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The dawn of archeomagnetic dating

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Abstract. The use of secular variation in Earth's magnetic field for dating purposes in archeology and volcanology began with the first developments in paleomagnetism. This paper traces the key contributions of Paul-Louis Mercanton, Pierre David, Bernard Brunhes, and Raymond Chevallier in the early 20th century, between the seminal works of Giuseppe Folgheraiter in the 1890s and Emile Thellier in the 1930s, all of whom expressed a strong interest in these applications. These researchers raised issues that are still at the forefront of present-day research, though archeomagnetists are now able to address them with modern tools and much larger sets of data. Surprisingly, in 1901, a first and long plea for the use of archeomagnetism as a dating tool came not from a paleomagnetist but from the limnologist François-Alphonse Forel.

Keywords. History of paleomagnetism, Archeomagnetism, Archeology, Secular variation, Archeomagnetic dating.
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1. Introduction

Archeomagnetism relies mainly on the analysis of the magnetic properties of archeological baked-clay artifacts, such as the elements of fired structures (floors and walls of all types of kilns), bricks, tiles, or pottery. Depending on the nature of these artifacts, found displaced or originating from the place of their firing, it is possible to determine the direction and/or intensity of Earth's magnetic field that prevailed at the time and place of their firing/cooling. These data allow researchers to compile regional geomagnetic secular variation curves or to add to existing curves as new archeomagnetic results of different ages are acquired. This discipline emerged at the end of the 19th century, thanks to the precursory and visionary work of Guiseppe Folgheraiter (1856–1913) [Folgheraiter, 1899; see also Courtillot and Le Mouël, 2007, Principe and Malfatti, 2020], before Emile Thellier (1904–1987) defined its main laws and applications in the 1930s [e.g., Thellier, 1938; see also Le Goff et al., 2006].

Archeomagnetism has developed impressively over the last twenty years, with a significant increase in the number of archeomagnetic studies and researchers in the world. The main reason for this renewed interest relates to the need to extend the records provided by direct/instrumental geomagnetic measurements into the past, which began, in incomplete form, in Western Europe around the second half of the 16th century [Alexandrescu et al., 1997, Jonkers et al., 2003]. The goal is to better describe and model regional and/or global geomagnetic field behavior on time scales ranging from tens of years to millennia [e.g., Constable and Korte, 2015, Korte et al., 2019]. Such studies provide a unique opportunity to decipher the dynamo processes that act in Earth's liquid outer core.

The compilation of archeomagnetic results now makes it possible to construct millennial-scale geomagnetic field directional and intensity variation curves for several regions of the world, even if most of the available data are still located in Europe [Brown et al., 2021, Genevey et al., 2008]. Beyond the applications of archeomagnetism in geomagnetism, the ever-increasing accuracy and reliability of secular variation curves reinforce applications turned in the opposite way, toward archeology especially through archeomagnetic dating. Archeomagnetic dating is based on the comparison between a direction and/or intensity obtained from artifacts of unknown or poorly known age and a dated reference secular variation curve, valid for a given region. To this end, various statistical comparison techniques, from which a time interval is determined, can be used [Gallet et al., 2009, Genevey et al., 2021, Hervé and Lanos, 2017, Le Goff et al., 2002, Livermore et al., 2018, Pavón-Carrasco et al., 2011]. Other applications of archeomagnetism also concern the determination of the provenance of artifacts, the testing for contemporaneity between different artifacts/structures based on direction and/or intensity data, or the deciphering of manufacturing processes thanks, for instance, to the evaluation of firing temperatures. The recent burgeoning of archeomagnetic dating studies has made archeomagnetism a major player in archeological research [Catanzariti et al., 2007, Genevey et al., 2021, Gómez-Paccard and Beamud, 2008, Schnepp et al., 2015].

