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# THE INTENSITY OF THE EARTH'S MAGNETIC FIELD IN THE HISTORICAL AND GEOLOGICAL PAST*

The authors suggest here a method for investigating the remanent magnetization of ancient vases and bricks. These measurements were used for determining the intensity of the earth's magnetic field of times past during which the investigated objects acquired their magnetization. A consistent and steady decrease of the earth's magnetic moment during the past two thousand years becomes evident; in some regions this decrease reaches 65%.

The methods proposed by the authors take into consideration all external influences during the magnetization process, and provide in particular, a way for eliminating the effect of repeated heating, the so-called "temperature cleaning" method.

The secular variations of the main magnetic field of the earth would be almost unknown if we would have to rely on direct measurements only. The earliest of these (very incomplete) date back to a comparatively late period, the 16th century. As we know, the study of the magnetization of igneous rocks or baked clays as well as of sediments allows us under favorable circumstances to measure indirectly the earth's magnetic field as it existed during the time of formation of these rocks. The problem of determining the magnetic field of the past is divided into two separate issues: (1) the historical and prehistorical epochs for which it can be hoped to retrace the changes of the magnetic field from century to century, and (2) distant geological epochs for which we examine the mean magnetic field over very long periods of time. In the first case we apply the term "archeomagnetism," in the second case, "paleomagnetism."

More often, the entire attention is focused only on the direction of the ancient field. This does not mean, however, that the intensity of the field is entirely without interest. The fact is that it is much more complicated to determine the intensity than the direction of the magnetic field. This explains why, until recently, this problem was little attractive to scientists.

Before reviewing the work done in this field, let us discuss first the earlier, more or less indirect and purely qualitative, experiments. Thereafter we shall present the results of our direct and quantitative investigation. First of all let us take a look at some of the principal magnetic and mineralogical characteristics inherent to rocks and baked clays.

## The Magnetic Properties of Rocks Pertaining to the Analysis of Their Natural Magnetization

### Magnetic Mineralogy

The minerals which are the bearers of residual magnetization occur as anisotropic ferromagnetic grains of all sizes, dispersed in a practically nonmagnetic medium which can acquire weak inductive magnetization only.

Magnetic mineralogy is being more and more accepted in the study of the magnetic properties of rocks.

The list of the diverse magnetic minerals has been increased considerably, and research in this field, both experimental and theoretical, has been expanded lately. Of special interest are the titanium-magnetite and ilmenite-hematite families.

The microscopic mineralogical complexity of a piece of rock the size of a hand specimen may be disregarded provided a sufficiently large portion of the rock compared with the volume of the largest magnetic grains is analyzed. It is therefore recommended in case of natural bodies to use relatively large specimens, on the order of one cubic decimeter. Due to the static effect (the demagnetization field of this shape is frequently very weak) the mean moment of remanent magnetization developing through the influence of the magnetic field has the same direction as this field. Since the mean intensity of magnetization may vary considerably from one specimen to the next, quantitative comparisons should be based only on magnetic moments developing during successive magnetizations of one and the same object.

## The Various Types of Remanent Magnetization

Rocks and baked clays are capable of acquiring different kinds of remanent magnetization. The experimental study of the laws of magnetization and of the characteristics of the various kinds of magnetism has been for a long time one of the research projects of our laboratory [25-29, 31, 35, 36, 39, 40]. The letters ARI (normal remanent magnetization)† shall denote the magnetization of a previously demagnetized specimen after it has been exposed to the influence of the field H for a short time interval, for instance, one minute (this shall be arbitrarily our unit time). The magnitude of specific remanent magnetization $\sigma_r$ increasing

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*Izv. Geophys. Ser. 1959, pp. 1296-1331, translated by I. A. Mamantov.

†The French abbreviations ARI, ATR, ARA are used instead of NRM, TRM and IRM respectively (Transl. Ed.)

ARI = TRM
ATR = TRM
ARA = ARM

during paleomagnetic investigations. Two conclusions which specify our method of investigation can be drawn from the large amount of experimental data concerning the changes which occur during heating.

1. Baked clays are usually either only very little sensitive or completely non-sensitive to heating. This can be explained by the fact that under natural conditions clays are formed through the slow, often longlasting and high temperature heating of the original minerals. This stabilization offers numerous opportunities for research.

2. Igneous rocks which interested us insofar as they open a door into the remote past did not yield a single case of good stability.

### Mineralogical Changes in Time, Induced or Spontaneous

Ancient rocks, igneous or sedimentary, could occur at depths of several kilometers. This caused them to become metamorphosed which led to considerable changes in their minerals. Near-surface rocks are subjected to chemical influences which may also change substantially their magnetic minerals. The results of this influence show up clearly as an increase in susceptibility of the soil to a depth of several centimeters beneath the surface, as Le Borgne discovered [20]. In addition to changes caused by physical or chemical influences we have to consider the possibility of spontaneous changes as a result of gradual transition from a metastable to a stable equilibrium. The phenomenon of exsolution of hard titanomagnetites studied by Kawai and his students [15] becomes extremely important from this point of view.

The first result of these mineralogical changes is somewhat analogous to what we observe during gradual heating. The rock we use for our experiments in order to compare its natural and artificial magnetizations, is no longer an original rock.

The second result of the mineralogical changes lies in a modification of the original magnetization regardless of the magnetization mechanism. For one, the minerals which are the bearers of magnetization lose it during their transformation; this may lead to the formation of weakly magnetic though highly magneto-susceptive rocks. On the other hand, the minerals which are formed acquire a parasitic magnetization since their crystal lattices develop very slowly in the earth's magnetic field. This magnetization stipulated by crystallization, artifically created recently by numerous scientists [4, 9, 12, 19, 21], can play an important role in rocks with very weak natural remanent magnetization. These changes of the original magnetization caused by mineralogical transformations are furthered, apparently, by the direct influence of physical agents - the earth's field itself which induces ARV, temperature changes which cause partial demagnetization and the development of new ATR during the cooling process; pressure [7], and, finally, lightning causing the appearance of intensive ARI due to the momentary field of the electric discharge (which renders the surface rocks frequently unusable).

## Review and Discussion of the Qualitative Experimental Investigations of the Intensity of Magnetization

### Results Obtained by Koenigsberger on Volcanic Rocks

One should think that a careful qualitative and quantitative determination of the ferromagnetic components of a volcanic rock or clay would allow a prediction as to its magnetic behavior and to determine the intensity $F_0$ of the earth's magnetic field by measuring the natural thermo-remanent magnetization $\sigma_r$. It is, however, not possible to establish such a relationship.

Indirect method based on the magnetic susceptibility. We may have a different approach available if we use the magnetic susceptibility $\kappa$ of the rock which can be measured easily and which depends, like $\sigma_r$, on every structural detail of the magnetic minerals. If we had a constant ratio Q, linking $\kappa$, the susceptibility of induced magnetization and the ratio $\sigma_r/F$ (which may be called formally: susceptibility of thermo-remanent magnetization), i.e., those values which depend solely on the nature, condition, and quantity of the ferromagnetic minerals, our problem would obviously be solved. We would also have to surmise that the minerals contained in the rock did not undergo any changes which are expressed in a decrease of $\sigma_r$ and an increase of $\kappa$ provided the newly formed minerals will be relatively magnetic.

Koenigsberger [19] measured the ratio $Q_n = \sigma_r/\kappa F$ on numerous rocks, where $\sigma_r$ is the "natural" magnetization of the specimen; $\kappa$ is its susceptibility; F is the intensity of the present field of the earth, arbitrarily put at 0.45 oersted. Thus, $Q_n$ is a parameter important for magnetic prospecting: relationship of the natural remanent magnetization of a rock to its in situ induced magnetization. Koenigsberger was particularly interested in this ratio. He found the following general regularity: the factor $Q_n$ has a tendency to decrease the older the rock. Although the author himself did not formulate this statement in that way, it seems to us that the regularity discovered by him can be considered indicative of a lower intensity of the earth's field during the earlier geological history.

Indeed, let $F_0$ be the intensity of the ancient field that caused the magnetization $\sigma_r$ which, according to our assumption, did not change. Factor Q which characterizes the specimen will then be $Q = \sigma_r/\kappa F_0$. Thus, quantity $Q_n = Q(F_0)/(F)$, proportional to $F_0$, would determine the relative intensity of the ancient field.

This conclusion holds, however, only if Q is of the same order for the entire suite of volcanic rocks. It is impossible, though, to prove this hypothesis even in rough approximation or for a limited group of rocks. Thus, one of the authors of this article used, after studying the intensity problem [33], as examples those experiments which were conducted on a single clay specimen annealed in the same field (13 oersteds), but at various temperatures and in varying media. The thus obtained values of $\sigma_r$ and $\kappa$ were used for calculating the Q factors (Table 1).

Table 1

Factor Q for One and the Same Clay Baked to Various Temperatures and in Various Media

| Temperature, °C | Medium | | |
|---|---|---|---|
| | Oxygen | Nitrogen | Illuminating gas |
| 400 | 0.95 | 1.2 | 6.1 |
| 580 | 1.9 | 2.15 | 9.85 |
| 670 | 2.75 | 3.85 | 6.15 |
| 870 | 4.75 | 13.1 | 2.0 |

Let us examine rocks of the same volcanic origin, e.g., Volvic andesite. This is a homogeneous formation the various portions of which, according to Lacroix, do not show any obvious petrographic differences. However, $\sigma_r$ and $\kappa$ of the various parts differ considerably, which, in turn, entails changes of $Q_n$ (see Table 2).

Table 2

Factor $Q_n$ at Various Points of an Andesite Flow from the Volcano Nouguer* (Volvic)

| Distance from base of lava flow, m | $Q_n$ | Distance from base of lava flow, m | $Q_n$ |
|---|---|---|---|
| 2 | 2.1 | 6 | 4.9 |
| 2.3 | 2.8 | 7 | 8.6 |
| 2.5 | 3.9 | 9 | 6.9 |
| 3 | 5.9 | 10 | 13.2 |
| 5 | 8.2 | 12 | 8.7 |

*Nuger? (Translator)

An analogous fact, based on investigations on consecutive lava flows, was described recently from New Zealand [10].

This variability of factor $Q_n$ may be caused in part by the mineralogical variations of the rocks [42], but is found also for Q during experiments with bodies obtained through accurate synthesis, for instance, rhombohedral agglomerations of iron sesquioxide or magnetite consisting of finely dispersed grains [29]. Minor variations in preparation or heating cause such prominent changes that, for instance, considerably different Q (13, 365, 598) were obtained for three specimens of rhombohedral iron sesquioxide.

*The new indirect method based on repeated thermomagnetization.* Koenigsberger tried to find the reason for the dispersion of the Q factor values by comparing each rock against itself in the following manner. In order to determine the factor $Q_n$ of the specimen he heated it to temperatures above its Curie point and measured the new thermoremanent magnetization $\sigma'_r$ and the new susceptibility $\kappa'$. Using these measurements he obtained $Q_t = \sigma'_r / \kappa' F$. This value of $Q_t$ represents in itself an actual Q of the given rock, but one which it acquired after having been heated to 600 or 700° C. If the mineralogical changes, stipulated by repeated slow heatings, are very minute, ratio $Q_{nt} = Q_n / Q_t$, computed by Koenigsberger for every rock, would be equal to $F_0/F$ and would allow the indirect determination of $F_0$.

Subjecting large numbers of volcanic rocks from Central Europe to this kind of investigation, Koenigsberger found that the ratios of $Q_{nt}$ [17, Fig. 13] of young rocks have a tendency to be around 1, i.e., to agree closely with the intensity of the present magnetic field of the earth; for rocks of Pre-Cambrian age $Q_{nt}$ becomes relatively small. Later investigations came up with analogical results [3, 11] - ratio $Q_{nt}$ for ancient volcanic rocks amounts generally to not more than a few tenths.

Let us recall Koenigsberger's interpretation of the result. Maintaining that the intensity of the earth's magnetic field, according to Einstein, must remain constant, he explained the decrease of $Q_{nt}$ (and that of $Q_n$) with the gradual eventual decrease of the initial thermoremanent magnetization $\sigma_r$. According to his opinion ratio $Q_{nt}$ would be not so much a measure of $F_0$, rather than a time measure on a geological scale [18].

Can we explain the variations of $Q_{nt}$ with changes in $F_0$ without having any evidence for the invariability of $F_0$? In this case we have to assume, for one, stability of the very earliest magnetizations, and, on the other hand, mineralogical stability throughout the repeated slow heatings, which would allow us to find the value of $\sigma'_r$ (as we pointed out, it would be impossible to assume that these conditions would be fulfilled in ancient rocks).

