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A geomagnetic excursion in the Brunhes epoch recorded in New Zealand basalts

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ABSTRACT

Anomalous geomagnetic directions are recorded in the thermoremanent magnetisation (TRM) of alkali basalt lavas from the Auckland volcanic field, New Zealand. The concordance of paleomagnetic directions both in different sites from individual eruptive centres and in sites from several different centres, as well as their relatively short age span compared with that of the field as a whole, indicates that these anomalous directions have a geomagnetic origin. The directions, which are dated between approximately 25 ka and 50 ka, do not represent full reversals of the geomagnetic field and are interpreted as excursions. Very few excursions have been reported from the Southern Hemisphere; this is the first such record known from igneous rocks and further supports the notion that excursions are global phenomena. The excursions here are tentatively correlated with those reported from Lake Mungo, Mono Lake and Laschamp.

1. Introduction

A geomagnetic excursion is a major swing of the geomagnetic field from the axial-dipole field direction. Data on such excursions, which have been reported as occurring over time scales as short as a few hundred years [1], provide important constraints on models of the geodynamo. However, since excursions were first reported in the literature they have been the subject of much controversy, even regarding their existence [2]. This is partly because many of the reports relate to sediment core samples where the results are not reproducible. Although core sampling has been successful in obtaining continuous magnetic records, the limited knowledge of how the sediments acquired their magnetisation often makes it diffcult to judge whether the measured anomalous magnetization reflects either the behaviour of the geomagnetic field, an anomalous sedimentary structure, or a disturbance of the core during coring. However, the existing results from onshore outcrop samples and more recent study of them clearly and strongly support the concept of magnetic field excursions. [3–7]

Uniquivocal records of geomagnetic excursions from thermoremanent magnetization (TRM) are scarce; those intermediate directions commonly reported [e.g. 8–10] may equally relate to transitions to full field inversions that were only partially recorded. Only a few reports are available for the Brunhes epoch [3,4,6] Although these are spatially and temporally 'single' samples, they are important because remanent magnetization measurements are both reliable and afford the opportunity to study paleointensities, an important factor in identifying excursions. In this paper, we report an excursion record preserved as a TRM in the basaltic igneous rocks of the Auckland volcanic field, New Zealand; this is, we believe, the first such record from igneous rocks in the Southern Hemisphere.

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2. The Auckland volcanic field

The Auckland volcanic field is the youngest of several fields of late Cenozoic intraplate volcanics in northern New Zealand [11]. The field contains at least 48 discrete centres of eruptive activity, each the result of a monogenetic eruption sequence producing ash and/or cinder cones with or without lava flows. Activity in the field is thought to have commenced at least by 140 ka B.P. [12] and the most recently active centre, Rangitoto Island, erupted about 1400 AD. The rocks of the field are mainly alkali basalts, basanites and nephelinites, although lavas from Rangitoto Island are transitional to tholeiitic; no intermediate or felsic rocks are known to occur in the field.

The ages presently available for the Auckland volcanic field are tabulated in Table 1.

3. Experimental methods

Sample collection was carried out in August 1988 and March 1990, respectively using standard procedures for hand sampling and drill sampling. Samples were collected from 28 sites at 21 vol-

TABLE 1

Paleomagnetic and age data of sites sampled from the Auckland volcanic field.

