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32. *Studies on the Variations of the Earth's Magnetic Field during Pliocene Time.*

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Contents

Summary

For the purpose of determining the mode of variation and the stability of a geomagnetic field through the geologic past, the author undertook a palaeomagnetic study of volcanic rocks belonging to the

Komoro, Shigarami and Enrei groups of formations (from the Upper Miocene to the Upper Pliocene).

At the same time, the author examined the magnetic stability of rocks of which the magnetic directions were indicated to be much deflected from the present geomagnetic direction.

From the results obtained, it was found that the geomagnetic field may have been reversed during Upper Pliocene time, and that during the time from the Upper Miocene to the Lower Pliocene it was normal.

During the transitional stage from the normal to the reversed, the geomagnetic pole seems to have migrated through the equator; thus the change of polarity or the reversal might, through the transitional phase, have taken place with the pole settling at various positions. This conception regarding the manner of reversal of the geomagnetic field differs completely from the hypothesis hitherto propounded.[1]

The intensities of total geomagnetic force during this transitional phase were inferred from the ratios of Jn to JTc of the rocks: it was suggested that the geomagnetic intensity decreased through the time of reversal and then began to increase again as the change in the reversal proceeded to its finality.

I. Introduction

Studies in search of the directions of geomagnetic fields during the geologic past by means of natural remanent magnetism retained in rocks have made great progress. Modern palaeomagnetic studies may be classed in two groups.

(i) The one aims at a scrutiny of the nature of geomagnetic fields with respect to stability, secular variation, reversal, etc.

(ii) The other examines what reality lies in the hypothesis of continental drift.

More researchers, however, have been concerned with the latter problem and have collected rock samples from many parts of the world, such as Europe, North and South America, Australia, India and Japan. In many countries other than Japan, researchers have based their work upon rocks of which the ages date back up to Pre-Cambrian times.

Among many investigators who have been concerned with Palaeomagnetism are Blackett[2], Runcorn[3], Irving[4],[5] and Nagata,[6] each having

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[1] K. MOMOSE, *Journ. Geomagn. Geoelectr.*, **10** (1958), 12.

[2] P. M. S. BLACKETT, *Lectures on Rock Magnetism* (Jerusalem, 1956), pp. 31-36, 69-82.

[3] S. K. RUNCORN, *Adv. in Phys.*, **4** (1955), 244.

[4] E. IRVING, *Geofisica Pura e Appl.*, **33** (1956), 23.

[5] E. IRVING, *Adv. in Phys.*, **6** (1957), 194.

[6] T. NAGATA, S. AKIMOTO, Y. SHIMIZU, K. KOBAYASHI and H. KUNO, *Proc. Jap. Acad.*, **35** (1959), 378.

been accompanied by his co-workers. Cox and Doell[7] and Irving[8] recently gave excellent lists of data hitherto obtained from various countries, and reviews of discussions concerned with palaeomagnetism.

Many instances that indicate the occurrence of geomagnetic reversal through geologic ages have been known among the records obtained from studies grouped as both (i) and (ii) in the foregoing paragraph. Roche[9],[10] was one of the earliest investigators who suggested that the reversal of magnetization of rocks in nature might be explained by the reversed geomagnetic field. After treating many rock samples taken from Auvergne and other localities in France, Roche emphasized that the stratigraphic situations of the reversal of magnetization of rocks seem to be located at several definite geological horizons; the examples are the ages about the Mio-Pliocene boundary and about the Plio-Pleistocene boundary.

As a notable instance that can be understood as indicating a reversal of geomagnetic field, Kato presented data demonstrating an interesting distribution of magnetic directions in a sedimentary rock (normal) and in a dyke rock (reverse) intruding into it. Within a mass of the Miocene green tuff exposed along the bank of the River Ōkuragawa near the City of Sendai, is found a set of dyke swarms consisting of basaltic andesite of which the age is assigned, according to I. Kato,[11] to the Upper Miocene or the Upper Pliocene. The magnetic polarizations in various parts of the dyke-rocks are in reverse direction, and the marginal zone of the country rock (green tuff) in direct contact with the dyke rock (approximately 60 cm thick) are reversely magnetized. As the country rocks are in general normally magnetized, the magnetic directions revealed in this zone of contact may be due to a reversal of geomagnetic field at the time when the dyke swarms intruded. The reversed magnetism of these dyke rocks and the baked sediment can hardly be explained without assuming that the geomagnetic field was reversed during the time of dyke intrusion.

A reversal of geomagnetism is widely suggested during the Early Pleistocene time from rock data taken from various sites all over the world. Among these data there is a report by Nagata and others concerning the reverse remanent magnetism of rocks of the Early

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[7] A. COX and R. R. DOELL, *Bull. Geol. Soc. Amer.*, **71** (1960), 645.

[8] E. IRVING, *Geophys. Journ. Roy. Astron. Soc.*, **2** (1959), 51.

[9] A. ROCHE, *Comptes rendus.*, **233** (1951), 1132.

[10] A. ROCHE, *ibid.*, **243** (1956), 812.

[11] Y. KATO, A. TAKAGI and I. KATO, *Journ. Geomagn. Geoelectr.*, **6** (1954), 206.

Pleistocene, based on samples collected from the Izu and Hakone district.[12]

Hospers[13),14] observed the existence of reversely magnetized basaltic lavas in Iceland. As early as 1950, Hospers made measurements of the magnetic directions of numerous lava flows in Iceland, of which the ages are estimated to range from Miocene to the present. The latest eruption of Mt. Hekla took place from 1947 to 1948. Following conclusions were stressed in Hospers' 1954 paper.[15] "Reversely magnetized igneous and sedimentary rocks have also been found. The reversely magnetized lava flows presumably occupy definite stratigraphic levels and can be traced as far as geological correlation permits. Zones of flows with normal and reverse magnetization alternate in comparable thicknesses. There are no significant differences in susceptibility and intensity of permanent magnetization between zones with normal and reverse magnetization. The large body of field evidence suggests that these zones are similar in every respect, except that they cooled down in fields of opposite directions and of similar strength. The same conclusion is indicated by the reversely magnetized sediments." Though the author suspects there may be some uncertainty in Hospers' statements, he can not help giving credit to the probability of the occurrence of repeated geomagnetic reversal in the past.

It is important to note that the suggested time lengths of reversed and normal geomagnetic field are roughly the same.

According to Hospers, it appears that the field changes to the opposite direction within one fiftieth of the period over which a normal or a reversed field persists. The latter period is thought to be 250,000–500,000 years. The reversal of geomagnetic fields was therefore thought to have taken place within a short period of about 10^3–10^4 years.

A few demonstrations of the transitional shifting of the pole through the short period of reversal have been supplied by both Sigurgeirsson[16] and Momose[17] who detected quite independently the existence of Pliocene rocks magnetized in the intermediate directions.

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12) T. NAGATA, S. AKIMOTO, S. UYEDA, Y. SHIMIZU, M. OZIMA, K. KOBAYASHI and H. KUNO, *Journ. Geomagn. Geoelectr.*, **9** (1957), 23.

13) J. HOSPERS, *Koninkl. Nederl. Akad. Van Wetenschappen Amsterdam* **B 56** (1953), 467.

14) J. HOSPERS, *ibid.*, **B 57** (1954), 112.

15) J. HOSPERS, *Journ. Geomagn. Geoelectr.*, **6** (1954), 172.

16) TH. SIGURGEIRSSON, *Adv. in Phys.*, **6** (1957), 240.

17) K. MOMOSE, *loc. cit.*, 1).

The author will stress that reversals of the polarity of the geomagnetic field might have taken place in such a manner that the direction of the field gradually shifted by 180°.

The present paper is a comprehensive report of the palaeomagnetic studies on the Shigarami, Komoro and Enrei formations conducted by the present author. Some of the items contained in the paper were already reported in the author's previous papers.[18),19)] In this paper, the mode of variation of geomagnetic intensity during the transient stage of field reversal will also be discussed. The study was made in the early days of 1960 and the results obtained were first reported in May of 1960 at the general meeting of the Society of Terrestrial Magnetism and Electricity of Japan held in Tokyo. Nagata introduced it in August of 1960 under the title "Detailed Feature of a Reversal of the Geomagnetic Field in Later Tertiary" in the Session of Commission 4 (on Palaeomagnetism) of the IAGA Assembly held at Helsinki.

II. Brief Summary on the Geology and Geologic Age of the Shigarami, Komoro and Enrei Formations

Rock samples were collected from three stratigraphic groups of formations, namely the Shigarami, the Komoro and the Enrei formation, each of which is located more than tens of kilometers apart from one another (Fig. 1). The time-stratigraphic correlation between these three groups, was given in a previous paper.[20)]

Some supplementary rock samples were used for the purpose of confirming the author's arguments. One group of rock samples was collected from dacite flows embedded within the Yashiro member of the Omine formation, which is considered to be the equivalent of the Upper Sarumaru formation. The geology and geological age of the Omine formation and those associated with it are to be found in a paper published by the Research Group for the Himekawa Region.[21)]

Another group of rock samples was collected from Mujinagoro, Wariga-take and from Funa-yama, all of which are considered to be equivalent to the Iizuna pyroclastic rock. The geological ages of the samples of both groups used for supplementary purposes are inferred

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18) K. MOMOSE, *loc. cit.*, 1).

19) K. MOMOSE, K. KOBAYASHI and T. YAMADA, *Bull. Earthq. Res. Inst.*, **37** (1958), 433.

20) K. MOMOSE, *loc. cit.*, 1).

21) RESEARCH GROUP FOR HIMEKAWA REGION, *Journ. Geol. Soc. Jap.*, **64** (1958), 431.

Geologic age		Shigarami group		Komoro group		Volcanic rocks around Lake Suwa		Direction
Quaternary	Pleistocene							
Tertiary	?				Ōkubo (and)		Takaosan (and.)	N
	Pliocene	Sarumaru Form.	Kuroiwa (basalt)	Nunobiki Form.		Enrei Form.	Utsukushi-ga-hara up. part Utsukushi-ga-hara low. part Mitu-mine, Suwa up (all and.)	Re
			Kamisoyama Watado (and) Machi (basalt) Hiraide-zawa (and.) Kawashimo A (and.)	Up. Ōkui Form.	Hanareyama, Yasuhara, Sehayagawa A (w.t.)		Kawagishi, Dōda, Suwa low. part Wada Pass (all and.) Wada (lip.)	Rw
		Shigarami Form.	West of Akefujbashi A		Sehayagawa (basalt) Porphyrite Higashizawa, Ōya (w.t.)			Rw
			West of Okkayo (and.) Akefuji bashi (Basalt)	Low. Ōkui Form.	Fukazawa (basalt)			N
	? Miocene		Seto					N

Form. Formation and. andesite w.t. welded tuff lip. liparite

Fig. 1. Geological correlation chart of various volcanic rocks belonging to the Shigarami, Komoro and Enrei groups of formations. The associate magnetic directions of these rocks are put in the right column.

to be the late Pliocene or the early Pleistocene.

(1) *Shigarami Formation*

The Shigarami formation consists of two major lithologic units of both water-deposited clastic sediments and volcanic pyroclastic rocks, and both facies are roughly synchronous in the interfingering relation.

The Shigarami formation is underlain conformably by the Ogawa formation, whereas it is overlain with partial disconformity by the Toyono formation. Stratigraphic constitution and the relative status of subunits, such as key beds and other beds with various rock facies of the Shigarami formation will be shown in Fig. 2. The signs t_4 and t_1 in Fig. 2 indicate the stratigraphic horizons of three tuff beds which are excellent time-markers.[22] From the lower part of the Hatayama sandy

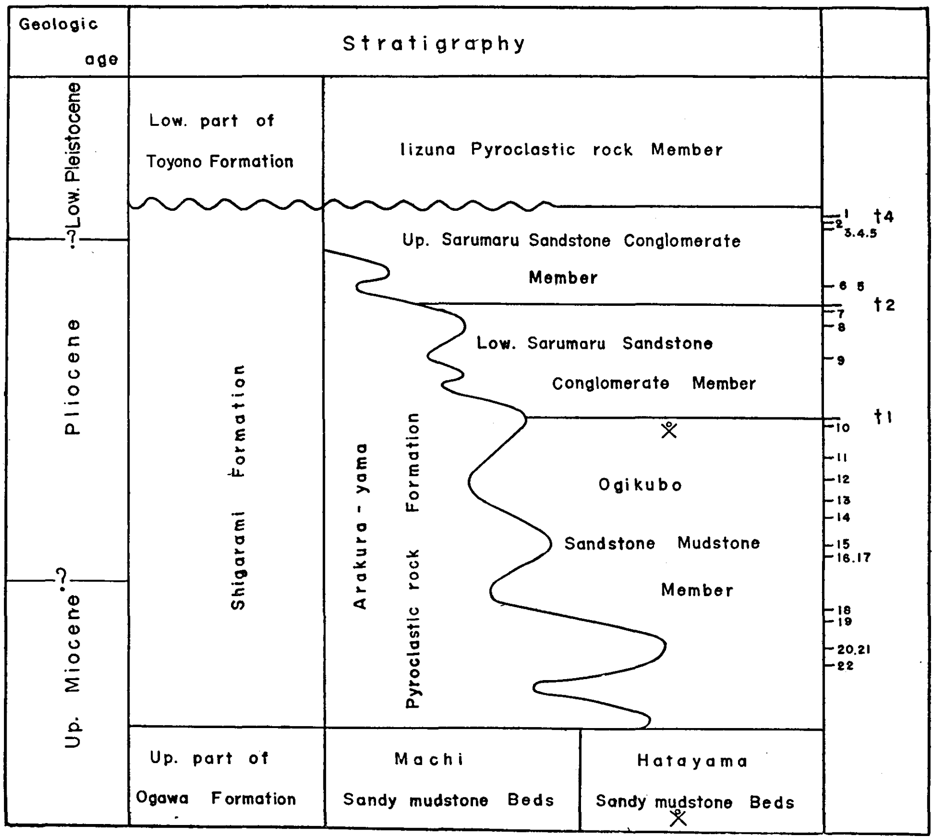

Fig. 2. Stratigraphic profile of the Shigarami formation, with the signs showing the stratigraphic situations of collected rock samples.

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22) H. TAKESHITA, Y. SAITO and K. MOMOSE, *Earth Science*, **49** (1960), 26.

mudstone member which is equivalent to the upper division of the Ogawa formation, the following fossil molluscs have been found: *Serripes makiyamai* (YOKOYAMA), *Dosinia Kaneharai* (YOKOYAMA), *Spisula sachalinensis* (SCHRENCK), *Spisula voyi* (GABB), *Lucina mochizuki* (KURODA). Most of these molluscan species are said to be of cool-water fauna and their age is tentatively put at Upper Miocene.

