Table 1. Mean differences between responses before and after exposure and standard deviations for three experimental conditions.

Condition	Difference (cm)	Standard deviation
E	+ 2.53	5.5
C_1	+ 0.56	5.6
C_2	+ .38	4.3

responses are made at O during the exposure of the hand when the left eye is used, then this direction of response would be expected to persist without visual guidance after the exposure period.

For this experiment the distance RY was 12 cm and that of YP was 25.5 cm. Assuming an interpupillary distance of 6 cm the distance LO was 41.5 cm and OP was 12.5 cm.

With feet in a fixed position and head immobilized in a support so that the eyes were 12 cm above the plane of an aperture 9.5×7 cm, 12 subjects (group E) were required to make 5 dots directly beneath the marked center without visual guidance before and after an exposure period. The right hand was used throughout. For the kinesthetically controlled centering responses before and after exposure, a cover bearing a central mark coincident with the left-right center of the aperture was placed over the opening and dots were made on the surface below so that they were judged to be in vertical alignment with the center mark. For the exposure period the cover was removed and the subject now viewed his right hand through the opening with his left eye. The right eye was covered. Thirteen dots, one every 13 seconds, were made on separate sheets of paper so that they were judged to be in vertical alignment with the center. The center was indicated by a line coincident with that on the cover used for the responses before exposure. Thus in the phases before and after exposure the position beneath the center of the aperture (which was covered) was judged kinesthetically and during the exposure period visual-kinesthetic judgments of the same position were made with only the left eye being used.

There were two control conditions. Since maintained motion of a limb in a given direction can result in a sensory spatial aftereffect (*3*), another 12 subjects (group C_1) performed the tasks before and after exposure but during the intervening period the aperture cover was left in place and the limb moved in the same manner as for the first group. Since it was also conceivable that maintenance of eye-position in one direction during the exposure period could alter apparent visual directions, a third group of 12 subjects (group C_2) merely observed their resting limb through the aperture for the same period. For all three conditions responses before and after exposure were the same.

A change in an expected direction occurred for E but no such change occured for either C_1 or C_2 (Table 1). An analysis of variance of the differences between the responses before and after exposure, the means and standard deviations of which are shown in Table 1, showed that over all groups there was a significant difference in the changes between groups ($P < .001$). Ancillary tests (*4*) indicated that compensatory change for E was significantly different from the changes for groups C_1 and C_2 ($P < .001$) but these two latter groups did not differ significantly ($P > .05$). A t-test applied to each of the three groups showed that only the change for group E differed significantly from zero ($P < .001$).

These results show that behavioral compensation (*3*) in manual centering responses occurs when the normal spatial relationship between visual and kinesthetic input is modified by monocular viewing. The effect is similar to the commonly reported behavioral changes which occur when the responding limb is viewed for a time through a prism or a lens. That the change in responding is not due to a sensory spatial aftereffect (*3*) or to visual muscular effects is indicated by the absence of an effect for the two control conditions.

The basis for this type of behavioral compensatory change is not yet entirely clear but we suppose that with a changed spatial relationship between vision (or hearing) and proprioceptive input new responses persist for a time after normal vision is restored (*3*).

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30 January 1967

Alpha-Hematite: Stable Remanence and Memory

Abstract. *Experimental evidence suggests that the magnetization of α-Fe_2O_3 consists of a soft spin-canted moment and a hard defect moment. The former is observed in the range −20° to 675°C; the latter is maintained across the transitions that bound the temperature range of the detectable spin-canted moment and is lost at the true Neel point of α-Fe_2O_3 of 725°C. Both memory and the highest coercivity fraction of remanence in α-Fe_2O_3 are due to the defect moment.*

The remarkably high remanent coercivity of α-Fe_2O_3 ensures that the natural remanent magnetization (NRM) acquired by certain rocks during their formation is magnetically stable. Magnetization acquired by hematite in Earth's magnetic field of approximately 0.5 oersted sometimes proves stable against demagnetizing fields of thousands of oersteds. This stability is important in paleomagnetism, by which one attempts to study the history of Earth's magnetic field from the NRM of rocks. Unfortunately, not all the magnetic minerals in rocks exhibit such high stability; nor indeed is the entire remanent moment of hematite magnetically hard. Therefore the possibility arises of magnetic noise caused by remagnetization of soft phases by modern fields.