Volcanic centre	Sample site	Grid ref.	*N*	Dec (°)	Inc (°)	α_{95}	VGP Lat. (°)	VGP Long. (°)	Intensity ($A\ m^{-1}$)	Group	Age	Method	Ref.
1	50	691898	8	357.8	−65.3	2.4	79.4	2.9	0.6		140 ka	TL	12
2	197	794893	13	358.6	−58.7	0.9	87.1	17.2	2.3				
	199	796884	8	2.9	−61.3	1.5	84.0	−25.9	1.8		750–770 a	^{14}C	13, 14, 15
3	196	712839	7	356.2	−49.7	3.1	82.9	147.1	0.6		660 a	TL	12
4	175	795843	8	0.1	−57.3	3.6	88.9	−9.3	2.7				
5	180	678798	7	329.1	−74.7	2.5	59.0	23.3	1.5				
	189	651785	8	328.4	−72.9	3.8	60.3	28.6	2.1		14.4 ka	TL	12
6	43	746776	8	9.9	−51.9	4.8	80.8	−120.4	2.8		9.0–9.4 ka	^{14}C	14, 16, 17
7	179	697732	8	21.7	−50.1	4.6	71.1	−107.3	1.1		17.1 ka	TL	12
8	188	629821	7	3.3	−50.3	1.9	83.6	−159.2	2.6		28 ka	^{14}C	14, 15
9	178	643762	8	352.7	−68.2	6.2	74.7	12.3	6.5				
10	187	723742	7	28.9	−60.1	2.3	67.2	−75.8	4.4				
11	184	749739	8	165.8	−22.4	5.0	−39.6	−23.4	0.9	S	28, 49 ka	^{14}C, TL	17,12
12	186	697711	8	357.5	−45.9	3.3	80.1	161.7	11.0		18, 27 ka	^{14}C	16
13	182	787723	8	343.3	−48.7	1.7	74.3	107.7	1.1				
14	183	796708	8	248.6	−43.8	4.1	−0.2	51.9	0.9	W			
15	195	792703	8	263.6	−36.0	3.4	7.0	65.1	1.1	W			
16	185	652689	7	359.3	61.7	2.4	10.2	174.3	0.8	Nd	23 ka	TL	12
17	49	656671	8	1.6	−56.1	4.7	88.7	−102.0	0.8				
18	181	657659	8	1.9	−51.4	2.6	84.9	−166.8	1.6		30, 38, 42 ka	TL, ^{14}C	14, 12, 17
19	48	733666	9	1.8	64.6	5.4	6.5	176.0	2.3	Nd	29 ka		
	193	730667	8	353.8	58.2	2.6	13.9	169.9	1.7	Nd			
	194	730669	14	356.3	60.3	3.2	11.7	171.9	0.7	Nd			
20	45	759648	8	359.2	64.9	2.4	6.1	174.3	1.2	Nd	25, 28 ka	^{14}C	16, 17
	190	757643	8	355.2	65.7	3.0	5.1	173.9	1.3	Nd			
	191	756647	8	358.5	63.9	2.7	7.3	171.5	1.3	Nd			
	192	757650	8	353.8	60.3	3.2	11.8	173.7	2.3	Nd			
21	46	746638	6	7.5	−49.7	5.6	81.0	−139.2	1.1				

Volcanic centre numbers refer to Fig. 1 and are as follows: 1 = Pupuke; 2 = Rangitoto; 3 = Mt Victoria; 4 = Motukorea; 5 = Mt Eden; 6 = Mt Wellington; 7 = One Tree Hill; 8 = Three Kings; 9 = Mt Roskill; 10 = Mt Smart; 11 = McLennan Hills; 12 = Mangere; 13 = Green Hill; 14 = Otara Hill; 15 = Hampton Park; 16 = Puketutu; 17 = Otatua; 18 = Maungataketake; 19 = Crater Hill; 20 = Wiri; 21 = Matakarua. Intensity is geometric mean after demagnetisation to 20 mT; sample volumes are approximately $1.2\times10^{-5}\ m^3$. Groups are identified for the intermediate sites only: S = south, W = west, Nd = north-down. ^{14}C and thermoluminescence (TL) ages refer to centres rather than sampled sites and are from published literature. *N* is the number of samples measured per site. Grid references refer to NZMS 260 sheet R11 1:50,000. The mean latitude and longitude of the sites is 36.9°S and 174.8°E, respectively. Negative latitude denotes southern hemisphere, negative longitude denotes easting.

canic centres (Fig. 1). At least eight independently oriented samples were taken from each site. All the samples were of basalt lava, except for one from a welded scoria site (site 194). Because two of the centres had been found to have intermediate magnetic directions from the results of the first survey, multiple sites were sampled at these centres during the later survey.

