Review Meeting on

PALEOMAGNETIC STUDY OF THE CIRCUM-PACIFIC AREA

U.S.-Japan Scientific Cooperation

Abstracts of Papers

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PREFACE

A meeting to survey the possibilities of U.S.-Japan Scientific Cooperative Study in Palaeomagnetism was organized by Professor Verhoogen and Professor Nagata in Tokyo at the end of 1962. During and subsequent to the meeting, several projects were selected for cooperative research and respective coworkers were chosen.

Actual activity started in the middle of the following year with the financial support of both the National Science Foundation and the Japan Society for the Promotion of Science.

The results obtained were later presented at the second seminar in 1964 at University of California, Berkeley. Twenty six papers were offered and actively discussed. Towards the end of the seminar, Kyoto was considered to be the best place to hold the final meeting.

Accordingly, the palaeomagnetic work of the circum-Pacific area was reviewed at Kyoto International Conference Hall on 27, 28 and 29th of October, 1966.

Thirty five papers were presented during five sessions under the following headings:

1. Age determination and palaeomagnetism.
   Oct. 27th, 9:15 - 10:20 chairman; Prof. Nagata

2. Archaeomagnetism.
   Oct. 27th, 10:20 - 11:45 chairman; Prof. Nagata

3. Palaeomagnetism in Tertiary and Quaternary.
   Oct. 27th, 13:15 - 15:25 chairman; Prof. Kato
   15:45 - 17:00 chairman; Prof. DuBois

4. Fundamental study of palaeomagnetism.
   Oct. 28th, 9:00 - 11:30 chairman; Dr. Cox
   Oct. 29th, 9:00 - 12:00 chairman; Prof. Kawai

5. Palaeomagnetism in pre-Tertiary.
   Oct. 29th, 13:30 - 15:00 chairman; Dr. Doell
   15:15 - 16:45 chairman; Prof. Verhoogen

At the end of the meeting, during the time for general discussion it was proposed that abstracts of the reports and the relevant discussions should be printed. In the following pages the abstracts and discussions are presented in the above order. Two further recommendations were strongly supported by all of the participants. These were

1. That similar meetings be held in the future at two or three year intervals.

2. That there should be a continuation of the exchange scheme of young palaeomagnetists between the two countries.

Grateful acknowledgment is made to both the National Science Foundation and the Japan Society for Promotion of Science for supporting the three years cooperation and for assisting in the organization of the semiar and review meetings.

December, 1966

Naoto Kawai

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(1) EXTENSION TO POTASSIUM-ARGON DATING TO HOLOCENE VOLCANIC ROCKS

G. B. Dalrymple

U.S. Geological Survey, Menlo Park.

The results of replicate potassium-argon age measurements on rocks from 0.4 m.y. to 159 m.y. old are in general agreement with estimates of dating precision that are based on theoretical considerations. These data, when extrapolated to younger ages, suggest that the potassium-argon technique can be extended to rocks less than 10^4 years old if suitable materials are used.

The main difficulty in dating rocks this young lies in reducing the amount of contaminating atmospheric argon in the dated material to a sufficiently low level. For most minerals this is not possible with present techniques. However, for sanidine the atmospheric argon-40 can be reduced to 1×10^{-12} moles/gram or less if careful sample preparation and handling techniques are used. Thus, for a 20-gram sample of sanidine, it is theoretically possible to obtain ages as young as 10^4 years with a precision (68 percent confidence level) of $\pm$ 20 percent or better.

Potassium-argon ages on sanidine from two domes in the Mono Craters of California confirm this prediction. Ages of 7,700 and 6,900 years were obtained from one dome and ages of 6,100 and 6,800 years from the other dome. These results indicate that the potassium-argon method can be easily extended to rocks less than 10^5 years old if sanidine is used for the analyses.

Kuno: Is the Ar contamination due to adsorption of the air around the sanidine crystals or due to technical difficulty?

Dalrymple: The atmospheric Ar contamination appears to be due to both factors. The small amount due to technical difficulties has been determined by experiments in which no mineral sample is used—in other words, a "blank" run. Most of the atmospheric Ar seems to come from the surfaces of mineral grains and from within the mineral lattice.

Minoru Ozima: At what temperature did you bake sanidine before the extraction?

Dalrymple: 300 degrees centigrade.

Kaneoka: Is there any other way to reduce air contamination other than baking samples?

Dalrymple: Yes, Feldspars (sanidine and plagioclase) can be treated with a dilute solution of hydrofluoric acid. This procedure removes the part of the crystals that is near the surface of the mineral grains and greatly reduces the amount of contaminating atmospheric argon. The method is particularly effective if it is done just a few minutes before the sample is placed in the vacuum extraction apparatus. Experiments by Professors Curtis and Evernden at Berkeley have shown that the HF treatment does not have any adverse effect on the age determinations.

(2) PALEOMAGNETISM AND K-A AGES OF BASALTS FROM RIO-GRANDE NEW MEXICO

M. Ozima, M. Kono, I. Kaneoka, H. Kinoshita,

K. Kobayashi, T. Nagata

University of Tokyo, Tokyo,

E. E. Larson

University of Colorado, Denver,

and

D. W. Strangway

Massachusetts Institute of Technology, Cambridge.

Successive lava flows exposed in the Rio-Grande gorge, near Taos, New Mexico, can be divided into three groups, each of different magnetic polarity: the upper and the lower groups have a normal polarity, whereas the middle one has a reversed polarity. K-A radiometric ages indicate that the base of the upper normal polarity sequence is about 3.7 m.y. old and that the reversed flows range from 3.7 m.y. to 4.4 m.y. The age difference between the base of the upper normal and the top of the adjacent reversed flow group is about 0.05 m.y., indicating rapid polarity switching.

Kuno: I would like to ask U.S. geologists who joined the trip to Rio Grande region whether there are some indications of weathering or erosion between a flow of normal polarity and another of reversal polarity?

Strangway: Between each of the lava flows there is a series of river-deposited sandstones and gravels indicating some time between each flow and therefore each of the reversals. The Rio Grande trench was on alluvial basin filling up with gravels and sediments and occasional lava flows coming into the sequence.

(3) RESOLVING POWER OF POTASSIUM-ARGON DATING FOR MEASURING POLARITY EPOCK BOUNDARIES, EVENTS, AND TRANSITION INTERVALS

A. Cox and G. B. Dalrymple

U.S. Geological Survey, Menlo Park.

A new statistical method for analyzing the distribution of the magnetic polarity of rocks and their potassium-argon ages has been applied to the data used to determine the time scale for geomagnetic reversals in the interval from 3.6 m.y. ago to the present. The objective of the analysis was to obtain an independent estimate of the precision of the dating technique based on the internal consistency of the data, and also to provide an objective basis for assigning ages to the boundaries between geomagnetic polarity epochs. For rocks about 2.5 m.y. old, the analysis indicates that the precision of the dating is 3.6 percent, which is in accord with earlier estimates obtained from replicate analyses. The following are the best statistical estimates of the ages of the boundaries between geomagnetic polarity epochs: Gilbert-Gauss boundary, 3.36 m.y., Gauss-Matuyama boundary, 2.5 m.y.; Matuyama-Brunhes boundary, 0.70 m.y. The duration of polarity events is estimated to vary from 0.07 to 0.16 m.y., and the best estimate of the time required for the earth's field to undergo a complete change in polarity is 4,600 years.

Heinrichs: What are the statistical limits on the determination of 4,600 years for the length of a transition of the earth's magnetic field?

Cox: The confidence limits at the 95 percent level are between 1,600 and 21,000, the asymmetry being due to the nature of the bimodal distribution.

Fuller: Is it possible to date the movement of the cooling front in a single intrusion by making determinations of the age in different parts of the intrusion?

Dalrymple: This has not been done but it would be possible although difficult. One problem is to find a suitable pluton. Such a pluton would have to have excellent vertical and horizontal exposure. The pluton would also have to be young (say 10 m.y.) in order to detect the small age differences that would be expected. The final difficulty is our lack of knowledge about diffusion of Ar in common minerals. It has not yet been possible to determine diffusion dimensions and the diffusion coefficient changes with T, so that the problem is rather complex.

Minoru Ozima: Is it possible to find sanidine in Hakone Volcano?
If not, any other suitable minerals of high K-content in Hakone volcanic rock?

Kuno: No sanidine phenocrysts are present in the Hakone rocks. The only possibility is to separate fine-grained crystals of anorthoclase (or Na-bearing sanidine) from the groundmass of the Hakone rocks. No other K-rich minerals are present in these rocks.
The most promising area to get sanidine crystals from rocks of known stratigraphic succession is Nii-zima Volcano in the island south of Hakone. The time range of eruption of rhyolite domes of this island is probably several tens of thousand years, the latest eruption having occurred in 5th century.

(4) ARCHAEOMAGNETIC RESULTS FROM SOUTHWESTERN U.S.

R. L. DuBois

University of Arizona, Tucson, Arizona.

Archaeomagnetic investigations have been made on samples of baked clay collected from archaeological sites located in the southwestern United States. The sites range in age from approximately 300 B. C. to present and have been dated by (the tree-ring) dendrochronological methods which uses annual growth rings as a basis for chronology. Seven to ten specimens were collected from each site and results presented for all sites (83) having a mean direction with an $\alpha 95$ value of 3.9° or less.

Declinations range from 15° E. to 15° W. and the most westerly declination occurred about 1100 A. D. The declination was to the east before and after the 1100 A. D. period. Inclination of the field has veried from 40° to 60° and minima have occurred at 1000 A. D. and 1400 A. D.

Virtual geomagnetic pole positions have been calculated from the data. The resulting pole data representation curve (PDRC) encircles the geographic pole in a counter-clockwise direction with a period of 1350 years. Smaller variations form loops on the curve approximately 120° apart with a period of 200-400 years duration.

The secular variations as shown by the PDRC can be explained by westward drift of the non-dipole field.

Strangway: Have you had a chance to study the minerals in the clay before it is heated?

DuBois: No.

Coe: What is the geographical spread of the samples?

DuBois: Sampling sites are a maximum of 600 miles apart.

Fuller: Has a comparison been made between the magnetic properties, e.g. coercive force, of the materials fired in ancient times and those fired in the recent experimental firings of the same site? It would be interesting to see if there were evidence of relaxation of imperfections.

DuBois: No, I quite agree that this would be interesting.

Kobayashi: Have you measured the Curie temperature of any of your specimens either by thermomagnetic analysis or by thermal demagnetization? You concluded that magnetic mineral in your specimens is αFe_2O_3 but Xray is less sensitive to co-existing Fe_3O_4 or titanomagnetites than to αFe_2O_3. Principal magnetic constituent in all the pottery and baked earth specimens I have ever measured was titanomagnetite or titanomaghemite. If your specimens have αFe_2O_3 only responsible for NRM, it may be very important for consistency test.

DuBois: Curie temperature measurements are in process. I have not as yet concluded the identity of the ferromagnetic mineral in these specimens. The only ferromagnetic mineral so far identified, has been by X-ray. This and polished section studies have been made but again only hematite has been identified.

(5) ARCHAEOMAGNETIC DIRECTIONS DATED BY THE RADIOCARBON METHOD IN JAPAN

N. Watanabe

University of Tokyo, Tokyo.

In the field of archaeology, the chronological framework for studies of prehistoric Japan has been well established by means of pottery types, and archaeomagnetic directions determined from baked earth of fireplaces of prehistoric dwelling pits were relatively dated by the type of pottery associated with the dwelling pit. Recently a number of radiocarbon dates were accumulated for those times and the chronological framework was provided with the absolute time scale in terms of these radiocarbon dates.

