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Absolute palaeointensity study of the Mono Lake excursion recorded by New Zealand basalts

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ABSTRACT

One of the geomagnetic excursions recorded in basalts of the Auckland volcanic field, New Zealand, has recently been correlated unequivocally with the Mono Lake excursion, making it the only confirmed record from the southern hemisphere. This record is also exceptional in occurring in five separate monogenetic basaltic volcanoes. Absolute palaeointensity determinations using the microwave technique, based on a comprehensive suite of samples of the Auckland basalts recording the excursion, show that the geomagnetic field in New Zealand at the time of the Mono Lake excursion was reduced to about 14 μT i.e. to 30% of its normal value. This result confirms previous estimates based on more limited sampling. In addition, it provides a comparison of the microwave and LDT-DHT Shaw methods of measuring palaeointensity, which give results that are statistically indistinguishable. The palaeointensities determined from the five different volcanoes are also indistinguishable, though the palaeodirection data suggest that a very small segment of the VGP path may have been recorded. This study confirms the reliability of palaeointensity and palaeodirection determinations from these particular New Zealand basalts, which together with their definitive ^{40}Ar/^{39}Ar ages, establishes this record of the Mono Lake excursion as one of the best documented. Consequently, there is significant potential in searching for records of this excursion elsewhere in the Pacific region for use as a stratigraphic marker in studies of recent volcanism and palaeoclimate reconstructions.

1. Introduction

The nature and timing of the Mono Lake geomagnetic excursion continue to be a source of controversy (e.g. Kent et al., 2002; Benson et al., 2003; Laj and Channell, 2007). It is therefore significant that a geomagnetic excursion recorded in the Auckland volcanic field, New Zealand, first identified by Shibuya et al. (1992), has recently been correlated unequivocally with the Mono Lake excursion on the basis of precise ^{40}Ar/^{39}Ar dating (Cassata et al., 2008).

The Auckland record is of exceptional value to studies of the geomagnetic field for several reasons. It is the only case to date where the Mono Lake excursion is known with confidence to have been recorded in basalts, which are generally highly suited to palaeomagnetic study and can be directly dated using radiometric methods. Two other possible such cases are reported from Hawaiian lava flows (Teanby et al., 2002), where no radiometric dates could be obtained but the Mono Lake excursion was inferred to have been recorded based on an age model, and secondly from Amsterdam Island (Carvallo et al., 2003), where large dating errors precluded discrimination between the Mono Lake and Laschamp excursions. Furthermore, the Mono Lake excursion recorded in Auckland uniquely occurs in five separate short-lived monogenetic volcanoes (Cassidy, 2006), each providing an independent temporal 'snapshot' of the geomagnetic field. Finally, this is the only confirmed record of the Mono Lake excursion in the southern hemisphere and therefore can provide a particularly valuable constraint for global models of the Earth's field and geodynamo processes during reversals and excursions.

Here we present a new comprehensive microwave palaeointensity study of all the basalts recording the Mono Lake excursion in Auckland. This work also provides a comparison between the microwave technique for measuring palaeointensities and the LTD-DHT Shaw method which was used by Mochizuki et al. (2006) to study a more limited range of basalts recording this excursion in Auckland. The microwave technique has the advantage over the Thellier method (Thellier and Thellier, 1959) of minimising laboratory-induced alteration (e.g. Hill et al., 2002) which is often problematic in basalts (e.g. Herrero-Bervera and Valet, 2005). Indeed, the Thellier method has previously been shown to be

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unsuccessful for the Auckland basalts (Mochizuki et al., 2006) for this very reason.

This microwave palaeointensity investigation, which includes a refinement of previous palaeodirectional results (from Cassidy, 2006), together with the recently reported $^{40}Ar/^{39}Ar$ ages (Cassata et al., 2008) and other previous palaeomagnetic and age data (Shibuya et al., 1992; Mochizuki et al., 2004, 2006, 2007; Grant-Taylor and Rafter, 1971), provides one of the most definitive records to date of the Mono Lake excursion.

2. The Auckland geomagnetic excursions

The Auckland excursions were originally discovered by Shibuya et al. (1992) from a pilot palaeomagnetic study of the Quaternary Auckland volcanic field, New Zealand. The Auckland field (Fig. 1) comprises 49 monogenetic volcanoes, including explosion craters, scoria cones and lava flows (Kermode, 1992). Volcanic rocks within the field consist mostly of alkali basalts or basinites which are typically hypocrystaline, with olivine and clinopyroxene being the dominant phenocrysts (Heming and Barnett, 1986). The ages of most of the volcanoes are poorly known, but the field may be at least 250 ka old (Shane et al., 2002). Because the volcanoes are of small volume and are short-lived (probably no more than several years), they each represent a temporal snapshot of the geomagnetic field i.e. different lava flows and scoria cones within each volcano can be together considered a single palaeomagnetic site for the purposes of statistical treatment. Outcrop for palaeomagnetic sampling is unfortunately rather limited, with the exception of a few quarries which provide good fresh exposures.

Shibuya et al. (1992) reported results from 21 of the 49 volcanoes, sampled mostly from a single lava flow per volcano. Three anomalous groups of palaeomagnetic directions were defined in this study, namely: 'north-down' (recorded by 3 volcanoes) which had a mean inclination/declination of $62^\circ/358^\circ$ (compared with $-60^\circ/19^\circ$ for the present day), 'west-up' (recorded by 2 volcanoes) with a mean inclination/declination of $-40^\circ/257^\circ$ and 'south-up' (recorded by 1 volcano) with a mean inclination/declination of $-22^\circ/166^\circ$. These events were tentatively correlated with either the Laschamp or Mono Lake excursions on the basis of existing, but uncorroborated, ^{14}C and TL dating. Cassidy (2006) subsequently found a further two volcanoes, initially identified from aeromagnetic data, belonging to the north-down group.

Mochizuki et al. (2006) determined absolute palaeointensities from measurements on a limited number of lava flows from five of the six volcanoes originally identified by Shibuya et al. (1992), using the low-temperature demagnetisation, double-heating technique (LTD-DHT), a variant of the Shaw method (e.g. Yamamoto et al., 2003). These measurements showed that the field was reduced to at least 25% of normal intensity during these events, thus corroborating the validity of the excursion records.

