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Paleomagnetic Investigation of the Beacon Group in the McMurdo Sound Region, Antarctica

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南極マクマードサウンド地域，ビーコン層群の古地磁気学的研究

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要旨: 南極マクマードサウンド地域には，デボン紀からジュラ紀にかけての，主に砂岩層を主体とするビーコン層群が広く分布する．この地域内のシアス山，ノブヘッド山，アランヒルズ，それにフレミング山から合計216個の古地磁気学用岩石試料を採集した．それぞれの採集地の地層は，デボン紀の初期あるいはそれ以前，デボン紀，二畳紀末から三畳紀初期，それに三畳紀である．この地域の各所にジュラ紀のフェラードレライトの岩床の貫入が見られ，採集された試料が堆積残留磁気(DRM)を持つのか，熱残留磁気(TRM)を持つのかを調べるため，自然残留磁気(NRM)の交流および熱消磁，ARMおよびTRMの獲得の様子，それにARMの交流消磁を行った．

実験結果，シアス山の試料はいずれも安定なTRMを持ち，デボン紀に獲得したDRMは完全に失われている．ノブヘッド山の試料も基本的にシアス山の試料と同じである．アランヒルズの一部の試料は安定なDRMを持ち，ドレライトの岩床による影響は，ほとんどなかったと考えられる．フレミング山の試料のうち，安定なNRMを持つ試料は，TRMを獲得していると考えられる．

以上の結果，あらたに二畳紀末-三畳紀にかけての東南極大陸のVGPが決定された．この位置はジュラ紀のVGPにきわめて近い位置にあり，この間東南極大陸は大きく移動しなかったと考えられる．これはオーストラリアから得られた結果と一致し，少なくとも両大陸はジュラ紀まで連続した大陸だったことを示している．

Abstract: A total of 216 paleomagnetic samples of the Beacon Group (sandstone) were collected from Mt. Circe, Mt. Knobhead, Allan Hills and Mt. Fleming. The respective sedimentary sequences are Pre- or Early-Devonian, Devonian, Permo-Triassic and Triassic. The representative samples were tested for NRM stability against AF and thermal demagnetization, ARM and TRM acquisition, and AF demagnetization of ARM. The following results were obtained.

The samples from Mt. Circe and Mt. Knobhead have stable NRM of parallel direction to that of the Ferrar dolerite. From this we conclude that these samples were remagnetized in the Jurassic Age and the primary magnetization disappeared. The samples from Mt. Fleming were also remagnetized by the dyke of the Ferrar dolerite or do not have stable NRM. However, parts of the samples from the Allan Hills have stable depositional remanent magnetization (DRM) of the Permo-Triassic Age. The direction of NRM for these samples is parallel to that of the Ferrar dolerite in the Jurassic Age. This suggests that East Antarctica had no shift of VGP. This conclusion is consistent with the results on the Mesozoic Age in Australia. Thus Australia must have been linked to Antarctica at least up to the Jurassic Age.

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1. Introduction

Paleomagnetic investigations of the Beacon Group were carried out with the samples collected from the Ferrar Glacier (78°S, 161°E) by TURNBULL (1959), and from the Wright and Victoria Valleys (77.5°S, 161.0°E) by BULL *et al.* (1962). They reached the general conclusion that NRM (Natural Remanent Magnetization) at these sites is parallel to that of indubitably younger dolerite sills (Ferrar dolerite) in spite of a separation of 150 m from the lower boundary of the sill. That is, a large intrusive mass of the Ferrar dolerite nearby caused sufficient heating to raise the Beacon Group to the Curie point and must have been remagnetized in alignment with the ambient geomagnetic field in the Jurassic Age.

According to the geological evidence in East Antarctica, the formations ranging in age from Middle Paleozoic to Messozoic were only the Beacon Group (sandstone) in the Transantarctic Mountains and the Prince Charles Mountains of the Lambert Glacier (*i.e.* RAVICH and FEDOROV, 1977). Therefore, it is very important to carry out an investigation of the Beacon Group paleomagnetically in order to elucidate the history of Gondwanaland, as the East Antarctic plate is probably situated in the center of that region.

2. Geology of the Beacon Group

In the McMurdo Sound more than 2100 m of sedimentary sequence, predominantly pale yellow quartz sandstone, is found, overlying unconformably the igneous and metamorphic rocks of the basement complex. These sandstone sequences, together with carbonaceous siltstone, feldspathic sandstone, and minor limestones commonly associated with them, were provisionally brought together under the same Beacon System, with the Beacon Sandstone (Group) of the McMurdo Sound area as the type rock (HARRINGTON, 1958). The sedimentation ages of these Beacon sandstone sequences range from Devonian to Jurassic, inferred from the evidence of fossils and trace fossils (MCKELVEY and WEBB, 1961; WEBB, 1963). In almost every section where an appreciable thickness of the Beacon Group is exposed, one or more horizontal sills of dolerite are present. These sills are a few meters to more than 300 m thick and most of the sills are of uniform thickness (GUNN and WARREN, 1962). Some recrystallization of the elastic quartz is found close to the contacts (especially near the lower surface of sills) but this is confined to a band only a few cm thick in most places.

The geology of the Beacon Group in the Dry Valley region was described by WEBB (1963); from the oldest to the youngest, the sandstone includes dark subgraywacke breccia and conglomerate (Boreas Subgraywacke Member), pink to gray arkose (Odin Arkose), almost pure quartz sandstone (Beacon Heights Orthoquartzite), a thin formation of red and green siltstone (Aztec Siltstone) and formations of quartz sandstone, carbonaceous sandstone, siltstone, and shale (Weller Sandstone). This geological evidence expands into the Beacon Heights and Mt. Knobhead regions.