Of 141 sets of inclination and declination values so far obtained from materials associated with the Jomon and Yayoi pottery in Honshu, main island of Japan, those which have comparatively small Fisher's radii were plotted on a graph according to radiocarbon dates of associated pottery types. As to 13 sets, charcoal was found from the same dwelling pit where baked earth samples were collected so that the radiocarbon date determined from the charcoal was directly connected with the magnetic directions. Radiocarbon age of plotted points ranges from 1400 to 8400 years B.P. Comparing to the wide time span of 7000 years, the plotted points are so sporadic as to reveal any probable trend or tendency in secular variation, but they are in general distributed with regard to the inclination and declination for various periods as follows: 50° - 60° in inclination and 0° - 20°E in declination for the period 1400 - 2300 years B.P., 50° - 60° and 0° - 20°W for 3000 - 3500 years B.P., 45° - 60° and 0° - 15°E for 4500 - 5000 years B.P., 40° - 55° and 15°E - 15°W for 5000 - 5500 years B.P., and 40° - 55° and 0° -25°W for 7800 - 8500 years B.P. Through these periods they are mostly within the range 40° - 60° in inclination and 20°E - 20°W in declination, and several outlying values deviate as much as 72° in inclination and 36°E and 40°W in declination.

Cox: Your data plot, Prof. Watanabe, appeared to indicate changes of 10 degrees or more during periods of less than one century. Would you comment on these short period changes?

Watanabe: A number of magnetic data are associated with one type of pottery. These data were plotted on the graph at positions around the relevant radiocarbon date in an arbitrary order. So the distance among these plotted points on the graph does not mean the difference in age.

(6) MOTION OF DIPOLE FIELD IN ARCHAEOLOGICAL EPOCH

N. Kawai and K. Hirooka

Osaka University, Toyonaka.

Result of archaeomagnetic investigations from several places on the northern hemisphere was compared with that of the instrumental records of the geomagnetic secular variation hitherto obtained in the world. As the result, following conclusion was drawn by the present authors. The details are summarized in the following items.

1. Since at least 100 B.C. the dipole axis of the geomagnetism has continued an anticlockwise rotation on a circular orbit about the geographic north pole.

2. The radius of the anticlockwise orbit was estimated to be 1000 km.

3. The estimated period of the complete one rotation is about 1500 years.

4. On the above-mentioned anticlockwise rotation is superimposed another minor rotation.

5. The sence of this minor rotation is clockwise and is opposit to the above-mentined major rotation.

6. The period of the clockwise rotation is about 500 years.

7. The radius of this minor rotation is about 500 km.

The dipole axis, therefore, shows a complicated pattern of its motion which can be represented by a combined motion of both the anticlockwise major and the clockwise minor rotation.

Yukutake: 1. What is the period for the virtual geomagnetic pole to complete its whole rotation?

2. It seems to me that some parts of polar wobble obtained by Prof. Kawai can be accounted for by the westward drift of the non-dipole field with a velocity of $0.3 \sim 0.4^{\circ}$/yr. This velocity suggest that the non-dipole field will complete its rotation during about 1000 years. The period thus obtained is very close to that estimated from the rotation of V.G.P. This seems to propose difficulty to reconcile the hyposesis of easterly rotating dipole with the westward drift of the non-dipole field.

Kawai: The period of the complete one anticlockwise rotation is 1500 year, and dose not agree with the period you estimated for the westward non-dipole shift. Furthermore, the would-wide data show three minor loops, and the periods when they occured coincide with each other despite of the three different places differing in longitude. In other words, it may be difficult to explane at least these looping motion on a basis of the westward drift of the non-dipole field alone.

(7) SHORT-TERM VARIATIONS OF

THE PLIO-PLEISTOCENE PALEOMAGNETIC FIELD IN THE WESTERN UNITED STATES

D. F. Heinrichs

Stanford University, Stanford.*

The natural remanent magnetization (NRM) of sixty-one lava flows from the Plio-Pleistocene Lousetown formation was measured. The field area extends from Virginia City, Nevada, to Truckee, California, on the eastern slope of the Sierra Nevada. The directions of remanent magnetization are used to analyze short-term variations of the paleomagnetic field.

Although the original magnetization of many flows is scattered, progressive step demagnetization experiments indicate that the secondary magnetization is removed in alternating fields of 200 to 300 oersteds. Results from demagnetization curves, storage tests, Curie temperatures, and polished sections suggest that the mean NRM directions were acquired parallel to the geomagnetic field when the flows cooled. The general extrusion sequence is determined by K-Ar dates together with geomagnetic polarity epochs and stratigraphic controls.

The flow mean directions separate into two distinct groups. Thirty-two flows at Lousetown Creek have intermediate directions of magnetization with $D \simeq 64^\circ$, $I \simeq -67^\circ$ while the remainder of the flows have more usual normal and reverse polarity directions with $D \simeq 20^\circ$, $I \simeq +46^\circ$ (north-seeking directions). Both sets of flows have directions of magnetization that are significantly different from an axial dipole field at the 95 percent confidence level. Excluding the intermediate directions, the average displacement of the geomagnetic field from the rotation axis is 22.7°,

* Now at Oregon State University, Corvallis.

with individual sections having displacements of 9.5°, 32.0°, and 37.2°. It cannot be determined from the data whether these displacements are due to changes of the rotation axis or to an inclined geomagnetic dipole shifting about a fixed rotation axis. The results are consistent with the suggestion there may be a contribution to the geomagnetic field spectrum with periods of 10^5 to 10^6 years from a random walk of the rotation axis.

The thirty-two flows with intermediate directions crop out in a continuous section with a reversed flow at the base and a normal polarity flow at the top. A recent K-Ar date gives an age of 6.8 m.y. for the first intermediate flow. Statistically the flows essentially represent a single direction of the geomagnetic field; the confidence interval of the mean and the confidence intervals of all the flows except the first intermediate flow overlap. Since the large number of flows with the same direction of magnetization requires a significant amount of time for extrusion it appears that during a transition the field changes in a series of "steps," rather than with a continuous motion.

Coe: Do you think the thirty-two flows with the anomalous easterly direction were extruded within a relatively short period of time? What length of time would you estimate?

Heinrichs: Yes, There are no indications of long periods of elapsed time between successive flows. There is only one thin gravel layer in the sequence of thirty-two flows. It is estimated the flows were extruded over a time interval of several hundred years.

Nagata: How reliable is the transition from reverse to normal polarity at 6.8 million years indicated by the Lousetown Creek samples?

Heinrichs: The suggestion for a transition is based on the stratigraphic location of the intermediate flows between a reverse and a normal polarity flow. The 6.8 m.y. age is from an intermediate flow.

(8) SOME PRELIMINARY PALEOMAGNETIC RESULTS FROM LUSON ISLAND, PHILIPPINES

I. Hsu, L. Scharon

Washington University, St. Louis

and

E. Sonido

University of Philippines, Quezon City.

A total of 1800 rock specimens was drilled from 155 sites on Luson Island in the Philippines. These specimens, extrusive and intrusive rocks, are mostly Jurassic to Recent in age. NRM properties of all specimens were measured and some were demagnetized in an ac field. Preliminary results of part of this investigation are presented. The mean RM direction of Quaternary volcanics averaged from 13 sites and after ac demagnetization gives a VGP at 38.3°E, 86.2°N and a confidence oval of dm = 9.8° and dp = 5.3° in which the Earth's rotation axis is included. The calculated VGP from the believed stable mean RM direction (after ac demagnetization) of 20 sites in Late Tertiary volcanics is located at 19.1°E, 84.2°N (dm = 9.0°, dp = 4.8°). Reversals in this series of rocks have been found. The influence of tectonics on the RM directions is rather pronounced in certain Late Tertiary volcanics, especially in the Marinduque Island. NRM directions for both intrusives (Mid Tertiary) and extrusives (Jurassic to Mid Tertiary) in the Central Cordillera complex group well and show high inclinations (greater than 65°). Results from 30 ac demagnetization curves indicate little change in NRM direction when the applied field is lower than 200 oe. The best grouping is at zero external field. These particular NRM properties may relate to secondary RM and /or tectonics.

Grommé: Does the pole position derived from the NRM measurements of Cretaceous-Early Tertiary rocks fall anywhere near the poles found by Cox from the Sileby River volcanics of Oregon and by Gromme' and Gluskofer from the Franciscan Formation in California? The latter poles are at low latitudes in the Atlantic Ocean area and the rocks are of similar age.

Scharon: The pole position calculated from the mean NRM direction is located in southeast China and is different from the pole positions found for the Sileby River volcanics and the Franciscan Formation, although the latter two have applied the tilt correction and have simpler rock types, age, and structure than the philippine rocks involved in the pole position.

Cox: What do you think is the origin of the magnetization remaining after ac demagnetization in fileds above 200 oes?

Scharon: At this stage in our analysis of the rocks from the Philippines I must admit that the origin of magnetization is not known nor am I prepared to even advance an idea as to what I think it may be. Thermal demagnetization of these rocks is planned which may give us an insight as to the origin.

(9) PALEOMAGNETISM OF TAIWAN, CHINA

I. Hsu, J. Kienzle and L. Scharon

Washington University, St. Louis.

Specimens (1364) of igneous rocks, ranging mostly from Miocene to Plio-Pleistocene in age, were collected from 160 sites in 8 geologically different areas in taiwan. Partial ac-demagnetization was used on the specimens and yielded paleomagnetic results of 154 sites for discussion. 64 sites of Plio-Pleistocene andesite and basalt from the Tatun Volcano Group (N and B), Penghu Islands (P), and Shiukuran River (S) show a mean pole position located at Latitude 85.9°N and Longitude 90.2°W. 14 sites of Miocene basalts and andesites from the Chiaopanshan (C) and Shiukuran River (S) areas indicate a mean pole position located at Latitude 81.4°N and Longitude 66.0°W. These andesites and basalts possess stable thermal remanent magnetization and exhibit, except the Tatun Volcano Group (N and B), reversed polarity. The consistency of pole positions indicates that Shiukuran River area (S) had two stages of andesitic activity during Miocene and Plio-Pleistocene and also indicates that no significant angular displacement has occurred between the Eastern Coastal Ranges and the western part of Taiwan. The original remanent magnetization of the dacite rocks in the Keelung Volcanic group (D) was extensively modified by chemical remanent magnetization causing their remanent magnetization directions to deviate and hence to be unreliable for paleomagnetic studies. Remanent magnetization properties are complicated and unstable for the basic and ultrabasic rocks in the Taitung area. The mean directions of remanent magnetization of the Taroko Gorge gneiss indicate that the last metasomatism might have occurred during late Tertiary time. Remanent magnetization intensities, magnetic susceptibilities and Q ratios are directly related to the types of iron oxides contained in the rocks and not necessarily to the rock type.

Strangeway: Did I understand you to say that the Q-ratio is higher when the ilmenite content is higher?

Scharon: To quote: "The former group of areas (magnetite as the chief oxide) have lower Q values (less than one) while the reverse is true for those groups which have ilmenite as the chief iron oxide". Reference is also made to the paper "Paleomagnetic Investigation of Taiwan Igneous Rocks", Bull. of Geological Survey of Taiwan, No. 17, 1966, PP. 27-81.

Cox: The mean virtual geomagnetic field for Plio-Pleistocene rocks from Taiwan (at 35.9°N and 90.2°W) agrees well with our Pleistocene results from the Galapogas Islands, Hawaii, western U.S. and Alaska. Don't you feel that this agreement in mean pole positions as determined from opposite sides of the Pacific Basin indicates that we are looking at a displacement of the main dipole field, rather than effects of the non-dipole field?

