THE ORIGIN OF REMANENT MAGNETISM IN SEDIMENTARY ROCKS

by

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ABSTRACT

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A method for producing artificial red sandstones was followed to find out whether a remanent magnetism was associated with this process. The process consisted of growing a coating of red ferric hydroxide on grains of sand or other material while under the influence of the earth's magnetic field. A remanent magnetism was indeed produced by this process, and the direction of this magnetism followed rather closely the direction of the earth field acting during the coating process if the grains being coated were spherical or randomly oriented, but could be made to differ significantly from the direction of the earth field if the grains were strongly anisotropic in shape and had some preferred orientation. From the nature of the magnetism and the conditions under which it was produced, the mechanism of magnetization commonly called "chemical magnetization" was clearly indicated. The effect of these findings on the interpretation of existing paleomagnetic data has been considered.

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Biography

The author, David Greenewalt, was born on March 26, 1931, in Wilmington, Delaware. He attended Tower Hill school in that city from 1934 to 1935, and from 1936 with 1945. He then entered Kent School in Kent, Connecticut, from which he was graduated in June of 1949, receiving upon graduation the English and the Physics prizes. He then entered Williams College, graduating in June of 1953, and receiving a degree with honors of Master of Arts.

During the summer of 1953, the author worked as an electrical engineer for the duPont Company in Wilmington, Delaware.

In September of 1953, the author entered the Massachusetts Institute of Technology, where he has held an assistantship in the Rock Magnetics Research Project.
Glossary of terms

Some of the terms used in this paper are peculiar to the subject, or are used in a special way by those engaged in the study of rock magnetism and paleomagnetism. For this reason, a glossary of terms is included here. A good general reference is Takisi Nagata's Rock Magnetism, 1953.

**Saturation magnetization:** the maximum intensity of magnetization acquired attainable by a ferromagnetic material in an external field of any intensity.

**Remanent magnetization:** the permanent magnetization of a material in the absence of an external field.

**Coercive force:** the magnetic field required to reduce remanent magnetization to zero after saturation magnetization has been achieved in the opposite direction.

**Domain:** a volume of ferromagnetic material within which the magnetization is equal to the saturation magnetization.

**Single domain grain:** a grain of ferromagnetic material sufficiently small so that it is energetically economical for it to be one domain rather than multidomain. For iron, a single domain grain is on the order of $10^{-6}$ cm. in diameter, and for magnetite, about $10^{-5}$ cm.

**Curie point; Curie temperature:** the temperature at which a material ferromagnetic at lower temperatures becomes paramagnetic.
Thermo remanent magnetization; TRM: remanent magnetization acquired by the cooling of a ferromagnetic material from a temperature above the Curie point while under the influence of a magnetic field.

Partial thermoremanent magnetization; PTRM: magnetization acquired by cooling an aggregate of fine grains of magnetic material through some temperature interval while under the influence of a magnetic field.

Isothermal remanent magnetization; IRM: remanent magnetization acquired in any unsaturated hysteresis loop, when the whole process is carried out at room temperature.

Depositional magnetization: remanent magnetization acquired by the physical alignment of already permanently magnetized particles of a sediment by an external magnetic field while they are free to move, as when in suspension in water. Permanence is attained when these particles are restricted in movement by their incorporation into the rest of the sedimentary material. A magnetization associated only with sediments and sedimentary rocks.

Chemical magnetization; CRM: remanent magnetization acquired by grains of magnetic material growing under the influence of an external magnetic field.

Total thermal demagnetization: the removal of remanent magnetization by heating to a temperature above the Curie point and cooling in zero magnetic field.
Partial thermal demagnetization: the removal of some of the remanent magnetization by heating to a temperature below the Curie point and cooling in a zero magnetic field. Sometimes used to remove less stable components of magnetization.

Alternating field demagnetization; a.c. demagnetization: the removal or partial removal of remanent magnetism by an alternating field slowly decreased to zero. A complete but relatively unavailable treatment of this subject as applied to rocks is given by Rimbert (1959).
SUMMARY

THE REMANENT MAGNETIZATION OF ARTIFICIALLY PREPARED RED SANDSTONES

The origin of natural remanent magnetism in red sandstone, a rock commonly used in paleomagnetic studies, is not clearly understood. Blackett (1) has suggested that the chemical process which causes the red coloring of these sandstones is also responsible for their magnetization. This suggestion might be strengthened if that coloring process could be reproduced artificially.

One such process for producing red coloring artificially in sands has been described by Lord Rayleigh (2), and preliminary measurements indicate that this process also gives rise to a remanent magnetization.

The process consists of moistening sand or other grains with a ferrous bicarbonate solution similar to, but more concentrated than naturally occurring chalybeate water. The solution is dried at a temperature of about 50° C, and the alternate wetting and drying is repeated several hundred times. When carried out in the magnetic field of the earth, a measurable remanent magnetism is produced, as well as the red ferric hydroxide grain coating reported by Lord Rayleigh.
Two kinds of samples have been artificially colored by the method described, in order to investigate the resulting direction of magnetization. One kind of sample was made of grains either spherical or, if aspherical, randomly oriented. The grain diameter of these samples was either .5 mm. or 3 mm., and most samples were 1 cubic inch in volume. The directions of magnetization of these samples along with the direction of the earth's field acting during the chemical process are shown in Fig. 1a, an equal area projection. Overall errors in orientation and measurement can account for about 10° of the scatter.

Another kind of sample was made of thin, flat, parallel plates, each slightly separated. About 90% of the total surface area of these samples was parallel to the planes of these plates. These samples were oriented during the coating process with the strike of the plates always perpendicular to the magnetic field, but with dips at 15° and 25° north, vertical, 80°, 75°, and 60° south. Three samples were coated in each orientation. The directions of magnetization of these samples deviated less than 5° from the vertical north-south plane, and are shown projected on that plane in Fig. 2a. In this figure, the fine lines represent the dip of the plates for each sample orientation, the
heavy arrow shows the direction of the earth's field, and the short arrows are the average (of three) directions of magnetization of the samples for each sample orientation. It can be seen that the directions of magnetization lie between the direction of the earth's field and its projection upon the plates of the sample; closer to the latter than the former.

It appears, therefore, that the chemical process described by Lord Rayleigh for the origin of color in red sandstones also produces a remanent magnetization, as suggested by Blackett. This magnetization will indicate with some precision the direction of the field acting during the chemical process if the grains being coated are randomly oriented and/or of high sphericity. If, on the other hand, the grains are strongly aspherical and have some preferred orientation, the magnetization may deviate in direction from that of the earth's field acting during the chemical process.

While it is not known to what extent the process of coloring suggested by Lord Rayleigh resembles that process for natural red sandstones, this work strengthens Blackett's suggestion for the origin of magnetization of red sandstones, and further suggests a circumstance in which systematic deviation of the direction of magnetization from that of the earth's field during magnetization could occur.
REFERENCES

(1) P.S.M. Blackett  Lectures on Rock Magnetism,
Weizmann Science Press, Jerusalem,
(1956)

(1946)
Fig. 1a
Isotropic Samples

Earth field direction at center of large circle; circle is 10° in radius
Fig. 2a
Flat-grained Samples

Average directions of magnetization for each set of samples in the same orientation are projected on the vertical, north-south plane.

Magnetic field direction: long heavy arrow
Dip angle of plates: long fine lines
Directions of magnetization: short arrows
Introduction

The Remanent Magnetization of Red Sandstones

While both igneous and sedimentary rocks are used in paleomagnetic studies, sedimentary rocks offer the advantages of clearer bedding planes, essential for restoring the bed to its original geologic attitude, and better age correlation of widely separated beds, while igneous rocks are more strongly magnetized, making measurement easier, and the origin of their magnetism is better understood. Of the sedimentary rocks, red sandstones are probably the most commonly used by paleomagnetists, as, for instance, the work of Irving and Creer (1955) on both the Old Red and New Red sandstones of England, Runcorn's (1956) work on the Supai formation of Western North America, and Bowker's (1960) investigation of the Triassic sandstones of the Eastern United States. The main reason for this use of red sandstones seems to be that they usually have a sufficient intensity of remanent magnetization to make them measurable with relative ease and accuracy. Whether they are in other ways suitable for paleomagnetic study, however, has not been clearly determined.

For the remanent magnetism of any rock to be useful in locating the past position of the earth's magnetic field, that magnetism must have been acquired (1) during or soon after the rock was formed, (2) in a direction parallel to the magnetic field then acting, and (3) the direction of that magnetization must have remained unchanged since that time.
An estimate of the extent to which various rock types fulfill these three requirements is of importance both in selecting rocks for future study and in evaluating existing data. It is usually helpful in making such an evaluation to know the mechanism by which a rock became magnetized. Knowledge of this mechanism is at present extremely limited for red sandstones, although two theories have been proposed to account for their magnetization. According to one of these theories, magnetic particles included in the sedimentary material are aligned during deposition by the acting magnetic field. This process is considered typical of varve clays, and has been described by Johnson, Murphy and Torreson (1948), and by Graham (1949), and carried out artificially by King (1955). Both field evidence and laboratory experiments indicate that the inclination of the magnetic moment acquired in this way will not always be parallel to that of the influencing field, thus violating condition (2), although in a somewhat predictable way. A coarser-grained rock magnetized by this means is also described by Graham (1949), but this rock proved to be magnetized randomly.

The other process, generally called Chemical Magnetization, has been suggested by Doell (1956), Blackett (1956), and Martinez and Howell (1956) as a process which could cause magnetization of sedimentary rocks, and, according to Blackett, particularly red sandstones. Blackett has suggested that the
chemical changes which produce the red coloring of these rocks are also responsible for their magnetization. Artificial reproduction of this process, were it known, should be useful both in determining the connection between magnetism and coloring matter, and in observing the distinguishing features, reliability, and general behavior of chemical magnetization.

Before investigating the particular problem of chemical magnetization in red sandstones, it is of interest to review the general theory of chemical magnetization, and then see to what extent it sheds light on the case of red sandstones.

Theoretical Aspects of Chem. Magnetization

Haigh (1958) has given a brief discussion of the theory of chemical magnetization, based principally on the theory for thermo remanent magnetization of small grains derived by Neel (1949). This theory shows how the chemical magnetization could occur, and how it would be affected by changes in certain variables. The discussion that follows is essentially that given by Haigh:

Two magnetic properties of very small grains appear to be dependent on the size of the grains. These are the coercive force and the relaxation time.
The dependence of coercive force on grain size has been observed experimentally by Kopelman (1952), Meiklejohn (1953) and Becker (1957), for some magnetic materials. As grain size decreases, coercive force increases to some maximum value, and thereafter decreases again. Such behavior has been observed for iron and cobalt grains, and the coercive force of magnetite grains has been observed to increase with decreasing grain size, but the process has not been carried farther. Other magnetic materials are thought to behave in this manner, but actual values of coercive force for a given grain diameter are unknown. Very small magnetic grains could possibly have a coercive force of the same order of magnitude as the magnetic field of the earth. This condition may or may not be sufficient to cause magnetization of a grain by the earth's field, as will be shown by a consideration of the relaxation time of the grain.

In a discussion of the relaxation time of a grain, it is most convenient to consider a single domain grain with one long axis. The magnetic moment of such a grain can have two orientations, making an angle of either 0 or \( \pi \) with the long axis of the grain. The relaxation time is a measure of the amount of time that the magnetic moment will remain in one orientation before thermal fluctuations cause a spontaneous change in its direction. Neel has derived an
expression for the relaxation time, $\tau_o$, in the absence of an external field, as follows:

$$\frac{1}{\tau_o} = Ge^{-\frac{H_c J_s v}{2kT}}$$

(1)

where $H_c$ is the coercive force of the grain material, $J_s$ its saturation magnetization, $k$ is Boltzmann's constant, $T$ the absolute temperature, and $v$ the volume of the grain. The value of $G$ is as follows:

$$G = \frac{\epsilon H_c}{2m} \left(30\lambda + DJ_s^2\right) \left(\frac{2v}{\pi GkT}\right)^{\frac{1}{2}}$$

(2)

where $\epsilon$ and $m$ are the charge and mass of the electron, $G$ is the shear modulus, $\lambda$ is the longitudinal magnetostriction at saturation, and $D$ a constant dependent on grain shape, and equal to about 3.

