Further Palaeomagnetic Results from South Victoria Land, Antarctica

C. Bull,* E. Irving and I. Willis

(Received 1961 July 31)†

Summary

A palaeomagnetic study has been made of rock samples taken from a 5 000 ft sequence in South Victoria Land. The sequence consists of granites, sediments and hypabyssal intrusives of Mesozoic, Palaeozoic and possibly Pre-Cambrian ages. The directions of natural remanent magnetization are *approximately* uniform throughout, but small and apparently real differences do occur between some of the units within the sequence. Laboratory tests using alternating magnetic fields suggest that these differences are due to the presence of unstable components of small but variable magnitude and that the mean directions of the *stable* components are parallel in all the units studied. This uniformity in direction could have resulted from the geomagnetic field in the region being constant in direction for a long period of time in the Palaeozoic and Mesozoic, or from the reheating of the whole area during the last phase of intrusion (that of the Ferrar dolerites) in Mesozoic times. The latter interpretation is favoured. The variations in magnetic properties through the Ferrar dolerite sheets are described and provide information relevant to theories of their emplacement and differentiation.

1. Introduction

This paper describes palaeomagnetic results from rock formations in the Victoria Valley area of South Victoria Land. The samples were collected by one of us (I.W.) during the Victoria University of Wellington Antarctic Expedition (1959–60). The physical measurements were made at the Institute of Advanced Studies in the Australian National University. Victoria Valley is ice-free and lies immediately north of Wright Valley from which palaeomagnetic results have already been described (Bull & Irving 1960, subsequently referred to as Paper I).

2. Geology and Sampling

2.1. The geological sequence in the Victoria Valley, which is shown schematically in Figure 2, is similar to that in the Wright Valley, described in Paper I (McKelvey & Webb 1959, 1961, see also Harrington 1958). A basement complex is overlain by several thousands of feet of Beacon Group sediments, and

* Now at the Institute of Polar Studies, Ohio State University, Columbus, U.S.A.
† Received in original form 1961 April 13.

sheets and sills of dolerite intrude both basement and sediments. A similar geological succession continues southward for at least 700 miles (Gould 1935). At each of 15 localities in the Victoria Valley area (numbered 11 to 25 inclusive in Table 1 and Figures 1 & 2) samples have been collected usually at several sites through the accessible exposures. The stratigraphic distribution of sites is given in Figure 2.

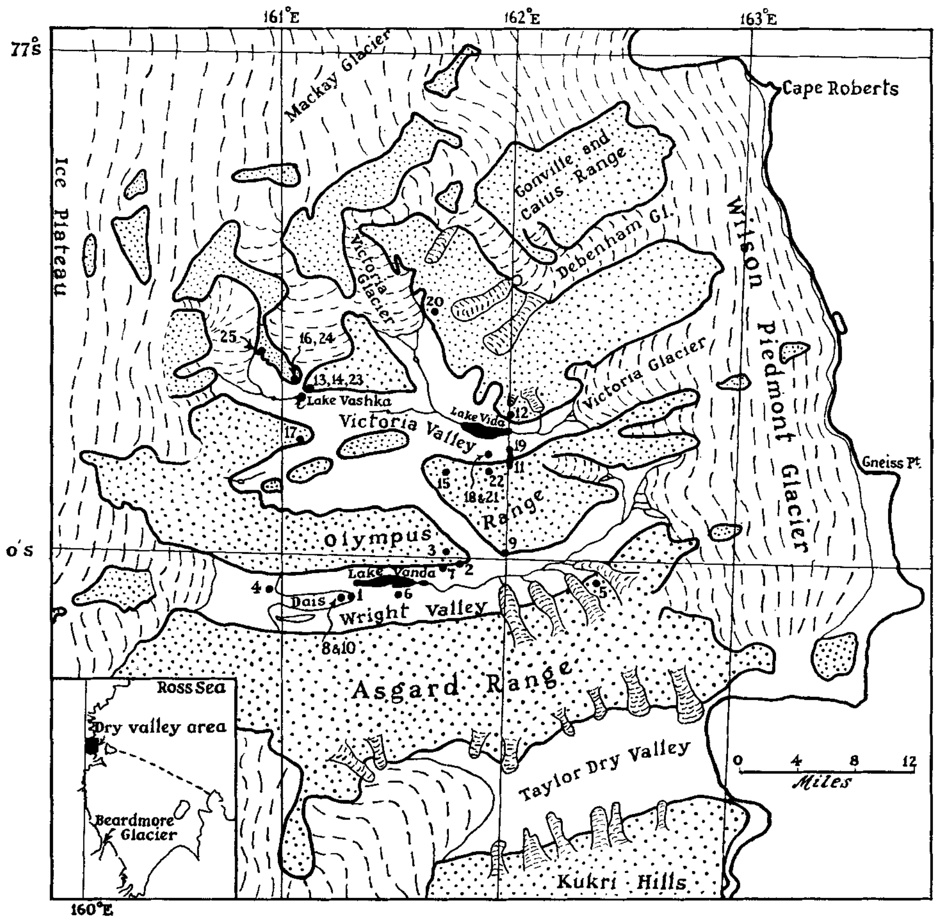

FIG. 1.—Sketch map of the Wright and Victoria Valleys. Glaciers are indicated by lines and land over 2 500 ft by stippling. Localities are indicated by dots, the numbering being consistent with that in Table 1 of Bull & Irving (1960) (localities 1–10), and with Table 1 of this paper (localities 11–25).

2.2. The basement complex consists of the Ross System metamorphics and Admiralty System intrusives, which are cut by a series of basic and acidic dykes called the basement dykes. The complex is Palaeozoic or Pre-Cambrian in age. A sample of paragneiss from Gneiss Point (Figure 1) has been cautiously dated at 520 million years by the A^{40}/K^{40} method (Goldich, Nier & Washburn 1958). The Admiralty granites, which here consist of an older porphyritic gneissic granite and a younger sheet-like body of horneblende granite, have been sampled at 9 sites at three localities; a single oriented sample was obtained at each site and between 2 and 6 disk specimens (35 mm in diameter and 7 mm in thickness) were cut from each sample. The basement dykes were sampled at 15 sites, each a separate dyke (see Table 1); at all except 18a two separately oriented samples were collected, from each of which a single disk was cut. At site 18a one sample only was obtained and two disks were cut from it, so that each dyke is represented by two specimens.