In a recent paper, Korte et al. [2019] synthesized the potential of archeo/paleomagnetic records and the secular variation models that can be constructed from them to provide chronological constraints for the Holocene Epoch, with applications extending well beyond the field of archeology. These authors attributed the introduction of the concept of archeomagnetic dating to Thellier [1938] (Figure 1). This concept was indeed addressed by Emile Thellier in his thesis, but in a very succinct and purely predictive manner, as follows (translated from the French):

> *But here arise many difficulties, besides those due to the measurements of these weak magnetizations: it is necessary, first of all, to be able to determine the age of the objects studied; then it would be necessary to know how to distinguish the thermal magnetization from the remanent magnetization if it exists; finally, it would be necessary to make sure that this thermal magnetization has not been modified. This interesting geophysical problem having been solved that is, the terrestrial field being known for a place, during a certain period one could then think of the inverse problem, which would be to date materials by studying their magnetization. Let us say, right away, that this too ambitious program is certainly not feasible for the geological periods, but it is, probably, for the whole historical period.*

Figure 1. Photo of Emile Thellier during an archeomagnetic sampling. The lady is Odette Thellier.

In fact, the use of geomagnetic secular variation in archeological practices, including volcanology, has its roots very early in the history of paleomagnetism. This manuscript traces the applications explored by Swiss and French paleomagnetists at the beginning of the 20th century, between the seminal works of Giuseppe Folgheraiter and Emile Thellier, with a particular focus on archeomagnetic dating.

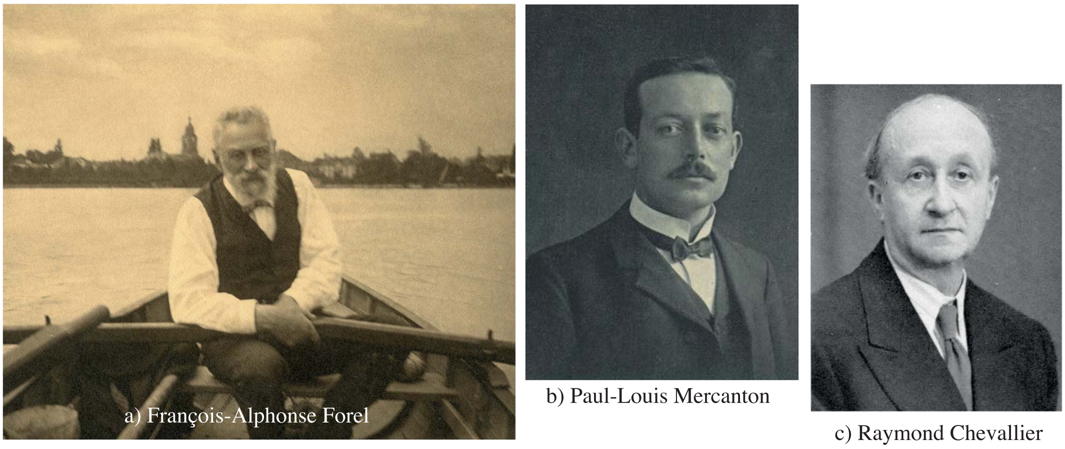

Figure 2. (a) François-Alphonse Forel in his boat off Morges (Switzerland), 1910; collection of the Léman Museum (gift of Mercanton to the museum). (b) Paul-Louis Mercanton in 1919 (from Wikipedia). (c) Raymond Chevallier (from Bolfa, 1965).

Their writings have proven to be particularly modern, in line with the approach followed by today's archeomagnetists.