From these equations, it can be seen that the relaxation time for a given material depends on $v/T$, and very critically, too. Neel has calculated some relaxation times for grains of iron, and finds that for $\tau_o = 10^{-1}$ sec., $v/T = 3.2 \times 10^{-21}$, while for $\tau_o = 10^9$ sec., $v/T = 7.0 \times 10^{-21}$. This range of $v/T$ might be called the critical range, i.e. the range in which $\tau_o$ goes from fractions of seconds to years. It is
of interest to note that at room temperature, this range of
grain diameter is from \(120\,\text{Å}^0\) to \(160\,\text{Å}^0\). Neel used a value
of \(H_c = 1000\,\text{Oe.}\) for this calculation, but from experimental
observations of the variation of \(H_c\) with grain size discussed
earlier, it appears that the coercive force is somewhat less,
as it reaches its peak value at a grain diameter of \(200\,\text{Å}^0\).
This will not alter the results greatly, however, and at
room temperature, the critical grain diameter should be only
slightly larger than that given above (since in this range
\(v/T\) varies inversely with \(H_c\), then at constant temperature
diameter will vary inversely as \(H_c^{-1/3}\)). For iron, the
region in which coercive force is comparable to the earth's
field is also a region where \(\tau_{\text{rel}}\) will be very short, so
that permanent magnetization could not be achieved in this
way by weak fields.

A similar calculation of the relaxation time for magnetite
grains shows that in the critical range, \(v/T\) is on the order
of \(10^{-19}\), so that at room temperature, grain diameter is
about \(200\,\text{Å}^0\). The actual value of \(H_c\) for this grain diameter
is unknown.

If a magnetic field \(h\) exists parallel to the long axis
of the grain, then it will have two relaxation times; one,
\(\tau(0,\pi)\) corresponding to movement of the magnetic moment
from 0 to \( \pi \), and the other, \( \tau(\alpha,0) \), for opposite movement of the magnetic moment. These are given as follows:

\[
\frac{1}{\tau(0,\pi)} = c\left(1 + \frac{h}{H_c}\right)\left(1 - \frac{h^2}{H_c^2}\right) e^{-\frac{-vJ (H_c+h)^2}{2H_c kT}}
\]

(3)

\[
\frac{1}{\tau(\pi,0)} = c\left(1 - \frac{h}{H_c}\right)\left(1 - \frac{h^2}{H_c^2}\right) e^{-\frac{-vJ (H_c-h)^2}{2H_c kT}}
\]

(4)

The number of grains with magnetic moments in the 0 direction relative to the number with magnetic moments in the \( \pi \) direction may be obtained from these relaxation times. If \( N_0 \) and \( N_\pi \) are the numbers of grains with magnetic moments in the 0 and \( \pi \) directions respectively, then the number of magnetic moments changing from 0 to \( \pi \) in unit time is given by \( \frac{N_0}{\tau(0,\pi)} \), while during that same time, the number changing from \( \pi \) to 0 is given by \( \frac{N_\pi}{\tau(\pi,0)} \).

Equilibrium conditions require that these two numbers be equal, or

\[
\frac{N_0}{\tau(0,\pi)} = \frac{N_\pi}{\tau(\pi,0)}
\]

or

\[
\frac{\tau(0,\pi)}{\tau(\pi,0)} = \frac{N_0}{N_\pi}
\]

(5)
Thus at any time, the ratio of the numbers of grains with magnetic moments in each of the two positions is given by the ratio of relaxation times. For $h$ positive, $\tau(0,\pi)$ will be greater than $\tau(\pi,0)$, or $N_0$ will be greater than $N_\pi$, and as $\gamma$ increases, through the critical region, more grains will become magnetized in the 0 than in the $\pi$ direction. From a rough calculation using equations (3) and (4), a 50% difference in the relaxation times would be expected when $h$ is only 0.5% of $H_c$, and thus for an aggregate of randomly oriented grains of magnetite growing in the field of the earth, one would expect considerable influence of that field on the final magnetization of the grains. For hematite grains, however, $H_c$ might well be very much larger (bulk value is given as 1000 Oe, compared to about 20 Oe. for magnetite) so that the effect of the earth field on the relaxation times would cause them to differ only slightly, and its effect on the chemical magnetization of a group of grains could be very small.

This theory of chemical magnetization shows the general process and factors influencing chemical magnetization. It also shows that for the prediction of the occurrence of chemical magnetization, a certain amount of experimental work is still needed, preferably with experimental conditions made to follow as closely as possible those conditions under which chemical magnetization is expected.
Artificially produced Chemical Magnetization

Haigh (1958) and Kobayashi (1959), working independently, have both succeeded in producing a chemical magnetization of magnetite by the process of converting small grains of \(\alpha\)-hematite into magnetite. This reduction was achieved in both cases at a temperature of around \(300^\circ\) C, and both experimenters were successful in showing that the magnetization was primarily chemical rather than isothermal or partial thermoremanent. Kobayashi gives the range of particle sizes both for hematite and for the magnetite produced from the hematite as from .1 to .6 \(\mu\), which is well beyond the size for which short relaxation times are to be expected, even at the temperature of reaction. Magnetization must have occurred as the grains of magnetite grew during the reaction, and so was of a chemical nature.

Haigh suggests that in nature, the reduction of hematite to magnetite could occur at ordinary temperatures, and it would be accompanied by a chemical magnetization. He further suggests that a chemical magnetization would occur during the growth of grains of hematite, as in red sandstone. The chemical magnetization of magnetite seems insufficient as proof that hematite may become magnetized by the same means. To take a very limited view, Haigh and Kobayashi have only shown that chemical magnetization can occur when \(\alpha\) hematite
is converted to magnetite at a temperature of 300° C, and when this original hematite is in a high concentration. If this conversion can occur at a lower temperature, given longer periods of time, the magnetization may or may not occur along with it. Other magnetic materials, with different properties, may react in very different ways to chemical changes. The chemical magnetizations produced by Haigh and Kobayashi add to the possibility that red sandstones are magnetized chemically, since their work brings that process of magnetization out of the realm of inference and into the realm of directly observable occurrence. Their process, however, is far from the sort which is likely to occur in red sandstones, since, in particular, as has been noted by Blackett (1956), these sandstones are often completely lacking in magnetite. If, on the other hand, a process could be carried out experimentally which produced a chemical magnetization, and which was similar to the process responsible for the coloring of red sandstones, then the suggestion that the magnetization of red sandstones is a chemical one would be considerably strengthened.

There appear to be various theories on the origin of the color of red sandstones, and before proceeding farther, some of these theories might well be reviewed.
The origin of red sandstones

There is as yet little agreement on the subject of the origin of red sandstones, and as has been suggested by Twenhofel (1932), these rocks may be formed through the action of a number of different environmental conditions. It seems generally agreed upon, however, that the red coloring typical of these rocks appears some time after actual deposition of the sand grains, and is a ferric oxide derived from an iron bearing solution, the latter being formed by the action of rain water on iron-bearing silicates as suggested by Raymond (1927). A magnetization caused by the ferric oxide will be of the depositioned type if the particles of the precipitate have developed a remanent magnetization before settling, and of a chemical type if they acquire magnetization after settling among or coating the sand grains.

The ferric oxide is generally thought e.g. by Nicholls (1955) to appear first in a hydrated form, typically of a yellow or yellow-brown color, and known as limonite, xanthosiderite, or goethite depending on the water content. A subsequent dehydration to turgite \( (2\text{Fe}_2\text{O}_3\cdot\text{H}_2\text{O}) \) or hematite is then necessary to produce the red color. This dehydration can be made to occur by heating the material to a temperature of over 200° C, but Crosby (1891) has suggested that given
enough time, dehydration can occur at lower temperatures. Dorsey (1926) holds a similar opinion, adding that the dehydrated form of ferric oxide is the stable one, and given enough time, dehydration will occur even under moist conditions and at normal surface temperatures.

A somewhat different view of the origin of red color in sandstones has been taken by Lord Rayleigh (1946). Near a chalybeate spring he observed a sandstone colored both brown and red, presumably by the spring water. Dehydration of some but not all parts of the sandstone seemed unusual, and partial heating of these parts to a temperature of over 200° C seemed even more irregular. He had also observed a darkening of red sandstone grains upon heating, even though some of these grains were from Pre-Cambrian sandstones, suggesting a dehydration to hematite of the red coloring matter, which had not occurred until the heating. He then set out to find by what process the red or brown coloring materials were formed, and how they differed. Using artificially produced chalybeate water, he discovered that on exposure to the air, both a yellow precipitate within the solution and a red coating on its surface were formed. Red sand grains could be produced by repeatedly moistening them with this solution, since a large surface area of solution for its volume was then presented to the air. On the other
hand, sand grains beneath the surface of a large volume of the solution would be colored yellow by the precipitate. The red sand grains thus produced were visually indistinguishable from grains of "old red" sandstone. The red and yellow materials appeared to be hydrated ferric oxides, the red containing 17.5 % water on the average, and the yellow containing 19.8 % water.

The applicability of Lord Rayleigh's process to the study of chemical magnetization

The process described and artificially carried out by Lord Rayleigh for the formation of red sandstones is well suited to the study of chemical magnetization, even if it is of minor importance in the formation of natural red sandstones. Confusion with depositional magnetization can be avoided since there is no settling of particles which could have become magnetic. Magnetic material simply grows from solution and remains in place during growth. Since high temperatures are not required, the confusion with thermoremanent or partial thermoremanent magnetization is avoided; a confusion which could be troublesome when very small grains with short relaxation times are involved. Finally, the process does not involve some event which will occur at ordinary temperatures only over long periods of time, and
so requires high temperatures if it is to be made to occur within a time reasonable for an experiment. To relate such an experimental process to a natural one would involve estimating the effect of reduced temperature on the magnetic result. Since Lord Rayleigh's process can be made to occur at a temperature almost realistic for natural processes, the difficulty of this kind of estimate is somewhat reduced.
Method for the Production and Measurement of Artificial Red Sandstones

**General Method**

A process of chemical magnetization used in this study is meant to be an imitation of a natural process. In the natural process, iron from iron-bearing silicates is dissolved by rain water, which contains carbon dioxide derived from the atmosphere. This iron-bearing solution then deposits a ferric oxide on grains of sand, usually as a grain coating. As the particles or very thin sheets of ferric oxide grow in the magnetic field of the earth, they can acquire a remanent magnetization through an increase in their volume, as described in the theory of chemical magnetization.

The imitative process carried out in laboratory conditions cannot be made exactly like the natural process. Some effort has been made, however, to conform to natural conditions when conveniently possible. The solution used, while many times stronger than ordinary natural solutions, is only a few times stronger than strong naturally occurring chalybeate waters. It is applied to sand or other grains while under the influence of only the magnetic field of the earth. Drying of the solution is hastened by use of heat, but the temperature has often been kept within the maximum recorded temperature at the surface of the earth (56° C). Thus except for time, the artificial process has not been made to differ greatly from the natural one. Duration of time, of course, has been changed by a factor of $10^4 - 10^6$. 
Solution

An iron bearing solution is produced by bubbling carbon dioxide through distilled water containing a piece of steel wool. This produces a ferrous bicarbonate solution analogous to natural chalybeate water. Using the same process, Moody (1906) has reported a concentration of \(0.225\text{g FeO/l}\) in 20 hours, \(1.39\text{ g FeO/l}\) in 26 days. Rayleigh (1946) used a solution containing \(0.138\text{ g Fe/l}\) for most of his work, and also gives a value of \(0.376\text{ g FeO/l}\) for the natural chalybeate water from Langenswalbach. The solution used here was prepared about once a week, but seemed to be somewhat stronger, averaging about \(0.6\text{ g Fe/l}\). This may have been due to the higher than atmospheric partial pressure of carbon dioxide. After bubbling through the solution, the gas was forced to bubble through 20 inches of water. This not only prevented any air from getting back into the bottle in which the solution was made, but also maintained a pressure of gas over the solution which was a convenience in drawing off solution for use. The temperature at which the solution was made was not controlled, but could not have varied far from \(20^\circ\text{C}\). The source of carbon dioxide was dry ice, slowly subliming in a Dewar flask, but depression of the solution temperature due to the cool gas flowing through it was not noticed.

On exposure to the air, ferric hydroxide begins to form from the ferrous bicarbonate solution, both as a yellow precipitate in the body of the solution, and as a red surface
coating. This oxidation probably occurs immediately, but
is not noticeable for two or three minutes at room tempera-
ture. At 50°C oxidation is apparent after about 1/2 minutes.
It was also found that the ferric hydroxide produced from
the solution could not be redissolved to form a ferrous
bicarbonate solution in the way that metallic iron (in the
form of steel wool) had originally been dissolved. That
same resistance to solution by carbonic acid was also
exhibited by both magnetite and hematite. The implication
of this finding is that a chemical magnetization produced
by the oxidation of a ferrous bicarbonate solution is not
likely to be dissolved by the action of rain water and later
redeposited.