"Shimonireki fauna", which marks the upper part of the Ogikubo sandstone-mudstone member, comprises the following molluscan species. *Anadara amicula* (YOKOYAMA), *Patinopecten Yamasakii* (YOKOYAMA), *Conchocele nipponica* (YABE & NOMURA), *Turritella saishuensis* (YOKOYAMA), *Patinopecten tryblium* (YOKOYAMA). The geologic age implied by this fauna is the lower Pliocene.[23]

Some rock samples were taken for magnetic measurements from lavas embedded in sediments. Most samples, however, were taken from numerous lava flows contained within a mass of tuff breccias of the Arakura pyroclastic rock.

Fig. 2 shows the number of localities from which each group of rock samples was taken.

(2) *Komoro Group*

The stratigraphic succession of the Komoro group is shown in Fig. 3. The Komoro group of lacustrine origin is, in descending order, classified as the Uryuzaka, the Nunobiki, the Upper Okui and Lower Okui formations, between which there is unlikely to exist any significant stratigraphic break. The Iwao formation covers unconformably the Uryuzaka formation—the uppermost division of the Komoro group, and the lowest division—the lower Okui formation also rests conformably upon the Ogawa group. As mentioned in the foregoing paragraph, no stratigraphic hiatus occurs in the Okui formation, and the lower boundary of the Upper Okui formation is therefore placed at the base of a welded tuff bed.

The Lower Okui formation consists principally of an alternation of conglomerates and tuff breccias, whereas the upper Okui formation consists of an alternation of conglomerate, sandstone and mudstone, and especially in its lower part is embedded the welded tuff as mentioned above.

Conformably below the Komoro group, Miocene formations such as the Ogawa, Bessho and Uchimura follow in descending order. The

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[23] T. TOMISAWA, *Kamiminochi-Gun-Chishitsushi* (Edit. T. YAGI, Nagano, 1958), pp. 318-319.

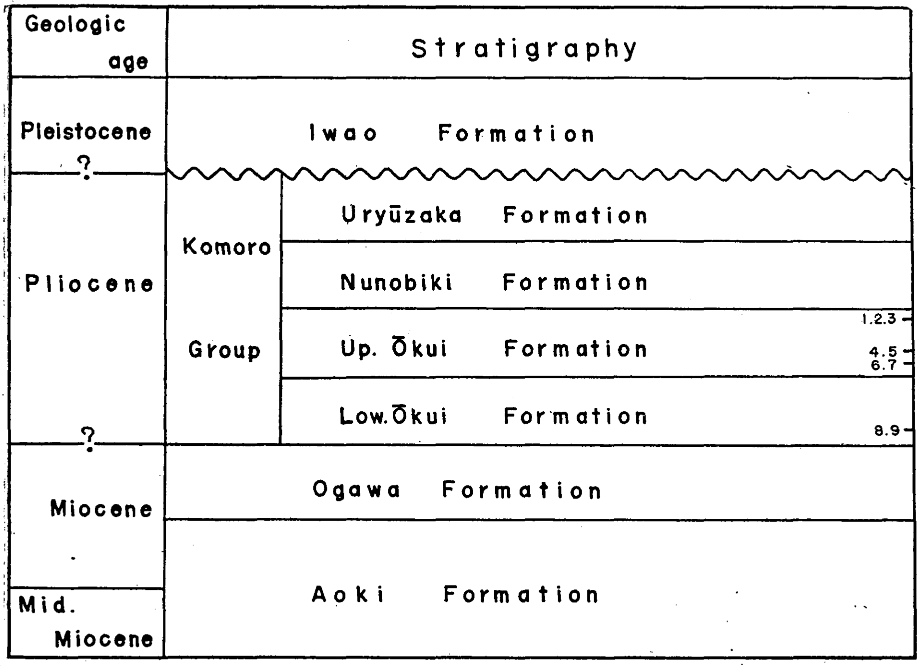

Fig. 3. Stratigraphic profile of the Komoro formation, with the signs showing the stratigraphic situations of collected rock samples.

geologic age of the Komoro group has been inferred from its stratigraphic relation to other stratigraphic units, especially the Ogawa formation which contains fossil mulluscs, to be within the range from the Upper Miocene or from the Lower Pliocene to the Pliocene.

Our knowledge on the geology of the Komoro group is based upon the studies made by the Shiokawa Research Group.[24),25)] Rock samples were collected from welded tuff and other rocks embedded in the Upper and the Lower Okui formations. Sehayagawa basalt is embedded in the Kabutoiwa formations and is to be correlated with the Okui formations. Since Yasuhara tuff lies upon the basalt of the Kabutoiwa formation, the correlation as noted above seems to be justified. The numbers in Fig. 3 indicate the locality of each group of samples.

(3) *Enrei Formation*

The Enrei group consists of tuff breccias and lava flows, especially

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24) N. Iijima, K. Taguchi, K. Isawa, M. Koda, G. Nakamura, K. Kifune, M. Kobayashi, K. Yano and Y. Yamagishi, *Earth Science*, **37** (1958), 46.

25) N. Iijima, Thesis (1961).

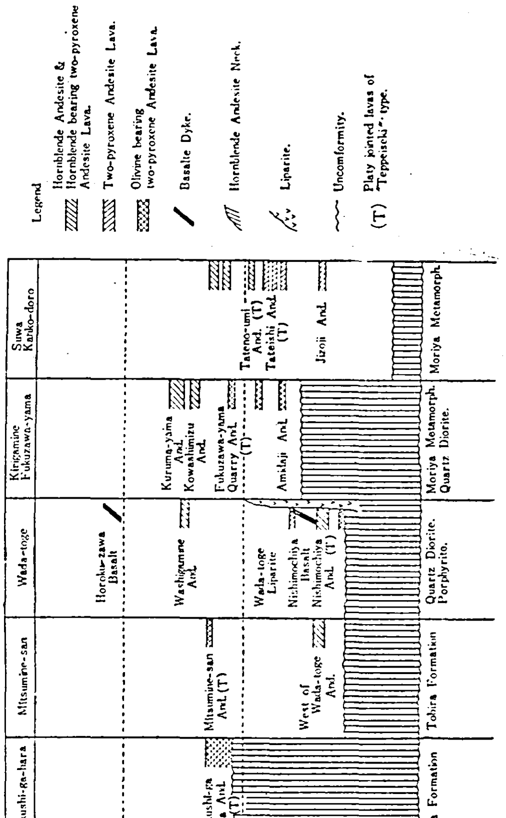

Fig. 4. Correlation chart basing upon geomagnetic and geologic studies of the Enrei formation.

the characteristic andesite lava flows commonly called "Teppeiseki" which are marked by well-developed platy joints. Fig. 4 represents a correlation chart of lava flows embedded at various horizons within the Enrei formation, as based upon both stratigraphic and palaeomagnetic considerations.

A tentative correlation between these three groups of formations inferred from geologic and palaeomagnetic observations, is shown in Fig. 1.

Geologic studies of the Enrei formations have long been carried out by (Kunio) Kobayashi,26),27 whom the author joined to make palaeomagetic studies. Some results of the joint studies have already been published in the Bulletin of Earthquake Research Institute.28)

Samples for palaeomagnetic studies were collected chiefly from lava flows of the Enrei formation. Many of the collected rocks were the so-called "Teppeiseki".

III. Magnetic Directions of Rocks collected from the Shigarami, Komoro and Enrei Groups of Formations and their Pole Positions

As will be noted in Chapter V, the remanent magnetism retained in the rocks dealt with in the present work is probably stable. Therefore their magnetic directions are considered to record the former geomagnetic field in situ during Pliocene time. There seems to be reasonable evidence for considering that the main geomagnetic field in these times may be called a centered dipole field. If so, it is possible to calculate from rock magnetism the former position of the geomagnetic poles. By choosing a system of geographical coordinates, the position (θ, ϕ) of the magnetic pole can be calculated by the following formula:

$$\left.\begin{aligned}\cos\theta &= \cos\theta'\cos\psi+\sin\theta'\sin\psi\cos D\,,\\ \sin(\phi-\phi') &= \sin D\sin\psi/\sin\theta\,,\end{aligned}\right\} \qquad (1)$$

where D denotes the declination of the former geomagnetic direction obtained from rock magnetism: θ' and ϕ' indicate respectively the corresponding latitude and longitude of the locality from which the rock sample was collected and ψ denotes the magnetic colatitude. Also based upon the hypothesis of the magnetic dipole, the relation between the geomagnetic inclination I and the geomagnetic colatitude is

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26) K. KOBAYASHI, *Geogr. Rev. Jap.*, (1953), 291.

27) K. KOBAYASHI, *Report of Japanese Neogene Tertiary—A Symposium* (Geological Society of Japan, 1958), 8-11.

28) K. MOMOSE *et al.*, *loc. cit.*, 19).

Table 1. Various magnetic properties of the samples taken from the Shigarami formation showing the directions, calculated directions of the centred dipoles, the intensities and the values of *Jn*/*JTc*.

Localities	Number of Samples	Rock Names	Directions		Error* 5%	Directions of the Centred Dipole		Intensity 10^{-3} *e.m.u./gr.*	*Jn*/*JTc*
Nakanochi 1	4	Welded tuff	164° E	−42°	7°	73° S	167°W	0.58	0.51
West of Seto 2	5	(Ho.) 2 Py. Andesite	157° E	−10°	10°	55° S	179° E	1.68	0.43
Kuroiwa 3	3	Ol. Aug. Basalt	167° E	−34°	17°	70° S	174° E	1.85	0.66
West of Seto 4	5	Ol. Aug. Basalt	158° E	−16°	7°	56° S	181° E	1.78	0.40
West of Seto 5	3	Ol. Aug. Basalt	137° E	−60°	16°	57° S	115°W	1.49	0.70
Kamisoyama 6	4	(Ho.) 2 Py. Andesite	130°W	−24°	11°	40° S	62° E	1.00	0.32
Watado 7	4	2 Py. Andesite	97°W	−49°	6°	22° S	23° E	0.82~0.9	0.37~0.38
Machi 8	4	Ol. Aug. Basalt	89°W	−46°	5°	15° S	23° E	1.28~2.47	0.39~0.50
East of Doai 9	3	Andesite	118°W	−42°	28°	35° S	38° E		
Hiraide-zawa 10	5	2 Py. Andesite	73°W	−24°	41°	5° N	29° E	0.53~0.77	0.24~0.28
Kawashimo 11	3	Andesite	77°W	27°	22°	17° N	50° E	0.29	0.15
Kawashimo A 12	4	Andesite	70°W	50°	18°	32° N	62° E	0.77	0.2
West of Akefuji-Bashi 13	3	2 Py. Andesite	94°W	−22°	29°	8° S	38° E	0.85	0.26
West of Akefuji-Bashi A 14	4	2 Py. Andesite	69°W	−68°	23°	15° S	8°W	1.28	0.35
West of Okkayo 15	5	2 Py. Andesite	20° E	64°	11°	72° N	175°W	0.96	0.56
Akefuji-Bashi 16	3	Ol. Aug. Basalt	18° E	55°	11°	75° N	141°W		0.61
Tsubone 17	5	2 Py. Andesite	10° E	66°	6°	76° N	160° E	0.78	0.20
Tochinoki~Seto 18 Loc. 5	3	(Ho.) 2 Py. Andesite	9°W	77°	6°	68° N	124° E	1.43	0.54
Seto 19 Loc. 6	3	(Ho.) 2 Py. Andesite	23° E	68°	4°	68° N	179° E	3.06	0.65
Konabe 20	2	(Ho.) 2 Py. Andesite	60° E	5°		26° N	119°W		
Seto 21	2	Andesitic tuff	48° E	70°	20°	53° N	177°W		
Setouchibashi 22	4	(Ho.) 2 Py. Andesite	12°W	76°	11°	60° N	127° E	1.12	0.50

*=The error angles for 5% are calculated by Fisher's method.

Table 2. Various magnetic properties of the samples taken from the Komoro formation showing the directions, calculated direction of the centred dipoles, the intensities and the values of Jn/JTc.

Localities	Number of Samples	Rock Names	Directions		Error* 5%	Directions of the Centred Dipole		Intensity 10^{-3} *e.m.u./gr.*	Jn/JTc
Yasuhara 1	4	Welded tuff	155°W	−47°	5°	67° S	59° E	3.80~8.70	0.73~2.11
Hanare-yama 2	4	Welded tuff	155°W	−36°	8°	63° S	70° E	7.67	1.23
Sehaya-gawa 3	6	Welded tuff	153°W	−45°	6°	65° S	58° E	1.30	0.64
Sehaya-gawa 4	4	Basalt	102°W	−63°	3°	32° S	9° E	1.70~1.89	0.39~0.41
Miyanoshita 5	4	Porphyrite	74°W	−52°	4°	8° S	9° E	0.17~0.62	0.10~0.27
Higashi-zawa 6	4	Welded tuff	79°W	14°	21°	12° N	44° E	0.31~0.63	0.11~0.22
Oya 7	4	Welded tuff	64°W	−22°	7°	12° N	20° E	0.27~0.37	0.15~0.18
Fukazawa 8	2	Basalt	13° E	64°		75° N	175° E	1.75	0.80
Fukazawa 9	2	Basalt	19° E	61°		74° N	169°W	1.63	0.75

*=The error angles for 5% are calculated by Fisher's method.

expressed as:

$$\cot \psi = 1/2 \tan I . \qquad (2)$$

In the present paper, the author adopted the latitude and longitude (36°15′ N, 137°58′ E) of Matsumoto for θ' and ϕ' in the formula (1).

(1) *Results Obtained from the Shigarami Formation and Komoro Group.*

Magnetic directions of rock samples taken from the Shigarami formation and Komoro group, and the corresponding positions of the virtual geomagetic poles are enumerated in Tables 1 and 2. The number put in these two tables is the same as the number for each locality cited in Figs. 2 and 3. Exposures of the Komoro group are horizontal and do not seem to have been dislocated, whereas the Shigarami formation takes a big synclinal structure, but the restoration of strata to their original dip can easily be made. The two lava flows used are situated near the horizontal axial part of the syncline and close to the key-beds t_1 and t_2 tuffs (Fig. 2), therefore only very little correction was needed. Examples of magnetic directions of the rock samples are projected stereographically in Figs. 5–18.

From these Figures and Tables, the following points will be noted.

