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EMILE THELLIER (1904-1987), a pioneer in studies of the "fossil" Earth's magnetic field.

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Abstract

Professor Emile Thellier was born in northern France in 1904 and passed away on May 11, 1987. Following studies at the Ecole Normale Supérieure de St. Cloud he received his Doctorate from the University of Paris in 1938 for his work on the thermoremanent magnetization of baked clays and its application in geophysics. Ten years later he was named Professor at the Faculty of Sciences of the same university. From 1956 to 1966, succeeding Charles Maurain and Jean Coulomb, he held the position of Director of the Institut de Physique du Globe de Paris. Thellier received many honours in his lifetime.

Throughout his long scientific career, Thellier devoted his life to the study of rock magnetism and its applications in geophysics, geology and archaeology. In the early phase of his career he developed very sensitive and accurate instruments that allowed measurements to be made undisturbed by the presence of the earth's magnetic field. Using magnetometers of his invention in a systematic study of the magnetisation of rocks, he discovered the laws of "magnetic memory", which were later confirmed theoretically by Louis Néel and are now known as the *Thellier-Néel* laws: they state that the baked clay retains a memory of the temperature, and of the direction and intensity of the field that was responsible for its thermoremanent magnetization. His work led to the field of archeomagnetism : in close collaboration with his wife he developed the first method to study the earth's magnetic field in the recent past and used it on a large number of archeological sites in Europe and North Africa. Their method is still used today worldwide. Improvements and refinements of the Thelliers' method continue to be made in the laboratory he created at the Observatoire du Parc Saint-Maur, now reunited with the Institut de Physique du Globe de Paris.

Emile Thellier's work revealed the non-cyclic secular variation of the earth's magnetic field and the changes in its strength over the last 25 centuries and demonstrated the wealth of information contained in rocks that can be used for archeological dating and understanding geomagnetism.

Introduction

Emile Thellier, a pioneer in rock magnetism and archeomagnetism, was born February 11, 1904 at Mont-en-Ternois (Pas-de-Calais), France and died May 11, 1987 in Paris. Following studies at the École Normale Supérieure de Saint-Cloud (1924-6), he taught at the École Primaire Supérieure de Bourges (1927-30). In spite of a heavy teaching load, 21 hours per week, he successfully completed the Licence ès-sciences physiques of the Faculté des Sciences de Paris, where he would spend the remainder of his career. His outstanding performance led his professors to urge him to embark on research. At the Sorbonne in the laboratory of Prof. Charles Maurain, he completed a Diplôme d'Études Supérieures (1931), studying the magnetism of baked clay, and the Agrégation de Sciences physiques (1932).

It had been known since at least the time of Brunhes (1906) that the thermoremanent magnetization (TRM) acquired by baked clays and volcanic rocks paralleled the direction of the geomagnetic field acting when they cooled and survived later reversals of the field. Maurain proposed to Thellier the idea of using the TRM of ancient pottery to deduce not only the direction but also the strength of the Earth's field at the time of firing. This program Thellier later carried out brilliantly during a long career, but his first desire was to reproduce TRM in the laboratory and understand its properties. His success in this undertaking makes him the true "discoverer of magnetic memory", in the words of his great confrere, Louis Néel. Working with clays from the famed Sèvres pottery factories, and later with volcanic rocks, Thellier minutely and exhaustively determined how TRM forms, producing a remarkable Docteur ès-Sciences thesis (Thellier, 1938).

This landmark paper, which has lost none of its immediacy today, launched his academic career at the Institut de Physique du Globe de Paris, where he became successively Physicien-adjoint (1943), Maître de Conférences (1945), Professeur (1948) and Director (1954-66). All his experimental research was done at the Observatoire du Parc Saint-Maur, in the suburbs of Paris where, in 1967 he established a CNRS Laboratoire de Géomagnétisme which he moulded into one of the world's leading rock magnetic and paleomagnetic research centres. Thellier received many honours in his lifetime. He was named an Officer of the Legion of Honour (1957), elected to the Académie des Sciences (1967), and awarded four prizes by the academy and one by the Université de Paris. His first love, to the end of his life, remained his research and the laboratory he had created.