Substance to which the solution is applied

In simulating red sandstone, the principle kind of
ferric hydroxide desired was the kind which formed on the
surface of the ferrous bicarbonate solution. The substance
to be moistened with solution had therefore to be fairly
cosre grained and porous, so that its moistened grains
would present a large part of their surface to the air.
At first, unconsolidated sand was used, and for convenience
in later handling, this had to be solidified. The solidi-
fication was done by soaking the sand with liquid parafin
after the grain coating process, and allowing it to cool and harden. It was thought, however, that there was too great a possibility of reorientation of the individual sand grains, either during the application of the solution or of the parafin, and this could cause a physical movement of the direction of magnetism of the sample. To avoid this source of error, use was made of pre-cemented material. Fire brick was found to be fairly convenient for this purpose, but was not sufficiently porous for good penetration of solution. A reduction of the sample size from 1 inch cubes to $\frac{1}{2}$ inch cubes improved the uniformity of coating, as did the drilling of several holes through the samples, but the final coating was still somewhat localized. Another form of sample used was made of glass beads 3 mm. in diameter and loosely fused into the form of 1 inch cubes. While these samples could be coated evenly, the proper fusing process was difficult and time consuming, and the samples were exaggeratedly coarse grained compared to natural sandstone.

These samples were isotropic with respect to average grain shape. It was also desired to coat samples whose grains had some average anisotropy of shape, in an attempt to represent natural sandstones containing e.g., large quantities of mica flakes whose planes were parallel to the bedding plane. A most extreme example of such a sandstone
was made by arranging thin, square glass plates so that each plate was parallel to the next and separated by 1/20 or 1/32 of an inch, and so that the whole group formed a cube. Four of the faces of such a cube would then be composed of plate edges, and to two of these faces were cemented square plates of the same kind (using an epoxy resin as a cement). A relatively structurally sound cube was thus formed, made up of parallel surfaces with each surface having free access to the air.

The samples were generally in the form of 1 inch cubes, although some of the firebrick samples were 3/8 inch cubes, and some of the glass plate samples were cubes 3/4 inch on an edge. A few samples were in the form of cylinders 1 inch long and 1 inch in diameter.

Application and drying of solution

Solution was periodically applied to the sample in small quantities as described in appendix I. Care was taken to prevent the formation of ferric hydroxide in the solution until it had reached the sample, and the quantity of solution applied was made to be just sufficient to moisten the sample, so that the grains of ferric hydroxide growing from solution remained in place throughout their growth, and depositional type magnetization was avoided. New solution was applied after the previous application had dried, and
this drying was hastened by the use of two "infra-red" lamps, usually placed somewhat above and on opposite sides of the sample to produce a fairly even temperature at least on its top surface. Unevenness of temperature in the sample was found to lead to an unevenness of ferric hydroxide coating, since a warm spot would tend to dry first, and the solution in the sample would tend to flow toward the dryer areas.

The temperature of the inside of the sample could be kept at less than 60° C if new solution was applied to the sample as soon as it had reached dryness. This temperature was measured with a mercury thermometer, the bulb of which was embedded in the sample 1/2 or 1/4 of an inch from the top surface. The top surface temperature was undoubtedly somewhat higher than that at the place of measurement, but was below 100° C as shown by the absence of boiling in small drops of water applied to the top surface of a recently dried sample. If the application of liquid was discontinued for several hours, the sample temperature rose; the maximum temperature observed being 118° C.

Several hundred applications of solution were usually made for each sample over a period of 2½ to 72 hours. The quantity of ferric hydroxide applied was weighed in some cases, and averaged about .4 g for samples 1 cubic inch in volume.
The orientation of each sample with respect to the magnetic field of the earth was observed both before and after the coating process. The direction of the magnetic field of the earth was measured both with a fluxgate magnetometer and with compass and dip needle. The latter instruments were found to be sufficiently accurate for the purpose, and within their limits of accuracy, showed no variation of the local magnetic field when observed over periods somewhat longer than the time of an experiment.

**Measurement of samples**

After a sufficient quantity of ferric hydroxide had been formed on the grains of a sample, its direction of magnetization was measured using an astatic magnetometer described in appendix II and by the method described in appendix III. Samples were usually measured within a week after coating. The accuracy of measurement for the instrument was about 2° for each sample orientation, while the accuracy of orientation of the sample both during measurement and during coating was from 2 to 10°.

Measurements of direction were made with respect to all three mutually perpendicular axes of the sample, and these angles were plotted on an equal area projection to give the resultant magnetic direction of the sample.
Results of Measurements

Results, general

In general, the samples made of grains isotropic with respect to average grain shape developed a magnetic moment parallel to the direction of the earth's field acting on them when coated by the method described. The results of this are shown in fig. 1, which includes all the samples of this kind made, including the crude first attempts. The directions of magnetization of these samples are given numerically in Table I.

The "flat-grain" samples were oriented in the field of the earth so that the strike of the grains was in the east-west direction, and the dip at various angles from 15° N to 65° S. The magnetic direction of these samples was not parallel to the direction of the field acting at the time of coating, but lay in the plane defined by the magnetic vector and its projection upon the flat grains, and at an angle of less than 20° from the grain surfaces. The directions of magnetization of these samples are shown in figures 14-16, and are given numerically in Table I.
Results of individual samples

Samples 1-8 were made principally to see whether and in what way a chemical magnetization could be produced, and so were not oriented with great care. They were made from various materials including rather dirty sand, crushed glass, crushed quartz, and glass beads. Samples 2, 3, and 4 were made of particles contained in a glass tube $\frac{1}{2}$ inch i.d. and $\frac{1}{2}$ inch long, and after coating, square pieces of cardboard were glued to the ends to keep the sand grains in place. Reorientation of some of the coated sand grains undoubtedly occurred during transportation and measurement. The other samples were solidified with liquid paraffin. Orientation accuracy for these samples could not have been better than $10^\circ$. The magnetic directions are shown in fig. 2.

Samples 9-17 were coated in one block $3 \times 3 \times 1$ inches, lying flat. This block was made of unconsolidated sand grains about .5 mm in diameter, washed and ignited, except for the central cube which was made of glass beads 3 mm in diameter. The whole block was solidified after coating, and cut into 1 inch cubes for measurement. For samples cut from a larger block, the numbering convention adopted has been as one reads, i.e., from left to right and from top to bottom if the sample block is viewed from the top with the north edge farthest, and the south edge closest to the viewer. The whole block
was oriented to within about 3° of the position given, but individual cubes were cut only to about 6°. The magnetic directions of these samples are shown in fig. 3. The direction of magnetization of the large-grain block does not differ markedly from the small-grain ones. The scatter of this group is somewhat greater than the accuracy of measurement; a feature observed in most of the later sample group.

Samples 18, 19, 20 were made of glass beads 3 mm in diameter, fused roughly into the form of 1 inch cubes. They were coated individually in a field about twice as strong as the magnetic field of the earth, which was produced with two permanent magnets, each at a distance of 15 inches from the sample. The intensity and direction of the field produced by the combined effect of the earth field and the magnets was measured with the flux-gate magnetometer, and in such a way that intensity was measured only crudely, but direction was measured within two degrees. The dip of this field was 45°, and the magnetic directions of these samples are shown in fig. 4. There appears to be a somewhat smaller scatter than that observed for earlier samples.

Samples 21-24 were made from a block of firebrick 2 X 2 X 1 inches lying flat when coated. The coating was quite uneven, and penetrated only about 1/4 inch into the
sample. It was heaviest at the south-east corner. This sample was cut into four 1 inch cubes for measurement, but only one cube, No. 24, was magnetically strong enough for proper measurement. The magnetic direction of this sample is shown in fig. 5.

Sample 25 was made from a 1 inch cube of firebrick with five small holes drilled from top to bottom to aid in the penetration of solution. As with the previous samples, a single heat lamp was used to hasten the drying of solution, and this was located above and to the east of the sample. While the holes helped in evening out the coating on this sample, there was still considerable localization of coating, especially along the top east edge. This was due to the greater heat being supplied there by the heat lamp, causing more solution to flow there during drying. This sample was measured as a whole, and then cut into eight 1 inch cubes, which were measured separately except for two of them, 25 e and 25 g, which were destroyed during the cutting process. Parts of a sample which were cut out and measured separately are usually designated by letters, the lettering being in the same order as numbering of larger blocks of samples, i.e. from left to right, from north to south, and from top to bottom. The various magnetic directions of this sample and its surviving parts are shown in fig. 5, and there it can be seen that the magnetic direction
of the whole sample is different from that of its parts. Accuracy of cutting of small cubes of firebrick, however, is not very good, probably from 5 to $10^0$ from the given direction.

Samples 26-29 were made from a block of firebrick $2 \times 2 \times 1$ inches lying flat for coating. Holes were drilled from top to bottom of this sample to aid the penetration of solution, and two heat lamps instead of one were used to produce a more even heat across the top of this sample. These lamps were placed above and on the east and west of the sample, at a distance of $1\frac{1}{4}$ inches from it. A $1/4$ inch hole was drilled into the north side of this sample, parallel to the top surface and $1/4$ inch from it, and into this hole was forced the bulb of a thermometer (partial immersion). The temperature measured at this point during the application of solution remained at $55^0 C$, but rose to $110^0 C$ on two occasions when the solution stopped flowing to the sample for a period of at least three hours. This sample was weighed before and after coating, and its weight had increased by $1.7 g$. It had been allowed to dry for 6 hours after the last application of solution, so that the additional weight was not mainly caused by wetness in the sample. This sample was cut into four 1 inch cubes for measurement, and later the top central $\frac{1}{2}$ inch cubes were cut out and measured separately. The directions of magneto-
tization for this group of samples are shown in fig. 6. The reason for the scatter and curious average direction of the group is difficult to explain.

Samples 30-33 were made in exactly the same way as 26-29. The temperature of this block also remained at $55^\circ C$ during the periodic application of solution, but once rose to $110^\circ C$ when this application stopped overnight. A weight increase after the coating process of 2.1 g. was measured. This block of samples was treated for measurement in the same way as 26-29, and the magnetic directions for these samples is shown in fig. 7. The four 1 inch cubes are clearly more scattered than are their central top corners.

Samples 34 and 35 were made from a block of firebrick 2 x 2 x 1 inches lying flat for coating, and with the heat lamps located at the east and west sides of the block as before. The temperature of this sample remained at $55^\circ C$ throughout the whole coating process, and by weighing, an addition of 1.67 g of ferric hydroxide was found to have been added. This coating, however, was localized in a central strip running north-south on the sample, and so the east and west sides were removed to a distance of $\frac{1}{4}$ inch, leaving a relatively evenly coated block 1 x 1 x 2 inches. This block was cut into two 1 inch cubes for measurement. The top half of each of these cubes was then separated, and each of these blocks cut into four $\frac{1}{2}$ inch cubes, during which
process, 34b and 34d were destroyed. The magnetic directions for each of these samples is shown in fig. 8.

Two sets of samples were then made, 36-43, from the same batch of solution, and which gained a weight of approximately 1.6 g/m^3 of firebrick, but which were all too weakly magnetic to be measured. The reason for this is not known, but it was suspected that a trace of HCl had been left in the solution tank after cleaning. This may have been responsible for the non-magnetic properties of the precipitate from this solution.

Samples 44 and 45 were made at the same time. Sample 44 was made of glass beads 3 mm in diameter loosely fused into a cylinder 1 inch in diameter and 1 inch long. It sat upon sample 45, which was made of firebrick \( \frac{1}{2} \times 1 \times 1 \) inches. Sample 45 was cut into four \( \frac{1}{2} \) inch cubes for measurement, and the magnetic directions of both these samples are shown in fig. 9.

Samples 46-49 were made of pre-cut \( \frac{1}{2} \) inch cubes of firebrick, embedded in a larger block of firebrick so that their tops were flush with the top of the whole block. A temperature of 55°C was measured during the coating process except for a rise to 90°C observed one morning when the solution had stopped flowing at some point during the previous night. Each of these samples was weighed separately.
before and after the coating process to determine the amount of ferric hydroxide deposited. The magnetic directions for these samples are shown in fig. 10.

Sample 50 was made of glass beads 5 mm. in diameter, loosely fused into a 1 inch cube, and coated along with sample 58. Samples 51 and 52 were made of glass beads 3 mm. in diameter fused into 1 inch cubes. These samples were coated separately, and with no temperature measurements. Absence of boiling of the solution when it was applied indicated a temperature of less than 100°C, however.