The formations exposed at Mt. Circe, located in the upper Olympus Range between the Wright Valley and the Victoria Valley, are the Odin Arkose, the Boreas Subgraywacke Member and the Beacon Heights Orthoquartzite of early pre-Devonian to middle-Devonian age. Their lower boundary is dolerite sill "c" 180 m thick, as described by McKelvey and Webb (1961). The Devonian Beacon Heights Orthoquartzite and Aztec Siltstone are exposed at Mt. Knobhead, located in the upper Ferrar and Taylor Glaciers. Intrusions of two dolerite sills, one on the top of the mountain and the other about 470 m below the top, can be observed on that mountain (Webb, 1963). A thick sequence of flat-lying Beacon Group with lower or middle Triassic plant fossils and carbonaceous beds is found at Mt. Fleming, on the upper Wright Glacier (Gunn and Warren, 1962). Ferrar dolerite sills with dykes 30–200 m in thickness intrude in this place according to our field observations.

The Allan Hills are situated about 200 km northwest of McMurdo Station in Ross Island. A synthesized geology of this area was given by Ballance and Watters (1971) as follows: Sedimentary rocks referred to the Beacon Group, having a coal bed and fossil plants, dominantly *Glossopteris* of Permian to Triassic, are exposed at the Allan Hills. Diamictite from volcanic mudflows is deposited on this sequence and basaltic dykes intrude into these formations. They estimate that basaltic activity occurred some time in the middle, perhaps the lower, Jurassic Age.

3. Samples and Sampling Sites

A total of 216 paleomagnetic samples were collected from the Beacon Group at Mt. Circe, Mt. Knobhead, Allan Hills and Mt. Fleming, as shown in Fig. 1. The sampling sites at Mt. Circe, from lower to higher, are sites A, B, C and D as shown in Fig. 1a, and the mutual vertical distances are about 10, 30 and 20 m respectively. Site A is situated 40 m above the upper boundary of a Ferrar dolerite sill 180 m thick, and is located at an altitude of 1500 m. The formation at these sites is identified as the Beacon Heights Orthoquartzite (Webb, 1962). Sampling sites A, B, C and D at Mt. Knobhead, with mutual vertical distances of 50, 20, and 20 m respectively from lower to higher, are situated on the north side of that mountain, as shown in Fig. 1b. Site A is located at about 2000 m in altitude and probably 140 m above the upper boundary of a dolerite sill. These samples from Mt. Knobhead are included in the Aztec siltstone formation (Webb, 1963). Sampling sites A, B, C and D at the Allan Hills, shown in Fig. 1c, are included in the same formation; the altitude of these sites is about 2000 m. Site A is located on the west ridge and sites B and C on the east ridge of the mountain. A dyke of 50–200 cm in

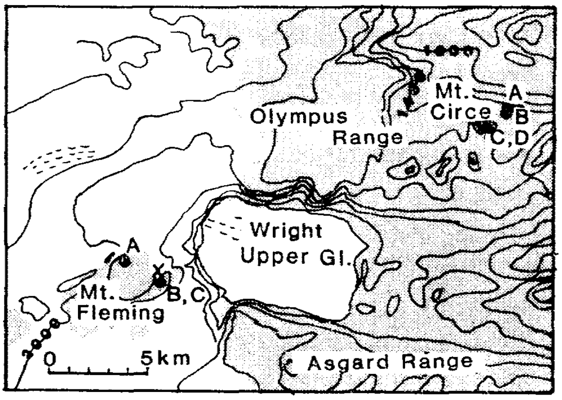

Fig. 1a.

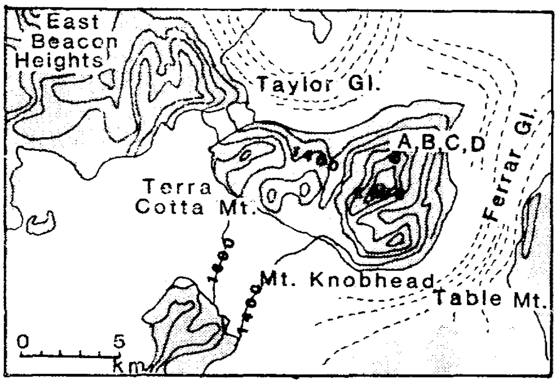

Fig. 1b.

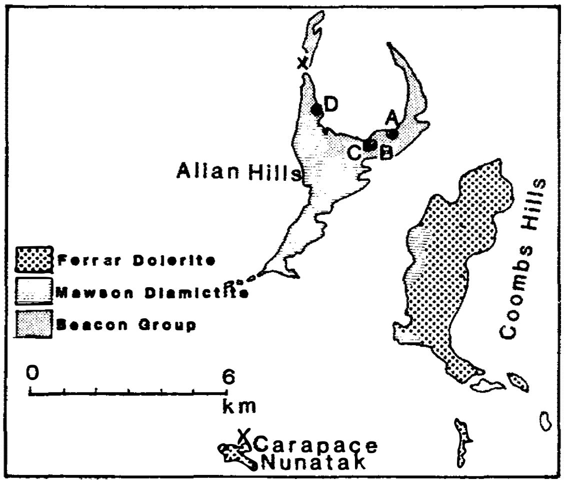

Fig. 1c.

Fig. 1. Sampling sites of the Ferrar dolerite (solid circles) and the Beacon Group (open circles). (a) and (b) are topographical and (c) is geological map.

thickness, resulting from the Ferrar dolerite sills, invades the Beacon Group at site C, and the samples were collected within 20 m from the dyke. However, there is no intrusion of the dyke at sites A and B.

