples of the Auckland basalts were obtained from Prof Singer's laboratory in late 2006. These initial results need to be confirmed by more detailed dating experiments which are currently being carried out. Despite their preliminary nature, the results are very promising. Firstly, it has been commonly thought that the Auckland basalts would prove very difficult or impossible to date because of problems with excess argon. However the initial experiments appear to give stable plateau ages and Prof Singer does not consider that dating will be as problematic as first thought. If this proves correct, it will be a key breakthrough in the long-standing question of whether the Auckland volcanoes can be accurately dated using radiometric methods. It is important to acknowledge however that the method is being applied close to its intrinsic limits of resolution.

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In addition, samples of Pupuke volcano (one of the oldest in the field) and Mt Eden volcano (one of the youngest) have also been collected as control samples and will provide dates spanning the presumed lifetime of the Auckland field.

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19 March 2007

Figure 1

Location of volcanoes (triangles) within the Auckland volcanic field and Auckland City (shaded grey). Volcanoes labelled 1-5 are likely to have erupted during a single episode: 1, Puketutu (PT); 2, Crater Hill (CH); 3, Wiri (W); 4, Mt Richmond (MR); 5, Taylor Hill (TH). Other volcanoes referred to in report: 6, Kohuora; 7, Mt St John; 8, Rangitoto.