(i) Ideal concentration in the directions of magnetization seems to be indicated in all the cases. For statistical treatment of these measured directions of magnetization, R. Fisher's method[29] has been

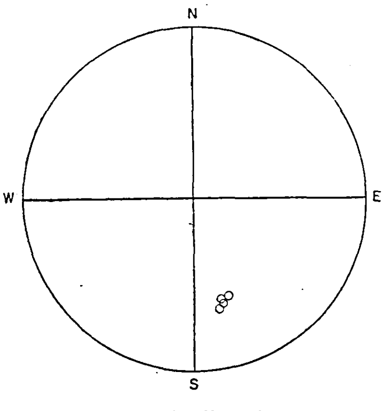

Fig. 5. Magnetic directions (*R.N.R.M.*) of the samples collected from Nakanochi. (Shigarami formation)

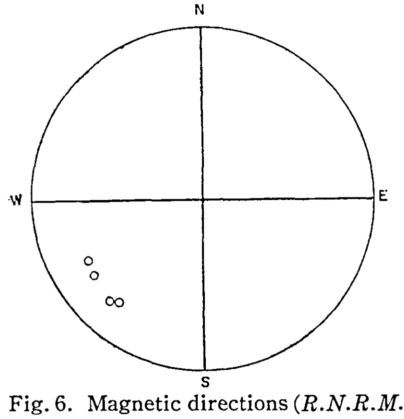

Fig. 6. Magnetic directions (*R.N.R.M.*) of the samples collected from Kamisoyama. (Shigarami formation)

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[29] R. A. FISHER, *Proc. Roy. Soc.*, **A 27** (1953), 295.

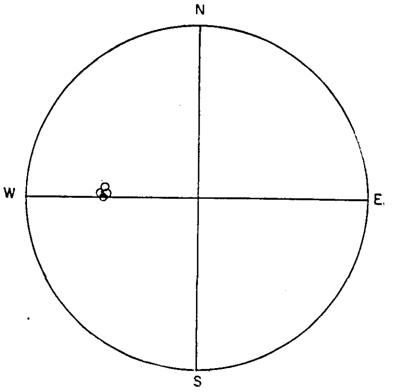

Fig. 7. Magnetic directions (intermediate) of the samples collected from Machi. (Shigarami formation)

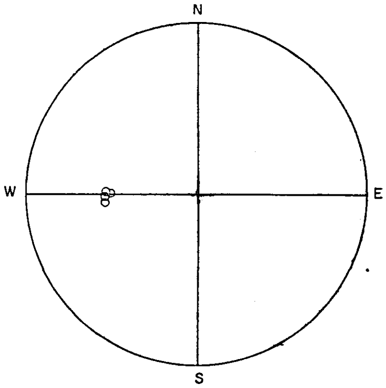

Fig. 8. Magnetic directions (intermediate) of the samples collected from Watado. (Shigarami formation)

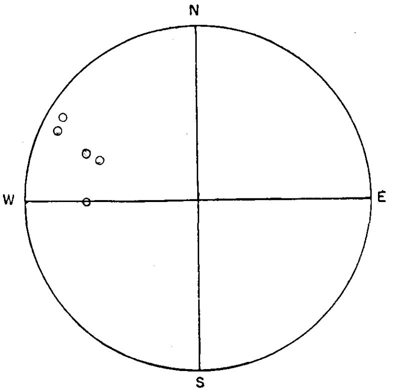

Fig. 9. Magnetic directions (intermediate) of the samples collected from Hiraide-zawa. (Shigarami formation)

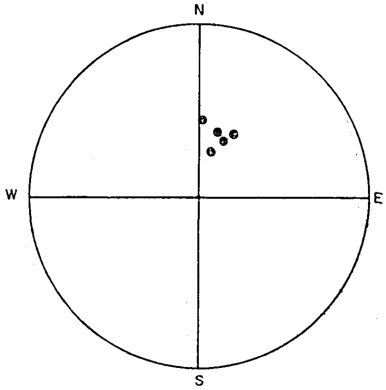

Fig. 10. Magnetic directions (*N.N.R.M.*) of the samples collected from Okkayo. (Shigarami formation)

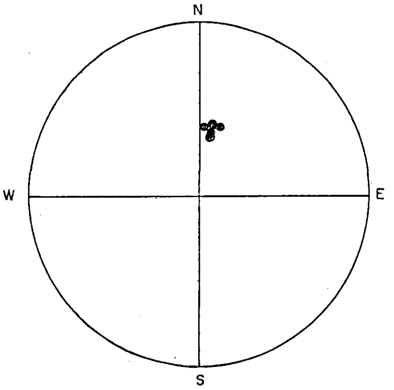

Fig. 11. Magnetic directions (*N.N.R.M.*) of the samples collected from Tsubone. (Shigarami formation)

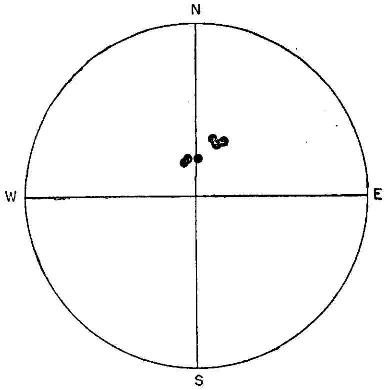

Fig. 12. Magnetic directions (*N.N.R.M.*) of the samples collected from Seto. (Shigarami formation)

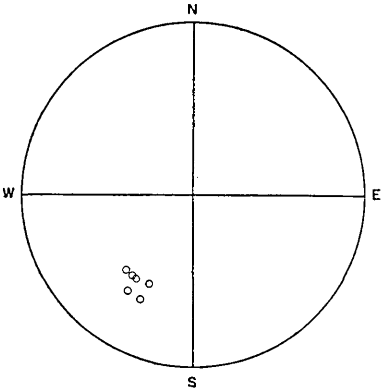

Fig. 13. Magnetic directions (*R.N.R.M.*) of the samples collected from Sehaya-gawa. (Komoro formation)

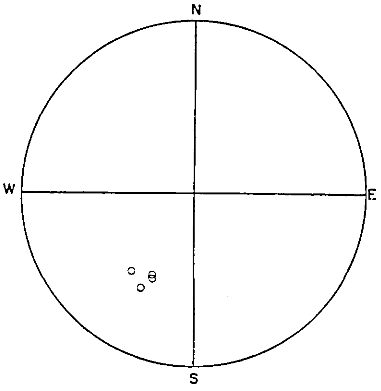

Fig. 14. Magnetic directions (*R.N.T.M.*) of the samples collected from Yasuhara. (Komoro formation)

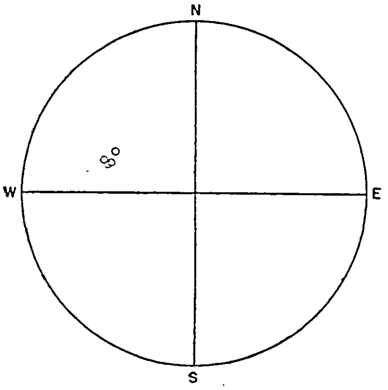

Fig. 15. Magnetic directions (intermediate) of the samples collected from Miyanoshita. (Komoro formation)

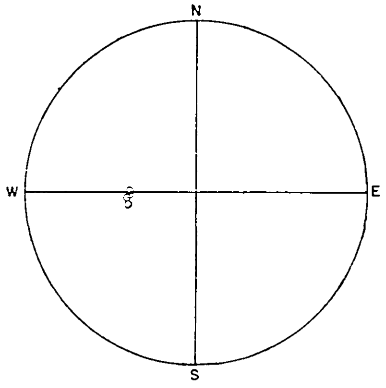

Fig. 16. Magnetic directions (intermediate) of the samples collected from Sehaya-gawa. A (Komoro formation)

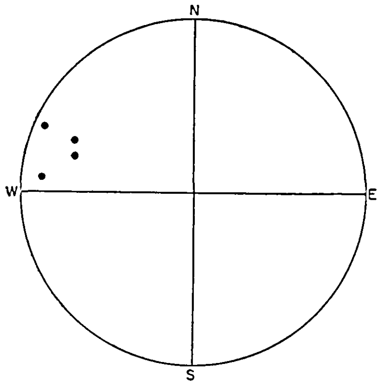

Fig. 17. Magnetic directions (intermediate) of the samples collected from Higashi-zawa. (Komoro formation)

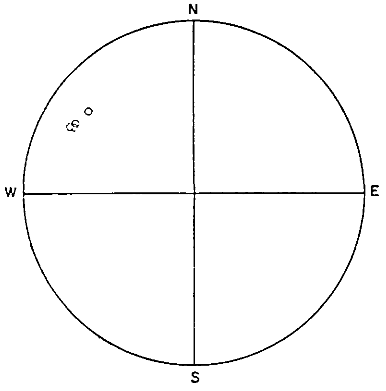

Fig. 18. Magnetic directions (intermediate) of the samples collected from Ōya. (Komoro formation)

used. The radius of the circle of confidence around each mean direction is calculated at the 5% level of significance.

As is known from Tables 1 and 2, despite the fact that only a few samples are measured, the error angles thus calculated prove to be small. This means the directions of magnetization obtaining in a single rock unit are in a state of good concentration.

(ii) As read in Tables 1 and 2, intensities of magnetization measured are within the order of 10^{-3} *e. m. u./gr.* throughout the samples taken from both formations.

(iii) The samples from a certain portion of the Shigarami formation ranging from the strata underlying t_1 tuff upward to the strata just underlying t_2 tuff; and the samples taken from the lower part of the Upper Okui formation of the Komoro group, such as those from Miyanoshita, Sehaya-gawa A, Higashi-zawa and Ōya indicate that the direction deflects considerably westward (approximately N 60°–110°W).

(iv) As shown in Tables 1 and 2, virtual pole positions determined from the above-mentioned rocks distribute in the area from 32°N to 35°S.

(v) On the other hand, virtual pole positions determined from the rock samples from any strata both underlying and overlying the above cited strata are located nearly at 75°N and 70°S.

Summarizing the results hitherto obtained, the author must stress that the pole position associated with the geomagnetic field might have shifted continuously within a rather short period sometime in the Pliocene from the North polar region to the South polar region.30)

The manner of reversal from the normal direction to the reverse direction obtained from both the Shigarami formation and the Komoro group, each several tens of kilometers apart, are shown in Fig. 19. Each path of polar shifting drawn respectively from the measurements of each formation is similar to the other.

In Fig. 19, black dots indicate that the pole positions obtained from Komoro group have shifted from Alaska by way of the Bering Sea, the central part of Africa and Cape Town, to the South polar region.

TH. Sigurgeirsson and T. Einarsson published in two reports the results of their studies made about the Late Cenozoic basalt flows in Iceland.

Sigurgeirsson31) (1957) and Einarsson32) (1957) stated that there were

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30) K. Momose, *loc. cit.*, 1).

31) Th. Sigurgeirsson, *loc. cit.*, 16).

32) T. Einarsson, *Neues Jb. Geol. Pal.*, **4** (1957), 159.

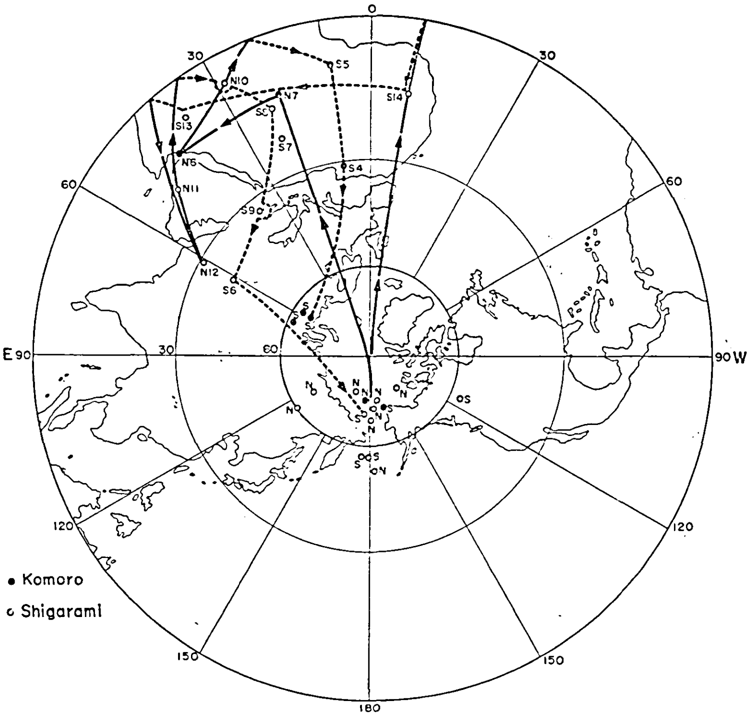


Fig. 19. Traces of migrating pole positions deduced from the two igneous rock series of the Pliocene age.

many groups of basalt flows characterized by normal and reverse magnetization, and that the reversal from *N* to *R* or from *R* to *N* might have taken place continuously.

Einarsson, (1957, p. 159) stated also that both duration of the normal and the reversed field might cover a time range from several hundred thousand to one million years, whereas the changing polarity might have taken place within a rather short period ranging from several thousand to even several hundred years.

(2) *Enrei Formation*

Samples were collected from lava flows at Wadatoge, Kawagishi, Mt. Mitsumine, Mt. Utsukushi-ga-hara and at various sites in the Suwa district. Correlation of these lava flows of the Enrei formation was noted in the foregoing chapter. Directions of magnetization of rock samples taken from the Enrei formation and the corresponding pole positions are enumerated in Tables 3 and 4. Directions of magnetization

Table 3. Various magnetic properties of the samples taken from the Enrei formation showing the directions, calculated directions of the centred dipoles, the intensities and the values of Jn/JTc.

Wada-toge group

Localities	Number of Samples	Rock Names	Directions		Error* 5%	Directions of the Centred Dipole		Intensity 10^{-3} *e.m.u./gr.*	*Jn/JTc*
Wa Ia	3	(Ol.) 2 Py. Andesite	166° E	−49°		76° S	160°W	0.790	0.760
Wa Ib	Xenolith	(Ol.) 2 Py. Andesite	176°W	−38°		75° S	115° E	1.490	0.920
	4~6	Liparite	177°W	−36°	5°	73° S	112° E		
Wa II	8~10	(Ho.) 2 Py. Andesite	151°W	53°	12°	16° S	110° E	0.140	0.113
Wa III	11~13	(Ho.) 2 Py. Andesite	180°	− 2°		56° S	135° E	0.360	0.218
Wa V	17	2 Py. Andesite	175°W	−41°		78° S	115° E	0.850	0.859
Wa VII	24~28	Liparite	164°W	−62°	7°	76° S	5° E	0.240	0.500
Kawagishi group									
Kw I	1~ 5	(Ho.) 2 Py. Andesite	160°W	−30°	6°	64° S	85° E	0.410	0.640
Kw IIIa$_1$	10~12	(Ho.) 2 Py. Andesite	160°W	−38°		67° S	78° E	0.240	0.462
Kw IIIa$_2$	13~14	(Ho.) 2 Py. Andesite	160°W	−35°	28°	65° S	83° E	0.330	0.643
Kw IIIb	16~17	(Ho.) 2 Py. Andesite	168° E	−42°		74° S	174°W	0.920	0.726
Kw IV	19~20	(Ol.) 2 Py. Andesite	141° E	−27°	27°	49° S	156°W	0.820	0.283
Kw V	23~27	(Ol.) 2 Py. Andesite	180°	−44°	2°	81° S	135° E	0.640	0.515
Mt. Mitsu-mine and Mt. Utsukushi-ga-hara group									
Mi I	9,11~16	(Ol.) 2 Py. Andesite	168° E	−19°	10°	64° S	161° E	0.810	0.750
Ut Ia	1~ 3	(Ol.) 2 Py. Andesite	142° E	−29°	11°	56° S	156°W	1.070	0.790
Ut Ib	6~10	(Ol.) 2 Py. Andesite	157° E	−27°	22°	61° S	175°W	0.650	0.410
Ut IV	1~ 4	(Ol.) 2 Py. Andesite	158° E	−20°	15°	59° S	178° E	0.810	

* The error angles for 5% are calculated by Fisher's method.

