PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Evidence for Changes in the Earth's Magnetic Field Intensity [and Discussion]

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Phil. Trans. R. Soc. Lond. A 1970 **269**, 47-55
doi: 10.1098/rsta.1970.0085

Phil. Trans. Roy. Soc. Lond. A. **269**, 47–55 (1970) [47]
Printed in Great Britain

Evidence for changes in the Earth's magnetic field intensity

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[Plate 3]

Archaeomagnetic investigations based on the measurement of remanent magnetization in baked archaeological objects and rocks show considerable changes in the Earth's magnetic field in the historical past. The curve characterizing the Earth's intensity during the past 8500 years has its maximum around 400 to 100 B.C. when the field reaches 1.6 times its present intensity and its minimum around 4000 B.C. when the field drops to around 0.6 times its present intensity. On the smoothed curves with a periodical change of approximately 8900 years, changes with shorter periods are superimposed which can also be observed in declination and inclination. Results of archaeomagnetic investigations of samples from different areas on the Earth's surface are discussed with the aim of defining the whole world and non-dipole changes in the field moment. Possible connexions between the Earth's magnetic field and ^{14}C decay are discussed on the basis of magnetic results, and the approximate character of changes in the Earth's field during the past 20000 years is given.

Changes in the present Earth's magnetic field

Our planet Earth can be considered similar to a large magnet; the magnetic field of the Earth is usually expressed in the first instance by the field of the magnetic dipole at the Earth's centre alined along the axis of rotation. The shape of the field on the Earth's surface indicates, however, a much more complicated character which points to the fact that on a homogeneous (dipole) field further components are superimposed. If the homogeneous field is subtracted from the observed one we obtain the non-dipole field which is composed of six continental (terrestrial) magnetic anomalies. On the chart of the Z component we may notice three positive anomalies (Asiatic, Antarctic, American) and three negative ones (African, Icelandic, Australian).

In addition to these there exist further components characterizing the dynamical effects of the Earth's field included as secular variation. When looking at the graphs of the geomagnetic intensity changes during last 50 years of some magnetic observatories lined up according to their geographical longitudes (figure 1) then the decrease of the field by 4000 γ‡, i.e. by 7 % in Baldwin (U.S.A.) took place while an increase of 5 %, for example, in Dehra Dun (India) can be observed. This is strong evidence for considerable changes of the Earth's field. When going westwards from the Asiatic to European observatories, at first we see an increase of the field, then in Europe a minimum occurred at around 1915 which was shifting in time. It was seen first by the east European observatories and later by observatories in western Europe. Remarkable is the steady decrease of the geomagnetic field intensity on the whole American continent during the last 50 years which represents approximately 7 % of the geomagnetic field value, and which is still continuing. When expressing the main features of the magnetic field by means of the eccentric dipole we see that its position now being 500 km off the Earth's centre is steadily moving toward China at the speed of 3 km/year (Malin 1969).

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‡ $1\gamma = 10^{-5}\text{Oe} = 10^{-2}/4\pi \text{ A m}^{-1} \approx 7.96 \times 10^{-4} \text{ A m}^{-1}$.

Westward drift of the geomagnetic field can also be observed on the charts of terrestrial magnetic anomalies and isoporic foci which represent magnetic isopores characterizing the equal changes of the magnetic field and the shift of isoporic foci (centres of maximum and minimum changes) during the past 40 years.