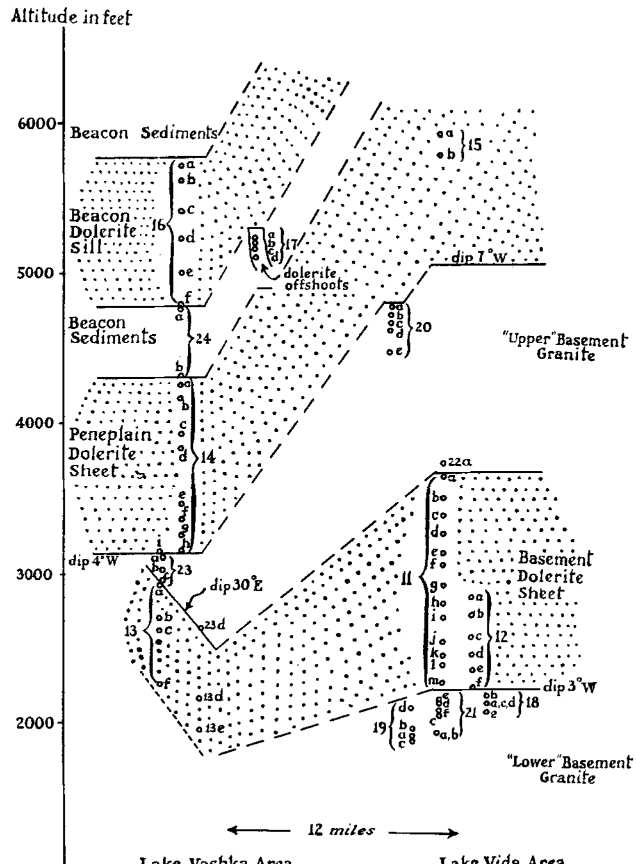

FIG. 2.—Schematic geological section. This shows the relative stratigraphic position of the sampling sites. The numbering is consistent with that in Table 1. The dolerite sheets are stippled.

2.3. The Beacon Group is restricted to the western part of the area. There is a small westerly dip of 3°–7° and the sediments thicken in this direction to about 4000 ft at the edge of the inland ice. The age of the sequence is estimated from fossil evidence (Woodward 1921, Seward 1914, Edwards 1928) and probably lies within the limits of Upper Palaeozoic and Triassic. Samples of Beacon sediments were obtained from three sites lower in the sequence than Edwards' Permo-Carboniferous level (Edwards 1928). Between 1 and 5 disks were studied from each sample.

2.4. The Ferrar dolerites, which are probably Mesozoic in age, occur throughout the area, occasionally as dykes but normally as sheets in the basement or as sills in the sediments. They are referred to collectively as "sheets".

Table 1

Site positions and direction in the hypabyssal intrusives

The locality and site numbers are continuous from Paper I. The site directions are specified by the declination (D_{11}) reckoned east of true North, and the inclination (I_{11}) given with respect to the horizontal at the site. D_{11}, I_{11} is the average of two specimen directions after treatment in alternating magnetic fields of 225 oersteds (peak). At localities 11, 12, 14, 15 and 16 in the regular sheets the distances from contacts of the top and bottom sites are given, and the distances from contacts of the intermediate sites can be obtained by interpolation. At locality 13 (zone of flexures) the structure of the intrusions is more complicated and specific information is given in each case.

Geological unit	Locality no.	Geographical coordinates	Locality description	Altitudes of sites ft	Site no.	D_{11}	I_{11}
Lower Dolerite sheet	11	77° 23′ S–77° 24′ S 162° 00′ E	SE of Lake Vida	3 630 (10 ft. below top contact)	11a	297	−41
				3 490	11b	244	−65
				3 360	11c	310	−83
				3 250	11d	283	−61
				3 120	11e	325	+17
				3 030	11f	235	−67
				2 900	11g	264	−69
				2 780	11h	274	−83
				2 690	11i	248	−48
				2 540	11j	233	−66
				2 430	11k	235	−58
				2 370	11l	262	−77
				2 250 (80 ft above lower contact)	11m	250	−67
	12	77° 22′ S 162° 00′ E	NE of Lake Vida	2 820 (860ft below top contact)	12a	—	—
				2 710	12b	—	—
				2 570	12c	—	—
				2 450	12d	—	—
				2 350	12e	—	—
				2 220 (10ft above lower contact)	12f	—	—
	13	77° 20′ S 161° 08′ E	Zone of flexure N of Lake Vashka	2 920 (120ft below top contact)	13a	275	−67
				2 690 (230ft below top contact)	13b	231	−77
				2 600 (350ft below top contact)	13c	241	−55
				2 160 (410ft below top contact)	13d	232	−72
				1 960 (610ft below top contact)	13e	254	−48
				2 240 (710ft below top contact, about 50ft above bottom contact)	13f	199	−72