Both hand samples and drill samples were cut into cylinders with diameters and heights of about 25 mm for the measurements. Two to four specimens were usually obtained from each sample. Measurements were performed with a Natsuhara Giken SMM-85 spinner magnetometer at the University of Osaka Prefecture. An alternating field (af) demagnetizer DEM-8601M (Natsuhara Giken Co.) capable of applied fields up to 70 mT was used for magnetic cleaning. One pilot specimen from each site was first subjected to progressive af demagnetization in twelve steps up to 70

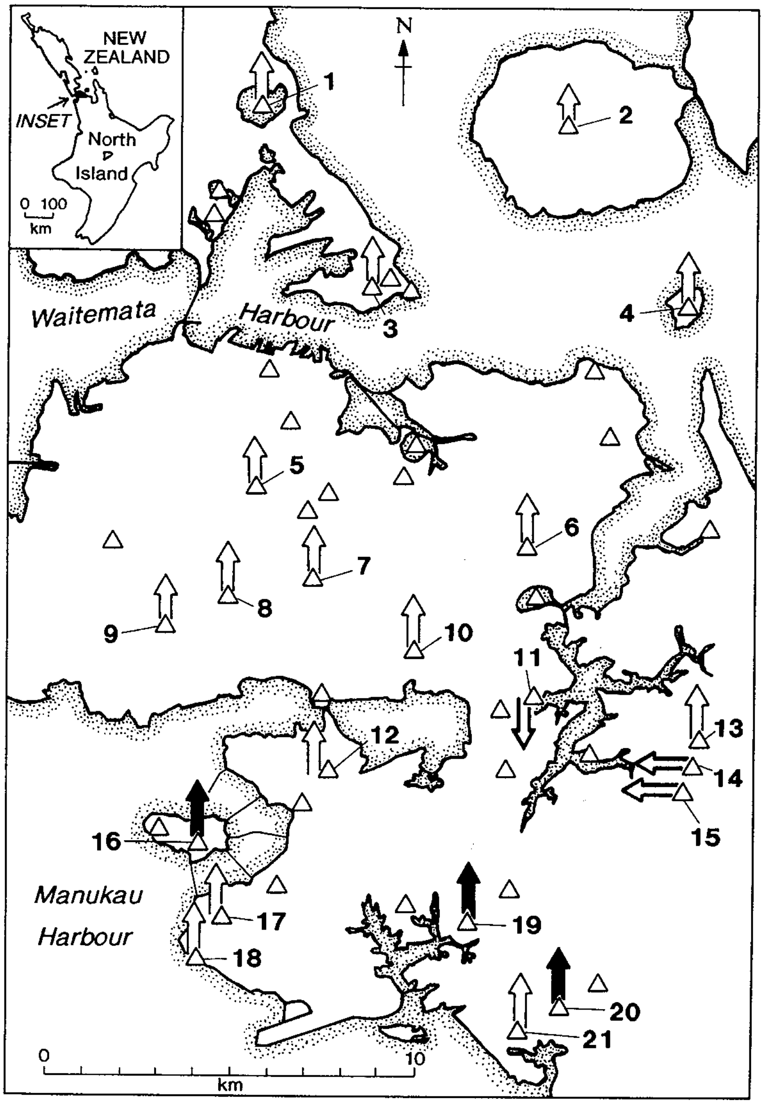

Fig. 1. Map showing the site distribution of volcanic centres within the Auckland field (open triangles) and the symbolic paleomagnetic direction for each sampled volcano. Centres with normal paleomagnetic direction are expressed as open north-pointing arrows. Other arrows show centres with intermediate directions. Numbers refer to volcanic centres indexed in Table 1.

mT. If the demagnetization results showed simple characteristics (i.e. essentially linear behaviour) all the other samples of the site were demagnetized at an appropriate step; otherwise, all other samples were also demagnetized progressively.