### Results of Investigations on Sedimentary Rocks

*Banded clays.* Johnson, Murphy, and Torreson [13] thought it possible to determine the intensity of the ancient magnetic field by conducting experiments on sedimentary rocks. Working with approximately 10,000 years old banded clays, reprecipitated after their natural magnetization had been measured, they established that the remanent magnetization of artificial banded clays is a definite and reproducible function of the intensity of a given magnetic field. Proceeding from here and assuming that the banded clays did not change after the original deposition they found that the intensities of magnetization corresponded to ancient magnetic fields of 1 to 2 oersteds.

Could these field intensity values be possibly correct for the northeastern USA of a few hundred years ago? There are many circumstances speaking against this (not to mention the possibility of a gradually acquired viscous magnetization). It should here be pointed out that the natural magnetization of banded clays is very low regardless of the (frequently substantial) content of magnetic minerals. There is not much hope that additional experiments would elucidate the significance of $F_0$ during those few ten thousands of years for which we have sufficiently dated little metamorphosed banded clays. Recent investigations [8, 16] lead to rather unsatisfactory conclusions as far as pinpointing former earth fields from these data is concerned, and we think it somewhat unlikely, that reliable quantitative results can be expected from this approach.

*Marine sediments.* Johnson, Murphy, and Torreson [13] tried to determine the magnetic intensity in cores from various points in the Pacific. Without experimenting with reprecipitation they undertook the following investigation. They placed a few small specimens cut from cores at various depths into a field of 2,000 oersteds and measured then the intensity of magnetization. They considered $\sigma_{rs}$, i.e., the normal remanent magnetic saturation based on the amount of magnetic material contained in each specimen [13]. Assuming then that the magnetization acquired *in situ* is proportional, for one, to this content, and, on the other hand, to the intensity of the effective field, these authors were able to determine older intensities $F_0$ from data based on measurements on considerably younger sediments in the present field of intensity F. They present thus (with reservations) intensity variations of the field for the last one million years [13, Fig. 17].

The following should be added to the general objections in reference to this method. The remanent thermomagnetic saturation is not directly related to the natural remanent magnetization of particles insofar as the latter depends primarily on the type of magnetization of these rocks which, disintegrating, provided the source material for the sediments. Let us assume that particles at two different levels are otherwise identical, that, however, some of them possess a very low original magnetization, others again, a very high one. Being exposed to the same field while in situ, the former will show low remanent magnetization, the latter a high one. However, hypothetically the values of ARI saturation (caused by a field of 2,000 oersteds which will practically destroy all other magnetizations) should be absolutely identical, and we may thus conclude that the specimens were post-depositionally affected by fields of extremely different intensities.

*Ancient sediments.* All recent publications concerning the orientation of the field during early geologic times (works of the English school [2]) postulate a post-depositional mechanism of magnetization the understanding of which is as yet not sufficiently clear. It is not possible at present to associate experiments to a larger or smaller degree with the deposition of banded clays for the purpose of defining the intensity of ancient fields.

### Coercive Force Methods

It can be assumed that the "resistance" of magnetization, expressed as a coercive force, depends on the intensity of the field in which it originated regardless whether we are speaking of thermoremanent magnetization, or magnetization specified by deposition or crystallization. Since the coercive force can be easily determined without heating of the specimen, shouldn't it be possible to determine the intensity of the original field by measuring this force?

This idea was adhered to by Althausen [1] who investigated natural magnetites: determination of the coercive force of natural remanent magnetization (which, we assume, is a thermoremanent magnetization) would lead us to the magnitude of the field which caused this magnetization. We need, however, for every material also a curve which presents the coercive force as a function of the magnetic field, which, in turn, requires successive heatings in order to obtain ATR in known fields. The author stresses this and points out that the magnetites underwent mineralogical changes during the slow, repeated heating process. The curves given in [1] were obtained with stabilized specimens. Their magnetization differs therefore already from the original state of natural magnetization, the subject of the investigation.

Methods based on the coercive force run into far more severe difficulties. Let us take a look at specimens with remanent magnetization. We may define the coercive force (the authors prefer the term "demagnetizing field") as that field which would be required to bring the remanent magnetization of a body down to zero. We have suggested two methods to achieve this:

(1) Use of a variable field. As pointed out before, the variable field $H_\infty$ able to cancel remanent magnetization is equal to the field which caused this magnetization, whereby in case of normal magnetization this is not dependent on the type of the body being investigated. If ATR is weak, $H_\infty$ will be large and practically independent of the magnetic field which caused this ATR; it will depend, however, on the investigated body [25, 28]. Thus the determination of the coercive force of a variable field is of value only for ARI.

(2) Cancellation of the magnetism under study by using a field with an orientation reverse to that of this magnetization whereby the intensity of the field is increased gradually until the remanent magnetization has been brought down to zero. This kind of investigation has been already conducted on clays [35], also on various synthetic and natural bodies [29]. These experiments lead to the conclusion that the process, if the initial magnetization is relatively hard (as in the case of ATR), follows a course during which the body, if its original magnetization remains stable, would acquire a reverse ARI, practically independent of the original hard magnetization. The disappearance of the remanent magnetization is not due to demagnetization, but due to the application of two independent magnetizations, equal in intensity but opposite in sign. The coercive force, therefore, does not characterize the magnetic hardness of the original magnetization, but depends primarily on the ability of the body to acquire ARI.

### The Direct Method in Case of Thermoremanent Magnetization

This method, used only in case of thermoremanent magnetization, is most simple. After measuring the natural magnetization of a body with ATR, it is demagnetized by heating to the Curie point, and the intensity of the field required to restore an ATR equal to the original natural remanent magnetization is determined. ATR appears practically proportional to the magnetizing field. Moment M of the natural remanent magnetization which, we assume, kept its original value obtained in the ancient field $F_0$, and moment M', obtained in the laboratory in the known field F, are measured. Then $F_0/F = M/M'$. This method, suggested and used by us since 1937 [33, 34], faces the same objections which have been made against the other methods: mineralogical changes with time, developing of parasitic magnetizations, alteration of minerals through heating. We used this method on baked clays which are much less sensitive toward these influences. The originality of the here described method lies in the additions (or complications) introduced by us into the original method so as to avoid these difficulties. Our improved method is quite complex but the obtained uniform results, as far as we can see, attest to its reliability.

## Qualitative Analysis. Gradual Perfection of the Measuring Method

### First Experiments Pointing to the Possibility of Employing the Direct Method

We presented in Ref. [34] the results of the first series of experiments conducted on 20 cylindrical specimens which had been cut from bricks and tiles of various age. The magnetization vector was measured with our astatic symmetrical coil magnetometer [35].

The results of the first mineralogical stability test using heat were exploited. The test proceeded as follows. After measuring in the laboratory the thermoremanent magnetization obtained in the known field F after heating the specimen rapidly to 670° C, we applied repeated heating and measured the new magnetization. The specimen was used only if both magnetizations were identical within the permissible margin of measuring error. Strictly speaking, this condition of stability is necessary but insufficient insofar as a general transformation of the mineral may occur. The probability for mineral changes to take place within such a very short time, however, is not great, and the experiments indicate that such changes, should they occur at all, require several heatings.

We made this attempt without great hopes, being well aware that magnetometric measurements on heterogeneous bodies could not be accurate. The results, however, proved to be very encouraging.

### First Quantitative Check

Abandoning magnetometric measuring during all later experiments we measured the remanent magnetization with our inductometer for high intensity homogeneous fields [35]. This eliminates the effect of the heterogeneous distribution of magnetic moments within the investigated object.

Only relatively weakly magnetic materials were used in order to avoid the influence of the demagnetization factor. It is easily seen that errors associated with the demagnetization factor become absolutely insignificant for magnetizations not much higher than $10^{-4}$ gauss.

During repeated heatings in an electrical furnace the effect of the alternating current caused by the furnace windings has to be eliminated. This could, for instance, cause parasitic ideal magnetization due to the presence of the earth's magnetic field. The furnaces built by us were equipped with permanent compensation for this alternating field [35].

Recognizing the possibility for the appearance of viscous magnetization we attempted, for one, to determine how widespread it might be so as to reject any specimen with noticeable magnetic viscosity, and, on the other hand, to correct any ensuing error for the samples left. The same problem arises if we concern ourselves with investigating the direction of the ancient field. The technique of "rotating (turning) in the earth's field" which has been used by us for over 20 years, found now widespread application. The specimens are placed in the laboratory for two weeks into the earth's magnetic field in the same orientation as they had been in situ. This restores practically their viscous magnetism, and the magnetization to be measured is the geometrical sum of the constant magnetization (which we are interested in) and the viscous magnetism. Thereafter the specimens are placed into the earth's magnetic field opposite to the original direction. They remain in this position for two weeks (180° turn around the magnetic E-W axis) and the new magnetization is then measured. We can assume that during the second two weeks the earth's field cancelled generally the first ARV of the specimen and created a new, reverse ARV. The half-sums and half-differences of both values for each of the three components of the measured magnetization are the components of the original magnetization and ARV which is created by the earth's field during two weeks. We presented examples of measurements, specimen after specimen, of the magnetizations following the direct and reversed positions in the laboratory field, in particular for specimens of Volvic andesite, which is a low viscosity rock, and for aged basalts (very viscous) [42]. Numerous similar determinations were carried out. Our so-called relative viscosity $\Delta M/M$ (M - observed thermoremanent magnetization; $\Delta M$ - ARV which developed during two weeks) is usually on the order of 1% for clay, while for hundreds of other rocks it may reach 10% or may even be well over this figure.

The latter is important for eliminating the effect of ATR reversal depending on the temperature, an effect studied by us in order to determine its importance [40], which, however, it seems, is being generally ignored.

Outside of the irreversible effects of heating, the changes in thermoremanent magnetization depend on the temperature just like the magnetic moment of any permanent magnet. If $M_t$ is its value at $t°$, and $M$ - at 20° C, we have

$$M_t = M\,[1 - a\,(t - 20)].$$

This is not unexpected, but is a consequence of temperature changes, of spontaneous magnetization, which in this case is of quite interesting magnitude: coefficient $a$ is usually on the order of 1/300, i.e., on the order of the expansion coefficient for gases. Our older measurements of magnetization have been corrected for temperature, the determination of coefficient $a$ for each specimen was, however, intricate and not very accurate. We are steering clear of this by working at a constant temperature which in our laboratory is stabilized at approximately 20° C.

In compliance with all these conditions we experimented with a set of 10 bricks baked in 1933 in an ironless furnace in a place where the intensity $F_0$ of the earth's field was known (Sainte Beuve cove on the Seine). The achieved results [37] appeared to be excellent: low viscosity, testing stability due to a sufficient number of repeated heatings, low dispersion of $F_0$ values. This led us to the conclusion that we had to use a value of 0.456 oersted for the initial field $F_0$, while the general magnetic survey of France gave a value of 0.464 oersted.

### New Indications. First Results Concerning the Historical Epoch

Our experiments with modern bricks from the St. Beuve cove contained an error which expressed itself as a decrease in $F_0$ for the initial baking. The cause of this error was concealed in magnetizations and demagnetizations stipulated by the

constant temperature changes to which the specimen was subjected.* Actually, should the magnetization created by the laboratory field F correspond entirely to the temperature interval between 670° and 20° C, the initial magnetization which is being compared with it is affected only slightly by changes in temperature.

It is easily shown that for $F_0 \gtrsim F$ the effect will without fail be directed toward a decrease.

We shall avoid the influence of changes in regular temperature during the following experiments through "cleaning" the magnetization for the purpose of eliminating thermoremanent magnetizations incurred at temperatures not much different from the regular. This boils down to a comparison of the previous against the new magnetizations acquired not between the Curie point $\theta$ and 20° C, but between $\theta$ (using hereafter always its upper limit of 670° C) and the "cleaning" temperature, for instance, 60° C in our first experiments.

This result is easily obtained if a specimen with original magnetization is heated to 60° C without external field, which gives us the old "clean" moment $M_{(670°,\, F_0,\, 60°)}$, whereafter the earth's magnetic field at 60° is removed during the cooling time by heating immediately to 670° C resulting in the new moment $M'_{(670°,\, F,\, 60°)}$. The ratio of these moments will give $F_0/F$.

Actually we prefer for certain reasons to replace the first operation with two consecutive heatings to 60° C with cooling to 20° C in the earth's field whereby the specimen is turned 180° around the magnetic E-W axis between heatings.

Thus, $F_0$ around the middle of the 18th century was found to be 0.481 oersted. The magnetic inclination at that time was large, on the order of 74° [35].

However, some interesting phenomena came to light: the natural moment did not decrease at all during heating to 60° C, while at the same time noticeable ATR developed between 60 and 20° C in the laboratory. Analyzing these facts we had to assume that these bricks had been heated some time ago to at least 60° C, which means that the value of 0.481 oersted will have to be considered the lower limit for $F_0$.