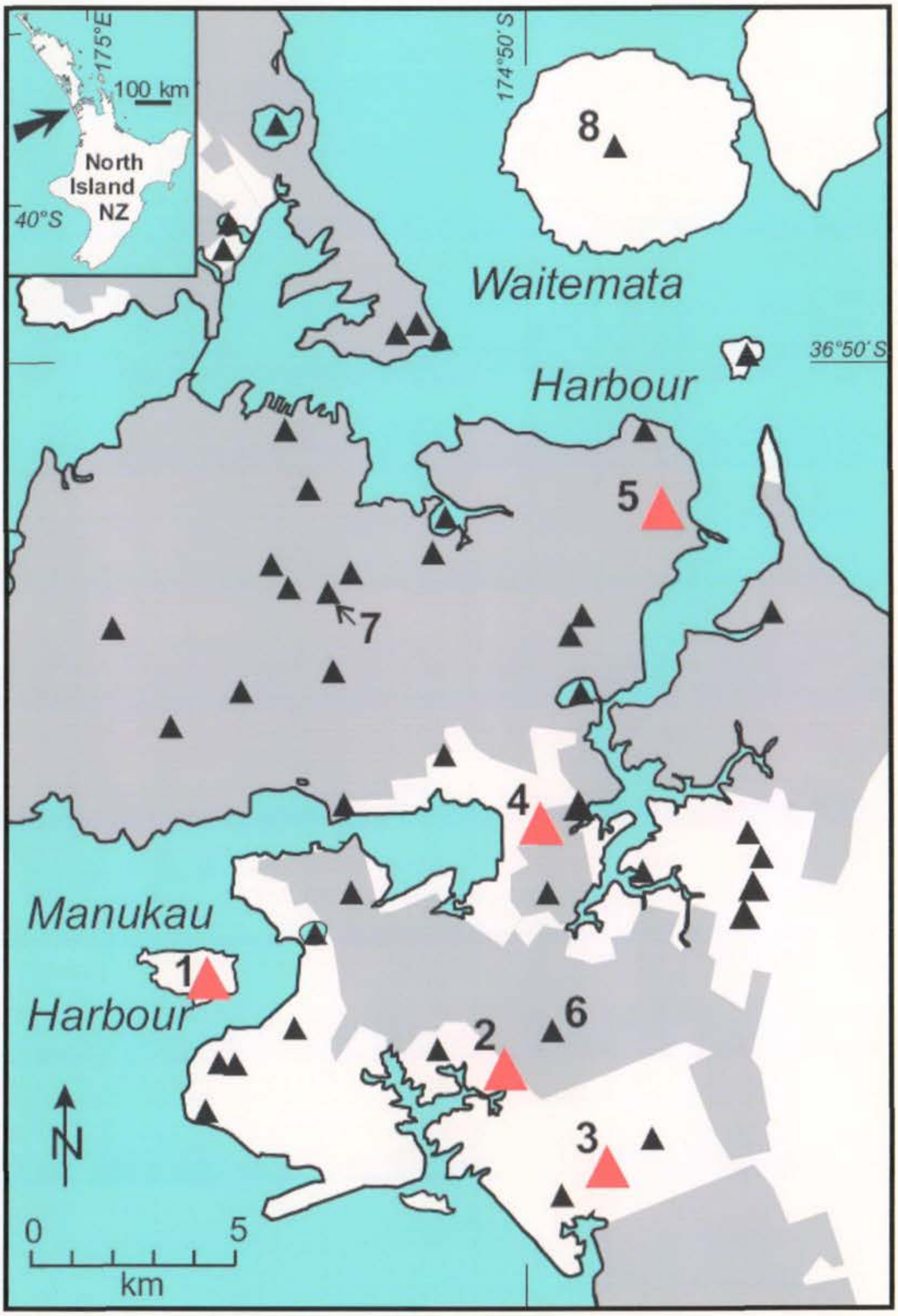
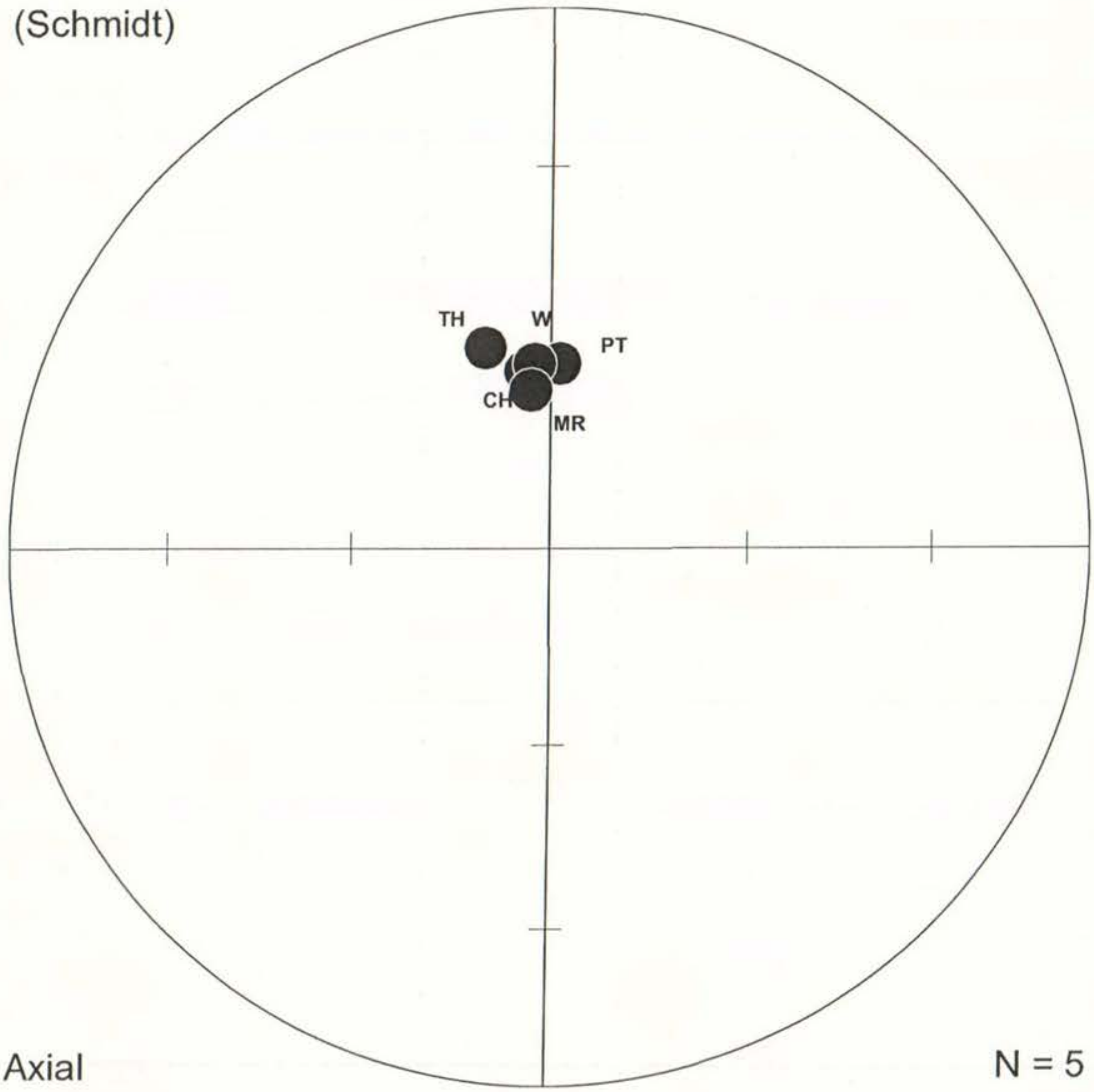


