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# Further K-Ar dating and paleomagnetic study of the Auckland geomagnetic excursions

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Three different excursional paleomagnetic directions were reported from eight volcanoes of the Auckland volcanic field in New Zealand: north-down (ND) directions obtained from five volcanoes, west-up (WU) from two volcanoes, and south-up (SU) from one volcano. K-Ar ages have been reported for two of these volcanoes: 27±5 ($1\sigma$) ka for the Wiri volcano of the ND group and 55±5 ka for the Hampton Park volcano of the WU group. In the present study, we have carried out further K-Ar age determinations on three other volcanoes and obtained reliable ages for two of them: 30±5 ka for the Puketutu volcano of the ND group and 50±6 ka for the McLennan Hills volcano of the SU group. The age of Puketutu agrees well with that of Wiri, and these two ages give a weighted mean age of 29±3 ($1\sigma$) ka for the ND group. The age of the ND group is distinguishable from those of the SU and WU groups at the $2\sigma$ level, confirming that excursions occurred at two different times separated by a few tens of thousands of years. The age of the SU group is indistinguishable from that of the WU group, and a weighted mean age of 53±4 ka can be calculated for this combined group (SU-WU group). The age of the ND group and that of the SU-WU group are distinguishable from the latest age estimate of the Laschamp excursion. Overall, these age data from volcanic rocks show that at least three excursions occurred between approximately 30 and 60 ka. These three excursions are likely to be confined in the weak dipole interval of 20–70 ka, and all of these excursions yield particularly low virtual dipole moments (VDMs) of $2\times10^{22}$ A m$^2$ or less. Since it is suggested that the larger virtual geomagnetic pole (VGP) deviations from the geographic pole are related to the lower VDMs, the excursional fields possibly have resulted from a significantly reduced dipole field and comparable non-dipole components.

**Key words:** K-Ar age, paleointensity, Auckland volcanic field, Auckland excursion, Laschamp excursion, Mono Lake excursion.

## 1. Introduction

Geomagnetic excursions are characterized by a swing of the paleomagnetic field direction that is larger than secular variation but distinct from polarity reversals. Recent geomagnetic excursions are generally identified by a virtual geomagnetic pole (VGP) departure from the geographic pole and its return to the original polarity. The criterion for an excursion is generally taken as a 45° departure in VGP latitude (e.g. Verosub and Banerjee, 1977), although other values have been used on occasion (e.g. 40°: Barbetti and McElhinny, 1976).

Geomagnetic excursions between 20 and 60 ka have been identified from a number of sedimentary and several volcanic environments. Two well-established excursions in this interval are the Laschamp excursion reported from the lava flows in France (Bonhommet and Zäringer, 1969), dated at 40.4±2.0 ka ($2\sigma$) (Guillou *et al.*, 2004), and the Mono Lake excursion identified from lake sediments in western North America (Denham and Cox, 1971), dated at approximately 30 ka (Benson *et al.*, 2003). These two distinct excursions are considered to have occurred at 30 and 40 ka, respectively, although a few researchers have noted that the Mono Lake excursion at the original locality may be a record of the Laschamp excursion (Kent *et al.*, 2002; Zimmerman *et al.*, 2006). In contrast to the 40 ka excursion, the 30 ka excursion is less often found in sedimentary records from other areas. In particular, a lack of paleomagnetic data, including paleointensities and radiometric ages, is the major obstacle to establishing a correlation (or making a distinction) between those young excursions and defining the geomagnetic field during the geomagnetic excursion.

Shibuya *et al.* (1992) first reported excursional paleomagnetic field directions from six volcanoes, some of which were dated between 20 and 50 ka, in the Auckland volcanic field, New Zealand (Fig. 1). Those excursional paleodirections were classified into three groups: a north-down excursional paleodirection from three volcanoes (ND group), a west-up from two volcanoes (WU group), and a south-up from one volcano (SU group). Cassidy (2006) recently

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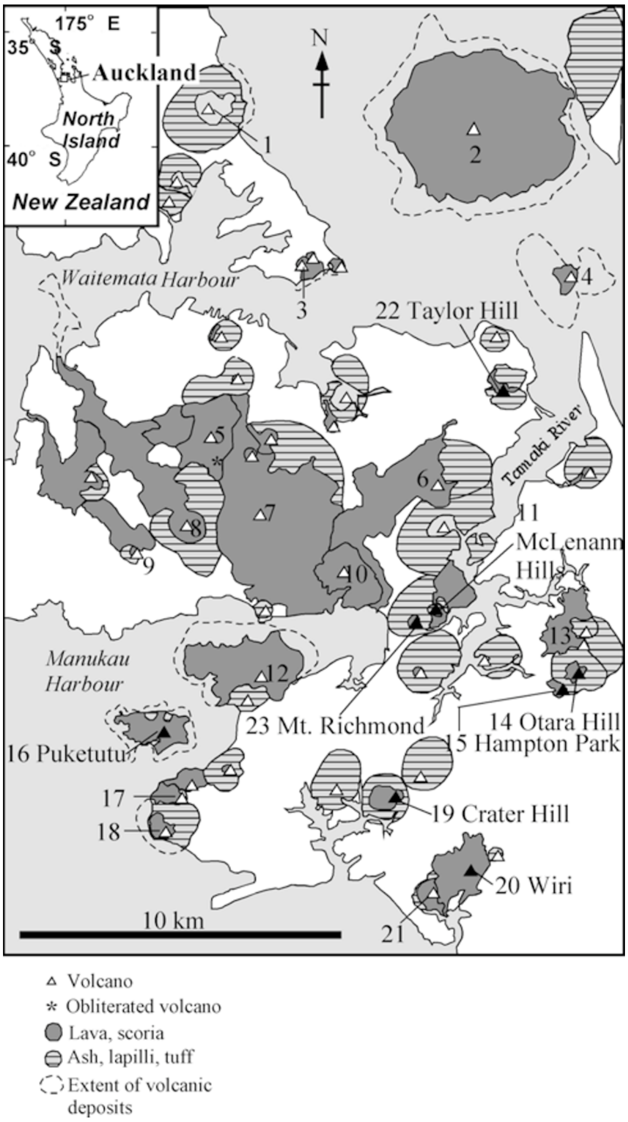