Samples 53 and 54 were made of glass beads 3 mm. in diameter very roughly fused into cubes ½ inch on a side, and coated at the same time.

Sample 55 was made like samples 51 and 52.

Sample 56 was made of fused glass beads of somewhat irregular overall shape. After coating, orthogonal faces made of plaster of paris were applied to the sample, with an estimated error of angle of less than 2°.

All the above samples (starting with no. 50) are plotted in fig. 11, along with samples 13 and 14. This figure shows the direction of magnetization for all the large grain (3 mm. diameter) samples.
Fig. 1
Isotropic Samples

Earth field direction at center of large circle; circle is 10° in radius
Fig. 2

Samples of various unconsolidated material

Magnetic field direction - °
Fig. 3
Simultaneously coated samples

Magnetic field direction - Θ

Grain size of sample 13 - 3 mm. diameter
Grain size of all other samples - .5 mm. diameter
Fig. 4
Samples coated in field of 1 Oersted

Magnetic field direction - Θ
Fig. 5
Firebrick Samples

Magnetic field direction - \( \Theta \)

Samples 24 and 25 are 1 inch cubes

Sample 25 subdivided into 6 1/2 inch cubes, a-d, f and h
Fig. 6
Firebrick samples

Magnetic field direction - $\Theta$

Samples 26-29 are 1 inch cubes

Samples 26d-29a are $\frac{3}{8}$ inch cubes

cut from samples 26-29 respectively
Fig. 7
Firebrick samples

Magnetic field direction - \( \Theta \)
Samples 30-33 are 1 inch cubes
Samples 30d-33a are \( \frac{1}{2} \) inch cubes
cut from samples 30-33
Magnetic field direction: halfway between samples a and c

Samples 34 and 35 are 1 inch cubes
Samples 34a and 34c are $\frac{1}{4}$ inch cubes cut from sample 34, and samples e-d are $\frac{1}{2}$ inch cubes cut from sample 35
Fig. 9
Glass bead and firebrick samples

Sample 44 is a cylinder 1 inch in diameter and 1 inch long made of glass beads 3 mm. in diameter. Samples 45a-d are 1/2 inch cubes of firebrick.
Fig. 10
Firebrick samples

Magnetic field direction - °

Samples 46-49 are 1/3 inch cubes
Magnetic field direction: halfway between samples 51 and 56

Samples 53 and 54 are 1/2 inch cubes

All other samples are approximately 1 cubic inch in volume
### TABLE I

**Directions of Magnetization**

This table gives the direction of magnetization of each sample measured with respect to the horizontal north directed reference line of the sample, designated as D for declination in the table, and with respect to the level plane of the sample, designated as I for inclination.

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</table>
Thermal Stability tests

Whether or not the magnetization produced in these samples is affected by temperatures near the temperature of formation is of interest in determining what kind of magnetization they have acquired. Partial thermoremanent magnetization would be characterized by a marked change of intensity when the temperature of formation of the sample was reached, while chemical magnetization should be relatively unaffected at this temperature. Large changes in magnetization occurring at nearly the same higher temperature for all the samples so tested could indicate that a chemical change had occurred in the magnetic material of the samples caused by that temperature, and resulting in a new chemical magnetization.

The method of test used was to heat a sample to some temperature and then cool it in the magnetic field of the earth, but in an orientation differing by 90° from the sample orientation during coating. Thus the supposed chemical magnetization originally produced is compared directly with partial thermoremanent magnetization superimposed on the sample in a new direction. The extent of movement of the magnetic vector of a sample toward the new position of the earth field with respect to the sample is a measure of the stability of magnetism originally produced.
The samples used for this test were for firebrick cubes \( \frac{1}{2} \) inch on a side, and three 1 inch cubes of fused glass beads. All samples were oriented with their +x reference axes pointing upward, and their +z axes directed horizontally south. The firebrick samples were heated to a temperature of 275\(^{\circ}\) C, cooled, and measured. The process was then repeated in 50\(^{\circ}\) C. steps up to 375\(^{\circ}\) C. The results of these measurements are shown in fig. 12. The glass bead samples were first heated to 175\(^{\circ}\) C, and thence in 50\(^{\circ}\) steps to 325\(^{\circ}\) C. The final heating of these samples reached a temperature of about 425\(^{\circ}\) C. The results of these measurements are shown in fig. 13. In both figures 15 and 16 the position of the magnetic field of the earth with respect to the sample is shown at the bottom of the figure as a circle, the projection being oriented with respect to the sample orientation rather than that of the earth field. The scatter to the left and right of the various positions of the magnetic vector gives some idea of the precision of orientation of the samples during the cooling process, as the vector should move in a direct line from its original position toward the new position of the magnetic field.
It can be seen from the relative stability of position of the magnetic vectors up to almost 275° C that their original magnetization could not have been partial thermoremanent magnetization, since the temperature of formation was probably between 50° C and 120° C. Further, no really sudden change of direction in a single temperature interval, consistent for all samples, seems to have occurred, indicating that there has not been a second chemical magnetization.
Samples are shown as oriented when originally magnetized, but were rotated about the E-W axis 90°, clockwise as viewed from the west, during the thermal process.

Magnetic field direction during thermal process - ⊙
Fig. 13

Thermal Remagnetization

Samples are shown as oriented when originally magnetized, but were rotated about the E-W axis 90°, clockwise as viewed from the west, during the thermal process.

Magnetic field direction during thermal process - ⊗
### Table II

**Thermal Stability Measurements**

This table gives the directions of magnetization with respect to the original horizontal north line and level plane, i.e., the same $D$ and $I$ as in Table I, after the sample had been heated to the various temperatures shown in Column 2 (in centigrade degrees) and then cooled in the field of the earth in a position $90^\circ$ from the original sample position.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
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<th></th>
<th></th>
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<tbody>
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<td>34a</td>
<td>-</td>
<td>N6.5E</td>
<td>-67</td>
<td>50</td>
<td>-</td>
<td>N3W</td>
<td>-72</td>
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<tr>
<td>34a</td>
<td>275</td>
<td>N16W</td>
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<td>175</td>
<td>N13E</td>
<td>-79</td>
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<tr>
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<td>-31</td>
<td>50</td>
<td>225</td>
<td>N27W</td>
<td>-81</td>
</tr>
<tr>
<td>34c</td>
<td>-</td>
<td>N17E</td>
<td>-68</td>
<td>50</td>
<td>275</td>
<td>N27W</td>
<td>-80</td>
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<td>S10.5W</td>
<td>-57.5</td>
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<td>S5.5E</td>
<td>-70</td>
<td>50</td>
<td>410</td>
<td>S6E</td>
<td>-56</td>
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<td>35a</td>
<td>-</td>
<td>N8E</td>
<td>-74</td>
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<td>-</td>
<td>N1W</td>
<td>-71.5</td>
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<tr>
<td>35a</td>
<td>275</td>
<td>due N</td>
<td>-38</td>
<td>51</td>
<td>175</td>
<td>N5.5W</td>
<td>-76</td>
</tr>
<tr>
<td>35a</td>
<td>375</td>
<td>S6W</td>
<td>-64</td>
<td>51</td>
<td>225</td>
<td>N17E</td>
<td>-81</td>
</tr>
<tr>
<td>35d</td>
<td>-</td>
<td>N12E</td>
<td>-72</td>
<td>51</td>
<td>275</td>
<td>N10.5E</td>
<td>-82.5</td>
</tr>
<tr>
<td>35d</td>
<td>275</td>
<td>S2.5E</td>
<td>-84</td>
<td>51</td>
<td>325</td>
<td>S25W</td>
<td>-86</td>
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<tr>
<td>35d</td>
<td>375</td>
<td>S1E</td>
<td>-49.5</td>
<td>51</td>
<td>410</td>
<td>S18W</td>
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<td></td>
<td></td>
<td>52</td>
<td>275</td>
<td>due N</td>
<td>-76</td>
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</tbody>
</table>
Anisotropic samples

A group of samples was made of thin, flat glass plates in such a way that the ferric hydroxide coating would lie in parallel sheets, rather than on randomly oriented surfaces. The sample as a whole had to be more or less in the shape of a cube for proper measurement, and so square glass plates were used, stacked parallel, and each one separated from the next by about 1/20 or 1/32 of an inch so that they formed a cube in overall shape. Various methods were used for holding the plates in this way, some of which could lead to errors in magnetic direction results. In the first method used, the plates were held one to the next by thin strips of plasticene lying near opposite edges of each plate. Not only did this produce a fragile, unevenly spaced sample, but also during the coating process, the plasticene softened so that the angle of the plates could shift. Another method involved separating the square plates with narrow strips of glass and fusing the whole sample at a high temperature. This was a difficult process, and the square plates became rumpled during the fusing, so that the sample was not the ideal plane, parallel surface type. The final method used was to cement a square plate to each of two opposite sides of the assembled stack of plates, so that two opposite edges of each plate of the stack was anchored to those two side plates. Plaster of paris was used as a cement at first, and produced fragile
samples. Later an apoxy resin was used as a cement.

Of the flat-plate samples used, 57 was held together with plasticene, and so is slightly suspect. Sample 58 was of fused glass, and while the plates were parallel on the average, they were somewhat curved in the fusing process. All other samples were reasonably well made and undeformed. Samples 59, 60-64 and 68-70 were 1 inch cubes in overall shape, while samples 65-67 and 71-73 were 3/4 inch cubes. For each of the samples except for 57 and 58, an estimate has been made of the amount of surface parallel to the plates, relative to the total surface of the sample. This depends upon the number of plates used to make up a sample, and on the space occupied by the cement.

These samples were all oriented so that the strike of the parallel plates was in the (magnetic) east-west direction, while the dip of these plates was set at various angles from 15° N to 65° S.

The description of these samples is given in Table III. Orientation, Column 2, is the dip of the plane parallel to the plates. Column 3 gives the area of surface of each sample which is parallel to the plates, relative to the total surface area of the sample.
### TABLE III

Orientation of dips of plates of sample and fraction of sample surface area parallel to the plates

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Dip</th>
<th>% Oriented Surface</th>
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<tbody>
<tr>
<td>57</td>
<td>90°</td>
<td>-</td>
</tr>
<tr>
<td>58</td>
<td>90°</td>
<td>-</td>
</tr>
<tr>
<td>59</td>
<td>80°S</td>
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<td>60</td>
<td>80°S</td>
<td>93</td>
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<tr>
<td>61</td>
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<tr>
<td>62</td>
<td>75°S</td>
<td>94</td>
</tr>
<tr>
<td>63</td>
<td>75°S</td>
<td>92.6</td>
</tr>
<tr>
<td>64</td>
<td>75°S</td>
<td>92</td>
</tr>
<tr>
<td>65</td>
<td>65°S</td>
<td>89</td>
</tr>
<tr>
<td>66</td>
<td>65°S</td>
<td>92</td>
</tr>
<tr>
<td>67</td>
<td>65°S</td>
<td>90</td>
</tr>
<tr>
<td>68</td>
<td>15°N</td>
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<tr>
<td>69</td>
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<tr>
<td>73</td>
<td>25°N</td>
<td>92.5</td>
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</table>

The magnetic directions of these samples are shown in fig. 1\(^4\) plotted on an equal area projection. It can
be seen that the position of the sample plates influenced the magnetic direction acquired by the sample, and the magnetic moment of a sample tended to lie nearly on the projection of the magnetic field upon the plane of the plates, rather than in the direction of the magnetic field. It can also be seen from fig. 11 that the scatter in the east-west direction is not particularly large, and this scatter can be neglected without serious loss of accuracy. A different display of these data is shown in fig. 15, a two dimensional representation in which the plane of the figure is the vertical north-south plane of fig. 14. The magnetic moments of the samples under discussion are now shown as arrows radiating from a center. The intersection of the plane of the diagram with the planes of the plates making up a group of samples is also shown on this diagram, as a radiating narrow line for each sample group. In this diagram, the relationship of the magnetic direction of a sample with the orientation of that sample is shown more clearly. These data are also given in Table IV, in which the angle between the earth's field and its projection upon the plane of the plates of each sample is given in Column 2, the angle between the magnetic moment and the plane of the plates is given in Column 3, and in Column 4, the angles of Column 3 are averaged for each group of samples with the
### TABLE IV
Relative Plate and Magnetization Angles

<table>
<thead>
<tr>
<th>Sample Number</th>
<th>Angle between Magnetic field and sample plates</th>
<th>Angle between mag. moment and sample plates</th>
<th>Average Angle: mag. moment and plates</th>
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<tr>
<td>57</td>
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<td>30</td>
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<tr>
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<td>14.1</td>
</tr>
<tr>
<td>73</td>
<td>45</td>
<td>8.5</td>
<td></td>
</tr>
</tbody>
</table>

same orientation with respect to the earth's field.