Figure 2

Equal area lower-hemisphere sterographic plot (Schmidt type) of measured paleomagnetic directions in the five related volcanoes (tick marks every 30^{o}): Puketutu (PT); 2, Crater Hill (CH); 3, Wiri (W); 4, Mt Richmond (MR); 5, Taylor Hill (TH). Sizes of circles represent confidence limits on magnetisation directions. Note that the symbols indicate downwards inclinations of directions, whereas the normal (present-day) magnetic field has upwards inclinations.



APPENDIX 1

Conference abstract

International Association of Volcanology and Chemistry of the Earth's Interior, General Assembly 2004, Pucon (Chile), 14-19 November

Relative timing of eruptions in the Auckland Volcanic Field, New Zealand

John Cassidy

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The Auckland Volcanic Field (AVF), a late Quaternary monogenetic basaltic field containing 50 eruption centres, poses a significant risk to New Zealand's largest city. Absolute and relative ages for eruptions are poorly known making it difficult to establish patterns of eruption and recurrence intervals necessary for quantitative hazard assessment. Fortuitously, volcanoes in the AVF have recorded a geomagnetic excursion. This potentially provides a relative timing index of high sensitivity since reported rates of change of geomagnetic field direction and intensity during excursions are anomalously high. Whilst three volcanoes in the AVF have been previously documented as sharing an identical anomalous magnetisation direction, new paleomagnetic measurements combined with high-resolution aeromagnetic data, have identified at least one, and possibly two, further centres which exhibit the same anomalous direction. Preliminary paleointensity measurements for four of these volcanoes, using recently developed microwave demagnetisation techniques, yield anomalously low intensities consistent with an excursion record. Ar-Ar dating of these basalts is currently in progress in order to confirm the identification of the excursion event, currently thought to be the Laschamp. Thus a strong temporal link, even contemporaneity, is implied between these five volcanic centres which are geographically spread throughout the field, making a simple structural link between the centres unlikely. Even assuming normal rates of secular variation, the total time period for these eruptions might be only several hundred years (an estimate consistent with the reported duration of the Laschamp event), which suggests a recurrence interval much less than any currently estimated for the field.

APPENDIX 2

Conference abstract

Geological Society of New Zealand Annual Conference, Taupo, 6-9 December

Contemporaneous eruptions in the Auckland Volcanic Field? Evidence from a geomagnetic excursion record

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Absolute and relative ages for volcanoes in the Auckland Volcanic Field (AVF) are poorly known, hence patterns of eruption and eruption frequency are poorly constrained. Recurrence intervals, a key parameter in quantifying hazard assessment, have only been crudely estimated, apart from where recent drill hole data have provided better constraints based on tephra layers. Fortuitously, basalts from Auckland's volcanoes have recorded a geomagnetic excursion, which potentially provides a relative timing index of high sensitivity since rates of change of the geomagnetic field during excursions are likely to be high. Three volcanoes have previously been documented as sharing an identical anomalous magnetization direction, which has provided the only evidence which might suggest that a number of different volcanoes are closely linked in time. A further two volcanoes have been identified from aeromagnetic data as having magnetic anomalies consistent with such anomalous magnetizations. Paleomagnetic directions and intensities recorded by basalts from all five volcanoes suggest that they erupted during the same excursion event. The age of this event is currently unknown but Ar-Ar dating of these basalts is currently underway. Thus a strong temporal link, perhaps contemporaneity, is implied for these widely separated volcanoes which appear to have no structural relationship within the field. Even assuming normal rates of secular variation, the total time period for these eruptions might be only several hundred years suggesting a recurrence interval much less than any currently estimated for the field and therefore having important consequences for hazard assessment.