Table 4. Magnetic directions and calculated directions of the centred dipoles of various samples in the environs of Enrei Formation.

Suwa Kanko-doro group

Localities	Number of Samples	Rock Names	Directions		Direction of the Centred Dipole	
Su VII	K 7	(Ho.) 2 Py. Andesite	177° E	−54°	86° S	140°W
Su VI	K22∼25	2 Py. Andesite	168° E	−40°	73° S	78°W
Su V	K29∼34	(Ol.) 2 Py. Andesite	147°W	2°	34° S	87° E
Su II	K 1∼ 6	2 Py. Andesite	150°W	−25°	55° S	75° E
Su III	K 7∼10	2 Py. Andesite	132°W	−42°	46° S	45° E
Su IV	K11∼16	2 Py. Andesite	177°W	−25°	67° S	127° E
Su I	K 9∼12	2 Py. Andesite	121° E	35°	12° S	168°W

Fukuzawa-yama group

Localities	Number of Samples	Rock Names	Directions		Direction of the Centred Dipole	
Ks II	Y20∼23	(Ol.) 2 Py. Andesite	142° E	−56°	59° S	120°W
Fu V	Y17∼19	(Ol.) 2 Py. Andesite	137° E	−45°	52° S	137°W
Fu IV	Y15	(Ol.) 2 Py. Andesite	144° E	13°	37° S	178° E
Ks I	KK12∼19	(Ol.) 2 Py. Andesite	127° E	−44°	44° S	127°W
Fu III	531281∼6 544101∼5	(Ol.) 2 Py. Andesite	128° E	−72°	49° S	90°W
Fu II	Y 8∼ 9	(Ol.) 2 Py. Andesite	120°W	−51°	40° S	61° E

of samples taken from each locality, are shown in stereographic projection is Figs. 20–24.

In Figs. 20–24 and in Tables 3 and 4, the following points may be observed;

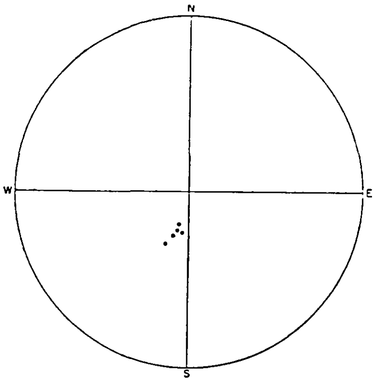


Fig. 20. Magnetic directions (*R.N.R.M.*) of the samples collected from the pass of Wada-toge. Wa VII (Enrei formation)

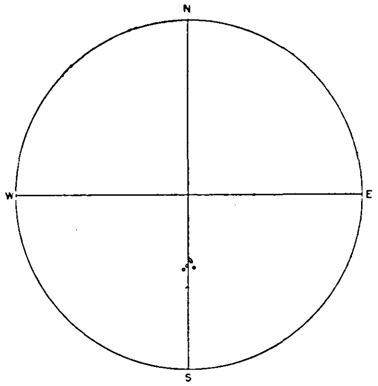


Fig. 21. Magnetic directions (*R.N.R.M.*) of the samples collected from Kawagishi. KwV (Enrei formation)

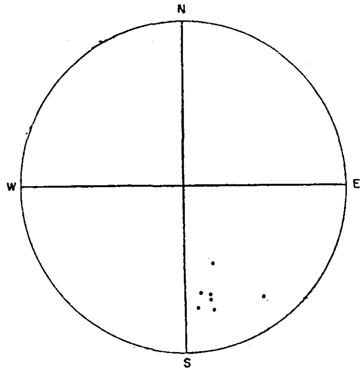


Fig. 22. Magnetic directions (*R.N.R.M.*) of the samples collected from Mt. Mitsumine. (Enrei formation)

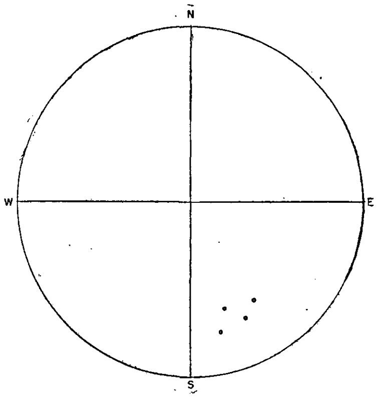
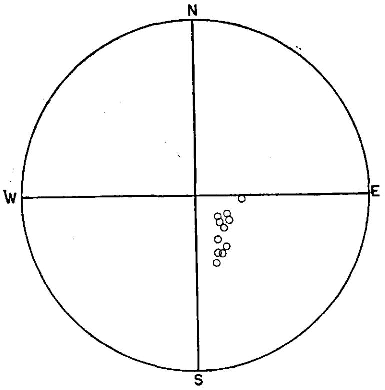


Fig. 23. Magnetic directions (*R.N.R.M.*) of the samples collected from Mt. Utsukushi-ga-hara. Ut IV (Enrei formation)



Eig. 24. Magnetic directions (*R.N.R.M.*) of the samples collected from Mt. Fukuzawa-yama. Fu III (Enrei formation)

(i) A good concentration in magnetic direction of the samples from the same rocks is indicated. The error angles[33] were calculated in the same way as in the cases of the Shigarami and the Komoro groups of formations. The results shown in Table 3, indicate that the dispersal of the measured magnetic directions is small.

(ii) The intensities of magnetization of all rock samples are within the order of 10^{-3} *e. m. u./gr.*

(iii) All the samples of the Enrei formations are, within the limit of the author's collection, reversely magnetized except for the normally magnetized andesite of Mt. Takaosan. As seen in Figs. 1 and 4, the lower parts of the Enrei formation indicate that they are reversely magnetized with a westward deflection, whereas the upper parts are reversed with an eastward deflection.

(iv) Fig. 25 illustrates the kinds of variations of the pole positions suggested by the magnetic directions of rocks in ascending order of strata. In this figure, both broken and continuous slender lines, afforded respectively by Fu-group and Su-group, denote the paths of the pole

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[33] R. A. FISHER, *loc. cit.*, 29).

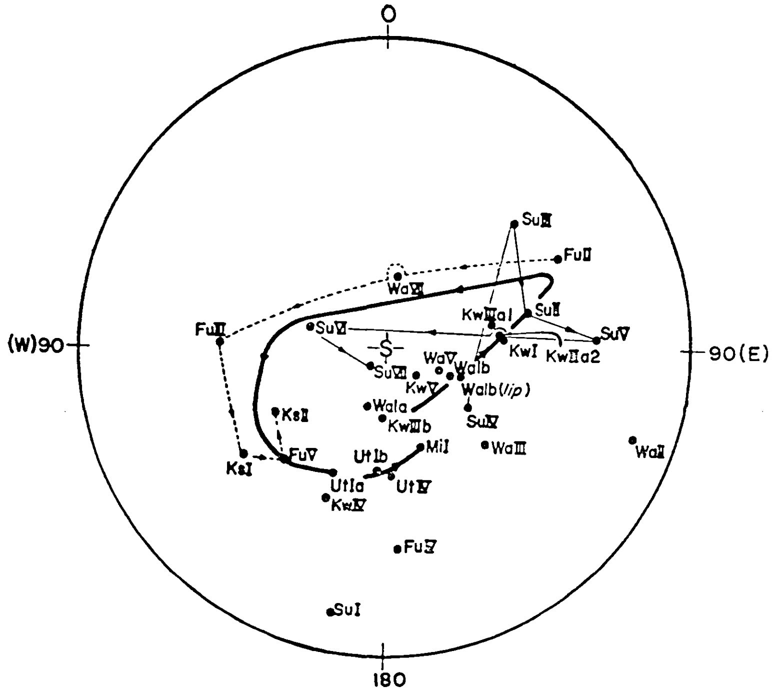

Fig. 25. Modes of the variation of pole positions which might have taken place during the time range of the Enrei formation. Pole positions calculated from measured magnetic directions of the samples taken from every locality are all plotted in this figure. Pole positions can be considered to have shifted along the two slender lines with arrow signs basing upon stratigraphic succession in two areas. Taking advantages of other data obtained from the samples of the Enrei formation, we can conceive that the pole position might have shifted along the thick line drawn in the figure during the whole range of the Enrei formation.

position. It should be noted that the samples of the Su-group which was dislocated by faulting are restored to their original dips to compare with the path of the pole position inferred from Fu-group. Though both lines do not coincide thoroughly with one another, the trend of the polar movement seems as a whole to be a westward shift. Polar variations recorded in other vertical sections of the Enrei formation indicate a similar manner of variation to those recorded in the Fu- and Su-groups. The bold continuous line in Fig. 25 indicates the mean trend of variation, and the arrows indicate the direction in which the pole seems to have shifted or migrated around the position of the rotation axis.

(3) *Supplementary Samples*

As was mentioned in Chapter II, the Yashiro dacite of the Omine formations is a correlative of the upper Sarumaru formation, and the andesites at Mujinagoro, Warigatake and Funayama are also the correlatives of the Iizuna pyroclastic rock members.

The volcanic body of Takaosan is neck-shaped and is recognized as an intrusive within the Enrei formations.

Much discussion has been offered as to the time of the intrusion because the andesite at Takaosan retains a normal magnetic direction (*N. N. R. M.*). The time of intrusion is now considered to be at about the Plio-Pleistocene boundary.

The dacite from the Omine formations is magnetically reversed and the direction seems to coincide with that of Nakanochi welded tuff, which is designated also as t_4 tuff by some geologists and is a useful key bed within the Shigarami formations.

In close agreement with geological interpretation, the reversed magnetic directions of both the Sarumaru and the Enrei formations are considered to be synchronous with one another. The magnetic directions of the rocks from Warigatake, Funayama and Takaosan are all normal.

Non-reversal magnetic direction (*N. N. R. M.*) was detected to occur in Japan in certain rocks of which the age is supposed to be at the earliest Pleistocene or at the latest Pliocene.[34] The geological ages of the rocks mentioned above have also been supposed stratigraphically to be of the latest Pliocene or the earliest Pleistocene.

Loc.	Directions		Dipole		*Jn/JTc*
Funayama	5°W	63°	79°N	113°E	0.37
Warigatake	3.4°W	52°	85°N	113°E	0.92
Muginagoro	10°W	63°	79°N	108°E	0.68
Iizuna A	5°W	45°	81°N	103°E	1.59
Iizuna B	1°W	46°	82°N	138°E	0.85
Takaosan	19°E	64°	73°N	175°W	0.86
O-mine	180°	−60°	84°S	138°E	1.10

IV. Examination of the Stability of Rock Magnetism

First, the hitherto proposed criteria of the magnetic stability of igneous rocks for palaeomagnetism are reviewed.

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34) T. NAGATA *et al.*, *loc. cit.*, 12).

(1) *General Features of Remanent Magnetism of Igneous Rocks*

Igneous rocks retain in general a remanent magnetism called "natural remanent magnetism" (*N.R.M.*), about which Nagata[35),36)] clarified that it should be assigned to the "thermo-remanent magnetism" (*T.R.M.*) produced in the earth's magnetic field at the time when the rocks were formed. Several characteristic features of *T.R.M.* will be mentioned in the following.

Magnetization is possible to a high degree even in such a weak field as a geomagnetic one (0.45 G). Intensities of natural remanent magnetism Jn of igneous rocks are generally within a range from 10^{-4} to 10^{-2} $e.m.u./gr$. In order to produce, at room temperature, such a strong "isothermal-remanent magnetization" (*I.R.M.*), it is necessary to apply a magnetic field with an intensity of about 300 Oe.

T.R.M. is very resistant against *A-C* demagnetization. *I.R.M.* produced within the field with the intensity of about 100 Oe can be demagnetized by the application of an *A-C* magnetic field of about 100 Oe. In contrast to this, *T.R.M.* produced within the geomagnetic field of 0.45 G is demagnetized only partially, say 30% by the application of an *A-C* demagnetization of 300 Oe–400 Oe.

T.R.M. is represented approximately as the sum of partial remanent magnetism—the addition law. *T.R.M.* produced through cooling 600°C to room temperature coincides in intensity with the sum of partial thermo-remanent magnetism acquired through several partial processes of cooling from T_1 to T_2°C that constitute the whole process from 600°C to the room temperature. *T.R.M.* thus produced through partial cooling is called "partial thermo-remanent magnetism" or briefly *P.T.R.M.* It is a characteristic nature of *P. T. R. M.* that the intensity acquired through the cooling process from T_1 to T_2°C is not influenced magnetically by any temperature variation below T_2°C. It is also characteristic that the weaker the applied magnetic field, the better the efficiency of producing *T.R.M.*

(2) *Magnetic Properties of Rock-forming Minerals*

Much information is available concerning this and it has become clear that the major natural ferromagnetic minerals are the iron oxides and the iron sulfides. The group of oxides contained in rocks comprises magnetite, titanomagnetite, maghemite, titanomaghemite, hematite,

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35) T. NAGATA, *Bull. Earthq. Res. Inst.*, **21** (1943), 1.

36) T. NAGATA, *Rock Magnetism* (Tokyo, 1961), pp. 147-195.

ilmenite, and the solid solution of hematite and ilmenite. The sulfide mineral, on the other hand, occurs as pyrrhotite in certain sorts of rocks, ore deposits and gneissic rocks, but the occurrences are rather confined within a limited part of the earth's crust. The part of rock magnetism we are mainly concerned with is due to the magnetism of the oxide minerals.

Chemically, ferromagnetic oxide minerals in rocks are composed mainly of FeO, Fe_2O_3 and TiO_2 involving small quantities of MnO, V_2O_3, MgO, Al_2O_3 and Cr_2O_3 as secondary components. Magneto-chemical knowledge of the FeO–Fe_2O_3–TiO_2 ternary system has been supplied by Pouillard37), Chevallier38) and Akimoto39)–41) etc. These authors made studies not only upon the ferromagnetic minerals in nature but also upon the man-made minerals. The results have shown that the following three systems of solid solution are involved among the ternary system above-mentioned, namely the system of $TiFe_2O_4$–Fe_3O_4 (spinel type in crystal structure), $TiFeO_3$–Fe_2O_3 (rhombohedral type in crystal structure), and Ti_2FeO_5–$TiFe_2O_5$ (rhombic system in crystal structure). 90% of the ferromagnetic oxide minerals included in igneous rocks show the spinel type crystal structure, and are known to be plotted in the system $TiFe_2O_4$–Fe_3O_4 or in the area cornered by the four components Fe_3O_4–$TiFe_2O_4$–Fe_2O_3–$TiFeO_3$.

