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Palaeointensities of the Auckland geomagnetic excursions by the LTD-DHT Shaw method

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Abstract

We report new palaeointensity results concerning the Auckland geomagnetic excursions using the double heating technique of the Shaw method with low temperature demagnetisation (LTD-DHT Shaw method). The excursional palaeodirections recorded in six volcanoes of the Auckland volcanic field, New Zealand, have been classified into three groups: north-down (ND), west-up (WU) and south-up (SU) directions. In the present study, five to six consistent palaeointensities have been obtained from each of five volcanoes recording the Auckland geomagnetic excursions. The Wiri (27 ka), Crater Hill and Puketutu volcanoes (ND group) yielded mean palaeointensities of 10.6 ± 1.2 (1σ), 11.8 ± 2.8 and 11.1 ± 0.4 μT, respectively. The Hampton Park volcano (55 ka; WU group) gave 9.5 ± 1.2 μT while the McLennan Hills volcano (SU group) gave 2.5 ± 0.5 μT. It is notable that consistent palaeointensities have been obtained from the three different volcanoes which have almost the same palaeodirections (ND group), possibly supporting the reliability of the palaeointensity data. These five palaeointensities for the Auckland geomagnetic excursions correspond to virtual dipole moments (VDMs) of $0.6–2.1 \times 10^{22}$ A m^2, whereas three mean palaeointensities obtained from the Auckland volcanoes having non-excursional palaeodirections are 13.1–40.0 μT giving stronger VDMs of $2.1–6.9 \times 10^{22}$ A m^2. These results suggest that the dipole component of the geomagnetic field reduced to about 2×10^{22} A m^2 or less during the Auckland geomagnetic excursions.

Keywords: Geomagnetic excursion; Palaeointensity; LTD-DHT Shaw method; Auckland

1. Introduction

Geomagnetic excursions are characterised by a swing of the palaeomagnetic field direction which is apparently larger than palaeosecular variation, but distinct from polarity reversals, and which occurs within a short period (e.g. 1500 years, Laj et al., 2000). 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 VGP departure in latitude is taken as 45° (e.g. Verosub and Banerjee, 1977) and other values (e.g. 40°: Barbetti and McElhinny, 1976).

A number of well-documented excursions at about 20–50 ka have been identified from volcanic and sedimentary rocks, for example in France (Bonhommet and Zähringer, 1969), Iceland (Kristjansson and Gudmundsson, 1980) and western North America

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(Denham and Cox, 1971), which are of importance for investigating the geomagnetic field behaviors during excursions. For the Laschamp excursion in France, most recently dated as 40.4 ± 2.0 ka (2σ, Guillou et al., 2004), and the Skalamaelifell excursion in Iceland at 42.9 ± 7.8 ka (2σ, Levi et al., 1990), the absolute palaeointensities reported were 4.2–13.9 μT which are less than one-third of the present-day field intensities (Roperch et al., 1988; Marshall et al., 1988; Chauvin et al., 1989; Levi et al., 1990). The geomagnetic field during excursions has been implicitly regarded as very weak on a global scale compared to the present-day value. For a better understanding of geomagnetic excursions, it is necessary to obtain palaeomagnetic and age data from volcanic rocks over a wider geographical area.