Fig. 1. Map of volcanoes in the Auckland volcanic field. Triangles indicate locations of monogenetic volcanoes. Numbers are given to 23 volcanoes which were studied by Shibuya *et al*. (1992) and Cassidy (2006). Eight volcanoes (solid triangles) are shown to record excursional paleomagnetic directions. This map is modified from Kermode (1992).

reported that five volcanoes in the Auckland volcanic field in total recorded a ND excursional paleodirection; two of which were newly identified from aeromagnetic and paleomagnetic measurements. Mochizuki *et al*. (2004a) determined K-Ar ages for the Wiri volcano (27±5 ka, $1\sigma$) of the ND group and the Hampton Park volcano (55±5 ka, $1\sigma$) of the WU group. These ages are statistically distinct at the $2\sigma$ level, indicating that the ND and WU groups record different excursions. Mochizuki *et al*. (2006) reported the mean paleointensities for five volcanoes recording the Auckland excursions and also for three volcanoes recording non-excursional paleodirections using the LTD-DHT Shaw paleointensity method (Tsunakawa and Shaw, 1994; Yamamoto *et al*., 2003). Weak paleointensities of 2.5–11.8 $\mu$T were obtained for the Auckland excursions and 13.1–40.0 $\mu$T for the non-excursional field. These results suggest that the dipole moment of the geomagnetic field reduced to about $2\times10^{22}$ A m$^2$ or less during the Auckland excursions.

In this study, we present new K-Ar dating results of samples from three volcanoes (Puketutu, Crater Hill, and McLennnan Hills) in order to refine the ages of the three groups of the Auckland excursions. Based on all the available K-Ar ages and paleomagnetic data of the Auckland excursions, we discuss the timing, correlations, and possible models of the geomagnetic excursions.

## 2. Auckland Volcanic Field and Sampling

Details on the Auckland volcanic field are given in elsewhere (see, for example, Smith, 1989), and we discuss here only the essential information on which this study is focused. The Auckland volcanic field is one of the predominantly basaltic Pliocene to recent intraplate volcanic fields in the northern North Island, New Zealand. It comprises about 50 monogenetic volcanoes within an area of 360 km$^2$ (Fig. 1) and has been active at least for the last 250 ka (Allen and Smith, 1994; Shane, 2002). Rocks of the volcanic field are mostly alkali basalt and basanite, although lavas from Rangitoto volcano are transitional to tholeiitic (Smith, 1989).

Samples were collected during sampling in March of 2000. All of the samples were from outcrops of basaltic lava. No outcrop of Otara Hill volcano (WU group) was found in the sampling period due to the development of residential land. Five other volcanoes recording the Auckland excursions have been subjected to K-Ar dating, and the data reported in Mochizuki *et al*. (2004a) and this study. For the three volcanoes (Wiri, Puketutu, and Crater Hill) of the ND group, samples were collected in quarry exposures: the sampling sites of Wiri and Puketutu are located in recent quarries, those of Crater Hill are in an older quarry.

## 3. K-Ar Dating Method

Fresh internal fragments (70–150 g) were firstly cut from the samples, then crushed and sieved to particles of 250–500 $\mu$m in diameter. Phenocrysts were removed from the sieved samples using a Franz isodynamic separator to avoid possible extraneous $^{40}$Ar in the phenocrysts (e.g., Dalrymple and Lanphere, 1969) which may have contaminated the Auckland basalts (McDougall *et al*., 1969). The final aliquots of groundmass grains were used for analysis. Potassium and Ar measurements were performed at the geochronology laboratory of Kyoto University. The $K_2O$ contents were determined twice for each sample using a flame emission photometry, following Matsumoto (1989). The average of two results was used for the age calculation. Radiogenic $^{40}$Ar was determined with a VG3600 mass spectrometer by the unspiked sensitivity method. The initial $^{40}$Ar/$^{36}$Ar ratio was corrected for the natural mass fractionation by a mass fractionation correction procedure (MFCP) (Itaya and Nagao, 1988; Takaoka *et al*., 1989; Matsumoto *et al*., 1989a) since the studies on historical lavas indicated that natural mass fractionation of initial Ar isotopic ratios should be corrected (Matsumoto *et al*., 1989b; Ozawa *et al*., 2006). Details of the K-Ar dating method is described in Mochizuki *et al*. (2004a).

Thin sections of all of the measured samples were observed petrographically; most showed no alteration of ei-

Table 1. K-Ar dating results of samples from the Puketutu, Crater Hill and McLennan Hills volcanoes in the Auckland volcanic field.