4. Experimental Technique

The NRM of rock specimens may be divided into several kinds of magnetization, such as thermal remanent magnetization (TRM), depositional remanent magnetization (DRM), isothermal remanent magnetization (IRM) and viscous remanent magnetization (VRM). These magnetizations are different not only in the mechanism of acquisition but also in their stability against demagnetization. In general, TRM and DRM are very stable (hard) as compared with IRM and VRM (soft). It is possible that the Beacon Group in the McMurdo Sound has TRM and the magnetic soft component, besides DRM. We have, therefore, defined these magnetizations as follows: The soft component is removed from the samples by AF (alternating field) demagnetization in a relatively weak alternating field. The NRM intensity of sediment is considerably weaker as compared with that of igneous rock, ranging from 10^{-7} to 10^{-4} emu/g (*i.e.* NAGATA, 1961). A consequent comparison of the intensities of the stable component of NRM and acquired TRM in the laboratory would suggest the NRM mechanism. However, this method may result in chemical alteration during heating. Therefore, anhysteresis remanent magnetization (ARM) was adopted as a substitute for TRM in this study. ARM has characteristics quite similar to those of TRM, including a proportionality with a weak steady magnetic field and magnitude of partial ARM (PATTON and FITCH, 1962). However, the low field susceptibility of ARM has a magnetic grain size dependence as suggested by LEVI and MERRILL (1976). Thus, it may be possible to determine the origin of NRM by means of synthesized results from ARM acquisition, AF demagnetization of NRM and ARM, thermal demagnetization of NRM and TRM acquisition properties.

A total of 6 typical samples were selected from each sampling site to examine their NRM characteristics: 3 samples to test AF demagnetization of NRM and another 3 to test thermal demagnetization of NRM. The samples which were used to test AF demagnetization of NRM were examined for ARM acquisition and the effects of AF demagnetization of ARM, and the samples which were used to test thermal demagnetization of NRM were examined for TRM acquisition.

As NRMs of samples of the Beacon Group are fairly weak, a superconducting rock magnetometer was used. The AF demagnetizer consists of a two-axis tumbler, and the stationary magnetic field intensity in the demagnetizer is less than 100 γ. In the case of the thermal demagnetizer, the magnetic field intensity is less than 20 γ. The applied alternating field ($\tilde{H}$) for AF demagnetization and ARM acquisition is up to 1000 Oe peak, and the maximum temperature is 600°C for thermal demagnetization and TRM acquisition. The steady magnetic field (h) is 0.42 Oe for ARM and TRM acquisition and the direction is parallel to $\tilde{H}$.

5. Experimental Results

The curves obtained for AF demagnetization of NRM and ARM and ARM acquisition for the 3 representative samples from each site were divided into the following categories, as shown in Fig. 2. Type 1: NRM intensity and direction are fairly stable against AF demagnetization up to 1000 Oe. The ARM acquisition curve shows a smooth increase and no saturation up to the maximum field. AF demagnetization of ARM is fairly similar to that of NRM. Thus, the inferred magnetic grains probably have a single domain structure. Type 2: Stable NRM is observed up to approximately 500 Oe but is destroyed in higher fields, ARM acquisition is smooth up to approximately 500 Oe but increases in a zigzag form above that field. The AF demagnetization curves of ARM are essentially the same as that of NRM. Type 3: The direction and inclination of NRM are quite unstable against AF demagnetization. However, ARM acquisition and AF demagnetization of ARM are fairly stable up to at least 500 Oe. That is, samples of this type are able to have a stable ARM, but the NRM is unstable. Type 4: Both NRM and ARM are fairly unstable up to 1000 Oe against AF demagnetization except when in a weak field. The ARM acquisition curve is also a zigzag on the whole. That is, a stable remanent magnetization is impossible. A multi-domain structure for the magnetic grains is inferred. Three representative samples collected from the same site were classified as essentially of the same type, although some may be included in the neighboring type. The types for each site are listed in Table 2 together with the mean NRM and ARM intensities and the NRM/ARM ratios.

Three samples were also selected from each site for step-by-step thermal demagnetization and TRM acquisition testing up to 600°C. The results of these experiments are classified into the following categories, as shown in Fig. 3. Type 1: The decay curves of NRM against thermal demagnetization have smooth and clear blocking temperatures of NRM between 550°C and 600°C. The directions are fairly stable up to 550°C and disperse at 600°C. Type 2: The intensities decay gradually from approximately 200°C to 450°C and the directions are stable up to at least 400°–500°C against thermal demagnetization. But both intensity and direction are unstable from 450°–500°C to 600°C. That is, various kinds of blocking temperature may be observed from 200° to about 450°C. TRM acquisition increases gradually up to approximately 450°C and then steeply to 600°C. Since no stable NRM was observed at temperatures over 450°C, the increasingly steep magnetization from 450° to 600°C is probably due to chemical