Thellier's Laws of Thermoremanent Magnetization

Thellier worked exclusively with samples containing very fine particles of minerals like magnetite (Fe_3O_4) and hematite (α-Fe_2O_3) which we now know contain only one magnetic domain (single-domain particles) or at most a very few domains. For such particles he established a series of universal properties (Thellier, 1938, 1941; Thellier & Thellier, 1941). A master experimentalist, he perfected astatic, translation and rotating-sample magnetometers of unprecedented sensitivity. Without such instruments, it would have been impossible to satisfy himself or others of the universality of laws such as the additivity of partial TRMs because the clays he used in his earliest work and the hematites used by his student J. Roquet (Roquet & Thellier, 1946; Roquet, 1954) were weakly magnetic compared to the volcanic rocks favored by others (Koenigsberger, 1938 ; Nagata, 1943).

The Thellier "laws" are most clearly stated in Thellier (1946), a masterpiece of mature reflection about results obtained in the preceding one and a half decades and their implications for theories of magnetism. (For alternative statements, see Roquet (1954, p.21-3) and Aubouin & Coulomb (1987).) Quoting Thellier (translated from the French original), we have the following general properties.

1. TRM (intensity) is proportional to field (strength) for weak fields.
2. All partial TRMs are parallel to the field H in which they were acquired.
3. A partial TRM acquired by cooling in H through the temperature interval (T_2, T_1) and in zero field through all other temperature intervals is unaffected by reheating in zero field to a temperature $\leq T_1$ and completely disappears after reheating to T_2.
4. A partial TRM (T_2, T_1, H) is independent of other partial TRMs acquired in temperature intervals outside (T_2, T_1), which may be due to fields differing from H in strength and direction.
5. All these partial TRMs add geometrically but each of them retains true autonomy and an exact memory of the temperatures and field in which they were acquired.

The first two properties were known or assumed before Thellier's time (e.g., Folgerhaiter, 1899). The latter three are entirely novel and are usually referred to as Thellier's laws. Thellier's statements recognize the vectorial nature of partial TRM additivity and independence, and form the basis for using thermal demagnetization to separate natural remanent magnetization (NRM) vectors of different ages in paleomagnetism. These statements go well beyond the usual scalar laws given in textbooks (e.g., Dunlop & Özdemir, 1997). Collectively, the five laws form a firm fundamental justification for determining the direction and strength of the paleomagnetic field from the NRM of rocks and baked materials, provided the NRM fraction utilized was produced originally as one or more partial TRMs carried by single-domain or nearly single-domain size grains. Number 3 is the basis for magnetic paleothermometry (e.g., Pullaiah et al., 1975).

Thellier-Néel Laws of Thermoremanent Magnetization

Louis Néel was intrigued by the apparent generality of the Thellier laws, clearly related to the fine size of the magnetic carriers and not to their chemistry. In 1949, he published his celebrated theory of thermal relaxation of single-domain grains which very elegantly and completely explained Thellier's observations. Partial TRM was seen to be acquired sharply at a blocking temperature T_B during cooling, as a grain passed from a superparamagnetic to a thermally blocked state, and demagnetized ("unblocked") at the identical temperature T_B during reheating. From this single property flow the three Thellier laws of reciprocity (blocking and unblocking as reciprocal processes), independence and additivity. This powerful and far-reaching theoretical picture remains the foundation of magnetic theory today, in both geophysics and magnetic recording. It is frequent in science that physical laws are discovered first by experiment and later explained by theory (Curie-Weiss laws for example). For this reason, the laws of TRM can properly be called the Thellier-Néel laws (L.Daly, 1979).