Fig. 16 is similar to fig. 15, but here average values of magnetic directions are plotted for each group of samples with the same orientation. It can be seen from either fig. 15 or fig. 16 that the magnetic field acting at the time of magnetization of the samples affects their direction of magnetism to the extent that the direction is between the earth field and its component in the plane of the sample. This is true for all samples but No. 59.
The difference between the magnetic directions for samples 68-70 and 71-73 and the other samples is curious, especially in the case of the two groups of samples 65-67 and 71-73, since for both these groups, the magnetic field of the earth was an equal distance from the planes of the samples. The amount of surface lying in the plane of the plates relative to the total sample surface seems to have little correlation with the direction of magnetism of a sample, but the surface area figures (Table III) do not vary greatly.
Fig. 14
Anisotropic samples

Magnetic field direction - Θ
Fig. 15

Anisotropic samples, projected on vertical north-south plane

Magnetic field direction: long, heavy arrow
Dip of sample plates - long fine lines
Directions of magnetization of samples - short arrows
Fig. 16

Average directions of magnetization of anisotropic samples, projected onto vertical north-south plane

Magnetic field direction: long, heavy arrow
Dip of sample plates: long, fine lines
Average directions of magnetization of samples in each orientation: short arrows
Discussion of Results

From the results of the experiments performed, a magnetization is clearly associated with the deposit of red ferric hydroxide coating the samples. Consideration should now be given to the kind of magnetization produced and the effect of the earth's field in directing that magnetization, both for samples isotropic in average grain shape, and for the anisotropic samples. It is also of interest to consider the probable effects of variations in the experimental conditions on the magnetization.
**Kind of Magnetization**

While it has been assumed so far that chemical magnetization was produced in the experiments, it should be shown that neither depositional nor partial thermoremanent magnetization offer as good an explanation of the magnetization of the samples.

Depositional magnetization could only be the mechanism for the magnetization of the samples if the ferrous bicarbonate solution applied to the samples contained particles of already precipitated ferric hydroxide which had in some way become magnetized. No such particles were observed in the solution before it was applied to the samples, and in fact, precautions were taken against just such a happening.

The temperature of formation of the samples was rather low for the occurrence of partial thermoremanent magnetization, the lowest temperature of formation recorded being 55°C throughout the formation process. While partial theremoremanent magnetization could occur at such a temperature, it would be inclined to be somewhat unstable at room temperature. At higher temperatures, that is, equal to or higher than the temperature of formation, such magnetization would be completely unstable. From the thermal
stability tests, then, it becomes clear that the magnetization of the samples is not of the partial thermoremanent type, since the magnetization of the samples tested was essentially unchanged at a temperature of 175° C, well above the highest recorded temperature of formation, and since some of the original magnetization remained even after the samples had been raised to a temperature of 400° C.

Chemical magnetization, then, remains as the best explanation of the magnetization of the samples, since growth of grains of magnetic material was clearly involved in the formation of samples. This growth could be observed in some cases, as the ferric hydroxide could first be observed as a thin film causing an interference pattern on the solution coating the sample, but grew to sufficient thickness to develop its own absorption color. This represented a change in thickness from the order of magnitude of one micron to at least ten microns, and chemical magnetization should occur in a range of growth rather close to this minimum observable thickness of the ferric hydroxide film. With little opportunity for any ferric hydroxide to be formed before the solution reached the sample, and with the temperature of the sample kept at a rather low temperature, the process of chemical magnetization is clearly indicated.
Effect of the magnetic field of the earth

For samples 1-53, that is, those samples isotropic with respect to average grain shape, it is clear that the magnetic field of the earth has directed the magnetic moments of the samples, as shown in fig. 1. There does, however, appear to be a scatter of directions about the direction of the influencing fluid. An investigation of the various experimental reasons for scatter may help to determine whether such scatter is a natural feature of chemical magnetization, or whether it is caused only by experimental errors. The various experimental reasons for variation in the directions of magnetization of the samples are as follows: error of measurement through inaccuracy of the magnetometer, error of measurement through improper placement of sample on the rotating stage, improper orientation of the sample with respect to the external field during coating, and, for the sets of samples made of un-cemented sand, movement of sand grains in the sample during and after the coating process. This last source of error seems to have caused scatter in samples 1-17, fig. 2 and 3, as these samples, all made of loose material, show a greater scatter on the average than do the other samples.
Improper orientation during the coating process of separate samples with respect to the magnetic field in the laboratory can cause a scatter in their magnetic directions. The extent of this source of error can be investigated by observing the relative scatter of groups of samples coated simultaneously while in one solid block. If the scatter is decidedly reduced for such a group, then improper orientation can be considered as an important cause for the scatter of the whole group of samples. While samples 45 a-d, fig. 9, show such a reduction of relative scatter, other groups such as 46-49 and 9-17, fig. 10 and 3, do not. Improper orientation, then, while it may account for 2 or 3° of error, was not the only cause of scatter.

Orientation for measurement was accomplished by making use of the six faces of the cubic samples. If these faces were not orthogonal, a consistent error of measurement would be introduced. Some scatter was undoubtedly caused by this source of error, since the sample faces were only within 5° of being orthogonal. This non-orthogonality of sample faces, however, was fairly consistent throughout the set of samples, so that a comparison of sample groups will not help in estimating the size of this error.
Another method for the interpretation of scatter involved the separate measurement of small cubes cut from a larger sample. Supposing for the moment that the chemical magnetization here produced was somewhat random in direction; then a large sample could be considered to be made of a number of smaller samples, and the magnetic direction of the larger sample would be some kind of average of the magnetic directions of the smaller samples. Thus if a group of small samples were cut from a group of larger samples, the former group should show a greater scatter of magnetic direction than the latter group. Sample 25, fig. 5 was cut into $\frac{1}{8}$ inch cubes, and the magnetic direction of the six $\frac{1}{8}$ inch cubes measured can be seen to be no more scattered than groups of larger samples (e.g. 30-33). The small samples cut from samples 34 and 35, fig. 6, show an even closer grouping than those cut from 25. Samples 26-29 and 30-33 were cut from two blocks of firebrick $2 \times 2 \times 1$ inches. These samples were then cut into $\frac{3}{8}$ inch cubes, and those $\frac{3}{8}$ inch cubes which had originally been in the top central portion of the large block were measured. As shown in figs. 6 and 7 the scatter for the smaller samples is somewhat less than that of the larger samples from which they were taken, even for the badly scattered samples 26-29. This particular decrease
of scatter for the small samples is probably caused by their greater uniformity of coating compared to the larger samples. Errors of measurement can be caused both by shape differing strongly from the sphere, and by non-coincidence of center of magnetization and geometrical center of the sample. Thus samples evenly coated should deviate less from the direction of the earth field than unevenly coated ones, and the small samples cut from samples 26-33 show this effect, being cut from the most evenly coated part of the original block. While unevenness of coating may be responsible for some of the scatter, it is not a principle source of error, since both sample 25, and samples 34 and 35 appeared quite evenly coated, but show no remarkable closeness of direction of magnetization to that of the external field. At any rate, it appears that scatter of magnetic directions does not increase with decreasing sample size, and so randomness of direction of magnetization is not a natural feature of chemical magnetization.

That scatter of magnetic direction is not related to the intensity of the influencing external field is at least indicated by the behavior of samples 18-20, fig. 4. These samples were formed in a field twice as large as that of the earth. Although there is an insufficient number of
these samples, it can be seen that no major change in the grouping of magnetic directions has been produced by the increase in influencing field.

In fig. 11, the directions of magnetization of the large-grained samples are shown. It can be seen that the larger grain size has had no effect on the directions of magnetization of these samples, as compared to the previous samples. The grouping of the magnetic vectors is, in fact, slightly better than that of the earlier samples. This might be caused by the fact that the grains of these samples were spheres and so had no opportunity for anisotropy of shape.

It is suggested, in conclusion, that the magnetic direction for a sample isotropic in average grain shape should be exactly parallel to the influencing field of the earth when magnetized by the process described, even when grains are as large as 3 mm. in diameter, and when samples are as small as 1/8 cubic inches in volume. Such characteristics of magnetization might be used to distinguish chemical from depositional magnetization, since for the latter the scatter of directions of magnetization for a group of samples should be greater both if the samples are large grained, and if they are small in volume, than if they are fine-grained and large. A more thorough
investigation of the scatter characteristics of depositional magnetization is needed, however, before such a distinction can be made.

Anisotropic samples

The directions of magnetization of samples 57-73, all made of flat parallel plates, are shown in fig. 14. These samples were all oriented so that the strike of the plates was in the E-W direction, and the dip set at various angles from 15° N to 65° S. It can be seen that the magnetic directions of these samples were not influenced by the strike of the sample plates, which was always perpendicular to the magnetic field, but was strongly influenced by the dip of those plates. The scatter of these samples may be estimated in fig. 14 from the spread of magnetic directions to the east and west of the north-south line of the figure. This scatter, being reasonably small, is omitted from figs. 15 and 16, which represent the N-S vertical plane of fig. 14, and show the dip of the plates as well as the projection of the magnetic directions into the plane of the figure.

From fig. 16, which shows the average magnetic direction for each group of samples with the same orientation, it
can be seen that the magnetic vector lies between the magnetic field direction and the plane of the plates, but closer to the latter. To estimate the effect of the plates of the samples on their resulting magnetic directions, account should be taken of that part of the sample surface not parallel to the plates. This was the sides of the samples, perpendicular to the sample plates, oriented in all cases parallel to the north-south vertical plane, and accounting for an average of 10% of the sample surface. Assuming that the magnetic direction of a sample with all its surface parallel to the plates would lie exactly in that plane, then for the actual samples used, with 90% of their surface parallel to the plates, the magnetic directions of these samples should make an angle with the plates which is 10% of the angle between the magnetic field and the plane of the plates. From fig. 16 or Table IV it can be seen that the angle in question is somewhat greater than 10% of the angle between the magnetic field and the plane of the plates. The reason for this might be that the plates of the sample are more weakly magnetized than the sides since for the plates, the effective intensity of the field causing magnetization is less than that for the sides by a factor equal to the cosine of the angle between the magnetic field and the plates.
The probable reason for the influence of the plane parallel surfaces on the direction of magnetization of these samples is that the ferric hydroxide coating is not randomly oriented, as it would be when deposited on spherical grains, but restricted to growth on a two-dimensional surface. Anisotropy of shape should cause magnetization parallel to the film of ferric hydroxide rather than perpendicular to it, so that when this film grows only in parallel sheets, magnetization should only occur in a direction parallel to the plane of those sheets.

From the magnetic directions of samples 57-73, then, it is concluded that for a sample made partly of plane parallel surfaces, the direction of the magnetic vector will fall between the direction of the external field and its projection on the plane surfaces. The fraction of the angle between these two lines which the magnetization makes with the magnetic field will depend on the fraction of sample surface which is composed of parallel planes, but these two fractions will probably not be equal, the former being less than the latter.

**Effect of Variations in the Conditions producing chemical magnetization**

The theoretical explanation for the occurrence of chemical magnetization was discussed briefly in an earlier part of this paper. It is now of interest to reconsider
this explanation, for the information which it can give about the chemical magnetization experimentally produced. In particular, it will be of interest to know what the effects will be on the magnetization if the conditions causing it are made more nearly like those of a natural occurrence. These conditions would involve weaker ferrous bicarbonate solution, lower temperature of formation, and longer duration of formation than were used in the experiments.