| Volcano (Paleodirection) | Sample ID[a] | Lab. ID[b] | Weight [g] | $K_2O$[c] [wt.%] | $^{40}Ar/^{36}Ar$ | $^{38}Ar/^{36}Ar$ | $^{40}Ar/^{36}Ar$ initial | $^{40}Ar$ rad.[d] [$10^{-9}$ $cm^3$ STP/g] | $^{40}Ar$ atm.[e] [%] | Age$\pm 1\sigma$[f] [ka] |
|---|---|---|---|---|---|---|---|---|---|---|
| Puketutu | NZ222-0-A | A03008 | 6.02 | 1.55 | 304.6±0.9 | 0.1886±0.0008 | 300.6±2.7 | 0.79±0.55 (1.80±0.18) | 98.7 (97.0) | 16±11 (36±4) |
| (North-Down) | NZ222-0-B | A05068 | 6.05 | 1.55 | 302.9±0.6 | 0.1864±0.0008 | 294.0±2.5 | 1.79±0.50 (1.48±0.12) | 97.0 (97.5) | 36±10 (30±2) |
| | NZ222-1-A | A05069 | 7.53 | 1.49 | 304.0±0.6 | 0.1874±0.0008 | 297.2±2.5 | 1.19±0.44 (1.47±0.10) | 97.8 (97.2) | 25±9 (31±2) |
| | NZ222-1-B | A05072 | 7.54 | 1.49 | 304.7±0.6 | 0.1857±0.0007 | 292.0±2.4 | 1.82±0.36 (1.32±0.09) | 95.8 (97.0) | 38±8 (28±2) |
| | | | | | | | | | Weighted mean | 30±5 (30±1) |
| Crater Hill | NZ214-9 | A03014 | 3.01 | 0.94 | 301.2±0.6 | 0.1886±0.0009 | 300.7±3.0 | 0.16±1.05 (1.97±0.21) | 99.8 (98.1) | 5±35 (65±7) |
| (North-Down) | NZ215-7 | A03011 | 3.02 | 0.95 | 300.9±0.7 | 0.1881±0.0008 | 299.0±2.5 | 0.59±0.82 (1.70±0.23) | 99.3 (98.2) | 19±27 (55±7) |
| | NZ215-8 | A03012 | 3.77 | 0.92 | 300.2±0.6 | 0.1894±0.0008 | 303.1±2.6 | −0.94±0.86 (1.48±0.20) | 101.0 (98.4) | −32±29 (50±7) |
| McLenann Hills | NZ217-1 | A05067 | 3.02 | 1.44 | 310.7±0.8 | 0.1868±0.0012 | 295.2±3.8 | 1.92±0.48 (1.88±0.10) | 95.0 (95.1) | 41±10 (40±2) |
| (South-Up) | NZ217-0 | A05074 | 6.78 | 1.41 | 313.0±0.6 | 0.1844±0.0012 | 287.8±3.8 | 2.88±0.45 (2.00±0.07) | 92.0 (94.4) | 63±10 (44±2) |
| | NZ217-3-A | A05070 | 4.50 | 1.27 | 305.0±0.7 | 0.1874±0.0009 | 297.1±3.1 | 1.37±0.54 (1.64±0.12) | 97.4 (96.9) | 33±13 (40±3) |
| | NZ217-3-B | A05073 | 4.51 | 1.27 | 302.0±0.6 | 0.1844±0.0012 | 287.8±3.9 | 2.63±0.72 (1.20±0.11) | 95.3 (97.8) | 64±18 (29±3) |
| | | | | | | | | | Weighted mean | 50±6 (40±1) |

Values in parentheses are calculated using the conventional procedure without the mass fractionation correction procedure (MFCP). The results from Crater Hill are thought to be less reliable, and a weighted mean age is not adopted in this study (see text).
[a]Sample ID consists of site and hand-sample numbers.
[b]Lab. ID is given to each measurement at the geochronological laboratory of Kyoto University.
[c]$K_2O$ content was measured twice and then averaged, with the exception of one sample (NZ217-0), for which there is only a single measurement.
[d]$^{40}Ar$ rad. means the volume of radiogenic $^{40}Ar$ in the samples.
[e]$^{40}Ar$ atm. means the percentage of the atmospheric $^{40}Ar$ in total $^{40}Ar$.
[f]Errors are $\pm 1\sigma$.

ther groundmass or phenocrysts. For the samples from the Crater Hill volcano, the rims of some large olivine phenocrysts are iddingsitized although there is no alteration in the groundmass.

## 4. Results

The K-Ar dating results for the Puketutu, Crater Hill, and McLennan Hills volcanoes are listed in Table 1. For the Puketutu volcano of the ND group, duplicate Ar isotope measurements were made for each of two block samples. Four K-Ar ages are consistent within $2\sigma$ of analytical error, yielding a weighted mean age of 30±5 ($1\sigma$) ka. For the McLennan Hills volcano of the SU group, duplicate Ar isotope measurements were made on a block sample and a single measurement on each of two block samples. Four K-Ar ages are consistent (33–64 ka) within $2\sigma$ analytical errors, giving a weighted mean age of 50±6 ka ($1\sigma$).

Three block samples from the Crater Hill volcano of the ND group gave ages between −32 and 19 ka, with relatively large analytical errors of 54–70 ka at the $2\sigma$ level. These large errors are due to the higher atmospheric Ar ratio of more than 98% (without MFCP) in the Crater Hill samples, which precludes reliable K-Ar age determinations. The higher atmospheric Ar ratio is basically a consequence of the combined effects of a higher atmospheric Ar content and a lower K content of the samples.

For the samples from Crater Hill, $^{36}Ar$ contents per unit mass, which are estimated from the original $^{40}Ar/^{36}Ar$ and total $^{40}Ar$ contents, are $3.2–3.5\times10^{-10}$ $cm^3$ STP/g. These values are almost twofold higher than those for the samples from other volcanoes ($1.1–2.0\times10^{-10}$ $cm^3$ STP/g), indicating that the atmospheric Ar contents per unit mass of the samples from Crater Hill are about twofold higher than those of the samples from other volcanoes. One factor underlying these increased values may be the alteration of the samples mentioned in the last section. In addition, the $K_2O$ contents of the Crater Hill samples (0.92–0.95%) are lower than those of the Wiri and Puketutu samples of the ND group (1.3–1.6%). Therefore, compared to the other samples, less radiogenic Ar would be produced in the Crater Hill samples for a particular period of time.

The alteration observed for the rims of the phenocrysts also imply that $^{40}Ar$ might have been partly lost from the measured groundmass of the Crater Hill samples. This alteration coupled with the large analytical errors suggests that the reliability of the ages of the samples from Crater Hill is lower than those of the other volcanoes. Therefore, we do not use the K-Ar results from the Crater Hill samples in the subsequent discussion.