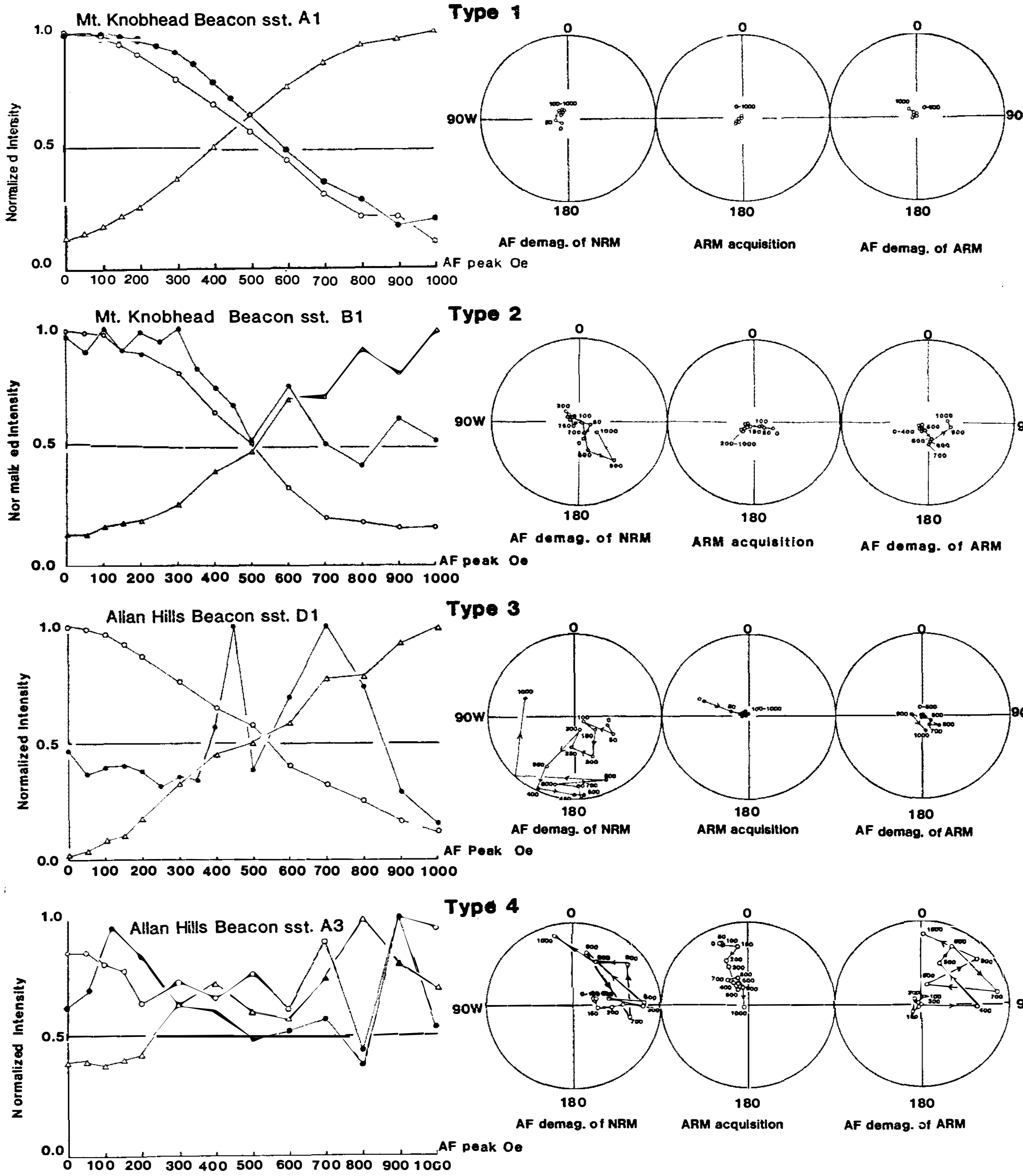

Fig. 2. Typical 4 AF demagnetization groups for the Beacon Group (sandstone) in the McMurdo Sound region. Solid circles: AF demagnetization curve of NRM. Triangles: ARM acquisition curve. Open circles: AF demagnetization curve of ARM.

alterations of magnetic grains. Type 3: The intensities and directions of NRM are stable to 300°C; this is the most stable type. TRM acquisition increases gradually to 300°C and then zigzags to 600°C; in many cases it is fairly unstable from 200° to 600°C. That is, the inferred blocking temperature must be very low or undefined. As the results of these thermal examinations are almost identical in samples collected