2. Forel's request

Giuseppe Folgheraiter (1856–1913) appears to have been the first to use dated archeological baked-clay artifacts, in this case, Greek, Etruscan, and Roman pottery, to produce a geomagnetic (inclination) secular variation curve [Folgheraiter, 1899 and references therein; see discussion in Courtillot and Le Mouël, 2007 and Principe and Malfatti, 2020]. As such, Folgheraiter deserves to be considered the pioneer of archeomagnetism, even though his work followed fundamental studies conducted by Macedonio Melloni (1798–1854) and Silvestro Gherardi (1802–1879) [Principe and Malfatti, 2020]. In their *brief history of magnetism*, Le Mouël and Poirier [2013] recalled a letter from Gherardi to Giuseppe Fiorelli, then director of the archeological excavations at Pompeii, following magnetic measurements made on a fragment of tile from this site [Gherardi, 1863; see also Principe and Malfatti, 2020; translated from the Italian]: *I am certain that this material has always kept alive its own magnetism, this ethereal movement, or this eminently subtle, imponderable, inconceivable substance* [...] *of which we can well say (without heresy!) that it forms, that it is, its soul, its spirit.*

In his 1899 review article, Giuseppe Folgheraiter showed remarkable insight regarding the ability of archeomagnetism to recover the directions (inclination and declination) and intensities of the ancient geomagnetic field, which would then form the basis of Emile Thellier's work some thirty years later. However, Folgheraiter did not mention the reverse approach that archeomagnetic dating represents, although he did use archeomagnetism to constrain the manufacturing processes (heating temperatures) of Etruscan pottery of the Bucchero Nero type [Folgheraiter, 1897; see also Principe and Malfatti, 2020]. This approach, necessarily very predictive at the beginning of the 20th century, was clearly expressed in the work carried out a little later by Paul-Louis Mercanton (1876–1963) at the University of Lausanne, Switzerland (Figure 2). It even appears that Mercanton's work in archeomagnetism was primarily motivated by a desire to verify Folgheraiter's inclination results for the first millennium BCE, which surprisingly showed negative values in central Italy during the 8th century BCE, and then to use the variation curve for archeological chronology purposes. With great humility, Mercanton admitted that this idea was provided by his colleague, a professor at the same university, François-Alphonse Forel (1841–1912; Figure 2). Particularly well known for his work on limnology (see Vincent and Bertola [2012] for a summary of his life and scientific achievements), Forel was a researcher with remarkably diverse interests and skills, including the archeology of lake sites ("palafittes") in Switzerland. In the first known archeomagnetic study by Mercanton, who presented himself as an electrical engineer, he quotes *in extenso* the letter he received from Forel in March 1901 [Mercanton, 1902]. Below is an excerpt from this letter, which appears as a true mission statement (translated from the French; the complete letter is provided in Text S1):

> *I wondered how the methods of Dr. Folgheraiter, of Rome, could be usefully applied to the study of ancient pottery found in pile-dwelling sites of the Swiss lakes. Here are my hopes in this regard:* [...]
>
> *As for the pottery of more ancient times, that of the Neolithic Stone Age and its various stages, you will perhaps one day be able to apply the same method of study to it, when the Folgheraiter curve has been studied well enough and completed far enough that one can determine the formula of the periodicity and extrapolate the probable values of the magnetic inclination to times prior to the established ages and dates. One is not yet at this point, far from it, it is necessary to admit it; but we have a reason to hope that one day one will arrive there, and then, thanks to this admirable application of the methods and measurements of the physics laboratory to the facts of pure archeology, you will tell us how to transform into accurate dates, in dates of historical chronology, the relative values of geological chronology. Up to now, we only have the order of succession of the human prehistoric epochs; you will show us, I have the firm hope, how to measure the duration of these periods and fix their dates on the calendar of the past centuries.*
>
> *Is this problem not attractive? The results that it suggests would be of sufficiently crucial importance for the history of humanity in our countries that, in spite of the undeniable difficulties that it presents, I dare to encourage you to approach it by calculation and by experiment.*

In his studies on Swiss vases, where he used the same experimental method as Folgheraiter, followed thereafter by measurements on older volcanic rocks [e.g., Mercanton, 1926, 1932] before he turned to study glaciology and wireless telegraphy, Mercanton was unable to confirm—for good reason—the largely erroneous results of Folgheraiter [Mercanton, 1902, 1906, 1907]. It is worth mentioning here that Folgheraiter, Mercanton, and Forel were already addressing questions close to the concerns of today's archeomagnetists, using valid arguments, notably concerning the firing positions of the materials studied and the application of the results, while not ignoring the pitfalls (see below).