Ferromagnetic minerals contained in the samples which the author has treated are chemically ascertained not to belong to the system of $TiFeO_3$–Fe_2O_3 and that of Ti_2FeO_5–$TiFe_2O_5$, and none can be identified by X-ray analysis with those belonging to either rhombohedral crystal system or rhombic crystal system. The nature of the solid solutions belonging to the system $TiFe_2O_4$–Fe_3O_4 was clarified especially by Akimoto42). He made studies consisting of: X-ray analytical studies, measurements of the intensities of Js (saturation magnetization) and the Curie point, and studies on the chemical composition of ferromagnetic minerals.

Such mutual relations of several physical and chemical characters as those existing between:

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37) E. Pouillard, *Ann. Chimie.*, **5** (1950), 164.

38) R. Chevallier and J. Girard, *Bull. Soc. Chim. France*, **5** (1950), 576.

39) S. Akimoto, *Advanc. Phys.*, **6** (1957), 288.

40) S. Akimoto, T. Katsura and M. Yoshida, *Journ. Geomagn. Geoelectr.*, **9** (1957), 165.

41) S. Akimoto and T. Katsura, *ibid.*, **10** (1959), 69.

42) S. Akimoto, *loc. cit.*, 39).

(i) the chemical composition and the intensity of Js.
(ii) the intensity of Js and the Curie point.
(iii) the variation of lattice constants and the Curie point.
(iv) the chemical composition and the lattice constants have been studied thoroughly to give the following conclusions:

The lattice constant varies within a range of 8.38 Å–8.49 Å. All of the titanomagnetite minerals with the lattice constants within this range reveal ferromagnetism.

The nearer to Fe_3O_4 the chemical composition of the ferromagetic minerals is, and moreover the nearer to 8.38 Å the lattice constants of the mineral are, the higher the Curie point and the greater the intensity of Js. Several constants with respect to magnetite are; $a=8.39\,Å$, $Cp=578°C$, $Js=93\,e.m.u./gr.$, while the lattice constant of titanspinel is: $a=8.53\,Å$ (paramagnetic).

Chemically, the system titanspinel-magnetite is expressed as $x\cdot TiFe_2O_4(1-x)Fe_3O_4$. A solid solution in the system titanspinel-magnetite is formed in the arbitrary ratio of two components, i.e. $0<x<1$. From the results obtained from experimental studies upon the ferromagnetic minerals separated out from many volcanic rocks, especially andesite and dacite, it is shown that many of the ferromagnetic minerals have chemical composition near to Fe_3O_4. Among various rocks in nature, some are known to contain the spinel-type solid solution minerals whose chemical composition is based on the system $TiFe_2O_4$–Fe_3O_4, and those whose chemical compostion is rather nearer to $TiFeO_3$–Fe_2O_3. While the latter group called titanomaghemite is known as the metastable ferromagnetic mineral produced by low temperature oxidation in the natural state, the former group is confirmed to be producible through the laboratory oxidation of the solid solution belonging to the system $TiFe_2O_4$–Fe_3O_4.[43]

(3) *Remanent Magnetism of Rocks to be Omitted from Palaeomagnetic Study*

In palaeomagnetism, it has been known that there are, among the observed magnetic directions of rocks, many instances in which the magnetic direction is approximately opposite to the direction of the present geomagnetic field. If the general features of $T.R.M.$ could really be warranted, actual occurrence of such reversely magnetized rocks ought to be a matter of great importance.

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[43] S. AKIMOTO *et al.*, *loc. cit.*, 38).

Nagata, Akimoto and Uyeda[44)-47)] undertook in 1951 a series of experimental studies chiefly of thermal treatment upon dacite, which was collected from the Haruna volcanoes. According to their experiments, the dacite pumice of Haruna volcano posesses peculiar magnetic properties by which it is magnetized in the direction opposite to the direction of the applied magnetic field. The addition law concerning *P. T. R. M.* does not hold good in this case of peculiar magnetic properties. The ferromagnetic minerals with the property of self-reversal are confirmed to belong to the solid solutions of the system $TiFeO_3$-Fe_2O_3. The minerals are ferromagnetic, and the Curie point varies from 100°*C* to 250°*C* as the amount of Fe_2O_3 changes from 15 to 35 *mol %*.

The ferromagnetic minerals belonging to the system ilmenite-hematite and those of the spinel type sometimes occur side by side in igneous rocks. Theoretical and experimental studies on the effect of the coexistence of these ferromagnetic minerals were made by Uyeda.[48)]

Both rocks which show any sign of self-reversal characteristics and those containing titano-maghemite should be omitted from palaeomagnetic studies.

I. R. M. is an unstable magnetism. Some *I. R. M.*, as a product of magnetic after-effect in the geomagnetic field, is considered to be retained in all kinds of rocks. The amount of *I. R. M.* is, however, extremely small compared with the total amount of the remanent magnetism in usual rocks. Caution should be put, however, on the secondary magnetism introduced by, for instance, lightning.[49)]

Rocks in nature often alter their chemical compositions through weathering etc. *C. R. M.* is said to be a sort of remanent magnetism supplied through chemical alteration which took place at low temperature in the geomagnetic field. Studies on the mechanism of magnetization and on the stability of *C. R. M.* were made in detail by Nagata[50)] and (Kazuo) Kobayashi. Kobayashi[51)] applied both *A-C* demagnetization and thermal demagnetization to *C. R. M.* which was produced by the processes $\alpha Fe_2O_3 \rightarrow Fe_3O_4$ or $Fe_3O_4 \rightarrow \alpha Fe_2O_3$. He obtained the result that

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[44)] T. NAGATA, S. AKIMOTO and S. UYEDA, *Proc. Jap. Acad.*, **27** (1951), 643.

[45)] T. NAGATA, S. UYEDA and S. AKIMOTO, *Journ. Geomagn. Geoelectr.*, **4** (1952), 22.

[46)] T. NAGATA, S. UYEDA, S. AKIMOTO and N. KAWAI, *ibid.*, **4** (1952), 102.

[47)] T. NAGATA, S. AKIMOTO and S. UYEDA, *ibid.*, **5** (1953), 168.

[48)] S. UYEDA, *Jap. Journ. Geophys.*, **2** (1958), 1.

[49)] H. MATSUZAKI, K. KOBAYASHI and K. MOMOSE, *Journ. Geomagn. Geoelectr.*, **6** (1954), 53.

[50)] T. NAGATA and K. KOBAYASHI, *Proc. Jap. Acad.*, **34** (1958), 269.

[51)] K. KOBAYASHI, *Journ. Geomagn. Geoelectr.*, **10** (1959), 99.

C.R.M. is nearly as stable as *T.R.M.* As *C.R.M.* of rocks retains a distinctive direction and is favoured by its stable nature, it is usable as a palaeomagnetic record, provided that the time of the chemical change is known. In the case of continuous weathering etc., it is usually hard to know any definite time for the reaction. Such being the case, the author selected unweathered samples to avoid dealing with problematic remanent magnetism.

(4) *Several Criteria of Judgement in the Examination of Rock Magetism*

(i) Firstly, modes of decrease of *N.R.M.* should be measured in relation to the rise of temperature. Secondly, after the heating assay mentioned above, modes of decrease of *T.R.M.* in relation to the rise of temperature should be observed. If the thermal demagnetization curves of *N.R.M.* (Jn–T) are similar to the thermal demagnetization curves of *T.R.M.* (JTc–T), the equality of *N.R.M.* and *T.R.M.* is likely. In the case when ferromagnetic minerals contained in rocks hold an appreciable amount of *I.R.M.* the above mentioned curves should not be similar to each other. The curves should be also dissimilar when the minerals are unstable on heating.

(ii) *I.R.M.* should be eliminated by applying *A-C* demagnetization. It is also useful to reexamine the magnetic direction of a sample after leaving it for a while in the geomagnetic field.

(iii) In the selection, the following criteria may be valid: Measurement of the variation of Js of the ferromagnetic minerals in the heating and cooling processes $Js(T)$. (The Curie point of the minerals in question can be determined at the same time.). Then we may be able to recognize the stability of the ferromagnetic minerals, as both curves obtained through the processes of heating and cooling should coincide with each other if the minerals are stable.

(iv) By *X*-ray analysis, it may be possible to determine to which series of TiO_2–FeO–Fe_2O_3 ternary system the ferromagnetic minerals contained in rocks belong.

(v) Calculate the ratios Jn (intensities of *N.R.M.*) to JTc (intensities of *T.R.M.*) of the sample. It has been said that if the ratio Jn/JTc obtained from a rock sample is much off the value 1, the rock in question should not be used, because the former geomagnetic intensities should be considered approximately the same as the present. In fact, however, there is no sufficient theoretical basis to prove that the former geomagnetic intensities have ever been much different from the present geomagnetic intensity.

The criteria by which the stability of rocks is examined have just been summarized above. The necessity of these criteria were already propounded in 1954 by Nagata[52] at the congress of I. U. G. G. held at Rome, Italy.

Among these criteria, the author would like to reconsider the meaning of the ratio Jn/JTc. Although a vast amount of palaeomagnetic knowledge has hitherto been supplied from many parts of the world, work concerning the intensities of former geomagnetic fields is surprisingly little. I dare say that we should now give more attention to this problem of geomagnetic intensity. Measuring the ratio Jn/JTc has merely been considered as a method for testing the reliability of natural remanent magnetism. One has therefore been prone to pay attention to the magnitudes of Jn/JTc only for the purpose of examining the reliability of *N. R. M.*

The ratio Jn/JTc, on the other hand, may be a crucial factor for inferring the magnitudes of the former geomagnetic intensity, so that it may not be appropriate to omit a sample even if its value of Jn/JTc is abnormally large or abnormally small.

It must be emphasized that we have never obtained any decisive evidence that the intensity of the former geomagnetic field has always been as that of the present geomagnetic field.

The author would expect that there may be cases when Jn/JTc of rocks in nature takes values smaller than the range 1.0–0.5, because of the weaker former geomagnetic intensity. The author, therefore, has not omitted intentionally the rocks giving a Jn/JTc ratio smaller than say 0.5.

V. The Results of the Tests

The author has made especially detailed examinations of the stability of the *N. R. M.* of rocks treated in the present work. One of the reasons for these examinations was to know if the author could prove the stability of the *N. R. M.* having intermediate directions of magnetization, which were detected in both the Komoro and Shigarami formations (Chapter III). Another reason for these examinations lay also in his suspicion if all the ratios Jn/JTc obtained were valid for the author's discussion.

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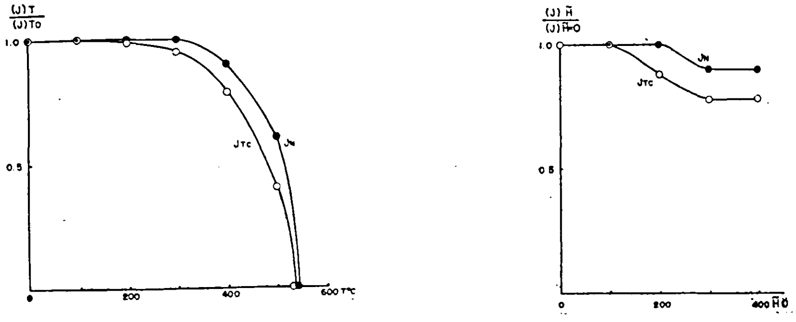
[52] T. NAGATA, *Special Report on Palaeomagnetism* (X-th Assembly, *A. T. M. E.*, *I. U. G. G.* Roma, 1954) 1-9.

The following 6 kinds of tests, numbered from (1) to (6), are indicated in the explanation under each group of figures.

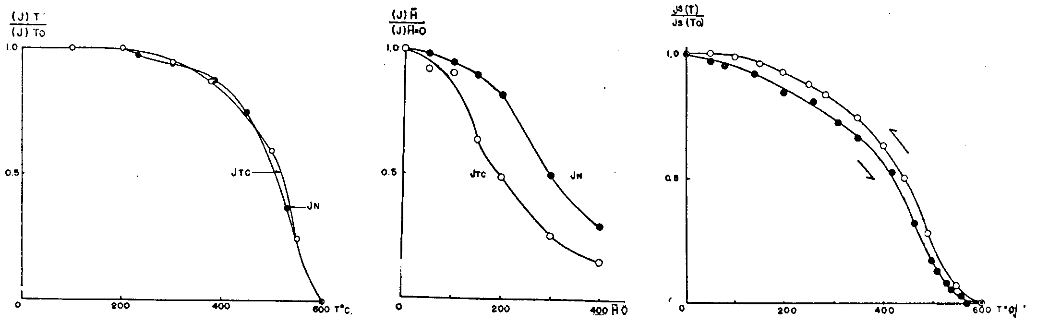
The results of the tests are shown in Figs. 26–46. Among these figures, those numbered from 26 to 37 are obtained from the samples of the Shigarami formations, those numbered from 38 to 43 and from 44 to 46 are obtained from the Komoro and the Enrei formations respectively. Each group of figures contains 3 kinds of figures designated as (a), (b) and (c); Fig. (a) shows the curves of thermal demagnetization applied to natural remanent magnetism (indicated by black circles) and to thermo-remanent magnetism (indicated by hollow circles). Fig. (b) indicates the curves of *A-C* field demagnetization applied to natural remanent magnetism (black circles) and to thermo-remanent magnetism (hollow circles). Fig. (c) indicates the changing mode of saturation magnetization $Js(T)$. The samples treated in this experiment (c) are ferromagnetic minerals separated from the same rock sample as those which are used in (a) and (b). In (c), black circles indicate the curve obtained through the process of heating, and hollow circles indicate those obtained through the process of cooling.

(1) For the measurements of Jn/JTc, $T.R.M.$ was produced through a cooling process from the Curie temperature. The sample was allowed to cool after being kept at Curie temperature for about 60 minutes in a non-inductive electric furnace and also in the air.