To enhance the signal-to-noise ratio, the soft fraction of remanence carried by low-coercivity phases in the rock is usually demagnetized, and the magnetically stable fraction alone is measured. Specimens are demagnetized by exposure to a slowly decreasing a-c field or by heat treatment. A simpler method of progressive demagnetization has been suggested (*1*), using the remarkable recovery phenomenon associated with such magnetic transitions as the Morin transition of hematite.

The term memory (2) describes the recovery of remanence in thermal cycles crossing the transition (Fig. 1). The implicit basis of the proposed method is that there is a relation between stable remanence and memory. In considering the possibility of such a relation, it is convenient to distinguish two representative types of remanent magnetization: (i) thermoremanent magnetization (TRM), which is acquired by materials cooled through their "Curie points" in the presence of a magnetic field; and (ii) isothermal remanent magnetization (IRM), which is acquired on exposure to magnetic fields at constant temperature.

Weak-field TRM is predominantly stable against demagnetization; a field greater by orders of magnitude than the inducing field is necessary to reverse the magnetization entirely. In contrast, IRM is destroyed by fields comparable to the inducing field. Weak-field TRM may be taken as the classic example of stable remanence. Memory is like weak-field TRM in that it is predominantly a high-stability magnetization; moreover the ratio of the memorized moment to the initial remanence is larger for weak-field TRM than for IRM (3).

Kobayashi and Smith (4) recently demonstrated that the reversible susceptibility of hematite is independent of the intensity of weak-field TRM and of memory, but decreases almost linearly with IRM; thus weak-field TRM and memory appear to be related and must be carried largely by a high-coercivity fraction of hematite that can be magnetized by the IRM process only in fields approaching the saturation value. The state of magnetization of this hard fraction does not affect the wall motions or rotations associated with reversible susceptibility.

Explanation of the magnetic properties of α-Fe_2O_3 involves two problems: (i) the origin of the observed ferromagnetism in a supposedly antiferromagnetic material; and (ii) the nature of the magnetization processes that account for the observed spectrum of remanent coercivities. It is suggested (5, 6) that the weak ferromagnetism is due to uncompensated antiferromagnetic domain walls; such walls are pinned to lattice imperfections, because only in the presence of the imperfection are they energetically favorable in α-Fe_2O_3.

In contrast with this model in which lattice defects play a crucial role,

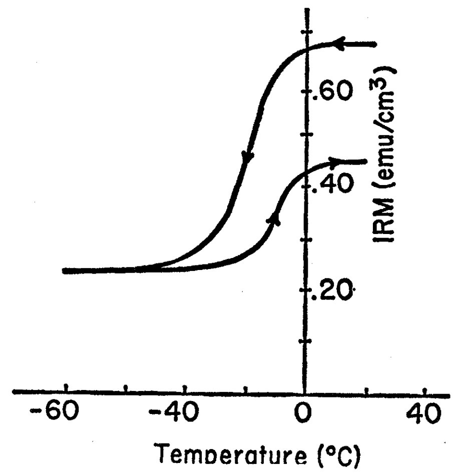

Fig. 1. Memory of remanence exhibited by α-Fe_2O_3 in thermal cycle across the Morin transition. *IRM*, isothermal remanent magnetization.

the Dzyaloshinsky-Moriya spin-canting model explains the ferromagnetism observed between the Morin transition (−20°C) and the Curie point (675°C) as a fundamental property of α-F_2O_3 implicit in its magnetic symmetry (7–9). The spin-canted moment arises from a slight departure from an antiparallel configuration of the spins in the two sublattices of hematite.

We now suggest that the magnetism of α-Fe_2O_3 is due to a hard defect moment present at all temperatures below the true Neel point of hematite (725°C) and to a softer spin-canted moment. Although the spin-canted moment dominates between the Morin transition and the Curie point, in this temperature range the stable fraction of remanence is due to the defect moment.

On the basis of differential thermal analysis (DTA), Aharoni *et al.* (9) have given a new interpretation of the magnetic behavior of hematite at high temperature, which has led to our explanation of the stable fraction of remanence. They proposed that the true Neel point of stoichiometric hematite is 725°C, approximately 50°C above the Curie point. They suggested that at the 675°C transition a sixfold anisotropy in the basal plane changes sign, thereby rotating the spin-canted moment by 30 deg, a suggestion justified by the similarity of the Morin and 675°C transitions in the DTA curves. They noted that if there is an asymmetry in the basal-plane anisotropy, such that the potential wells are broader than the maxima below 675°C, the observed sharp drop in magnetization is explicable: the spin-canting moment would be much reduced by the increase in anisotropy energy against which the spins must turn.