Table 1—*continued*

Geological unit	Locality no.	Geographical co-ordinates	Locality description	Altitudes of sites ft.	Site no.	D_{11}	I_{11}
Peneplain Dolerite sheet	14	77° 20′ S, 161° 08′ E	N of Lake Vashka	4 250 (150 ft below top contact)	14a	220	−63
				4 150	14b	248	−61
				3 910	14c	274	−69
				3 810	14d	233	−73
				3 430	14e	207	−73
				3 330	14f	272	−65
				3 230	14g	227	−62
				3 130	14h	224	−66
				3 050 (10 ft above bottom contact)	14i	264	−73
	15	77° 25′ S 161° 45′ E	SW of Lake Vida	5 910 (760 ft above bottom contact)	15a	272	−64
				5 770 (620 ft above bottom contact)	15b	289	−64
Dolerite intrusives into the Beacon Group	16	77° 20′ S, 161° 04′ E	Main sill, NW of Lake Vashka	5 700 (50 ft below top contact)	16a	208	−45
				5 600	16b	230	−63
				5 400	16c	261	−57
				5 210	16d	236	−62
				4 980	16e	237	−63
				4 760 (10 ft above lower contact)	16f	247	−68
	17	77° 23′ S 161° 08′ E	Sills and dykes, apophyses of the main sill	5 180	17a	specimens broken	
				5 160	17b	217	−77
				5 150	17c	233	−80
				5 100	17d	253	−66
Basic Dykes	18	77° 23′ S, 161° 52′ E	S of Lake Vida (in lower granite)	2 140	18a	275	−58
				2 330	18b	239	−79
				2 130	18c	221	−50
				2 140	18d	240	−66
				2 060	18e	246	−66
Acid dykes	19	77° 23′ S, 162° 00′ E	SE of Lake Vida (in lower granite)	1 880	19a	235	−58
				1 930	19b	225	−70
				1 870	19c	241	−59
				2 080	19d	245	−48
	20	77° 17′ S, 161° 43′ E	E of Upper Victoria Glacier (in upper granite)	4 700	20a	214	−58
				4 750	20b	246	−63
				4 650	20c	226	−63
				4 650	20d	233	−67
				4 650	20e	231	−66

The lowest sheet lies almost wholly within the basement, and is called the basement dolerite sheet. It has a general westward dip of 5° and is usually found along or near the contact of the two granites, but south of Lake Vida it intrudes the younger granite only. In the Ross metamorphics, further east, the sheet ascends, sub-parallel to the foliation, and lenses out. South of Lake Vida there is evidence of two phases of injection, referred to as the lower and upper intrusions. North of Lake Vashka, and in the central Wright Valley the basement sheet has upward flexures which are truncated by the peneplain dolerite sheet (see below) and in one location in the Wright Valley the upward flexure carries it above the basement-Beacon contact.

In general the second dolerite sheet lies along the junction between the basement and the Beacon sediments, and is called the peneplain dolerite sheet. In a few places upward flexures expose the basement-Beacon contact. The thickness varies between 600 and 1 500 ft. It has a regional dip of about 3° westwards. The basement and peneplain dolerite sheets are the northerly continuations of the lower and upper dolerite sheets of Paper I.

The sills in the Beacon Group do not have the lateral extent of the basement and peneplain sheets and frequently step from one horizon to another. The thickest of these (1 000 ft) has been sampled (locality 16) together with dyke-like and sill-like offshoots (locality 17).

The sampling sites were placed vertically as evenly as practicable (Table 1 Figure 2). Two samples were taken at each site except at sites 11b, 13e, 14f, 15a and 15b. In general one disk was studied from each sample, but in some cases where special tests (see Section 3) were carried out two disks were used. At the sites just listed only one sample was obtained, and from each of these two disks were studied, so that all sites are represented by at least two disks. The samples at locality 12 (6 sites) were not reliably oriented, being the first attempt at sampling on this expedition. Also they tended to be somewhat weathered. At site 17a the samples were broken during cutting in the laboratory. Directions at these 7 sites have not therefore been recorded.

All samples except those from locality 12 are fresh in hand specimen. Twenty-five thin sections made from samples representing all the igneous rock types studied were examined under the microscope and in all cases the outlines of the iron-minerals are clean and sharp and there is no indication of recent weathering.

Altogether in the present work 127 samples (141 disks) have been collected from 71 sites in the Victoria Valley area. Together with the previous year's collection this makes a total of 164 samples (218 disks) from 98 sites in the region of South Victoria Land depicted in Figure 1.

3. Experimental methods: treatment of partial instability in the igneous samples

The intensity and direction of magnetization were measured by astatic magnetometers using the methods described by Collinson, Creer, Irving & Runcorn (1957). Declinations (D) are reckoned clockwise from geographic north, and inclinations (I) are given relative to the present horizontal.

In our previous work in Wright Valley (Paper I) the natural remanent magnetization ($\mathbf{M}_n$) of some specimens contained unstable components directed along the present Earth's magnetic field, and the results from such specimens were not used in the analysis. In the present work an attempt has been made to remove the effect of such components by partial demagnetization in alternating magnetic fields, so that the results from all specimens may be used and the selection used in Paper I is unnecessary. The alternating magnetic field conditions required to do this have been estimated from the following experiment, using the apparatus and methods described by Irving, Stott & Ward (1961). Four disks each from sites 14i, 16c, 16d, 17b, 17d, 20a were treated in alternating fields ($H_p \sim$) of 150, 225, 300, 375 and 450 oersteds (peak) in the absence of a steady field with intermediate measurements of the directions of magnetization. It was found, (1) that agreement in the directions at any site compared with that initially obtained either improved slightly or remained unchanged in fields between 150 and 300 oersteds (the variation within this range being negligible) and the mean site directions either did not change or moved away from the present Earth's field by a few degrees, and (2) that treatment in fields greater than this increased the scatter without changing the mean site direction significantly. The first effect is interpreted as being due to removal of unstable components directed approximately along the present Earth's field, the second to the progressive randomization of the stable magnetization as the strength of the alternating field increases. These effects are similar to but not so marked as those detailed previously (Irving & others 1961). It is concluded that the field strength required is between 150 and 300 oersteds. For uniformity all specimens have been treated in an alternating magnetic field of 225 oersteds. The directions of the magnetization after this treatment, are termed the *stable magnetization directions* ($\mathbf{M}_{st}$).

Although *most* specimens have high magnetic stability the precaution of removing the small unstable components is considered to be a worthwhile refinement since the mean directions of particular groups tend to move away from the present field direction. For example (Figure 4(c) & (d)) the initial mean direction of magnetization of the specimens from the peneplain dolerite sheet is $D = 254°$, $I = -73°$, whereas after treatment ($H_p \sim = 225$ oersteds) it becomes (251°, −69°), a change of 4° away from the present field.