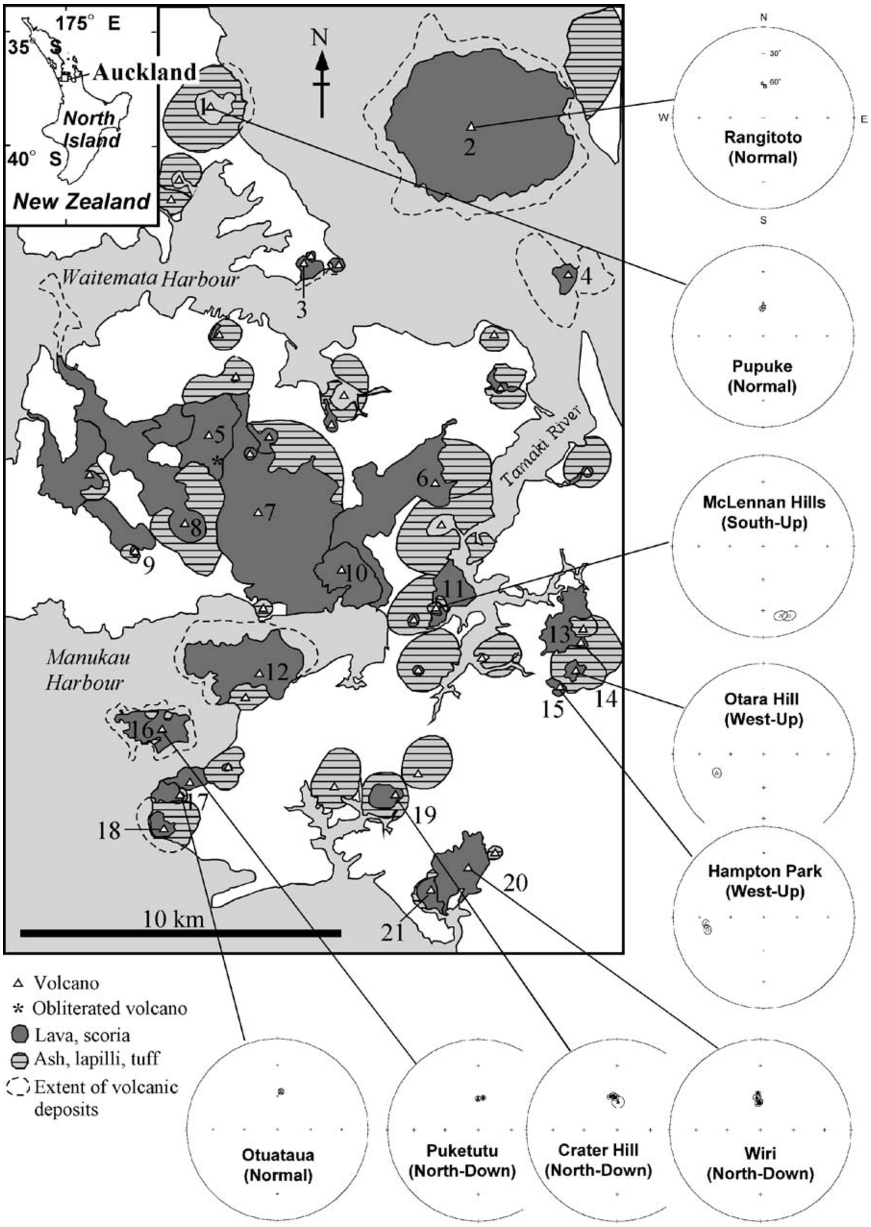

Fig. 1. Map of volcanoes in the Auckland volcanic field. Triangles indicate eruption centres of monogenetic volcanoes. Numbers are attached to 21 volcanoes studied by Shibuya et al. (1992). This map is modified from Kermode (1992). Equal area projections show palaeomagnetic directions from eight volcanoes used in this palaeointensity study and the Otara Hill volcano. Circles, the palaeomagnetic directions in this study; triangles, those in Shibuya et al. (1992).

Shibuya et al. (1992) first reported excursional palaeomagnetic field directions from six volcanoes, which were dated approximately between 20 and 50 ka, in the Auckland volcanic field, New Zealand (Fig. 1). Those excursional palaeodirections were classified into three groups: a north-down excursional palaeodirection from three volcanoes (ND group), a west-up from two volcanoes (WU group) and a south-up from one volcano (SU group). Mochizuki et al. (2004a) determined K-Ar ages for the Wiri volcano (27 ± 10 ka, 2σ) of the ND group and Hampton Park volcano (55 ± 10 ka, 2σ) of the WU group. These ages are statistically distinguishable at 2σ level indicating that the Auckland volcanic field recorded at least two geomagnetic excursions. As the Auckland geomagnetic excursions were recorded in lavas of several volcanoes, it provides an excellent opportunity for a palaeointensity study of the excursional geomagnetic field. It should be noted that three different volcanoes have recorded the ND excursional direction and are approximately aligned on a trend close to the regional NNW-SSE structural trend, suggesting a spacio-temporal link (Cassidy et al., 1999). Therefore, these three volcanoes can be used for an internal consistency check of palaeointensity determinations.

2. Samples

The Auckland volcanic field is one of a number of Pliocene to recent intraplate volcanic fields in the northern North Island, New Zealand (Smith, 1989). The volcanic field comprises about 50 volcanoes within an area of 360 km^2 (Fig. 1) and has been active for the last 250 ka (Allen and Smith, 1994; Shane, 2002). The individual volcanoes are monogenetic, resulting from a single eruption or a very short sequence of eruptions (Kermode, 1992), and rocks of the volcanic field are mostly alkali basalt and basanite though lavas from Rangitoto volcano are transitional to tholeiitic (Smith, 1989).

K-Ar ages have been determined for two of the volcanoes recording the Auckland excursions: 27 ka for the Wiri volcano (ND group) and 55 ka for the Hampton Park volcano (WU group) (Mochizuki et al., 2004a). For the other volcanoes recording the Auckland excursions, the available ^{14}C and thermoluminescence (TL) ages range between 20 and 50 ka (see Table 3) though their reliabilities are considered to be lower than the present K-Ar ages. Three volcanoes with non-excursional palaeomagnetic directions were also investigated in this study: Pupuke volcano, with a 140 ka TL age (Wood, 1991), Rangitoto volcano with ^{14}C ages of 750 and 770 years BP (Grant-Taylar and Rafter, 1963) and Otuataua volcano (of unknown age). More detailed discussion of these radiometric ages is given in Mochizuki et al. (2004a).

Palaeomagnetic samples are from Shibuya et al. (1992), supplemented with new samples from the present study. The new sampling included five volcanoes which record the Auckland excursions (Wiri, Crater Hill, Puketutu, Hampton Park and McLennan Hills volcanoes) and two volcanoes with non-excursional palaeodirections (Pupuke and Otuataua volcanoes). Rock magnetic and palaeomagnetic results for samples from these seven volcanoes and the Rangitoto volcano (with non-excursional palaeodirection) are presented in Sections 3–5.

All the samples were collected from lava flows, except for a site of welded scoria (NZ211) at Crater Hill volcano. Where possible, multiple sites within a single lava flow were collected to include a wide variation in rock magnetic properties (e.g. high-temperature oxidation states of titanomagnetite grains). For the Wiri volcano, a 10 m high and 100 m wide outcrop was sampled at five sites (NZ201–NZ205), which were horizontally and vertically distributed.

More than eight 1 in. cores were drilled from individual volcanoes by using a portable engine drill, except for the Hampton Park volcano. The cores were orientated by a sun or magnetic compass. For the Hampton Park volcano, 10 block samples were collected from a 20 m wide outcrop with orientation by a magnetic compass, and 1 in. cores were cut in the laboratory.

3. Rock magnetic properties

Thermomagnetic analyses were performed on at least two samples from each volcano with a vibrating sample magnetometer (VSM, Princeton Measurements Corporation MicroMag 3900) in helium gas. Representative thermomagnetic curves of the samples are shown in Fig. 2. These indicate that Curie temperatures of dominant phases are 550–580, 400–500 and 100–200 °C, suggesting titanium-poor to titanium-rich titanomagnetites. Thermomagnetic curves during heating and cooling cycles are nearly reversible except for a few samples. For the Pupuke volcano, a sample from an upper flow of two flows shows an irreversible thermomagnetic curve suggesting the inversion from titanomaghemite to magnetite. For palaeointensity measurements we excluded samples from that flow.