Forel's expectations were therefore unfulfilled. However, 120 years later, the period of the first millennium BCE studied by Folgheraiter and Mercanton became the subject of intense research activity due to evidence for exceptionally strong and rapid geomagnetic variations both in direction and intensity [Osete et al., 2020, Shaar et al., 2016, Tema et al., 2021]. This archeological period lends itself particularly well to the wishes expressed by Forel, although the humid environment of the ancient lake sites, as well as the firing of the ceramics in a reducing atmosphere, for the most part, makes us fear disappointing archeomagnetic results for anyone who might undertake such a study.

3. French contribution

In France, prior to Thellier's work, three scientists, Pierre David, Bernard Brunhes, and Raymond Chevallier, had expressed a strong interest in the application of magnetism in archeology and volcanology. Following Melloni, Gherardi, and Folgheraiter, the initial objective for Brunhes and David was to further demonstrate the persistence in time of the magnetization acquired by materials, baked clay or volcanics, during their cooling, this thermoremanent magnetization not being thus rapidly replaced by a magnetization acquired in the present-day magnetic field [see the early developments in rock magnetism for instance summarized by Courtillot and

a)
b)

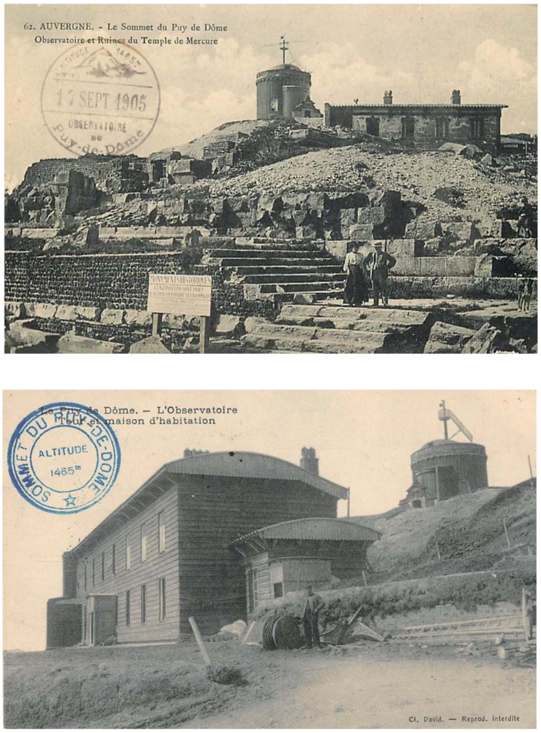

Figure 3. Photos of the meteorological observatory of Puy de Dôme where Bernard Brunhes and Pierre David carried out their magnetization measurements. (a) Observatory built in 1876–1877, with at its feet the ruins of the Gallo-Roman temple dedicated to the god Mercury. (b) The observatory rebuilt in 1907, where Pierre David lived permanently. The photo appears to have been taken by David himself (see another photo in Figure S1). These photos are from postcards (collection Y. Gallet; note that no less than seven different postcards showing photos taken by David have been found by the author).