Scharon: When one looks at his own data from a single area on the globe and sees this phenomena of two age periods grouping well with their ovals of confidence intersecting each other yet barely excluding the position of the axial dipole of the present geomagnetic field, his tendency might be, as was in our case, to relate this to a strong element of permanence in the earth's non-dipole field. On the other hand your observation is certainly a logical one and it is quite possible that we are indeed looking at a displacement of the main dipole field.

Our group however should like to point out that data obtained from Japan, China, Philippines, and Korea indicate VGP positions different from those VGP positions obtained from Taiwan and the west Pacific areas of the United States. This tends to influence one's thinking that we are seeing effects of the non-dipole field rather than an effect of the main dipole field.

Nagata: How did you distinguish different kinds of origin of remanent magnetization of your rock samples, i.e. CRM, TRM or their mixture?

Scharon: All of our analyses to date have been a combination of two specific methods. These are (1) thorough petrographic analyses (up to 1000 magnification) and (2) field evidence. Petrographic work is carried out on both thin sections and polish sections where we are looking for evidence of secondary origin of the magnetic minerals, alteration of magnetite and titanomagnetite to titanomaghemite or hematite. At the same time we are concerned with ovserved field conditions such as faulting, metamorphism especially low grade metamorphism and volcanic activity that may produce hydrothermal alteration.

(10) INTENSITY OF THE GEOMAGNETIC FIELD

IN PLIOCENE AND PLEIOCENE

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Thelliers' stepwise-double-heating method was applied to volcanic rocks of a few million years b.p. in order to obtain the intensity of the paleo-geomagnetic field. Samples were collected in three younger volcanic fields: basalt lava flows of the Rio Grande gorge (K-A ages range from 3.6 to 4.5 million years), near Taos, New Mexico. U.S.A.; middle or late Pliocene basalt lavas, south of Flagstaff, Arizona, U.S.A.; and about one-million-years-old andesite lavas of Usami, in Hakone-Izu volcanic region, Japan. The stability of NRM of these samples was confirmed by various paleomagnetic stability tests and the detailed studies of magnetic minerals of these samples was confirmed by various paleomagnetic stability tests and the detailed studies of magnetic minerals of these samples suggest that self-reversals are highly unlikely.

All the heatings in Thellier experiments were carried out in air under the influence of the geomagnetic field ($F=0.461$ oe) in Kakioka laboratory. The double heating procedure was repeated seven to nine times between room temperature and a temperature slightly higher than the Curie point of each sample. The remanent magnetization of a sample at each step was measured by an astatic magnetometer after the sample was cooled to room temperature.

In total, 11 originally normal and 28 originally reversed samples from 35 lava flows were studied. Out of these 39, eight gave good linear relations between the intensity of demagnetized NRM (J_n) and the intensity of partial acquisition of TRM (J_t), and 17 showed fairly good relations of J_n-J_t. The rest (14) are qualitatively still useful, but J_n-J_t relations are rather inconsistent in these samples.

The intensity ratios F/F_0, which is the ratio of the intensities of the ancient and present geomagnetic fields at the sampling site, for "good" or "fairly good" lava flows are listed below in the order of lava flow succession (except 818, 820 and UV17 whose exact positions are not clear).

Rio Grande			Arizona			Usami		
lava	polarity	F/F_0	lava	polarity	F/F_0	lava	polarity	F/F_0
830	N	0.95	842	R	1.33	UV06	R	0.85
829	N	0.65	843	R	0.74	UV07	R	1.52
827	R	1.25				UV11	N	1.10
826	R	0.67				UV12	N	1.02
822	R	1.51				UV13	N	1.17
821	R	0.77				UV14	N	0.79
818	R	1.19				UV17	N	1.80
832	R	1.23						
831	N	0.66						

Thus the applicability of Thelliers' method to volcanic rocks of several million years was demonstrated. Although this study is only preliminary, it is quite remarkable that the intensity ratios for lava flows of these three localities are very near unity (1.00) regardless of their NRM polarities, which seems to suggest that the intensity of the geomagnetic field has been, on the whole, not quite different from the intensity of the present field, except the polarity swiching period.

It seems fairly dangerous to assume the ratio of the intensities of total NRM and TRM (J_n/J_{Tc}) is the same as F/F_0, since many of the samples in this study have undergone some physico-chemical change when the samples were heated to 400 or 500°C.

Rikitake: Theoretical point

A steady dynamo can maintain any field, so the discussion should be based on a non-steady dynamo. The intensity of the field depends on the driving force. As far as the same driving force is retained, the limit of growth of the field would be the same either for normal or reverse polarities.

Kume: You mentioned that Thelliers' method is applicable to the Quaternary and Tertiary rocks. Could you show some idea on the variation of the past geomagnetic field from the results obtained so far?

Kono: As far as my data are concerned, I think we have a strong suggestion that the intensity ratio F/F_0 is nearly the same, irrespective of their original magnetic polarities, and that the mean value is nearly 1.0. But the data must be accumulated first.

(11) GEOMAGNETIC SECULAR VARIATION DURING THE BRUNHES POLARITY EPOCH

R. R. Doell and A. Cox

U.S. Geological Survey, Menlo Park.

The direction of the geomagnetic field at 211 points in time distributed over the past million years has been determined from a paleomagnetic study of lava flows from St. Paul Island and Nunivak Island, Alaska (60° North Latitude), the western United States (40° N L), Hawaii (20° N L), and the Galapagos Islands (Equator). An analysis of virtual geomagnetic poles corresponding to these field directions leads to the following conclusions about the geomagnetic field during the past million years: (1) The wobble of the main dipole has had an angular standard deviation of less than $11\frac{1}{2}°$. (2) The average magnetic dipole axis, and possibly also the rotation axis, has undergone a displacement of 5°. (3) The angular dispersion of virtual geomagnetic poles produced by the nondipole component of the field was more pronounced at high latitudes than at the equator. (4) The present subdued expression of the nondipole field in the central Pacific has persisted during the past million years; it is probably not the result of attenuation by electromagnetic induction in the mantle, but rather may reflect the supression of fluid eddies in the earth's core by lateral temperature differences in the mantle.

Strangway: We now have events and epochs in which the magnetic field reverses and today two papers discuss transients of 90 degree. If we do not reject spurious data will we find that 90° transitions are just as important as events?

Cox: Within polarity epochs we find angular secular variation up to about 60 degrees in the western United States and Alaska, and these unusual directions are about as common as events. However they appear to be different from events in being much shorter. The intra-epoch angular fluctuations probably have periods comparable with secular variation (10^2 to 10^3 years), whereas events last about 10^5 years.

Rikitake: Cause of the low non-dipole field according to the recent theory a down flow of core material has been found underneath the Pacific. This might be the cause of the non-dipole low there. The method applied is different from Vestine's one.

Cox: This model would certainly be consistent with the paleomagnetic data, provided some mechanism (such as lateral temperature differences in the mantle) can be found to sustain such connection for periods of the order of 10^6 years.

Kono: You divided St. Paul Isaland samples into three groups, 1,2 and 3. Is this subdivision based on some geologic evidences or is this by the direction of NRM?

Cox: The groups were defined on the basis of the direction of the NRM of individual lava flows. However there is a rather strong correlation with the ages of the flows. Most of the flows of Group 2 are of about the same age, and most of the flows of Group 1 are older.

Heinrichs: What is the magnitude of the time interval between your Group 1 and Group 2 flows?

Cox: The only evidence is geological. Enough time elapsed between the extrusion of Groups 1 and 2 to permit extensive faulting. What this means in years I'm unable to say.

(12) PALEO-INTENSITIES OF THE GEOMAGNETIC FIELD DETERMINED FROM TERTIARY AND QUATERNARY ROCKS

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Thelliers' method was used to determine paleointensities of the geomagnetic field from volcanic rocks collected in the western U.S. In this method the natural remanent magnetization (NRM) remaining after each temperature step of thermal demagnetization is compared to the thermoremanent magnetization (TRM) acquired by cooling a sample from the same temperature in a known magnetic field. In the ideal case the ratio of the ancient intensity to the applied field equals the ratio of the NRM to the TRM for all temperature intervals.

There are several types of non-ideal behavior which are displayed by rocks in Thelliers' method. The most important in young rocks arises from irreversible changes in the TRM spectrum incurred during heating in the laboratory. These were demonstrated directly by redetermining the TRM in a given temperature interval after heating to higher temperatures. Irreversible changes in the saturation magnetization also occur frequently, but in general bear no simple relation to the changes in TRM. This latter type of change may be due to disordering of the Fe and Ti ions of the magnetic minerals at elevated temperatures.

Viscous remanent magnetization (VRM) is present in the low blocking temperature portion of the NRM of older rocks. This portion of the original TRM should be in equilibrium if the external field never changed, and accordingly the VRM is most evident in rocks of reversed magnetization. Spontaneous decay probably occurs only when the average geomagnetic intensity is less than the field which produced the natural TRM. Because of field reversals, the intensity averaged vectorially over the past several million years may be close to zero, but unambiguous effects of spontaneous decay could not be proved in samples which were at least 6.5 million years old.

Nonlinearity in the acquisition of TRM with field could cause deviations from ideal behavior, but errors in paleo-intensity resulting from neglect of this factor appear to be at most a few percent for the rocks tested in this study. Another disturbing mechanism which has a more serious effect arises from the sample demagnetizing field. Approximate calculations show that the paleo-intensity determined by Thelliers' method could be as much as 15 percent too high or 33 percent too low for the most highly magnetic samples, in which the ratio of total TRM to the applied field which produces it is about 0.06.

Finally, non-ideal behavior may be inherent in some mechanisms of acquisition of TRM by multidomain magnetic grains. Samples of dacite from Mt. Lassen, which were extruded in 1915 in a field of 0.54 oe, suggest this possibility. Comparison of the NRM and artificial TRM associated with different temperature intervals yields paleo-intensities which vary from two-thirds to twice the correct value, whereas simple comparison of the virgin NRM and the total TRM yields an average of $0.53 \pm .06$ oe for 11 samples. One possible explanation of this phenomenon, involving the effect of the grain demagnetizing field on domain wall movement, is outlined.

Quantitative paleo-intensities were determined for two points in time: $0.223 \pm .009$ oe for a Recent basalt and $0.153 \pm .007$ oe for a baked sediment with KA age about 6.5×10 years. These unusually low values are accompanied by a normal direction of NRM in the former case and an intermediate one in the latter. The latter case may imply the field was in transition, but the former certainly does not. A less precise determination of $0.10 \pm .02$ oe on basalt samples provided by N. Watkins from a definite Miocene transition zone (Watkins, 1965, Nature, 206, 801-803) also suggests that the geomagnetic intensity decreases during a field reversal.

Paleo-intensities for five other points in time were derived with standard deviations between 5 and 20 percent, and those for the remaining ten points were even less precise of the eitht points that were estimated to lie between zero and ten thousand years B. P., five were considered usuful for paleo-intensity determinations, yielding an average of $0.43 \pm .12$ oe. In addition, eight units with ages estimated between ten thousand and ten million years were studied besides the two with directions intermediate between normal and reversed mentioned above. Five of these were considered suitable, and yield a mean paleo-intensity of 0.30 ± .08 oe, about 0.6 times the present value.

Kono: Is there any significant relations between the rock types of the samples and the percentage of success you have got in your experiments?

Coe: Not really samples with apparently simple magnetic mineralogies gave the best results. Many more samples must be tested before meaningful generalizations can be made.

Uyeda: 1) When the rock contains "self-reversing" component, Thellier curve can be quite complicated and yet perfectly reproducible. Have you considered about it?
2) Have you tested Thelliers' method on contemporary basalts?