What is not generally recognized is that Thellier himself anticipated Néel's ideas, albeit in qualitative rather than quantitative form, three years earlier. Again quoting from Thellier (1946): "These facts, which do not as yet seem to have attracted the attention of theoreticians, seem to me to demand a mechanism of immobilization of elementary magnetic moments below a temperature Θ, this temperature having a strong variation from point to point within a body. One can imagine the body to be constituted of elementary domains, perhaps very tiny, each with spontaneous magnetization. Above Θ, their moments will be free (rotation, wall displacement or reversal) and the magnetic state of the body will establish itself by the combined action of the field and of thermal agitation (a sort of paramagnetism). Below Θ, the elementary moments will be bound to equilibrium positions from which they undergo only reversible displacements in weak fields. The temperature Θ will vary at each point in the body, perhaps with the dimensions and the shape of the crystalline grains, and will be broadly distributed between the Curie point and room temperature. One can thus explain thermoremanence by the progressive fixing, in the course of cooling, of moments which find themselves held fast when they pass through their individual temperature Θ.

One can also account for the shape of thermomagnetic curves, in particular the strong increase in susceptibility below the Curie point."

In this remarkable paragraph are all the essential ingredients of Néel's picture: blocking temperature Θ; unblocked or superparamagnetic state above Θ in which thermal agitation establishes an equilibrium; freezing in of the equilibrium in cooling with only reversible changes possible below Θ; and distribution of Θ values due to variable sizes and shapes of grains, explaining the spectrum of partial TRMs comprising the total TRM of the body. Thellier even anticipates the explanation of the Hopkinson peak in susceptibility at high temperature. Although Thellier's ideas were not crystallized into a quantitative theory, his intuition was correct in every essential.

Néel did not directly acknowledge these early theoretical ideas but his appreciation of Thellier's enormous experimental contributions is clear in his commentary on a paper summarizing all of Thellier's results (Thellier, 1951, p. 217; translated from French): "Among the phenomena demonstrated in the magnetization of baked clays and lavas, we should distinguish carefully (total) TRM on the one hand and the independent magnetizations acquired in non-overlapping temperature intervals (i.e., partial TRMs) on the other… The second is a much more remarkable phenomenon and it is to Thellier that we owe our experimental knowledge of it."

Anhysteretic Magnetization and AF Demagnetization

Thellier's earliest scientific achievements were made in collaboration with three remarkable women, whose contributions tend to be overlooked. First was his wife Odette Thellier, who participated in experiments showing that thermal demagnetization of TRM to a temperature T_1 resulted in precisely the same intensity as suppressing the field at T_1 during initial cooling from the Curie point T_C (i.e., pTRM (T_C, T_1, H) (Thellier & Thellier, 1941). From these experiments evolved the pTRM reciprocity law. Odette Thellier was also her husband's full partner in archeomagnetic research on both paleodirections and paleointensities throughout the 1940s and 1950s, culminating in their famous paper, Thellier & Thellier (1959) (see following section).

Thellier's second collaborator, Juliette Roquet, extended investigations to synthetic minerals of both fine and coarse grain sizes and natural materials containing different size fractions. Her thesis (Roquet, 1954) is the first systematic rock magnetic study of grain-size trends in isothermal and thermal properties of partial TRM and other remanences. It sets a standard that has yet to be surpassed, thanks to her dedication and the exacting standards set by her mentor.

Third was Francine Rimbert, who constructed one of the first AF demagnetizers and used it to demonstrate that anhysteretic remanent magnetization (ARM) is almost as strong and resistant to alternating fields as TRM and that ARM, in weak magnetic fields H, is proportional to H (Thellier & Rimbert, 1954). They pointed out the need to scrupulously eliminate any extraneous fields during AF demagnetization, including the ambient geomagnetic field, to avoid contaminating NRM by unwanted ARMs. This was the pioneering study in AF demagnetization which was then developing as a standard paleomagnetic cleaning method.

Rimbert's thesis (Rimbert, 1959), another monumental piece of work testifying to her ability and her supervisor's stringent expectations, is a complete experimental and theoretical study of ARM, partial ARMs, and AF demagnetization. It is the ultimate justification of AF bias methods for encoding magnetic information, for example in analog audio and video recording, and of AF cleaning of successive generations of primary and secondary NRMs in rocks. Laws analogous to those of Thellier for partial TRM have since been verified for fine-grained magnetic oxides (Dunlop & West, 1969) and ferromagnetic thin films (Papusoi & Apostol, 1979), ARM playing the role of TRM and AF substituting for temperature.