Establishing the chronology of the Auckland volcanoes has been very problematic on account of typically imprecise and discordant results (Allen and Smith, 1994; Shane and Hoverd, 2002). As a consequence, the global significance of the Auckland excursions has not been fully appreciated. Mochizuki et al. (2004, 2007) carried out unspiked K–Ar dating on samples from four of the volcanoes recording the excursions; this work yielded somewhat imprecise ages, but did strongly suggest that both the Laschamp and Mono Lake excursions had been recorded in Auckland. In view of the fact that the K–Ar dating method is especially susceptible to errors caused by excess argon (as was noted in the Auckland basalts by McDougall et al., 1969), Cassata et al. (2008) more recently carried out a detailed $^{40}Ar/^{39}Ar$ investigation in order to provide more definitive dates for the Auckland excursions so that they could be globally correlated with more confidence. This $^{40}Ar/^{39}Ar$ study confirmed unequivocally that both the Laschamp and Mono Lake excursions are recorded in Auckland and yielded dates of 39.1 ± 4.1 and 31.6 ± 1.8 ka, respectively, the latter date being the age of the north-down group, which is the subject of this paper.

3. Field sampling and rock magnetism

Sampling was carried out at 14 sites from the five volcanoes that record the Mono Lake excursion: Crater Hill, Mt Richmond, Puketutu, Taylor Hill and Wiri (see Fig. 1). Sites included a range of exposure quality from fresh quarry faces to natural outcrops; each site consisted of a separate single flow unit or scoria cone at which 5–9 core samples were drilled and oriented by sun compass or geographical sighting. Petrographically, the samples range from hard dense basalt (lava flows), through highly vesicular basalt and welded scoria, to soft red oxidised scoria (scoria cones).

Rock magnetic experiments to determine isothermal remanent magnetisation (IRM) acquisition and back field, hysteresis and thermomagnetic characteristics were carried out on all samples (64 in total) for which successful palaeodirections had been determined in this and previous studies (Cassidy, 2006). These experiments were performed using a Variable Field Translation Balance (MMVFTB). IRM acquisition and hysteresis plots show that saturation is achieved by 300 mT. On a plot of hysteresis properties (c.f. Day et al., 1977) (Fig. 2a), samples lie close to the theoretical mixing curves for single domain (SD) and multi-domain (MD) magnetite grains (Dunlop, 2002) showing that the samples contain varying proportions of SD and MD grains. Typically, the thermomagnetic curves for heating and cooling cycles are fairly reversible (Fig. 2b), however some samples from Puketutu and Wiri exhibit highly irreversible behaviour indicating alteration to a more strongly magnetic phase (Fig. 2c). Curie temperatures of $\sim 200\,^\circ C$ and $500–580\,^\circ C$ are indicated, with different samples having different proportions of these magnetic phases. The rock magnetic results indicate that the dominant magnetic mineral is titanomagnetite with varying amount of titanium consistent with samples having undergone varying amounts of high-temperature oxidation. This is consistent with the findings of Mochizuki et al. (2006) who in addition, observed different degrees of high-temperature oxidation of titanomagnetite grains under microscopic examination. In general, systematic differences in rock magnetic properties are not seen between the volcanoes (apart from in some samples from Wiri and Puketutu as mentioned above), with samples from each volcano exhibiting a range of magnetic behaviour.

4. Palaeodirection analysis

In this study, analysis of primary palaeomagnetic directions from two new sites in the Mt Richmond volcano (MR) were undertaken in order to reduce the α_{95} uncertainty on the mean palaeodirection as determined from the previous study of Cassidy (2006), in which it was suggested that the palaeodirections might form a segment of an excursion path. 17 samples were collected from these sites which consisted of a welded scoriaceous flow and a scoria cone. Laboratory measurements were carried out using a Magnetic Measurements Thermal Demagnetiser and Molspin spinner magnetometer, with temperature steps of $50\,^\circ C$ up to 500 and $25\,^\circ C$ steps subsequently up to 575°. As in the previous thermal (Cassidy, 2006) and AF (Shibuya et al., 1992; Mochizuki et al., 2006) demagnetisation studies, samples characteristically exhibited high stability during progressive stepwise demagnetisation. During thermal demagnetisation, any viscous component of magnetisation was usually removed by $200\,^\circ C$, with blocking temperatures typically in the range $400–500\,^\circ C$, consistent with the rock magnetic properties discussed previously.