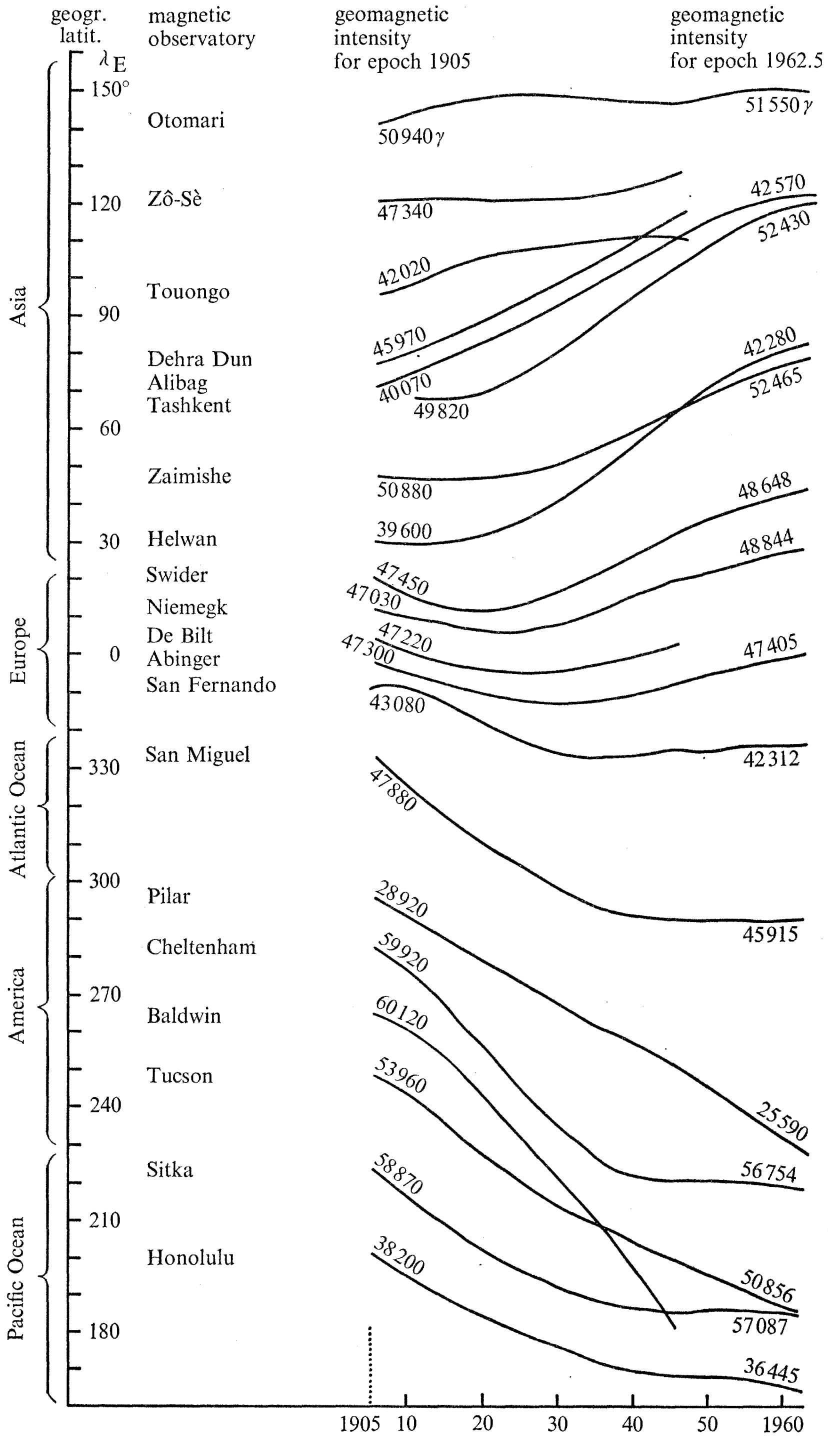

Figure 1. Changes in the Earth's magnetic intensity on some magnetic observatories lined up according to their geographical longitudes.