4. Results

The samples were generally well behaved under demagnetization, as might be expected for basalts. Orthogonal diagrams for af treatment

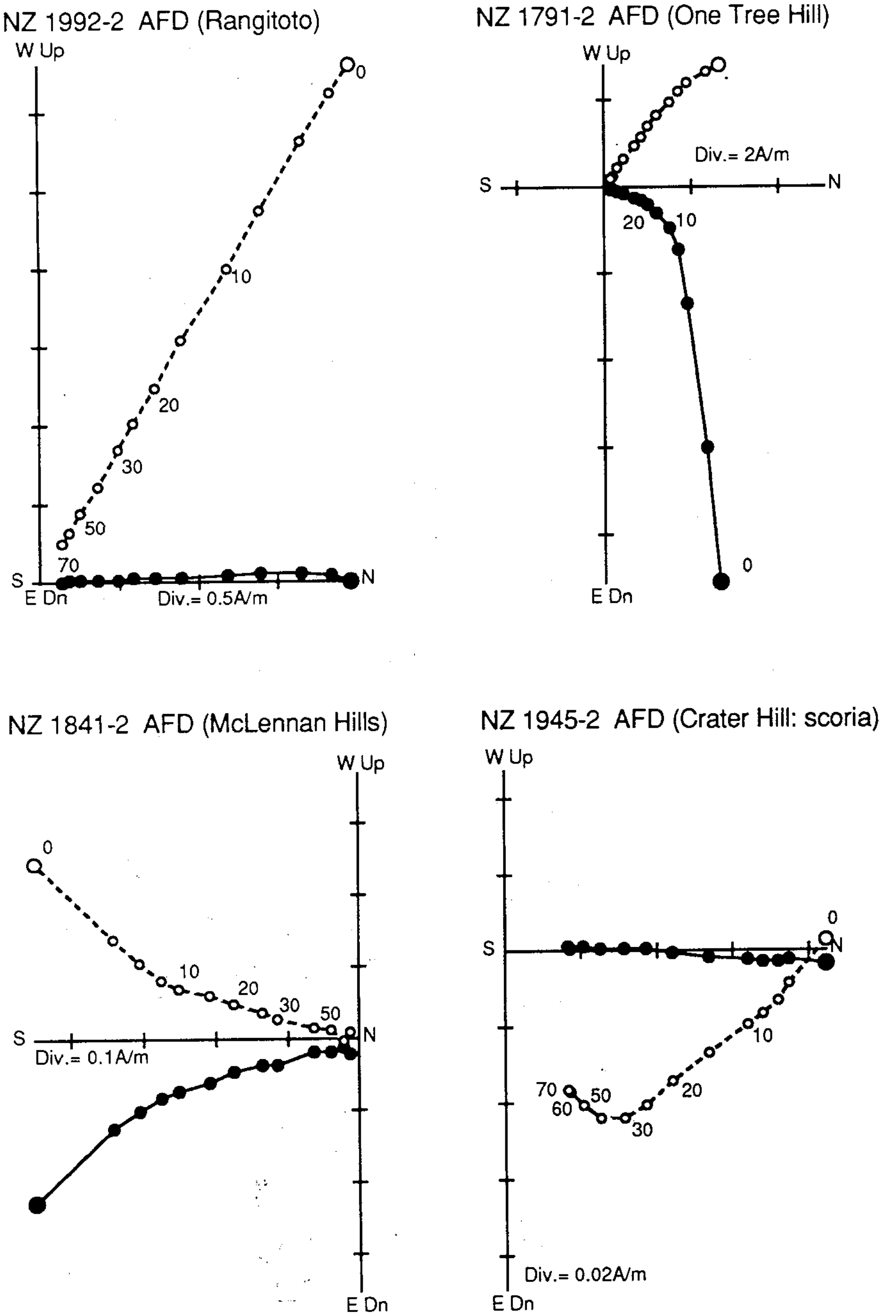

Fig. 2. Orthogonal vector demagnetization plots of representative specimens. Dots represent projection onto horizontal plane and circles represent projection onto east–west vertical plane. Numbers are demagnetisation steps (mT). The first three digits of sample labels refer to site numbers listed in Table 1.