Archeomagnetism and the Thellier-Thellier Paleointensity Method

Archeomagnetism is the study of the direction and intensity of the geomagnetic field during historical times. Directional work is on the face of it more straightforward than determining paleointensity because loss of part of the primary NRM does not affect the direction of the remainder. Loss of NRM intensity, on the other hand, translates directly into a diminished estimate of paleointensity, a problem the Thellier-Thellier method was designed to overcome.

In spite of the comparative ease of directional measurements and the early beginning made by Émile and Odette Thellier, they published during the 1940s and 1950s only sporadic determinations of inclination I (for pots and bricks for which only paleohorizontal at the time of firing was known) or both I and declination D (for fixed objects such as the kilns in which firing took place). This was not for want of experimental work but because of the Thelliers' desire to have a complete and trustworthy picture of the variations of D and I through time before publishing a master curve that would certainly be widely used by archeologists as a dating tool. Thus it was only after investigations were complete for about 100 sites in France, Turkey, Cambodia and North Africa that Émile Thellier revealed in a presentation at the 1971 IUGG assembly in Moscow the fruits of all their labors, curves of secular variation of the field throughout the past 2000 years. His final paper, written in 1981 when he was 77 , presented all their results, for more than 200 ovens and 50 sets of bricks, describing the directional behavior of the geomagnetic field in France during the period 0 – 1800 AD.

The Thelliers moved more quickly to establish the historical record of field intensity. For paleodirectional work, Émile Thellier had perfected a sensitive spinner magnetometer on a grand scale, still in use today, capable of measuring the NRMs of intact pots with dimensions as large as 50 cm without the need to subsample these priceless archeological treasures. Paleointensity work required a methodological invention of equal ingenuity, the Thellier-Thellier protocol, still the standard method used today.

The Thellier-Thellier method compares NRM, produced thermally in an unknown ancient field H_A, with a TRM produced in a known laboratory field H_L. This basic idea had been put forward earlier by Folgerhaiter (1899) and Koenigsberger (1938) but no trustworthy results emerged. Folgerhaiter, quoted by Thellier (1938, p. 287), says (translated from French) “One could also arrive at some conclusion about the intensity of the terrestrial field by reheating ancient vases and comparing the ancient and presently acquired intensities of magnetization; but measurements made on vases heated and reheated in repeated experiments have shown me that this method leads to too uncertain results.” The reason for the uncertainty is alteration of the chemistry and physical state of the magnetic minerals resulting from heating, demonstrated very clearly by Koenigsberger’s progressive heating experiments on igneous rocks.

The novelty of the Thelliers’ procedure is in the interweaving of pairs of heating-cooling steps to successively higher temperatures, instead of a single heating-cooling to T_C. In their original version (Thellier & Thellier, 1959), both heatings to a particular temperature T_i were carried out in the presence of a laboratory field (the ambient Earth’s field in their experiments) but the sample was rotated 180° between heatings. In the currently most used version (Coe, 1967), the first heating-cooling is in zero field and the second in H_L. In the Coe version, the first heating serves to demagnetize that part of the NRM with $T_B \leq T_i$, while the second heating replaces this loss with a partial TRM (T_i. T_o, H_L). The NRM and partial TRM are not generally in the same direction, so that they must be obtained by vector subtraction of the results of the two heatings. In the original version, equal partial TRMs in opposite directions are acquired in the two heatings, but the vector subtractions are still straightforward. Although the modified version gives a neater segregation between NRM loss and partial TRM gain, the original version has some bonuses: the two heatings have perfect symmetry and no null field is needed.

The Thellier-Thellier method is firmly rooted in Thellier's three laws of partial TRM. This protocol has three tremendous advantages, not matched by other techniques:

1. There is a built-in test of the TRM origin of the NRM, namely constancy of the ratio of NRM lost/ partial TRM gained over successive heating steps.
2. Portions of the NRM that are unreliable can be recognized and discarded. A common contaminant at low T_i is viscous remanent magnetization (VRM) produced by the present Earth's field. Alteration of mineral microstructure or chemistry tends to occur at high T_i.
3. Linear least-squares fitting to the set of acceptable NRM and partial TRM data can be used to obtain the mean paleointensity ratio H_A/H_L and its associated error. This procedure, the Arai plot, was introduced later, by Nagata et al. (1963) but it is a natural consequence of the linear replications in the Thellier-Thellier method.