Le Mouël, 2007]. In the early years of the 20th century, they worked at the meteorological observatory located at the summit of the Puy de Dôme volcano, near Clermont-Ferrand, France, with Brunhes (1867–1910), professor at the Faculty of Sciences of Clermont, being the director and David (1877–not known) his assistant (note that David lived permanently at the observatory; see Didier and Roche [1999] and Kornprobst [2019] for a summary of the life and career of Bernard Brunhes). To escape the magnetic disturbances caused by the electric streetcars in Clermont-Ferrand, they installed at the Puy de Dôme observatory a declinometer designed by Eleuthère Mascart [Mascart, 1900, p. 191] to measure rock magnetization [Brunhes, 1905a]. This observatory was located next to the ruins of the Gallo-Roman temple dedicated to the god Mercury, excavated during the second half of the 19th century (Figure 3). Pierre David had the idea to analyze samples from four paving slabs from this temple, which were made of a volcanic rock called domite (i.e., a trachyte). He found homogeneous magnetic directions in three slabs, from two samples of each, but different directions between the four slabs, thereby proving the stability of the thermoremanent magnetization since at least the construction of the temple [David, 1904]. His paper also mentions scattered results obtained from blocks of volcanic scoria and domite taken from a wall. Similar conclusions had been drawn by Melloni [1853] from the analysis of blocks of volcanic rocks taken from the amphitheater of Pompeii, Gherardi [1862] from baked-clay bricks of buildings in Turin, as well as by Folgheraiter [1896], who had measured the magnetization of baked-clay bricks from ancient monuments in Rome and its surroundings. Apart from finding the persistence of remanent magnetization, David wrote (translated from the French):

> *Moreover, the constancy of the absolute value of the inclination seems to indicate that all these slabs were taken from the same quarry where they would have been removed from parallel layers, as is frequently the practice in current quarries. At the time of setting, some of them would have been laid upside down, which would explain the change in sign of the inclination. As for the declination, the size of the slabs may have modified it in some way.*
>
> *We also notice that two cubes of similar dimensions have the same magnetic moment. There might be a way to solve the much debated question of the origin of the huge blocks that were used to build the temple, whose ruins are still imposing after*

Figure 4. Poster highlighting the French participation in the 1905 Great Exhibition in Liège to celebrate Belgium's 75th anniversary. It should be noted that the person to the right with the bowler hat resembles (likely by chance) Bernard Brunhes. The French delegation organized a series of conferences, with, among the speakers, two Nobel Prize winners in Physics and Chemistry (H. Becquerel and P. Sabatier, respectively) and Bernard Brunhes, who presented there the first evidence of geomagnetic polarity reversals.

> *2000 years.*

This includes a clear reference to the use of magnetization measurements to constrain the practices of Gallo-Roman quarrymen and the provenance of the artifacts studied. The following year, in a lecture entitled *Recent works on terrestrial magnetism in central France. The present and magnetic past of the Auvergne volcanoes*, given on August 28, 1905, as part of the Great Exhibition of Liège in Belgium (Figure 4), the text of which has been published [Brunhes, 1905a], Bernard Brunhes reviewed these findings to further emphasize their interest for archeological purposes (translated from the French):

> *Our declinometer informs us today about the way Gallo-Roman workers cut and placed the slabs of a temple, more than two thousand years ago. Terrestrial magnetism thus attempts to render to archeology the services that archeology has rendered to it.*

Interestingly, Brunhes [1906] also mentioned additional data obtained by Pierre David, which they used to cautiously propose, based on a similarity in magnetic inclination values, that the stones of the Temple of Mercury were extracted from quarries from the Puy de Clerziou located a few kilometers north of the Puy de Dôme. This interpretation would possibly give information on the path used to transport these rocks to the summit of the Puy de Dôme.

In his 1905 lecture in Liège, Brunhes recalled Folgheraiter's desire to work on fired materials found in situ, such as a pottery kiln or burnt remains, in order to obtain information on both magnetic declinations and inclinations announcing (translated from the French):

> *It is this wish that we believe we have realized by the magnetic study of the natural brick produced by lava flows by coming to rest on clay strata.*

After two studies on geologically baked clay, or "natural brick," sampled in quarries near Beaumont and in Royat, close to Clermont-Ferrand [Brunhes and David, 1901, 1903], another conducted on the Miocene outcrop near the bridge and hamlet of Pontfarein (now Pont Farin) in Cantal, central France (Figure 5) led to the discovery of geomagnetic polarity reversals [Brunhes, 1905b, 1906; see also Laj et al., 2002, Kornprobst, 2019]. The latter results were presented at this conference. He wrote (translated from the French):