## 5. The Ages of the Auckland Excursions

The ages and paleomagnetic data for the Auckland excursions are summarized in Table 2. For the ND group of the Auckland excursions, the K-Ar age determined for Puketutu (30±5 ka, $1\sigma$) is in agreement with the reported K-Ar age of Wiri (27±5 ka), thereby confirming that the ND excursional paleomagnetic direction occurred in New Zealand at approximately 30 ka. The $^{14}C$ (uncalibrated) ages reported for Wiri and Crater Hill are 25–30 ka (Polach *et al.*, 1969; Grant-Taylor and Rafter, 1971), which are in agreement with their K-Ar ages. A weighted mean of 29±3 ($1\sigma$) ka is calculated from the two K-Ar ages and, hereafter, is adopted for the age estimate for the ND group of the Auckland excursions. The age estimate of the ND group is distinguishable from the K-Ar ages of the SU and WU groups at the $2\sigma$ level, indicating that at least two excursions occurred in New Zealand (Mochizuki *et al.*, 2004a).

The K-Ar age for McLennan Hills of the SU group is 50±6 ($1\sigma$) ka. A $^{14}C$ (uncalibrated) age of 27 ka is reported for wood samples within the Panmure tuff, which is thought to be older than the lava flows of McLennan Hills (Polach *et al.*, 1969). This $^{14}C$ age is disconcordant with the K-Ar result but is not a direct age estimate for the lava of McLenann Hills. In the present study, the K-Ar age of 50±6 ka is adopted for the age of the SU group since our K-Ar age is a direct age estimate for the lava of McLennan Hills and is also considered to be more reliable than the reported $^{14}C$ age.

Table 2. Summary of the ages and paleomagnetic data for the Auckland geomagnetic excursions.

| Volcano | $N_{DIR}$ | Dec (°) | Inc (°) | $\alpha_{95}$ (°) | VGP Lat (°) | VGP Long (°) | $N_{INT}$ | Intensity $\pm 1\sigma$ ($\mu$T) | VDM $\pm 1\sigma$ ($10^{22}$ A m$^2$) | K-Ar age $\pm 1\sigma$ (ka) | $^{14}$C age (ka) | Directional Group |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Wiri | 57 | −5.1 | 61.6 | 1.6 | 10.2 | 171.0 | 6 | 10.6±1.2 | 1.78±0.20 | 27±5 | 25, 28 | North-Down |
| Crater Hill | 67 | −7.3 | 62.5 | 1.8 | 8.9 | 169.5 | 6 | 11.8±2.8 | 1.96±0.47 | — | 29, 30 | North-Down |
| Puketutu | 40 | 3.5 | 62.3 | 2.4 | 9.4 | 177.3 | 5 | 11.1±0.4 | 1.85±0.07 | 30±5 | — | North-Down |
| Mt Richmond | 17 | −14.4 | 62.5 | 3.4 | 8.2 | 164.4 | — | — | — | — | — | North-Down |
| Taylor Hill | 23 | −18.4 | 58.0 | 3.7 | 12.5 | 160.2 | — | — | — | — | — | North-Down |
| Hampton Park | 18 | 260.4 | −36.4 | 2.6 | 4.7 | 63.1 | 6 | 9.5±1.2 | 2.11±0.27 | 55±5 | — | West-Up |
| Otara Hill | 8 | 248.6 | −43.8 | 4.1 | −0.2 | 52.0 | — | — | — | — | — | West-Up |
| McLennan Hills | 20 | 162.1 | −20.8 | 3.7 | −39.5 | 331.8 | 5 | 2.5±0.5 | 0.62±0.12 | 50±6 | <27 | South-Up |
| | | | | | | | | | | Weighted mean | 29±3 | North-Down |
| | | | | | | | | | | Weighted mean | 53±4* | South-Up and West-Up |

$N_{DIR}$, number of samples used for calculating each mean paleodirection; Dec, declination; Inc, inclination; VGP Lat., virtual geomagnetic pole latitude; VGP Long., VGP longitude; NINT, number of samples used for calculating each mean paleointensity; VDM, virtual dipole moments.
Paleodirectional data are compiled from those of Shibuya *et al.* (1992), Mochizuki *et al.* (2006), and Cassidy (2006). Paleointensities are from Mochizuki *et al.* (2006). K-Ar ages are from Mochizuki *et al.* (2004a) and this study. The $^{14}$C (uncalibrated) ages reported are also tabulated (see text).
*Note that this is a weighted mean age for the South-Up and West-Up groups. This age is used if we assume that these two groups are the records of the same excursion. Details are explained in the text.

The age of the SU group is distinguishable from the age of the ND group (29±3 ka) at the 2$\sigma$ level, while it is indistinguishable from that of the WU group (55±5 ka). These age data suggest that the SU group may be of the same excursional record as the WU group. If the SU and WU groups are the record of a single excursion, a weighted mean age of 53±4 (1$\sigma$) ka can be used to estimate the age of this excursion (SU-WU group). For the Auckland excursions, the ND and SU-WU groups are considered to occur at about 29 and 53 ka, respectively.

The paleointensities reported for the SU and WU groups are 2.5±0.5 (1$\sigma$) and 9.5±1.2 $\mu$T, respectively, and the paleodirections deviate by about 150° (Table 2). The differences in paleointensity and paleodirection suggest a variable weak geomagnetic field during the excursion which cannot be explained by an excursion model assuming a large change in the direction of a constant dipole field. We will come back to this point later in this report.

As noted above, it is plausible to regard the SU and WU groups as records of a single excursion since the mean K-Ar ages of these groups are indistinguishable. However, we cannot completely exclude the possibility that these two groups may record two distinct excursions. If the latter is the case, the ND, SU, and WU groups occurred at about 29, 50 and 55 ka, respectively, although the interval between the ages of the SU and WU groups (approx. 5000 years) is not much more than estimated durations for geomagnetic excursions (1500–2000 years; Benson *et al.*, 2003; Laj *et al.*, 2006).