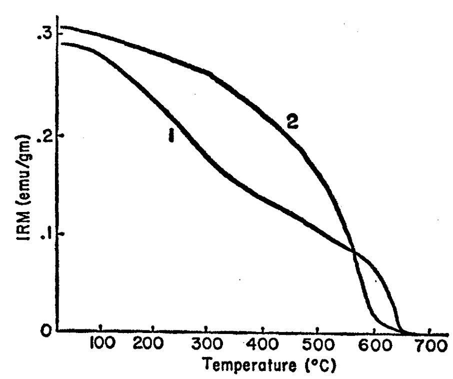

Fig. 2. Thermal demagnetization of saturation isothermal remanent magnetization.

Figure 2 shows the manifestation of the two transitions observed by Aharoni *et al.* (9), in a curve of saturation remanent magnetization against temperature; these continuous curves of thermal demagnetization were obtained with a vibration magnetometer (*10*). The specimen is a natural crystal from Saint Gothard (4, specimen 23) containing 8 percent Ti. Curves of saturation magnetization versus temperature, obtained by Kawai, have also revealed the two transitions; he noted that the separation as well as the absolute values of the transitions depends on the Ti content (*11*). Curve *1* of Fig. 2 represents the initial heating of the specimen. We see that the saturation IRM is lost at the Neel point of 650°C, which is approximately 40°C higher than the Curie temperature of 615°C, which was measured independently with a Kawai balance (*12*). Curve *2* is a repetition of the first experiment; it shows enhancement of the spin-canted moment and progressive loss of the high-temperature moment. "High-temperature moment" describes the magnetization observable above the temperature range of detectable spin-canting—for example, in the range 675°C $< T <$ 725°C for stoichiometric α-Fe_2O_3. Annealing, inherent in the experiment, destroyed a significant fraction of the high-temperature moment which is, therefore, clearly structure-sensitive.

The high-temperature moment can be shown to have a higher microscopic remanent coercivity than has the spin-canted moment. At room temperature one places the hematite in a field of 1.1×10^4 oersteds and then in a reverse field sufficiently strong to switch the direction of the bulk magnetization (that is, $|-H| >$ bulk remanent coercivity); and one observes the thermal-demagnetization curve of the composite magnetization. The spin-canted moment (Fig. 3), which can be seen below 612°C, is in the sense of the smaller negative field, but the high-temperature moment retains the direction of the original field of 1.1×10^4 oersteds, so it was not switched by the negative field. Samples containing less than 0.05 percent Ti have yielded similar curves, and the transition temperatures found agree with those described (*9*). These experiments show that high-coercivity remanence at room temperature is associated with the high-temperature moment and not with the spin-canted moment.

A small low-temperature moment, observable below the Morin transition, has been reported (*13*); it is known to be sensitive to impurity atoms (*14*) and oxidation-reduction effects (*15*). We have correlated it with the high-coercivity fraction of remanence at room temperature in this way: The specimen was again placed successively in the field of 1.1×10^4 oersteds and in the smaller, negative field; thus the hard component was again set in the opposite sense to the soft spin-canted moment. When the specimen was cooled to below the Morin transition, the spin-canted moment disappeared. The small low-temperature moment proved to be in the direction of the first field, so it had not been reversed by the field that switched the spin-canted moment. Thus the low-temperature moment is associated with the high-coercivity fraction of remanence at room temperature.

The magnitude of the low-temperature moment in specimen 23 (*4*) was 0.03 emu/g. This intensity was measured immediately below the Morin transition and is the same as the value of stable TRM defined for the specimen by the reversible-susceptibility experiment (*4*). Alternating-current demagnetization of memory in this specimen revealed a small soft moment ($H_c < 50$ oersteds) and a stable moment of 0.03 emu/g ($H_c \gg 50$ oersteds).

Thus it apears that stable remanence and the stable part of memory can be quantitatively explained by the structure-sensitive moment. This magnetism is seen below the Morin transition as the low-temperature moment; above the Curie point as the high-temperature moment.