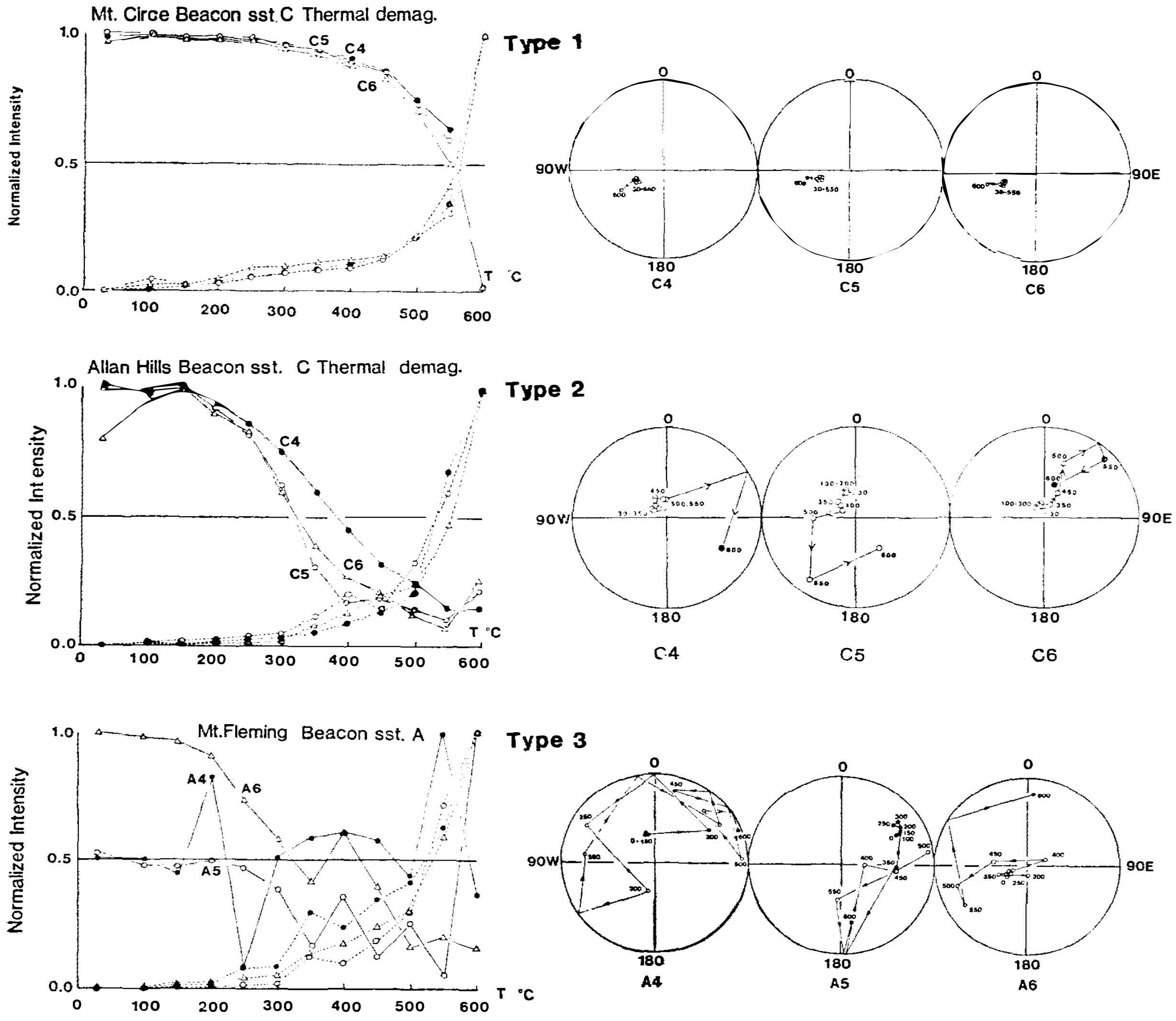

Fig. 3. Typical 3 thermal demagnetization groups for the Beacon Group (sandstone) in the McMurdo Sound region. Solid line: thermal demagnetization curve of NRM. Dotted line: TRM acquisition curve (h=0.42 Oe.). The properties of 3 representative samples are shown in each type.

from the same site, the classified types from each site are listed in Table 1.

NRMs of 216 samples collected from 4 formations of the Beacon Group were measured before and after optimum AF demagnetization. Based on the results of AF demagnetization of representative samples, the samples with an optimum 100 or 150 Oe AF demagnetization field were chosen. Obtained results of the mean value are summarized in Table 2. The NRMs of mean intensities of the samples from Mt. Circe are strong, 8.74×10^{-7}–8.82×10^{-6} emu/g, as compared with those from Mt. Knobhead, Allan Hills and Mt. Fleming. The samples from the Allan Hills and Mt. Fleming are weak, with a magnitude of 10^{-8}–10^{-7} emu/g. Most of the samples are magnetized to the normal polarity but some samples from Allan Hills D and Mt. Fleming B are magnetized to reverse polarity. Individual NRM directions for all samples from one site formed a cluster in the case of the samples from all sites of Mt. Circe, A and B sites of Mt. Knobhead and site C of Allan Hills and Mt. Fleming, but were scattered for the others. The mean intensities of clustered samples from each site are generally larger than those of scattered ones; and the mean directions are limited from −62.3° to −82.3° inclination and 230.9° to 280.7° declination.

Table 1. Mean intensities of NRM and ARM ($\tilde{H}=1000$ Oe, $h=0.42$ Oe, $h/\!/\tilde{H}$), and classified types at room temperature of the Beacon Group in the McMurdo Sound.

AF demag. group: AF demagnetization of NRM and ARM and ARM acquisition.

Thermal demag. group: thermal demagnetization of NRM and TRM acquisition.

		NRM (emu/g)	ARM $h/\!/\tilde{H}$ (em/g)	ARM/NRM	Type	
					AF demag. group	Thermal demag. group
Mt. Circe	A	3.28×10^{-6}	9.50×10^{-6}	2.89	1	1
	B	9.03×10^{-7}	1.37×10^{-6}	1.52	1	1
	C	9.41×10^{-6}	9.12×10^{-6}	0.97	1	1
	D	1.42×10^{-6}	3.29×10^{-6}	2.31	1	1
Mt. Knobhead	A	1.05×10^{-6}	1.57×10^{-6}	1.50	1	1
	B	3.568×10^{-7}	1.25×10^{-6}	3.51	2	2
	C	7.07×10^{-8}	3.51×10^{-7}	4.96	3, 4	3
	D	1.63×10^{-7}	4.54×10^{-7}	2.78	2, 3	2, 3
Allan Hills	A	6.71×10^{-8}	1.26×10^{-7}	1.88	3	3
	B	9.84×10^{-8}	1.64×10^{-7}	1.67	3, 4	3
	C	3.48×10^{-7}	2.82×10^{-6}	8.11	1, 2	2
	D	3.66×10^{-8}	4.10×10^{-7}	10.97	3	3
Mt. Fleming	A	1.64×10^{-7}	2.75×10^{-7}	1.67	3, 4	3
	B	3.56×10^{-8}	1.85×10^{-7}	5.21	3	3
	C	1.071×10^{-7}	1.49×10^{-7}	1.40	2	2, 3

Table 2. Paleomagnetic results of the Beacon Group in the McMurdo Sound.