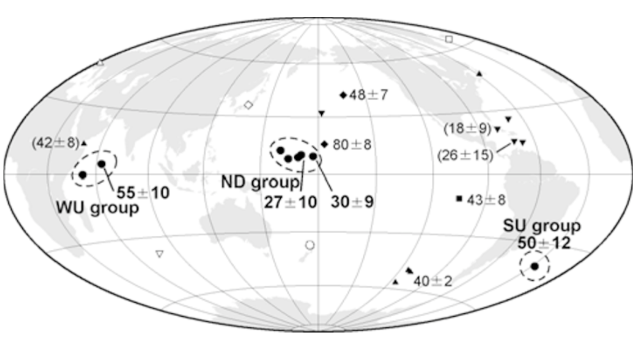


Fig. 2. The revised equal area projection of virtual geomagnetic poles (VGPs) of the Auckland geomagnetic excursions and other young (≤80 ka) excursions reported from volcanic rocks. Closed symbols denote the VGPs and open symbols denote the corresponding sites. Available weighted mean K-Ar and/or $^{40}$Ar/$^{39}$Ar ages with two standard errors are also shown with the VGPs. Single age data with two experimental errors are in parentheses. These plots are composed of the Auckland excursions (circles: Table 2), the Laschamp excursion (triangles: Bonhomet and Zähringer, 1969; Roperch *et al.*, 1988; Chauvin *et al.*, 1989; Guillou *et al.*, 2004), the Skalamaelifell excursion (squares: Marshall *et al.*, 1988; Levi *et al.*, 1990), the Amsterdam excursion (inverse triangles: Watkins and Nougier, 1973; Carvallo *et al.*, 2003), and the Ontake excursion (diamonds: Tanaka and Kobayashi, 2003). ND, SU, and WU denote north-down, south-up and west-up, respectively.

## 6. Discussion

### 6.1 Comparison with the Laschamp excursion data

We compared the ages of the Auckland excursions with the latest age estimate of the Laschamp excursion (40.4±1.0 ka, 1$\sigma$: Guillou *et al.*, 2004). The age of the ND group (29±3 ka, 1$\sigma$) is distinguishable from the age of the Laschamp excursion at the 2$\sigma$ level. The age estimate for the SU-WU group is 53±4 ka (1$\sigma$) and is also distinguishable from the age of the Laschamp excursion at the 2$\sigma$ level. These age data suggest that the ND and the SU-WU group of the Auckland excursions are not correlated with the Laschamp excursion.

It has been suggested that at least three excursions occurred with an interval of about $10^4$ years. Recent studies suggest that more than 20 excursions can be recognized in the Brunhes chron (e.g. Oda *et al.*, 2004), giving an average rate of one excursion per $4\times10^4$ years. Thus, the interval between 29 and 53 ka is likely to be a period of a relatively high excursion rate.

One may consider that VGP positions can be used for to correlate excursions at different localities (Fig. 2). However, the geomagnetic field during an excursion is likely to be complex; in other words, it will not be well represented by a simple dipole field (Merrill and McFadden, 2005). We therefore did not use the VGP positions for the purpose of correlating the Auckland excursions and those elsewhere.

### 6.2 Comparison with other excursional data

A detailed discussion of the other excursions with ages between approximately 29 and 55 ka is given in Mochizuki *et al.* (2004a). The ND group of the Auckland excursions is considered to be reliable evidence for the approximately

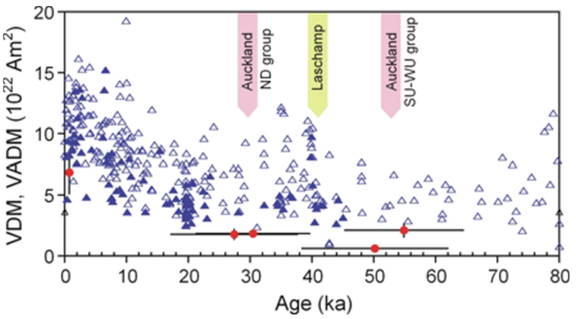


Fig. 3. Virtual dipole moments (VDMs) (virtual axial dipole moments, VADMs) versus ages on the basis of results of the present study (closed circles), the selected data from the PINT2003 database (open triangles), and the microwave data from SOH1 (Gratton *et al.*, 2005: solid triangles) for the past 80 ka. Error bars are $2\sigma$. The upper labels denote the mean ages for the ND group and for the combined group of the SU and WU groups of the Auckland excursions (see details in text) and the latest age estimate for the Laschamp excursion.

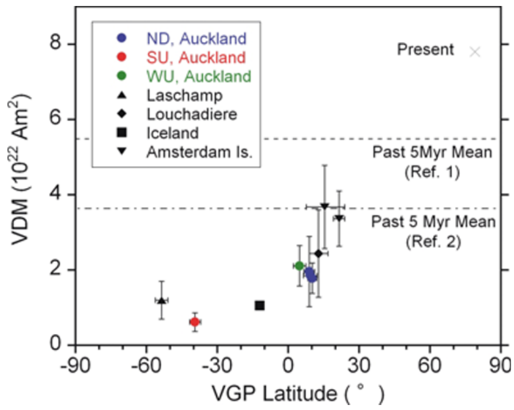


Fig. 4. The relation between VDMs and VGP latitudes of the Auckland geomagnetic excursions and other excursions reported from volcanic rocks of younger than 80 ka. Dashed line and dotted line denote the past 5 Myr mean VADMs (Ref. 1: Juarez and Tauxe, 2000; Ref. 2: Yamamoto and Tsunakawa, 2005).

30 ka geomagnetic excursion that is contemporary with the Mono Lake excursion dated at approximately 30 ka (Benson *et al.*, 2003; Mankinen and Wentworth, 2004).