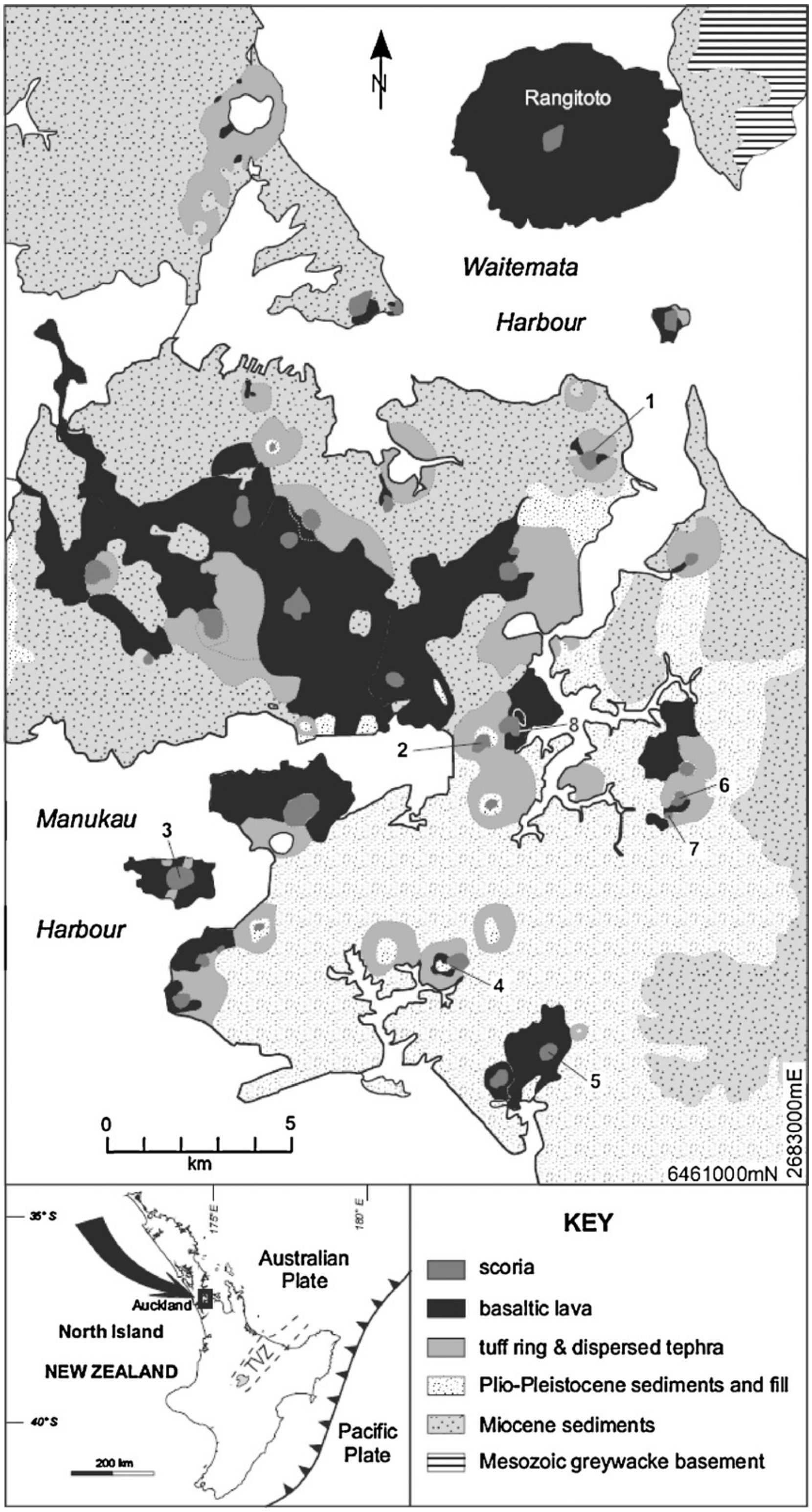

Fig. 1. Map of Auckland volcanic field showing associated volcanic deposits (after Kermode, 1992). Volcanoes 1–5 are those which record the Mono Lake excursion: (1) Taylor Hill, (2) Mt Richmond, (3) Puketutu, (4) Crater Hill and (5) Wiri. Other numbered volcanoes are those which also record excursion directions: 6. Otara Hill, 7. Hampton Park and 8. McLennan Hills (see Mochizuki et al., 2006). The inset shows North Island, New Zealand, with the area covered by the main map and the present-day plate boundary marked (teeth on the upper plate).

For statistical purposes in this analysis, samples from two previous sites (MR1a and MR1b of Cassidy, 2006) have been combined into a single site (MR1) since they are possibly from the same lava flow, whereas the two new sites (MR3 and MR5) are entirely separate. Also, site MR2 from this previous study is omitted from the present analysis because, although giving similar palaeodirection results to other sites, the samples were not cored in the field and therefore orientation errors are likely to be greater. Principal

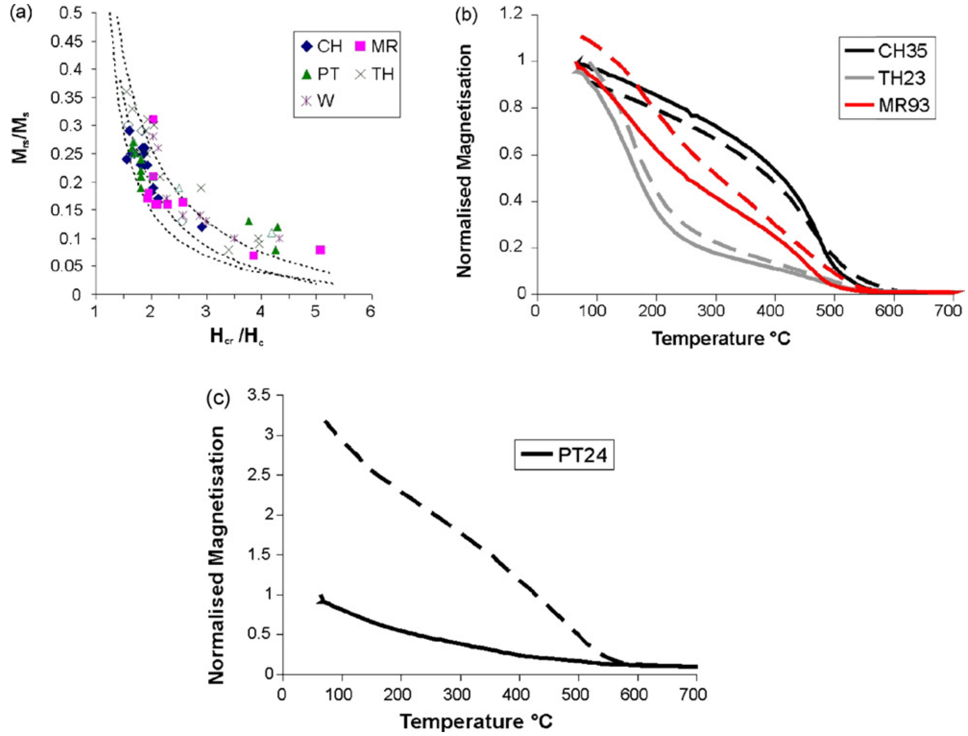

Fig. 2. Rock magnetic properties. (a) Day et al. (1977) plot with the theoretical mixing curves of Dunlop (2002). Open symbols indicate the two sites (CH1 and PT2) that give anomalously low palaeointensity compared to other sites from the same volcano. (b) Three examples of thermomagnetic behaviour showing the range of behaviour, solid (dashed) lines are the heating (cooling) curves. (c) Example of highly irreversible behaviour in the heating/cooling curves of a sample from Puketutu.

component analysis of orthogonal vector demagnetisation plots (OVPs) (Fig. 3a) shows that samples from the Mt Richmond sites have predominantly single-component magnetisations indicative of primary magnetisation directions. All three sites from this volcano (MR1, 3 and 5) give concordant palaeomagnetic directions, with small intra- and inter-site scatter (Fig. 3b), and with a combined mean direction (and α_{95} uncertainty) comparable with the mean directions (and α_{95} uncertainties) of the other four volcanoes (Fig. 3c and Table 1).

The final palaeodirectional data set presented in Fig. 3c is based on a total number of 25 sites (including those of Shibuya et al., 1992; Cassidy, 2006; Mochizuki et al., 2006) and is better resolved than previously. Four of the volcanoes, including Mt Richmond, share indistinguishable palaeodirections that form a tight grouping, whilst the fifth volcano, Taylor Hill, has a palaeodirection that is just distinguishable as an outlier. The recent ^{40}Ar/^{39}Ar dating study of Cassata et al. (2008) was unsuccessful for both the Mt Richmond and Taylor Hill volcanoes; however, given the close similarly of palaeodirections for the whole group of five volcanoes, it is highly likely that they have all recorded the same excursion event. Taylor Hill volcano is the most geographically separate from the group and could have a slightly different age related to spatio-temporal controls within the Auckland volcanic field, hence its palaeodirection may reflect a real variation of the geomagnetic field during the excursion. As argued by Cassidy (2006), on the basis of observed rates of palaeodirectional change during excursions, the total time span represented by these data might be of the order of only 100 years i.e. well beyond the best possible resolution of ^{40}Ar/^{39}Ar dating.