Coe: 1) Yes, I have encountered seveal rocks with self-reversing components, including a basalt and a dacitic pumice.
2) No. It should be done. The only contemporary lava tested was the 1915 dacite flow from Mt. Lassen, which I discussed earlier.

Minoru Ozima: How is the effect of demagnetizing field on the intensity measurments?

Coe: I have tried to deal with this problem, but it is too complicated to present now. If $J_N \leq 3 \times 10^{-3}$ emu/cm^3 the maximum error in the experimentally determined paleo-intensity is 2.5 percent, considering only the effects of the "bulk" demagnetizing field of the whole sample. The effects of the demagnetizing field within each ferromagnetic grain has not been considered.

Strangway: Can the local magnetic field in a volcanic terrain vary enough to cause significant variations in the palaeointensity measurements?
Local magnetic anomalies in these terrains can be very large, often a matter of thousands of gammas or more on a rough surface and very close to that surface.

Coe: Anomalies should not be greater than $2^{\pi} J_n$. Thus, for instance, the maximum anomaly due to Mt. Lassen $(J_n \approx 3 \times 10^{-3}$ emu/cm^3) is about 0.02 oe. The geomagnetic intensity there is about 0.54 oe, so the uncertainty is no greater than $\pm$ 4 percent.
If J_n is 10 times stronger, the maximum effect is 10 times as great, and the effects of the self-demagnetizing field must be considered also. This is difficult, but I have attempted to approach this problem, too.

Fuller: There are certain magnetic minerals whose magnetic properties are changed substantially by short annealing at high temperature ($600° \rightarrow 700°C$).

Coe: I find this easy to believe, especially in rocks with self-reversing tendensies.

Heinrichs: How reliable do you believe your paleo-intensities are? Accuracy vs. precision?

Coe: This is a difficult question which should be carefully considered by everyone working on paleo-intensities. The only positive criteria for reliability are
(1) the degree of straightness of the NRM-TRM curve of a single sample
(2) the consistency between samples of the same "volcanic unit" with differing magnetic properties
(3) reasonableness of the values compared with other units of the same age.
The other criteria are all negative: the absence of effects which would be likely to systematically bias the experimentally determined paleo-intensities. These could be

physico-chemical changes, VRM, etc. However, one can never be sure he has considered all the possible sources of systematic error. There can be no absolute proof of the reality of a given paleo-intensity.
Nevertheless, I tentatively believe the paleo-intensities I have determined are reliable within the confidence limits indicated by the scatter of the values, because I know of no systematic effects which seem likely to have significantly disturbed the results.

Scharon: Is there any relation between your ancient field values and the predominate magnetic mineral type?

Coe: Seemingly not.

Kobayashi: The paleo-intensity determination of the earth's field appears to me very important and proming. Within a few years it is hoped that we may obtain a good information on the intensity variation of the field from Precambrian to the present. It will not only help us solving the problem of the history of the core development but also provide more information to the analysis of the paleo-field configuration.
For this purpose one important basis knowledge may be the change of magnetic "structure" of rockforming ferromagnetic minerals secularly with geological time as well as by heating. We have particular interest in annealing of the internal stress. We would like to propose to examine the spectrum of Hc or related properties when we use the Thellier's heating method. We also would drow your attension to the possibility of secular annealing of internal stress. The effect may be treated as a type of diffusion after effect with which rock magnetism has little been concerned so far.

(13) NEW DEVELOPMENTS IN THE GEOMAGNETIC REVERSAL TIME SCALE FOR THE QUATERNARY

A. Cox, R. R. Doell and G. B. Dalrymple

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The past 2 years have seen the addition of many new polarity determinations which have been important in refining the Quaternary reversal time scale. The most important of these have been the revision of the Brunhes-Matuyama boundary from 1.0 to 0.7 m.y. ago, and the discovery of the Jaramillo normal event near 0.9 m.y. ago. It has also been possible to divide the available data objectively into a primary and secondary group, the former being considered reliable for defining precisely the time scale, and the latter being generally restricted to stratigraphic assignments. There are now nearly 100 determinations in the primary group.

Recent paleomagnetic studies on deep-sea cores by workers at Columbia University, New York, indicate that the reversal time scale determined from the primary data group (based on paleomagnetic and potassium-argon age determinations of extrusive rocks) is essentially complete for the last 3.6 m.y.

Kono: Have you any qualitative or quantitative definition when you say that the direction of NRM is "intermediate"?

Doell: In general, the answer must be "no". However, in the case of the "intermediate" direction associated with the Jaramillo event, this direction falls in between normal and reversal directions measured in rocks, all of which have K-A dates, and thus it may be inferred that this direction is probably one obtained during a polarity transition. In such a case it may be helpful to use the term, "intermediate."

Kuno: The reversal of polarization found in some lavas of Usami Volcano as mentioned by Kono this morning probably corresponds to the short reversal period 0.7 m.y. old found by Cox, Doell and Dalrymple, because this assignment agrees well with the geological observation on these lavas.

(14) PLIOCENE REVERSAL TIME SCALE

G. B. Dalrymple, R. R. Doell, C. S. Grommè and A. Cox

U.S. Geological Survey, Menlo Park.

Paleomagnetic and potassium-argon investigations have been made on 44 Pliocene and late Miocene volcanic units from the western conterminous United States and Alaska in order to gain information on the timing of pre-Pleistocene reversals of the earth's magnetic field. The ages of the units studied range from about 2 to 16 m.y., and the rocks with reversed polarity are about equal in number to those with normal polarity.

The data suggest that the frequency of geomagnetic reversals during Pliocene time probably did not differ much from that of the last 3.6 m.y. Although the density of data is not sufficient to define polarity epochs during this interval of time, we have been able to establish the ages of four epoch or event boundaries, each of which has been designated by the number of one of the relevant samples; the W10 R/N boundary at 3.7 ± 0.1 m.y., the A12 N/R boundary at 4.9 ± 0.1 m.y., the W32 N/R boundary at 9.0 ± 0.2 m.y., and the W36 R/N boundary at 10.8 + 0.3 - 1.0 m.y.

Because absolute dating errors generally increase with age, only the boundaries of major Pliocene polarity epochs will be resolvable with random sampling techniques. In contrast, boundaries that are represented in stratigraphic successions will be more easily identifiable than epochs or events. Thus, it is important to find Pliocene sequences of datable normal and reversed flows that narrowly bracket epoch or event boundaries. We estimate that a minimum of between 200 and 400 carefully determined points will be needed to define the broad pattern of reversals during Pliocene time.

(15) ANOMALOUS DIRECTION OF N. R. M. IN MIOCENE VOLCANIC ROCKS IN JAPAN

N. Kawai and K. Hirooka

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N.R.M. of some of the upper Miocene lava flows and granite in Kinki district in Japan possess quite an unusual direction as demonstrated in the earlier work by Kawai and in the recent studies by Hirooka and Ito.

Rocks were found magnetized rather strongly in a direction which is neither normal nor reverse.

Similar direction was also reported by Momose but he assumed the age of his lava flows to be middle Pliocene.

In the first place, in order to clarify the age of our lava flows, K-Ar method of dating was undertaken. And it was found that all of those rocks have their ages in a very limited interval of geologic time ranging from 14.3 m.y. to 13.1 m.y., despite of the different locality of the exposures and also of the different rock kinds.

Next, the Thellier's method of estimating the palaeomagnetic field intensety was applied to those rocks. The results show that the past intensity of the field under which the rocks in question were magnetized was about 0.3 - 0.5 times smaller as compared with that of the present field.

The study, therefore, seems to support the idea that the dipole field became smaller in that particular period and the existing non-dipole field may have been the major component of the magnetizing field for those rocks when they were cooling in the filed.

Cox: The conclusion that the geomagnetic field is predominantly nondipolar during a transition was drawn from the fact that the VGP path defined by the Japanese rocks is different from that found for rocks from California and Iceland. However this conclusion is valid only if the same transition is involved. Have you any evidence for this?

Hirooka: We have no direct evidence because of few dated rocks showing anomalous n.r.m. But it has reported no similar virtual geomagnetic pole path of Upper Miocene from any part of the world except Japan.

Nairn: The problem of the anomalous direction is aggravated by several difficulties.
(1) The upper Miocene has never been stratigraphically defined.
(2) Within the volcanic rocks of the Carpathian province four "zones" can be recognized two normal two reversed. However it is impossible to state whether these truly represent epochs or events.
Within the lower Upper Miocene and upper Middle Miocene of the Carpathian province, approximately 10 percent of the sites gave anomalous directions. This appears to be the time range in which kawai's anomalous directions are found. The intensity of magnetization at these anomalous sites whilst low, lay within the intensity range of rocks from the whole province which formed a log normal distribution.

(16) STUDY ON IRREVERSIBLE CHANGE OF MAGNETIC PROPERTIES OF SOME FERROMAGNETIC MINERALS

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and

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Some ferromagnetic minerals of which megnetic properties such as Curie point or saturation magnetization change irreversively in heating in vacuum are studied and one explanation for the mechanism of such irreversible change in presented.

Magnetic minerals separated from some acidic rocks undergoes an irreversible change in Curie point and saturation magnetization when they are heated in vacuum: Curie point and saturation magnetization decrease in heating in vacuum. Microscopic observation on polished sections revealed that all rocks which show such an irreversible change in the thermomagnetic curve contain some amount of titanomaghemite in addition to titanomagnetite. All the other experimental results such as chemical analysis, X-ray analysis and thermomagnetic analysis at low temperature range indicate that such an irreversible change is caused by reduction of titanomaghemite to titanomagnentite.

Magnetic properties of Mohole basalt EM7 were investigated. This sample also shows an irreversible change in the magnetic properties in heating in vacuum. Magnetic mineral is a single phase of highly-oxidized titanomaghemite and the Curie point and saturation magnetization increase largely without chemical change in heating in vacuum.

This may be explained by a change in the ionic configuration of the magnetic mineral. Other basalts dredged from West Pacific sea mounts also showed such an irreversible change as seen in EM7. Physico-chemical condition in the case of lava eruption in a deep sea may have some essential role in the formation of the magnetic minerals which show such an irreversible change in heating.

Minoru Ozima: This paper has intevesting relevance in paleomagnetism. Lately we are more and more realizing that most of titanomagnetite contains considerable amount of titanomaghemite phase. Since titanomaghemite is believed to be formed by low temperature oxidation below cuire point, the remanent magnetization carried by maghemite should be considered as secondary magnetization, or the time of the acquisition of remanent magnetization by maghemite must differ from that when lava erupted. When maghemite grain is fine, we observed that remanent magnetization was very stable. Therefore, high stability of remanence does not necessarily mean that such rock can be used for paleomagnetic study, if considerable amount of titanomaghemite phase exists.

Strangway: Comment - we have been studying the properties of dolerite dikes from Colorado. These samples are stable to A.C. demag., Thermal demag., and low temp-cleaning. However the magnetization directions are very random and they are very rich in maghemite. It seems important that we consider the microscope as an important tool for stability tests.

Mituko Ozima: It seems interesting to study these maghemite containing rocks which have stable but anomalous direction of remanent magnetization. The remanent magnetization may be produced by low temperature oxidation, or CRM. If so, the remanent magnetization would not represent the paleo-geomagnetic field at the time of the lava eruption.

Heinrichs: How reproducible are the results when more than one specimen from the same sample are measured? My results from the Lousetown formation indicate a wide range of behavior from different samples from the same lava flow, and even from the same sample.

Mituko Ozima: I examined two cases.
In one case, I sampled an andesite sample from two sites of the same lava flow. These two showed the same type of thermomagnetic curve (J_s-T).
From one hand specimen, I took several pieces of rock flakes. They also showed the same thermomagnetic curve.
In order to obtain good reproducible results, it is important to carry out J_s-T measurement in very high magnetic field which is sufficient to produce saturation magnetization.