The SU-WU group of Auckland excursions is older than the Laschamp excursion by about $10^4$ years. A few excursions of similar age have been reported from other areas, such as a lava flow dated to $48\pm4$ ($1\sigma$) ka on the Ontake volcano in Japan (Tanaka and Kobayashi, 2003).

Excursions occurred repeatedly in New Zealand, the Arctic Ocean, and North America between 30 and 60 ka. Since low virtual dipole moments (VDMs) of $0.6–2.1\times10^{22}$ A m$^2$ were reported for the Auckland excursions (Mochizuki *et al.*, 2006), multiple dipole low periods are considered to have occurred in this interval. This is also suggested from a sedimentary record from the western Equatorial Pacific. Four relative paleointensity drops between 30 and 60 ka were found from a sedimentary sequence in the Southern Papua New Guinea margin (Blanchet *et al.*, 2006). Their ages were estimated to 31, 37, 45, and 48 ka, respectively, where the third and fourth ones are estimated on the basis of a constant sedimentation rate between the 36 ka $^{14}$C age (calibrated) and the 59 ka marine isotope stage boundary 3/4.

### 6.3 Implications for the excursional fields based on the ages and paleointensities

The paleointensities and ages of the Auckland excursions are compared with the available paleointensity datasets (Fig. 3) in order to clarify the characteristics of the geomagnetic excursion. From the PINT 2003 paleointensity database (Perrin and Schnepp, 2004), we selected mean paleointensities measured by the Thellier method with pTRM checks, with a flow mean error of less than 20% and a minimum of two samples per flow mean. From the microwave paleointensity data of SOH1 (Gratton *et al.*, 2005), we selected the mean paleointensities with inclination on the basis of the same criteria noted above. The Thellier data are generally higher than the microwave data (Gratton *et al.*, 2005), with some of the difference possibly explained by overestimation by the Thellier method (e.g. Yamamoto *et al.*, 2003; Mochizuki *et al.*, 2004b; Oishi *et al.*, 2005). We therefore use the general trend in those VDMs or the virtual axial dipole moments (VADMs). As shown in Fig. 3, the strength of the geomagnetic field seems to be relatively weak over the entire period between 20 and 70 ka (Mankinen and Champion, 1993; Laj and Kissel, 1999; Laj *et al.*, 2002; Teanby *et al.*, 2002). For the weak dipole period of 20–70 ka, three excursions are inferred from volcanic rocks in New Zealand and France to have occurred at 29, 40, and 53 ka, yielding particularly weak VDMs of $2\times10^{22}$ A m$^2$ or less (Roperch *et al.*, 1988; Mochizuki *et al.*, 2006). These paleointensity data suggest that the reduction of the dipole field is characteristic for the excursions.

There are two possible causes of the excursional fields: (1) a large change in the direction of the dipole field, and (2) a combination of a reduced dipole field and comparable non-dipole components (e.g. Merrill and McFadden, 2005). The diagram of VDMs versus VGP latitudes for geomagnetic excursions reported from volcanic rocks younger than 80 ka is shown in Fig. 4. This figure suggests that the larger VGP deviations from the geographic pole are related to the lower VDMs, which may support the excursion model (2) of a reduced dipole and comparable non-dipole components.

New values of mean VDM or VADM have been reported recently using the improved paleointensity method and/or the strict selection criteria. If we compare the VDMs of the Auckland excursions with the past 5 Myr mean VADM ($3.64\times10^{22}$ A m$^2$; Yamamoto and Tsunakawa, 2005), where all of these values are determined by the LTD-DHT Shaw paleointensity method, the reduction of the dipole component for the excursional fields is estimated as 1/6–1/2. If we use a past 5 Myr mean VADM from the Thellier paleointenisty data set ($5.49\times10^{22}$ A m$^2$; Juarez and Tauxe, 2000), the reduction of the dipole component is estimated as 1/9–1/3.

## 7. Conclusions

We have newly obtained K-Ar ages of two volcanoes recording the Auckland geomagnetic excursions. On the basis of all the available K-Ar ages and paleomagnetic data of the Auckland excursions, we conclude the following.

(1) The K-Ar age of 30±5 ($1\sigma$) ka newly obtained for the Puketutu volcano of the ND group agrees well with that of the Wiri volcano (27±5 ka; Mochizuki *et al.*, 2004a) of the same group. These two ages give a weighted mean of 29±3 ka for an age estimate of the ND group. The K-Ar age of 50±6 ka is newly determined for the McLennan Hills volcano of the SU group. The age of the ND group is distinguishable from those of the SU group (50±6 ka) and the WU group (55±5 ka; Mochizuki *et al.*, 2004a) at the $2\sigma$ level, indicating that the Auckland excursions comprise at least two different excursions.

(2) If the SU and WU groups record a single excursion, a weighted mean age of 53±4 ka can be used as the best estimated age. However, we cannot completely exclude the possibility that these two groups record distinct excursions.

(3) The age of the ND group (29±3 ka) of the Auckland excursions is distinguishable from the latest age estimate of the Laschamp excursion. Also, the age of the SU-WU group (53±4 ka) recognized in Auckland can be distinguishable from the age of the Laschamp. Overall, these age data show that at least three excursions are recognized from volcanic rocks of ages between approximately 30 and 60 ka.

(4) The three excursions are likely to be confined to the weak dipole interval of 20–70 ka, and all of the three excursions yielded particularly weak VDMs of $2\times10^{22}$ A m$^2$ or less. Since it has been suggested that the larger VGP deviations from the geographic pole are related to the lower VDMs, the excursional fields possibly have resulted from a significantly reduced dipole field and comparable non-dipole components.

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## References


Allen, S. R. and I. E. M. Smith, Eruption styles and volcanic hazard in the Auckland volcanic Field, New Zealand, *Geosci. Repts. Shizuoka Univ.*, **20**, 5–14, 1994.