5. Microwave palaeointensity analysis

Palaeointensity measurements were carried out using two 14 GHz microwave systems (Böhnel et al., 2003; Shaw and Share, 2007) at the Geomagnetism Laboratory, University of Liverpool, following the procedures outlined by Hill et al. (2005). For the older system, microwave power was applied to the samples for 5 s, increasing stepwise from 20 W to 80 W; in some cases, where

Table 1
Mean palaeomagnetic directions.

MR sites and volcano means	n/N	Dec. (°)	Inc. (°)	α_{95} (°)	k	VGP_{lat} (°)	VGP_{long} (°)
MR1	9/11	346.8	66.9	1.9	775	2.7	166.3
MR3	9/9	355.0	64.1	3.8	189	7.1	171.3
MR5	8/8	356.4	65.8	8.0	49	4.9	172.4
Crater Hill	6/6	351.6	63.2	4.9	156	8.0	168.8
Mt Richmond	3/3	352.9	65.7	3.9	1021	5.0	170.0
Puketutu	4/4	3.0	62.2	4.0	358	9.6	177.0
Taylor Hill	3/3	341.6	58.4	4.2	880	12.2	160.3
Wiri	6/6	354.5	61.6	2.3	214	10.2	171.0

n/N, number of samples/sites yielding result (n) as a subset of total number of samples/sites (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. Overall mean inclination and declination for 5 volcanoes is 62.4° and 352.5°, respectively; corresponding VGP is 9.1°N, 169.3°E (α_{95} = 4.3°). Volcano means other than Mt Richmond are from Cassidy (2006).

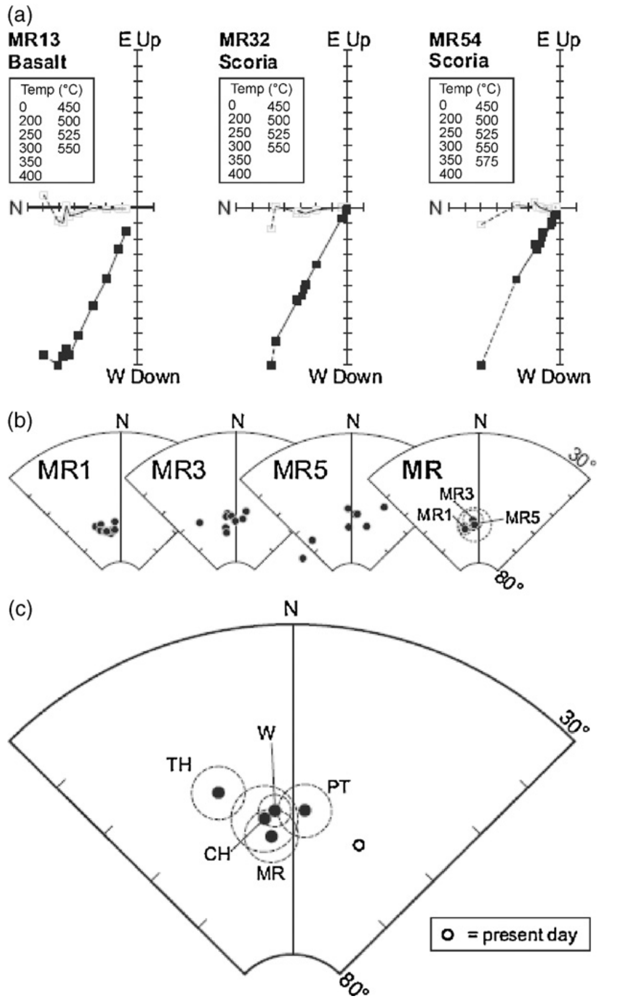

Fig. 3. Palaeomagnetic directions from volcanoes recording the Mono Lake excursion. (a) Orthogonal vector plots of relative magnetic intensity for thermal demagnetisation of selected samples from each site in Mt Richmond (MR) volcano; open (closed) symbols denote horizontal (vertical) plane. (b) Equal-area lower hemisphere stereo plots of characteristic magnetisation directions of samples (after demagnetisation) from all three corresponding sites (MR1, MR3 and MR5) and of site means for MR, showing α_{95} values (cone of 95% confidence) as dashed circles. (c) Mean characteristic magnetisation directions for all 5 volcanoes recording the Mono Lake excursion with α_{95} circles (data for volcanoes other than MR are from Cassidy, 2006). Present-day field direction (upwards inclination) shown as open circle.

complete demagnetisation was not achieved by this point, the application time at 80 W was increased to as much as 15 s. With the newer system, less microwave power is needed for demagnetisation and was routinely applied for 3 s up to about 60 W. Alternatively, lower power but longer times (up to 10 s) were used. Samples from 13 of 15 sites spanning all five volcanoes were measured, involving 8–18 sample measurements per volcano. Of the samples collected previously by Cassidy (2006) and for this study, 65% were accepted for palaeointensity analysis, the others being rejected on the basis of having either a significant secondary component of magnetisation (or significant scatter) on the OVPs or visible signs of weathering, potentially adverse factors in palaeointensity experiments. Both the perpendicular applied field palaeointensity method (Kono and Ueno, 1977; Hill and Shaw, 2007) and the double-heating Coe analogue palaeointensity method (Coe, 1967; Thomas et al., 2004) were used as a check on the consistency of the experimental results; 8 experiments were performed on the same samples using both methods and gave consistent results.

The experiments also incorporated partial microwave thermal remanent magnetisation (pT_MRM) tail and pT_MRM measurements (as described in Hill et al., 2005) for checks on alteration and multi-domain behaviour; acceptable palaeointensity results were obtained from 52 of 64 samples i.e. an 81% success rate. The mean NRM fraction (f) used was 0.56 and the mean Coe et al. (1978) quality factor (q) was 16. Individual sample results are given in Table 2. Twelve samples failed the microwave experiments due to directional instability and alteration of minerals during progressive microwave exposure (as seen by failure of the pT_MRM checks and non-linearity in the NRM/T_MRM plot). Instability of the NRM automatically leads to failure of the perpendicular applied field method.