Sampling site		Demag	N	R (emu/g)	I	D	K	α_{95}	pLat (S)	pLong (W)
Mt. Circe	A	0	6	3.55×10^{-6}	−78.2	267.7	1040	2.1		
		150		3.30×10^{-6}	−77.1	266.9	1258	1.9	61.9	223.1
	B	0	16	8.74×10^{-7}	−75.4	261.0	123.2	3.3		
		150		8.31×10^{-7}	−72.6	257.0	460.1	1.7	53.5	139.4
	C	0	17	8.82×10^{-6}	−63.5	254.7	151.2	2.9		
		150		8.51×10^{-6}	−62.3	255.6	169.8	2.7	39.4	134.0
	D	0	8	1.36×10^{-6}	−75.9	251.7	526.5	2.4		
		150		1.29×10^{-6}	−73.9	247.5	1342	1.5	53.5	148.2
Total		150	47	4.00×10^{-6}	−69.9	255.9	118.9	1.9	49.1	138.0

Table 2 (continued).

Sampling site	Demag	N	R (emu/g)	I	D	K	α_{95}	pLat (S)	pLong (W)
Mt. Knobhead A	0	37	9.78×10^{-7}	−81.8	277.0	132.4	2.1		
	150		9.79×10^{-7}	−81.7	280.7	354.4	1.3	76.6	136.9
B	0	10	3.47×10^{-7}	−75.6	231.3	14.4	13.1		
	150		3.22×10^{-7}	−84.1	245.3	55.5	6.5	69.9	165.8
C	0	17	1.51×10^{-7}	−88.1	234.3	5.7	16.4		
	100		1.42×10^{-7}	−87.0	201.5	4.5	19.0		
D	0	21	1.30×10^{-7}	−75.9	281.5	6.7	13.3		
	100		4.73×10^{-8}	−68.6	245.1	7.5	12.4		
A+B	150	47		−82.4	275.1	159.6	1.7	71.7	143.6
Allan Hills A	0	8	7.07×10^{-8}	−65.2	279.1	2.8	41.3		
	100		1.07×10^{-7}	−71.8	273.8	2.6	43.7		
B	0	14	6.97×10^{-8}	−62.7	196.9	1.7	46.2		
	100		6.86×10^{-8}	−67.0	206.2	2.1	38.3		
C	0	12	3.06×10^{-7}	−82.1	319.5	13.5	12.3		
	150		3.62×10^{-7}	−78.8	253.5	97.2	5.3	62.3	151.4
D	0	17	5.29×10^{-8}	−27.1	221.7	1.9	36.9		
	100		5.62×10^{-8}	−53.3	313.8	2.8	32.0		
Mt. Fleming A	0	8	1.79×10^{-7}	−67.3	193.5	1.8	34.1		
	100		1.57×10^{-7}	−66.1	206.4	1.7	35.9		
B	0	15	4.72×10^{-8}	−42.5	190.0	1.2	76.4		
	150		4.12×10^{-8}	3.7	214.1	1.4	59.3		
C	0	10	1.79×10^{-7}	−77.2	243.8	29.3	9.1		
	150		1.57×10^{-7}	−77.1	244.5	24.5	9.9	58.2	154.5

Demag=optimum AF demagnetization field, N=sample number, R=mean intensity of NRM. I, D=mean inclination and declination of NRM, K=precision parameter, α_{95}=radius of 95% confidence circle about mean direction.

6. Paleomagnetic Discussion

Turnbull (1959) and Bull *et al.* (1962) pointed out that the directional NRMs of the Beacon Group from the Ferrar Glacier and the Wright and Victoria Valley regions were parallel to that of the Ferrar dolerite. Obtained results in this study support not only their results but also expand the area to include the region from Mt. Knobhead to the Allan Hills. This uniformity of direction for the Beacon Group and the Ferrar dolerite may be caused by the geomagnetic field in this region being constant in direction from the Devonian to the Jurassic period, or by the reheating of the Beacon Group during the intrusion of the Ferrar dolerite in the Jurassic period. The following analysis is carried out in order to find a solution to this problem by applying the different types of AF and thermal demagnetization groups and the mean directions of NRM for each site. The significance of each type of AF demagnetization group may be estimated as follows:

Types 1 and 2: As the AF demagnetization curves of NRM and ARM are similar, the inferred origin of NRM may be DRM when both intensities differ greatly. Type 3: Although NRM is unstable, it has stable ARM. DRM and TRM cannot be acquired, and the ratio ARM/NRM is large. Type 4: As there is no possibility of stable remanence, it cannot be judged whether the samples were heated or not.

The representative samples from Mt. Circe, A, B, C and D, are similar not only in the ratio ARM/NRM but also in their classified type for the AF and thermal demagnetization groups as shown in Table 1: the ratios range from 0.97 to 2.89 and the samples all belong to one type. The sequence of the Beacon Group at Mt. Circe is estimated to be of Devonian time. According to the standard polar-wander path of Gondwanaland (McElhinny, 1973), the expected VGP position of Devonian time for Antarctica is situated at the outer boundary of the present day Weddell Sea. However, the obtained VGP position for whole samples from Mt. Circe is in 49.1°S latitude and 138.0°W longitude with 1.9° α_{95} as shown in Table 2. This discrepancy is probably due to remagnetization by intrusion of the Ferrar dolerite in the Jurassic Age. A dolerite sill 180 m thick intruded into the boundary between the basement complex and the Beacon Group (McKelvey and Webb, 1961), and the sampling site at Mt. Circe is within a vertical distance of 50 m from the upper boundary of that sill. Taking into account the calculation of temperature in the neighborhood of the intrusive sheet (Jaeger, 1957, 1959), it is possible that the temperature at the sampling site rises to over 570°C; a Curie point at 570°C is estimated for Type 1 of the thermal demagnetization group. The NRM direction for the Ferrar dolerite collected from the Olympus Range is $-69.4°$ inclination and 237.6° declination with 2.4° α_{95}, magnetized to the normal polarity (Funaki, 1983), while that for the Beacon Group for whole samples from Mt. Circe is $-69.9°$, 255.9° and 1.9° respectively, magnetized to the same direction. Since the mutual angular deviation (Θ) of the NRM direction between these formations is 6.4°, their NRM directions are practically equal to each other, taking into account the α_{95} values. This suggests that the Beacon Group around the sampling sites at Mt. Circe was heated to over 570°C and remagnetized during cooling down through that temperature during the Jurassic Age.