### Definitive Method (Gradual Heating)

The observation described above motivated us to raise the "cleaning" threshold to 100° C. And furthermore, we divided the interval from 670° to 100° C into a series of intervals and compared the partial remanent magnetization, both old and new, for every single one. Each interval $t_1 - t_2$ for a given object gives us an $F_0$ value, so long as $F_0/F = M_{(t_1,\, F_0,\, t_2)}/M'_{(t_1,\, F,\, t_2)}$, and, at the same time, a new criterion of accuracy for each specimen after these various values have been brought into line. This harmony could certainly not exist if the original ATR were distorted by considerable ARI (caused, for instance, by lightning) or by secondary ATR (caused, perhaps, by repeated heatings during a fire). The direction of the remanent magnetization $M_{(670°,\, F_0,\, t)}$ would change at the same time also.

From this originated the conception of the method which we have been using already for some time in studies of the temperature history of baked clays, e.g., for determining whether a construction had experienced a fire in the past, or whether crockery (pottery) had undergone some previous heating. This method may be used also for determining the heating temperature.

It is quite obvious that the $F_0$ values of the various temperature intervals will not be identical if the temperature increase causes changes of the ferromagnetic mineral components in the clays. This progressive mineralogical change can be brought to light also by a more direct method. We use here an additional control insofar as we, after determining the magnetization $M'_{(t_1,\, F,\, 20°)}$ acquired in the present field at temperatures between $t_1$ and 20°, determine again this magnetization after repeated heatings to temperature $t_2$ (which is higher than $t_1$). Mineralogical changes occurring between $t_1$ and $t_2$ can be recognized from a change of this new magnetization.

We shall bring here examples of simple cases where the temperature interval between 670° and 100° C was subdivided into 300° stages, and cases which have only few heating stages.

Example of two stage heating. Let us examine Roman title No. 13 of the time of Augustus, belonging to a lot which shall be discussed later. The directions of the axes, Ox, Oy and Oz were taken along the length, width and thickness of this tile. We shall determine the direction of magnetization in the specimen from the "inclination" I obtained from the formula $\tan I = x/\sqrt{y^2 + z^2}$ (where x, y, and z are components of remanent magnetization). We know that these Roman tiles were baked in a vertical position wherefore I is the ancient inclination if Ox was exactly vertical in the furnace in which they were baked. This angle serves only as orientation of the direction of magnetization.

A double heating to 100° C done as described above for heating to 60° C gives us the values for the components x, y, and z of the original moment $M_{(670°,\, F_0,\, 100°)}$, and of x', y', and z' of the moment $M'_{(100°,\, F,\, 20°)}$ acquired in the laboratory field F between 100° and 20° C. In the same manner we apply double heating to 300° C and obtain the components of the old moment $M_{(670°,\, F_0,\, 300°)}$ and of the moment $M'_{(300°,\, F,\, 20°)}$ acquired in the laboratory field between 300° and 20° C. Finally, heating to 670° C gives us the moment $M'_{(670°,\, F,\, 20°)}$. At this time, namely, we are also conducting control measurements so as to bring out any changes in mineralogical content. A new heating to 300° C allows us to determine the moment between 300° and 20° C acquired by the specimen in the mineralogical state which it had entered after being heated, and to compare this moment with the first value of $M'_{(300°,\, F,\, 20°)}$. We conclude this series of measurements with a second heating to 670°. Table 3 presents the values of the moments and their components in electromagnetic units.

Components y', which should be equal to zero, are caused by accidental measuring errors or, in addition, by an inaccurate position of the tile in the furnace. Obviously, there is no reason to worry about these values.

The value of I is very stable; this indicates that the original magnetization is "clean." The magnetization acquired between 300° and 20° C after the first heating to 670° C is very similar to the

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*This means reversible processes in previous measurements. It is assumed that remanent magnetization measurements are being carried out now always at a temperature of 20° C.

Table 3

Roman Tile No. 13, Heated in Stages

| t, °C | Previous Moment, e.m.u. gauss·cm$^3$ | | | | | Moment Obtained Between t and 20° | | | |
|---|---|---|---|---|---|---|---|---|---|
| | x | y | z | M | I | x' | y' | z' | M' |
| 20 | 3.835 | 1.465 | 1.750 | 4.462 | 59°15' | -- | -- | -- | -- |
| 100 | 3.550 | 1.367 | 1.555 | 4.110 | 59°45' | 0.146 | +0.019 | 0.243 | 0.284 |
| 300 | 1.533 | 0.577 | 0.702 | 1.782 | 59°15' | 0.799 | -0.027 | 1.508 | 1.707 |
| 670 | -- | -- | -- | 0.0 | -- | 1.332 | -0.056 | 2.512 | 2.843 |
| 300 | -- | -- | -- | -- | -- | 0.783 | -0.011 | 1.472 | 1.667 |
| 670 | -- | -- | -- | -- | -- | 1.349 | 0.0 | 2.536 | 2.873 |

one obtained earlier by the specimen between the same temperatures. On the other hand, the second heating to 670° C provokes barely noticeable changes. Under these conditions mineralogical stability seems to be assured.

According to Table 3, the ratio $F_0/F$ is 1.64 for the interval between 100° and 300° C, and 1.57 for the interval between 300° and 670° C. A comparison of these ratios with those of later heatings indicates that better agreement should not be expected. We can assume that the analyzed specimen has a single thermoremanent magnetization, and that the ratio $F_0/F$ corresponds to the entire temperature interval between 670° and 100° C. Since the field intensity F at the location of the furnace is 0.464 oersted, we get for $F_0$ a value of 0.74 oersted, with a possible error of a few percent.

Heating in several stages. Occasionally heating to 300° C following a main heating to 670° C enables us to detect changes in the mineralogical content. We cannot know in that case when the mineral changes initiated and the experiment has to be considered unsuccessful. This prompted us to increase the number of heatings. The method used by us presently provides for two repeat heatings after each 100° C. In order to avoid possible superposition of magnetizations repeat heatings were conducted occasionally after every 50° C. This means that very slow heating (twice) to temperature t and cooling infield F from t° to 20° is followed again by heating to t° + 50° and cooling to 20° (always), and so on.

We can construe under these conditions a magnetization curve against the temperature t which would show the changes of the original remanent magnetization $M_{(670^\circ,\, F_0,\, t)}$, and a magnetization curve showing $M'_{(t,\, F,\, 20^\circ)}$. In the particular case of "clean" ATR obtained in a field $F_0$ which is equal to F these two curves may be superimposed according to the laws of thermomagnetization since they are symmetrical to a line drawn parallel to the t-axis through their mean ordinate. If $F_0$ differs from F (we shall assume that $F_0/F = k$) superposition will occur if the second curve is changed by multiplying the values of its ordinates by k. Consequently, if we find this k value the magnetization curve can be changed by k times and reversed in order to make it coincide with the demagnetization curve. This allows the conclusion that the original magnetization is a "clean" ATR, and enables us to find the value of $F_0$ which is equal to kF.

It is not difficult to see that this reduction will be less feasible if the mineralogical composition of the specimen changes during the progressive heating. However, reduction will be feasible at low temperatures below those at which the mineralogical changes become incipient, just as reduction is impossible if the original magnetization does not represent a "clean" ATR, which may cause an increase in remanent magnetization within certain intervals with rising temperature t. This is found frequently near room temperature in view of minor secondary warm-ups to which the specimen, resp. ARI, may be exposed. It is therefore better to interconnect the middle parts of both curves, i.e., to give them an arbitrary common point, for instance, for the abscissa 300° (Fig. 1).

Fig. 1 pertains to experiments conducted with an offering vase from the temple of the goddess Tanit (Carthage), dating back to about the 8th or 7th century B.C. Due to the size of the vase it had been heated in a gas furnace the temperature of which could not be higher than 600° C, which, however, does not really matter. Fig. 1 shows the curves of the demagnetization $M_{(670^\circ,\, F_0,\, t)}$, and of the magnetization $M'_{(t,\, F,\, 20^\circ)}$ in the field of the furnace (F = 0.450 oersted), and the same curve reversed, i.e., changed by a ratio k = 1.71 and tied into the first curve (see above). This ratio which makes the curves coincide for a great length can, apparently, be used also for the determination of $F_0$ which may be equal to 0.450 × 1.71, i.e., approximately 0.77 oersted. The ends of the curves show discrepancies which can be explained as follows: minor mineralogical changes may occur above 500° C, while the effect of secondary heating is felt as we approach ordinary temperatures (see above). This heating, puzzling at first, can be explained, we feel, with the Punic offering ritual. Indeed, scientists are discovering vases filled with calcified bones and charcoal, which could have raised the temperature of the vase above 100° C if these contents were put there while hot.

## The Intensity of the Earth's Magnetic Field in the Distant Historical Past

So far we have been giving consideration to methodological discussions. In the following we shall present the obtained results arranged according to place and time.

### Gallo-Roman Epoch. France

Intensity determinations were made on bricks from two Gallo-Roman buildings which are important, though, regrettably, inaccurately dated: the Thermae of Julian in Paris (located on St. Michel Boulevard, in ensemble, including the Cluny Museum) and the amphitheater in Fréjus (Provence, St. Raphael region). The results of our studies have been partly described in paper [43].

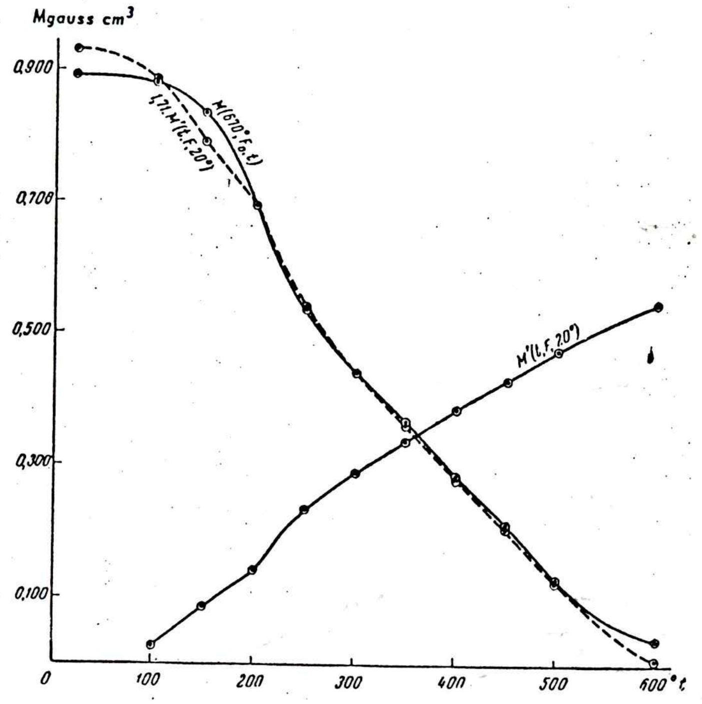

Fig. 1. Clay dish No. 13 from the sanctuary of the goddess Tanit. Magnetization and demagnetization curves

Thermae of Julian (Thermae of Cluny). The first series of intensity determinations, to which we have not attached any importance so far, was done on bricks which had been used during the first experiments on the inclination of the earth's magnetic field [35]. Of nine selected pieces the investigation of which indicated a magnetic inclination of 64° 0', six were retained for intensity studies. This investigation was done using the old method of heating to only 60° and 670° C which limited the control possibilities, and the dispersion of the derived values of $F_0/F$ appeared anomalous to us. This strong dispersion is apparent in Table 4 which presents our measurements. The question arises whether it might have been a mistake on our part to disregard these results.

We believe that the main reasons for the dispersion lie, for one, in the extremely small measured values of the magnetic moments (which entails large routine errors), and, on the other hand, in the exceptionally high magnetic viscosity of these baked clays as analyzed by us in more detail farther below.

Table 4

Thermae of Cluny (First Series of Investigation)

| Specimen No. | $M_{20}$ | $M_{60}$ | M' | M" | $M'_{60}$ | $F_0/F$ |
|---|---|---|---|---|---|---|
| 1 | 0.838 | 0.827 | 0.554 | 0.534 | 0.516 | 1.60 |
| 2 | 0.319 | 0.320 | 0.204 | 0.198 | 0.189 | 1.69 |
| 4 | 0.342 | 0.335 | 0.268 | 0.241 | 0.253 | 1.32 |
| 5 | 0.425 | 0.415 | 0.338 | 0.323 | 0.319 | 1.30 |
| 6 | 0.581 | 0.584 | 0.446 | 0.440 | 0.419 | 1.39 |
| 9 | 0.354 | 0.351 | 0.223 | 0.211 | 0.207 | 1.70 |

Note: The moments here and further on are expressed in electromagnetic units. $M_{20}$ is the original moment; $M_{60} = M_{(670^\circ,\, F_0,\, 60^\circ)}$; M', M" = $M'_{(670^\circ,\, F,\, 20^\circ)}$; $M'_{60} = M'_{(670^\circ,\, F,\, 60^\circ)}$.