Examples of microwave palaeointensity NRM/T_MRM plots for representative samples from all five volcanoes are shown in Fig. 4 (Crater Hill, Mt Richmond and Puketutu) and in Fig. 5 (Taylor Hill and Wiri), the latter figure comparing the results of the perpendicular applied field and Coe analogue methods. The results for Crater Hill, Mt Richmond and Taylor Hill typically show clear linear plots and are therefore straightforward to interpret. Some samples from Puketutu and Wiri however, show more ambiguous behaviour with two linear segments (see Fig. 4) and therefore interpretation is more subjective. The initial steeper slope which characterizes these NRM/T_MRM plots may be due to an overprint (as we interpret here) or it could be that some of the samples are exhibiting non-linear behaviour. However, this does not appear to be an influence of domain state since all pT_MRM checks pass the acceptance criteria during the palaeointensity experiment and there is no correlation with hysteresis parameters. Palaeointensity values for individual samples range from 1 to 24 μT, with Puketutu and Wiri notably giving the lowest palaeointensity estimates.

Palaeointensities have been successfully obtained from a wide petrographic range, from dark non-vesicular basalt, sampled from mid-flow, to soft completely oxidised red scoria. There is no obvious correlation between palaeointensity values and hysteresis parameters or Curie temperature, therefore the degree of high-temperature oxidation of the samples, nor domain state, appear to be biasing the results. However, for some (but not all) Puketutu and Wiri samples, there does seem to be a correlation between lower palaeointensity estimates (and more ambiguous microwave demagnetisation behaviour) and the occurrence of highly irreversible Curie curves. Possible reasons for this could be either undetected alteration or that the samples contain titanomaghaemite and hence are contaminated with a CRM.

Site mean palaeointensity results are given in Table 3 and plotted in Fig. 6. Some variation is seen within-site, however only two sites have standard deviations about the mean of greater than 5 μT (c.f. Tauxe and Staudigel, 2004). Site means are concordant (i.e. within 4 μT) for three of the five volcanoes, but for Crater Hill and Puketutu a larger variation (>6 μT) between sites is found. Sites 2 and 3 from Crater Hill give consistent mean palaeointensities of 18 μT, whereas site 1 gives a mean palaeointensity of 9 μT (i.e. 50% less). Similar behaviour is seen at Puketutu with two out of the three sites giving consistent results (~9 μT) whereas site 2 gives a value of 3 μT (i.e. more than 60% lower). Samples from CH1 and PT2 are indicated on the Day et al plot in Fig. 2. For Crater Hill, there is no reason discernable from the rock magnetic experiments why site 1 is different from sites 2 and 3. However for Puketutu, all the samples from site 2 exhibited irreversible Curie curves, whereas sites 1 and 3 are characterized by more stable sample behaviour similar to that from other volcanoes.

Volcano mean palaeointensities are given in Table 3. As is evident regarding volcano mean values, it makes little difference if the mean value is calculated from all individual results or is calculated from the means of the sites. The overall mean palaeointensity

Table 2
Microwave palaeointensity sample results.

Site	Sample	Method	N	f	g	β	q	F (μT)	se	Error (1/q)
CH1	CH11	perp	14	0.36	0.85	0.0216	14.14	8.73	0.19	0.62
	CH11b	*perp*	*9*	*0.46*	*0.81*	*0.0155*	*24.23*	*5.64*	*0.09*	*0.23*
	CH12		Fail							
	CH13	dh	9	0.48	0.81	0.0340	11.45	10.18	0.35	0.89
	CH15	perp	6	0.66	0.72	0.0234	20.46	8.07	0.19	0.39
	CH16		Fail							
CH2	CH21		Fail							
	CH23	perp	10	0.72	0.85	0.0301	20.17	15.61	0.47	0.77
	CH24	perp	9	0.79	0.85	0.0643	10.38	12.34	0.79	1.19
	CH25		Fail							
	CH26	dh	6	0.67	0.53	0.0156	22.86	17.92	0.28	0.78
	CH26b	*perp*	*5*	*0.46*	*0.70*	*0.0257*	*12.46*	*19.46*	*0.50*	*1.56*
	CH27	dh	11	0.94	0.86	0.0426	18.97	23.51	1.00	1.24
	CH28	perp	7	0.35	0.78	0.0476	5.71	20.51	0.98	3.59
CH3	CH31	dh	9	0.84	0.82	0.0437	15.77	19.27	0.84	1.22
	CH32	perp	7	0.51	0.77	0.0213	18.38	15.75	0.34	0.86
	CH33	perp	7	0.75	0.74	0.0340	16.21	18.63	0.63	1.15
	CH34	dh	8	0.78	0.80	0.0136	45.72	13.28	0.18	0.29
	CH34b	*perp*	*8*	*0.47*	*0.83*	*0.0096*	*40.77*	*15.54*	*0.15*	*0.38*
	CH35	dh	8	0.90	0.80	0.0421	17.15	19.70	0.83	1.15
	CH36	dh	11	0.88	0.87	0.0316	24.07	18.17	0.57	0.75
MR1b	MR14	perp	9	0.46	0.82	0.0281	13.49	14.18	0.40	1.05
	MR17	dh	11	0.77	0.88	0.0375	17.97	23.61	0.89	1.31
	MR17b	*perp*	*5*	*0.57*	*0.68*	*0.0214*	*18.03*	*25.40*	*0.54*	*1.41*
	MR18	perp	6	0.60	0.79	0.0383	12.28	12.85	0.49	1.05
MR1a	MR82	perp	7	0.55	0.58	0.0223	14.25	7.79	0.17	0.55
	MR84	dh	7	0.34	0.81	0.0846	3.23	10.46	0.89	3.24
	MR93		Fail							
	MR94	dht	5	0.32	0.52	0.0813	2.05	7.58	0.62	3.70
	MR95		Fail							
	MR97	perp	11	0.61	0.84	0.0272	19.08	7.33	0.20	0.38
MR3	MR34	dht	8	0.62	0.76	0.0233	20.09	9.86	0.23	0.49
PT1	PT11		Fail							
	PT13	perp	10	0.83	0.66	0.0343	16.00	8.32	0.29	0.52
	PT14		Fail							
	PT15	perp	4	0.41	0.66	0.0158	17.10	10.68	0.17	0.62
	PT16	perp	7	0.48	0.81	0.0304	12.58	6.79	0.21	0.54
PT2	PT21	dh	7	0.47	0.76	0.0536	6.74	1.21	0.07	0.18
	PT22	dh	6	0.43	0.64	0.0677	4.05	1.71	0.12	0.42
	PT23	dh	7	0.28	0.79	0.0405	5.40	4.35	0.18	0.80
	PT24	perp	8	0.14	0.76	0.0947	1.15	3.12	0.30	2.72
	PT25	perp	6	0.49	0.78	0.0430	8.84	5.44	0.23	0.62
	PT27		Fail							
PT3	PT34	dh	9	0.38	0.81	0.0817	3.74	13.70	1.12	3.67
	PT35	dh	6	0.36	0.74	0.1034	2.60	10.15	1.05	3.91
	PT36	perp	9	0.61	0.87	0.0113	46.93	8.94	0.10	0.19
	PT37	perp	4	0.37	0.59	0.0347	6.30	8.54	0.30	1.36
	PT38	dh	5	0.55	0.67	0.0377	9.74	5.42	0.20	0.56
TH1	TH11	perp	6	0.56	0.58	0.0079	40.33	7.51	0.06	0.19
	TH11b	*dh*	*8*	*0.41*	*0.84*	*0.0571*	*6.06*	*7.07*	*0.40*	*1.17*
	TH12	dht	14	0.98	0.91	0.0058	155.17	17.13	0.10	0.11
	TH14	dht	7	0.41	0.82	0.0565	5.99	12.40	0.70	2.07
	TH15	perp	7	0.75	0.77	0.0370	15.66	23.47	0.87	1.50
	TH15b	*dh*	*7*	*0.63*	*0.64*	*0.0328*	*12.39*	*17.60*	*0.58*	*1.42*
	TH16	dh	8	0.50	0.81	0.0907	4.44	7.52	0.68	1.69
	TH17	perp	7	0.50	0.76	0.0860	4.41	22.15	1.91	5.02
	TH19	dh	6	0.35	0.64	0.0491	4.58	19.96	0.98	4.36
	TH19b	*perp*	*8*	*0.53*	*0.78*	*0.0195*	*21.10*	*18.22*	*0.36*	*0.86*
TH2	TH23	dht	9	0.61	0.79	0.0562	8.58	10.93	0.61	1.27
	TH24	dht	10	0.61	0.84	0.0361	14.23	18.63	0.67	1.31
	TH24b	*perp*	*5*	*0.51*	*0.74*	*0.018*	*20.66*	*20.78*	*0.38*	*1.01*
	TH25	perp	7	0.64	0.63	0.0244	16.43	19.68	0.48	1.20
TH3	TH31	perp	6	0.63	0.70	0.0503	8.78	22.25	1.12	2.54
	TH32	perp	8	0.67	0.73	0.0367	13.36	17.40	0.64	1.30
W1	W13	dh	8	0.45	0.82	0.0775	4.74	5.88	0.46	1.24
	W15		Fail							
	W17	dh	6	0.26	0.78	0.0785	2.54	2.66	0.21	1.05