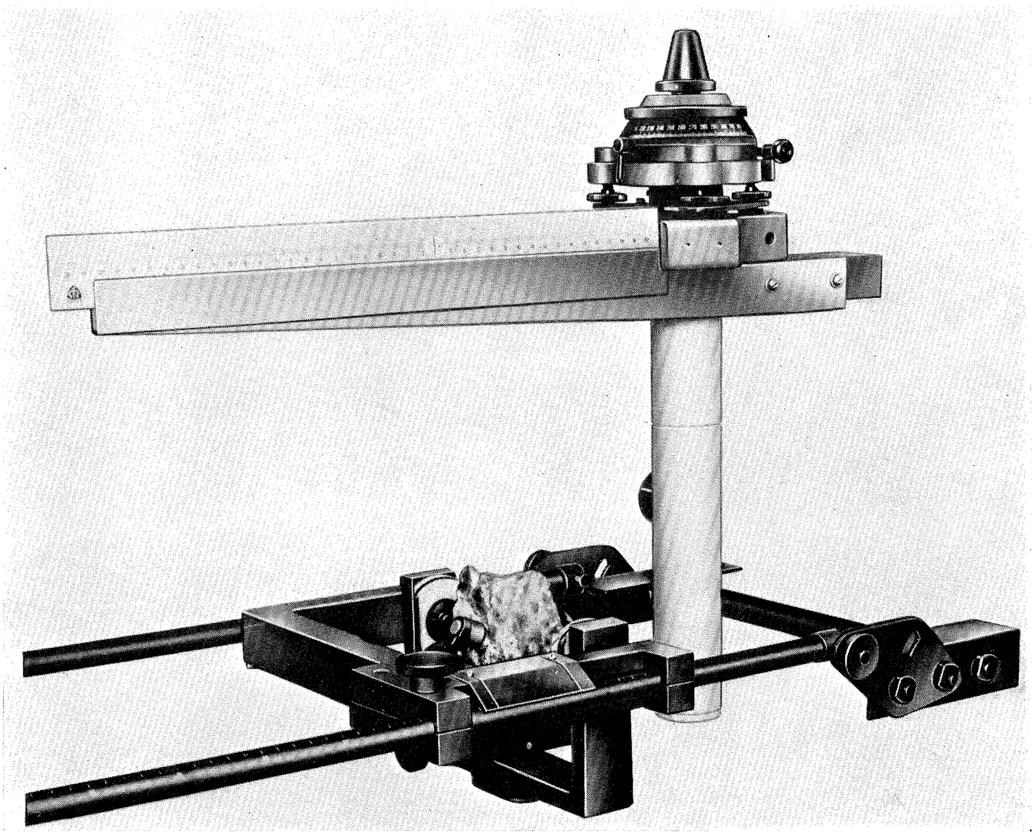

FIGURE 2. Astatic magnetometer of Pesina.

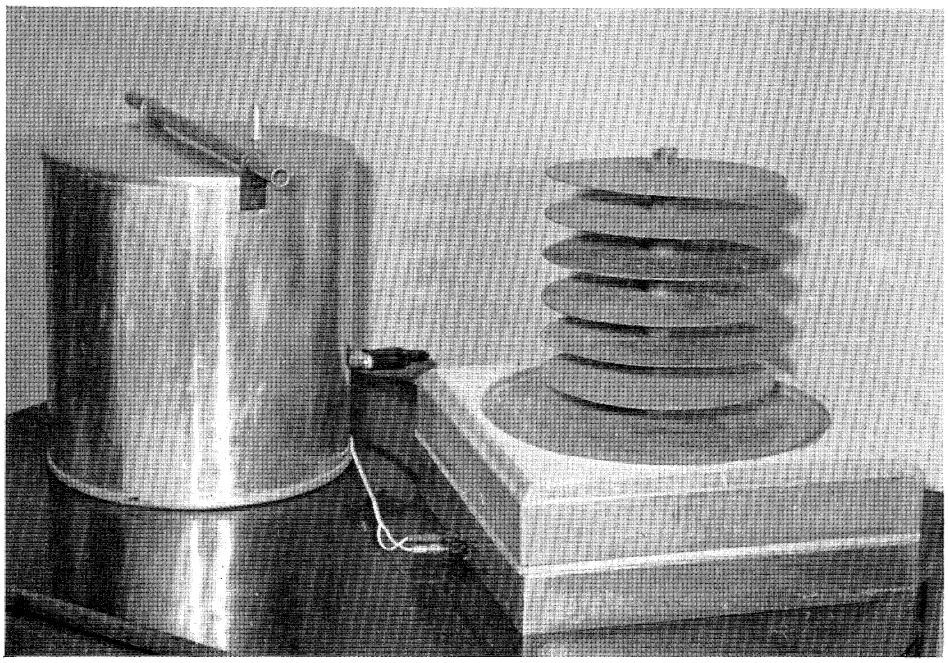

FIGURE 3. Non-magnetic oven for archaeomagnetic double-heating method.