Thus, if we assume that the ratio $F_0/F$ has a mean value of 1.50, and since the intensity of field F at the locality of the furnace during the time of the experiments was 0.459 oersted, we obtain $F_0$ = 0.69 oersted.

The second, more extensive, series of investigations - the results have been published in 1946 - was performed on a new lot of specimens consisting of six bricks collected at a later date from a different part of the Thermae of Cluny (the bricks were taken on purpose from a spot not too far from archeological indications of a fire in order to uncover possible repeated heatings).

This lot of bricks has some shortcomings causing considerable dispersion of the measured data, which is somewhat inconvenient for a detailed comparison. The investigated specimens, for one, have a rather irregular shape which can produce measuring errors related to the position of the bricks in the furnace. For our present investigations the specimens are, in the first place, bored out again. On the other hand, strong temperature fluctuations (climax of the organizational period) which necessitated considerable corrections were observed during these measurements. Finally, the bricks from the Thermae of Julian possess a viscous magnetization which greatly exceeds the common standards for baked clays: ratio ΔM/M, according to preliminary determinations, exceeds 5%. The effect of viscous magnetization is eliminated in our experiments by maintaining the following difficult condition: the time from the end of the cooling period to taking the measurement has to be the same in all cases.

Comparison of the demagnetization and magnetization curves for each brick enables us to recognize incidental heatings up to 120° C. This points to the necessity of increasing the "cleaning" temperature by one stage, to 180° C.

As for mineralogical stability during heating, direct tests in addition to the usual repeat heating to 670° C were conducted. However, this was done only after heating first to 670° C, for repeat determination of the magnetization $M''_{180}$ acquired by the body between 180° to 20° C which could then be compared with magnetization $M'_{180}$ acquired within the same interval after the initial heating to 180° C (See Table 5).

Table 5

Thermae of Cluny. Stability Tests by Means of Heating (Second Series of Investigations)

| Specimen No. | $M_{20}$ | $M'_{180}$ | $M'_{670}$ | $M''_{180}$ | $M''_{670}$ |
|---|---|---|---|---|---|
| 11 | 0.623 | 0.260 | 0.605 | 0.233 | 0.610 |
| 12 | 1.102 | 0.202 | 0.732 | 0.183 | 0.723 |
| 13 | 1.004 | 0.184 | 0.615 | 0.170 | 0.602 |
| 14 | 0.702 | 0.134 | 0.440 | 0.134 | 0.422 |
| 15 | 0.504 | 0.102 | 0.354 | 0.103 | 0.361 |
| 16 | 1.049 | 0.161 | 0.628 | 0.184 | 0.626 |

If we take into account the so-called "possible mistakes," these tests appear satisfactory for each of the six specimens which can be considered nonsensitive to heating. Table 6 gives the ratio $F_0/F$ for five temperature intervals which are sufficiently large in order to assure a reliable determination of the comparative moments.

Table 6

Thermae of Cluny. Ratio $F_0/F$ Within the Various Temperature Intervals (Second Series of Investigations)

| Specimen No. | 120-420° | 120-670° | 180-420° | 180-670° | 300-670° |
|---|---|---|---|---|---|
| 11 | 1.79 | 1.46 | 1.86 | 1.44 | 1.14 |
| 12 | 1.64 | 1.64 | 1.79 | 1.76 | 1.79 |
| 13 | 1.78 | 1.92 | 1.84 | 1.97 | 2.08 |
| 14 | 1.56 | 1.79 | 1.70 | 1.91 | 1.87 |
| 15 | 1.68 | 1.73 | 1.64 | 1.71 | 1.68 |
| 16 | 1.68 | 1.76 | 1.64 | 1.74 | 1.60 |
| Mean | 1.69 | 1.72 | 1.75 | 1.75 | 1.69 |

The mean value 1.75 corresponding to the interval 180-420° C, which eliminates at the same time any speculation that the original magnetization was changed by the fire, or that changes in the mineralogical content occurred during heating to sufficiently high temperatures, appears entirely plausible, although some doubts may exist since the values used for its computation show some dispersion. The ratio of 1.75 gives us a value of $F_0 = 0.404 \times 1.75$ which comes to ~0.71 oersted.

Both series of specimens from the Thermae of Cluny, studied independently with sufficiently different methods, give thus well agreeing results (0.69 resp. 0.71 oersted). These values are certainly somewhat unexpected. We should remember, however, that during the epoch when the bricks of the thermae were being baked (possibly around 200 A.D.) the intensity of the earth's field in the vicinity of Paris was close to 0.70 oersted.

As far as the inclination associated with this value is concerned, we will note that all six specimens of the first series showed 63°15' for natural magnetization and 63°30' after cleaning at 60° C, while the second series showed an inclination of 56°45' for natural magnetization (altered through the fire) and of 61° after cleaning at temperatures over 120° C. The inclination at Paris during the epoch of the construction of the thermae was therefore approximately 62°15'.

The Amphitheatre at Fréjus. We selected pieces of bricks, numbering them 6 through 16, from this structure. The results of intensity studies on the first eight pieces were published in Ref. [43]. The studies were extended later to include the remaining three pieces. Below are discussed all 11 specimens which comprise an extremely interesting series for our intensity investigations.

Actually, this series did not disclose any of the defects characteristic for the brick series from the Thermae of Cluny (shape, effect of viscous magnetization, heating during a fire). Only the effect of reversible changes in magnetization was observed, since the temperature during the measurements fluctuated by approximately 15° to 25° C throughout the entire study.

The entire series was run uniformly through heatings to 100°, 300°, and 670° C (see Table 7).

The first criterion of stability - approximate equality of M' and M'' - is fulfilled to good satisfaction, with the exception of specimens No. 11 and 12 which differ by over 5% from the mean moment, and which were therefore omitted in paper [43]. The second criterion - equality of the ratios $F_0/F$ in both the 100-300° and 300-670° C intervals for each individual specimen - is satisfactory considering that these values are the quotients of the division of two differences. Finally, the last criteria - stability of the ratios $F_0/F$ from one sample to the next is, without doubt, acceptable, regardless of the rather great dispersion of the values (1.31 to 1.80) for the total interval 100-670°, if all specimens are considered.

Thus, setting specimens No. 11 and 12 aside and adding the new Nos. 14-16, we get for this series $F_0/F = 1.60$ and $F_0 = 0.404 \times 1.60$, i.e., ~0.65 oersted. This is somewhat lower than expected; it would, however, become higher than expected if specimens 11 and 12 had not been taken into account.

Table 7

Amphitheatre at Fréjus. Stability Tests

| Specimen No. | $M_{20}$ | $M_{300}$ | $M'_{670}$ | $M''_{670}$ | $F_0/F$ | | |
|---|---|---|---|---|---|---|---|
| | | | | | 100-300° | 300-670° | 100-670° |
| 6 | 1.495 | 0.984 | 1.029 | 1.046 | 1.52 | 1.58 | 1.56 |
| 7 | 1.489 | 1.251 | 0.970 | 0.948 | 1.80 | 1.75 | 1.76 |
| 8 | 4.673 | 3.602 | 3.260 | 3.274 | 1.52 | 1.42 | 1.45 |
| 9 | 0.764 | 0.450 | 0.498 | 0.510 | 1.58 | 1.69 | 1.64 |
| 10 | 0.924 | 0.715 | 0.605 | 0.598 | 1.72 | 1.82 | 1.80 |
| 11 | ~~1.082~~ | 0.556 | 0.967 | 0.916 | 1.39 | 1.24 | 1.31 } omit |
| 12 | ~~0.985~~ | 0.774 | 0.620 | 0.563 | 1.69 | 1.73 | 1.72 |
| 13 | 1.399 | 0.661 | 0.963 | 0.957 | 1.74 | 1.43 | 1.57 |
| 14 | 1.089 | 0.769 | 0.739 | 0.716 | 1.69 | 1.58 | 1.61 |
| 15 | 4.229 | 2.046 | 2.786 | 2.793 | 1.56 | 1.58 | 1.57 |
| 16 | 0.375 | 0.224 | 0.233 | 0.236 | 1.60 | 1.60 | 1.60 |
| | | | | | 1471 | (14.45) | 14.57 -> 1.62 |

As far as the magnetic inclination is concerned, the stability of the values $I_{100°}$ and $I_{300°}$ for each specimen, calculated for "clean" magnetization at temperatures of 100° and 300° C, is very substantial, which is additional proof of the cleanness of natural magnetizations: any change either due to heating or a considerable viscosity effect would certainly cause considerably stronger deviations. The averages of three series of I are almost identical and equal 60°30', which value we shall associate with the intensity of 0.65 oersted in the Provence at the beginning of the first century.

## Roman Epoch. Switzerland

Roman tile from Augst (Augusta rauracorum). The walls from which these tiles were taken belong to "room" 45, according to the nomenclature by R. Laur-Belart, director of excavations, who believes this structure to date back to 150-200 A.D.

The magnetic inclination measured on 14 objects was 63°30'. The tile had been baked in a vertical position in accurately assembled pyramids since the dispersion of the inclinations is relatively small. This proves at the same time that the structure was not destroyed by fire, a fact which agrees with direct archeological observations.

Intensity investigations were conducted on six tile specimens which are, like the entire lot, of striking freshness. Investigation of the viscous magnetization of four of these showed a change of 1.5% in ΔM/M (where M - original moment) during only one week. This is slightly higher than the value for baked clay, but does not entail any dangerous consequences.

The experiments were conducted in the St. Maure Park Laboratory at constant temperature; the heating took place, however, in a more quiet field than in Paris, of intensity F = 0.464 oersted.

The four specimens were subjected to consecutive heatings to 100°, 300°, and 670° C during the investigation. A control heating to 300° C was inserted between two heatings to 670° C. A heating to 585° C was added to the last two specimens, followed by a control heating to 300° C. Tables 8 and 9, using customary designations, present the most important results for either case.

As a comparison of $M''_{300}$ and $M'_{300}$ shows, changes in mineralogical content occurred in the first group (specimen No. 3, Table 8). We exclude this specimen, although $F_0$ would not change noticeably even if it were left in. The remaining three specimens displayed sufficient stability.

Stability in the second group (Table 9) was good up to a temperature of 585° C. It is better in this case to limit computation of $F_0/F$ to the intervals

Table 8

Tile From Augst. Remanent and Acquired Moments

| Specimen No. | $M_{100}$ | $M_{300}$ | $M'_{100}$ | $M'_{300}$ | $M'_{670}$ | $M''_{300}$ | $M''_{670}$ |
|---|---|---|---|---|---|---|---|
| 3 | 1.210 | 1.074 | 0.030 | 0.122 | 0.820 | 0.177 | 0.777 |
| 5 | 7.208 | 4.994 | 0.429 | 1.948 | 5.140 | 1.939 | 5.165 |
| 13 | 4.110 | 1.782 | 0.284 | 1.707 | 2.843 | 1.667 | 2.873 |
| 15 | 1.469 | 0.822 | 0.116 | 0.569 | 1.111 | 0.568 | 1.102 |

Table 9

Tile from Augst. Remanent and Acquired Moments

| Specimen No. | $M_{100}$ | $M_{300}$ | $M_{585}$ | $M'_{100}$ | $M'_{300}$ | $M'_{585}$ | $M''_{300}$ | $M'_{670}$ | $M''_{670}$ |
|---|---|---|---|---|---|---|---|---|---|
| 18 | 2.879 | 1.834 | 0.013 | 0.133 | 0.738 | 1.749 | 0.731 | 1.696 | 1.660 |
| 21 | 1.912 | 1.315 | 0.082 | 0.083 | 0.494 | 1.337 | 0.507 | 1.338 | 1.327 |

Table 10

Tile from Augst. Ratios $F_0/F$ and Inclinations

| Specimen No. | $F_0/F$ | | | Inclination of Previous Magnetization | | |
|---|---|---|---|---|---|---|
| | 100-300° | 300-670° | 100-670° | $I_{20}$ | $I_{100}$ | $I_{300}$ |
| 5 | 1.46 | 1.56 | 1.53 | 64°45' | 65°30' | 67°0' |
| 13 | 1.64 | 1.57 | 1.60 | 59°15' | 59°45' | 59°15' |
| 15 | 1.43 | 1.52 | 1.48 | 57°15' | 54°45' | 54°45' |
| 18 | 1.73 | 1.81 | 1.78 | 70°45' | 70°30' | 70°45' |
| 21 | 1.45 | 1.46 | 1.46 | 68°30' | 68°30' | 67°45' |
| | 7.81 | 7.92 | 7.85 | | | |
| | 1.54 | 1.684 | 1.57 | | | |

below 585° C. Table 10 gives the ratios for five other specimens computed for those temperature intervals: 100-300° C, 300-670° C (resp. 585° C) and 100-670° C (resp. 585° C), as well as the inclinations $I_{20}$ computed for both not cleaned and clean magnetization at 100 and 300° C.