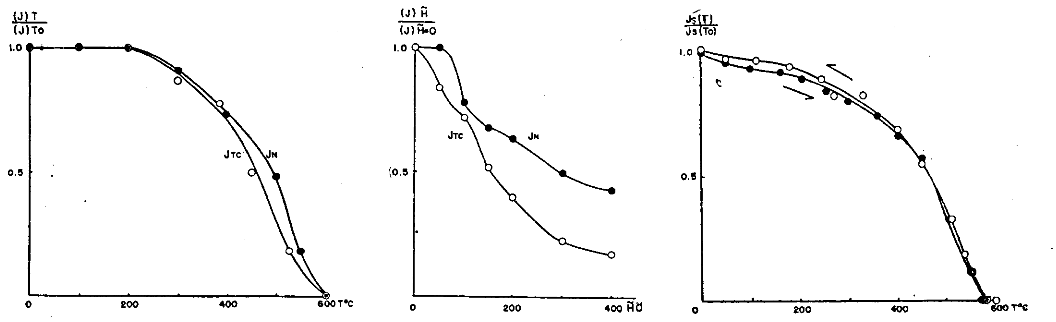
(a) (b)

Fig. 26. Laboratory tests of natural remanent magnetism:
Sample: Kuroiwa (Basalt)
Direction: reverse direction
Test 1) $Jn/JTc=0.66$
2) see Fig. 26, (a)
3) see Fig. 26, (b)



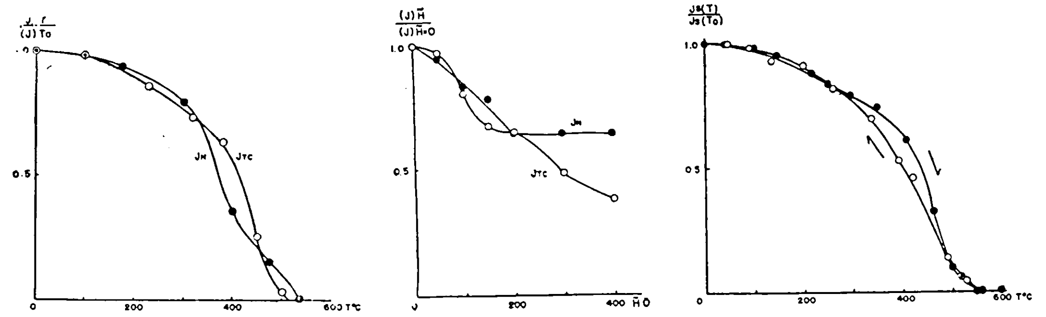
(a) (b) (c)

Fig. 27. Laboratory tests of natural remanent magnetism:
Sample: Nakanochi (tuff)
Direction: reverse direction
Test 1) $Jn/JTc=0.51$
2) see Fig. 27, (a)
3) see Fig. 27, (b)
4) see Fig. 27, (c)
5) $Tc=560^\circ C$
6) X-ray $a=8.418\pm0.002\,\mathring{A}$



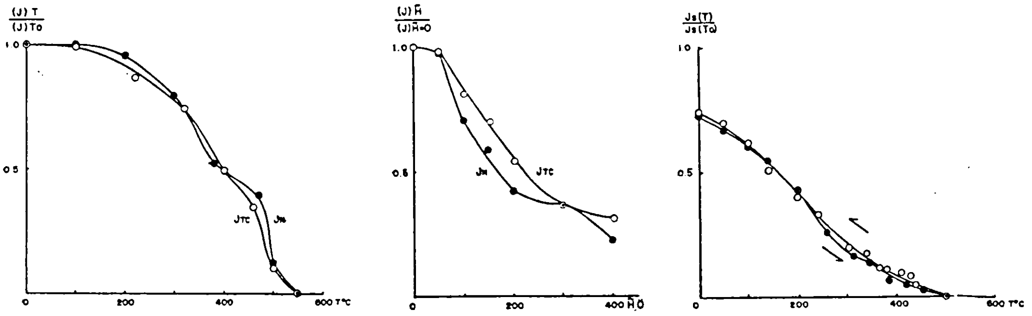
(a) (b) (c)

Fig. 28. Laboratory tests of natural remanent magnetism:
Sample: Kamisoyama (Andesite)
Direction: reverse direction
Test 1) $Jn/JTc=0.32$
2) see Fig. ?8, (a)
3) see Fig. 28, (b)
4) see Fig. 28, (c)
5) $Tc=570^\circ C$
9) X-ray $a=8.386\pm0.002\,\mathring{A}$



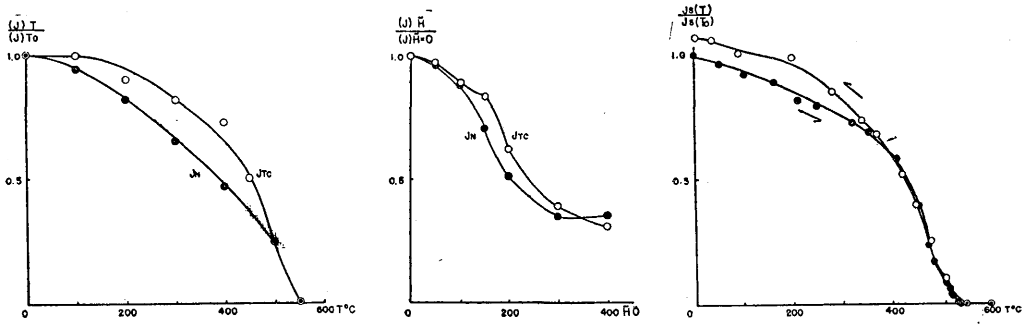
(a) (b) (c)

Fig. 29. Laboratory tests of natural remanent magnetism:
Sample: Watado (Andesite)
Direction: intermediate direction
Test 1) $Jn/JTc=0.37\text{-}0.38$
2) see Fig. 29, (a)
3) see Fig. 29, (b)
4) see Fig. 29, (c)
5) $Tc=520°C$
6) X-ray $a=8.408\pm0.004\,\mathring{A}$



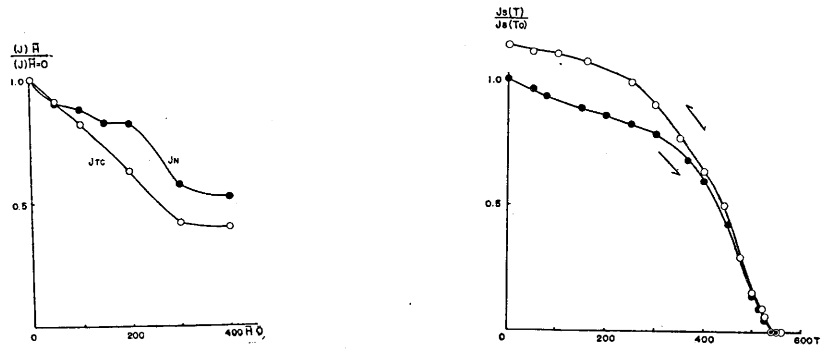
(a) (b) (c)

Fig. 30. Laboratory tests of natural remanent magnetism:
Sample: Machi (Basalt)
Direction: intermediate direction
Test 1) $Jn/JTc=0.39\text{-}0.50$
2) see Fig. 30, (a)
3) see Fig. 30, (b)
4) see Fig. 30, (c)
5) $Tc=260°C\text{-}510°C$ max. $Tc=510°C$
6) X-ray $a=8.450\pm0.003\,\mathring{A}$



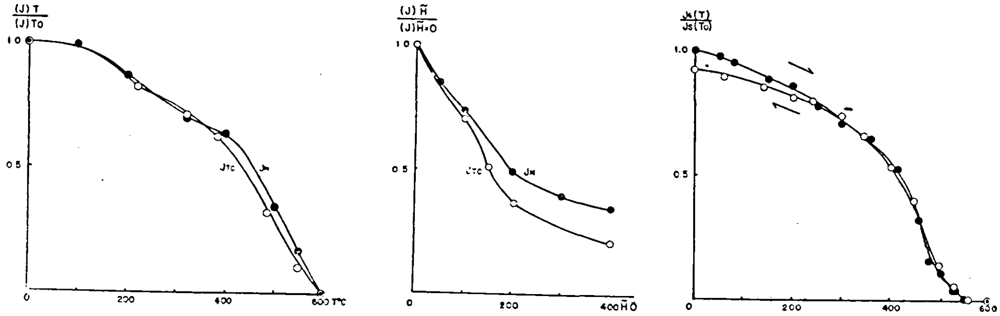
(a) (b) c)

Fig. 31. Laboratory tests of natural remanent magnetism:
Sample: Hiraide-zawa (Andesite)
Direction: intermediate direction
Test 1) $Jn/JTc=0.24\text{-}0.28$
2) see Fig. 31, (a)
3) see Fig. 31, (b)
4) see Fig. 31, (c)
5) $Tc=520°C\text{-}545°C$
6) X-ray $a=8.408\pm0.003\,\mathring{A}$



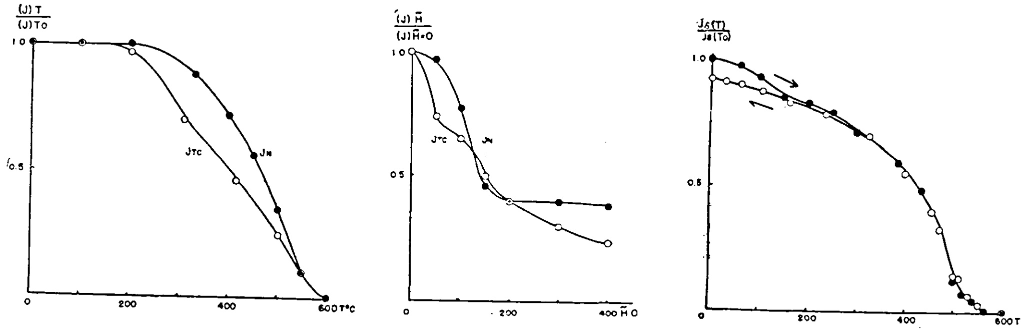
(b) (c)

Fig. 32. Laboratory tests of natural remanent magnetism:
Sample: Kawashimo A (Andesite)
Direction: intermediate direction
Test 1) $Jn/JTc=0.20$
3) see Fig. 32, (b)
4) see Fig. 32, (c)
5) $Tc=550°C$
6) X-ray $a=8.413\pm0.004\,\mathring{A}$



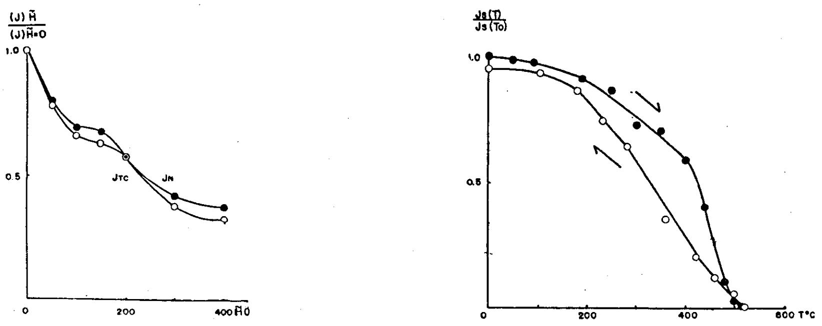
(a) (b) (c)

Fig. 33. Laboratory tests of natural remanent magnetism:
Sample: West of Akefuji-bashi
Direction: intermediate direction
Test 1) $Jn/JTc=0.26$
2) see Fig. 33, (a)
3) see Fig. 33, (b)
4) see Fig. 33, (c)
5) $Tc=530°C$-$560°C$
6) X-ray $a=8.407\pm0.003\,\mathring{A}$



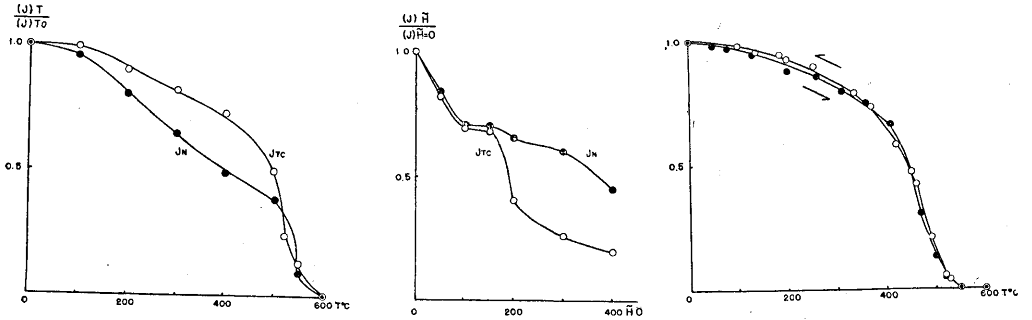
(a) (b) (c)

Fig. 34. Laboratory tests of natural remanent magnetism:
Sample: West of Akefuji-bashi A
Direction: intermediate direction
Test 1) $Jn/JTc=0.35$
2) see Fig. 34, (a)
3) see Fig. 34, (b)
4) see Fig. 34, (c)
5) $Tc=530°C$-$565°C$
6) X-ray $a=8.396\,\mathring{A}$



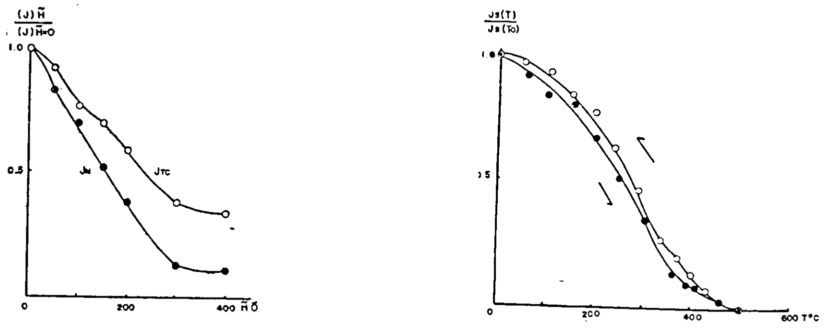
(b) (c)

Fig. 35. Laboratory tests of natural remanent magnetism:
Sample: Shigarami Loc. 5 (Andesite)
Direction: normal direction
Test 1) $Jn/JTc=0.54$
3) see Fig. 35, (b)
4) see Fig. 35, (c)
5) $Tc=510°C$
6) X-ray $a=8.408\pm0.004\,\mathring{A}$



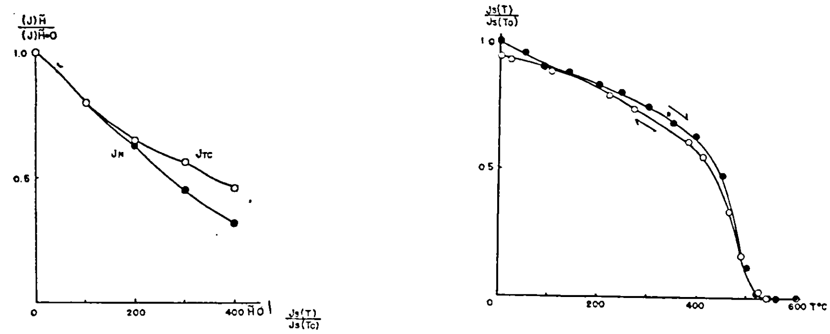
(a) (b) (c)