Magnetic hysteresis properties at room temperature were also measured with the VSM. The Day plot (Fig. 3) (Day et al., 1977) shows that most data points are distributed along the theoretical mixing lines of single domain (SD) and multidomain (MD) grains (Dunlop, 2002). According to Oishi et al. (2005), the samples lying

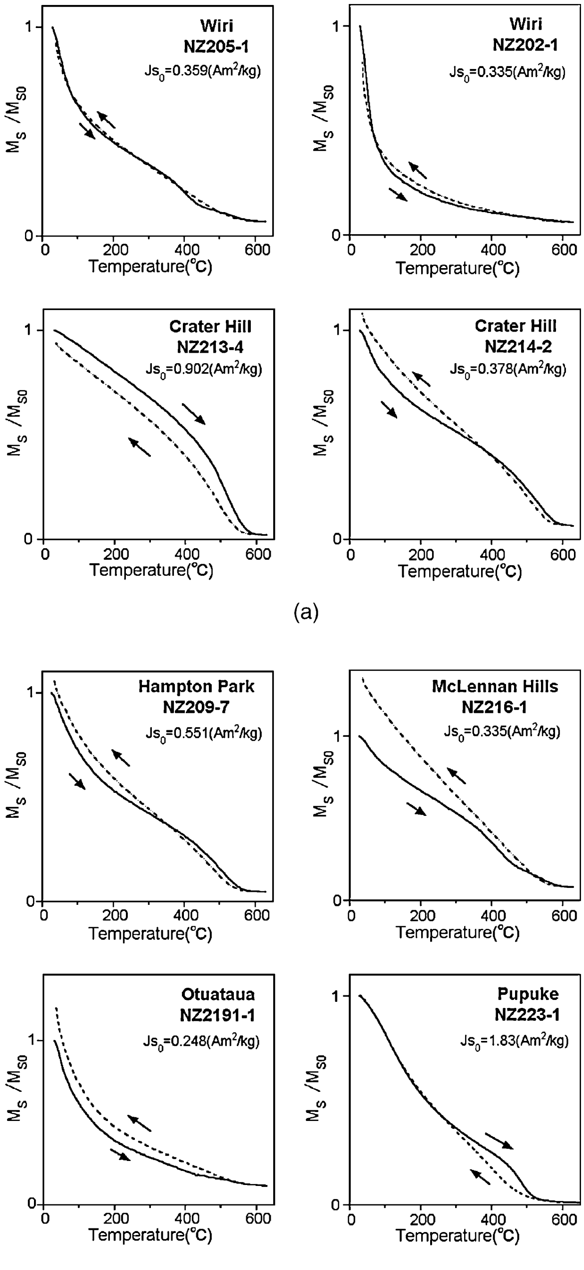

Fig. 2. Representative thermomagnetic curves of the samples from the volcanoes of (a) north-down (ND) group and (b) other directional groups. The vertical axis is saturation magnetisation (M_s) normalised to that at room temperature (M_{s0}). Solid and dashed lines indicate heating and cooling curves, respectively.

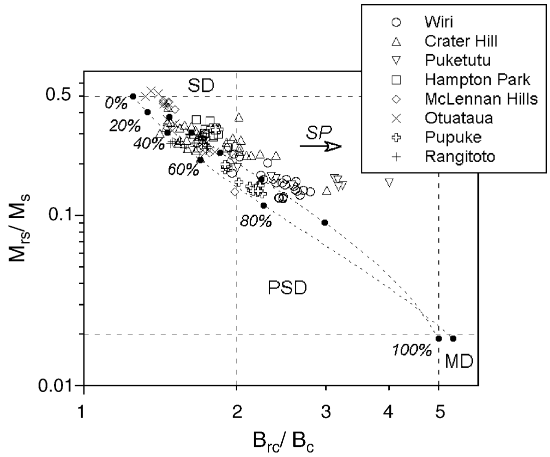

Fig. 3. A Day plot of the samples from the volcanoes in the Auckland volcanic field. M_{rs}, M_s, B_{rc} and B_c stand for saturation remanence, saturation magnetisation, remanent coercivity and coercivity, respectively. SD, single domain; PSD, pseudo-single domain; MD, multidomain. Theoretical mixing lines between SD and MD grains (Dunlop, 2002) are also shown (dashed lines). Solid dots on the dashed lines indicate the volume fractions of MD grains with each 20% interval in all SD and MD grains. An arrow indicates the trend with increase in superparmagnetic (SP) particles.

close to the SD + MD mixing lines might give overestimated intensities in the Thellier method (Thellier and Thellier, 1959).

The polished samples in this study were observed under a reflected-light microscope. Magnetic grains were often seen to have ilmenite lamellae which probably originated from titanium-rich titanomagnetite grains and were oxidised due to high-temperature oxidation during early cooling. More than 20 large magnetic grains (>10 μm) of the polished samples were counted and classified into three groups: oxidation indices of C1, C2–C5 and C6–C7 according to Haggerty (1991), which were characterised by titanomagnetite with no ilmenite lamella, titanomagnetite with ilmenite lamellae and formation of pseudobrookite, respectively. The grains observed were classified into either C1 or C2–C5. No grain was into C6–C7. Backscattered electron images using an electron probe microanalyser (EPMA) for typical grains are shown in Fig. 4. The variability shown by the thermomagnetic curves and their hysteresis properties (Figs. 2 and 3) indicates different degrees of high-temperature oxidation of titanomagnetite grains. Since titanomagnetite grains with intermediate high-temperature oxidation states (oxidation indices of C2–C5) were frequently observed in the samples, these samples seem to be unsuitable for Thellier experiments (Yamamoto et al., 2003; Mochizuki et al., 2004b; Oishi et al., 2005).

4. Palaeodirections

Natural remanent magnetisation (NRM) in the samples was first subjected to low temperature demagneti-