Both indirect criteria for the invariability of the mineralogical content of each specimen - for one, the equality of $F_0/F$ within the various temperature intervals, and, on the other hand, the equality of the inclinations $I_{100}$ and $I_{300}$ - are satisfactory. And furthermore, the dispersion of the ratios $F_0/F$ from one specimen to the next is moderate. We believe that once the reasons for the dispersion are known, it would be difficult to find a group of specimens with more uniform characteristics and, therefore, more realiable. Thus, the approximate intensity of the field in the vicinity of Basel in 175 A.D. was 0.73 oersted - a figure to which we relate the previously mentioned inclination of 63°30', based on the investigation of the total number of the given lot.

Tile from Aqua Helvetiae and Vindonissa, left by Roman legionnaires. Approximately 20 tiles bearing the markings of the 21st and 11th legions, collected at the site of Aqua Helvetiae (in the museum at Baden), and approximately 20 other tiles (21st legion) from Vindonissa (in the museum at Bruegge) were investigated. Our objective was to establish the magnetic inclination effective at about the middle of the Roman occupation, i.e., in 60 and 85 A.D. To our surprise we found that, although measurements on the majority of these tiles yielded acceptable inclination values (provided the tiles were baked in a vertical position), three tiles of the same lot (21st legion, Baden) gave values which exceeded the acceptable limits. We have here apparently specimens which were exposed to high heat during a fire - the possible fate of many Román tiles.

In order to corroborate this we need our method of successive heatings which can be used also for intensity measurements. We selected three tiles: one average (No. 10) and two anomalous. The investigation of the latter two revealed a difficulty of interpretation of complex magnetization which does not allow any determination of the field intensity. Only the first tile (No. 10) is of interest to us. The heatings were conducted in a field of 0.450 oersted. Analysis of the measurement results shows that there is only one original magnetization. A control test by means of heating to 350° C shows a change which is cleaned at 550° C. This change is well evident on the curves in Fig. 2, analogous to those in Fig. 1, i.e., to the case of Punic crockery, which demonstrate the dependence of changes in $M_{(670°,\ F_0,\ t)}$ and in the reverse $kM'_{(t,\ F,\ 20°)}$ (k - reduction coefficient, here equal to 1.52) on t. Our investigation of the Baden tile No. 10 gives us thus an intensity value $F_0$ for the ancient field of 0.450 × 1.52, i.e., ~0.68 oersted.

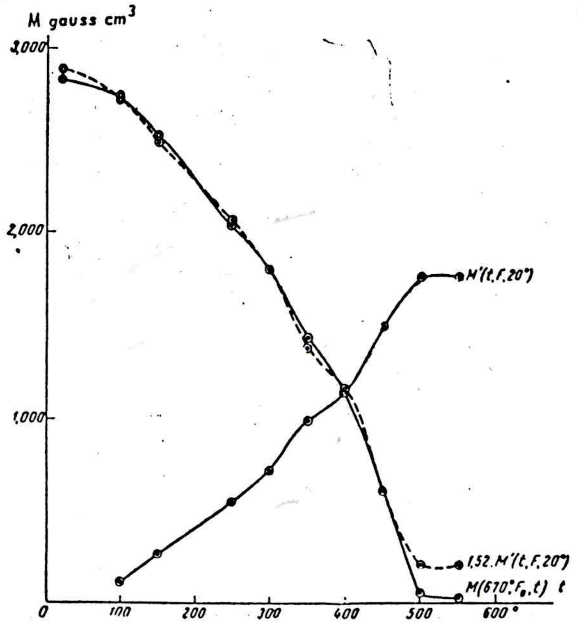

Fig. 2. Baden tile No. 10. Magnetization and demagnetization curves

Hearth stones of the Augst. epoch. We collected numerous differently oriented specimens from the bases of domestic tile hearths which had been studied by R. Laur-Belart, and which, we hoped, would enable us to determine the declination and inclination for the epoch when these stoves were abandoned. The hearths had to be very powerful so as to heat the entire thickness of the base from top to bottom, a necessary prerequisite in order that the tiles would possess only a single magnetization acquired in the position in which they were found at the time of collection. Actually we found a rather substantial dispersion of the magnetic declination and inclination values for different specimens from the same base. It was, however, observed that some tiles were getting hot faster than others. Measurements taken on these tiles yielded D and I values close to those which may be expected for the Roman epoch in Switzerland. We decided to check whether this was actually a case of single magnetization. We heated therefore a specimen (electric furnace, F = 0.464 oersted) marked according to our nomenclature as No. 25, collected from stove No. 31 which was, apparently, in use around 70-80 A.D., (see Table 11).

Table 11

Tile No. 25 Collected from the Base of a Stove of the Augst. Epoch

| t, °C | Remanent Moment | | | | | Obtained Moment, M' |
|---|---|---|---|---|---|---|
| | x | y | z | M | $I_t$ | |
| 20 | 0.482 | 0.280 | 0.916 | 1.072 | 58°45' | |
| 100 | 0.451 | 0.277 | 0.868 | 1.017 | 58°30' | 0.065 |
| 200 | 0.401 | 0.237 | 0.770 | 0.900 | 59°0' | 0.138 |
| 250 | 0.374 | 0.213 | 0.718 | 0.837 | 59°0' | 0.170 |
| 300 | 0.357 | 0.182 | 0.655 | 0.768 | 58°30' | 0.239 |
| 350 | 0.318 | 0.165 | 0.594 | 0.694 | 58°45' | 0.276 |
| 400 | 0.294 | 0.153 | 0.552 | 0.644 | 59°0' | 0.347 |
| 450 | 0.236 | 0.146 | 0.461 | 0.538 | 59°0' | 0.453 |
| 550 | 0.075 | 0.020 | 0.136 | 0.157 | 60°30' | 0.903 |
| 670 | | | | | | 0.913 |
| 350 | | | | | | 0.247 |

As far as the orientation of the remanent moment is concerned, the conclusions will in this case be the same as for Baden tile No. 10, with a good stability of $I_t$. Analysis of the changes in M and M' indicates here the occurrence of mineralogical changes which make it impossible to raise the temperature above 350° C during the investigation of $F_0$. A value of about 0.69 oersted was obtained.

These two last determinations on the Baden tile of the 21st legion, resp. on the piece of stove base, interest us more as archeological discoveries rather than as actual field intensity measurements of the past which require their final verification in accordance with the values obtained for various objects of the same origin. However, these figures confirm once again the previously obtained data for the Roman epoch in our regions.

## Punic Epoch. Carthage

Walls of Punic furnaces of the second century B.C. P. Cintas suggested in 1950 the investigation of the walls (interior surfaces) of kilns in Carthage. We were fortunate to collect oriented samples from three kilns - two Punic kilns dating back to the fall of Carthage (146 B.C.) and one Roman kiln (approximately 300 A.D.). This allowed the determination (which we consider very accurate) of the magnetic declination and inclination for two epochs [44]. The field intensity was studied later on.

We limited our investigations to two Punic kilns - the oldest and most accurately dated ones. The investigation concerned six specimens shaped like parallelepipeds. These were cut from the two largest oriented blocks, our Nos. 15 and 16, and from four large non-oriented pieces selected for

Table 12

Walls of Punic Kilns (Carthage)

| t, °C | Specimen No. 15 | | | Specimen No. 16 | | | Specimen C | | |
|---|---|---|---|---|---|---|---|---|---|
| | M | I | M' | M | I | M' | M | I | M' |
| 100 | 0.804 | 59°15' | 0.026 | 1.108 | 57°45' | 0.059 | 0.824 | 58°15' | 0.022 |
| 200 | 0.741 | 59°0' | 0.078 | 1.008 | 57°30' | 0.122 | 0.748 | 58°30' | 0.070 |
| 300 | 0.610 | 59°0' | 0.166 | 0.701 | 58°0' | 0.316 | 0.623 | 58°0' | 0.155 |
| 400 | 0.408 | 59°30' | 0.301 | 0.374 | 58°0' | 0.546 | 0.436 | 58°30' | 0.286 |
| 300 | | | 0.179 | | | 0.364 | | | 0.171 |
| 500 | 0.065 | | 0.538 | 0.081 | | 0.781 | 0.190 | | 0.485 |
| 300 | | | 0.190 | | | 0.383 | | | 0.187 |
| 600 | | | | | | | 0.016 | | 0.612 |
| 300 | | | | | | | | | 0.192 |
| | Specimen A | | | Specimen B | | | Specimen D | | |
| 100 | 1.256 | 59°15' | 0.057 | 0.675 | 57°15' | 0.028 | 1.434 | 58°45' | 0.046 |
| 200 | | | | 0.602 | 57°0' | 0.076 | 1.322 | 59°30' | 0.111 |
| 300 | 0.945 | 60°15' | 0.269 | 0.483 | 57°30' | 0.148 | 1.150 | 59°45' | 0.216 |
| 400 | 0.602 | 59°15' | 0.515 | 0.321 | 56°45' | 0.267 | 0.814 | 59°45' | 0.416 |
| 300 | | | 0.329 | | | 0.151 | | | |
| 500 | | | | 0.116 | | 0.435 | 0.236 | | 0.813 |
| 300 | | | | | | 0.162 | | | 0.288 |
| 670 | | | | | | | 0.0 | | 0.985 |
| 300 | | | | | | | | | 0.341 |

this purpose. The heating was done in an electric furnace at St. Maure Park (F = 0.464 oersted) in 100° C stages and included a control heating of 300-20° after each stage starting with 400° C. This schedule was, however, only partly realized since the specimens turned out to be mechanically unstable during heating to 670° C. The principal results of the measurements are given in Table 12.

The cleanness of the original magnetization is undoubtedly expressed in the considerable stability of orientation of the remanent magnetization after each heating as can be judged from a comparison of the inclination I of the remanent moment on the surface of each object.

A comparison of consecutive magnetization values M' from specimen to specimen acquired at temperatures between 300° and 20° C reveals obvious and systematic changes in mineralogical content. This change is as yet not too noticeable from the mean values at 400°, and it seems logical to us to retain the value 1.54, corresponding to 300° C (Table 13). We believe that dispersion of the values of $F_0/F$ occurs from specimen to specimen and that it is of the same order as the one we obtained previously.

Table 13

$F_0/F$ for Specimens from the Walls of Punic Kilns

| Temperature Intervals, °C | Specimen No. | | | | | | Average |
|---|---|---|---|---|---|---|---|
| | 15 | 16 | C | A | B | D | |
| 100-300 | 1.39 | 1.58 | 1.51 | 1.47 | 1.60 | 1.67 | 1.54 |
| 100-400 | 1.44 | 1.51 | 1.47 | 1.42 | 1.48 | 1.68 | 1.50 |
| 100-500 | 1.44 | 1.42 | 1.37 | -- | 1.37 | 1.56 | 1.43 |

Thus, the intensity of the earth's magnetic field at about the middle of the 2nd century B.C. in northern Tunisia had to be on the order of 0.464 × 1.54, i.e., 0.71 oersted; the magnetic inclination approached 58°, and the declination was, according to our previous measurements, 0°30' W.

Punic crockery. A broad investigation was made on crockery found in the sanctuary of the goddess Tanit (Carthage), dating back to the period from the 8th to the middle of the 2nd century B.C. We investigated the magnetic inclination of these epochs, and made, in addition, interesting archeological observations. We shall discuss here only the aspects of the magnetic field intensity which was studied on four vessels.

1. Vase No. 13 (our nomenclature) is used as an example in discussing our progressive heating method. The vase is of simple shape, grayish-white in color, and without additional ceramic coloring. P. Cintas attributes it to the 8th or 7th century B.C. We found it to possess a single magnetization, at least after thermal cleaning at temperatures slightly above 100° C. This magnetization obtained during baking of the vase corresponds to a magnetic field with an intensity of 0.77 oersted. We do not have any indication as yet as to the inclination of the field during the corresponding epoch since the old inscriptions give us reason to believe that these vases could have been stacked in the furnace in any possible manner.