Verhoogen: Does the irreversible change you observed also occur when heating in air?
I would suggest that the irreversible changes may be due in part to changes in cation distribution (order-disorder) rather than to reduction.

Mituko Ozima: When the experiment was done in air, the degree of the irreversible change is much less in comparison with those done in vacuum. The irreversible change occurs at about 500°C. I feel that in order for cations to move to rearrange, the temperature should be much higher than 500°C at which the irreversible change does occur. As a matter of fact, we have experienced that quenching of various types of titanomagnetite grains from 1200°C to cold water has never shown any change in the J -T curve. I feel that a simple heat tretment could not cause any ordering or disordering of cations in the case of titanomagnetite. I also observed slight decrease in weight of the sample after the heat-treatment.

Kobayashi: I believe that we can still rely upon Dr. Katsura's chemical analysis even if your results indicate a reduction in a ferromagnetic constituent in which he found no bulk chemical change by the heat-treatment. The reason is that it may be very likely to have two phases (one reduced and one oxidized as a whole before heating. Thermomagnetic analysis is more sensitive to the oxidized one (with higher T) and if the two are not discontinuous in composition, only one T may be detected. Chemical analysis gives the average of these phases. After heat-treatment one oxidized phase will be reduced and reduced one oxidized, keeping the total composition the same, but the thermomagnetic analysis is so sensitive to the higher T phase that the decrease in higher T is clearly observed.

(17) MAGNETIC AND PETROGRAPHIC STUDIES OF VOLCANIC ROCKS FROM ULEUNG ISLAND, KOREA

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Uleung Island along with Cheju Island, Korea and Oki Island, Japan are a part of the Japan Sea alkali-rock petrographic province. From 16 sites located on this island 129 specimens were drilled in Plio-Pleistocene trachytes, trachyandesites, phonolites, and basalt. There are no significant magnetic or petrographic differences between normal and reversely magnetic specimens. The measured NRM intensities fall into two groups which contain both normal and reversed magnetization. One group exhibits magnetic intensities greater than 1×10^{-3} and the second has intensities smaller than 1×10^{-3}. Those specimens of the first group are stable and contain only titanomagnetite with secondary hematite. Most of the specimens in the second group contain unstable components of magnetization which are attributed to titanomaghemite formed by oxidation of the original titanomagnetite. Ratios of J_{NRM} to J_{TRM} are very low for those specimens containing titanomaghemite indicating that the NRM of these specimens is not entirely due to TRM. Site mean directions after ac demagnetization are nearly antipolar. A mean direction calculated by projecting reversed sites to normal yields a VGP of 49.5°E, 79.2°N with an oval of confidence (dp = 10.0°, dm = 13.7°) that includes the Earth's rotational axis.

Kuno: I found that maghemite is present in nearly all magnetite crystals in volcanic rocks but appears to be rather rare in plutonic rocks. This fact should be remembered in using volcanic rocks for paleointensity study. I have a feeling that the oxidation producing maghemite **is caused by water vapor seaping from** crystallizing lava flows. It might be also produced partly by weathering.

Scharon: During our petrographic observations of volcanic rock samples from Taiwan and Korea it was noticed quite frequently that a few grains of an equidimensional, isotropic opaque mineral which exhibits a whiter color and a higher reflectivity than that which ordinary titanomagnetite possesses. Nevertheless, they do not show the typical blush tinge of maghemite or the titanomaghemite as observed in the petrographic analysis of the Uleung Island rocks. The whiter colored mineral may be a transitional phase between titanomagnetite and titanomaghemite. As has been pointed out by some petrographers grinding of polished sections could cause a change in reflectivity. We are not sure at present whether this type of mineral is titanomaghemite.

It is certainly clear to us that the presence of maghemite greatly hinders the use of volcanic rocks in which it occurs. It is also discouraging to have to eliminate many samples in your final analysis. As expressed by others I think that the maghemite occurrence should be given a full attack of investigation. Only then can we use successfully such rocks, in which maghemite is present.

Mituko Ozima: Maghemite may be produced by the oxidation due to the escaping water vapor as you pointed out.

However, it is important to emphasize that maghemite is generally unstable at high temperatures, i.e., pure maghemite decomposes at about 300°C. Therefore, any process which might caused the maghemite production must occured relatively at low temperatures. The remanent magnetization carried by maghemite should be considered to be of a secondary origin CRM, that is, the time when maghemite acquired the remanent magnetization (CRM) may significantly differ from that for the time of the eruption of the lava.

(18)(19) STABLE REMANENCE AND MEMORY IN

MULTIDOMAIN MATERIALS

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and

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The essential characteristics of the memory of magnetite in thermal cycles across the K=0 point will be reviewed. In particular we shall consider.

1. the symmetrical nature of the high and low temperature phases of magnetization,

2. the reciprocal nature of the two phases of memory,

3. the high stability of memory,

4. the latent state of memory and demagnetization in the latent state,

5. the moment which may be generated across the K=0 point,

6. the independence of memory from soft remanence.

The explanation of these phenomena by a purely magnetostatic model appears to be very difficult and so the possibility of a magnetoelastic control has been investigated.

The internal stress of the materials would provide the source of stress energy in the magnetoelastic effect. Therefore if magnetoelastic pinning is important, memory and stable remanence should be very different in well annealed and in cold worked materials. We have found that both the occurrence of the transition of remanence and the magnitude of memory are very sensitive to the state of internal stress in Nickel and Cobalt. Nickel in the "factory" state, which is effectively cold worked, does not exhibit a transition of remanence at the K=0 point, but after annealing the same specimen has a transition with associated memory. In Cobalt both cold worked and annealed specimen show memory. These experiments demonstrate the importance of internal stress and suggest the necessity of a certain balance between magnetoelastic and magnetocrystalline energy.

The explanation of memory involves understanding the way in which the stress controls the magnetization throughout the thermal cycle. A preliminary model of stable remanence and memory is given which invokes a cooperative effect of stress and magnetocrystalline anisotropy to pin the magnetization within limited regions. This cooperative effect is destroyed when the crystalline anisotropy constant changes sign. The region then becomes an extremely favourable site for a wall because the anisotropy due to stress and that due to magnetocrystalline energy are out of phase. To a first approximation the energy of an individual spin is independent of its orientation. The polarity of the region carrying memory is preserved as the polarity of the wall which does not contribute significantly to the bulk remanence. When the crystalline anisotropy reverts to its original configuration the cooperative effect reoccurs.

The nature of the cooperative effect will then be considered. The highest microscopic coercivity of Cobalt is greater than that of magnetite which is greater than that of Nickel. This indicates that although stress energy is important it is only in cooperation with the crystalline energy that the pinning of stable remanence and memory is achieved.

If calculations similar to those made by Verhoogen (1957) are repeated for Nickel, Cobalt and magnetite, we find that single dislocations are only capable of pinning a part of wall or a domain but that pile-ups or arrays of pile-ups should be capable of pinning a whole domain through the mechanism developed in the model.

A series of annealing experiments has been begun in an attempt to identify the source of internal stress which controls magnetic properties. The investigation makes use of the well known fact that in the early stages of annealing quenched material, point defects migrate to form dislocation loops which later anneal out. Thus in the early stages of annealing the dislocation density increases before its eventual decrease. We have found that remanent coercivity and coercive force in hematite bahave in just the same way. The effect is seen in quenched, irradiated and natural samples but not in fractured samples. The process takes place very quickly in low titanium hematite, so that very substantial changes occur after two minutes annealing at 700°C. In some specimens TRM follows the same pattern as H_c but in others the two follow opposite trends. These results suggest that dislocations rather than point defects or impurities are the critical sources of internal stress which control magnetic properties.

We conclude that stable remanence and memory in multidomain materials can be best understood in terms of a cooperative effect between magnetocrystalline and magnetoelastic energy. Such a mechanism may account for the medium range of microscopic coercivity found in rocks e.g. for magnetite bearing rocks approximately 400 Oe to 1000 Oe.

Verhoogen: 1. How do we explain that in $\alpha\ Fe_2O_3$ and $\gamma\ Fe_2O_3$ the saturation TRM may equal the spontaneous magnetization.

2. Is it permissible to use an average λ rather than the coefficient appropriate to the direction of the dislocation.

Fuller: To question 1.

The saturation TRM of $\alpha\ Fe_2O_3$ is, as far as our specimens are concerned, not equal to its spontaneous magnetization but amounts to $\frac{1}{2} \sim \frac{1}{3}$ of the spontaneous magnetization. Kobayashi and Smith's measurement of reversible susceptibility χ_r has indicated that TRM smaller than about $\frac{1}{3}$ of the saturation TRM has a real TRM-characteristic, independent of the χ_r value but larger TRM acquired in a high field contains a fraction of IRM which reduces the χ_r - value. Some $\alpha\ Fe_2O_3$ may have saturation TRM equal to the spontaneous magnetization. In such specimens the internal stress may be greater or denser than in our specimen. In general since magnetic anisotropy in the basal hexagonal crystal plane of $\alpha\ Fe_2O_3$ is mostly due to the magnetoelastic energy (Iida et al 1966), these results indicating larger fraction of TRM compared to Fe_3O_4 are quite understandable. Its small value of spontaneous magnetization may, of course, help preventing the shielding effect by the soft magnetic components through the self-demagnetizing energy.

To 2nd question:
In natural Fe_3O_4 crystal the direction of dislocation may be assumed, as an approximation of the first order, to be so randomly oriented that it may probably be permissible to use the average isotropic magnete-striction λ.
For more detailed discussion preference of directions of dislocations in crystal must be taken into account.
If the action generating the dislocations is of the uniaxial nature, a certain ordering of dislocations may occur as the Stanford group demonstiated uniaxial anisotropy induced in nickel single crystal rolled in one direction (Shive and Syono, private communication).

(20) PRESSURE EFFECT ON MORIN TEMPERATURE OF α-HEMATITE

N. Kawai and F. Ono

Osaka University, Toyonaka.

By using an astatic magnetometer and a nonmagnetic pressure vessel, placed underneath, the effect of hydrostatic pressure upon the Morin transition point of α-hematite was examined and it was found that the latter is very much sensitive to the former.

The Morin point was elevated significantly when the pressure surrounding the crystal was increased.

The rate of the increase was found to be 0.01°/bar. This means that the application of pressure about 3 kb is sufficient to elevate the sub-zero transition point up to above room temperature, producing a perfact antiferromagnetic state of the material having spin alignment all along the crystallographic C-axis.

The pressure effect was so large indeed that, instead of changing temperature, it was possible to study the memory effect of α-hematite by changing pressure. In fact, the remanent magnetism disappeared during elevating hydrostatic pressure and appeared during releasing.

So far the transition point has been thought of as a point at which the dipole energy of spins and their crystalline energy are counterbalanced, both energies being expressed by different functions of temperature.

However, taking into consideration the above unexpectedly large shift of the Morin transition point by pressure, it would be desirable to assume the two energies as much sensitive to lattice parameter and/or c/a of the crystal.

Next, in order to apply a kind of "negative pressure", mechanical tension was applied. Decrease of the transition point with increasing amount of uniaxial tension was observed.

Actual crystal may have experienced many mechanical or thermal stresses since its formation. The observed change of the transition due to both the compression and tension is so large indead that we may reasonably assume that even in a single crystal there exist many regeons which have suffered the tension stress and whose transition point is, therefore, lowered significantly.

In the experiment of "memory effect" of this crystal cooling down experiments so far made were till to the boiling temperature of liquid nitrogen and were not sufficient enough to make these region perfect antiferromagnetic crystal having no parasitic ferromagnetism. The above region where the remanent survives in the basal plane of the crystal will become a seed domain from which the remanent develops on the heating procedure up to room temperature by means of antiferromagnetic coupling of the spins at the boundary. The mechanism may clarify the memory effect of the α-hematite crystal.