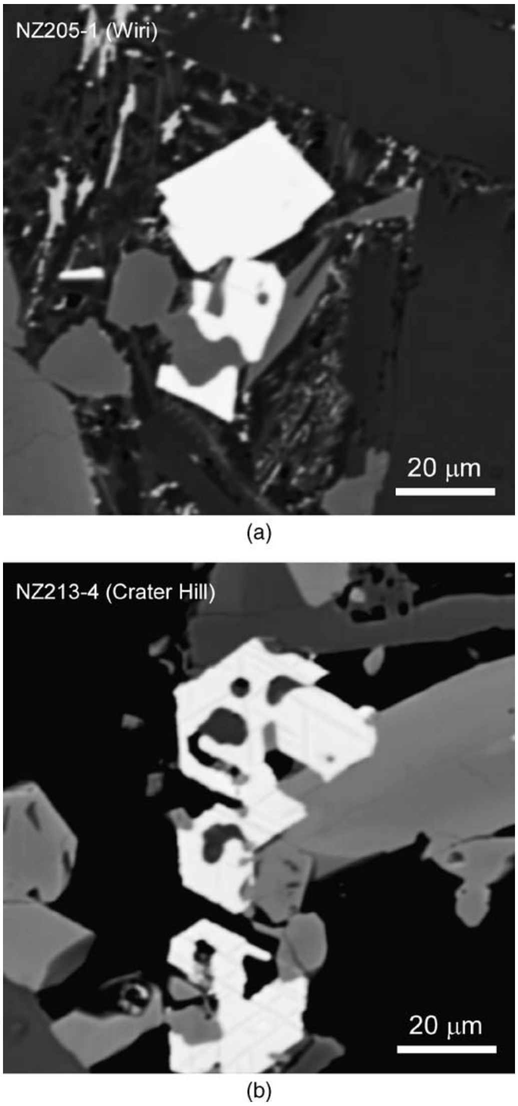

Fig. 4. Backscattered electron images of typical magnetic grains. (a) Titanomagnetites (lighter in colour) with no ilmenite lamella, which are classified into oxidation index of C1. (b) Titanomagnetites (lighter in colour) with ilmenite lamellae (dark), which are classified into oxidation indices of C2–C3.

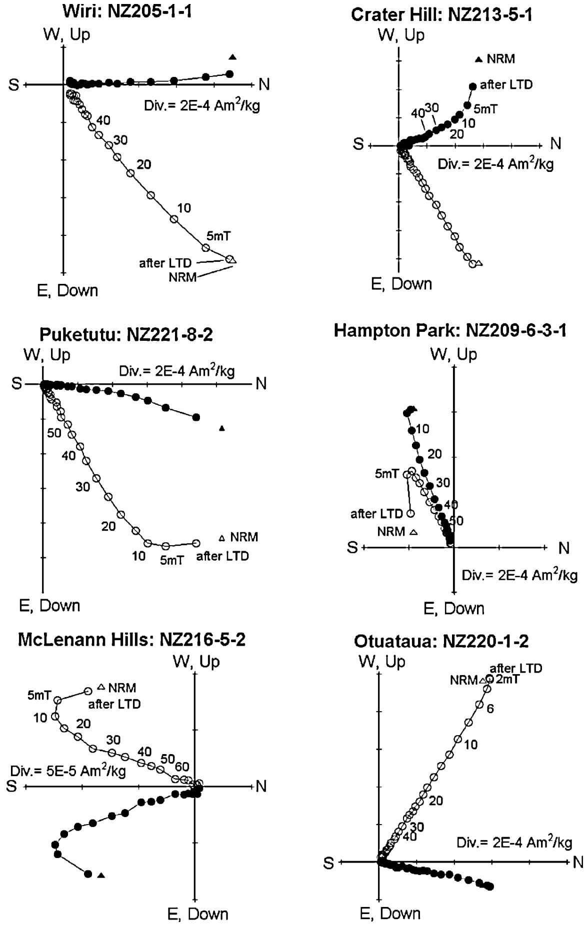

Fig. 5. Representative examples of orthogonal vector plots for LTD and AF demagnetisation of NRM. Closed and open symbols denote horizontal and vertical projections, respectively.

sation (LTD) at liquid nitrogen temperature and subsequently alternating field (AF) demagnetisation up to 140 or 160 mT at 2–10 mT intervals. These procedures were performed in the LTD-DHT Shaw palaeointensity experiments, details of which are described in Yamamoto et al. (2002, 2003).

Unstable, presumably secondary, components were mostly erased by LTD and AF demagnetisation (≤25 mT) as shown in Fig. 5. Consequently, stable components of high coercivity were taken to be primary, the directions of which were analysed by principal component analysis (Kirschvink, 1980). The measured palaeodirections give 95% confidence levels of about 2–5° (Table 1). Since they are almost the same as those reported by Shibuya et al. (1992), the former overall excursional palaeodirections for these volcanoes are reconfirmed in this study (Fig. 1). For the Wiri volcano, however, the mean palaeodirection from this study is distinguishable at the 95% confidence level from Shibuya et al. (1992) at some sites (Table 1). This difference might possibly be caused by rapid changes in the geomagnetic field during the excursion. For the other volcanoes, our data are consistent with those of Shibuya et al. (1992) at the 95% confidence level.

VGP positions calculated from the palaeodirections are also listed in Table 1. Mochizuki et al. (2004a) have compiled the published excursional palaeodirections and point out that there are several VGP clusters: near eastern Africa, central to northern Pacific region

Table 1
Palaeodirectional results of volcanoes recording the Auckland geomagnetic excursions and the non-excursional fields

Volcano	Site	*N*	Dec (°)	Inc (°)	α_{95} (°)	VGP latitude (°)	VGP longitude (°)	Directional group	Ref.
Wiri (37.00S, 174.85E)	045, 190, 191, 192, 202–205	15	355.0	58.0	3.2	14.2	170.8	North-down	a
	045	8	359.2	64.9	2.4	6.1	174.3		b
	190	8	355.2	65.7	3.0	5.1	173.9		b
	191	8	358.5	63.9	2.7	7.3	171.5		b
	192	8	353.8	60.3	3.2	11.8	173.7		b
Crater Hill (36.99S, 174.83E)	047, 048, 193, 194, 211, 213–215	14	352.0	59.3	3.7	12.6	168.5	North-down	a
	048	9	1.8	64.6	5.4	6.5	176.0		b
	193	8	353.8	58.2	2.6	13.9	169.9		b
	194	14	356.3	60.3	3.2	11.7	171.9		b
Puketutu (36.96S, 174.76E)	185, 221	13	8.4	60.4	2.1	11.3	181.2	North-down	a
	185	7	359.3	61.7	2.4	10.2	174.3		b
Hampton Park (36.95S, 174.89E)	209	10	257.8	−36.6	3.7	2.9	61.5	West-up	a
	195	8	263.6	−36.0	3.4	7.0	65.1		b
Otara Hill (36.95S, 174.90E)	183	8	248.6	−43.8	4.1	−0.2	52.0	West-up	b
McLennan Hills (36.92S, 174.85E)	216	12	159.6	−19.6	5.1	−39.2	328.5	South-up	a
	184	8	165.8	−22.4	5.0	−39.6	336.6		b
Otuataua (36.99S, 174.74E)	219, 049	8	5.2	−55.1	2.2	85.6	248.7	Normal	a
	049	8	1.6	−56.1	4.7	88.7	258.0		b
Pupuke (36.79E, 174.76E)	223, 050	11	0.1	−63.8	2.1	81.3	354.2	Normal	a
	050	8	357.8	−65.3	2.4	79.4	2.9		b
Rangitoto (36.77E, 174.89E)	197	13	358.6	−58.7	0.9	87.1	17.2	Normal	b
	199	8	2.9	−61.3	1.5	84.0	−25.9		b