2. Vase No. 15. Found in the same layer but very different from the previous one: more carefully made of finer clay, it displays colorful decorations (one chestnut stripe and two green stripes). The demagnetization by progressive heating indicates two jumps corresponding to temperatures of 250° and 405° C. This makes us believe that the vase was heated first to 405° C and then again to 250° C in order to fasten the coloring. The magnetization consists of three differently oriented vectors formed (1) at temperatures from 670-405° C, (2) between 405 and 250° C, and (3) between 250 and 100° C. Taken individually, these three vectors have comparable inclinations of the same, negative sign. The vase was obviously baked and then again heated in an upside-down position, which occurs frequently.

The approximate intensity of the field corresponding to each magnetization vector can be determined as 0.85; 0.60; 0.78 oersted. Trying to evaluate the error to be apprehended in this kind of determination on individual magnetizations, we may state, that these intensities are of the same order and agree with the intensity observed for this epoch under more favorable conditions. We are facing here an archeological problem which will have to be solved. We, for our part, are satisfied to have brought out the whole complex of related facts which point to a high intensity of the field in the distant historical past.

3. Vase No. 50. According to P. Cintas this vase is from the 7th or 6th century B.C. It is a "pot-bellied" vase, which looks rather old and which was, apparently, decorated with a colored stripe. We are inclined to believe it might have been at a certain time in a place struck by lightning through which the vase quite likely acquired a relatively high ARI.

4. Vase No. 247, nomenclature of P. Cintas, who believes it to be of later origin than the previous vases (5th or 4th century). Its behavior during progressive demagnetization (as always after cleaning at 100° or 150° C) is very regular. It has single magnetization since the three directional cosines of its moment vector remain stable during heating, and the curves M and M' as a function of t are approximately identical. The stability of the ratios $F_0/F$ holds up well and we may therefore use the same figure (1.68), which gives us approximately 0.76 oersted for $F_0$.

We may draw only one conclusion from all these investigations on Punic crockery: $F_0$ at about the middle of the second century B.C. was on the order of 0.71 oersted. It seems that until that time (a few centuries earlier) this value was higher, possibly 0.76 oersted. We feel that this figure should be corroborated through investigations on additional pieces of crockery; we hope, however, to be in a position to examine ancient Punic furnaces in North Africa which, in all possibility, will reduce the interest in pottery, at least from an archeomagnetic point of view. Certainly, an investigation of furnace walls will yield more information than just on the orientation of the field; we are almost certain in this case that later thermal influences were nonexistent, and that, in addition, the exact place of heating is known, while pottery could have been transported to a different place.

Table 14

| Place | Epoch | I | $F_0$, Oersted | Type of Measurements |
|---|---|---|---|---|
| Paris | 1955 | 64°36' | 0.464 | Direct in Observatory |
| Paris | 1930 | 64°35' | 0.459 | Direct in Observatory |
| Paris | 1885 | 65°19' | 0.463 | Direct in Observatory |
| Paris | 1848 | 66°45' | 0.471 | Direct Accumulative |
| Versailles | 1750 | 74°0' | > 0.48 | Archeomagnetic |
| Lille | 1460 | 63°0' | 0.56 | Archeomagnetic |
| Paris | 200 | 62°15' | 0.70 | Archeomagnetic |
| Basel | 175 | 63°30' | 0.73 | Archeomagnetic |
| Fréjus | 25 | 60°30' | 0.65 | Archeomagnetic |
| Carthage | -146 | 58°0' | 0.71 | Archeomagnetic |
| Carthage | -600 ? | | 0.76 | Archeomagnetic |

### Conclusions Based on the Investigation of the Intensity of the Earth's Magnetic Field in the Historical Past

Many of our experiments, to begin with, pointed the way toward obtaining information on the intensity changes of the earth's magnetic field. We may now already attempt a summary and interpretation of our results no matter how particular. As always in archeomagnetism, we are up against the problem of simultaneous variations in time and space. We tried first of all, to define more accurately the first dependence, limiting our investigations to a very small part of the world, although the distance from Lille to Tunis is rather large over which the intensities of the present field show already a noticeable difference: 0.47 resp. 0.43 oersted. Table 14 presents our results supplemented with values which characterize recent epochs, based on direct measurements.

If the structure of the average earth's field for a given epoch would be the same as for a centered dipole, and if the secular variations could be reduced to a displacement of this structure with changes in M (the dipole moment), the intensity $F_0$, proportional to M, would be a function of the magnetic inclination:

$$F_0 = \frac{2M}{R^3\sqrt{1+3\cos^2 I}}.$$

Proceeding from here we could correct the values for $F_0$ by bringing them to the same inclination, and the changes of $F_0$ at constant I would allow us eventually to draw conclusions on the changes of the aggregate moment of the earth. It is this line of thought (which we advance with caution) that induced us to associate each obtained intensity value with the inclination during the corresponding epoch and at the corresponding place. If we correct thus the values of $F_0$ in Table 14 by bringing them to an arbitrary inclination of 65°, we may get:

| Epoch | -146 | 25 | 175 | 200 | 1460 | 1750 | 1848 | 1885 | 1930 | 1955 |
|---|---|---|---|---|---|---|---|---|---|---|
| $F_0$, oersted | 0.78 | 0.69 | 0.74 | 0.73 | 0.57 | >0.43 | 0.460 | 0.462 | 0.461 | 0.466 |

These figures lead to the opinion that the aggregate moment of the earth should, beginning with the Punic epoch, decrease at an uninterrupted rate and almost lineally. At the start of the Christian era this moment should have been approximately 5/3 of its present figure.

The magnetic field on the earth's surface differs, to our regret, considerably from the first member of Gauss' field, and no general relationship exists between magnetic inclination and intensity during any of these epochs. The intensity, for instance, is not constant along the isocline. Thus, according to the magnetic maps of the world compiled by the Carnegie Institute for the epoch 1945, 0, the intensity varies between 0.46 and 0.57 oersted along the 65° isocline. Furthermore, the structure of the field changes its shape from century to century; under these conditions a knowledge of the changes of $F_0$ in a certain region does not allow any conclusions concerning changes in the aggregate moment of the earth.

We may rule out the possibility that the course of the earth's field during a few thousand years might have been considerably different from the present, on hand of observations which indicate that the recent development of paleomagnetism as a whole is based on secular variations consisting solely of fluctuations of the extremely slowly changing dipole field. Our results, on a historical scale, seem to prove a general decrease of the moment of the earth's magnetic field, at least during the last two thousand years. It would be desirable to corroborate this with observations from the most remote corners of the world, far from those regions in which our investigations were carried out; for instance, in countries with ancient civilizations like India and China.

### Discussion of the Results

Two very controversial problems are concerned with the quasiregular decrease of the intensity of the earth's field during the more than 2,000 years, as stated by us: a decrease of Gauss' moment as calculated from direct magnetic measurements, and the degree of validity of the carbon-14 method for archeological purposes.

Demagnetization of the earth according to Bauer. Bauer's arguments on the decrease of the aggregate moment of the earth are well known. He noticed, beginning, with 1903, a considerable decrease occurring at a rate of 1/2580 due to which $H_0$ decreased from 0.3281 oersted in 1838 to 0.3229 oersted in 1884. The author's paper of 1928 reported a decrease at the annual rate of 1/1500. Several new analyses have been made since then; the results, however, concerning the same epoch, are quite different. This necessitates a great amount of caution in comparing our results with older analyses made at a time when the magnetic station network was still thin. As far as the direction of the geomagnetic axis is concerned, it should be noted that all pole positions, based on analyses since the first polar year, are concentrated in a relatively small area in which we find the pole during the epoch of 1885 as well as during the epoch of 1945. Contrary to widespread opinion it seems impossible to us to speak of a definite drift of the present Gauss pole. As to the value of the moment, the changes exceed by far any dispersion. The Gauss moment of the earth continues to decrease quite regularly. Thus, the average $H_0$ was 0.3134 oersted in 1922 (two analyses) and 0.3103 oersted in 1945 (five analyses).

We encountered already double measurements after "rotation (turning) in the earth's magnetic field," which, however, was done at regular temperatures in order to be able to study the effect of time. Here we have now repeated heatings. According to the laws of thermo-magnetization, moment $M_1$, measured after the first heating to 60° C, has two components: the original moment obtained in the field $F_0$ during cooling to 60° C, $M_{(670^\circ,\, F_0,\, 60^\circ)}$, and the moment acquired in the laboratory field F between 60° and 20° C, $M'_{(60^\circ,\, F,\, 20^\circ)}$ (this moment, however, is augmented by ARV obtained in the same field F during the days preceding the measurement).

In moment $M_2$, measured after the second heating, the first component remained the same while the second one changed its direction. The half-sums and half-differences of the components $M_1$ and $M_2$ represent the old decreased moment $M_{(670^\circ,\, F_0,\, 60^\circ)}$, and the newly acquired $M'_{(60^\circ,\, F,\, 20^\circ)}$, respectively.

After a heating in field F to 670° C, a single "reverse" heating of the specimen to 60° C is sufficient to obtain by one and the same method both $M_{(670^\circ,\, F,\, 60^\circ)}$ and $M'_{(60^\circ,\, F,\, 20^\circ)}$. This operation yields thus both moments - old and new ("cleaned" at a temperature of 60° C), the ratio of which should be $F_0/F$. A comparision of both moments $M'_{(60^\circ,\, F,\, 20^\circ)}$, obtained under identical conditions but after heating to 670° C, is a test of the mineralogical stability. Its accuracy, however, is low since these moments are frequently weak.

It could be shown that the "cleaned" moments obtained by this method are practically free from the influence of the viscosity effect. We should note, incidentally, that the old "clean" moment $M_{(670^\circ,\, F,\, 60^\circ)}$ is liable to allow a better determination of the direction of the old field with respect to the specimen.

Using this method we investigated three lots of French bricks dating back to the 15th and 18th centuries.

The first lot included 10 bricks from the Palais Rihour at Lille, baked in 1465.[*] Seven of these turned out to be very stable and showed only a very slight dispersion of the $F_0/F$ values. We may deduce that the intensity of the field $F_0$ in Lille around 1465 was in the vicinity of 0.56 oersted, and the magnetic inclination at that time approximately 63°15', according to our measurements. The three exceptional specimens showed mineralogical changes which were quite considerable in two of them (comparative test of M' and M'',[†] dispersion of the $F_0$ values, as well as control measurements of the magnetic susceptibility ARI taken before and after heating to 670° C). We explain these changes incurred during heating with the saturation of the specimen with organic matter.

The second lot included 12 bricks from the Tristan House (la Maison de Tristan) at Tours, belonging in all probability to the same epoch as the previous lot. Regrettably they were highly contaminated with organic matter, and considerable chemical reactions occurred during the heating. The final result - a strong dispersion of the $F_0$ values - was not surprising. This negative experiment, as far as the accumulation of data was concerned, impressed upon us the necessity for the extreme cleanness of the selected objects. Thereafter we began cleaning the objects chemically so as to remove organic matter and accidentally newly formed minerals.

The third lot consisted of 16 bricks from the Chateau de Versailles, which were baked around the year 1750. Their mineralogical stability during heating was very good, and the scattering of individual $F_0$ values fully permissible.

Since the publication of our first paper [41] concerning intensity measurements for epochs for which there were still no direct measurements available, we can speak of a strong decrease of the earth's moment during the last five hundred years. Our new data comprising a time interval of over two millenniums should, in spite of some stipulations, corroborate this fact which seemed coincidental as the analyzed time interval was less than one hundred years.

Age determination of archeological objects by the carbon-14 method. The idea of changes in the magnetic moment of the earth creates some doubts among physicists-archeologists concerning the accuracy of epoch determination with radioactive carbon. This method, which was developed as a result of the universally known publications by Libby and his school which is now very widely in use, assumes that the formation of carbon-14 on earth through bombardment of nitrogen atoms with neutrons of cosmic radiation, is constant. This, however, postulates that the earth's magnetic field which affects the original cosmic radiation must be constant also. In this connection, some scientists were perturbed by our first archeomagnetic results. Developing certain hypotheses and simplifications Elsasser, Ney and Winckler [5] solved the difficult problem of possible dating errors. They demonstrated on examples the importance of secular intensity variations in the earth's magnetic field as a source for new errors in addition to the already known.

Certainly, our results will have to be proved correct on a global scale. The authors mentioned above state therefore that our investigation covers only a limited area of the earth (they are familiar only with our investigations in France) and that the results of this investigation could be explained virtually with the enormous regional effect of secular variations. Actually, such a tremendous regional effect does not appear very probable. And furthermore, as already brought out, we spread our investigations over a larger area. It is of course of great interest that intensity determinations be made also in other regions of the earth.

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[*] The results of this investigation, together with a detailed description of the diverse moments measured on each object, were published in [14].

[†] M' is new moment $M'_{(670^\circ,\, F,\, 20^\circ)}$ obtained after the first heating to 670° C; M'' is analogous moment after the second heating to the same temperature.