Table 2 (*Continued*)

Site	Sample	Method	N	f	g	β	q	F (μT)	se	Error (1/q)
W2	W21	dh	7	0.35	0.80	0.0851	3.28	11.67	0.99	3.56
	W21b	*dh*	*9*	*0.21*	*0.80*	*0.0479*	*3.44*	*8.19*	*0.39*	*2.38*
	W22	dh	9	0.60	0.83	0.0433	11.62	4.40	0.19	0.38
	W22b	*perp*	*11*	*0.63*	*0.86*	*0.0271*	*19.88*	*5.29*	*0.14*	*0.27*
	W23	perp	12	0.48	0.83	0.0273	14.70	6.98	0.19	0.47
	W24	dh	Fail							
	W26	dh	Fail							

Method dh is double-heating Coe analogue, dht is double-heating Coe analogue (carried out using the new microwave system incorporating the Tristan magnetometer) and perp is perpendicular applied field method. N is the number of points used in the determination, f, g, β and q are the Coe et al. (1978) quality parameters, F is the palaeointensity estimate with se the error calculated from the slope of the best fit line and error (1/q) is the uncertainty in the palaeointensity estimate as determined by (1/q)F. Results in italics are from duplicate sister samples that were the less reliable of the pair, based on quality criteria, and were not included in the means.

value based on the five volcano means is $11 \pm 5\,\mu$T. Excluding data from Puketutu and Wiri, on account of the irreversible thermomagnetic behaviour of some of those samples (discussed above), gives a mean palaeointensity of $14 \pm 3\,\mu$T, which could be regarded as more reliable.

Mochizuki et al. (2006) investigated 54 samples from the Crater Hill, Wiri and Puketutu volcanoes using the LTD-DHT Shaw method. Seventeen samples gave acceptable results, which equates to a 31% success rate. These results (plotted along with those from this study in Fig. 7) are within the error bounds of the microwave results. The overall mean for the three volcanoes measured in common is 11.2 ± 0.6 and $9 \pm 5\,\mu$T, for the LTD-DHT Shaw and microwave measurements, respectively. Note that sister samples were not investigated, nor were samples taken from the same sites, therefore it is only possible to compare results at the volcano level. The results obtained using the microwave method show considerably more scatter than those from the LTD-DHT Shaw method, which appear especially consistent both within and between volcanoes (Mochizuki et al., 2006). The lower microwave palaeointensity mean (and greater scatter) partly reflects the low values associated with the highly irreversible thermomagnetic behaviour already noted; however, irrespective of whether the Puketutu and Wiri results are omitted from the analysis, the standard deviations of the overall means for both methods overlap.

For these Auckland samples therefore, the LTD-DHT method, whilst having a lower success rate (Mochizuki et al., 2006) than the microwave method, gives more consistent results. A greater number of microwave experiments would be needed in order to obtain a comparably reliable mean, however as the microwave success rate is higher and the experiments are less time-consuming,