The representative samples from Mt. Knobhead are of different kinds of type of AF demagnetization group for each site. The samples from sites 1 and 2 are Types 1 and 2 respectively for both the AF and thermal demagnetization groups, and have small ARM/NRM ratios of 1.50 and 3.15. That is, the inferred origin of NRM at these sites is probably TRM for the same reasons as given for the samples from Mt. Circe. The samples from site C are classified as Type 3 or 4 for the AF and thermal demagnetization groups; NRM is generally unstable, but some are capable of stable remanence. Therefore, it may be assumed that the samples at site C were not placed under conditions of DRM acquisition, and were not then heated up to Curie temperature. The samples from site D are classified as Types 2 and 3 for both AF and thermal demagnetization groups, having a small ARM/NRM ratio of 2.78; all samples are capable of stable remanent magnetization, and some of them actually show stable NRM. Therefore, the formation at this site was probably heated up to the same temperature, limited from 200° to 450°C. Consequently, the samples which have a blocking temperature below that temperature would acquire TRM. Dolerite sills intrude into Mt. Knobhead at the top (2400 m) and at about 540 m below the top (Webb, 1963). The vertical distance of sampling site A from the lower sill is estimated as about 140 m above. The mean NRM direction for whole samples from sites A and B shows an inclination of -82.4° and a declination of 275.1° with a α_{95} value of 1.7°. TURNBULL (1959) obtained the NRM directions for the Ferrar dolerite sills from the upper Ferrar Glacier region. As Mt. Fleming is also situated in the same region, the representative NRM direction for the Ferrar dolerite from the upper Ferrar Glacier region, referring to his data, should show an inclination of -76° and a declination of 255° with a α_{95} value of 2.7°. Since the angular deviation is $\Theta = 7.3^\circ$, the directions of both formations can be considered as parallel, taking into account the α_{95} values. Therefore, these sampling sites may have been heated by a dolerite sill to more than 570°C for site A and less than that temperature for the other sites. Later many samples were remagnetized completely or partially to the geomagnetic field direction during the Jurassic Age.

In the case of the Allan Hills, the representative samples from site C have stable NRM; they are classified as Type 1 or 2 for the AF and thermal-demagnetization groups. As the ARM/NRM ratio is large, (i.e. 8.11), it may be estimated that the formation was magnetized as DRM rather than as TRM. The samples from sites A, B and D are of Type 3 or 4 AF demagnetization group.

The results of chemical analysis of coal from near site C in the Allan Hills are shown in Table 3 together with other coal data from the hills (GUNN and WARREN, 1962). The values of volatile matter, fixed carbon and calorific value suggest that samples (1) and (2) are anthracite but sample (3) is low grade coal. The value of the fuel ratios (volatile matter/fixed carbon), ranging from 16.9 to 20.4, shows that this coal includes a relatively large quantity of volatile matter in the case of anthracite. That is, it may be concluded that these samples were not heated between the Permian Age and the present. Thus, the surface of the Allan Hills was probably not heated, and the DRM of the samples from site C has survived.

The earth's geomagnetic field from the late Permian to the middle Triassic period showed alternate changes of normal and reversed polarity, but prior to the Permian age it showed only reversed polarity (Kiaman Interval) (MCELHINNY and BUREK, 1971). Therefore, the magnetization polarity of the Allan Hills would suggest the age confirmed

Table 3. Chemical analyses of coals from Allan Hills. (1) this study; analyzed by The Coal Mining Research Centre, Japan. (2) and (3) GUNN and WARREN (1962).

Samples		(1)	(2)	(3)
Moisture	(wt%)	4.80	1.91	2.67
Ash	(wt%)	11.4	12.92	43.4
Volatile matter	(wt%)	12.8	12.32	9.76
Fixed carbon	(wt%)	71.0	72.85	44.17
Sulphur	(wt%)	0.72	4.77	3.02
Calorific value	(cal/g)	6520	6445	3833
Fuel ratio		18.0	16.9	20.4

by fossil evidence, namely from the late Permian to the early Triassic period.

The NRM direction of the Ferrar dolerite in this area has an inclination of $-67.6°$ and a declination of 262.6°, and a α_{95} value of 5.1°. An angular deviation between the Beacon formation at site C and the Ferrar dolerite is $\Theta=11.5°$. That is, both directions are in mutual agreement taking into account these α_{95} values. Since the inferred age of the Beacon Group at the Allan Hills ranges from Permian to Triassic (TOWNROW, 1966; BALLANCE and WATTERS, 1971), it may be concluded that the shift of Antarctica against VGP was small from the Permo-Triassic to the Jurassic Age. This conclusion is consistent with the results of analysis of Mesozoic rocks from Australia (IRVING, 1963; IRVING *et al.*, 1963); directional magnetizations from Lower Triassic to Lower Crataceous are approximately uniform for Eastern Australia including Tasmania Island. Hence it seems that Australia was separated off from East Antarctica in early Tertiary time.