Barbetti, M. F. and M. W. McElhinny, The Lake Mungo geomagnetic excursion, *Philos. Trans. R. Soc. A*, **281**, 515–542, 1976.

Benson, L., J. Liddicoat, J. Smoot, A. Sarna-Wojcicki, R. Negrini, and S. Lund, Age of the Mono Lake excursion and associated tephra, *Quat. Sci. Rev.*, **22**, 135–140, 2003.

Bonhommet, N. and J. Zähringer, Paleomagmetsim and potassium argon age determinations of the Laschamp geomagnetic polarity event, *Earth Planet. Sci. Lett.*, **6**, 43–46, 1969.

Blanchet, C., N. Thouveny, and T. Garidel-Thoron, Evidence for multiple paleomagnetic intensity lows between 30 and 50 ka BP from a western Equatorial Pacific sedimentary sequence, *Quat. Sci. Rev.*, **25**, 1039–1052, 2006.

Cassidy, J., Geomagnetic excursion captured by multiple volcanoes in a monogenetic field, *Geophys. Res. Lett.*, **33**, L21310, doi:10.1029/2006GL027284, 2006.

Carvallo, C., P. Camps, G. Ruffet, B. Henry, and T. Poidras, Mono Lake or Laschamp geomagnetic excursion event recorded from lava flows in Amsterdam Island (southern Indian Ocean), *Geophys. J. Int.*, **154**, 767–782, 2003.

Chauvin, A., R. A. Duncan, N. Bonhommet, and S. Levi, Paleointensity of the earth's magnetic field and K-Ar dating of the Louchadiere volcanic flow (Central France). New evidence for the Laschamp excursion, *Geophys. Res. Lett.*, **16**, 1189–1192, 1989.

Dalrymple, G. B. and M. A. Lanphere, *Potassium-Argon Dating*, 258 pp., San Francisco, 1969.

Denham, C. R. and A. Cox, Evidence that the Laschamp polarity event did not occur 13,300–30,400 years ago, *Earth Planet. Sci. Lett.*, **13**, 181–190, 1971.

Grant-Taylor, T. L. and T. A. Rafter, New Zealand Radiocarbon age measurements—6, *N. Z. J. Geol. Geophys.*, **14**, 364–402, 1971.

Gratton, N. M, J. Shaw, and E. Herrero-Bervera, An absolute palaeointensity record from SOH1 lava core, Hawaii using the microwave technique, *Phys. Earth Planet. Inter.*, **148**, 193–214, 2005.

Guillou, H., B. S. Singer, C. Laj, C. Kissel, S. Scaillet, and B. R. Jicha, On the age of the Laschamp geomagnetic excursion, *Earth Planet. Sci. Lett.*, **227**, 331–343, 2004.

Itaya, T. and K. Nagao, K-Ar age determination of volcanic rocks younger than 1 Ma, *Mem. Soc. Geol. Jpn.*, **29**, 143–161, 1988 (in Japanese with English abstract).

Juarez, M. T. and L. Tauxe, The intensity of the time-averaged geomagnetic field: the last 5 Myr, *Earth Planet. Sci. Lett.*, **175**, 169–180, 2000.

Kent, D. V., S. R. Hemming, and B. D. Turrin, Laschamp Excursion at Mono Lake?, *Earth Planet. Sci. Lett.*, **197**, 151–164, 2002.

Kermode, L. O., Geology of the Auckland urban area, Scale 1:50 000, Institute of Geological and Nuclear Sciences geological map 2, 63 pp., 1 map, Institute of Geological and Nuclear Sciences Ltd, Lower Hutt, New Zealand, 1992.

Laj, C. and C. Kissel, Geomagnetic field intensity at Hawaii for the last 420 kyr from the Hawaii Scientific Drilling Project core, Big Island, Hawaii, *J. Geophys. Res.*, **104**, 15317–15338, 1999.

Laj, C., C. Kissel, V. Scao, J. Beer, D. M. Thomas, H. Guillou, R. Muscheler, and G. Wagner, Geomagnetic intensity and inclination variations at Hawaii for the past 98 kyr from core SOH-4 (Big Island): a new study and a comparison with existing contemporary data, *Phys. Earth Planet. Inter.*, **129**, 205–243, 2002.

Laj, C., C. Kissel, and A. P. Roberts, Geomagnetic field behavior during the Iceland Basin and Laschamp geomagnetic excursions: A simple transitional field geometry?, *Geochem. Geophys. Geosyst.*, **7**, Q03004, doi:10.1029/2005GC001122, 2006.

Levi, S., H. Audunsson, R. A. Duncan, L. Kristjansson, P.-Y. Gillot, and S. P. Jakobsson, Late Pleistocene geomagnetic excursion in Icelandic lavas: confirmation of the Laschamp geomagnetic excursion, *Earth Planet. Sci. Lett.*, **96**, 443–457, 1990.

Mankinen, E. A. and D. E. Champion, Latest Pleistocene and Holocene geomagnetic paleointensity on Hawaii, *Science*, **262**, 412–416, 1993.

Mankinen, E. A. and C. M. Wentworth, Mono Lake excursion recorded in sediment of the Santa Clara Valley, Calfornia, *Geochem. Geophys. Geosyst.*, **5**, Q02H05, doi:10.1029/2003GC000592, 2004.

Marshall, M., A. Chauvin, N. Bonhommet, Preliminary paleointensity measurements and detailed magnetic analyses of basalts from the Skalamaelifell excursion, southwest Iceland, *J. Geophys. Res.*, **93**, 11681–11698, 1988.

Matsumoto, A., Improvement for determination of potassium in K-Ar dating, *Bull. Geol. Surv. Jpn.*, **40**, 65–70, 1989 (in Japanese with English abstract).