N, number of the measured samples.
[a] This study
[b] Shibuya et al. (1992).

and southern Atlantic region, etc. Most of the VGP clusters fall near the equator and are composed of different sites/ages. Therefore, they suggest that some common factors, which are presumably expressed by some common Gauss coefficients other than the geocentric axial dipole (GAD), control the palaeodirections associated with the excursions.

5. Palaeointensities

5.1. Thellier experiments

Thellier palaeointensity experiments were preliminarily made on the samples from the volcanoes in the Auckland volcanic field (Shibuya et al., 1995). Coe's version of the Thellier method (Thellier and Thellier, 1959; Coe, 1967) was applied to several samples. For most samples, the Arai plots lose linearity over 300 °C where the pTRM checks are negative, suggesting strong thermal alteration by laboratory heating. Also, the NRM vectors deviate towards the laboratory DC field direction above 200 °C. These indicate that chemical remanent magnetisation (CRM) acquisition due to laboratory heating started at relatively low temperature steps. Besides, relatively lower blocking-temperature (T_B) components without laboratory thermal alteration are often affected by secondary components such as viscous remanent magnetisation. As a result, the pure thermoremanent magnetisation (TRM) in NRM is available in quite narrow temperature range, providing no or little fraction of NRM for palaeointensity estimation. Shibuya et al. (1995) tried to correct measurement results of high blocking temperatures for laboratory CRMs applying some assumptions. Although some of the corrected Arai plots seem to give palaeointensity values, those results do not match the modern selection criteria for the palaeoin-

Table 2
Accepted palaeointensity results of the LTD-DHT Shaw method for samples from volcanoes recording the Auckland geomagnetic excursions and the non-excursional fields

Sample	F_L (μT)	NRM (10^{-5} A m^2/kg)	First heating					Second heating					F (μT)
			ΔH (mT)	$Slope_{A1}$	$Slope_N$	f_N	r_N	ΔH (mT)	$Slope_{A2}$	$Slope_T$	f_T	r_T	
Wiri													
NZ045-8-2	20	50.6	10–100	0.784	0.488 ± 0.007	0.722	0.998	0–100	0.724	1.01	1.00	0.996	9.8 ± 0.1
NZ191-1-3s	20	45.0	35–140	0.327	0.462 ± 0.014	0.491	0.995	0–140	0.868	1.04	1.00	0.999	9.2 ± 0.3
NZ191-1-3	20	50.9	15–100	0.468	0.480 ± 0.010	0.667	0.996	0–100	0.818	1.01	1.00	0.998	9.6 ± 0.2
NZ202-1-1	10	89.2	15–100	1.33	3.93 ± 0.07	0.400	0.997	5–100	1.18	0.956	0.831	0.997	39.3 ± 0.7[#]
NZ203-2-1	10	118	45–100	1.01	1.14 ± 0.02	0.150	0.996	5–100	0.927	0.978	0.768	0.998	11.4 ± 0.2
NZ205-1-1	10	131	5–100	0.985	1.15 ± 0.03	0.886	0.996	25–100	1.17	0.968	0.704	0.997	11.5 ± 0.3
NZ205-2-1	10	122	0–100	1.26	1.22 ± 0.03	1.00	0.995	0–100	1.06	1.00	1.00	0.999	12.2 ± 0.3
Mean (N = 6)													10.6 ± 1.2
Crater Hill													
NZ048-2-2	20	163	25–140	0.828	0.571 ± 0.014	0.748	0.996	40–140	1.02	1.05	0.410	0.998	11.4 ± 0.3
NZ193-8-3	20	86.6	10–100	0.791	0.492 ± 0.010	0.863	0.996	0–100	0.846	1.05	1.00	0.998	9.8 ± 0.2
NZ211-5-1	10	339	25–100	0.829	1.63 ± 0.03	0.809	0.998	10–100	1.05	1.04	0.850	0.999	16.3 ± 0.3
NZ213-5-1	10	118	10–100	0.691	0.817 ± 0.011	0.792	0.998	15–100	0.974	0.980	0.930	0.999	8.2 ± 0.1
NZ214-5-1	10	143	10–100	0.872	1.24 ± 0.03	0.516	0.995	5–100	0.847	1.01	1.09	0.999	12.4 ± 0.3
NZ215-2-1	10	100	45–100	0.790	1.29 ± 0.04	0.191	0.995	40–100	0.799	0.959	0.523	0.999	12.9 ± 0.4
Mean (N = 6)													11.8 ± 2.8
Puketutu													
NZ221-3-2	10	84.4	5–100	1.56	1.07 ± 0.02	0.826	0.995	20–100	0.927	0.951	0.732	0.999	10.7 ± 0.2
NZ221-3-3	10	99.3	15–100	1.09	1.09 ± 0.02	0.513	0.996	0–100	0.887	0.967	1.00	0.999	10.9 ± 0.2
NZ221-4-1	10	107	5–100	1.50	1.14 ± 0.02	0.747	0.997	40–100	0.863	0.961	0.486	0.999	11.4 ± 0.2
NZ221-4-3	10	110	15–100	1.11	1.16 ± 0.03	0.514	0.995	0–100	0.879	0.972	1.00	1.00	11.6 ± 0.3
NZ221-8-2	10	139	25–100	0.932	1.07 ± 0.02	0.568	0.998	0–100	0.916	0.950	1.00	0.999	10.7 ± 0.2
Mean (N = 5)													11.1 ± 0.4
Hampton Park													
NZ209-1-3-1	10	90.5	15–100	0.941	0.961 ± 0.022	0.726	0.996	60–100	1.13	0.980	0.315	0.995	9.6 ± 0.2
NZ209-1-4-1	10	62.6	15–100	1.13	0.876 ± 0.016	0.991	0.997	0–100	0.922	1.00	1.00	0.999	8.8 ± 0.2
NZ209-6-1-1	20	77.5	15–100	0.741	0.552 ± 0.012	0.689	0.996	55–100	1.00	0.951	0.315	0.996	11.0 ± 0.2
NZ209-6-3-1	10	64.5	15–100	0.931	0.812 ± 0.012	0.863	0.998	0–100	0.852	1.03	1.00	0.998	8.1 ± 0.1
NZ209-6-4-1	10	50.2	15–100	0.957	0.873 ± 0.017	0.831	0.997	0–100	1.03	0.993	1.00	0.999	8.7 ± 0.2
NZ209-7-1-1	10	121	0–100	0.770	1.09 ± 0.02	1.00	0.996	0–100	1.17	1.01	1.00	0.995	10.9 ± 0.2
Mean (N = 6)													9.5 ± 1.2