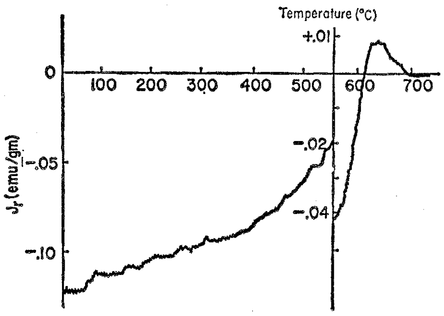

Fig. 3. Demonstration of high-temperature moment in α-Fe_2O_3 (containing 8 percent Ti) between the Curie point (615°C) and the Neel point (650°C), and its high coercivity.

To study the spectrum of coercivity of the structure-sensitive moment, we must isolate it from the spin-canted moment. Moreover, for experimental convenience, one would like to do this at room tempearture. A possible method would be use of a-c demagnetization, but the fields necessary to define the entire spectrum of coercivity are prohibitively high. Therefore, we observed the field dependence of the displacement of hysteresis loops of a specimen carrying high-field IRM (field of 1.1×10^4 oersteds); the specimen was from the same hand sample as was the one in which we first demonstrated the structure-sensitive remanent moment (Fig. 2, curve *1*). Thus the spin-canted moment was inhibited and the structure-sensitive moment was more-than-usually prominent. When the specimen was magnetized in a field of 1.1×10^4 oersteds, both spin-canted and structure-sensitive moments were set. Hysteresis loops were then obtained, first in low fields of the order of 100 oersteds and then in progressively higher fields.

In the low fields the loops were substantially displaced along both *J* and *H*; in higher fields, of the order of 1000 oersteds, the displacement decreased, but even at 3000 oersteds the loop was not perfectly symmetric [$|H(+) - H(-)| = 30$ oersteds; $|J(+) - J(-)| = 10^{-2}$ emu/g]. The low-field loops reveal a soft component having a coercive force of less than 100 oersteds.

From the earlier experiments, which demonstrated the low coercivity of the spin-canted moment, we interpret the low-field loops as predominantly an expression of the spin-canted moment. In contrast, the displacement of these low-field loops indicates the presence of a moment in the direction of the initial field of 1.1×10^4 oersteds. The persistence of the displacement in the high-field loops shows that the high-coercivity structure-sensitive moment is not entirely demagnetized by a 3000-oersted field. Thus the microscopic coercivity of the structure-sensitive moment extends to thousands of oersteds and is therefore sufficiently high to account for stable remanence.

The precise relation between the spin-canted and the structure-sensitive moments is not clear. We attempted to demonstrate nucleation of the alignment of the spin-canted moment by the structure-sensitive moment: Hematite was field-cooled to its Curie point at 675°C before the cooling was continued to room temperature in zero field; no evidence of alignment of the spin-canted moment by the high-temperature structure-sensitive moment was seen. (This failure may reflect elimination of the structure-sensitive moment by the heat treatment, or a shielding effect of the soft spin-canted moment.)

When attempts were made to observe the nucleation of memory by the low-temperature moment, nucleation was seen, but the pattern was not simple. For example, if a specimen was again placed successively in the field of 1.1 $\times 10^4$ oersteds and in the smaller, negative field, the sign of the memory could be switched independently of the sign of the low-temperature moment. Nevertheless, the relations between the magnitude of the negative field, the low-temperature moment, and the memory were systematic and can be interpreted by the following simple model. The low-temperature moment is carried by local regions whose coercivity is proportional to their volume. The magnitude of the low-temperature moment therefore equals the product of the number of the regions and their average size.

The memory is nucleated in a manner that is relatively insensitive to the volume of the nucleating center and is, therefore, only critically dependent upon the number of centers. Thus, in the experiment involving the same pair of fields, the low-temperature moment is the sum of the positive magnetization of large, high-coercivity regions and the negative magnetization of smaller, low-coercivity regions. Depending on the ratio of the number of positive to number of negative regions, memory nucleates as either a positive or negative moment at the Morin transition. Therefore memory can be either positive or negative when the low-temperature moment is positive.

The experimental results have demonstrated a high-coercivity structure-sensitive moment that occurs in supposedly antiferromagnetic hematite; this we interpret as a form of defect ferromagnetism which we consider to be due to local departures from the truly self-compensating antiferromagnetic configuration. It is maintained across the Morin transition and the Curie point, which bound the temperature range within which detectable spin-canting has been described. The defect ferromagnetism is lost only at the Neel point of hematite. This interpretation does not preclude the existence of a small spin-canted moment above the Curie point, but denies the importance of any such moment in the phenomena we have studied.