Kume: Is there any change of the remanent magnetization of α-hematite in direction before and after cooling through its Morin temperature?

Kawai: We have not examined this kind of change yet. We will soon carry out it in some future.

(21) PAST CONFIGURATIONS OF

THE EARTH'S MAGNETIC FIELD

J. Verhoogen

University of California, Berkeley.

A spherical harmonic analysis of all Tertiary paleomagnetic data yields improbably high values for the non-dipole coefficients. Factors other than non-dipole components contribute to the observed dispersion of virtual geomagnetic poles.

The dispersion of Permian virtual geomagnetic poles is much reduced by applying the continental rotations deduced by Bullard, et al (1965), from the fit of the Atlantic Coast lines.

Nairn: Have you attempted to exclude results which may be influenced by tectonics (within continental limits) as for example the Spanish Permian or Watkins Tertiary measurements from the Sierra Nevade?

Verhoogen: 1. In Bullard's closing of the Atlantic, Spain is treated separately and rotated independently of the rest of Europe (This rotation is in agreement with paleomagnetic data)

2. Intracontinental rotations were not considered in Tertiary data. They are, however unlikely to be an important, source of fictitious non-dipole components, as harmonic analysis of Quaternary data gives very much the same non-dipole terms as the Tertiary data.

(22) WESTWARD DRIFT OF THE GEOMAGNETIC FIELD IN HISTORIC TIMES

T. Yukutake

University of Tokyo, Tokyo.

Old records of magnetic measurements and archeomagnetic data at various places were collected to see whether the westward drift had been a persisting feature of the earth's magnetic field and to investigate to which extent drifting of the field had effect on the obseved secular variation.

It turned out that such main features of the secular variation as maxima and minima of magnetic declination and inclination were very likely to have drifted westwards with a velocity of about 0.36°/yr during the last 1000 years.

Comparison of the observed time variation with the spatial distribution of the present geomagnetic field suggests that the westward drift of the non-dipole field is responsible for producing main parts of secular variation of even such long periods as 1000 years.

Tsuboi: Is the variation in magnetic angles with time observed at a particular station due exclusively to the so-called "Westward drift"?
Is not some irregular wandering motion of the non-dipole field possible?

Yukutake: The time variations observed at stations are affected partly by irregular motion of the non-dipole field, as you point out, and also by growth or decay of the non-dipole field. However, analyses for world-wide observatory data indicate that the westward drift is the most predominant feature and plays the most significant part in producing the observed time variation.

Merrill: Is there any difference between the rate of western drift in the Northern and Southern Hemispheres?

Yukutake: There is no marked differences, on an average, as far as recent observatory data are concerned. However, if such specific features as may be expressed by m = 2 or 3 in terms of spherical harmonics, a considerable amount of difference in the drift velocity in the two hemispheres can be noted.

(23) A POSSIBLE CAUSE OF HIGH MAGNETIC STABILITY IN VOLCANIC ROCKS

D. W. Strangway and E. E. Larson

Massachusetts Institute of Technology,

Cambridge.

It has now been established that only volcanic rocks with very small particle sizes are highly stable magnetically. This conclusion is based on the detailed magnetic and microscopic studies of many volcanic rocks. These small grain sizes can be produced by initial crystallization or by autooxidation at high temperatures. In the latter case well developed exsolution lamellae of magnetite and ilmenite are formed. This exsolution takes place in the (111) plane of the magnetite. When two of the (111) planes only are involved a series of rod shaped particles with very great elongations and very smooth surfaces can be produced. It is probable that these particles are single domain in size and have lateral dimensions of about a micron. Moreover these particles have a range of blocking temperatures and can account for extremely stable magnetizations formed at temperatures below the curie temperature. These particles probably account for the extremely stable components of magnetization found in some volcanic rocks, which cannot be demagnetized even in A.C. fields over 1000 oe.

Kuno: Is the microphoto showing the exsolution texture for magnetite from a volcanic rock?

Strangway: Yes.

Mituko Ozima: By Buddington and Lindsley's work (1964), it was established that magnetite-ilmenite assemblage (of intergrowth texture) is produced by a high-temperature-oxidation (probably, T $\gtrsim\sim 600°C$ several handreds degree) of titanomagnetite during cooling to room temperature. If a rock sample has such texture of magnetic minerals, i.e. magnetite ilmenite lamellae, the sample has a intense, stable and original TRM. Furthermore, such a texture is safely considered as stable at room temperature.

Strangway: We are in full agreement with this observation.

Uyeda: At what temperature during the first cooling of lava, is the lamellae structure formed? Such a structure is magnetically steble but may not be stable mineralogically.

Strangway: To the best of our knowledge this is mineralogically stable and takes place above 600°C. The best reference to this is Buddington and Lindsley's paper in the Journal of Petrology (1964).

Kobayashi: Have you considered a spin-closure state between the multidomain and single domain states?
Morrish and Yu have calculated this case for a needle-shaped Fe_3O_4 and γFe_2O_3 and shown that the spin-closure configuration may exist before the single domain state is reached. This state seems to be more important at high temperature just below the Curie temperature which you mainly considered here and thus may make the critical size of single domain behaviour some what smaller than your calculation unless the internal stress or an other effect coexist.

Strangway: No, we have not. I suppose that the critical size change would be slight

and therefore the size argument would not be affected significantly.
However it is very important to look at the temperature dependence of this effect since it may affect the blocking temperature argument.

Fuller: Is it possible that either surface pinning may take place or alternatively that the exchange energy may overcome the lamellae boundary?

Strangway: It seems probable that the individual lamellae are too wide to have either surface pinning as in their films or exchange energy acting between magnetic lamellae separated by non magnetic lamellae.

(24) PRELIMINARY STUDY OF THE CHEMICAL DEMAGNETIZATION OF THE NATURAL REMANENT MAGNETIZATION OF ROCKS

Haruo Domen

Yamaguchi University, Yamaguchi.

In 1963 Kawai[1] proposed a technique to clarify minerallogical control of NRM by dissolving the ferromagnetic minerals contained in concentrated bydrochloric acid. The rate of the solution becomes slow as the titanium contents increases in titanomagnetite towards ulvospinel.

The present author has applied this technique to examine a stability of NRM of rock specimens taken from the so-called "intermixing zone" of both normal and reversed NRM at Kawajiri-Misaki, Yamaguchi Prefecture, West Japan. The intensity and the direction of the NRM of thin sections cut from these basalt samples were examined by means of an astatic magnetometer before and after the etching.

No significant differences of dissolving modes thus obtained were found between the normal and the reversed NRMs. On the other hand, ac demagnetization experiments carried out on the same sample have shown that the NRM intensity of the reversed group is more stable than that of the normal group. According to the thermo-magnetic analysis undertaken, it seems that the reversed group contains larger amounts of Ti-poor and Ti-rich magnetites whilst the normal group contained much titanomagnetite with intermediate Ti-contents. The experiemental results thus obtained are discussed with the data from the chemical demagnetization experiment.

1) Kawai, N.; 1963, 1963 Annual Progress Report of the Rock Magnetism Research Group in Japan, 8-10.

Kuno: According to my understanding, you conclude that the normal and reverse magnetizations of the two different portions of your sample are due to difference of Ti content in magnetite. If we assume that Ti content was uniform throughout the lava when the magma was extruded, the difference in Ti content of magnetite should be compensated by Ti content difference in other minerals, such as pyroxene, or the proportion of magnetite and ilmenite in the rock.

Domen: I think that the Ti-content in titanomagnetite is closely related to the sign of magnetization in the rock described, but a difference in the Ti-content might occur by solid phase transformation as shown by Kawai several years ago. Of course, the Ti-content might not differ originally in such a small portion of the lava. I had already reported[1] that, roughly speaking, the original lava flow in this district might have the phases of titanomagnetites which show the intermediate Curie points (150–450°C) which during geological time might have gradually exsolved into two phases, Ti-rich and Ti-poor magnetites. On chemical demagnetization, Ti-rich magnetite should be dissolved first, and then the titanomagnetites with intermediate Ti-content. So far as my experiment is concerned, the normal specimen appears to have contained such unexsolved phases to a great extent than the reversed specimen which contained exsolved phases. It is consistent that the NRM of reversed specimen shows the higher stability in ac demagnetizing field and also the NRM/TRM ratio of reversed group is much larger than that of the normal one.

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1) Domen, H.; 1956, Kagaku (Science) 26, (3) 145 (in Japanese).

(25) PRESSURE EFFECT ON MAGNETISM OF ROCK-FORMING MAGNETITE

Takesi Nagata and Hajimu Kinoshita

University of Tokyo, Tokyo.

Some results of experimental studies on the magnetism of natural titanomagnetite will be presented. Main subjects of the experiments may be divided into two;

I-(1). A remanent magnetization (PRM) induced by an uniaxial compressional stress in the presence of an external magnetic field.

I-(2). Dependence of initial susceptibility of titanomagnetite series on the uniaxial compression.

and

II. A preliminary result of pressure dependence of K_1 and λ_s of magnetite under high hydrostatic pressure.

In these experiments all the measurements were carried out at pressure less than 5kb and at room temperature due to a limited strength of a high pressure vessel made of Cu-Be alloy.

The results are as follows;

I-(1). The intensity of pressure remanent magnetization (PRM) is proportional to a weak external magnetic field, i.e.

$$J_{prm} = K \cdot f(p) \cdot H_{ex}$$

where f(p) is a function of external stress p. For the case of titanomagnetite fine grains J_{prm} does not exceed 5·(IRM) acquired in the same magnetic field.

I-(2). Initial susceptibility of fine grains of titanomagnetite decreases asymptotically with compression.

Dependence of initial susceptibility or pressure-remanent magnetization on an uniaxial compressional stress may be explained as the result of change in magnetic domain structures. In order to clarify the mechanism of the change of domain structure under compressional stress, the effect of pressure on the intrinsic magnetic properties such as magnetocrystalline anisotropy and saturation magnetostriction constants of ferromagnetics must be studied. In the present study the pressure used for the purpose of these experiments was a hydrostatic compression.

II. Relative change in $K_1(p)$ and $\lambda_s(p)$ of titanomagnetite natural single crystal (almost pure magnetite composition) are shown in the figure. $|K_1(p)|$ decreases slightly with pressure and on the contrary $|\lambda_{100}(p)|$ or $|\lambda_{111}(p)|$ increases asymptotically amounting to about 30 percent of the initial value at 2kb compression. The measurements of $K_1(p)$ under high hydrostatic pressure were carried out by means of a torque method. The torque meter of this type was well developed by Mr. Tajima, Inst. for Solid State Physics, Univ. of Tokyo (detailed report is in press).

From geophysical view-point, further studies on the magnetic properties of rock-forming ferromagnetics reported here should be extended to more wide ranges of temperature and pressure.

Cox: From the point of view of paleomagnetism, PRM is an important source of experimental noise which we would like to remove by partial demagnetization. Could you comment on the magnetic stability of the PRM produced in rock-forming minerals during your experiments?

Kinoshita: The decay mode of PRM against A.C. field is rather simillar to that of IRM acquired in the same field intensity. Therefor, the stability of PRM may be much less than that of TRM or ARM. This was also confirmed by the A.C. field demagnetization experiments comparing with the results of Rimbert on the ARM of magnetite fine grains. Moreover, absolute intensity of PRM is much less than that of TRM (10^{-2} times or less) for the same magnetic field. Therefore pressure effect on NRM is negligible noise for paleomagnetic studies.