The theoretical explanation for chemical magnetization given in an earlier part of this paper concerned single-domain grains with single long axes all parallel to the external field if it exists. The explanation dealt with the relationship of the relaxation time, $\tau_0$, to the grain volume, $v$, and the equations derived by Neel (1949) relating relaxation time to grain volume, Kelvin temperature $T$, coercive force, $H_c$, and saturation magnetization, $J_s$, was given as follows:

In zero external field,

$$\frac{1}{\tau_0} = C e^{-\frac{H_c J_s v}{2kT}} \quad (1)$$

where $k$ is Boltzmann's constant. In an external field $h$, two relaxation times, for movement of the magnetic moment
from an angle with the long axis of the grain equal to 0 to one equal to π, and for opposite movement, that is, from π to 0, were given as:

\[ \frac{1}{\tau(0,\pi)} = C\left(1 + \frac{h}{H_c}\right)\left(1 - \frac{H_c^2}{h^2}\right)^{\frac{1}{2}} e^{-\frac{vJ_s(H_c + h)^3}{2H_c kT}} \]  

(3)

\[ \frac{1}{\tau(\pi,0)} = C\left(1 - \frac{h}{H_c}\right)\left(1 - \frac{H_c^2}{h^2}\right)^{\frac{1}{2}} e^{-\frac{vJ_s(H_c - h)^3}{2H_c kT}} \]  

(4)

The ratio of these relaxation times in equations (3) and (4) was equal to the ratio of the numbers of grains \( N_0 \) and \( N_\pi \) with magnetic moments in the 0 and π directions. This ratio may be given in terms of \( H_c, h, V, J_s, k \) and \( T \) as:

\[ \frac{\tau(0,\pi)}{\tau(\pi,0)} = \frac{N_0}{N_\pi} = \frac{H_c - h}{H_c + h} e^{-\frac{2vJ_s h}{kT}} \]  

(5)

The relative effect of rate of growth will first be considered, using equation (1).

Consider first a large number, \( N \), of grains in the absence of a magnetic field, all of the same volume, and all growing at the same constant rate such that they require a time \( \Delta t \) to grow an increment of volume \( \Delta v \). The
relaxation time of these grains, depending on volume, increases in such a way that if it has a value $\tau$ at a volume $v$, then $\Delta t$ seconds later it will have a value $p\tau$, where

$$p = e^{\frac{HsJ}{2kT} \Delta v}.$$ 

$2\Delta t$ seconds later, its value will be $p^2\tau$, and $n\Delta t$ seconds later, its value will be $p^n\tau$. The value of $p$ will depend upon the size of $\Delta v$, but will always be greater than 1. The number of changes of direction of magnetic moments of all the grains occurring in an interval of time $\Delta t$ and at some volume $v$ is given by

$$N = N_1 \frac{\tau}{\tau_0},$$

where $\tau'_0$ is the average value of relaxation time for a volume between $v$ and $v + \Delta v$. At some volume, $v_c$, $\tau'_0$ will be equal to $\Delta t$, so that the number of changes of direction of magnetic moments of the grains will be $N$, the total number of grains, and in the next interval of time, $\Delta t$, it will be $N/p$. In subsequent intervals of time it will be $N/p^2$, $N/p^3$, $\cdots$, $N/p^n$ and so will decrease in some number of $\Delta t$'s to essentially zero for a finite number of grains. The directions of magnetization can then be considered as fixed at some time, say 100 $\Delta t$, after volume $v_c$ has been reached.
If now two groups of grains are considered, with rates of growth such that each grain in group 1 grows an element of volume $\Delta v$ in a time $\Delta t_1$, while each grain in group 2 requires a time $\Delta t_2$ to grow the same element of volume $\Delta v$, ($\Delta t_2 > \Delta t_1$) then for group 1, the directions of magnetization can be considered fixed when the volume is $v_{c1} + 100 \Delta v$, or begin to become fixed at volume $v_{c1}$ when $\tau_0 = \Delta t_1$, while for group 2, directions of magnetization do not reach the same condition until volume is $v_{c2}$, when $\tau_0 = \Delta t_2$. Since $\Delta t_2$ is greater than $\Delta t_1$, $v_{c2}$ is greater than $v_{c1}$. The volume $v_c$ at which, at least for comparisons, the magnetization of a group of grains begins to become fixed might be called the critical volume. The critical volume, then, will be larger for slow growing than for fast growing grains.
Magnetization is caused by an external field through the effect of that field on equations 3 and 4. It can be seen that \( \tau(0,\pi) \) will be larger than \( \tau(\pi,0) \) and that these two relaxation times will differ more as \( h \) increases. That difference will also be increased, with \( h \) constant, if \( H_c \) decreases. Since chemical magnetization depends on the difference in these two relaxation times, being more probable or more intense or both as the difference increases, then it can be seen that large values of external field, or low values of coercive force both favor chemical magnetization.

Equation 5 shows the ratio of the two relaxation times, or the ratio of the number of grains in the 0 and in the \( \pi \) direction, in an external field, and it is apparent that this ratio increases with volume, as well as with decrease of temperature. The increase of this ratio, since it increases the number of grains with magnetic moments in the 0 direction relative to those with magnetic moments in the \( \pi \) direction, favors the occurrence of chemical magnetization, and so it would seem that both an increased critical volume and a decrease of temperature would lead to a more intense or more probable chemical magnetization, if coercive force and external field remain constant.

Now, comparing a process somewhat like the one carried out experimentally in this work, but in which a weaker solution of ferrous bicarbonate was used, and in which the
oxidation of this solution occurred at a lower temperature, with the process experimentally carried out, it is clear that the imagined process will require more time for deposit of an equal quantity of ferric hydroxide. The rate of growth of grains of magnetic material, in this slower process, will also be reduced both because of the lower temperature and because of the weaker solution. It has been shown that such slow grain growth will lead to a larger critical volume during chemical magnetization. Since both large volume and low temperature increase the ratio of magnetic moments in the 0 direction to those in the π direction, then comparing the fast and slow processes of chemical magnetization, the magnetization of the slower process should be more intense than that of the faster one, provided coercive force and external field are the same. If coercive force decreases with increased volume, an even more complete magnetization for the slower process can be expected, while increase of coercive force with volume could, unless it was quite extreme, still permit the chemical magnetization of the slower process to be greater than or equal to that of the faster process. The behavior of coercive force with grain size is, however, unknown for ferric hydroxide.

Since chemical magnetization has been shown to occur in the experiments carried out, it may then be concluded that it will also occur for the more nearly natural conditions of lower concentration of solution and lower temperature of oxidation.
Chemical magnetization of natural red sandstones

The process described by Lord Rayleigh, and followed in this work for the artificial production of red sandstones may or may not occur on a large scale in nature. Assuming that it does, however, an examination of the magnetic effects resulting from such a process, as indicated by the experiments reported here, would be useful to the study of paleomagnetism. It is of interest in that field of study to know whether a remanent magnetism can be caused by this process, to what extent that magnetism is directed by the earth field acting at the time of magnetization, and whether there is a possibility for systematic deviation from the influencing field of the magnetic moment produced. It is also of interest to know when the magnetization occurred relative to the age of the rock in which it occurs, how long it took to form, and whether it is likely to have been stable over long periods of time.

That the process in question would be accompanied by a chemical magnetization seems likely from the results of the experiments performed, and from a consideration of the effects of changes in some of the experimental conditions referred to in the last section. This magnetization should be influenced by the magnetic field of the earth acting during the process of magnetization, and if the grains of the sand or sandstone being coated are in random orientations,
and so isotropic with respect to shape, the resulting direction of magnetization of the sandstones should be parallel to the field of the earth at that time. If, however, the grains of the sandstone have some preferred orientation with respect to their shape, a direction of magnetization for the sandstone different from the direction of the earth's field will occur. One form of anisotropy of shape which could commonly be expected in a sandstone would be caused by the presence of flat grains lying parallel to the bedding plane. The direction of magnetization of such a sandstone should have a lower inclination than the external field causing magnetization, but the declination should be the same. By way of example, if the inclination of the magnetic field is 60°, and influences the chemical magnetization of a sandstone containing flat-lying mica flakes such that twenty percent of the grain surface is in planes parallel to the bedding plane, then the inclination of the resulting magnetic moment of the rock could well be only 50°. The apparent magnetic latitude indicated by this sandstone would then be about 31° rather than its actual latitude of about 41°, or a pole position would be falsely indicated about 650 miles farther away than its actual position. This kind of systematic deviation of the direction of remanent magnetism from the field influencing it is, incidentally, also characteristic of depositional magnetization. Thus the two mechanisms thought
to cause the magnetization of sedimentary rocks may both lead to the same kind of error in paleomagnetic investigations.

The declination of the magnetic moment of a sandstone could also be affected by the presence of flat grains in the sandstone arranged with their planes parallel, provided that these planes were not horizontal, and their strike was not perpendicular to the direction of the magnetic field. While such an arrangement of grains could occur in small areas, it could not be expected to be consistent over areas of several hundred square miles or more, so that consistent errors of declination should not be caused by grain shape of the sandstone provided that sandstone covers a large area.

The process of chemical magnetization under discussion could have occurred at any time after the deposit of the grains making up the sandstone, and thus the actual time of magnetization would be later than the time of magnetization assumed by paleomagnetists. If the sandstone was tilted before magnetization, then the usual assumption that magnetization occurred when the rock was flat-lying would lead to errors both in inclination and declination of the direction of magnetization of that rock. (Errors of declination would not occur if the strike of the bed was perpendicular to the magnetic field of the earth). Tilting, however, would have to be consistent in strike and dip over wide areas if such misinterpretation were to remain undetected.
The likelihood of magnetization occurring long after deposition is not known, however, since the time at which the red coloring appears in sandstones is not clearly established.

Hatch (1938) gives a description of the grains of some red sandstones which are alternately coated with iron oxide and quartz in successive shells, indicating "successive periods of ferruginous and siliceous cementation". It would seem that some of these periods of ferruginous cementation could have taken place well after the original deposition of the sand.

Another case in which a sandstone was presumably colored red long after it was deposited was described by Lord Rayleigh. The sandstone was located near a chalybeate spring, and showed a considerable variation of color, being deeply colored along cracks in the stone, and in some areas, not colored at all. While the sandstone was Carboniferous in age, the coloring must have been caused by the spring water, and was then quite a recent occurrence. This sandstone, however, showed a localization of red coloring, which might well be a general indication that the age of the sandstone does not coincide with the age of its red coloring material. It is hard to imagine how a bed of sandstone several hundred feet thick could be colored evenly by chalybeate water, so that for sandstone which is evenly
colored over great areas and thicknesses, the coloring process most probably occurred along with sedimentation. For such sandstones, the time of magnetization and the age of the rock should coincide, and further, the duration of the magnetization process, for the bed as a whole, may be sufficiently long so that the magnetization would represent only the average field of the earth at the time of magnetization, unless deposition was exceedingly rapid.

That a sandstone is indeed evenly colored over large volumes is not always easy to tell. Supposing that the coloring can penetrate several tens of feet into a sandstone, and occurs at or near the surface of exposure of the rock, then a natural outcropping of such a rock could appear to be evenly colored both laterally and vertically, when, in fact, that color was only even at or near the exposed surface. A recent and deep penetration into the rock, such as a deep road-cut, should, of course, reveal the extent of evenness of rock coloring.

The stability of remanent magnetism of a rock, or its ability to retain its original magnetization over long periods of time can depend upon a number of features of the magnetism of the rock, as well as on various events which could have occurred since magnetization. Rocks to be used for paleomagnetic investigation must, of course, have remained stable since their original magnetization.
Instability of red sandstones magnetized by the method described here could be caused by a long-term decay of the original magnetization due to the relaxation time for the grains of magnetic material being shorter than the time since magnetization. The relaxation time could be short if grain growth stopped before those grains were large enough to become stable from the long term point of view. High temperatures could have a similar reducing effect upon the relaxation times of the magnetic particles if these were sufficiently small. Temperatures higher than about 1000°C are unlikely for most sedimentary rocks, so that if the results of the experimental thermal stability tests are meaningful when applied to natural red sandstones, it would seem unlikely that the stability of these rocks would be affected by any temperatures to which they would normally be subjected. The thermal stability tests also indicated that if any chemical change in the magnetic material is caused by raising its temperature, that change has no pronounced effect on the magnetization of the sample. Whether long term chemical changes may occur which affect the magnetization of red sandstones is unknown. One kind of chemical change which could occur is the solution and redeposition of the ferric hydroxide coating of the sand grains, caused by the action of rain water, in the same way
as the original coating process occurred. If this happened, the magnetization of the rock would constantly move with the field of the earth, or would be unstable. It has been suggested by Dorsey (1926), however, that ferric hydroxide is quite resistant to weathering, and that the source of the iron in chalybeate water is not from iron oxides, but from iron bearing silicates in igneous rocks.

Red sandstones, then, may or may not be stable over long periods of time. From the experiments performed, stability certainly exists to a limited extent. Furthermore, some natural red sandstones have been shown to be stable for a long time at least, if not since formation. Irving and Creer (1955) have shown that a number of red sandstones in England have remained stable since folding, making use of a test for stability devised by Graham (1949). In this test, the magnetic directions are measured for samples taken at intervals from a folded bed. If the magnetic directions are closely grouped after correcting for geology, or "flattening out" the fold, but are widely separated before this correction, stability is indicated. If the converse is true, the bed must have been magnetized after folding, and so, is probably unstable.