4. The observed directions of magnetization

4.1. *Admiralty granites* (Figure 3d).—Five samples from the "lower granite" at locality 21 (161° 52′ E, 77° 23′ S) (Figures 1 and 2) were collected at distances from the lower contact of the basement dolerite sheet varying from 70 to 300 ft. All of the 5 sites are more than 20 ft from the nearest dyke. From these 5 samples 15 specimens were measured. After treatment in an alternating field of 225 oersteds the mean direction is (257°, −77°). $R_{21} = 14{\cdot}39$ (notation explained in Section 5) closely similar to that of the dolerites.

One sample was collected at each of four sites in the "upper granites" all within 100 ft of dolerite contacts (22a, 23a–d). In three cases the magnetization is not stable, the directions becoming scattered after treatment in alternating fields of 225 oersteds or more. In the remaining sample (site 23c, in the "upper granite" 6 ft above the upper contact with the basement sheet, 161° 8′ E, 77° 22′ S) the directions are stable and the mean of six disks from it gives (256°, −64°).

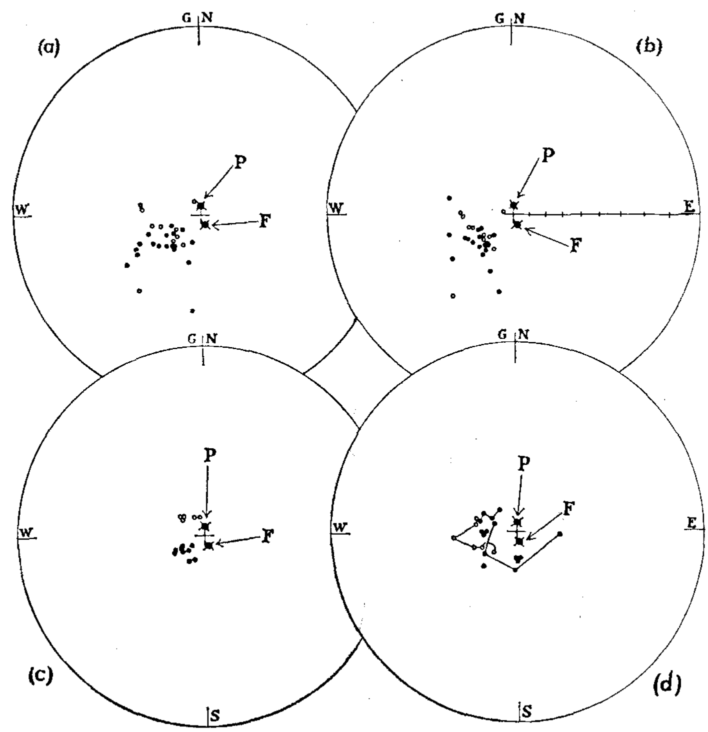

FIG. 3.—Directions of magnetization in the basement rocks and in Beacon Group sediments. Stereographic projections are used, the primitive being the horizontal at the site. (a) gives the directions of natural remanent magnetization, $\mathbf{M}_n$, and (b) the stable directions, $\mathbf{M}_{st}$, (after treatment in 225 oersteds, $H_p \sim$) observed in the basement dykes; all directions have negative inclinations and are indicated by circles (basic dykes) and dots (acid dykes). (c) gives the directions ($\mathbf{M}_n$) in Beacon sediments collected near (one site, 24a, circles) and distant from (two sites, 24b and 25, dots) igneous contacts. (d) gives the directions ($\mathbf{M}_{st}$) after treatment in 225 oersteds ($H_p \sim$) at 5 sites (locality 21) in the Admiralty granites distant from contacts (dots), and at one site (23c) near contacts (circles). In (c) and (d) directions in disks from the same sample are linked together. In (c) and (d) all inclinations are negative.

4.3. *Beacon sandstones.*—Samples of sandstone have been collected at two sites some distance away from dolerite contacts. At site 25 (160° 56′ E, 77° 17′ S) to the east of the Webb Glacier, two samples were obtained at an altitude of 3 230 ft) 450 ft from the nearest dolerite contact. At site 24b (161° 04′ E, 77° 20′S, further to the south-east, two samples were obtained at an altitude of 4 300 ft, about 100 ft from the nearest dolerite contact. The sandstones are medium to fine-grained well-bedded buff-coloured sandstones. From the four samples nine disks have been studied. The mean direction of the natural remanent magnetization ($\mathbf{M}_n$) is (232°, −74°) $R_{21} = 8{\cdot}97$. The intensities are high compared with sediments of this type collected elsewhere, being comparable to those in red beds; at site 25 $M_n = 2{\cdot}9 \times 10^{-5}$ e.m.u./cm^3 (mean of 5 disks), and at site 24a $M_n = 1{\cdot}7 \times 10^{-5}$ (mean of 4 disks). The intensity falls by a factor of 15 and 32 respectively and the directions change by 20° after treatment in alternating fields $H_p \sim\ = 900$ oersteds.

At locality 24a (161° 4′E, 77° 20′S, altitude 4750 ft) two samples of Beacon sandstone were obtained at the lower contact of the Beacon dolerite sheet. The mean direction of magnetization ($\mathbf{M}_n$) of 5 disks from these is (325°, −75°), and the mean intensity is $3{\cdot}8 \times 10^{-5}$. The magnetization is very stable, the directions change only two or three degrees and the intensity falls by a factor 3 after treatment in $H_p \sim\ = 900$ oersteds.