Fig. 36. Laboratory tests of natural remanent magnetism:
Sample: Shigarami Loc. 6 (Andesite)
Direction: normal direction
Test 1) $Jn/JTc=0.65$
2) see Fig. 36, (a)
3) see Fig. 36, (b)
4) see Fig. 36, (c)
5) $Tc=550°C$
6) X-ray $a=8.409\pm0.002\,\mathring{A}$



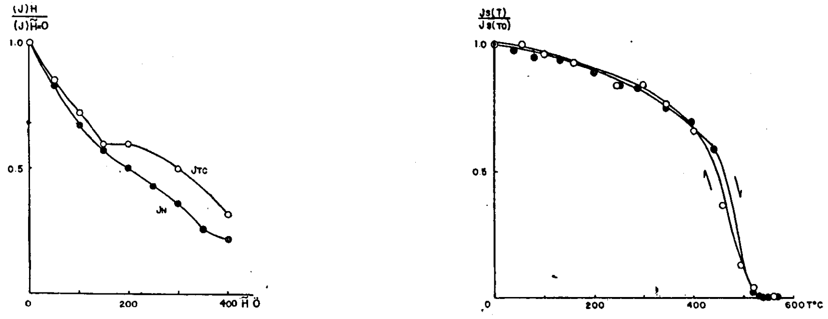
(b) (c)

Fig. 37. Laboratory tests of natural remanent magnetism:
Sample: Setouchi-bashi (Andesite)
Direction: normal direction
Test 1) $Jn/JTc=0.50$
3) see Fig. 37, (b)
4) see Fig. 37, (c)
5) $Tc=370°C$-$510°C$ max. $Tc=510°C$
6) X-ray $a=8.395\pm0.001\,\mathring{A}$



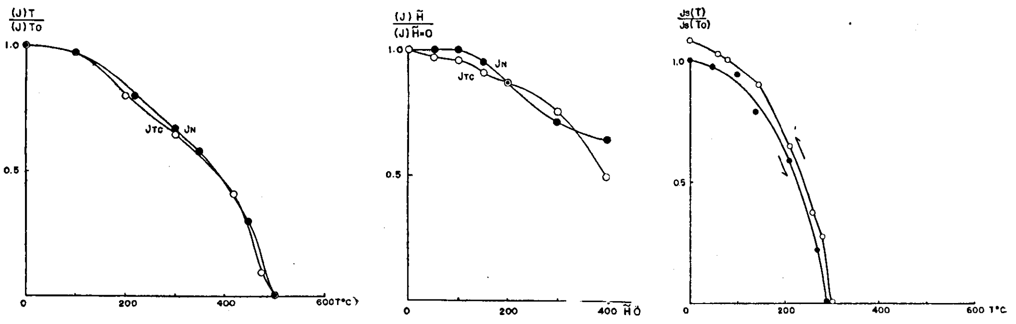
(b) (c)

Fig. 38. Laboratory tests of natural remanent magnetism:
Sample: Yasuhara (Welded tuff)
Direction: reverse direction
Test 1) $Jn/JTc=0.73$-2.11
3) see Fig. 38, (b)
4) see Fig. 38, (c)
5) $Tc=530°C$
6) X-ray $a=8.394\pm0.002\,\mathring{A}$



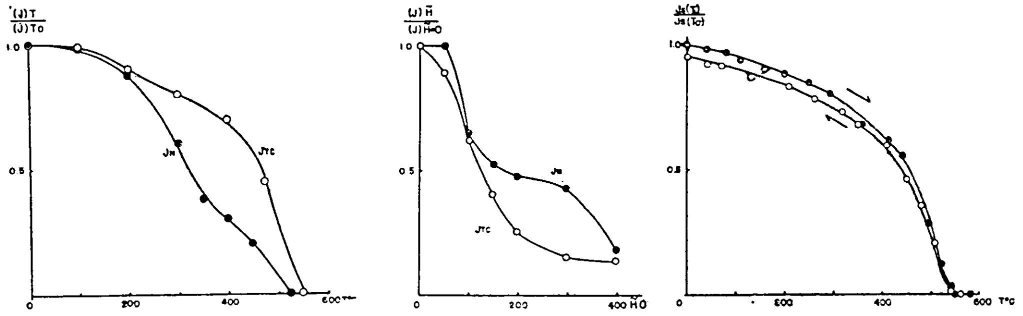
(b) (c)

Fig. 39. Laboratory tests of natural remanent magnetism:
Sample: Sehaya-gawa (Welded tuff)
Direction: reverse direction
Test 1) $Jn/JTc=0.64$
3) see Fig. 39, (b)
4) see Fig. 39, (c)
5) $Tc=535°C$
6) X-ray $a=8.385\pm0.004\,\mathring{A}$



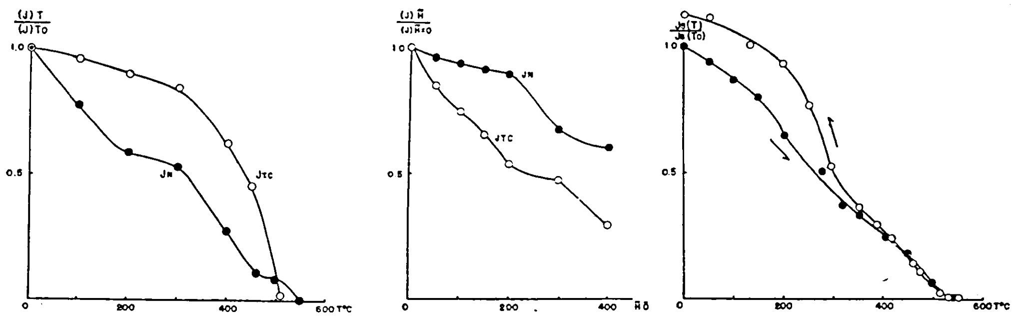
(a) (b) (c)

Fig. 40. Laboratory tests of natural remanent magnetism:
Sample: Sehaya-gawa (Basalt)
Direction: intermediate direction
Test 1) $Jn/JTc=0.39\text{-}0.41$
2) see Fig. 40, (a)
3) see Fig. 40, (b)
4) see Fig. 40, (c)
5) $Tc=330°C$
6) X-ray $a=8.412\pm0.004\,\mathring{A}$



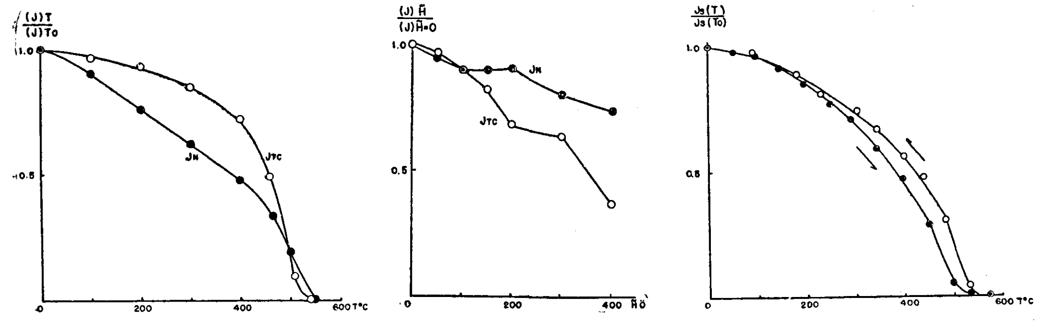
(a) (b) (c)

Fig. 41. Laboratory tests of natural remanent magnetism:
Sample: Miyanoshita (Porphyrite)
Direction: intermediate direction
Test 1) $Jn/JTc=0.10\text{-}0.27$
2) see Fig. 41, (a)
3) see Fig. 41, (b)
4) see Fig. 41, (c)
5) $Tc=555°C$
6) X-ray $a=8.383\pm0.002\,\mathring{A}$



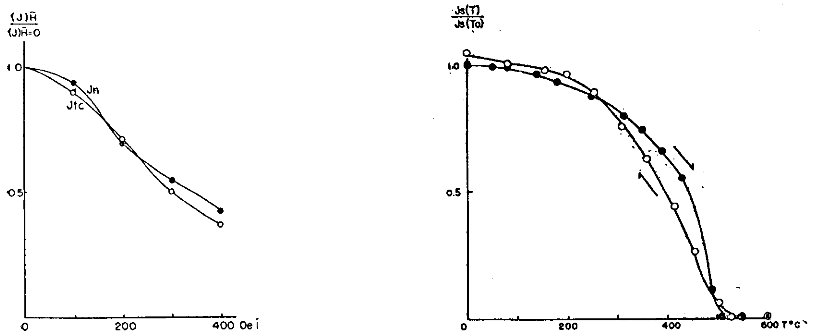
(a) (b) (c)

Fig. 42. Laboratory tests of natural remanent magnetism:
Sample: Higashi-zawa (Welded tuff)
Direction: intermediate direction
Test 1) $Jn/JTc=0.11\text{-}0.22$
2) see Fig. 42, (a)
3) see Fig. 42, (b)
4) see Fig. 42, (c)
5) $Tc=335°C$, $540°C$
6) X-ray $a=8.394\,\mathring{A}$



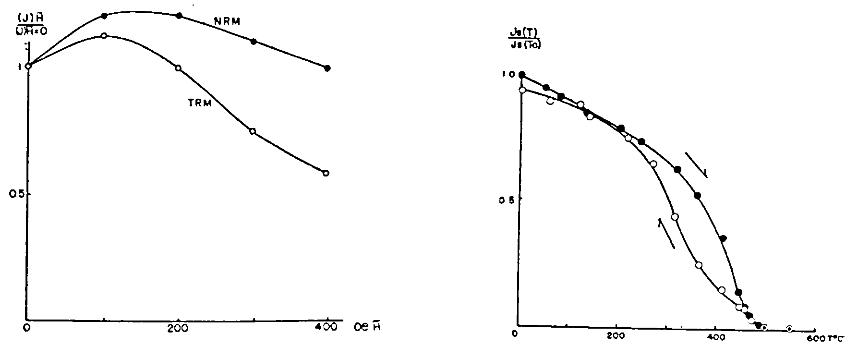
(a) (b) (c)

Fig. 43. Laboratory tests of natural remanent magnetism:
Sample: Ōya (Welded tuff)
Direction: intermediate direction
Test 1) $Jn/JTc=0.15\text{-}0.18$
2) see Fig. 43, (a)
3) see Fig. 43, (b)
4) see Fig. 43, (c)
5) Tc=heating 520°C, cooling 550°C
6) X-ray $a=8.374\pm0.002\,\mathring{A}$



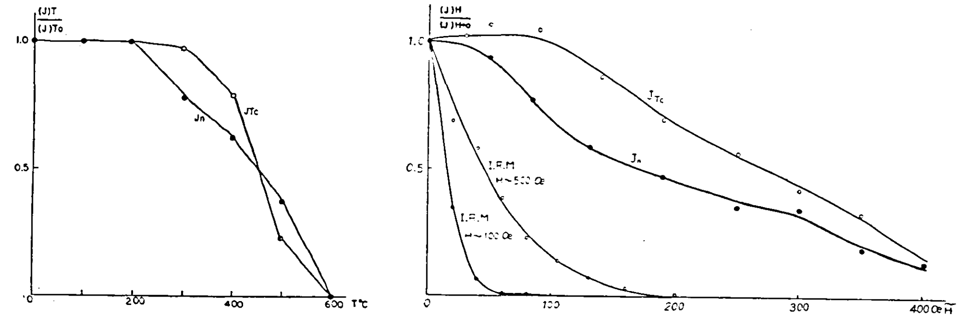
(b) (c)

Fig. 44. Laboratory tests of natural remanent magnetism:
Sample: Kawagishi (Andesite)
Direction: reverse direction
Test 1) $Jn/JTc=0.515$
3) see Fig. 44, (b)
4) see Fig. 44, (c)
5) $Tc=520°C$
6) X-ray $a=8.423\pm0.003\,\mathring{A}$

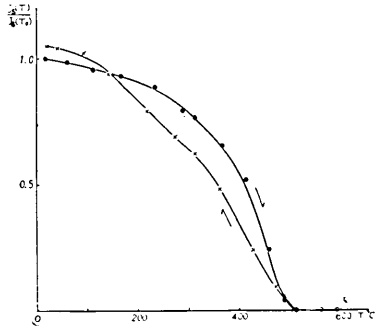


(b) (c)

Fig. 45. Laboratory tests of natural remanent magnetism:
Sample: Utsukushi-ga-hara (Andesite)
Direction: reverse direction
Test 1) $Jn/JTc=0.79$
3) see Fig. 45, (b)
4) see Fig. 45, (c)
5) Tc=heating 490°C, cooling 380°C, 490°C
6) X-ray $a=8.371\pm0.002\,\mathring{A}$



(a) (b)



(c)

Fig. 46. Laboratory tests of natural remanent magnetism:
Sample: Fukuzawa-yama
Direction: reverse direction
Test 1) $Jn/JTc=0.52$-0.63
2) see Fig. 46, (a)
3) see Fig. 46, (b)
4) see Fig. 46, (c)
5) $Tc=490°C$
6) X-ray $a=8.382\,\mathring{A}$
(Fig. 46. (b), (c) After Akimoto's measurements.)

(2) For thermal demagnetization assay, a square pillar with the section of 2 *cm* square and 5 cm long, was cut off from the rock sample. The axis of the pillar was taken parallel to the direction of *N. R. M.* After measuring *Jn–T*, *JTc* was obtained through the thermal treatment in which the rock pillar, whose axis was put parallel with the direction of the geomagnetic field, was heated in a non-inductive electric furnace up to Curie temperature and cooled down to the room temperature after being kept for about 60 minutes at Curie temperature. The inclination of geomagnetic field is about 49°30′ in the author's laboratory.

The manner of demagnetization is such that 50% of both *Jn* and *JTc* were demagnetized at the temperatures ranging from 400°*C* to 500°*C*. (The results obtained are shown in (a) of Figs. 26, 28–31, 33–34, 36, 40–43 and 46) In other words, the magnetism in question was probably acquired at high temperatures, so that the remanent magnetism of such rock samples may be understood to be stable.

Throughout the tests just described, on indication of self-reversal of *T. R. M.* was observed.

(3) The samples used for *A-C* field demagnetization and those used for thermal demagnetization are similar in shape. *JTc* was obtained through a process similar to that used for thermal demagnetization. The intensity of the remanent magnetization was measured through the *A-C* field demagnetization process at intervals of 50 *Oe* from zero to 400 *Oe*. The results are shown respectively in figure (b) of Figs. 26–46. In Fig. 46 are shown 2 modes of *A-C* demagnetizations of *I. R. M.* of the andesite of Teppeiseki type. One of the *I. R. M.* was produced by the application of $H=100\,Oe$ and another of $H=500\,Oe$. As will be understood from the figure, these *I. R. M.*s can be demagnetized by applying a magnetic field approximately 200 *Oe*. It may thus be known that the mode of *A-C* field demagnetization of *I. R. M.* is quite defferent from that of natural remanent magnetism.