> *And I don't see that it is possible to conclude otherwise than by stating that in the Miocene Epoch there was certainly a moment when our north pole of today was directed upwards.*

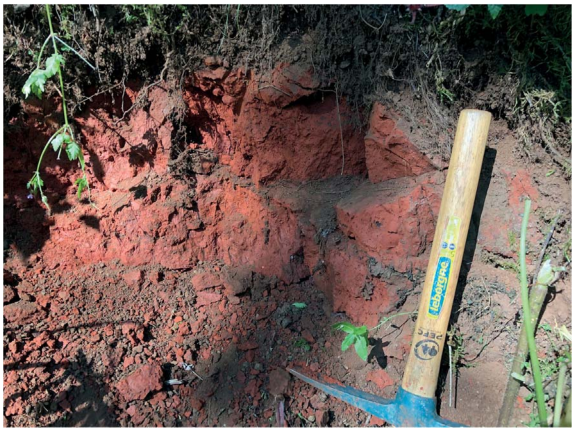

Figure 5. Natural brick (clay heated by the emplacement of a lava flow) from the Pontfarein outcrop (Cantal, France) studied by Bernard Brunhes. @ Y. Gallet.

This major discovery is thus intimately associated with research on archeomagnetism. It also explains why Brunhes and Mercanton, the latter having made similar observations on volcanics sampled in northern regions [Mercanton, 1926, 1932], maintained fairly favorable assessments of Folgheraiter's results [as opposed to the skepticism of Carlheim-Gyllensköld, 1897], although they could not confirm them.

Regarding the issue of magnetic dating, other statements by Brunhes [1905a] echo recurrent remarks in the modern literature. The following example is from Korte et al. [2019]: *However, as often noted, paleomagnetic field evolution cannot give unique age information because values of field intensity and directions recur over time [e.g., Aitken, 1970, Thellier, 1977, Clark et al., 1988], even though variations are not periodic. It has been suggested, e.g., by Emile Thellier [see Aitken, 1970] that the term "magnetic dating" should be used with reserve.* Bernard Brunhes wrote (translated from the French):

> *When our first notes were published, we were asked whether we could date volcanic phenomena in the past. I do not think so, and here is why: Even supposing, which is not the case, or at least has not always been the case, that the secular variations of the compass adopt a regular periodicity, we would have the instant of the period in which the eruption occurred: the number of elapsed periods would not be given to us. We still remember this curious railway accident that occurred in Paris, at the Montparnasse station: a train that could not stop in time broke through the façade of the terminal station and, as there was a difference in level, we saw the locomotive fall from the second floor onto the public square; in piercing the façade, the train cut the wires that electrically distributed the time to the clocks in the station, and the next day we could read on these clocks, stopped at the same minute, the exact time of the accident. If everything had been found as it was after a year, after a century, the sight of these dials and the stopped hands would have given us the minute and the hour, but not the date of the accident. In the same way, since the last volcanic eruptions, at least in Auvergne, the needles of the two declination and inclination compasses would have had time to rotate around their dials several times: knowing at which points on their dials the eruption seized them does not tell us how many turns they have made since.*
>
> *Does this mean that the information provided is to be disregarded? No, certainly not, and, to continue my comparison, the fact of knowing the time of an event in the past without having the date will allow a wise historian to draw important conclusions. He will be able to say, for example, of two given events, that they were not, as was believed, simultaneous; the geologist who knows how to handle a declinometer will be able to say in the same way: two volcanic flows were not contemporaneous.*

The possibility of using magnetization measurements to test the contemporaneity of two volcanic

Figure 6. Photo of the train accident that occurred on October 22, 1895 in the Montparnasse station in Paris, mentioned by Bernard Brunhes in his lecture given in Liège on August 28, 1905 to illustrate the problems inherent to magnetic dating. From wikipedia.