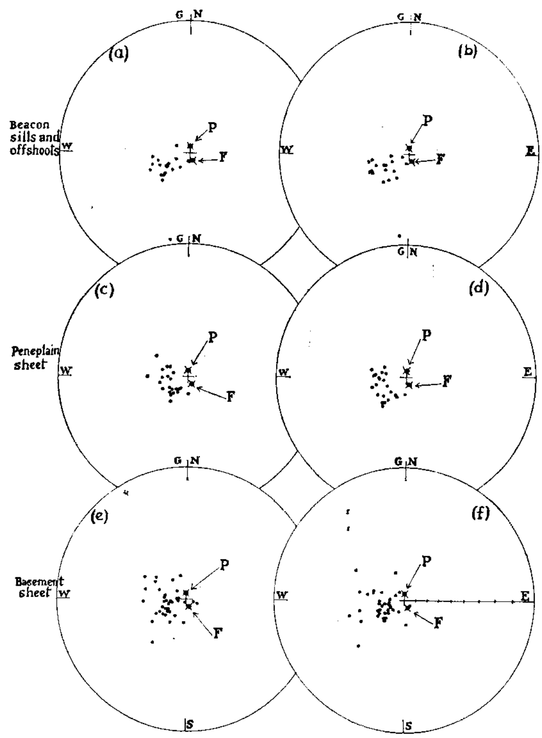

FIG. 4.—Directions of magnetization of the Ferrar dolerites, Victoria Valley. (a), (c) and (e) give the directions of natural remanent magnetization ($\mathbf{M}_n$) observed in the three sheets. (b), (d) and (f) give the stable directions ($\mathbf{M}_{st}$) which are those obtained after treatment in 225 oersteds alternating magnetic field. Stereographic projections are used, the primitive being the horizontal at the sampling sites. All directions plotted on the upper hemisphere have negative inclinations and are indicated by dots, except the directions from site 11e which have positive inclinations and are marked by crosses. The dipole field (**P**) and the present field directions (**F**) are indicated by crossed dots.

4.4. *Ferrar dolerites.*—The individual specimen directions for each sheet before and after treatment in 225 oersted ($H_p \sim$) are plotted in Figure 4. The site directions after treatment are in Table 1.

In addition to these results from the Victoria Valley a few results have been obtained for Ferrar dolerites from the Beardmore Glacier region (83° 22′ S, 164° 10′ E) 450 miles to the south. One sample from each of 5 sites was collected by Mr R. I. Walcott, of the New Zealand Geological Survey Antarctic Expedition 1959–60. The geological sequence in this area is similar to that in the Wright and Victoria Valleys. Two sites are near the middle of the peneplain dolerite sheet and three sites are spread through a vertical distance of 100 ft in another sill more than

300 ft thick, intruded into Beacon sediments. Two disks cut from each sample were measured. After treatment in an alternating magnetic field of 225 oersteds the mean direction is (279°, −78°) R_{22} = 4·81, and the error in the mean is 17°. This direction is in good agreement with those observed further north.

5. Analysis of the directions of stable magnetization (M_{st})

The results from the basement dykes and the Ferrar dolerites have been subjected to an analysis based on Fisher's treatment of dispersion on a sphere (Fisher 1953). The data from the granites and sediments are not sufficient to merit detailed treatment. The specimens obtained previously from Wright Valley (Paper I) have been subjected to the same uniform demagnetization treatment and the results incorporated. In the earlier work the number of specimens per site was rather variable, and in this analysis only two specimens per site have been used from the 1958–59 collections so as to render the treatment uniform throughout (see Appendix). The results from site 11e are not used since the directions, although stable, depart widely from the main group (Table 1, Figure 3a). This is unlikely to be due to an orientation error since results from separately oriented samples agree. The inclusion of these results would not significantly affect the analysis.

In the analysis a distinction is made between the *site* (groups of results from several specimens at the same site) and the *geological unit* (results from different sites in a rock unit) levels using the methods described by Watson & Irving (1957). The statistical results obtained at each level are distinguished by suffixes, the first number of which gives the level to which the value refers, and the second gives the level at which the results have been combined. In Table 1 the mean direction at each site (D_{11}, I_{11}) is given; this is the direction of the resultant (length R_{11}) obtained by summing N specimen unit vectors at a site. The mean direction for a geological unit (D_{22}, I_{22}) is the direction of the resultant (length R_{22}) of B site mean directions each given unit weight. R_{21} is the resultant of ΣN specimen unit vectors irrespective of their grouping into sites, and k_{21} and k_{22} are estimates of the within- and between-site precision for a geological unit.

Results at the geological unit level are given in Table 2. Estimates of within- and between-site precision are somewhat variable between different dolerite sheets but the average for all the Ferrar dolerites is closely similar to the average obtained from the basement dykes, the agreement in k_{22} being particularly good. The mean directions in the three sheets are not significantly different from one another, and the mean direction of all dolerites is not different from that of the dykes.

The validity of this analysis depends on whether or not the within-site and between-site dispersions follow Fisher's distribution. In order to carry out this test adequately at least 40 directions are needed (Watson & Irving 1957) so that the within-site dispersion cannot be tested, but the 46 site directions for the dolerite sheets provide data for a useful test of the between-site dispersion which is the more important in the estimation of errors. This is done by plotting the site directions on a stereogram so that the calculated mean (Table 2) coincides with the centre of the net. The azimuthal angle and the departure from the mean for each site is then read off and the distribution tested against that expected on Fisher's model by using the statistic chi-squared. The azimuthal symmetry is tested first.

Range (arbitrary zero)	1–90°	91–180°	181–270°	271–360°
Number observed	9	14	11	12
Number expected	11·5	11·5	11·5	11·5

Table 2

Analysis of directions in the hypabyssal intrusives

The results from samples collected on both the 1958–59 and 1959–60 expeditions are summarized. The directions used are those obtained after treatment of specimens in 225 oersteds (peak) alternating magnetic field. R_{22} is the vector sum of the B site directions each given unit weight; R_{21} is the vector sum of the ΣN specimen directions each given unit weight; R_{11} is the vector sum of N specimens at each site. The within- and between-site and overall precision are given in the columns headed k_{21}, k_{22} and k_{20}. D_{22}, I_{22} are the declination and inclination of the mean direction obtained by averaging the site mean directions (D_{21}, I_{21}), and a_{20} is the radius of the cone of confidence (P = 0·05).