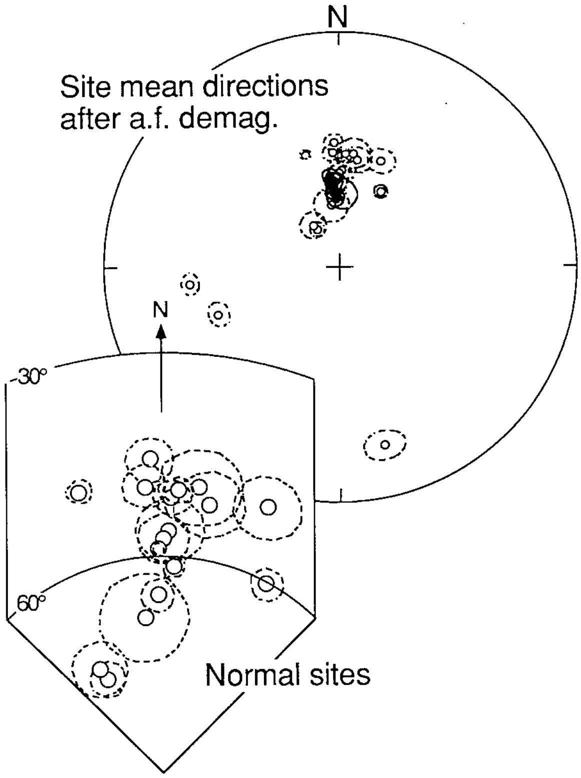

Fig. 3. Equal area plot showing the site mean directions and 95% confidence limit for all sites, and enlarged diagram is for the normal sites.

show a simple and stable single-component nature with or without a present field VRM (Fig. 2). Generally, most of the magnetization was erased before 70 mT of demagnetization. Very good clustering of the magnetization directions at each site, except for site 194, was obtained after af demagnetization to 20 mT. A few samples of site 194 exhibited a stable secondary magnetization coincident with the present field direction. Thus, a specimen from each sample in this site was subjected to progressive af demagnetization in 10 mT intervals up to 70 mT and an appropriate step for each sample was selected for the site mean calculation.

Although most of the sites are of normal polarity, eleven sites from six centres clearly have intermediate directions. Site mean directions with 95% confidence circles are presented in Table 1, and illustrated in Fig. 3. The angular standard deviation of the VGP from the geographical north pole for the normal sites is 13.7° for the normal sites, which is smaller than that reported for the North Island of New Zealand [18]. This may reflect the sporadic and short-lived nature of volcanic events in the Auckland volcanic field. Further discussion on this discrepancy will take place in a separate paper which reports results from other volcanic fields in the Auckland region. The intermediate sites were grouped into three by their directions: groups with north-down, west and south directions (Fig. 4). The north-down group of three centres includes two which have multiple sites. The site mean directions of this group are very tightly clustered. Indeed three sites have virtually the same paleomagnetic direction.

5. Discussion of results

The intermediate directions reported here are considered to be due to a geomagnetic excursion, for the following reasons:

(1) All of the sites giving intermediate magnetic directions are from quarry faces or road cuttings, and it is clear that small-scale rotations have not taken place.

(2) Remanence directions within and between centres are consistent. Seeing as the distance between sites at each centre is several hundred metres, and in the case of concordant samples from Wiri and Crater Hill are 3 km apart, large block rotations are ruled out.