### Attempts to Extend the Investigation to Geological Epochs

The method discussed here should allow us to determine the intensity of the earth's magnetic field for thermomagnetized rocks. This requires that neither the original magnetization nor the mineralogical content of the rock be changed to any considerable extent. As previously mentioned, it is not very likely that very old rocks would be free from such changes, regardless of the mechanism of their magnetization. We hoped, however, that things would be different, for "young" geological epochs. So far, we conducted two experiments: on metamorphic clays of the Middle Quaternary and on Volvic andesite of Upper Quaternary age.

### Metamorphic Clays (Natural Terra Cotta)

In 1948 we assembled a collection of specimens of natural terra cotta (baked clay) from two deposits, investigated by Brune, which has been heated by lava flows and intrusions of the Gravenoir volcano in southern Clermont-Ferrand. Our objective was to duplicate Brune's determinations of the orientation of the magnetization (declination and inclination) under improved experimental conditions. Since it was our intention to extend the investigation to other deposits the results, presented in Table 15, were not published.

Table 15
Orientation of the Magnetization of Metamorphic Clay on the Gravenoir Plateau

| Specimen No. | D | I |
|---|---|---|
| 1 | 15°15' W | +56°0' |
| 2 | 14°45' W | +58°45' |
| 3 | 1°45' W | +51°45' |
| 4 | 13°0' W | +59°45' |
| 5 | 19°15' W | +60°45' |
| 6 | 15°15' W | +60°45' |
| 7 | 14°0' W | +57°45' |
| 8 | 8°0' W | +61°15' |
| 9 | 11°30' W | +59°0' |
| Mean | 12°30' W | +58°30' |

The data show a convergence seldom encountered in paleomagnetism. This set of specimens possesses direct magnetization in a direction fairly similar to the present field. It could be shown that there is no doubt in the existence of such a convergence for material with high magnetic viscosity. We attempted to investigate the intensity on four non-oriented specimens designated with the same number as the nearest diagnostically oriented block. The heatings conducted in Paris a rather long time ago in a 0.404 oersted field consisted of only three stages: 100°, 300°, and 670° C. The material not coated by us beforehand with a protective film disintegrated as a rule during heating to 670° C, which made any control heating impossible. This work had preliminary character; it should be repeated on some other better preserved clay. Table 16 shows the results of our measurements for each specimen.

Table 16
Orientation of the Magnetization of Metamorphic Clay on the Gravenoir Plateau

| t, °C | Specimen No. 3 | | | Specimen No. 4 | | |
|---|---|---|---|---|---|---|
| | M | arc cos x/M | M' | M | arc cos x/M | M' |
| 20 | 0.487 | 63°15' | | 1.847 | 42°15' | |
| 100 | 0.421 | 65°45' | 0.119 | 1.830 | 42°30' | 0.076 |
| 300 | 0.276 | 64°15' | 0.386 | 1.642 | 41°45' | 0.409 |
| 670 | | | 1.115 | | | 3.657 |
| | Specimen No. 7 | | | Specimen No. 8 | | |
| 20 | 0.965 | 58°15' | | 0.847 | 63°45' | |
| 100 | 0.898 | 57°30' | 0.085 | 0.806 | 63°15' | 0.116 |
| 300 | 0.751 | 56°0' | 0.481 | 0.454 | 60°15' | 0.990 |
| 670 | | | 2.330 | | | 2.062 |

Since the axes were entirely arbitrary, the directional cosines of the moment of each specimen do not have any common characteristics. We give here, for example, the arc-cosine corresponding to x; a check, however, gives as good results for the other two axes. It seems thus that the natural magnetization is indeed only a single one. The ratios $F_0/F$ obtained as quotient of two magnetizations - lost resp. acquired within the temperature intervals of 100°-300°, 300°-670°, and 100°-670° C - are given in Table 17.

Table 17

Metamorphic Clays., $F_0/F$ Ratios

| Specimen No. | 100-300° | 300-670° | 100-670° |
|---|---|---|---|
| 3 | 0.543 | 0.379 | 0.423 |
| 4 | 0.565 | 0.506 | 0.511 |
| 7 | 0.371 | 0.406 | 0.400 |
| 8 | 0.403 | 0.424 | 0.414 |

.437

The differences for one and the same specimen can be considered permissible if we remember that for the temperature interval 100°-300° C the difference of the moments is very small. The dispersion of the ratio from specimen to specimen is undoubtedly large but not so large as to cause any distortion. Due to the lack of direct experiments these data are the only usable criteria of stability. The average ratio corresponding to the maximum interval of 100°-670° C for $F_0$ is 0.18 oersted which we associate with the previously determined inclination of 58°30'.

This may possibly be taken as evidence that the intensity of the earth's magnetic field which, as we saw, decreased rather steadily during the historical period, did not always decrease. Can we, however, contend that the magnetic minerals contained in this baked clay which showed traces of weathering were not altered with time, which, in turn, by causing some of the original magnetization to disappear and new minerals to form, would necessarily entail a decrease in the ratio $F_0/F$? More extensive investigations, including direct stability tests, are therefore undoubtedly necessary.

Andesitic Lava of the Volcano Nuger (Volvic)

Numerous specimens were collected in 1942 from this lava. Their investigation disclosed a surprisingly homogeneous remanent magnetization which allowed the assumption that no important disturbances occurred at the localities where the specimens were collected. This characteristic, as well as the weak magnetic viscosity of the rock and its well preserved petrografic state compelled us to use further on just these specimens for our intensity investigations. We knew the rock to be somewhat sensitive if heated to 670° C, but since this effect seemed relatively weak we could hope to disregard it at low temperatures.

The first series of experiments was conducted in Paris (1946) on three specimens using only four-stage heatings. We found the orientation of the remanent magnetization to be very constant. This proves the cleanness of the magnetization. However, the ratios $F_0/F$, obtained at different temperature intervals showed considerable dispersion due, partly, to very weak magnetizations corresponding to the interval 100°-300° C, which impedes working with this rock, and partly caused by mineralogical changes which are difficult to bring to light due to the small number of heating stages.

The second series of experiments was again conducted on three specimens. More heatings than in the previous series were applied, and these were accompanied for each temperature beginning with 400° C, by a test consisting of a determination of the moment $M'_{(300°, F, 20°)}$. As in the first experiment, the ratios $F_0/F$ showed considerable variation (see Table 19). Disregarding for the time being specimen No. 2 let us discuss a total of five other specimens. There is no doubt that the dispersion, even if the most erracti ratios $F_0/F$ obtained at minute differences in moment are thrown out, is still substantial. One of the reasons for this are the mineralogical changes which appear during control heating to 300° C. Table 18 demonstrates that the successively obtained values of $M'_{(300°, F, 20°)}$ for each specimen change as t increases. This weak mineralogical change during heating does not eliminate a second possibility: the dispersion could be due to mineralogical changes occurring over a greater length of time. We may here think of the effect which the disintegration of titano-magnetites, discovered by Kawai [14, 15], might have.

Nevertheless, the lack of a present component with low Curie point (after M' changes depending on t) is no reason to attach too much importance to this mechanism as far as the investigation of the andesite is concerned.

Table 18

Volvic Andesite. New Experimental Intensity Investigations

| t, °C | Specimen No. 1 | | | Specimen No. 2 | | | Specimen No. 13 | | |
|---|---|---|---|---|---|---|---|---|---|
| | M | I | M' | M | I | M' | M | I | M' |
| 20 | 1.062 | 66°45' | | 1.684 | 63°15' | | 0.478 | 65°45' | |
| 100 | 1.035 | 66°15' | 0.030 | 1.670 | 63°45' | 0.020 | 0.463 | 65°15' | 0.017 |
| 200 | 0.967 | 65°15' | 0.045 | 1.648 | 63°15' | 0.060 | 0.438 | 64°15' | 0.029 |
| 300 | 0.869 | 63°45' | 0.073 | 1.595 | 62°45' | 0.099 | 0.339 | 66°15' | 0.091 |
| 400 | 0.706 | 61°45' | 0.148 | 1.415 | 62°30' | 0.269 | 0.238 | 67°45' | 0.215 |
| 300 | | | 0.083 | | | 0.107 | | | 0.101 |
| 500 | 0.417 | | 0.404 | 1.017 | | 0.644 | 0.063 | | 0.639 |
| 300 | | | 0.093 | | | 0.114 | | | 0.193 |
| 590 | 0.026 | | 1.096 | 0.018 | | 1.783 | 0.018 | | 1.086 |
| 300 | | | 0.069 | | | 0.102 | | | 0.148 |
| 670 | | | 1.087 | | | 1.712 | | | 1.067 |
| 670 | | | 1.076 | | | 1.686 | | | 1.063 |
| 300 | | | 0.075 | | | 0.120 | | | 0.100 |

Table 19

Volvic Andesite. New Experimental Investigations of the Ratio $F_0/F$

| Specimen No. | 100-300° | 100-400° | 200-500° | 300-500° | 500-590° | 300-670° | 100-670° |
|---|---|---|---|---|---|---|---|
| 1 | 3.86 | 2.79 | 1.53 | 1.36 | 0.57 | 0.86 | 0.99 |
| 2 | 0.96 | 1.03 | 1.08 | 1.06 | 0.88 | 1.00 | 0.99 |
| 13 | 1.68 | 1.14 | 0.61 | 0.50 | 0.10 | 0.35 | 0.44 |

Let us return to specimen No. 2. Table 19 shows it as having a relatively low dispersion of the ratios $F_0/F$. In addition, Fig. 3 indicates that the demagnetization curve M = f(t) and the reversed unreduced (i.e., at k = 1) magnetization curve M' = f(t) agree well.* Does this mean that the ancient intensity $F_0$ was of the same order as the present? We cannot draw this conclusion since we lack the most important criterion - an equality of the intensities during our investigations of the diverse specimens of the same epoch. We shall discuss six $F_0$ values which could be obtained by utilizing the total temperature interval of 100°-670° C. These are (oersted): 0.32, 0.27, 0.30, 0.46, 0.46, 0.20.

It would seem that in petrographically very similar rocks [42] mineralogical changes would take a parallel course, excluding thereby the possibility for strong dispersion of the ratio $F_0/F$ which is a measure of these changes. Under these circumstances we should not draw any conclusions from this investigation which would not have at least some bearing on all our results concerning historical terra cotta.

Thus, the foundation was laid for the investigation of the intensity of the earth's field during geological epochs, which we intend to continue, regardless of the difficulties discussed in this paper; for one, on additional clay specimens, in an attempt to find true baked clays (whereas the sedimentary rocks of the volcano Gravenoir were marly to a considerable degree), and, on the other hand, on various volcanic rocks.

Whatever our first results might be, they will help to impress the important conception that the almost constant decrease of the earth's field which has been in progress obviously for over two thousand years, will probably not have to be extended over the entire Quaternary epoch.