Rock Unit		No. Sites, B				Resultants			Precision			Mean directions		
		Wright	Victoria	No. samples	ΣN	R_{22}	R_{21}	ΣR_{11}	k_{21}	k_{22}	k_{20}	D_{22}	I_{22}	a_{20}
Ferrar dolerites	Beacon intrusives	—	9	18	18	8·80	17·29	17·67	28	172	376	236	−66	7
	Peneplain sheet	3	11	24	28	13·43	27·44	27·87	107	84	846	251	−69	5
	Basement sheet	5	18	41	46	22·36	44·39	45·66	67	47	800	255	−69	5
	All dolerites	8	38	83	92	44·86	88·99	91·20	57	63	1877	250	−68	3
Basement dykes		15	14	48	58	28·17	55·94	57·38	47	67	1 134	247	−64	4

χ^2 is 1·1, which is not significant, so that the observed values are considered to be uniformly distributed over the range 0–360°. The observed and expected angular departures from the mean are compared below.

Range	0–4½°	4½–9½°	9½–14½°	14½–19½°	> 19½°
Number observed	6	15	16	5	4
Number expected (k = 39·3)	5·4	13·9	13·1	8·3	5·3

χ^2 is 2·5, again not significant, so that the observed distribution of site directions for the dolerite specimens shows no substantial departure from Fisher's distribution. In some cases (for example Figure 4b) the distribution appears slightly elongate, but tests like that just given show that there is no significant departure from circular symmetry.

6. Comparison with previous results from the region

In the previous work in the Wright Valley, small, but significant differences were observed between the mean directions of the basement dykes and the dolerite sheets (Paper I, Table 3); these means, which differed by 16° each had an error of 7° (P = 0·05), and were computed from the directions of natural remanent magnetization ($\mathbf{M}_n$) using only those specimens which were considered to be unaffected by unstable components. In the present work no such selection was made and the mean directions are computed from the stable magnetization ($\mathbf{M}_{st}$) obtained after treatment in 225 oersted ($H_p \sim$); the means of dykes and dolerites differ by 4° which is accommodated by the errors (Table 2). It appears therefore that in Paper I the results retained for analysis did, in fact, contain small unstable components which tended to be somewhat greater in the specimens from the sheets than in those from the dykes. It may be noted that the coercivity of remanence is, on average, higher in the dykes than in the sheets (Section 8) indicating the higher stability of the former. These present results refine the earlier work but do not invalidate it, since the mean directions for the dykes and sheets (Table 2) do not differ significantly from those in Table 3 of Paper I.

The mean magnetization direction of the dolerite sheets are in broad agreement with the results obtained by Turnbull (1959) from the Ferrar dolerites sampled in the Ferrar Glacier region (78° S, 161° E); for specimens from 5 sites he obtained a mean direction of natural remanent magnetization (255°, −76°), the inclination being 8° higher than that obtained here. Turnbull gives the 95 per cent error in this direction as 2·7°, so that the difference from our mean direction would appear to be significant. However, his error may be too small, being computed by giving the direction of each *specimen* unit weight without regard to their grouping into sites. In addition, Turnbull's results may be affected by small unstable components since the directions of natural remanent magnetization were used.

7. Intensity and susceptibility in the Ferrar dolerites

The variations of the intensity of natural remanent intensity, M_n, and initial volume susceptibility, σ, through the three sheets in Victoria Valley are shown in Figure 5, where they are compared with the results of a similar investigation of the dolerite sill at Mt Wellington, Tasmania. Although the coverage is incomplete some general features are clear. The variation of M_n through the Beacon dolerite sheet (curve (e)) resembles that in the Mt Wellington sill (curve (a)) by showing one maximum, near the top, and an increase towards the lower margin.

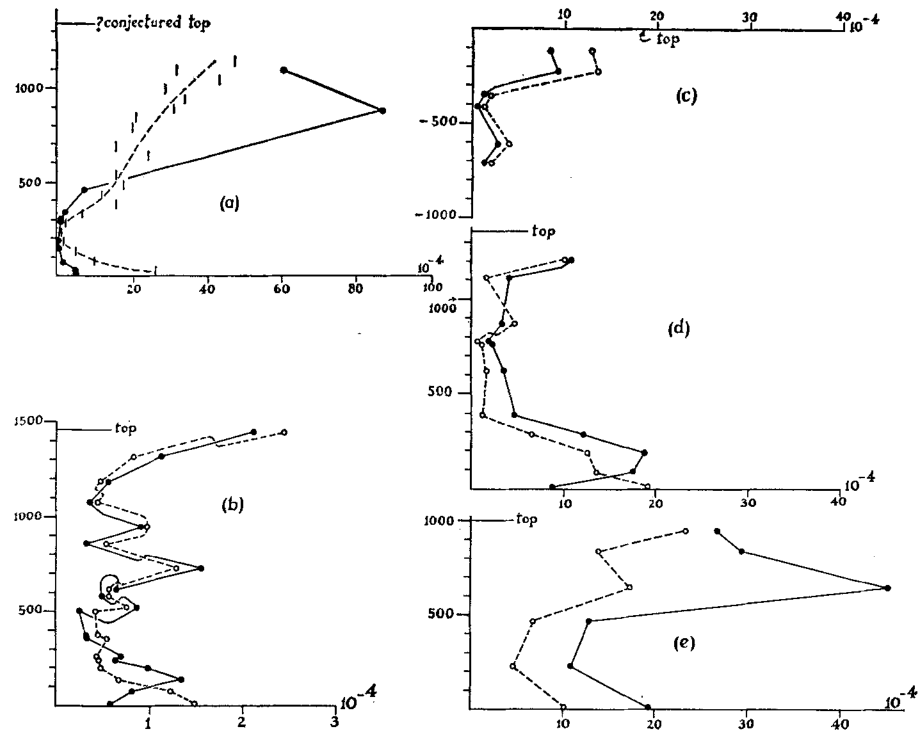

FIG. 5.—Variations in intensity natural remanent of magnetization, M_n, and initial susceptibility, σ, through the Ferrar dolerites. The mean values of M_n at each site are indicated by dots connected by solid line. The mean value of the initial susceptibility (measured in 0·54 oersteds) at each site is shown in (b), (c), (d) and (e) by a circle, and in (a) by a short vertical line giving the average through a range; the mean values are connected by a broken line. Magnetic units are in emu/cm³, and the vertical scale is in feet above the base in (a), (b), (d) and (e), or below the top (c). To avoid confusion the individual sites have not been numbered but the numbers may be obtained by comparing the altitudes with those given in Table 1.