Matsumoto, A., K. Uto, and K. Shibata, K-Ar dating by peak comparison method: new technique applicable to rocks younger than 0.5 Ma, *Bull. Geol. Surv. Jpn.*, **40**, 565–557, 1989a.

Matsumoto, A., K. Uto, and K. Shibata, Argon Isotopic Ratios in Histric Lavas—importance of correction for the initial argon in K-Ar dating of young volcanic rocks, *Mass Spectr.*, **37**, 353–363, 1989b (in Japanese with English abstract).

McDougall, I., H. A. Polach, and J. J. Stipp, Excess radiogenic argon in young suaerial basalts from the Auckland volcanic field, New Zealand, *Geochim. Coschim. Acta*, **33**, 1485–1520, 1969.

Merrill, R. T. and P. L. McFadden, The use of magnetic field excursions in stratigraphy, *Quat. Res.*, **63**, 232–237, 2005.

Mochizuki, N., H. Tsunakawa, H. Shibuya, T. Tagami, A. Ozawa, J. Cassidy, and I. E. M. Smith, K-Ar ages of the Auckland geomagnetic excursions, *Earth Planet. Space*, **56**, 283–288, 2004a.

Mochizuki, N., H. Tsunakawa, Y. Oishi, S. Wakai, K. Wakabayashi, and Y. Yamamoto, Palaeointensity study of the Oshima 1986 lava in Japan: implications for the reliability of the Thellier and LTD-DHT Shaw method, *Phys. Earth Planet. Inter.*, **146**, 395–416, 2004b.

Mochizuki, N., H. Tsunakawa, H. Shibuya, J. Cassidy, and I. E. M. Smith, Palaeointensities of the Auckland geomagnetic excursions by the LTD-

DHT Shaw method, *Phys. Earth Planet. Inter.*, **154**, 168–179, 2006.

Oda, H., M. J. Dekkers, C. G. Langereis, L. Lourens, and D. Heslop, A paleomagnetic record of the last 640 kyr from an eastern Medieterranean piston core and a review of geomagnetic excursions in the Brunhes, *EOS Trans. AGU*, **85**, GP41B-08 (Abstract), 2004.

Oishi, Y., H. Tsunakawa, N. Mochizuki, Y. Yamamoto, K. Wakabayashi, and H. Shibuya, Validity of the LTD-DHT Shaw method and Thellier palaeointensity methods: a case study of the Kilauea 1970 lava, *Phys. Earth Planet. Inter.*, **149**, 243–257, 2005.

Ozawa, A., T. Tagami, and H. Kamata, Ar isotopic composition of some Hawai'ian historical lavas, *Chem. Geol.*, **226**, 66–72, 2006.

Perrin, M. and E. Schnepp, IAGA paleointensity database: distribution and quality of the data set, *Phys. Earth Plant. Inter.*, **147**, 255–267, 2004.

Polach, H. A., J. Chappell, and J. F. Lovering, ANU radiocarbon date list III, *Radiocarbon*, **11**, 245–262, 1969.

Roperch, P., N. Bonhommet, and S. Levi, Paleointensity of the earth's magnetic field during the Laschamp excursion and its geomagnetic implications, *Earth Planet. Sci. Lett.*, **88**, 209–219, 1988.

Shane, P., Maar drilling provides new insights into late Quaternary volcanism and paleoclimate in Auckland (Abstracts), GSNZ Annual Conference Northland 2002, *Geol. Soc. N.Z. Misc. Publ.*, **112A**, 50, 2002.

Shibuya, H., J. Cassidy, I. E. M. Smith, and T. Itaya, A geomagnetic excursion in the Brunhes epoch recorded in New Zealand basalts, *Earth Planet. Sci. Lett.*, **111**, 41–48, 1992.

Smith, I. E. M., Northland, in *Intraplate volcanism in eastern Australia and New Zealand*, edited by R. W. Johnson, pp. 157–162, Cambridge University Press, Cambridge, 1989.

Takaoka, N., K. Konno, Y. Oba, and T. Konda, K-Ar dating of lavas from Zao Volcano, Northeastern Japan, *J. Geol. Soc. Jpn.*, **95**, 157–170, 1989.

Tanaka, H. and T. Kobayashi, Paleomagnetism of the late Quaternary Ontake Volcano, Japan: directions, intensities, and excursions, *Earth Planet. Space*, **55**, 189–202, 2003.

Teanby, N., C. Laj, D. Gubbins, and M. Pringle, A detailed palaeointensity and inclination record from drill core SOH1 on Hawaii, *Phys. Earth Planet. Inter.*, **131**, 101–140, 2002.

Tsunakawa, H. and J. Shaw, The Shaw method of palaeointensity determinations and its application to recent volcanic rocks, *Geophys. J. Int.*, **118**, 781–787, 1994.

Verosub, K. L. and S. K. Banerjee, Geomagnetic excursions and their paleomagnetic record, *Rev. Geophys. Space Phys.*, **15**, 145–155, 1977.

Watkins, N. D. and J. Nougier, Excursions and secular variation of the Brunhes epoch geomagnetic field in the Indian Ocean region, *J. Geophys. Res.*, **78**, 6060–6068, 1973.

Yamamoto, Y. and H. Tsunakawa, Geomagnetic field intensity during the last 5 Myr: LTD-DHT Shaw palaeointensities from volcanic rocks of the Society Islands, French Polynesia, *Geophys. J. Int.*, **162**, 79–114, 2005.

Yamamoto, Y., H. Tsunakawa, and H. Shibuya, Palaeointensity study of the Hawaiian 1960 lava: implications for possible causes of erroneously high intensities, *Geophys. J. Int.*, **153**, 263–276, 2003.

Zimmerman, S., S. R. Hemming, D. V. Kent, and S. Y. Searle, Revised chronology for late Pleistocene Mono Lake sediments based on paleointensity correlation to the global reference curve, *Earth Planet. Sci. Lett.*, **252**, 94–106, 2006.

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