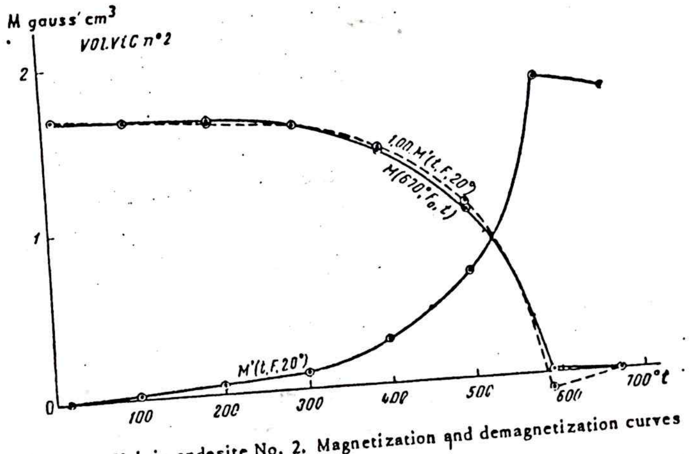

Fig. 3. Volvic andesite No. 2. Magnetization and demagnetization curves

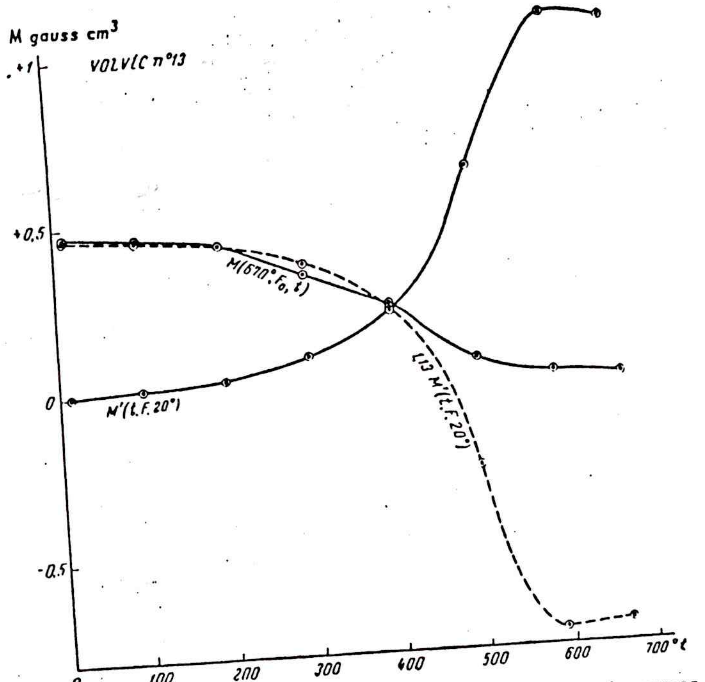

Fig. 4. Volvic andesite No. 13. Magnetization and demagnetization curves

## CONCLUSIONS

The foregoing has been an attempt to describe a method for determining the intensity of the ancient magnetic field of the earth with sufficient accuracy from thermoremanent magnetization. The method in principle is very simple since it involves the comparison of the natural thermoremanent magnetization of any given specimen with the thermoremanent magnetization acquired by the same specimen in a certain field; it presupposes, however, the existence of many strict stipulations as we mentioned above. We were compelled to develop an entire complex of control operations in order to be able to eliminate any specimens which did not satisfy one or the other of these requirements. This whole complex of operations supplemented by our double heating and rotation method, represents something like a "staircase" comprising the following steps: (1) individual checks to

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*Fig. 4, in contrast, brings as an example specimen No. 13 which experienced obviously intense mineralogical changes above 400° C. We put k = 1.13 relating it to 200° C, which ensures approximate agreement at low temperatures.

which each specimen is subjected: the direction of the original remanent magnetization, progressively decreased by heating, must remain constant (I, resp. arc cos x/M test); new magnetizations obtained under identical conditions must give identical values for the acquired moments (M', M" and $M'_{300^\circ, F, 20^\circ}$ test). Finally, the old magnetization lost during heating, and the newly acquired one, must retain the same ratio within successive temperature intervals, ($F_0/F$ test); (2) group control. Different specimens of the same lot must give similar values for the investigated intensity $F_0$. This test becomes the more important the greater the number of specimens included in a given set, and the more different they are among themselves from any point of view; (3) final general control. The values obtained from one and the same place but for different epochs, must display a certain coordination. It is true that such tests have so far been made only for the historical period of western Europe. This was, as we saw, quite satisfactory since it allowed us to recognize immediately our own mistakes as well as those made by archeologists in affiliating a given object with a certain epoch.

We should not overlook the fact that the application of this method to intensity determinations of the earth's field during a given epoch and in a given place requires very extensive and tedious work which may be rendered futile at any moment should even one of the experiments give negative results.

Certain improvements of this method can be suggested.

We expected in the beginning to find that ATR (both old and new) would be proportional to the field which creates it. As we know, this proportionality is usually well developed in weak fields. Our assumption, however, turned out to be incorrect.

As far as cleaning the old magnetization of a specimen from ARI and ARV, or magnetization during crystallization is concerned, we apply in these cases the temperature cleaning method whereby successive heatings allow us to generalize. Mentioned was also the "chemical cleaning" method which can destroy newly formed minerals as well as parasitic magnetizations on such minerals.

The lack of a cleaning method by means of alternating fields may seem strange since we are using them extensively in our investigations [28]. While rating this method very highly, as an excellent means for separating ARI and ATR, we should necessarily bear in mind that an analysis using alternating fields for determining the orientation of the field by archeomagnetic and paleomagnetic methods is feasible only if the natural magnetization can be gradually destroyed. If the intensity investigations are accompanied by the formation of new ATR, we are apprehensive of the "polarization" effect of the alternating field which was studied by Rimbert [28] as to its ability to cause ARI. Its magnitude was a surprise to us.* Even though this type of investigation was beyond the scope of our endeavor we, nevertheless, preferred to protect our specimens from the influence of any kind of alternating field.

Intending to continue our intensity investigations we have, in order to save time and effort, become very strict in the selection of specimens for any new investigation. We need a very critical approach from the archeological (resp. geological) standpoint: it is inexpedient to study terra cotta (baked clay) if we do not know the exact time of formation, place of heating, and the changes which might have occurred. We need also a strict approach as far as the study of the mechanical and mineralogical characteristics is concerned: it is useless to study specimens which have obviously aged or which are liable to age during heating to high temperatures. Finally, we believe that it is also inexpedient to study any set of specimens which does not allow a reliable determination of the magnetic inclination. Similar limitations compelled us to abandon our study of pottery from the halls of Ra, although greatly attracted by their very high age.

We intend to carry our work far beyond the borders of France and to extend the investigations as far back into the past as possible.

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## REFERENCES

1. Althausen, O., Détermination du Champ Magnétique Terrestre Aux Différentes Epoques Géologiques. Bull. Acad. Sci. USSR, 8, 1944.
2. Various authors: Notes in Phil. Mag. Sup., 6, No. 22, 1957.
3. Bruckshaw, J. M. and S. A. Vincenz, The Permanent Magnetism of the Mull Lavas. M.N. Roy. Ast. Soc. Geophys. Sup., 6, 1954.
4. Doell, R. R., Remanent Magnetization of the Upper Miocene "Blue" Sandstones of California. Trans. Amer. Geophys. Union, 37, 1956.
5. Elsasser, W. M., E. P. Ney and J. R. Winckler, Cosmic-Ray Intensity and Geomagnetism. Nature, 178, 1956.
6. Graham, J. W., Changes of Ferromagnetic Minerals and Their Bearing on Magnetic Properties of Rocks. J. Geophys. Res., 58, 1953.
7. Graham, J. W., Paleomagnetism and Magnetostriction. J. Geophys. Res., 61, 1956.
8. Griffiths, D. H., The Remanent Magnetism of Varved Clays from Sweden. M.N. Roy. Ast. Soc. Geophys. Sup., 7, 1955.
9. Haigh, G., The Process of Magnetization by Chemical Change. Phil. Mag., 3, 1958.
10. Hatherton, T., The Permanent Magnetization of Horizontal Volcanic Sheets. J. Geophys. Res.. 59, 1954.
11. Herroun, E. F. and A. F. Hallimond, Laboratory Experiments on the Magnetization of Rocks. Proc. Phys. Soc., 55, 1943.
12. Howell, L. G., J. D. Martinez and E. H. Statham, Some Observations on Rock Magnetism. Geophysics, 23, 1958.

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*Magnetization which develops through the complementary effect of an alternating current is called "ideal" or "inhysteretic" in the Russian literature.

13. Johnson, E. A., T. Murphy and O. W. Torreson, Pre-History of the Earth's Magnetic Field. Terr. Magn. and Atm. El., 53, 1948.
14. Kawai, N., S. Kume and S. Sasajima, Magnetism of Rocks and Solid Phase Transformation in Ferromagnetic Minerals. Proc. Japan Acad., 30, 1954; 31, 1955.
15. Kawai, N., S. Kume and K. Yasukawa, Exsolution of Titanomagnetite and its Time Effect on Rock-Magnetism. Proc. Japan Acad., 32, 1956.
16. King, R. F., The Remanent Magnetism of Artificially Deposited Sediments. M.N. Roy. Ast. Soc. Geophys. Sup., 7, 1955.
17. Koenigsberger, J., Grössenverhältnis von Remanentem zu Induziertem Magnetismus in Gesteinen; Grösse und Richtung des Remanenten Magnetismus. Z. Geophys., 6, 1930.
18. Koenigsberger, J., Die Abhängigkeit der Näturlichen Remanenten Magnetisierung bei Eruptivgesteinen von Deren Alter und Zusammensetzung. Beitr. Angew. Geophys., 5, 1935.
19. Koenigsberger, J., Natural Residual Magnetism of Eruptive Rocks. Terr. Magn. and Atm. El., 43, 1938.
20. Le Borgne, E., Susceptibilité Magnétique Anormale du Sol Superficiel. Ann. Géophys., 11, 1955.
21. Martinez, J. D. and L. G. Howell, Paleomagnetism of Chemical Sediments, Nature, 178, 1956.
22. Nagata, T., S. Uyeda and M. Ozima, Magnetic Interaction Between Ferromagnetic Minerals Contained in Rocks. Phil. Mag. Sup., 6, 1957.
23. Néel, L., L'inversion de L'aimantation Permanente des Roches. Ann. Géophys., 7, 1951.
24. Néel, L., Some Theoretical Aspects of Rock-Magnetism. Phil. Mag. Sup., 4, 1955.
25. Rimbert, F., Sur la Désaimantation, Par Action de Champs Magnétiques Alternatifs, de la Magnétite et du Sesquioxyde der fer α. C.R. Acad. Sci., 242, 1956.
26. Rimbert, F., Sur l'Action de Champs Alternatifs sur des Roches Portant une Aimantation Rémanente Isotherme de Viscosité. C. R. Acad. Sci., 242, 1956.
27. Rimbert, F., Sur l'Aimantation Rémanente Anhystérétique des Ferrimagnétiques. C. R. Acad. Sci., 245, 1957.
28. Rimbert, F., Contribution à l'Étude de l'Action de Champs Alternatifs sur les Aimantations Rémanentes des Roches. Applications Géophysiques. Thèse, Paris, 1958.
29. Roquet, J., Sur les Rémanences des Oxydes de fer et Leur Intérêt en Géomagnétisme. Thèse, Paris, 1953; Ann. Géophys., 10, 1954.
30. Roquet, J., Étude des Propriétés Magnétiques de Roches Volcaniques à Aimantation Naturelle Inversée. Ann. Géophys., 11, 1955.
31. Roquet, J. and E. Thellier, Sur des Lois Numériques Simples Relatives à l'Aimantation du Sesquioxyde der fer Rhomboédrique. C. R. Acad. Sci., 222, 1946.
32. Thellier, E., Sur l'Aimantation Dite Permanente Des Basaltes. C. R. Acad. Sci., 204, 1937.
33. Thellier, E., Aimantation Des Terres Cuites; Application à la Recherche de l'Intensité du Champ Magnétique Terrestre Dans le Passé. C. R. Acad. Sci., 204, 1937.
34. Thellier, E., Recherche de l'Intensité du Champ Magnétique Terrestre Dans le Passé: Premiers Résultats. Ann. IPG., Paris, 15, 1937.
35. Thellier, E., Sur l'Aimantation des Terres Cuites et ses Applications Géophysiques. Thèse, Paris, 1938; Ann. IPG Paris, 16, 1938.
36. Thellier, E., Sur les Propriétés de l'Aimantation Thermorémanente des Terres Cuites. C. R. Acad. Sci., 213, 1941.
37. Thellier, E., Sur la Vérification d'ume Méthode Permettant de Déterminer l'Intensité du Champ Magnétique Terrestre Dans le Passé. C. R. Acad. Sci., 212, 1941.
38. Thellier, E., Propriétés Magnétiques des Terres Cuites et des Roches. Rapport au Colloque sur le Ferromagnétisme et l'Antiferromagnétisme, Grenoble, 1950, J. de Phys., 12, 1951.
39. Thellier, E. and F. Rimbert, Sur l'Analyse d'Aimantations Fossiles Par Action de Champs Magnétiques Alternatifs. C. R. Acad. Sci., 239, 1954. Sur l'Utilisation en Paléomagnétisme de la Désaimantation par Champs Alternatifs, C. R. Acad. Sci., 240, 1955.
40. Thellier, E. and O. Thellier, Sur les Variations Thermiques de l'Aimantation Thermorémanente des Terres Cuites. C. R. Acad. Sci., 213, 1941.
41. Thellier, E. and O. Thellier, Sur l'Intensité du Champ Magnétique Terrestre, en France, Trois Siècles Avant les Premières Mesures Directes. C. R. Acad. Sci., 214, 1942.
42. Thellier, E. and O. Thellier, Recherches Géomagnetiques sur des Coulées Volcaniques d'Auvergne. Ann. Géophys., 1, 1944.
43. Thellier, E. and O. Thellier, Sur l'Intensité du Champ Magnétique Terrestre, en France, à l'Époque Gallo-Romaine. C. R. Acad. Sci., 222, 1946.
44. Thellier, E. and O. Thellier, Sur la Direction du Champ Magnétique Terrestre Retrouvée sur des Parois de Fours des Époques Punique et Romaine, à Carthage, C. R. Acad. Sci., 233, 1951.
45. Uyeda, S., Thermoremanent Magnetism and Coercive Force of the Ilmenite-Hematite Series. J. Geomagn. and Geoel., 9, 1957.