(3) Recent aeromagnetic surveys (unpublished) of Wiri and Crater Hill show negative anomalies inconsistent with a normal magnetisation. Although modelling studies are still in progress, the results clearly contrast with those from normally magnetised centres which show the expected positive anomalies. Again, this confirms that the bulk NRM of these two centres is anomalous.

(4) Reports of excursions have been attributed to the effect of self-reversal [19]. However, creating an intermediate direction by self-reversal requires a particular balance between the normal and reversed parts of the total magnetisation. There are three reasons why this is unlikely to be the case. Firstly, the orthogonal demagnetisation diagram shows good linearity and since it is unlikely that both the normal and reversed components have the same coercivity spectrum the straight-line demagnetisation profile implies a

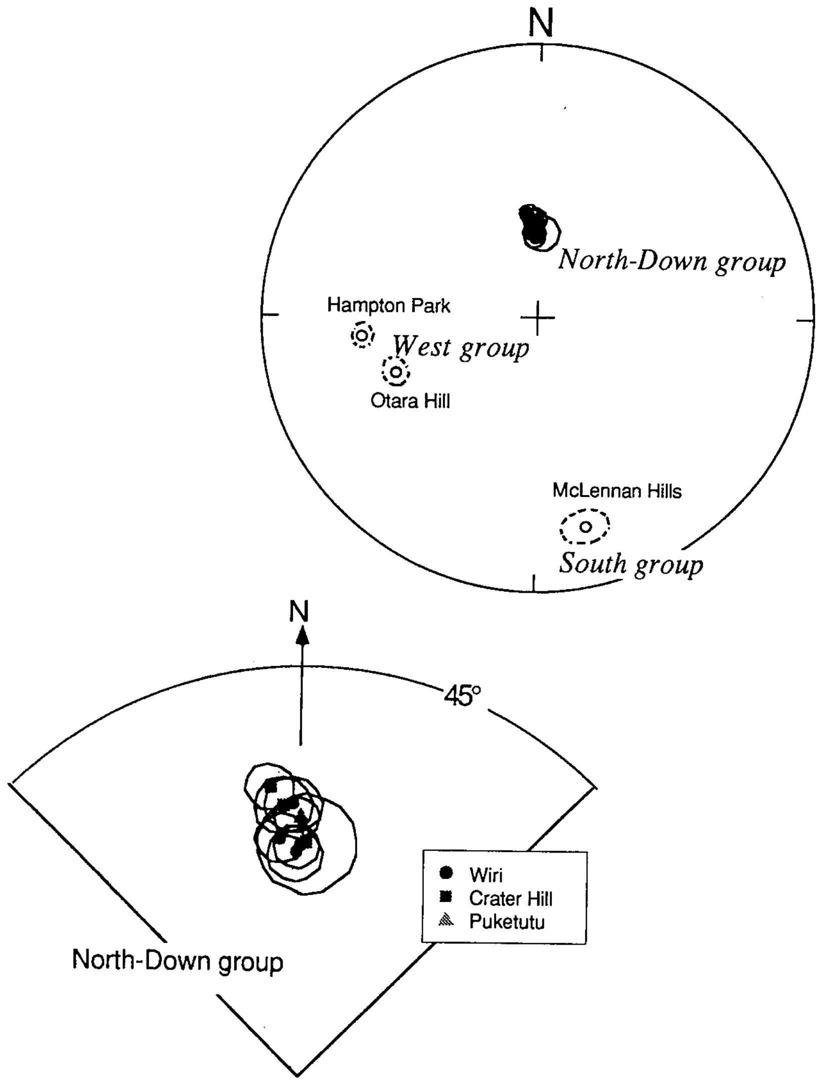

Fig. 4. Equal area plot of intermediate sites. The north-down group is enlarged in order to distinguish each volcanic centre.

single origin for the magnetisation. Secondly, the tight cluster of magnetisation directions in samples from spatially separated sites would be difficult to explain by self-reversal, which is likely to be very sensitive to small changes in magnetic mineralogy. Thirdly, the existance of a 'self-intermediate' magnetisation is unlikely because the normal and reversed directions are the only two singular and therefore likely magnetic directions.