The representative samples collected from site C at Mt. Fleming are classified as Type 2 or 3 for AF and thermal demagnetization groups, and the ARM/NRM ratio is small, 1.40. The NRM direction of the dyke from which the Ferrar dolerite originates, showing an inclination of $-76°$ and a declination of 255° with α_{95} of 2.7°, was obtained at a site separated by 30 m from site C (FUNAKI, 1983). The angular deviation Θ between the mean NRM direction of the Beacon Group at site C, shown in Table 2, and that of the dykes is 6.6°; they are mutually parallel taking into account the α_{95} values. A total of 10 samples from site C were collected from the area between a dyke of 50 to 100 cm thick and 20 m away from the dyke. It is impossible to determine from the NRM direction whether the formation at site C was heated by the dyke or not, because the inferred ages of the Beacon Group and the Ferrar dolerite are Triassic and Jurassic respectively and, as mentioned above, the NRM directional change during Mesozoic time was small. From the ARM/NRM ratio, however, the formation must have been heated to above the Curie point. The samples at sites A and B, including the same formations as site C, are of Type 3 or 4 of the AF and thermal demagnetization groups; they were not heated up to the Curie point. From this, it may be concluded that the samples which were heated by dykes (site C) have a stable NRM, but samples which were not heated (sites A and B) do not have a stable NRM.

The four obtained VGP positions of the Beacon Group, for (1) Mt. Circe, (2) Mt. Knobhead, (3) Allan Hills and (4) Mt. Fleming, are illustrated in Fig. 3 together with those of previous data about the Beacon Group ((5) TURNBULL, 1959; (6) BULL *et al.*, 1962), (7) Ferrar dolerite and (8) the present geomagnetic pole. The VGP of Ferrar dolerite is estimated as the average position of 10 independent data from the whole Transantarctic Mountains (FUNAKI, 1983). The VGPs of the Beacon Group from the Wright and Victoria Valley regions (1) and (6) are distributed on the low latitude side. This is consistent with the results of analysis of the Ferrar dolerite from the Wright and Victoria Valley regions; the latitude of VGP is the lowest for these 10 data. In general, VGP distribution in Fig. 4 resembles that of the Ferrar dolerite in the Jurassic Age fairly closely. VGP (3) shows the location of the geomagnetic pole position for the Allan Hills during the Permo-Triassic period. However, it is included in the cluster of VGPs from the Beacon Group which were heated by the Ferrar dolerite as shown in the figure. As mentioned above, therefore, Antarctica probably did not shift during the late Permian to Jurassic periods.

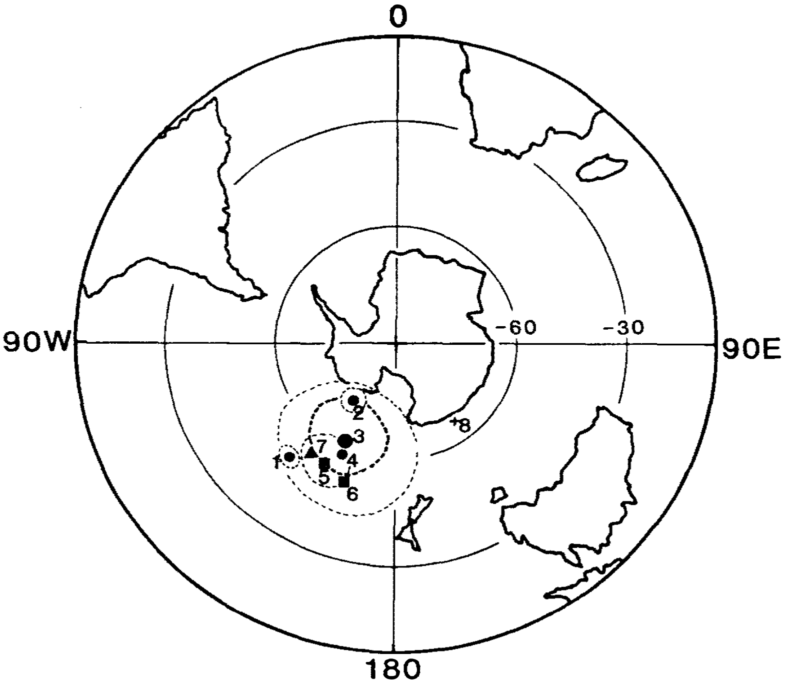

Fig. 4. Obtained VGP positions from the Beacon Group in the McMurdo Sound. 1: Mt. Circe, 2: Mt. Knobhead, 3: Allan Hills, 4: Mt. Fleming, 5: Ferrar Glacier (TURNBULL, 1959), 6: Wright and Victoria Valley (BULL et al., 1962), 7: Mean VGP position of the Ferrar dolerite (FUNAKI, 1983), 8: present geomagnetic field direction. 1-4: this study.

7. Concluding Remarks

The formation of the Beacon Group in Mt. Circe was completely remagnetized by a Ferrar dolerite sill in the Jurassic period; the temperature of the formation increased to more than 570°C. Consequently, it acquired a fairly stable TRM and the directional NRM was aligned to that of the sill at the Wright Valley. The samples from Mt. Knobhead were probably heated to at least the Curie point and remagnetized to the field direction of the Jurassic dyke. However, the increased temperature is probably high, more than 570°C for site A and less than 570°C for sites B, C and D. The samples from sites A, B and D of the Allan Hills do not have DRM, although most of the samples are able to have stable remanent magnetization. However, the sample from site C probably has stable DRM. The direction of NRM is almost parallel to the Jurassic dyke at the Allan Hills; East Antarctica probably had almost no shift of VGP from the Permo-Triassic to the Jurassic period. The samples from sites A and B at Mt. Fleming do not have a stable NRM like that of the Allan Hills. The samples from site C may have been heated by dykes of the Ferrar dolerite and remagnetized parallel to the Jurassic geomagnetic field.

The intensity of the Beacon Group in the McMurdo Sound is fairly weak, 9×10^{-6} to 4×10^{-8} emu/g. In general, samples with a stable NRM have a stronger intensity than those with unstable NRM.

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