Final Report

Research Project 03/491: Eruption patterns in monogenetic volcanic fields

General abstract

How often do new volcanoes erupt in volcanic fields such as Auckland? Geophysical research has shown that five volcanoes, geographically spread throughout the Auckland volcanic field, may have erupted at the same time. These volcanoes are Puketutu, Crater Hill, Wiri, Mt Richmond and Taylor Hill. This multiple volcanic event, which occurred about 30,000 or more years ago, has been recognized from magnetic measurements on volcanic rocks which have recorded an unusual perturbation of the Earths magnetic field. The first high-precision radiometric dating of the Auckland volcanoes is currently being undertaken to confirm the date of this event and to provide other dating information crucial for understanding the timing of eruptions in Auckland. Planning for the re-awakening of volcanic fields such as Auckland has not previously envisaged the possibility of contemporaneous eruptions from several widespread volcanoes. The results of this research identify that the possibility of such a scenario needs to be considered in hazard assessment and mitigation planning for Auckland City and also have important implications for cities elsewhere in similar settings.

Technical abstract

Five monogenetic volcanoes within the Quaternary Auckland volcanic field are shown to have recorded a virtually identical but anomalous paleomagnetic direction (mean inclination and declination of 61.7° and 351.0°, respectively), consistent with the capture of a geomagnetic excursion. The volcanic rocks also record that the paleointensity of the geomagnetic field was $8 - 21\ \mu T$, i.e. on average about 20% of normal values, thus confirming the occurrence of an excursion event. High-precision ^{40}Ar - ^{39}Ar dating of these volcanoes appears to confirm that a single excursion event has been recorded by the volcanic rocks, though the exact age of the event is currently subject to confirmation. Based on documented rates of change of paleomagnetic field direction during excursions, the narrow spread of directions implies that the volcanoes may have all formed within a period of only 50-100 years and possibly erupted contemporaneously. These temporally linked volcanoes are widespread throughout the Auckland volcanic field and appear not to be structurally related. Hence these results provide the first clear evidence for widespread multiple eruptions in the Auckland field and by analogy for multiple eruptions in any other similar monogenetic volcanic field. This finding challenges conventional risk calculations for monogenetic fields such as Auckland since the general paradigm for their reawakening is that only a single new volcano or group of closely spaced vents is created, typically at intervals of several hundred years or more. The work therefore has critical importance to volcanic hazard assessment in Auckland, and also elsewhere, since the impact of renewed eruptive activity could be significantly under-estimated.

Purpose of project

To provide new information on the relative timing and possible coincidence of eruptions within the Auckland Volcanic Field, factors critical to accurate hazard assessment.

Rationale of project

The question of how often new volcanoes form in monogenetic volcanic fields, such as the Auckland volcanic field (AVF), is a critical factor in hazard assessment and mitigation planning. An accurate quantification of eruption hazard in volcanic fields requires a knowledge of the frequency of occurrence of eruptions (or 'return-time'), eruption duration and spatio-temporal eruption patterns. However, the lack of reliable age data[1] for Auckland's volcanoes, which have intrinsic uncertainties of at least thousands of years, has been a major limitation in understanding the nature of past activity and hence in assessing future risk.

The Auckland Regional Council *Contingency Plan for the Auckland Volcanic Field*[2] states that "a future eruption will involve *a* new volcano" (P4) and that "it is expected that any vents in a multi-vent episode will be in relatively close proximity" (P6). This conservative approach reflects a general paradigm for the behaviour of monogenetic fields such as Auckland[3] and elsewhere[4]. However, early paleomagnetic data[5], which perhaps had not been fully appreciated, showed that three volcanoes (Crater Hill, Wiri and Puketutu) have recorded a rare geomagnetic excursion and therefore that they may be temporally linked. New paleomagnetic and age data were deemed to have the potential to make a significant contribution to this question.

Objectives of project

- To determine the relative timing of eruptions at several distinct volcanic centres and establish if multiple centres were contemporaneously active.
- To determine the spatial extent of contemporaneous activity and investigate if there are any structural or other relationships between such centres.
- To identify which global geomagnetic excursion event has been recorded by the Auckland volcanics and determining an absolute age for the rocks that record it.
- To estimate the duration of eruptive activity in volcanoes of the AVF.
- To identify any significant relationships between timing, volumes, spatial distribution and related factors which better define the patterns and nature of volcanic activity in the AVF.

Methodology

The two key methodologies of the project were:

- *Paleomagnetic measurements* to investigate the magnetic signatures of the Auckland volcanic rocks. Any rocks that have recorded a geomagnetic excursion may carry novel information about the relative timing of events and potentially offer a relative timing index of far greater sensitivity than conventional dating.