(5) The sites with intermediate magnetic directions are restricted in age; all of the ages available for the cones show that these intermediate directions are between 23 ka and 49 ka old.

The excursion identified here is characterised by quite variable geomagnetic directions. Indeed, during the excursion period a fully normal field direction is also indicated (site 18). This latter result may serve to emphasise the erratic behaviour of the field during excursion. However, it could also be a result of the relatively poor age control (see Table 1). Therefore, while it is clear that an excursion did occur at about the time indicated it is not yet possible to place precise age limits on it.

6. Discussion

It is commonly difficult to correlate Brunhes geomagnetic excursions on a global scale, partly because their age typically falls in a gap between two major dating methods (K-Ar and ^{14}C), and partly because an excursion is so short that there are too few reports to make a systematic correlation. Here we attempt to correlate the Auckland excursion with those reported from onshore outcrop examples only, because of their greater reliability. There are few such reported excursions younger than 100 ka; the most well known are the Lake Mungo, Mono Lake and Laschamp excursions.

The age of the Lake Mungo (Southeast Australia) excursion is reported as 25–30 ka [4], which is concordant with the Auckland excursion both spatially and temporally. A problem with the Lake Mungo excursion is that the samples were from an archaeological site (a fireplace), and thus impossible to re-examine. Furthermore, the very high paleointensity reported suggests that the magnetization may be the consequence of lightning [20]. Although we are still carrying out the paleointensity study, the remanence intensity histogram that has been obtained to date (Fig. 5) does not show that the intermediate directions are associated with anomalously high values of

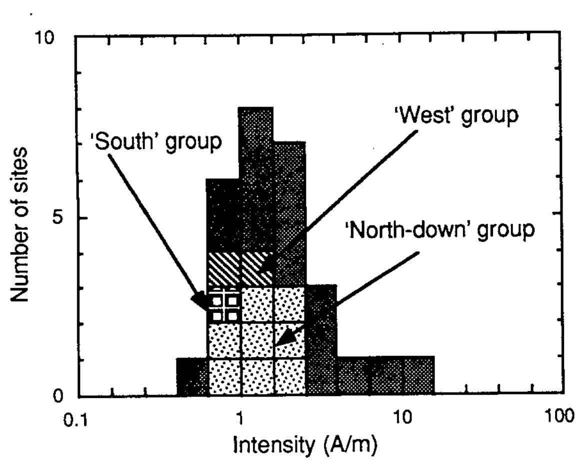

Fig. 5. Histogram of remanence intensity after 20 mT of af demagnetization. The geometric mean was used to calculate the intensity at each site.

intensity compared to the normal samples. The reported Mono Lake excursion is thought to range in age from 26 to 29 ka [1]. It also, therefore, is consistent in age with the Auckland excursion.

Many investigations have been performed to determine the age of the Laschamp excursion. The K-Ar and TL ages are scattered around 40 ka, which is consistent with the upper age of the Auckland excursion. Furthermore, there is the opinion that the difference in ages between Lake Mungo and Laschamp is not conclusive [2]. A notable difference between the Laschamp and Auckland excursions is that the former is a full reversal while the latter is not. However, this is not a conclusive difference because in a statistical sense both excursions have been obtained from essentially single samples.

Although there remain difficulties in correlating excursion events, especially because of uncertain age determinations, it is quite plausible that some excursions represent a world wide phenomenon. We can at least say that there was a period of unstable geomagnetism between about 50 and 25 ka and that this phenomenon has been recorded in igneous rocks in New Zealand. Improvement of dating methods will make the most significant contribution to resolving some of these questions.

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