The two features of the magnetization of red sandstones which appear most likely to make them unsuitable for paleomagnetic use, still assuming that they are magnetized by the
method here described, are the possible decrease in inclination of the magnetic moment of the rock relative to the field acting during magnetization, and the possible non-coincidence of the time of magnetization and time of origin of the rock. That these two processes may have occurred in nature can be seen from reviewing some paleomagnetic data.

Considering first the decrease in inclination which may accompany a chemical magnetization, a quotation from P.S.K. Blackett's Lectures on Rock Magnetism seems quite appropriate. He is discussing the direction of magnetization of British Triassic rocks, measured by Clegg, Almond, and Stubbs (1954) as an indicator of continental drift and polar wandering, and says:

"Further, the fact that the inclination of these rocks was about 30° compared with the value of 65° corresponding to the central dipole, led to the conclusion that England was probably markedly nearer the equator than today. However, as already mentioned, the inclination of the magnetism of sedimentary rocks, at any rate when magnetized by deposition, is apt to be less than that of the ambient field .... However, if the magnetism of these rocks was acquired by a chemical process,
then the inclination measurements may well give a more reliable estimate of latitude."

From the experiments here performed with flat-grained samples, there is a possibility that the last sentence of the above quotation is not correct, and that inclination measurements of a chemically magnetized rock are as apt to be less than that of the ambient field as are dispositionally magnetized rocks. The magnetic declination of the rocks referred to above was, incidentally, about N34°E, and was interpreted as an indication that Britain had rotated 34° clockwise with respect to the north magnetic pole since the time that these rocks were magnetized. Since these rocks were nearly flat lying and taken from a number of well separated sites, their declination cannot be explained either by grain shape, or by magnetization after tilting.

Another possible example of decreased inclination of the remanent magnetism of red sandstones may be found in the results of a survey carried out by Bowker (1960) on the Triassic rocks of Eastern North America. A reasonably consistent pole position was indicated by the red sandstones of this age, sampled from New Jersey to North Carolina, and this pole position is shown in fig. 21 (No. 4), along with the various pole positions indicated by the igneous...
FIG. 17  MASS. - SEDIMENTARY
FIG. 18  N.J. AND EAST PA. - SEDIMENTARY
FIG. 19  MD. AND WEST PA.-SEDIMENTARY
FIG. 21  AVERAGE POLE POSITIONS
rocks collected (Nos. 1, 2, 3). It can be seen from this figure that the sedimentary pole position lies farther away from the sampling area than does the present north pole, but is on the great circle joining the two. This situation could, perhaps, be explained by saying that the magnetic dipole in Triassic times coincided with the present geographic pole, and that the magnetic pole indicated by Triassic rocks differs from its true position because of the decrease in inclination of the magnetic vector for those rocks. The pole positions for the igneous rocks do not support this explanation, unless they could be said to represent short term variations in the Triassic pole position, shown because of the rapid magnetization.

Turning now to the possibility that chemical magnetization can occur long after sedimentation, the magnetic directions of the Triassic sandstones of Eastern North America are again of interest. Figs. 17, 16, 19, and 20 show the directions of magnetization of samples collected from Massachusetts, New Jersey and Eastern Pennsylvania, Western Pennsylvania and Maryland, and Virginia respectively. All these directions are uncorrected for tilt of the bedding. The bedding for the Massachusetts rocks dips generally 30° south, while for the other formations, the dip is from about 10° to 30° north. If it is assumed that these rocks were magnetized before tilting, then when the beds are
returned to a level position, the three latter figures would indicate the pole position shown in fig. 21, No. 4, some 75° northward from the sampling site, while the Massachusetts sandstones would indicate a pole position about 20° northeast of Massachusetts. If, on the other hand, the beds are assumed to have become magnetized after tilting, then the average magnetic direction in each of the figures lies approximately north with a dip about 10° less than that of the present magnetic dipole field (shown as an open circle in the figures). It is possible that the magnetic field being represented by all these rocks is the present dipole field, and that the discrepancy in magnetic dip is caused by flat grains in the sandstone. A different interpretation made by Bowker, was that only the Massachusetts sandstones were magnetized after the beds had tilted, the other rocks, when corrected for tilt, actually representing the Triassic pole position. In either case, it would seem that the Massachusetts rocks were probably magnetized after tilting. Unless their magnetization was merely unstable, some form of magnetization is implied which could occur well after deposition. Chemical magnetization is strongly suggested here since the only other known possibility would be thermoremanent, and this would require high temperatures, the source of which would be hard to imagine. Furthermore, as has been pointed out by Bowker, these sandstone beds rest upon the Deerfield diabase and
are, according to Willard (1952) redder near the contact. If the diabase is the main source of iron which causes the reddening of the sandstone, as indicated by Willard's observation of the color gradation, then a chemical process is suggested for the transport of iron from the diabase to the overlying sandstone, and this chemical process, which could, it seems, produce a remanent magnetization could have occurred after the tilting of the beds.

Another case where chemical magnetization occurring well after deposition may have caused error in paleomagnetic results is suggested by the work of Clegg, Deutsch, Everitt, and Stubbs (1957) on baked sediments of carboniferous age from the English Midlands. These rocks were found to differ in magnetic direction by more than 50° from the magnetic directions measured by Belshe (1957) for unbaked carboniferous sediments. Of the various suggestions given to explain this discrepancy, Clegg and his coworkers listed the following:

"That some of the rocks acquired their present magnetization at a time later than the Carboniferous. It is hardly conceivable, however, that this can be true of the baked sediments, for the fact that the intensity of magnetization invariably falls off with distance from the contact provides overwhelming evidence to suggest that the magnetization was acquired at the time of emplacement of the molten magma".
One way to make the possibility of later magnetization conceivable, of course, is to assume that when the sediments were baked, they were free of magnetic material. They were chemically magnetized much later, with the igneous material furnishing a source of iron, so that a higher concentration of ferric oxide would be found near the igneous rock than away from it, and the magnetization would be most intense near the contact.

The sources of error caused by decreased inclination and indefinite time of magnetization described above for this process of chemical magnetization, do not, it should be noted, make the rock magnetically useless. It might be difficult or impossible for the paleomagnetist to determine the exact time of magnetization, but an upper limit to this time is certainly given by the age of the rock. The possible decrease in inclination is also open to interpretation, and declination should reflect the influencing field with considerable exactitude. Stability, the lack of which makes a rock truly useless to the study of paleomagnetism, may well be high, as indicated by the few tests made so far on red sandstones.

Compared to depositional magnetization and thermoremanent magnetization, chemical magnetization is the only one which can occur long after the formation of the rock.
From consideration of the possible depth of penetration of chalybeate water mentioned previously, however, the occurrence of chemical magnetization at the same time as sedimentation may be more probable than otherwise.

Decrease of inclination is a feature of deposition magnetization as well as chemical magnetization, and may be more pronounced in the former than in the latter. In depositional magnetization, any of the already permanently magnetized grains causing magnetization of the final sediment will be magnetized along their long axes if such an axis exists. While these grains are settling through water, they will be aligned by the field of the earth, but on reaching the bottom, they will tend to lie flat, so that inclination will be reduced unless that of the earth field is either horizontal or vertical. Compaction of the sediment should further reduce its magnetic inclination.

For chemical magnetization, decrease of inclination should depend on the amount of horizontal surface relative to the total surface area of the grains making up the sandstone. For a sandstone composed of essentially spherical grains, or grains randomly oriented with respect to shape, the magnetic inclination of the rock should be equal to that of the influencing field. Grains with high sphericity should tend toward random orientation. If, however, the sandstone contains grains of low sphericity, those grains
with a single short axis should lie with the short axis perpendicular to the bedding plane, and those grains with a single long axis should lie with that axis in the bedding plane. Such an arrangement should lead to a reduction of inclination for the chemically produced magnetic vector. It is hard to give any general value for the sphericity of sand grains or the mica content of a sand. The mica content often depends on the grain size of the sediment, silts usually having higher mica content than coarse sands, according to Pettijohn (1949). The mica content, however, varies considerably, and it is common to find sandstones with highly micaceous beds in them as described by Mencher (1960). As to sphericity, Rusnack (1957) gives what may be typical values for various sands, as ranging from .7 to .8. As a rough approximation such grain sphericity can be represented by rectangular prisms with side dimensions a, b, and c in which for half of these prisms, a = b = 2c, sphericity = .76, and for the other half, a = b = \frac{3}{2}c, sphericity = .77. If these prisms are lying either with the one short axis perpendicular to the bedding plane, or with the one long axis in the bedding plane, then the first group will have 50 % of the grain surface horizontal, and the second group, 40 %. Since for cubes, 33 % of the surface would be horizontal, then an excess of 17 and
horizontal surface is represented by the two groups. Thus an average excess of 12 % horizontal surface might be present in ordinary sands, provided that the grains lie flat. It is just possible that this situation could lead to a decrease in declination of 5° at latitudes of 40-50°. This, however, is a small error, even if consistent.

Both depositional and chemical magnetization may then lead to errors of inclination, but these errors are probably less severe in the chemical than in the depositional process. Chemical magnetization does, however, have the added source of error involved in its time of occurrence.

The other main process, theremoremanent magnetization, is confined almost completely to igneous rocks, so that accurate bedding planes, useful in determining the original attitude of the rock and in conducting stability tests, are often hard to find. This kind of magnetization should be free from the two main errors of chemical magnetization, but may possibly be less stable, as suggested for example by Bowker (1960), and may occur in so short a time as to reflect the short term, rather than dipolar field of the earth. The importance of magnetostriction, discussed by Graham (1956) has not yet been fully analyzed, but may cause considerable deviation of the magnetic vector from its original
position, and may be particularly important in igneous rocks because of forces caused by thermal expansions and contractions.

Chemical magnetization, then, would seem no less reliable for palcomagnetic studies than any other method of magnetization, especially if interpreted properly. Whether or not it really occurs in the way described in this paper is hard to say, but the conditions under which it was produced artificially did not differ strongly from certain (perhaps isolated) conditions in nature. It is certainly a conceivable mechanism of magnetization for sedimentary rocks.
Suggestions for future work

Certain further experiments could be made with relative ease, and would be useful in extending the knowledge of the origin and behavior of the magnetization of red sandstones. In one group of experiments, a comparison of the magnetic properties of natural red sandstones and of the artificial samples should be made. Some of the more important properties to be compared are the following:

1. Thermal demagnetization curves.
2. Curie temperatures.
3. Temperatures (if any) at which a chemical change altering the magnetization occurs.
4. Natural intensity of magnetization per unit weight of magnetic material.
5. Intensity of magnetization at saturation per unit weight of magnetic material.
7. Magnetic susceptibility.
8. Alternating field demagnetization curves.

Another group of experiments could be carried out to learn more of the effect of parallel flat grains on the
direction of magnetization of a sample. Variations both in flat grain orientation with respect to the external magnetic field, and in quantity of flat parallel surface relative to the total sample surface would aid in obtaining a numerical relationship between the direction of magnetization, the orientation of flat surfaces with respect to the external field, and the fraction of flat surface present in the sample. The effect of flat parallel grains in natural sandstones on the direction of magnetization could also be investigated for samples taken from a site in which there was a large variation, both laterally and vertically, of grain sphericity.

Finally, it would be useful to know just what features of magnetization can be used to distinguish chemical from depositional magnetization. From the investigation of scatter in the artificial chemical magnetization, it has been suggested that the scatter of directions of magnetization for a group of samples is probably independent of sample size for chemical magnetization, but dependent on sample size for depositional magnetization, provided the sample is in the right size range. Experiments to determine the relationship between scatter of directions of magnetization, sample size, and grain size for depositional magnetization are still needed, however, before any attempts can be made to distinguish chemical from depositional magnetization by this means.
Appendix I

Application of Solution

A large number of applications of solution to a given sample was required before that sample became sufficiently magnetic for accurate measurement. It soon became apparent that some automatic means of application would be necessary if samples were to be coated in a reasonable amount of time. It was also found that a slow continuous flow of solution onto the sample produced a coating far too localized around the region where the solution first arrived, that is, periodic application of a few cc's of solution was required. Use of valves and pumps to handle the solution was found to be difficult because of the tendency for ferric hydroxide to form around the moving parts and harm their operation.