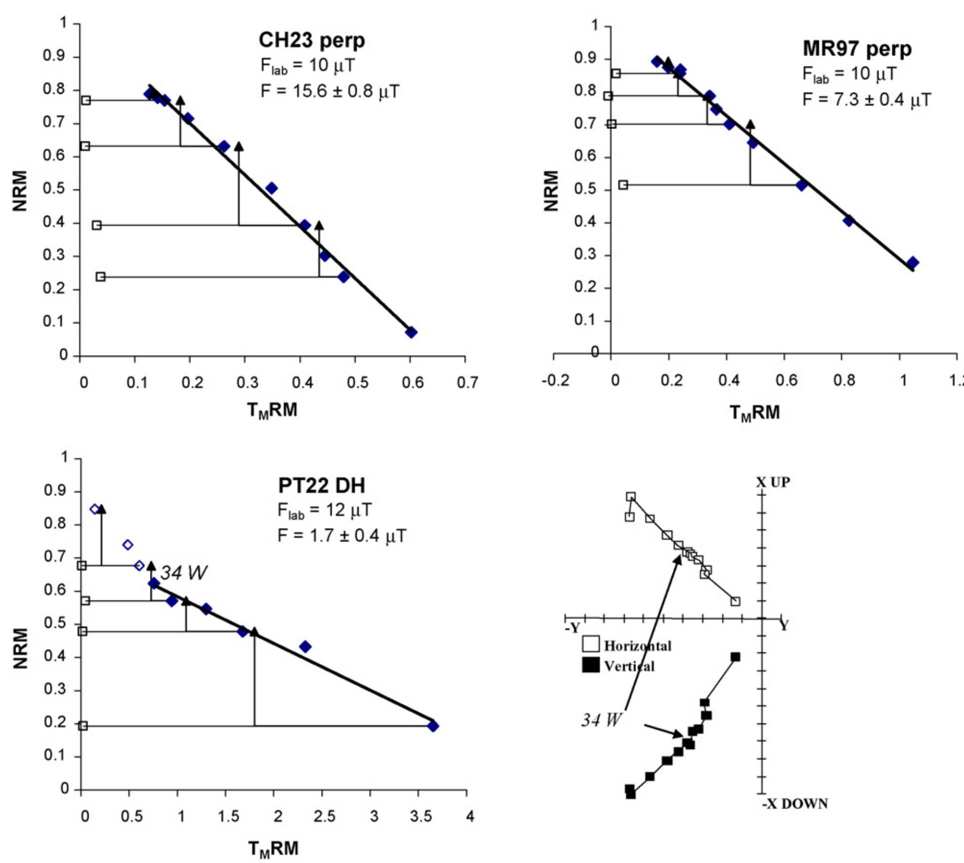

Fig. 4. Examples of microwave palaeointensity results where 'perp' indicates a result obtained using the perpendicular applied field method and 'DH' the double-heating Coe analogue method. On the NRM/T_MRM plots, solid (open) diamonds represent accepted (rejected) data points, narrow lines with arrows are pT_MRM checks, and dashed lines with open squares at the end represent the pT_MRM tail checks. The OVP (sample coordinates) from the demagnetisation steps is shown for the 'DH' result. The applied laboratory field F_{lab} and the palaeointensity estimate F are indicated.

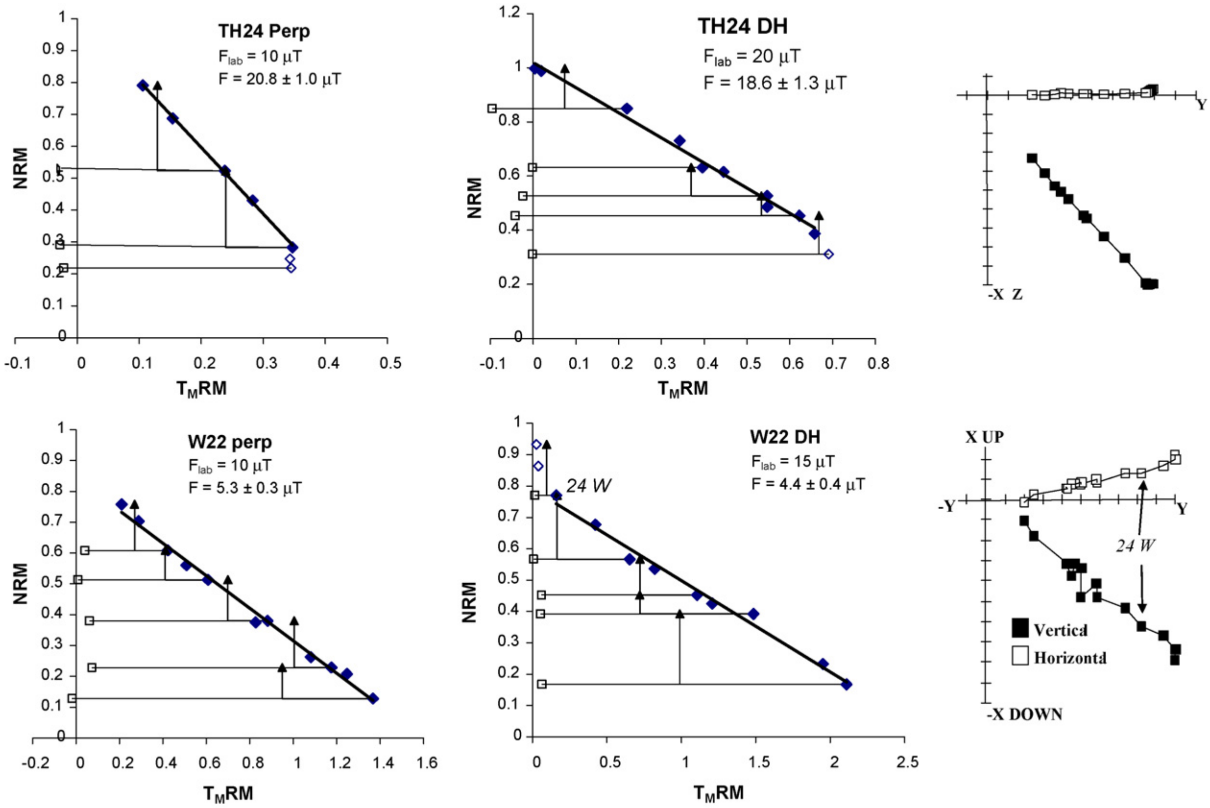

Fig. 5. Duplicate sister sample results using the perpendicular applied field and the double-heating Coe analogue methods for two samples. Symbols as in Fig. 4.

this is readily achieved. The LTD-DHT Shaw method seems particularly suited to these samples which have a low coercivity overprint that is readily removed with low-temperature demagnetisation and low AF fields. Further experiments are planned to investigate the effect of AF cleaning with microwave de(re)magnetisation and investigating sister samples with the two methods. This is only the second study where both microwave and LTD-DHT Shaw methods have been used to determine palaeointensities for the same group of rocks, the first being two independent studies of the 1960 Hawaiian lava flow (Hill and Shaw, 2000; Yamamoto et al., 2003).

6. Discussion

This study confirms that the geomagnetic field in New Zealand at the time of the Mono Lake excursion was reduced to about 14 µT (virtual dipole moment, VDM, of 2.4×10^{22} A m^2) i.e. to 30% of its normal value, which is in accord with the commonly reported observation of significantly weakened dipole fields during excursions (e.g. Lund et al., 2006; Laj and Channell, 2007). The Auckland record is valuable in providing the only definitive measurements to date of absolute palaeointensity associated with the Mono Lake excursion since it is the only record where the rocks have been

Table 3
Mean palaeointensity results.