flows was also raised by Brunhes and David [1901]. Brunhes's analogy with the train (Figure 6) seems somewhat bold, but it expresses well the recurrence of the geomagnetic directions and intensities known today for a given region at certain periods and indicates that archeomagnetists, when they want to provide chronological constraints, must take into consideration the help of archeologists or other dating tools, such as radiocarbon. In France (and more generally in Western Europe), for instance, recurrences in directions occur between the Roman and present periods and between the 7th–8th centuries and the 17th century [Figure 7a; Le Goff et al., 2020]. Recurrence is more frequent for intensities, such as between the 6th and 9th–10th centuries or between the 14th and 15th centuries [Figure 7b; Genevey et al., 2016, 2021]. It obviously follows that archeomagnetic dating based on both direction and intensity is more likely to provide a unique dating determination, especially if the reference time interval is only one or two millennia [Tema et al., 2015]. This combined approach, capable of resolving the "train-induced ambiguity" mentioned by Brunhes, is now possible in Europe, thanks to recent advances made in our knowledge of geomagnetic secular variation over the past few millennia.

Also, during the Great Exhibition of Liège, Brunhes mentioned magnetic analyses performed on vases from Lezoux, a production center of Samian ware located near Clermont-Ferrand. These very first French archeomagnetic analyses (sensu stricto) unfortunately remain undocumented. Other studies were conducted by Raymond Chevallier (1891–1965; Figure 2), at the College de France in Paris in the early 1920s, before he moved his research to the University of Nancy, where he focused on mineral magnetism (see Bolfa [1965] for a summary of his career). He analyzed the magnetization in both baked-clay bricks, with largely inconclusive results [Chevallier, 1923, 1926], and lavas from Etna with much more success and detail [Chevallier, 1925]. In the latter publication resulting from his thesis, he attempted the magnetic dating of two volcanic flows of uncertain age (translated from the French):

> *Let's look at the dates when the declination reached 9.5° East. Assuming a periodic variation of period 750 years, and a variation in the inclination corresponding to a symmetrical and periodic reproduction (T =* 750 *years) of the portion of the known curve, we have the following table* [...], *where I have included the dates of known eruptions closest to the times when the declination is 9°5.*
>
> *As the Sona flow is very posterior to the Roman period but prior to the XIIth century, we can see that a date of 812 is perfectly suitable for it; the magnetic inclination of the flow of 61°3 is also very close to the expected inclination of 64°5.*
>
> *For the lava of Aci-Castello, there is nothing to delimit the possible dates. Therefore 565 and 65 would both be suitable. To decide it would be necessary to employ other chronological data.*

Even if the approach used by Chevallier was based on an invalidated hypothesis about the periodic behavior of the geomagnetic field (see also in Forel's letter; Text S1), and on the incorrect dating of his dated results [while the magnetic measurements were fairly good; see discussion in Tanguy et al., 1999], these are