(a) Mt Wellington sill (top not seen). Susceptibilities from Jaeger (1958), natural remanent magnetization from Irving (not previously published).
(b) Basement sheet, Lake Vida area, localities 11 and 12.
(c) Basement sheet, Lake Vashka area, locality 13 (base not seen).
(d) Peneplain sheet (localities 14 and 15).
(e) Sill on Beacon sediments (locality 16).

In the basement sheet near Lake Vashka (curve (c)) and near Lake Vida (curve (b)), high values are again found towards the top. In the latter case, where the sheet is twice as thick (Figure 2), high values are also encountered in the centre of the sheet. This could be due to the presence of two distinct injections referred to in Section 2.4. The peneplain sheet (curve (d)) shows an increase towards the base and the suggestion of a second one towards the top. In most cases the variations in σ and M_n follow each other closely.

The values of M_n vary over a range of less than 20 : 1 being as low as 4 : 1 in the Beacon sill. This is much less than in the Mt Wellington sill where the range is 400 : 1, suggesting that in these dolerites less differentiation of the iron minerals has occurred than in the Mt Wellington sill.

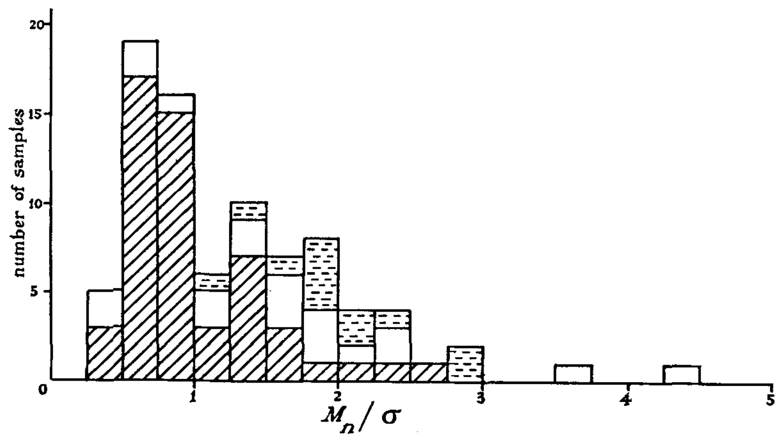

FIG. 6.—Histogram of the ratio M_n/σ in the Ferrar dolerites. There is a single value for each sample. Results from the basement sheet are shown by diagonal lines, results from the peneplain sheet are left blank, and results from the Beacon intrusives have broken shading.

The ratio (M_n/σ) of the natural remanent magnetization and susceptibility are plotted in Figure 6. The lowest value is 0·4 and the highest, 4·5. The averages for the three sheets are 1·0 (basement sheet), 1·7 (peneplain sheet) and 2·0 (Beacon intrusives).

8. Isothermal remanent magnetization

The saturation isothermal remanent magnetization (M_{sat}) and (H_c) the back field (the coercivity of M_{sat}) required to nullify this have been measured for a representative collection of 23 specimens of Ferrar dolerites and basement dykes, using the methods described in Paper I. For the Ferrar dolerites, H_c is usually between 500–700 oersteds, with some values as low as 200 or as high as 1600. For the dyke specimens H_c is usually greater than 1000 oersteds but for one specimen is only 250. The values of M_{sat} in both dolerites and dykes vary between 50×10^{-4} and 80000×10^{-4} e.m.u./cm^3. The field required to saturate is usually about 5000 but ranges between 2000 and 8000 oersteds. The generally high values for H_c which are similar to those recorded in Paper I (Table 2) indicate the high stability of the magnetization.

9. Interpretation of the observations

9.1. *Origin of the magnetization.*—The following points summarize the results.

(a) The directions ($\mathbf{M}_{st}$) in various rock units in the Wright and Victoria Valley are uniform over an area of about 150 square miles and through a stratigraphic thickness of several thousands of feet. Similar directions are found over 400 miles further to the south. Samples of sediments and granites collected near or far away from dolerite contacts, when stable, all show directions parallel to the dolerite.

(b) The site directions in the dolerites and in the dykes are uniformly distributed about their mean directions and differ from the directions of the present and dipole fields.

(c) The demagnetization curves of some igneous specimens (see Paper I, Figure 4) are of a type associated with thermoremanent magnetization.

(d) The coercivities of remanence are usually high (Section 8).

(e) In many cases individual specimen directions are not greatly changed in alternating fields up to 600 oersteds and in some cases are little changed in fields up to 745 oersteds (see Paper I, Figure 5c).

(f) In the dolerites the susceptibility (σ) and the intensity of natural remanent magnetization (M_n) usually vary systematically through each of the sheets. The variation in the ratio M_n/σ is much less than the variation of either M_n or σ separately. The most commonly occurring values for the ratio M_n/σ are about unity.

These features are consistent with the view that the directions of magnetization, $\mathbf{M}_{st}$ in both dolerites and dykes are thermoremanent in origin and are parallel to the Earth's field during cooling. The magnetization of the sediments and granites could be original, or could be related to a period of later reheating. Thus, there appear to be two possible explanations of observations of directions.

(1) The geomagnetic field remained constant in direction and polarity in this region during a long span of time in the Palaeozoic (possibly Pre-Cambrian) and Mesozoic. The time spanned by these samples is not known accurately, but the occurrence of many phases of intrusion separated by peneplanation and sedimentary deposition suggests a period of the order of 10^8–10^9 years.

(2) The rocks (basement dykes, granites and sediments) within not less than 450 ft of dolerite contacts were heated sufficiently during intrusion of the Ferrar dolerites to cause the obliteration of any previous magnetization and the build-up of a new one during cooling, so that the palaeomagnetic record given in Figures 3 & 4 provides information only about a comparatively short period of time.