(26) SUPPLEMENTAL STUDY OF THE "PIEZO-REMANENT MAGNETISM"

Haruo Domen

Yamaguchi University, Yamaguchi.

Several years ago the present author reported the acquisition of the remanent magnetization caused by uni-directional high pressure. Such a remanent magnetization has been called "piezo-remanent magnetization (PRM)"[1].

In this paper, some additional results of experiments on the PRM are given :- the acquisition of the PRM caused by uni-directional high pressure was confirmed using a natural magnetite powder from the Nagasaki Prefecture, Kyushu Island, Southwest Japan; the time effect of pressure on the remanent magnetizations, that is the changes of the intensity and the direction of a remanent magnetization produced thermally and iso-thermally in artificially prepared rock specimens stored for rather long periods of time under the relatively low constant pressure; and further data on the relationship between pressure and the magnetization of ferromagnetics.

The PRMs caused by both elastic and plastic deformations of specimens are discussed by analogy to metals. The present author has proposed that the PRM should be classified into two categories, the Elastic- and the Plastic-PRM, caused respectively by elastic or plastic deformation of the ferromagnetic materials.

Fuller: Carmichael at the University of Pittsburgh has carried out some experimental studies of PRM. PRM has been induced in nickel rods which were

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1) Domen, H.; 1957, Bull. Fac. Educ. Yamaguchi Univ., 7, 41-43: 1962, J. G. G., 13, 66-72.

twisted (up to 180°/ 6 cms length) in a field of 8 oe. The intensity of the moment and its stability are comparable with IRM in the same specimen. Measurements of Hc revealed magnetic softening when the direction of twist was reversed. It is interesting to note that Prof. Nagaoka (1890) demonstrated a self reversal when twisting nickel wire under tensile stress.

(27) EFFECT OF PRESSURE ON THE THERMOREMANENT MAGNETIZATION OF FERROMAGNETIC MINERALS

S. Kume

Osaka University, Toyonaka

and

M. Koisumi

Osaka University, Sakai.

A great deal is known on the natural remanent magnetization of volcanic rocks and a number of experiments is also reported on their thermoremanent magnetization. Considerably less is known either on natural or thermoremanent magnetization of plutonic rocks, since the way of acquisition of magnetization in this kind of rocks is not simple compared with that of volcanic rocks and there are several factors which have influence on the direction and the intensity of the magnetization. Among them, one of the most important seems to be the effect due to pressure which had worked on the rocks at and after the time of formation.

To examine this effect experimentally, was measured the remanence of a single crystal of magnetite and α-haematite magnetized on cooling through their Curie points under the application of various magnitudes of hydrostatic pressures up to 1 kb in the geomagnetic field. The direction of the remanent magnetization obtained in this way was parallel to that of the geomagnetic field but the intensity decreased with the increase of the applied pressures and it came down to nearly one tenth of the ordinary thermoremanent magnetization when the pressure exceeded over 0.5 kbars.

Mitsuko Ozima: (1) Two years ago I found a nice correlation between the intensity of NRM of granite and the grain size distribution of magnetite crystal contained in granite, i.e., granite which has an intense and stable NRM contains many small grains of magnetite ($d < 0.005$mm) as well as large grains.
(2) As Verhoogen pointed out, it will be important to examine the effect using polycrystals. I think that magnetite crystal does acquire TRM in any direction other than in [111]. Actually we can produce TRM in any direction of magnetite single crystal.

Kume: (1) The mechanism of the acquisition of t.r.m. in plutonic rocks is more complicated than that in volcanic rocks, and there are several factors which control the intensity of t.r.m. of plutonic rocks. The size of grain seems to be one of them. In some cases, however, the effect of pressure can be the most important and I have just mentioned an example of this kind.
(2) No polycrystalline magnetite was used here, because we wanted to treat the results as simple as possible. When we come to some conclusion on the single crystals, we would like to extend the experiments to the polycrystalline.

Rikitake: In Matsushiro area we have observed changes in the geomagnetic field in association with seismic activity. Combining pressure effect and actual geomagnetic observation, we would have a way of estimating mechanical stresses within the earth.

Kume: Experimental results should be applied to phenomena observed in nature, and your suggestion seems to be very important and interesting to me. We wish to know more detail on this matter and work out your result from the experimental point of view if possible.

Fuller: Domain pattern observations have been reported which suggest that at very low pressures small reversible wall movements dominate. However at pressures which are still comparatively small (a 1 kbar for magnetite) the whole domain configuration changes irreversibly.

Kume: As you suggest, the internal stress alters its distribution when a material is compressed. It follows an irreversible change in physical properties. Our present results of the decrease of t.r.m. are partly due to this mechanism and therefore thermal annealing in prior to each pressure experiment is inevitable procedure to obtain reproducible results.

(28) PALEOMAGNETIC STUDIES OF THE CRETACEOUS GRANITIC ROCKS IN NORTH-EASTERN JAPAN

Yoshio Kato and Isao Muroi

Tohoku University, Sendai.

Recently K. Kawano and Y. Ueda of the Institute of Mineralogy, Petrology and Economic Geology, Tohoku University studied the K-Ar dating of the granitic rocks in Kitakami, Abukuma and Asahi Massifs in north-eastern Japan.

Most of these granitic rocks intruded during cretaceous. The K-Ar age of granitic rocks in Abukuma Massif is 100 million years, that of granitic rocks in Asahi Mountain, ranges from 85 to 61 million years and that of Kitakami Massif, ranges from 119 to 107 million years.

The authors collected these granitic rocks from same places and investigated the direction of the remanent magnetization of there granitic rocks. The direction of NRM of each specimen are scattered but the mean directions of NRM of these specimen seem to be significant, and we calculated that mean pole positions and compared with the other results obtained by various investigators.

(29) REVERSALS IN JURASSIC-CRETACEOUS PLUTONIC ROCKS IN THE SIERRA NEVADA, CALIFORNIA

R. T. Merrill, C. S. Gromme*, J. Verhoogen

University of California, Berkeley

and

N. Kawai

Osaka University, Toyonaka.

Extensive experimental work to determine the origin of mixed magnetic polarities observed in specimens from the Buck's pluton (late Jurassic) of the Sierra Nevada mountains in California has been recently completed at the Universities of California and Osaka. Results from a. c. demagnetization, thermal demagnetization, and direct analysis of the mineralogy are interpreted to indicate field reversal, as recorded in the core of the pluton, plus self-reversal in its outer portion. From microscope observations, electron probe analysis, and Curie temperature measurements, the magnetic minerals of the self-reversing zone are found to be ilmenohematite (10% to 15% ilmenite in solid solution with hematite), and pure magnetite. The magnetic moments of these two minerals are nearly anti-parallel as determined by magnetic measurements on specimens which have been etched in concentrated HCl. Low temperature oxidation of hemoilmenite through the order-disorder transformation which separates ferromagnetic from antiferromagnetic befavior to ilmohematite may have been the cause of this paleo-self-reversal.

* Now at U.S. Geological Survey, Menlo Park.

Coe: I think more tests, such as the etching experiment of Dr. Kawai, which identify in which minerals the TRM resides, would be of great use in paleomagnetism.

(30) TECTIONIC SIGNIFICANCES OF PALEOMAGNETIC RESULTS OF SOME KOREAN CRETACEOUS ROCKS

J. Kienzle and L. Scharon

Washington University, St. Louis.

Samples were collected from 5 different areas in South Korea in Cretaceous andesites, dacites, and rhyolites. After partial ac demagnetization the calculated mean virtual geomagnetic pole was 73.9°N and 140.6°W. Comparison of this result with late Paleozoic and Mesozoic VGP's from Japan indicate that southwest Japan has rotated about 15° clockwise and northeast Japan has rotated about 40° counter-clockwise relative to Korea. The corrected VGP's for Japan and the Cretaceous VGP for South Korea group very well but are 10° to 20° from Mesozoic VGP's for North America and the Asiatic mainland. This might indicate possibly a post-Cretaceous movement of Korea as well as further movement of Japan.

Dalrymple: What is the basis for the Cretaceous age assigned to your Korean rocks?

Scharon: The geological map and report prepared by Gallagher and Chong (1946). The former you know is from the U.S. Geological Survey at Menlo Park, California.

Minoru Ozima: In connection with the question of Dalrymple I should like to report that we dated a biotite schist and a granite not far from sampling site number 2 (Pohang area). The former is believed to be Precambrian and the latter to be Cretaceous. The K/A ages are 15×10^8

yrs. for the former and 1.7×10^8 yrs. for the latter.

Scharon: I am not sure of the exact location of the area Dr. Ozima refers to but I can say that throughout central South Korea there have been mapped belts of granites and schists dated on field evidence as Precambrian. At the same time granites occurring in the same general area have also been assigned as Cretaceous in age. In our case we had to resort to geological correlation of the igneous rocks in relation to sedimentary rocks and their fossil content. I should also make it clear that in the areas of Cretaceous rocks we avoided sampling granites and confined our sampling to andesites and dacite. Thus the K/A dates determined by Dr. Ozima do not deal with the Cretaceous rocks we sampled and as defined by Gallagher and Chong. If such age dates have been or are in the process of being determined it would be well for the paleomagnetic program that some correlation of effort be made. I propose therefore that geologic maps of our sampling areas in Korea be made available to Dr. Ozima with the hope that such radiometric age-dating may coincide with the rock magnetic sample sites where at all possible.

(31) PRE-TERTIARY PALAEOMAGNETIC RESULTS IN THE CIRCUM-PACIFIC AREA; JAPAN, KOREA, CHILE, MEXICO AND ALASKA

N. Kawai, K. Hirooka

Osaka University, Toyonaka,

K. Yaskawa

Fukui University, Fukui,

H. Domen

Yamaguchi University, Yamaguchi

and

H. Ito

Shimane University, Matsue.

To carry out pre-Tertiary palaeomagnetic study in the countries around the Pacific Ocean, Cretaceous, Jurassic and some Carboniferrous red sediments and black shales as well as granites were first sampled from Korea (1964).

Then the collecting trip was extended to the other side of the Pacific Ocean, such as Chile (1964), Mexico and Alaska (1965). Various volcanic rocks, granites and sedimentary rocks in age ranging from Palaeozoic to Mesozoic were obtained from there.

Measurement of the N.R.M. of those rocks was followed. While, A.C. and thermal demagnetization in a non-magnetic space produced by means of -metal box are now in a stage of advance.

Although the study is still too preliminary to be published, we obtain conspicuous discrepancies inbetween the respective pole positions and the pole wondering paths obtained from various places. Of them, however, some can be explained on a basis of geotectonic disturbances which have been taken place at the late Mesozoic epoch around the Ocean.

(32) DRIFT OF THE HONSHU ISLAND AS INFERRED FROM CRETACEOUS PALAEOMAGNETISM IN SOUTHWEST JAPAN

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Palaeomagnetic studies on Cretaceous volcanic rocks in S.W.Japan have been carried out during the term of the U.S.-Japan scientific cooperation on palaeomagnetism. The results so far obtained have been summarized.

Most of rocks were taken from the various kinds of rock-bodies with different stratigraphic horizon and the N.R.M. of about 250 specimens from 27 sites was measured by an astatic magnetometer. As the result of termal- or ac-demagnetization test, almost all N.R.M.s of specimens were confirmed to be reliable as a fossil magnetization excepting some diorite specimens.

By connecting the mean Cretaceous pole obtained from S.W.Japan (long.=157W, lat.=44N) with that of the Palaeogene (155W, 64N) previously reported by the same authors, we have got the polar wandering path ranging from Cretaceous to recent. When we compare this Cretaceous palaeomagnetic pole with those calculated from the published data in the Asiatic mainland (160E, 62N) and North America (167W, 67N), a significant departure of the former from the latter is evident. One of the simplest interpretation of the fact may be that a considerable drift of the Honshu Island relative to the Asiatic mainland was required in order to reconcile their different two results, and that some 30 degrees' clockwise retation of the island relative to North America was sufficient to account for the discrepancy between their poles.