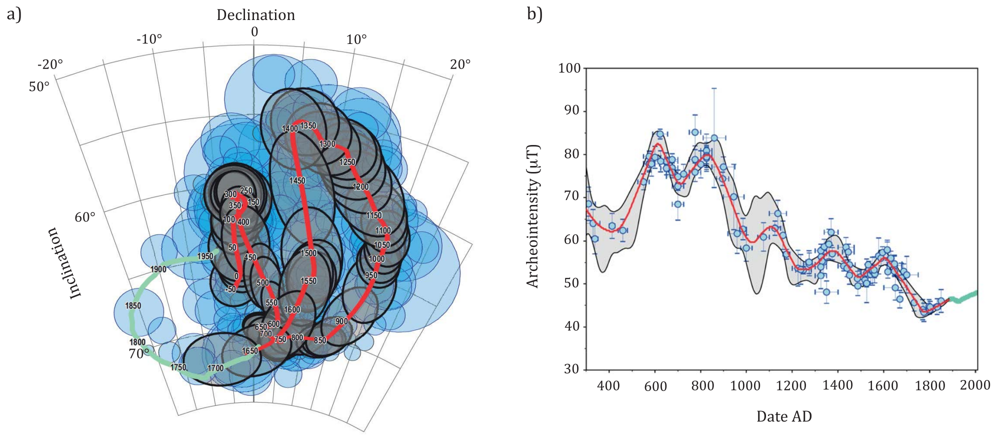

Figure 7. Geomagnetic secular variation in France revealed by archeomagnetic data. (a) Directional variations since the first century BC derived from the database compiled by Le Goff et al. [2020]. The data are exhibited in light blue. The mean curve (thick line in red) and its 95%-confidence intervals (gray ovals) are determined from the method developed by Le Goff et al. [2002] based on the bivariate extension of Fisher's statistics. See details in Le Goff et al. [2020]. The pale green line indicates the directional variations after 1650 AD determined using instrumental measurements [after Le Goff and Gallet, 2017]. All data were transferred to the latitude of Paris (48.9° N). (b) Geomagnetic field intensity variations over the past 1500 years. The database is the one recently compiled by Genevey et al. [2021]. All data were transferred to the latitude of Paris (blue dots). The red curve shows the median curve estimated using the AH-RJMCMC method developed by Livermore et al. [2018] [same parameters of calculations as in Genevey et al., 2021]; the gray area indicates its 95% credible interval. The green curve covering the past two centuries shows the instrumental intensity measurements.

likely the first two tangible examples of magnetic dating. Furthermore, having obtained inclination data for a series of recent bricks in Paris that were similar to each other (i.e., considering the angles on the same face), but different from those expected at the assumed time, Chevallier [1926] pondered on their age but without suggesting an interpretation. The scientific contributions of Raymond Chevallier are largely ignored by most paleomagnetists today [Courtillot and Le Mouël, 2007], but there is one that also deserves mention. He was the first to analyze bricks from the Near East (Chaldean bricks dated to the 3rd century BCE and about 3000 BCE, with no further details), a region that is now the subject of intense archeomagnetic research, with exciting possibilities for archeomagnetic dating [Gallet et al., 2014, Shaar et al., 2020, Stillinger et al., 2016, Vaknin et al., 2020].

4. Conclusion

This paper highlights some of the key contributions of Paul-Louis Mercanton, Pierre David, Bernard Brunhes, and Raymond Chevallier, all of whom expressed a strong interest in the application of magnetization measurements to archeology and volcanology in the early 20th century. It recalls that the limnologist François-Alphonse Forel also played an important role by proposing to Mercanton in 1901 to use archeomagnetism, on the basis of Folgheraiters's results, as a tool for dating ancient Swiss cultural phases. What is striking is the modernity of some of their writings, which perfectly accord with the preoccupations of today's archeomagnetists, although the latter now have modern tools and detailed databases at their disposal, which will enable them to develop archeomagnetism even further in the coming years.

Acknowledgments

This article is born from the withdrawal in 2019 of IPGP from the Saint Maur observatory, where Emile Thellier developed his research in archeomagnetism in the 1930s. The tedious sorting of documents (and thousands of samples accumulated since Thellier's time) allowed me to find and read the articles used in this study. I am very grateful to my "old Saint Maurien" colleague, Maxime Le Goff and Agnès Genevey, without whom my work in archeomagnetism would have been totally different and so much less enriching! I also thank Jean Besse, Alexandre Fournier, Phil Livermore, and Ron Shaar for their helpful comments on the manuscript. Special thanks to Jacques Kornprobst and Stuart Gilder, whose constructive reviews improved the quality of this article. This is IPGP contribution no. 4228.

Supplementary data

Supporting information for this article is available on the journal's website under https://doi.org/10.5802/crgeos.73 or from the author.

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