Table 2 (*Continued*)

Sample	F_L (μT)	NRM (10^{-5} A m^2/kg)	First heating					Second heating					F (μT)
			ΔH (mT)	$Slope_{A1}$	$Slope_N$	f_N	r_N	ΔH (mT)	$Slope_{A2}$	$Slope_T$	f_T	r_T	
McLennan Hills													
NZ216-2-2	5	25.4	15–140	0.711	0.346 ± 0.009	0.982	0.995	20–140	1.02	0.951	0.960	0.999	1.7 ± 0.0
NZ216-5-1	10	12.4	35–140	0.610	0.284 ± 0.008	0.478	0.996	50–140	0.926	1.02	0.645	0.999	2.8 ± 0.1
NZ216-5-2	2	14.5	15–140	1.21	1.28 ± 0.03	0.906	0.995	60–140	1.00	1.05	0.637	0.999	2.6 ± 0.1
NZ216-7-1	5	20.0	15–140	1.08	0.537 ± 0.014	0.774	0.995	100–140	1.18	1.04	0.172	0.995	2.7 ± 0.1
NZ216-7-2	2	17.7	20–140	1.13	1.44 ± 0.03	0.714	0.996	0–140	0.945	1.03	1.00	0.998	2.9 ± 0.1
Mean (N = 5)													2.5 ± 0.5
Otuataua													
NZ219-1-2	20	85.9	0–160	0.887	1.28 ± 0.01	1.00	0.998	0–160	0.928	1.05	1.00	0.999	25.6 ± 0.2
NZ219-3-2	20	109	24–160	0.746	1.39 ± 0.01	0.385	0.999	14–160	0.880	0.996	0.598	0.999	27.8 ± 0.2
NZ219-5-1	20	81.8	0–100	0.893	1.32 ± 0.02	1.00	0.998	0–100	0.850	0.964	1.00	1.00	26.4 ± 0.4
NZ219-9-1	20	102	25–100	0.427	1.00 ± 0.02	0.413	0.996	0–100	0.787	0.975	1.00	0.998	20.0 ± 0.4
NZ219-9-2	20	98.9	10–160	0.673	0.933 ± 0.010	0.650	0.998	35–160	0.688	1.05	0.519	0.998	18.7 ± 0.2
NZ220-1-1	20	122	25–100	0.353	1.02 ± 0.02	0.262	0.997	0–100	0.855	0.970	1.00	0.998	20.4 ± 0.4
NZ220-1-2	20	110	6–160	0.578	1.10 ± 0.01	0.863	0.999	0–160	0.837	0.960	1.00	0.999	22.0 ± 0.2
Mean (N = 7)													23.0 ± 3.6
Pupuke													
NZ223-1-1	30	272	40–160	1.01	0.394 ± 0.008	0.172	0.995	40–160	1.02	0.953	0.270	0.996	11.8 ± 0.2
NZ223-2-1	30	270	40–160	1.00	0.417 ± 0.007	0.172	0.997	0–160	0.898	0.961	1.00	0.999	12.5 ± 0.2
NZ223-9-1	30	144	15–160	0.978	0.454 ± 0.009	0.546	0.995	40–160	0.980	0.957	0.249	0.998	13.6 ± 0.3
NZ224-0-1	30	167	15–160	0.993	0.487 ± 0.009	0.519	0.995	45–160	1.01	0.967	0.230	0.998	14.6 ± 0.3
Mean (N = 4)													13.1 ± 1.2
Rangitoto													
NZ197-7-1	50	131	0–160	0.913	0.896 ± 0.007	1.00	0.999	0–160	0.978	0.991	1.00	0.999	44.8 ± 0.4
NZ197-8-1	50	174	0–160	0.974	0.809 ± 0.007	1.00	0.999	0–160	0.983	1.01	1.00	0.998	40.5 ± 0.4
NZ199-5-1	50	208	5–160	0.752	0.692 ± 0.006	0.801	0.999	0–160	0.987	1.01	1.00	1.00	34.6 ± 0.3
Mean (N = 3)													40.0 ± 5.1

ΔH, AF steps taken for the linear portions in the NRM-TRM1* and TRM1-TRM2* diagrams; $Slope_{A1}$ and $Slope_{A2}$, slopes for the portion of ΔH in the ARM0-ARM1 and ARM1-ARM2 diagrams, respectively; $Slope_N$ and $Slope_T$, slopes of the linear portions in the NRM-TRM1* and TRM1-TRM2* diagrams; f_N and f_T, NRM and TRM1 fractions of the linear portions in the these diagrams; r_N and r_T, correlation coefficients of the linear portions in the these diagrams; F_L, laboratory field; F, observed palaeointensity and its error. NZ191-1-3s is an 1cm-diameter core sample cut from NZ191-1-3.