If a defect moment occurs in α-Fe_2O_3, it is not likely to be an isolated phenomenon; for example, we would expect to find a similar moment in Cr_2O_3, which is isomorphous with hematite. Moreover, the presence of a moment in Cr_2O_3 would more clearly demonstrate defect ferromagnetism because Cr_2O_3 has fully compensated Dzyaloshinsky-Moriya spin-canting (*7*). The Neel point of Cr_2O_3 is 37°C. When we attempted to observe the predicted moment at low temperature, hysteresis was seen at −196°C in a commercial powder; the remanence in the quenched state was 2.9×10^{-3} emu/g and in the annealed state, 1.7×10^{-3} emu/g.

Thus this magnetic moment in Cr_2O_3 is structure-sensitive. The recovery of the initial annealed value, after a second anneal following the quench, suggests that we are not observing changes in grain size that might otherwise explain the moment (*16*). We interpret the presence of a moment in Cr_2O_3, and its structure-sensitivity, as confirmation of the idea of defect ferromagnetism in this material and in α-Fe_2O_3.

The origin of the defect ferromagnetism is not established. We noted previously that Li (*5*) and Jacobs and Bean (*6*) considered the polarization of antiferromagnetic walls pinned by dislocations as the origin of such a moment. However, a severe objection to this mechanism is that the pinning of the walls restricts changes of net remanence to the movement of Bloch lines (*6*). Jacobs and Bean (*6*) and, more recently, Meiklejohn (*17*) and Roth (*18*) have suggested that "ferromagnetism" may occur in antiferromagnets because of the local breakdown of antiferromagnetism in the vicinity of lattice defects. The regions of ferrimagnetism, which are held responsible for the "ferromagnetism," are considered to be in exchange coupling with the antiferromagnetic lattice.

The idea of ferrimagnetic regions coupled by exchange to the antiferromagnetic spins is attractive in hematite because it appears that memory would be a natural consequence of the proposed mechanism; when the antiferromagnetic spin configuration changes at the Morin transition, there will be a change in the spin coupling of the ferrimagnetic region to the antiferromagnet. This transition zone of perturbed spins between the ferrimagnet and the antiferromagnet could determine the variation of remanence in thermal cycles [see Iwata (*19*)].

Nevertheless one should note that the high remanent coercivity of the pinned regions must be due to their inherent anisotropy. Exchange anisotropy can couple the ferrimagnetic regions to the antiferromagnet, but it cannot couple the ferrimagnet tightly to the lattice because the anisotropy in the basal plane of hematite is low. We therefore conclude that stable remanence in hematite is due to small ferrimagnetic regions caused by lattice imperfections, and that memory arises because of a transition zone of spins that couple the ferrimagnetic regions to the antiferromagnet.

The geophysical significance of this work lies in the insight it may give to the NRM of rocks. It is immediately clear that, although a defect moment is magnetically stable, it is sensitive to lattice adjustments and therefore could be relatively unstable mechanically. Thus we should expect changes in remanence if the concentration or configuration of defects changes. Such change may be caused naturally during geological time by transient stress fields, radiation effects, or heating. We may learn to recover information about these factors. Moreover, although the defect moment could introduce some difficulty into paleomagnetism, it is also possible that the range of materials that may be used paleomagnetically may be extended to include antiferromagnets having suitable Neel points (for example, FeS). Defect ferromagnetism may also occur in ferrimagnets, although it would not be so evident as in the antiferromagnets or hematite.

In the light of these ideas and the reported weak remanence of alkali halides (*20*), perhaps the question of which naturally occurring materials may carry interesting magnetic information should be considered in a wider setting than hitherto.

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21. We thank K. Kobayashi whose work made our study possible; E. R. Eller, Carnegie Museum, for the loan of samples; and members of the Earth Magnetism group, Department of Earth and Planetary Sciences, University of Pittsburgh, for many helpful discussions.

6 February 1967; 27 March 1967

Mitosis: On the Mechanism for Invariable Sister Chromatid Segregation

The report of Lark, Consigli, and Minocha (*1*) on the nonrandom segregation of sister chromatids during mitosis of embryonic mouse cells carries much significance for an ancient puzzle: What makes sister chromatids almost invariably go to opposite poles during normal mitosis?

The data of Lark, Consigli, and Minocha reveal that at, or after, the second mitosis following the administration of ^{3}H-thymidine to a cell culture, the radioactivity in DNA is distributed unequally and nonrandomly among progeny nuclei. Their interpretation, which seems most reasonable, is that their data reflect the following mechanism: "When the con-