The results obtained through *A-C* field demagnetization are summarized as follows: The curves $(Jn)\tilde{H}$, $(JTc)\tilde{H}$ indicate that all of the present samples are magnetically stable, and moreover that curves obtained respectively from *Jn* and *JTc* have a close resemblance to one another.

(4) For the group of rocks of which the direction of magnetization is intermediate, the samples were left for a while in the present geomagnetic field and were remeasured. The results obtained through this "reexamination method" will be shown in the following. Sehaya-gawa

basalt specimens (from Loc. No. 4 shown in Fig. 3) showed that their directions of magnetization deflected slightly after 456 days from the first measurements (see next table). Although both of declination and inclination differ a little in the table, such differences may be caused by errors in our normal handling of the apparatus, so that they are by no means indicative of the generation of magnetic after-effect. The treatment therefore indicates that these samples may be stable. The magnetic direction of these samples on the other hand distribute, as is already known, within an error circle with an angle of about 3° and have long been deflected in a direction approximately at a right angle to the present geomagnetic field in situ. Both these facts seem to imply that their magnetic property is stable enough to keep the former direction of geomagnetic field in situ.

	Declination		Inclination	
	Original	after 456 days	Original	after 456 days
No. 1	94°W	92°W	−65°	−68°
No. 2	89°W	88°W	−64°	−65°
No. 3	104°W	101°W	−62°	−64°
No. 4	95°W	94°W	−63°	−63°

(5) In $Js(T)$ measurements through both processes of heating and cooling, there were some cases in which the curves of heating and cooling did not coincide with each other. These may be due to the oxidation or the reduction of the sample. But the change of Js was found to be only 4–5% of the value of Js measured before the heating.

Except for the samples collected from Mt. Utsukushi-ga-hara, Ōya and Higashi-zawa, all the samples were found to have a Curie point of single phase within a range 500°C–570°C. Throughout the thermal treatment, no change of the Curie point was observed for any of the samples, except for the following two samples from Ōya (Fig. 43) and Utsukushi-ga-hara (Fig. 45).

(6) The results obtained from the X-ray analysis of the lattice constants are expressed as; $a=8.37\,\mathring{A}$–$8.45\,\mathring{A}$ for all the samples. Curie point of Machi basalt of the Shigarami formation shown in Fig. 28, is between 260°C and 510°C, and the lattice constant of the contained ferromagnetic minerals are measured to be 8.45 Å. The ferromagnetic minerals of Sehaya-gawa basalt show that their Curie point is 330°C and the lattice constant is 8.41 Å. These minerals are rather peculiar

in their properties, but except for these two, all other samples have Curie points of about $525^{\circ}C$ and lattice constants of about 8.40 Å. Moreover, the ferromagnetic minerals were observed under a reflection microscope (×1030). The results indicated that they were mostly fresh magnetite. Several micro-photographs are shown in Fig. 47. Among

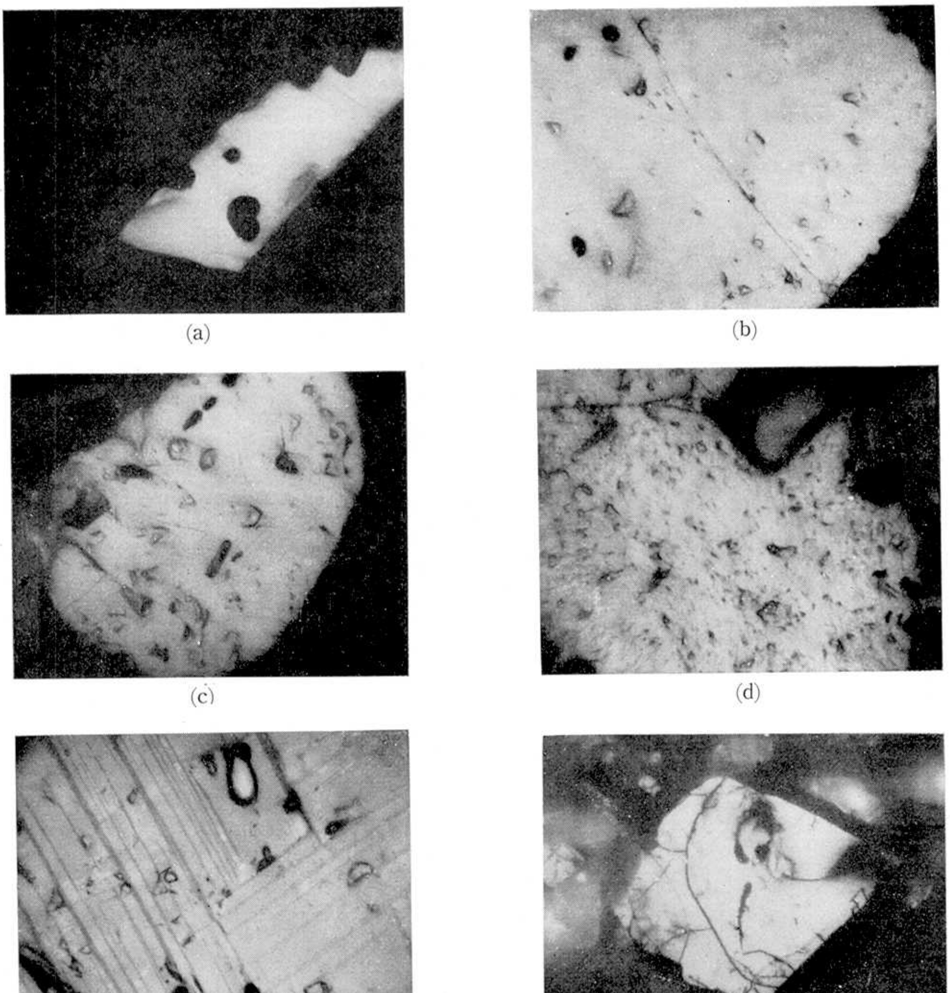

(a) (b)
(c) (d)
(e) (f)

Fig. 47. Reflection microscopic photographs of polished surface of magnetic minerals contained in rock. (×1030)
(a) Machi (Basalt) (b) Hiraide-zawa (Andesite) (c) Kawashimo A (Andesite)
(d) Ōya (Welded Tuff) (e) Miyanoshita (Porphyrite) (f) Sehaya-gawa A (Basalt)

these, a photograph of the sample from Miyanoshita indicates the inclusion of a small amount of ilmenite. The amount, however, is very little compared with that of magnetite. According to the X-ray data, magnetite appears to be dominant and traces of ilmenite are slightly indicated. As are seen in the photographs in Fig. 47, magnetite grains show no sign of decomposition, except for those contained in the samples from Miyanoshita. The observations made through the reflection microscope were undertaken by I. Kushiro of Tokyo University.

The ratio Jn/JTc is calculated from the measured values of Jn and JTc. As JTc is producible only in the air, most curves of $Js(T)$ in this paper were obtained from the experiments made also in the air. 75% of the measured values Jn/JTc are believed to be usable for the author's purpose, as the heating and cooling curves of $Js(T)$ of these samples are similar.

Even the remainder of the values Jn/JTc may also be reliable because the change of values of Js due to heating experiments was only 4–5% of Js measured before the heating. In the measurement of Js of the samples taken from Kawashimo A (Fig. 32), an increase of Js by reduction was recognized after heating in the vacuum state, while a decrease of Js was recognized after heating in the air. By assuming $JTc \propto Js$, the real values Jn/JTc of the sample showing a decrease of Js due to heating may be thought to be smaller than the values calculated. In conclusion, the values Jn/JTc obtained from the above-mentioned rocks may be an indication of the intensities of the former geomagnetic fields in which the rocks were laid.

None of the results hitherto obtained are inconsistent with the general features of thermo-remanent magnetism.

VI. Pole Positions and Values of *Jn/JTc*

Since the values of Jn/JTc are considered to be controlled by the magnitudes of the intensity of the earth's magnetic field, the author has surveyed the relation between the pole positions and the values of Jn/JTc obtained from the same samples.

The results showing the correspondences existing between the latitudes of pole positions and the magnitudes of geomagnetic intensities inferred from the Jn/JTc ratios are shown in Fig. 48.

As the pole position shifts from the north polar region southward to the belt of low latitudes, the associated intensity seems to decrease,

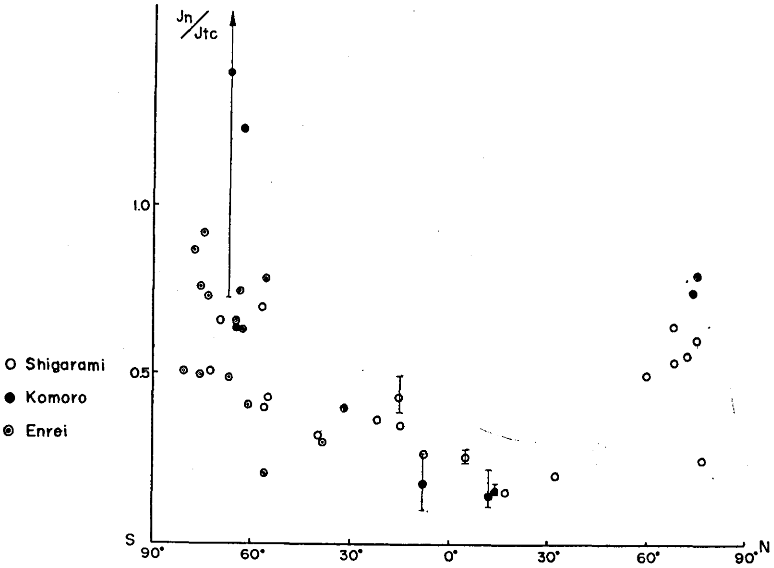


Fig. 48. Distribution of the values *Jn/JTc* in relation to latitudes of pole positions suggested by the Komoro, Shigarami and Enrei formations.

then turns to increase again as it shifts southward to the area of high latitudes of the south polar region.

Jn/JTc takes values within the range of 0.15–0.45 when the pole position locates in the tropical belt. Assuming that the total force of the present geomagnetic field is approximately 0.45 *G* at Matsumoto, we obtain the approximate values ranging from 0.067 *G* to 0.20 *G* when the pole position was in the equatorial belt, and the values are equivalent to merely one third or one tenth of the present geomagnetic intensity.

Inasmuch as geomagnetic field might possibly be represented by the dipole field, geomagnetic intensity at the magnetic pole should theoretically be expresed as: $Z=2M/R^3$ and that at the magnetic equator as: $H=M/R^3$.

Therefore, if Matsumoto were located at a site on the magnetic equator at the time when these rocks were laid, the geomagnetic intensity of Matsumoto should have been about one half (0.3 *G*) of that at the magnetic pole through that time. Accordingly it may be perilous to conclude immediately that the former geomagnetic field were once weakened even if the ratio *Jn/JTc* was found to be small.

Suspicions may, however, be demolished from the following two points. First, the inferred geomagnetic intensities calculated from the ratios Jn/JTc include significantly smaller values than $0.3\,G$. Secondly, the inclination of the $N.R.M.$ of the samples whose associated pole position are in the lower latitudes is considerably large in angle. As shown in Tables 1 and 2, the averages of the inclinations directed upward and downward are 43° and 30° respectively. These indicate that Matsumoto was not in the "equatorial" zone when the pole was in the lower latitude.

The above-mentioned values of inclination and Jn/JTc may seem to merit confidence that the geomagnetic intensity might have decreased at the time when the associated poles were near the present equator. Samples whose pole positions are in the high latitudes take intensities not dissimilar to those of the present.

Sigurgeirsson published opinions in 1957 that are almost the same as the present author's. Sigurgeirsson[53)] (1957, p. 246) stated "the mean magnetization of all normally and reversely magnetized samples is about $2\times 10^{-3}\,e.m.u./gr.$, while for samples showing intermediate directions it is only half as much." Although the author has not yet ascertained enough instances to obtain an unquestionable conclusion, Jn/JTc of a certain andesite (Iizuna A) and a certain welded-tuff (Yasuhara) are found to take values reaching as large as 2.0. In this connection, the discussions afforded by E. Thellier and O. Thellier[54)] who stressed that the geomagnetic intensities were possibly stronger during historic ages than at present, are suggestive and noteworthy.

VII. Conclusion

(1) During the time from the Upper Miocene to the Lower Pliocene, directions of the geomagnetic field were approximately the same as the present.

(2) During the time of reversed geomagnetic field of the later Pliocene, the pole position seems to have shifted considerably around the south pole of the rotation axis.

(3) During the span of the middle part of the Pliocene time, the geomagnetic field seems to have reversed continuously from the normal to the reverse.

(4) Through this period of geomagnetic reversal the geomagnetic force might have gradually weakened, as the pole position shifted

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[53)] TH. SIGURGEIRSSON, *loc. cit.*, 16).

[54)] E. THELLIER and O. THELLIER, *Annales de Geophysique*, **15** (1959), 285.

southward, then again it strengthened as the pole position proceeded southward to the South polar region.

(5) In view of many pole positions observed by the author, it may be concluded that throughout younger geologic times through which continental shifting has been imperceptible, most data concerned with the pole positions tell us that both pole positions of the normal and the reversed were near the present poles.

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To all of these persons, the author should express his sincere thanks.

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32. 鮮新世における地球磁場の変動に関する研究

地震研究所　百　瀬　寛　一

Pliocene における地球磁場の変動を究明する目的で小諸層群，柵（しがらみ）累層および塩嶺累層の古地磁気学的研究を行なつた，その結果次のことが明らかとなつた.

(1) Upper Miocene—Lower Pliocene には地球双極子のS極は北極圏にあり，Later Pliocene

には，S極は南極圏にあつて，いずれの場合にもS極の分布は現在の地球回転軸の近傍にある．

(2) 第25図はLater Plioceneにおける双極子のS極が南極圏にあつて，現在の地球回転軸を中心として，さまよつていたように，見うけられることを示している．このことは地球磁場逆転の一つの証拠として重要である．

(3) 第19図は(1)に述べた現象の中間 (Pliocene のほぼなかごろ) において，地磁気が北極圏より南極圏へ，あたかも短期間の極移動が起こつたかのごとく中間の方向をとりつつ移動する経過を示している，また第48図に示すごとく双極子の方向が逆転する途中では，その強さは著しく減少してしまつている．

地質時代のうちでContinental Driftが極めて微量であつたと考えられるPliocene以降における古地磁気学の結果は(1)に述べた事実（S極の分布）とよく一致している．このことは(3)に述べたような過渡的段階の発見が極めて少ないことと相まって地磁気逆転の周期や逆転の経過に要する時間を知る手がかりとして重要なことであると思われる．