In view of the very good agreement between the sheets and dykes we are inclined to favour the second possibility, but the question cannot be decided until results are available from rocks of pre-dolerite age collected many miles from igneous contacts so that there is little chance of their having been reheated.

The close agreement between sills and dykes of highly variable dimensions and altitudes makes it most unlikely that the directions of magnetization have been influenced by the shape or orientation of these igneous bodies.

9.2. *Palaeomagnetic pole positions.*—The field relationships and petrological evidence show that the three dolerite sheets were not injected simultaneously (McKelvey & Webb 1961), and the basement dolerite sheet may have been formed by two separate intrusions. During the cooling of dolerite sheets of this type the time taken for the Curie point isotherm to pass from the margin to the centre is calculated to be about 500 years (Jaeger 1957). The composition of the dykes varies widely and it is therefore unlikely that they were intruded at the same time.

In the Wright Valley basic dykes sampled at two localities belonged to two swarms which cut each other. At one locality in the Victoria Valley (not sampled) basic dykes cut older acid dykes. Thus for both the sheets and dykes it is likely that the time range is of the order of several thousand years or more. This would also have been the case for the dykes if the whole region had been reheated during the intrusion of dolerites. If this is assumed to be the case then the mean direction of each will correspond to the dipole field direction. The pole positions for the Ferrar dolerite (mean location of sites 161° 37′ E, 77° 24′ S) is 140° W, 45 ° S and that for the basement dykes (mean location of sites 161° 37′ E, 77° 27′ S) is 140° W, 40° S. These results supersede the results given in Paper I (Table 3). The pole position for the basement dykes may be related to the period of reheating consequent on the intrusion of the Ferrar dolerites. The palaeomagnetic latitude at this time (Mesozoic) was about 60°—very much less than the present latitude. These new data do not affect in any important way the discussion given in Paper I (p. 222) of the comparison between the palaeomagnetic results from the Ferrar dolerites and those from the Mesozoic dolerites from other southern continents.

9.3 *Secular variation.*—The magnitudes of the dispersions given in Table 2 are of interest. The within-site precision (k_{21} in Table 2) depends on experimental errors and the physical properties of specimens. The between-site precision k_{22} may be affected by the secular variation and by relative tectonic movements between sites, but the latter are probably very small in the undeformed formations of the region studied. The between-site dispersion may therefore be interpreted as an estimate of the magnitude of the secular variation during the time in which rocks at the various sites cooled through their Curie points. The results for both sheets and basement dykes are closely similar and are equivalent to a circular standard deviation of about 10°. This is comparable in magnitude to the departures from the geocentric dipole field observed today.

10. Acknowledgments

The expedition on which these collections were taken was only made possible by the generous help of the United States Operation Deep Freeze Authorities, the University of New Zealand, the Victoria University of Wellington and many individuals and commercial firms in New Zealand. We also wish to record our thanks to Mr R. I. Walcott who collected samples from the Beardmore Glacier region. The physical measurements were made during the time in which one of us (C.B.) held a Visiting Fellowship at the Australian National University.

(C.B.) *Dept. of Physics,*
Victoria University of Wellington,
New Zealand.

(E.I.) *Dept. of Geophysics,*
Institute of Advanced Studies,
Australian National University,
Canberra, A.C.T., Australia.

(I.W.) *Department of Geology,*
Victoria University of Wellington,
New Zealand.

Appendix

In Paper I the site directions given were obtained from the natural remanent magnetization. The following list gives the site directions after treatment of specimens in alternating magnetic fields of 225 oersteds (peak) so that Table I of Paper I is brought into line with Table I of the present paper. The site numbers are given followed by the declination and inclination in parentheses. Site 1a (245, −74); 1b (290, −70); 2a (262, −63); 2b (264, −67); 2c (244, −65); 3a (257, −75); 4a (275, −74); 5a (254, −68); 6a (270, −71); 6b (264, −59); 6c (262, −62); 6d (217, −39); 6e (253, −50); 7a (252, −59); 7b (241, −57); 7c (281, −64); 7d (266, −75); 7e (234, −77); 8a (291, −77); 8b (220, −67); 8c (252, −71); 9a (277, −45); 10a (298, −64).

References

Bull, C. & Irving, E., 1960. *Geophys. J.*, **3**, 211 (Paper I).

Collinson, D. W., Creer, K. M., Irving, E. & Runcorn, S. K., 1957. *Phil. Trans. Roy. Soc. A.*, **250**, 73.

Edwards, W. N., 1928. *Geol. Mag.*, **65**, 323.

Fisher, R. A., 1953. *Proc. Roy. Soc. A.*, **217**, 295.

Goldich, S. S., Nier, A. O. & Washburn, A. L., 1958. *Trans. Amer. Geophys. Un.*, **39**, 956.

Gould, L., 1935. *Bull. Geol. Soc. Amer.*, **46**, 973.

Harrington, H. J., 1958. *Nature* (*Lond.*), **182**, 290.

Irving, E., Stott, P. M. & Ward, M. A., 1961. *Phil. Mag.*, **6**, 225.

Jaeger, J. C., 1958. *Proc. Roy. Soc. Tasmania*, **91**, 129 (appendix to a paper by G. A. Joplin).

Jaeger, J. C., 1957. *Amer. J. Sci.*, **255**, 306.

McKelvey, B. C. & Webb, P. N., 1959. *N.Z. J. Geol. Geophys.*, **2**, 718.

McKelvey, B. C. & Webb, P. N., 1961. *Nature* (*Lond.*), **189**, 545.

Seward, A. C., 1914. British Antarctic Expedition 1910–13, *Natural History Reports* (*Geology*), No. 1, 1–49.

Turnbull, G., 1959. *Arctic*, **12**, 151.

Watson, G. S. & Irving, E., 1957. *Mon. Not. R. Astr. Soc. Geophys. Suppl.* **7**, 289.

Webb, P. N. & McKelvey, B. C., 1959. *N.Z. J. Geol. Geophys.*, **2**, 120.

Woodward, A. S., 1921. British Antarctic Expedition, 1910–13; *Natural History Reports* (*Geology*), No. 2, 51–62.