The name of Koenigsberger has been associated by some with this method and given precedence over the Thelliers themselves (so-called KTT method). This misrepresents the facts. In four of Koenigsberger's papers published in German journals between 1930 and 1936 and in his summary work in English (Koenigsberger, 1938), there is no indication that he was aware of partial TRMs or their properties. The only paper by Thellier he cites is on determining directions. He did carry out stepwise heatings with H_L parallel or antiparallel to NRM but these were separate, not interwoven, experiments, and there was no attempt to use the results to estimate field strength. Most of his samples altered so much in the first set of heatings that there was no symmetry between $+H_L$ and $-H_L$ curves.

Koenigsberger espoused the idea that NRM spontaneously decayed with time (what we would nowadays call viscous decay) so that the ratio Q_n = NRM / kH would be systematically lower than Q_t = TRM/ $k'H$ for rocks of increasing age. Here k, k' are susceptibilities measured before and after TRM acquisition and H is the local present Earth's field. He viewed this as an age determination, not a paleointensity, method. Thellier (1938, p. 293) correctly ascribed the differences between Q_n and Q_t to increased susceptibility resulting from alteration during heating and not to spontaneous decay of NRM. Thellier went on to suggest that the ratio Q_n/Q = (NRM/TRM) (k'/k) might serve as a rough estimate of the paleointensity ratio H_A/H_L. This is a slight improvement on Folgerhaiter's prescription, H_A/H_L = NRM/TRM, in that it takes some account of alteration of a sample through the ratio k'/k, but it is far from being an earlier incarnation of the powerful and sophisticated Thelliers' method.

Viewing the considerable alteration evidenced by the differences between k' and k in Koenigsberger's igneous samples, Thellier soon came to the reasonable conclusion that the suggested correction procedure was unjustified, particularly since the quantitative relation between remanence and susceptibility depends strongly on mineralogy and grain size. He says (Thellier, 1938, p. 293) "The susceptibility has changed markedly as a result of heating for many of these rocks; they should be rejected for the purpose of studying the intensity of the terrestrial field." Since then, many intricate and ingenious schemes have been proposed for "undoing" the effects of alteration during heating but none in the final analysis gives results that most paleomagnetists would trust. There is really no substitute for the Thellier-Thellier method (under which we include microwave heating methods that heat the magnetic minerals but not the rock matrix), nor for the uncompromising standards set by Émile Thellier.

Other geophysical research.

During his long career in the University and the CNRS, Emile Thellier was entrusted with many research, advisory and administrative responsibilities. He thus came to play a part in developing many other areas of geophysics: study of the ionosphere, oceanography, atmospheric electricity, climatology, magnetic exploration methods, and measurement of the geomagnetic field, including drift of the magnetic poles.

While he was an Assistant at the Faculté des Sciences de Paris, Commander Charcot, during the 1935 Arctic voyage of the "Pourquoi-Pas?", entrusted to him the task of carrying out regular monitoring of short-wave radio emissions, a practical if indirect method of studying the ionosphere (Thellier, 1935). He followed this work with direct studies of the ionosphere with Jouaust, who had just developed an ionospheric sounder. Their studies allowed the intensity of the terrestrial magnetic field in the ionosphere to be determined, starting from the shift in the sounding curves caused by the anisotropy of the ionized medium resulting from this field (Thellier, Jouaust & Jardy, 1939).

On board the "Pourquoi-Pas?" during the same voyage, he was also in charge of making salinity and temperature measurements along the entire track traversed by the ship in the Arctic (Thellier, 1935). About the same time, he initiated the development of magnetic measurements at sea by acquiring a high-quality marine magnetometer for the Institut de Physique du Globe. Thus France began to develop measurement programs using various ships, particularly those of the Naval Hydrographic Service. One example is the completion of a series of magnetic profiles across oceanic ridges in the southern oceans.