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The drift of terrestrial anomalies and isoporic foci in a westward direction is important as evidence that part of the Earth's core is liquid. It can be explained on the basis of the assumption that the angular velocities of rotation of the Earth's mantle and upper Earth's core are different. In the model of Bullard *et al.* (1951) the Earth is divided into three concentric shells rotating at different rates. The inner two are in the core, and here the dynamo-mechanism regenerating the Earth's magnetic field arises as a consequence of different velocities.

Hence, the Earth's field is very probably regenerated due to motions of fluid in the viscous core. Such a system, which can maintain a magnetic field due to motions in an electrically conducting field, is designated as a hydro-magnetic dynamo. The reason for its activity in the Earth's interior is convection probably arising due to the heat caused by radioactivity in the Earth and by rotation or Coriolis force occurring simultaneously in conducting fluid of large linear dimensions. In order to verify these theoretical conclusions and to make clear dynamic processes inside the Earth, further results concerning the changes of the geomagnetic field for longer time intervals in the past are sorely needed.

Results of the archaeomagnetic investigation

Direct magnetic measurements have been carried out during only the past 300 or 400 years on the Earth's surface. The investigation into the magnetic properties of some rocks and baked archaeological clay objects has shown that they are suitable for the indirect determination of the geomagnetic field direction and intensity and their variations in the past. The thermoremanent magnetization (t.r.m.) of baked clay samples which was generated as a result of the temperature effect, providing they have been mineralogically stabilized, is proportional to the intensity of the Earth's magnetic field acting on the clay as it cooled down from heating.

In this way, the investigation of archaeological material for the last 9 millennia by means of the step-by-step technique of heating the samples to successively higher temperatures up to 600 °C has brought some interesting results. Measurements of t.r.m. are made on a static magnetometer (figure 2, plate 3). For heat treatment we use a non-magnetic furnace (figure 3, plate 3). By comparing the strength of the t.r.m. found in an archaeological baked-clay sample with the value acquired after reheating in the present-day Earth's field, the ratio of the ancient and present-day geomagnetic intensity is obtained. Some examples are given for samples from Arizona and Mexico in figure 4 (Bucha, Taylor, Berger & Haury 1970) where the ratio of the sections on the axes x, y determines the coefficient k which is proportional to the ancient geomagnetic field. In all, we have investigated about 500 archaeological samples mainly from Europe and Central America. It made possible the detection of detailed changes of the geomagnetic intensity for Europe during the past 9 millennia and for Central America during the past 4000 years (Bucha 1969). Each point in these figures is a mean value of several samples. For Europe it is evident that the curve characterizing the Earth's magnetic field intensity has two maximum values, the larger one around 400 B.C., when the field reached more than twice its present intensity. Conversely, a minimum occurred around 5000 B.C. when the field decreased to around 40 % of its present intensity. For older time periods the field is higher again. The archaeomagnetic results for Central America show two maximum values, again up to more than twice the present geomagnetic intensity. These cycles in changes seem very probably to be due to the westward drift of the terrestrial geomagnetic anomalies.