[#] This value is excluded in the average calculation for Wiri because it is distinguishable at 2σ level from the average.

tensity studies on the Arai plots and/or the orthogonal vector plots. Thus, the standard Thellier method is considered to be inappropriate for the samples from the volcanoes in the Auckland volcanic field.

5.2. LTD-DHT Shaw experiments

For the samples used in this study, the double heating technique of the Shaw method with low temperature demagnetisation (LTD-DHT Shaw method: Tsunakawa et al., 1997; Yamamoto et al., 2003) is considered to be more appropriate than the Thellier method because thermal alteration by laboratory heating can be corrected by the ARM correction and also because the secondary components have been erased by the LTD and/or AF demagnetisation as noted in Section 4. Detailed experimental procedures and the selection criteria of the LTD-DHT Shaw method are described elsewhere (Yamamoto et al., 2003; Mochizuki et al., 2004b; Oishi et al., 2005). For most specimens, remanence measurements, AF demagnetisation and anhysteretic remanent magnetisation (ARM) acquisition were carried out with an automated spinner magnetometer with AF demagnetiser (Natsuhara-Giken DSPIN-2). For specimens with relatively weak magnetisation, remanence was measured with a spinner magnetometer with a higher sensitivity (Natuhara-Giken ASPIN-A), and AF demagnetisation was carried out with an AF demagnetiser (Natuhara-Giken DEM8601-C). The samples were heated in a vacuum of 5–100 Pa at 610 °C for 15–20 and 30 min in the first and second heating, respectively. TRM was imparted in a 2–50 μT DC field while ARM was given in a 100 μT DC field with 140 or 160 mT AF.

Ninety samples from the eight volcanoes recording the excursional or non-excursional geomagnetic field were measured by the LTD-DHT Shaw method. Forty-three out of these samples passed the selection criteria. The accepted palaeointensity results are listed in Table 2 and representative examples are shown in Fig. 6. As noted above, the secondary components were easily removed by LTD and AF demagnetisation by 25 mT and thus the resultant high coercivity components can be used for palaeointensity calculation in the NRM-TRM1* diagrams (see Figs. 5 and 6), where TRM1* is TRM in the first heating after the ARM correction (Rolph and Shaw, 1985). The main reasons for rejecting samples are insufficient linearity of NRM-TRM1* diagrams (low correlation coefficient, $r_N < 0.995$) and/or negative double heating check (non-unity of TRM1-TRM2* diagrams, slope_T <0.95 or >1.05, Tsunakawa and Shaw, 1994).

Five to seven palaeointensities were obtained from each of five volcanoes recording the Auckland excursions. These results generally show good internal consistency within each volcano though some samples seem to be slightly curved in the NRM-TRM1* diagrams. It should be stressed that concordant mean palaeointensities are obtained from three different volcanoes of the same ND group: 10.6 ± 1.2 μT (1σ, N = 6) for Wiri, 11.8 ± 2.8 μT (N = 6) for Crater Hill and 11.1 ± 0.4 μT (N = 5) for Puketutu. The good consistency in the palaeointensity results of ND group possibly supports the reliability of the palaeointensities determined in this study. The Hampton Park volcano (WU group) gave an average palaeointensity of 9.5 ± 1.2 μT (N = 6) while the McLennan Hills volcano (SU group) an average of 2.5 ± 0.5 μT (N = 5).

We also obtained mean palaeointensities from three volcanoes with non-excursional palaeodirections: 23.0 ± 3.6 μT (N = 7) for Otuataua, 13.1 ± 1.2 μT (N = 4) for Pupuke and 40.0 ± 5.1 μT (N = 3) for Rangitoto.

No remarkable correlations were found between the palaeointensities and the rock magnetic properties. For Wiri, a palaeointensity from sample NZ202-1-1 was excluded as an outlier in comparison with the other Wiri palaeointensities. Since NZ202-1-1 contains a single phase of Ti-rich titanomagnetite (Fig. 2a), thermal alteration due to laboratory heating may possibly arise an exceptional palaeointensity result. Similar results have been observed in the LTD-DHT Shaw experiments of other volcanic rocks and the multi-specimen test of internal consistency can evaluate those exceptions (Yamamoto et al., 2003; Mochizuki et al., 2004b; Oishi et al., 2005).

As noted above, the Thellier experiments for the samples in this study were failed mainly due to thermal alteration during laboratory heating even at low temperature heating steps. In the LTD-DHT Shaw experiments, thermal alteration of the magnetic grains is corrected by ARM changes, where the sample passes the strict selection criteria including the double heating test. Also, it should be noted that LTD and AF demagnetisation effectively removed the secondary components of the samples in this study.

6. Discussion

The palaeointensity results reported here indicate that all three excursional geomagnetic fields (ND, WU and SU groups) had weak intensities of 2.5–11.8 μT which are ca. 5–20% of the present-day intensity (54 μT). These palaeointensities yielded low virtual dipole