In the method finally adopted, the solution flowed slowly but continuously into a vessel which emptied periodically. Slow flow was achieved by the use of a long thin tube reducing the rate of outflow from the source, which was at slightly above atmospheric pressure. As the resistance to flow for a tube is directly proportional to length and inversely proportional to the square of the area of cross-section, use of a long tube permitted a larger
cross-sectional area for a given rate of flow, and the tendency toward clogging was thus reduced.

Periodic flow was achieved by the use of a vessel the behavior of which was similar to, but not so subtle as, the flushing operation of a toilet. As shown in fig. 22A, liquid is introduced into reservoir B through pipe A, and its level rises gradually in both reservoir B and pipe C. When level L is reached, liquid flowing into and down pipe D will siphon off all the liquid in the vessel. Pipes C and D must be sufficiently small in diameter so that liquid rising to the appropriate level will fill completely the junction between pipes C and D, even though the rate of inflow be small.

Since air-solution contact had to be avoided until the solution reached the sample, this vessel was kept filled with CO₂ which was coming constantly from the tank in which the solution was made. This gas was also piped into a jacket E around the end of pipe D to reduce oxidation of drops of solution remaining around the end of that pipe after it had discharged. This is shown in fig. 22B. Fig. 22C shows the actual arrangement of the vessel. It can be seen that it is the same as fig. 22B, but the parts have been rearranged for convenience of construction.
The volume of liquid ejected by this device is determined by the volume of reservoir B plus pipe C up to level L. The rate of flow divided by this volume determines the frequency of ejection.

For coating a given sample, a vessel of sufficient volume to moisten completely the sample at a single discharge was selected. Rate of flow and heat supplied to the sample were then adjusted so that the sample dried almost completely before each new discharge of solution.

In actual practice this device would work for only 2¼ hours or less without attention. Of the various devices used for periodic application of solution, however, it was the most dependable and troublefree.
FIG. 22-A

FIG. 22-B

FIG. 22-C

FLOW CONVERTER
Appendix II

Magnetometer

Because of the structural weakness of the samples and their size variation, the rock generator type magnetometer which was available could not be used for sample measurement since such measurement required the rotation of the sample at nearly 300 r.p.s., and since the instrument was designed for the measurement of cylindrical samples one inch in diameter and one inch long. An astatic magnetometer was therefore constructed for measurement of the samples.

The astatic magnetometer has been described in detail by Blackett (1952), but with particular attention to the highest accuracy and sensitivity. Such sensitivity was not required in this investigation since the intensity of magnetization of the samples to be measured could be made relatively large ($10^{-4}$ to $10^{-5}$ c.G.s.). Thus the factors affecting the design of the magnetometer to be used were speed of operation and ease of construction, gained at the loss of sensitivity.

Principle of the Astatic Magnetometer

The remanent magnetism of an object may be measured by the effect of its field upon a magnet free to turn about
an axis perpendicular to its direction of magnetization. When the magnetic field of the object being measured is weak compared to the field of the earth, the measuring magnet must be insensitive to the latter field, but influenced by the former. This condition is achieved in the astatic magnetometer by the use of two magnets of equal magnetic moment, mounted at either end of a rigid bar as shown in fig. 23A. The bar is suspended from one end by a thin fiber so that it may rotate about the axis of the fiber. A uniform magnetic field will not cause rotation of the magnet suspension, since its effect will be equal but opposite on each magnet. A non-uniform magnetic field stronger near one magnet than the other, and with a component in the plane perpendicular to the suspension fiber will, of course, cause rotation of the magnets. Such a field would be produced by a magnetic specimen held near one of the magnets. The angle of rotation depends on the strength and direction of the local field and on the restoring torque of the suspension fiber, and is measured by means of a mirror fastened to the magnet suspension.

Design considerations

In the design of this magnetometer, the relationship
between sensitivity, period of oscillation, and magnet size is of particular interest. The deflection angle, $\Phi$, of the magnet suspension produced by a field $H$ acting on only one magnet will be

$$\Phi = \frac{HM}{\sigma}$$

where $M$ is the magnetic moment of that magnet, and $\sigma$ is the restoring torque of the fiber.

Then the sensitivity, $S$, is given by

$$S = \frac{\Phi}{H} = \frac{M}{\sigma} \quad (1)$$

The free period of oscillation, $T$, of the system is given by

$$T^2 = 4\pi^2 \frac{I}{\sigma} \quad (2)$$

where $I$ is the moment of inertia of the magnet suspension. It is here convenient to assume that $I$ is the moment of inertia of the magnets alone. Combining (1) and (2),

$$T^2 = 4\pi^2 S \frac{I}{M}$$

Then for constant sensitivity, $\frac{I}{M}$ should be small for short
period. Magnet material with high remanent magnetization is indicated, and the magnets should be short in their direction of magnetization.

Assuming that magnet material and shape are kept constant, consider the effect of magnet size. If some magnet dimension be designated by \( r \), then \( I \propto r^5 \); \( M \propto r^3 \) and with constant sensitivity, \( T \propto r^2 \) or \( T \propto r \). Thus a reduction in magnet dimensions reduces period proportionally. With constant sensitivity, the torque (from (1)) varies with \( r^5 \). For a suspension fiber of given length, \( \sigma \propto a^2 \) where \( a \) is the area of cross section of the fiber. Then \( a \propto r^{3/2} \) for constant sensitivity. The strength of the fiber being directly proportional to \( a \), and the tension applied being proportional to mass supported, or \( r^3 \) then there will be some minimum allowable strength which will be directly proportional to \( r^3 \). Hence as \( r \) is reduced with sensitivity kept constant, the fiber becomes relatively stronger. It then appears that a small size for the magnets is desirable to produce a short period and hence rapid operation, and this small size will also lead to a more rugged instrument.

The moment of inertia, \( I \), was considered to be that of the magnets alone. This situation can be roughly
approximated for magnets large compared with the rest of the suspension and mirror, and as magnet size is reduced, the diameter of the bar to which they are fastened may also be reduced. The mirror, however, may not be reduced in size indefinitely without loss of resolving power or effective shortening of the light beam which leads to loss of sensitivity.

Magnet spacing

In equation (1), the sensitivity of the magnetometer was calculated as if the field $H$ acted on one magnet only. If the sample to be measured is placed on the line which passes through the centers of both magnets, and is at a distance $r_1$ from the lower magnet and $r_2$ from the upper magnet, $r_1 < r_2$, then it can be shown that the action of its field on the upper magnet reduces the sensitivity given in (1) by a factor $1 - \left( \frac{r_1}{r_2} \right)^3$. Then it can be seen that if $r_2$ is more than twice as big as $r_1$, loss of sensitivity compared with the sensitivity at infinite magnet separation is small. Since the effect on the instrument of non-uniform stray fields becomes less as magnet separation is decreased, it is desirable to place
the magnets as close together as possible. The magnet separation can then be determined by finding what distance \( r_1 \) the weakest samples must be from the lower magnet to produce a measurable deflection of the suspension, when \( r_2 \) is much greater than \( r_1 \). When this value \( r_1 \) is found, \( r_2 \) can then be reduced, e.g., such that \( r_2 = 3r \), without serious loss of sensitivity. The magnet separation is, of course, \( r_2 - r_1 \).

**Balancing of magnets**

It has been assumed so far that the magnets are of equal magnetic moment, exactly oppositely directed. Loss of sensitivity results if this is not the case, so that it is important to attain this situation of balance as nearly as possible. The method used to achieve this, although crude, proved to be reasonably effective. The magnets used were cylindrical with the magnetic moment approximately, but not necessarily exactly, along the axis of the cylinder, and were mounted so that these axes were parallel with each other and perpendicular to the bar supporting them. The magnets could be rotated about their cylindrical axes, so that if the magnetic moment of one magnet did not lie exactly along the cylindrical axis of that magnet, it could be rotated into a position in which
it at least lay in the same plane as that of the other magnet. The relative strength of the magnets was adjusted by placing bits of iron wire along the side of the stronger magnet, reducing its effective magnetic moment until equal to that of the other magnet. When a small rotation of the support of the suspension fiber caused an equal rotation of the magnet suspension when the magnets were acted on by the field of the earth, the magnets were considered to be in balance.

**Description of magnetometer**

**Magnets:** Material - Almico V; Length - 3/16";
Diameter - 1/8"; Spacing - 2"

**Mirror:** 9 mm. square, .5 mm thick front surface mirror.

**Suspension fiber:** Material - Nylon; Length - 150 mm.;
Diameter - .02 mm.

**Damping:** Copper cup around lower magnet.

**Light Beam:** 8 feet from magnetometer mirror to scale.

The magnetometer is shown in fig. 23B.

**Effect of Earth Field**

While with a properly balanced magnetometer the earth field, being essentially uniform, should have no effect on
the instrument, it is customary to remove the effect of the earth field in the region of the instrument with an equal and opposite magnetic field produced by Helmholtz coils. This was found to be unnecessary for the low-sensitivity use of the instrument in this study.

The effect of reversible magnetization induced in the sample by the earth field was removed from the measurements by setting up the magnetometer in such a way that the plane defined by the magnetic moments of the magnets contained the line of the earth field, when the magnets were in rest position. Thus the magnetization induced in the sample had no effect on the movement of the magnets.

To avoid stray magnetic fields and curvature of the earth field, the magnetometer was housed in a small house made of wood and fastened with aluminum nails. This house was 300 feet from the nearest dwelling and 30 feet from a fox-wire fence. This avoidance of ferromagnetic materials was somewhat unnecessary, although it was found impossible to use the magnetometer in building 20, both because of stray fields and building vibration.
FIG. 23
MAGNETOMETER

A

S

N

magnet

mirror

N

S

magnet

magnet suspension

full scale

B

suspension fiber

magnet suspension

window

copper damping cup

one half scale
Appendix III

Method of Measurement

The sample to be measured is centrally placed on a rotating stage under the magnetometer, the axis of rotation being coincident with a line through the center of both magnets, and the angle of rotation being measurable with the aid of an attached circle. The stage may be moved vertically so that the sample center can be placed from 1" to 6" from the lower magnet. For magnetic direction measurement, a reference axis on the sample is located with respect to the scale on the stage. With the sample at its lowest position, the position of the light beam is noted. The sample is then raised and rotated until the light beam returns to its original, or "zero" position. The horizontal component of the magnetic moment of the sample is then parallel to the magnetic moment of the lower magnet; in either of the two possible positions. These two positions are easily distinguished, and, knowing the polarity of the lower magnet, the polarity of the sample may be identified. The angle which this component of the magnetic moment makes with respect to the reference axis of the sample may then be determined from the degree scale. A similar measurement made with respect to a
different reference axis in the sample would be sufficient
to determine the direction of magnetism in the sample. A
number of possible sources of error can be eliminated,
however, if a larger number of measurements is made. In
practice, both polarities of magnetic direction are measured
for each of the six faces of the sample facing upward.

Errors caused by improper position of the scale pointer,
eccentricity of the sample's magnetic center, and non-
coincidence of the center of the stage with the center line
of the magnetometer are averaged out by this means. Errors
caused by drift in the instrument, hysteretic behavior of
the suspension fiber, and effect of the sample on the magnet
when the former is at its lowest position may be removed
by repeated raising and lowering of the sample near each
of its "zero" positions.

Since six orientations of the sample were required
for each complete measurement, the position occupied by
the operator during measurements was placed within reach
of the sample. The body temperature of the operator
appeared to have no effect on the magnetometer, and it was
only found necessary to remove magnetic material from the
pockets before making measurements.
Bibliography

Becker, J.J. *J. Metals* Vol. 9 p. 59 (1957)


Blackett, P.S.M. *Lectures on Rock Magnetism* Weizmann Science Press, Jerusalem (1956)


Clegg, J.A. Almond, K. and Stubbs, P.H.S. *Phil Mag* Vol. 45 p. 583 (1954)


Crosby, W.O. *Am. Geol.* Vol. 8 p. 72 (1891)


Dorsey, G.E. *Jour. Geol.* Vol. 34 p. 131 (1926)


Haigh, G. *Phil. Mag.* Vol. 8 Ser. 3 p. 267 (1958)

Martinez, J.D. and Howell, L.G. Nature Vol. 178 p. 204 (1956)
Mencher, E. (private communication) (1960)
Nagata, T. Rock Magnetism Maruzen, Tokyo (1953)
or Adv. in Phys. Vol. 4 p. 113 (1955)
Nicholls, G.D. Adv. in Phys. Vol. 4 p. 113 (1955)
Rimbert, F. Thesis Universite de Paris (1959)
Runcorn, S.K. Adv. in Phys. vol. 4 p. 244 (1955)
Twenhoffel, W.H. Treatise on Sedimentology p. 283 Williams and Wilkins (1932)