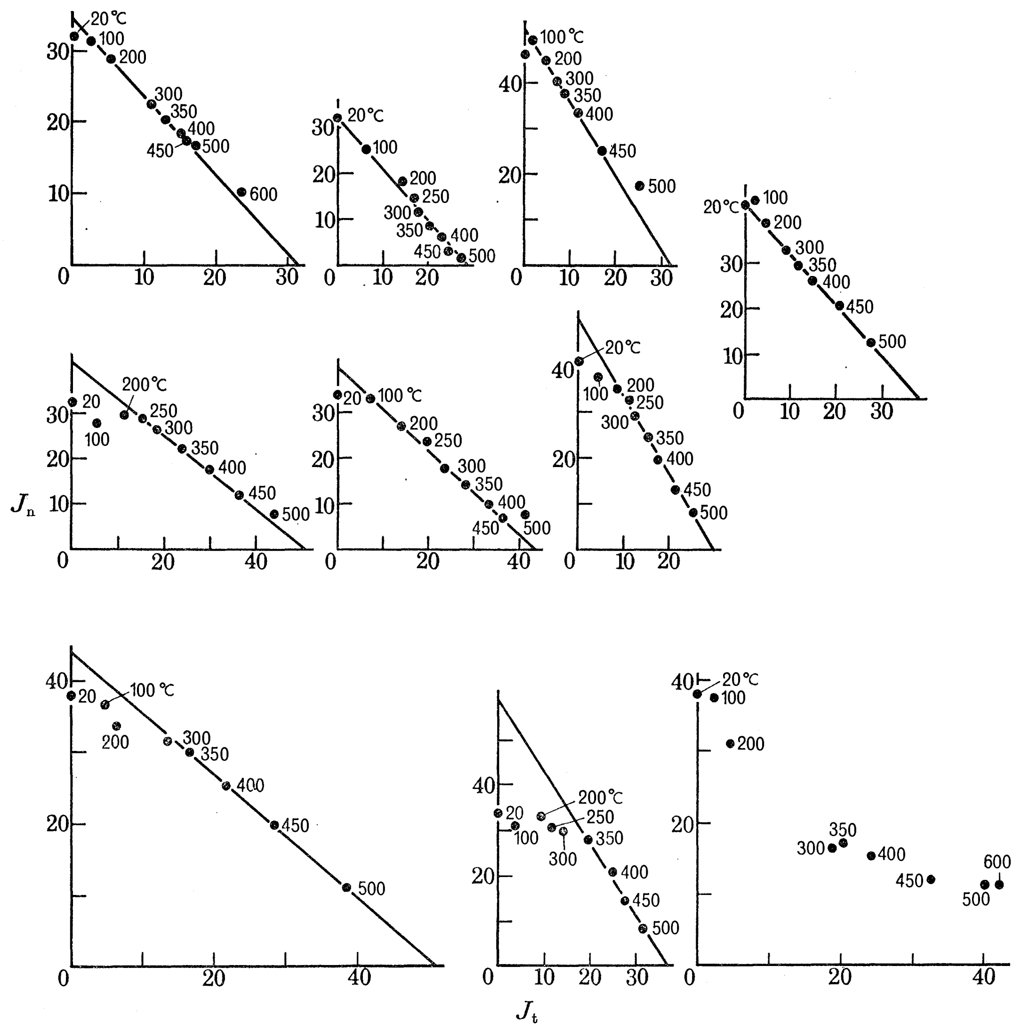

FIGURE 4. Graphs of demagnetization and remagnetization defining the coefficient k which is proportional to the ancient geomagnetic field, by means of the ratio of the sections on the axes x, y.

WESTWARD DRIFT OF THE EARTH'S MAGNETIC FIELD

When looking at the course of the present non-dipole field along the continuum joining Europe, Central America and Japan (figure 5) we see two maximum and two minimum values, in dependence on the geographical longitude. The maximum in Asia is very well developed. Three archaeomagnetic curves—for Europe, Central America (Bucha *et al.* 1970) and Japan (Nagata, Arai & Momose 1963; Sasajima 1965) provide convenient material which can be subjected to an analysis concerning the past westward drift in dependence on time (Bucha 1969). Moreover, the territories from which these samples were used are equally distributed on the globe when geographical longitudes are considered (Europe 15° E, Central America 255° W, Japan 135° E). We can see a remarkable dependence and a shift in the time occurrence of maximum values when going westwards from Europe to Japan. This westward drift between maximum values amounts to approximately 500 years for 120° of longitude, i.e. 0.24°/year.

Westward drift in the Southern hemisphere is evident also from archaeomagnetic measurements of South American pottery (Nagata, Kobayashi & Schwarz 1965) that showed a similar increase of the geomagnetic field at a approximately the same time period as our results on Central American pottery indicate.