The probable drift of the island, accompanying simultaneous rotation of more than 40 degrees, from its possible ancient situation is computed in some detail.

Considering from a number of late Tertiary palaeomagnetic investigations in Japan, it appears certain that the mean palaeomagnetic pole at that time was in good agreement with the present geographic pole. Therefore, such a drift of the Honshu Island had been completed for the most part until early Miocene, to establish the present situation of the island.

The distance and duration of the drift can be estimated at 1,500 km and 80m.y. respectively, and thus resulting mean rate of 2cm/year is nearly comparable to those of the other continents so far estimated and reported by several authors.

Another important result to be mentioned is that a prominent reversal of N.R.M. was found throughout 1,000m thickness of the Akoh Formation, being correlated stratigraphically to middle Senonian in age.

Kume: It is one of the most important fact for interpretation of Honshu island to consider the geological evidences.
For example, between South Korea and S.W. Japan, Prof. K. Ichikawa suggested me that the so-called Kammon red shale group was almost same age that of South Korea.
If we considered the Honshu drift, this fact become very important for geological evidence.

Sasajima: Thank you very much for your valuable comment.

Uyeda: Marine geophysicists now suggests Japan Sea is a rift and Japanese Island driffed South ward.
What is your opinion as to this, Dr. Kuno?

Kuno: The geology of northeastern Korea and eastern Siberia is not similar to the geology of the Japan Sea coast of Japan. It is still difficult for geologists to accept Murauchi's suggestion about the south east ward movement of the Japanese Islands.

(33) POLAR WANDERING AND CONTINENTAL DRIFT IN THE MESOZOIC

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A sufficient number of paleomagnetic pole positions has now been obtained from late Mesozoic rocks of North America to indicate that from about 138 m.y. ago to about 84 m.y. ago (Early and early Late Cretaceous time) polar wandering did not occur. Conversely, during the interval from about 200 m.y. ago to about 138 m.y. ago (Late Triassic and Jurassic time) apparent polar wandering relative to North America occourred at rates of the order of 6 cm/yr or more. It has been shown by other workers that relative to Australia apparent polar wandering was negligible from Early Permian time until early Tertiary time, and that relative to the African continent significant polar wandering occurred between Early Permian and Late Triassic time but was absent during the interval from the beginning of the Jurassic until mid-Cretaceous time. Thus during Mesozoic time the periods of rapid apparent polar wandering are not at all synchronous for these three continents, which appears to indicate that apparent polar wandering was due entirely to continental drift.

Nairn: In a earlier (single) examination of the succession of virtual pole positions it seemed that the periods of maximum displacement occurred at different time on different continents, hence drift was a more or less continuous process.

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Can you see any possibiluty that is true in your detailed analysis?

Grommé: It appears that there was a long period of time in the Mesozoic during which displacements of North America, Africa, and Australia did not occur. It is not yet clear whether all other continents were also apparently stationary of that time. Thus it is still possible that, considering all continents together, drift may be a continuous process, but drift of single continents is clearly not continuous.

Coe: 1. Didn't earlier interpretations of paleomagnetic data of the Paleozoic require polar wandering for continental reconstructions?
2. Is there not evidence of polar wandering in the consistency of "polar wandering curves" determined for the different continents?

Grommé: 1. Yes, for exact and unambiguous reconstructions.
2. Older polar wandering curves for North America need to be revised; when this is done, consistency among curves for various continents during the Mesozoic seems not to exist, Paleozoic paleomagnetic data are not yet sufficiently detailed, especially with respect to the exact ages represented by pole positions, and the similarites of polar wandering curves during Paleozoic time from various continents may turn out not to be real.

(34) PALAEOMAGNETISM OF SEAMOUNTS IN THE WESTERN PACIFIC AND SOME VOLCANOES IN JAPAN

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Assuming the uniformity of magnetization, the direction and intensity of magnetization of nine seamounts in the western Pacific off coast of Japan have been computed from the topographic and magnetic surveys. Except for the cases of the two easternmost seamounts, the palaeomagnetic poles tend to cluster in the North Atlantic:average palaeomagnetic pole of three seamounts in the Pacific Basin is at 56° N, 65° W which agrees in latitude with the average pole position 51° N, 14° W obtained previously from another group of four seamounts : a group of three seamounts west of the Izu-Bonin Arc (Shikoku Basin) gave an avrage pole position of 74° N, 53° W. The difference in latitude between the pole positions of the group within and outside the Pacific Basin can be interpreted as caused by a northerly drift of the Pacific Ocean floor since Cretaceous times. Radiometric age of the dredged rock samples indicated a Cretaceous origin of the seamounts studied. Same method of analysis has been applied on three Japanese active volcanoes over which aeromagnetic surveys had been made. Among these cases, two volcanic islands, Oshima and Sakura-Jima Volcanoes gave the palaeomagnetic pole positions not far from the present pole. Inland volcano, Volcano Aso, seems to present difficulties in satisfying the assumption of isolated body.

Detailed information regarding the present work will be published in the Bull. Earthquake Research Institute, Univ. of Tokyo.

Kono: Is there any appropriate reason to assume that a seamount is magnetized uniformly from some certain level upward and non-magnetic below this level? Is there considerable amount of change in results if you take other models?

Uyeda: There is no sufficient reason. But numerical experiments done by Richards and others (1966) on Hawaiian Seamount showed that the directional change due to various assumptions regarding the depth of the bottom of the seamount is only several degrees.

Heinrichs: Does your suggestion for northward drift for the Pacific Ocean floor include a "model" for the linear anomalies?

Uyeda: No. But the present suggestion is very general and if it is compatible with "models" of lineations will be a future problem.

Strangway: Do any of the seamounts have a reversed magnetization? This could be a test for bias in the calculations due either to a VRM or a susceptibility effect.

Uyeda: Yes, three seamounts off California studied by Richards et al. (1966) are magnetized reversely.
According to Mrs. Ozima's measurement Q-ratio of the basalts from the seamount is very high (>40).

Fuller: Is there any evidence of features such as Mendocino in the western Pacific?

Uyeda: As far as we have surveyed, no.

Mituko Ozima: I examined magnetic **properties** of basalts dredged from those sea mounts. Q ratio ($J_N/\chi H$) measurement of all those basalts gives an usual value of 40 50 as volcanic rocks in land.

Kuno: If we look at the geologic map of Japan, we can notice that the Sanbagawa crystalline schist belt (upper Cretaceous) is traversed a fault now hidden underneath the bay of Ise-wan south of Nagoya City. The fault appears to trend from north to south, and the schist belt on the eastern side of the fault has moved northward relative to its western side. Most of the active faults in Japan which moved during the last century strike north-south or northwest-southeast, and are left lateral. So we have some indication that the Pacific Ocean side of the island arc has moved northward relative to the other side since younger Cretaceous. San Andrews fault in California is right-lateral, suggesting that the Pacific Ocean moved northward.

Dalrymple: Would you tell us about your K-Ar age determinations on the seamounts? In particular, I would be interested in the petrography of the basalts-if there is any alteration or glass in them- and whether or not you think the ages are reliable.

Minoru Ozima: In the attached table, I show the results of K-A dates of sea mounts. As indicated in the table, DR-1, 2, 8 are rather badly altered and the ages may not be very reliable. DR-6 has, however, rather fresh plagioclase. The age obtained for plagioclase does not differ from that for the total rock. We feel that the plagioclase age may give a fairly good measure of the true age of DR-6.

K–A ages of basalts dredged from sea mounts in the Eastern Pacific

Samples	Rock type	mafic, plagioclase minerals		Whole rock age					Mineral age				
				$K(\%)$ 1)	$(A^{40})^{*}$ 2) moles/gr	$(A^{40})^{*}/A^{40}$ (%)	$(A^{40})^{*}/K^{40}$ 3)	t (y)	$K(\%)$ 1)	$(A^{40})^{*}$ moles/gr	$(A^{40})^{*}/A^{40}$ (%)	$(A^{40})/K^{40}$	t (y)
DR 1-a	Thole b (?)	×	△	3.44	4.497×10^{-10}	78.5	4.295×10^{-3}	72×10^{6}					
-b	〃	×	△		4.44×10^{-10}	80.2	4.241×10^{-3}	72×10^{6}					
DR 2-a	Thole b (?)	×	△	0.627	2.852×10^{-11}	30.2	1.495×10^{-3}	25.3×10^{6}					
DR 6-a	Alk.Olv. b(?)	△	○	0.829	9.536×10^{-11}	60.8	3.780×10^{-3}	63.5×10^{6}	0.216	3.0547×10^{-11}	11.0	4.647×10^{-3}	79.2×10^{6}
-b	〃	△	○	0.876	11.82×10^{-11}	75.2	4.434×10^{-3}	74×10^{6}					
DR 7-a	Thole b	△	○	1.399	2.233×10^{-10}	89.4	5.245×10^{-3}	87.3×10^{6}					
-b	〃	△	○	1.384	2.414×10^{-10}	79.0	5.731×10^{-3}	95.5×10^{6}					
DR 8-a	Thole b	×	△	1.824	5.982×10^{-11}	26.5	1.078×10^{-3}	18.2×10^{6}					

○ ······· fresh
△ ······· partly altered
× ······· completely altered

} after I. Kushiro's microscopic observation

1) determined by isotope dilution method.
corrected for $\sqrt{m_1/m_2}$

2) $\lambda_e = 0.585\times10^{-10}$ y
$R = 0.124$

3) $K^{40}/K = 1.19\times10^{-4}$ moles/moles.

The significance of this result is that it suggests that at least some of the very scattered British Carboniferous virtual pole positions, if not entirely due to secondary magnetization, might be due to tectonic causes. By logical extension it may prove to be general that highly scattered virtual pole positions may at least in part be a reflection of tectonic history. If such be the case then it has obvious implications for the interpretation of continental displacement.

Strangway: Do your data from Europe still indicate that all Permian and Lower Triassic and Upper Carboniferous rocks are reversely magnetized?

Nairn: In general terms our results from Europe indicate no normal direction above Westphalian B/C, the lowest horizon we have studied in detail. In the lower Carboniferous normal directions do appear to occur although reliable data is still scanty.
The European Permian data is primarily reversed, although it must be remembered that in western Europe at least all the Permian rocks studied have been of lower Permian age. Upper Permian results from Russia are also reversed although at the highest Permian or lowest Triassic, there is I believe some age doubt, normal directions appear. Within the lower Triassic normal directions are common.

Nairn: The principal result of the detailed study of restricted areas of Upper Carboniferous rocks has been to indicate significant differences in the mean direction of magnetization of rocks of the same age. As both sets of data represent directions after magnetic cleaning, and as such are called stable, the obvious interpretation seems to involve relative rotation, since for a

variety of geological reasons, Permian overprinting can be ruled out.
If, at the centre of the European continental block, evidence of differential movement can be found, then direct continental comparisons cannot be carried out for it means that the effects of tectonic movement must be recognised and removed before directions from older rocks can be used. From this point of view all older results must be regarded with caution and it may be dangerous to assume that measurements made in Britain automatically represent Europe as a whole. The method used by Grommé, Doell and others, as discussed at this meeting of working backwards to progressively older rocks seems to offer the most secure results with caution however I still believe that the "polar wandering" curve, which is after all only a succession of virtual pole positions, has value, and that Hales and Helsley's arguments using such curves to try and find unique continental assemblages is still valid.