Volcano	Site	n/N	Site mean F (µT)	sd	Volcano mean (based on samples)			Volcano mean (based on sites)	
					n/N	F (µT)	sd	F (µT)	sd
CH	CH1	3/5	9.0	1.1	14/18	15.8	4.7	14.8	5.0
	CH2	5/7	18.0	4.3					
	CH3	6/6	17.5	2.5					
MR	MR1	7/9	12.0	5.8	8/10	11.7	5.4	10.9	-
	MR3	1/1	9.9	–					
PT	PT1	3/5	8.6	2.0	13/16	7.0	3.9	7.0	3.4
	PT2	5/6	3.2	1.8					
	PT3	5/5	9.4	3.0					
TH	TH1	7/7	15.7	6.7	12/12	16.6	5.7	17.3	2.2
	TH2	3/3	16.4	4.8					
	TH3	2/2	19.8	–					
W	W1	2/3	4.3	–	5/8	6.3	3.4	6.0	–
	W2	3/5	7.7	3.7					

Symbols as for Tables 1 and 2. n/N, number of samples yielding acceptable palaeointensity results (n) as a subset of total number of samples (N) per site/volcano, sd is the standard deviation on the corresponding F values. Volcano means are calculated using both individual sample results and from the site means, showing there is no significant difference.

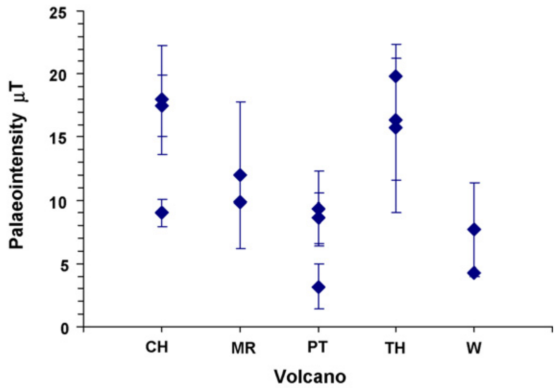

Fig. 6. Site mean palaeointensities (with error bars) for each volcano.

well dated (Cassata et al., 2008). Regarding the possible Mono Lake records from elsewhere (referred to earlier), microwave palaeointensity measurements on the Hawaiian flows gave a minimum value for the geomagnetic field of 8 μT (20% of normal) (Gratton et al., 2005) and Thellier measurements on Amsterdam Island lavas gave higher VDMs of about 3.5×10^{22} Am^2 (i.e. 40% of normal) (Carvallo et al., 2003).

These absolute palaeointensity measurements, although few, appear to confirm that the reduction in the geomagnetic field during the Mono Lake excursion was somewhat less than that during the Laschamp excursion, commonly reported from other absolute palaeointensity studies to be as low as 10% of normal (see review of Laj and Channell, 2007). This is in accord with the increasingly reported observations of relative palaeointensity from marine sediment cores, which typically show the Mono Lake excursion as a lesser peak (e.g. Blanchet et al., 2006; Lund et al., 2006), as do data which track the related cosmogenic nuclide production rate (Wagner et al., 2000). As a consequence, it is possible that the duration of the directional anomaly for the Mono Lake excursion is correspondingly shorter, which together with its smaller magnitude, may explain why it is often missed in sediment cores compared to the Laschamp signal (e.g. Roberts and Winklhofer, 2004).

There is no apparent difference in palaeointensities recorded by the different volcanoes, which would be expected given their closely similar palaeomagnetic directions. Typically, these volcanoes all have distinctive chemical compositions and mineralogies (Smith et al., 2008) and therefore provide an unusual opportunity to compare the consistency of any experimental method of palaeointensity determination. The overall mean VGP for these sites plots very close to previously published VGP paths for the Mono Lake excursion (e.g. Channell, 2006), as noted by Cassata et al. (2008), and there is a hint in the Auckland data of a W-E trajectory, which is also consistent with the trend of that path.

The Auckland record is the only confirmed case of the Mono Lake excursion from the south Pacific region and provides a rare and therefore very valuable southern hemisphere constraint for global models of the geomagnetic field. Since the timing and magnitude of the Mono Lake excursion intensity low are now well verified for Auckland, it should also have significant potential as a stratigraphic marker for studies of recent volcanism and palaeoclimate reconstructions in the Pacific-New Zealand region.

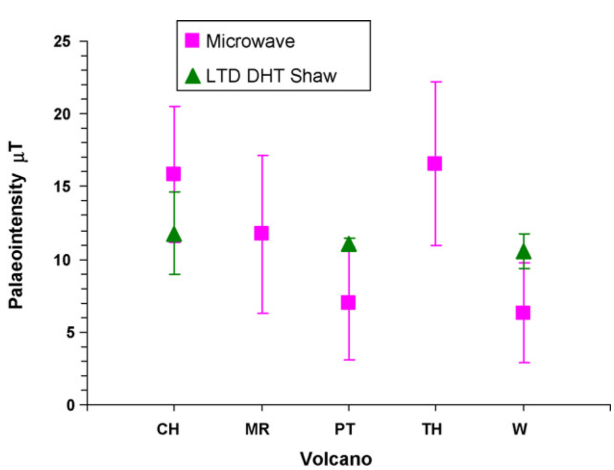

Fig. 7. Mean palaeointensity results (with error bars) for each volcano (calculated as the mean of individual sample results in this case). Also shown are the results from the study of Mochizuki et al. (2006) obtained using the LTD-DHT Shaw method.

7. Conclusions

This microwave palaeointensity study of five different volcanoes from the Auckland volcanic field, New Zealand, provides a robust value of $14 \pm 3\,\mu$T for the absolute geomagnetic palaeointensity during the Mono Lake excursion. The palaeointensity value is consistent with previously reported results from three of these volcanoes based on the LTD-DHT Shaw method (Mochizuki et al., 2006), It confirms that in New Zealand, the geomagnetic field was 30% of normal intensity (VDM of 2.4×10^{22} Am^2). The present study also provides a comparison of the microwave and LDT-DHT Shaw methods of measuring palaeointensity, both applicable to the Auckland basalts that were previously found unsuitable for standard Thellier methods. It appears that in the present case, the microwave method has a higher success rate but produces more scattered results, however the two methods give overall results that are statistically indistinguishable. This study confirms the accuracy and reliability of palaeointensity and palaeodirection determinations from these New Zealand basalts, which together with their definitive ^{40}Ar/^{39}Ar ages, establishes this record of the Mono Lake excursion as one of the best documented.

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