In atmospheric electricity, an important subject in the 1940's and one which he taught at the Faculté des Sciences, he and his wife (who had chosen this as her thesis subject) compared the ionization of the lower atmosphere in the cities and in the countryside. This was the beginning of long-term measurements, before and during the war, of air quality in Paris, bearing on the problem of urban air pollution and leading to a publication (Thellier &.Thellier, 1941).

While he was a Lecturer at the Faculté des Sciences de Paris, Charles Maurain put him in charge of the climatological station at the Observatoire du Parc Saint-Maur. At the same time as continuing a century-old tradition of high-quality measurements, he developed with A. Cailleux a simple device for directly reading the depth or thickness of frozen soil (Thellier & Cailleux, 1947). Subsequently, the Department of Public Works and the Climatological Service adopted the use of this simple and reliable device, enabling them to track the thawing of the soil, from the surface to deeper layers and vice versa.

Four highlights stand out from the period when E. Thellier was responsible for terrestrial magnetism measurements at the Institut de Physique du Globe:

In 1946 and 1947, he and Selzer established the French network of stations where the geomagnetic field elements are remeasured every five years to monitor regional geomagnetic secular variation (Thellier & Selzer, 1949).

Using induction magnetometers of his own devising to measure magnetic moments of magnets, he worked out a simple procedure for determining correction factors for temperature and induced magnetization when measuring the horizontal component of the Earth's magnetic field by Gauss' method (Thellier, 1944).

His exhaustive study with Odette Thellier of magnetic records of solar flares made it possible to categorize solar storms. Storms that begin abruptly do not have the 27-day periodicity typical of those with a gradual onset. The sporadic occurrence of very large storms is consistent with their abrupt onset character (Thellier, 1947; Thellier & Thellier, 1948). They also showed that the 27-day periodicity was more marked during the waning phase of solar activity and that it was indeed an intrinsic property of gradual-onset storms (Thellier & Thellier, 1949).

During the International Geophysical Year of 1957-58, acting as chair of the Committee on Instruments of the Association of Terrestrial Magnetism and Electricity, he published a report on the best techniques for studying rapid and very rapid magnetic variations (Thellier, 1957).

In magnetic exploration, the Thelliers and E. Schneider used gridded measurements with a Schmidt balance to locate and delineate diapirs of Triassic ophite. They published some of the results and a discussion of the theories of emplacement of the ophite (Thellier, Thellier & Schneider, 1948).

An old idea, still current in the 1960's, that the geomagnetic pole has drifted in a SE-NW direction since the time of Gauss was proven wrong by Thellier, using the results of several spherical harmonic analyses published after the last war. He proposed the simple idea that the pole has remained fixed over the intervening century in an article in the Encyclopedia of the Pleiade (Thellier, 1959). In 1963, he asked G. Toulouse to carry out for his thesis research a definitive test by making a spherical harmonic analysis using only data from the locations used by Gauss in his 1835 analysis. If a real movement has occurred, the pole thus obtained should fall among recent poles; if not the pole will be offset towards Gauss's pole, as is indeed found to be the case.

The Thellier school

Finally, members of the "Thellier school", students of the Laboratoire de Géomagnétisme du Parc-Saint-Maur created by Thellier in 1967, have contributed and continue to contribute to our understanding of the magnetism of rocks in a variety of areas: magnetic anisotropy (L. Daly, 1970 and B. Henry, 1980); piezomagnetism (J.P. Pozzi, 1973); magnetic mineralogy and geomagnetic reversals (M. Prévot, 1975); depositional and post-depositional remanent magnetization (D. Biquand, 1974); viscous remanent magnetization (C. Plessard, 1967); fidelity of the magnetic record of volcanic rocks (J.C. Tanguy, 1980); archeomagnetism (I. Bucur, 1986); thermoremanent and crystallization remanent magnetization (M. Bina, 1966); properties of hematite (A. Lecaille, 1972); instrumental development (M. LeGoff, 1975). Many foreign visitors, among them two of the authors, have worked in the St-Maur laboratory, establishing fruitful collaborations and links to the broader international paleomagnetic community. The heritage of Emile Thellier continues undiminished.

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