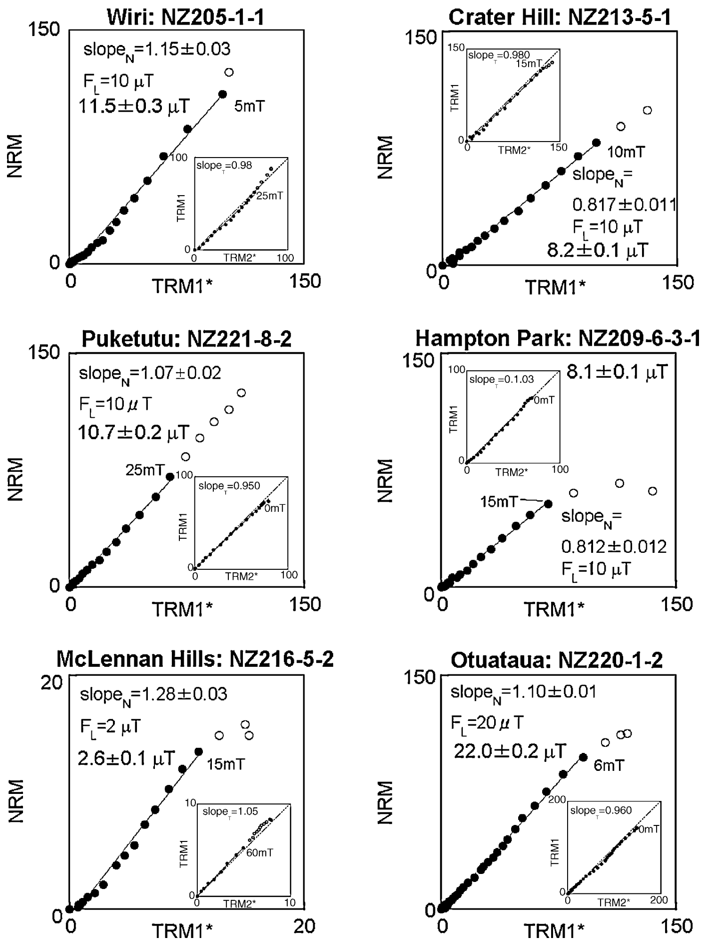

Fig. 6. Representative diagrams of NRM vs. TRM1* by the LTD-DHT Shaw method. Units are 10^{-5} A m^2/kg. TRM1–TRM2* diagrams used for checking applicability of the ARM correction are also shown. Orthogonal vector plots of these samples are given in Fig. 5.

moments (VDMs) of 0.6–2.1 × 10^{22} A m^2 (Table 3) which are about a quarter or less of the present-day dipole moment. On the other hand, the three non-excursional palaeomagnetic records yielded 13.1–40.0 μT, giving VDMs of 2.1–6.9 × 10^{22} A m^2. These results show that the weak geomagnetic intensity, corresponding to VDM of less than about 2 × 10^{22} A m^2, is one of the important characteristics of the Auckland excursions. The palaeointensity of 13.1 μT for the Pupuke volcano of a non-excursional palaeodirection is comparable with those of the excursions, which could possibly be interpreted as a minimum intensity in palaeosecular variation or as a pre- or post-excursional field intensity. The weakest palaeointensity is observed for the McLennan Hills volcano (SU group), suggesting the possible occurrence of another excursion (with a different age). Precise age determination for the McLennan Hills volcano will be required to confirm this.

Palaeointensities reported from volcanic rocks in France (Roperch et al., 1988; Chauvin et al., 1989) and Iceland (Marshall et al., 1988; Levi et al., 1990), i.e. recording the Laschamp and Skalamaelifell excursions, indicated low geomagnetic field intensities of 4.2–13.9 μT corresponding to VDMs of 1.1–2.4 × 10^{22} A m^2. These VDMs also suggest a threshold value of about 2 × 10^{22} A m^2 for geomagnetic excursions. However, palaeointensities associated with the Amsterdam excursion (recorded in two lavas of 18 ± 9 (2σ) and 26 ± 15 ka (2σ) ^{40}Ar/^{39}Ar ages) were reported as 24.0 and 24.6 μT, i.e. corresponding to relatively larger VDMs of 3.4 × 10^{22} and 3.7 × 10^{22} A m^2 (Carvallo et al., 2003). From lavas of Ontake volcano in Japan, a relatively stronger VDM of 6.6 × 10^{22} A m^2 was reported for the 48 ± 8 ka (2σ) excursion, while a low VDM of 0.8 × 10^{22} A m^2 for the 80 ± 8 ka (2σ) excursion (Tanaka and Kobayashi, 2003). Clearly, further palaeointensity data are required for establishing the morphology of excursions on a global scale.

Table 3
Summary of the palaeomagnetic and age data for the Auckland geomagnetic excursions and the non-excursional fields

Volcano	N_{DIR}	Dec (°)	Inc (°)	α_{95} (°)	VGP latitude (°)	VGP longitude (°)	N_{INT}	Intensity (μT)	VDM (10^{22} A m^2)	K-Ar age (ka; 1σ)	Other ages (ka)	Directional group
Wiri	47	356.0	61.9	1.5	9.8	171.9	6	10.6 ± 1.2	1.77 ± 0.20	27 ± 5	25,28; C	North-down
Crater Hill	45	355.4	60.5	1.9	11.4	171.3	6	11.8 ± 2.8	2.01 ± 0.48	–	29, 30; C	North-down
Puketutu	20	5.3	60.9	1.8	10.9	178.8	5	11.1 ± 0.4	1.88 ± 0.07	–	22; TL	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	–	27, 49; C, TL	South-up
Otuataua	16	3.4	−55.6	2.4	87.1	249.1	7	23.0 ± 3.6	4.16 ± 0.65	–	–	Normal
Pupuke	19	359.2	−64.4	1.5	80.5	358.2	4	13.1 ± 1.2	2.11 ± 0.19	–	140; TL	Normal
Rangitoto	21	0.2	−59.7	1.0	86.2	353.1	3	40.0 ± 5.1	6.89 ± 0.88	–	0.75, 0.77; C	Normal

Mean palaeodirections are calculated from the datasets in Table 1. C and TL denote ^{14}C (uncalibrated) and thermoluminescence ages, respectively (see text).

7. Conclusions

We have carried out a palaeointensity study of the samples from eight separate volcanoes, which record three different excursional palaeodirections (ND, WU and SU groups) of the Auckland geomagnetic excursions and non-excursional palaeodirections, in the Auckland volcanic field, New Zealand. Five to six consistent palaeointensities are obtained for each of five volcanoes recording the Auckland geomagnetic excursions using the LTD-DHT Shaw method. In particular, concordant mean palaeointensities have been obtained for three volcanoes belonging to the ND group, which supports the reliability of the palaeointensities determined in this study. All the mean palaeointensities for each volcano recording the Auckland geomagnetic excursions range between 2.5 and 11.8 μT corresponding to VDMs of $0.6–2.1 \times 10^{22}$ A m^2, which are about a quarter or less of the present-day dipole moment. The mean palaeointensities obtained for the three volcanoes with non-excursional palaeodirections are 13.1–40.0 μT which correspond to $2.1–6.9 \times 10^{22}$ A m^2. These results suggest that the dipole component of the geomagnetic field reduced to about 2×10^{22} A m^2 or less during the Auckland geomagnetic excursions.

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