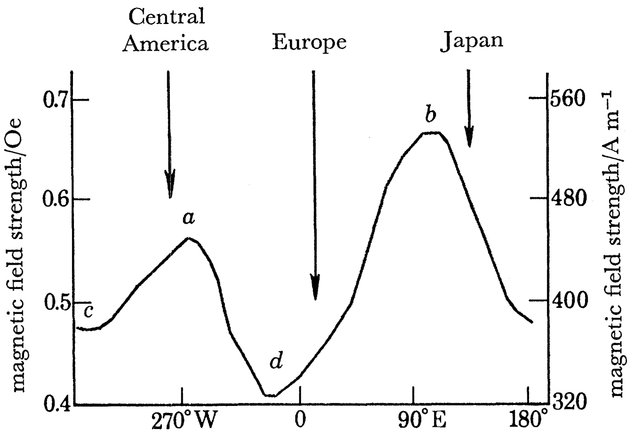

FIGURE 5. Course of the present non-dipole Earth's magnetic field along the continuum joining Europe, Central America and Japan *a*, *b*, maximum, *c*, *d*, minimum values.

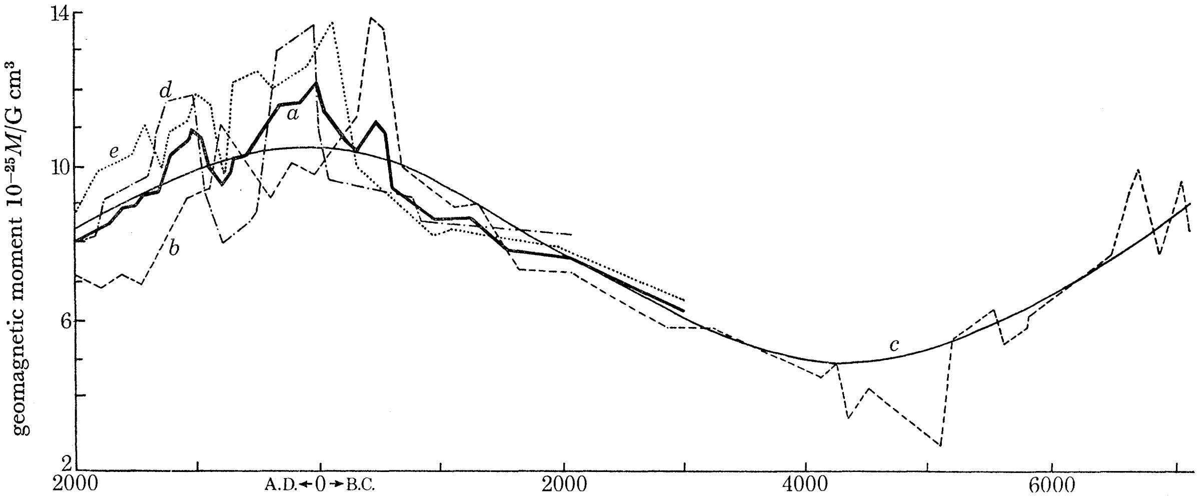

FIGURE 6. Changes of the reduced Earth's magnetic moment (——) determined from European (– – – – –), Central American (–·–· –·) and Japanese (.....) results.

CHANGES IN THE EARTH'S MAGNETIC MOMENT

Archaeomagnetic results from these three regularly distributed territories were further used for determination of the Earth's magnetic moment and its changes during the past. The values of a reduced magnetic moment according to the method of Smith (1967) were determined from Japanese and our own intensity measurements (figure 6). The averaged curve *a* represents changes of both magnetic dipole moment and non-dipole field moment. The smoothed curve *c* characterizing main changes of the Earth's magnetic moment during the past 8500 years may be expressed as sinusoidal in the first approximation

$$M(t) = 2.8 \sin \frac{2\pi}{8900}(t+405) + 7.7 \times 10^{21}\ \mathrm{T\ cm^3}.$$

Its period is approximately 8900 years.