- *Precise ^{40}Ar - ^{39}Ar dating* of volcanic rocks. This should provide the first definitive dates for any of Auckland's volcanoes and establish the date of the geomagnetic excursion. This will enable data on the same excursion from studies elsewhere to be applied to the Auckland case and help advance our understanding of eruption patterns.

Analysis of existing geophysical data

A detailed analysis of existing aeromagnetic data[6] over Auckland was carried out and identified for the first time a number of volcanoes which had anomalous magnetic signatures which appeared similar to those known to have recorded the geomagnetic excursion. These volcanoes were Taylor Hill (tentatively identified in the original proposal), Mt St John, Mt Richmond and Kohuora. Kohuora volcano is a tuff ring with no basalt outcrops, therefore a ground-based magnetometer survey was carried out to investigate its magnetic anomaly. This survey proved that the volcano is in fact normally magnetized, so the volcano was eliminated from the study.

Existing and new paleomagnetic data from the Auckland volcanoes were analysed and their suitability for further paleodirection and new paleointensity measurements were assessed and discussed with overseas collaborators.

Fieldwork

A comprehensive sampling plan (insofar as outcrop allowed) for the three newly identified target volcanoes was devised; also, repeat sampling was planned for the three volcanoes originally identified as anomalous. Permissions were secured to access and collect samples at all these volcanoes. The sampling sites included active commercial quarries, Auckland City reserves and works, and a private housing cooperative. Having a range of different sampling sites from each of the different volcanoes is very important for statistical purposes and fortunately a number of new in-situ outcrops (some hidden or previously unknown) at these volcanoes were able to be located. This allowed three good quality independent sites from each of the volcanoes to be established (except Mt St John for which only two poor quality sites exist). Sample sites consist of either a single flow unit or scoria deposit from which typically 5-9 core samples from in situ outcrops were drilled and oriented by sun compass or geographical sighting for later paleomagnetic measurements (75 cored samples in total for this project). Both basalt lava and welded scoria were sampled.

Further samples especially suitable for ^{40}Ar - ^{39}Ar dating were collected from several sites, which had not previously been sampled, from five of the volcanoes. A further two volcanoes (Hampton Park and McLennan Hills) were also sampled; these had been identified previously[5]

as giving somewhat anomalous paleodirections and it is possible that these volcanoes too are associated with the same excursion event and are therefore relevant targets to date.

Paleomagnetic measurements and results

Experimental measurements were carried out at the Geomagnetism Laboratory, University of Liverpool (UK), which is a leading research centre in paleomagnetism and houses the only operational microwave paleointensity facility in the world. The microwave method has significant advantages over conventional paleointensity methods since the samples are not heated, thus minimising thermo-chemical alteration during the experiment, a common cause of failure with conventional methods.

Paleodirection measurements and analysis

Characteristic paleomagnetic directions for the 75 new samples from Taylor Hill, Mt Richmond and Mt St John volcanoes samples were determined using thermal demagnetization techniques following standard procedures. Laboratory measurements were carried out using a Magnetic Measurements Thermal Demagnetiser and Molspin spinner magnetometer, with temperature steps of 50°C up to 500°C, and 25°C steps subsequently. Samples characteristically exhibit high stability during progressive stepwise demagnetization, after any component of viscous magnetization is removed. Principal component analysis of vector demagnetization plots shows that the samples have predominantly single-component magnetizations which can be interpreted as the primary magnetization directions acquired during cooling. These primary directions are well-determined for all sites within each volcano.

The results for Taylor Hill and Mt Richmond agree very closely with the previous data from Puketutu, Crater Hill, and Wiri[5]. Further re-analysed results for the latter three volcanoes are also concordant with previously published data and serve to significantly improve the statistical quality of the total data set. The results for Mt St John show that despite having an apparently anomalous ground-based magnetic signature, the samples exhibit normal paleomagnetic directions and hence this volcano is not deemed to be linked to the anomalous group of five.

Sites within *individual* volcanoes also show a generally tight grouping of directions which are statistically indistinguishable, therefore it was deduced that detailed profiling through individual volcanic successions would be unlikely to yield any useful further information about relative timing within and between volcanic centres.

Paleointensity measurements and analysis

Paleointensity data are required to confirm the validity of the excursion event, since low field intensity is diagnostic of excursions, and also these data potentially provide a further timing index for eruptions. Paleointensity measurements are more difficult and lengthy to perform than directional analysis; the suitability of rock samples for intensity measurements depends on their magnetic mineralogy and cannot be predicted in the field. Prior to paleointensity measurements, the rock magnetic properties of several test samples from each site was

investigated using a Variable Field Translation Balance; these results suggested that most samples would be suitable for carrying out paleointensity measurements.

Over 120 experiments on samples from 12 sites from all five volcanoes (Puketutu, Crater Hill, Wiri, Mt Richmond and Taylor Hill) were carried out; about 30% satisfied the recommended acceptance criteria for quality (a percentage that is not unusual for such measurements). Four of five volcanoes proved suitable for this type of measurement, the exception being Wiri which gave unstable results. The results give paleointensities in the range 8 – 21 μT which clearly show that the Earths field was of low intensity (about 20-30% of normal intensity) during the eruptions i.e. consistent with an excursion event. There appears to be no significant difference between the volcanoes (at the level of statistical error), which is consistent with the notion that a single excursion event has been recorded.

These results are important in validating that an excursion has been recorded, and therefore that data from elsewhere in the world can be used as an analogue for the timing of events in Auckland. Given the similarity of the measured paleointensity values and their statistical spread, it appears that paleointensity variations recorded in the Auckland rocks are unlikely to be an effective timing index to investigate eruption sequences.

Implications of results

These results provide compelling evidence that all five volcanoes in the Auckland volcanic field (see Figure 1) have recorded a particular and anomalous magnetisation direction, consistent with a geomagnetic excursion, and hence very strongly imply a temporal linkage. The results also hint at a clustering of the four southernmost volcanoes (see Figure 2) with Mt Taylor volcano being a slight outlier from this group (both paleomagnetically and geographically), possibly indicating a very slightly different eruption timing.

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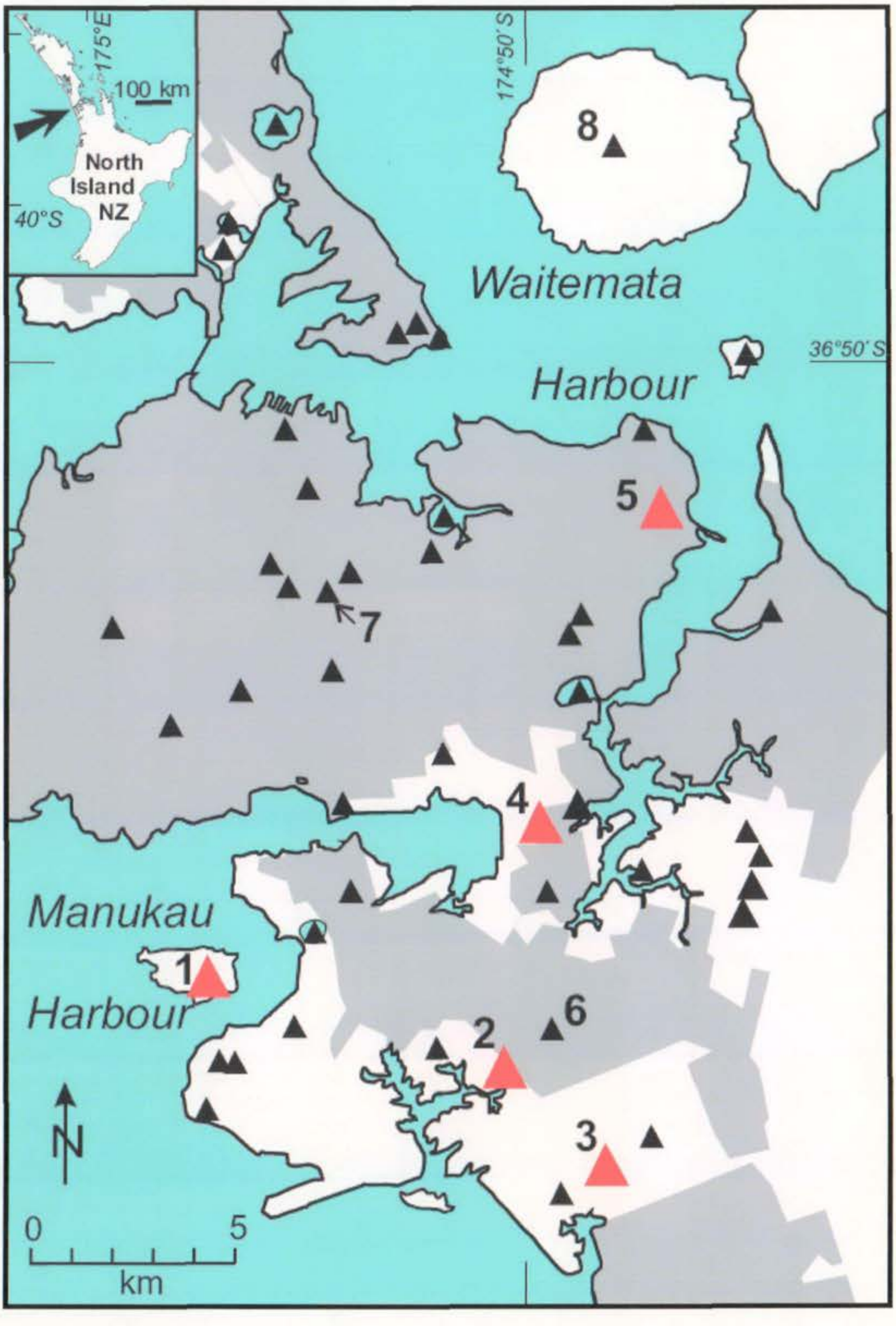
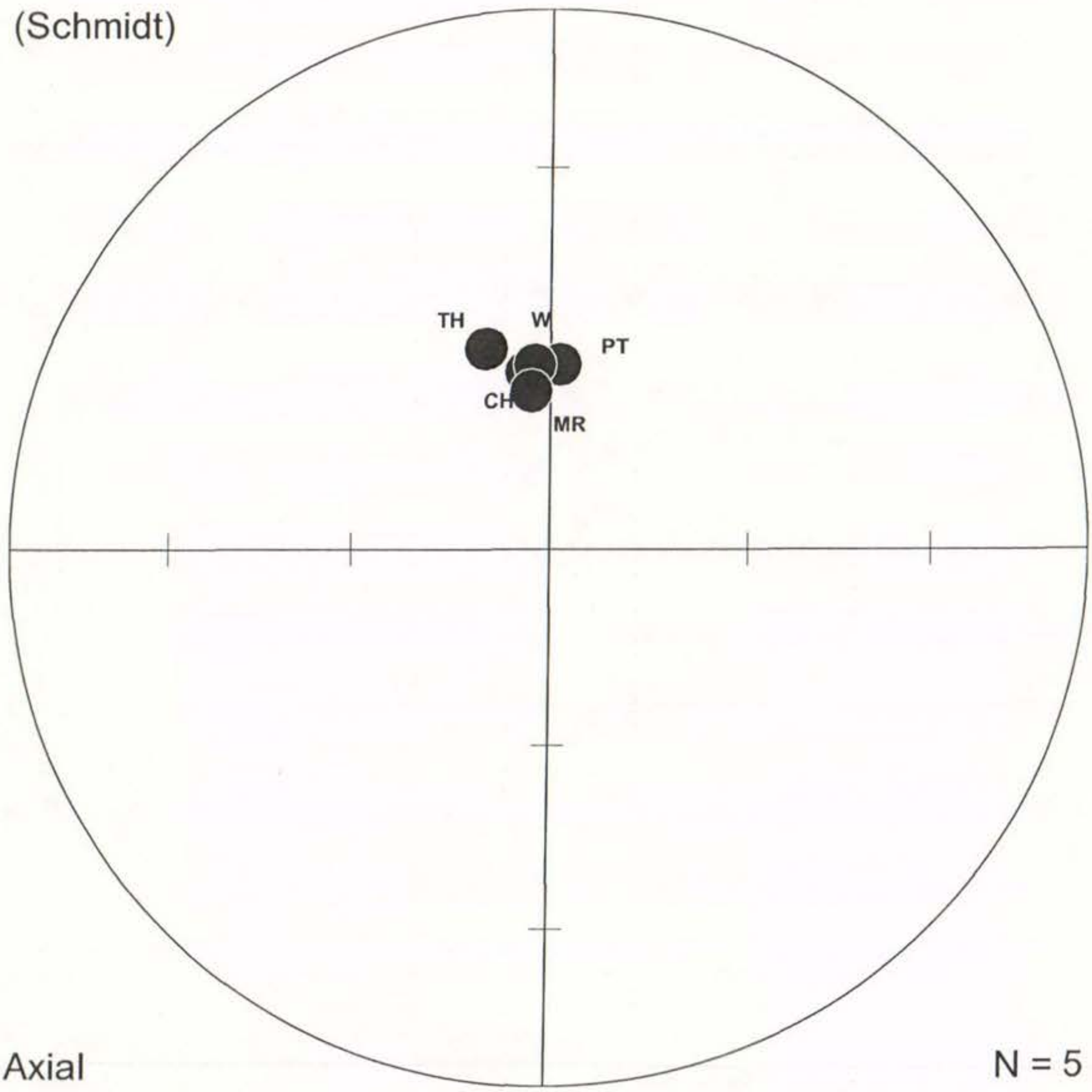


Figure 2

Equal area lower-hemisphere sterographic plot (Schmidt type) of measured paleomagnetic directions in the five related volcanoes (tick marks every 30°): Puketutu (PT); 2, Crater Hill (CH); 3, Wiri (W); 4, Mt Richmond (MR); 5, Taylor Hill (TH). Sizes of circles represent confidence limits on magnetisation directions. Note that the symbols indicate downwards inclinations of directions, whereas the normal (present-day) magnetic field has upwards inclinations.



APPENDIX 1

Conference abstract

International Association of Volcanology and Chemistry of the Earth's Interior, General Assembly 2004, Pucon (Chile), 14-19 November

Relative timing of eruptions in the Auckland Volcanic Field, New Zealand

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The Auckland Volcanic Field (AVF), a late Quaternary monogenetic basaltic field containing 50 eruption centres, poses a significant risk to New Zealand's largest city. Absolute and relative ages for eruptions are poorly known making it difficult to establish patterns of eruption and recurrence intervals necessary for quantitative hazard assessment. Fortuitously, volcanoes in the AVF have recorded a geomagnetic excursion. This potentially provides a relative timing index of high sensitivity since reported rates of change of geomagnetic field direction and intensity during excursions are anomalously high. Whilst three volcanoes in the AVF have been previously documented as sharing an identical anomalous magnetisation direction, new paleomagnetic measurements combined with high-resolution aeromagnetic data, have identified at least one, and possibly two, further centres which exhibit the same anomalous direction. Preliminary paleointensity measurements for four of these volcanoes, using recently developed microwave demagnetisation techniques, yield anomalously low intensities consistent with an excursion record. Ar-Ar dating of these basalts is currently in progress in order to confirm the identification of the excursion event, currently thought to be the Laschamp. Thus a strong temporal link, even contemporaneity, is implied between these five volcanic centres which are geographically spread throughout the field, making a simple structural link between the centres unlikely. Even assuming normal rates of secular variation, the total time period for these eruptions might be only several hundred years (an estimate consistent with the reported duration of the Laschamp event), which suggests a recurrence interval much less than any currently estimated for the field.

APPENDIX 2

Conference abstract

Geological Society of New Zealand Annual Conference, Taupo, 6-9 December

Contemporaneous eruptions in the Auckland Volcanic Field? Evidence from a geomagnetic excursion record

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Absolute and relative ages for volcanoes in the Auckland Volcanic Field (AVF) are poorly known, hence patterns of eruption and eruption frequency are poorly constrained. Recurrence intervals, a key parameter in quantifying hazard assessment, have only been crudely estimated, apart from where recent drill hole data have provided better constraints based on tephra layers. Fortuitously, basalts from Auckland's volcanoes have recorded a geomagnetic excursion, which potentially provides a relative timing index of high sensitivity since rates of change of the geomagnetic field during excursions are likely to be high. Three volcanoes have previously been documented as sharing an identical anomalous magnetization direction, which has provided the only evidence which might suggest that a number of different volcanoes are closely linked in time. A further two volcanoes have been identified from aeromagnetic data as having magnetic anomalies consistent with such anomalous magnetizations. Paleomagnetic directions and intensities recorded by basalts from all five volcanoes suggest that they erupted during the same excursion event. The age of this event is currently unknown but Ar-Ar dating of these basalts is currently underway. Thus a strong temporal link, perhaps contemporaneity, is implied for these widely separated volcanoes which appear to have no structural relationship within the field. Even assuming normal rates of secular variation, the total time period for these eruptions might be only several hundred years suggesting a recurrence interval much less than any currently estimated for the field and therefore having important consequences for hazard assessment.