The reasons for fluctuations of the magnetic moment values should be found in the sources of the Earth's magnetic field, i.e. hydromagnetic processes in the boundary liquid layers of the Earth's core and mantle.

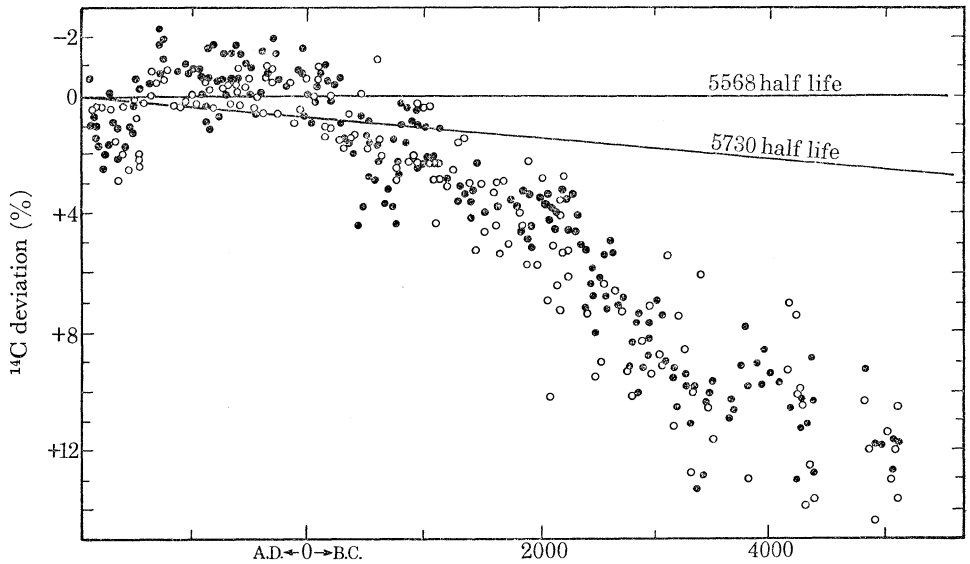

FIGURE 7. Deviation of ^{14}C contents from standard oak sample: ○, according to Ralph & Michael (1969); ●, according to Suess (1969).

CORRELATION BETWEEN ^{14}C DEVIATIONS AND CHANGES IN THE EARTH'S MAGNETIC MOMENT

It was found by Elsasser, Ney & Winckler (1956) that the decrease of the magnetic moment is followed by an increase of the cosmic ray flux and therefore by an increase in the production rate of carbon-14. Higher values of the field have the opposite effect. New radiocarbon measurements carried out on dendrochronologically and historically dated samples have made it possible to find deviations from the radiocarbon content as calculated with a half life of 5568 and 5730 years (Suess 1969; Ralph & Michael 1969; Berger & Libby 1967) (figure 7). An interesting comparison can be made (figure 8) when radiocarbon deviations as well as changes of the Earth's magnetic moment are compared and a close correlation of both events seems to be apparent.

The increase of magnetic moment around A.D. 900 is immediately followed by the decrease of carbon-14 deviations to negative values. The same is valid for older periods. The differences in the course of both curves *a* and *b* between 1600 and 1900 can be a result of the unavailability of North American archaeological samples. On the other hand, combustion of fossil fuels (Suess's effect) could be the cause of carbon-14 irregularities during the past century. We can say that all changes of the magnetic moment seem to cause approximately at the same time (maximally after 100 years) changes in the cosmic-ray flux. Changes within shorter periods are probably due to the non-dipole magnetic field. The increase of the Earth's magnetic moment may be caused by intensification of turbulent processes in the Earth's interior.

When applying the sinusoidal curve from figure 6 to figure 8 we see a very good coincidence not only for the main changes of the Earth's magnetic moment but also for radiocarbon deviations. This is especially true if we use a slightly different value for the carbon-14 content of biological materials and when applying the half life of 5730 years. (The dotted sinusoidal curve in figure 8 for deviations with the half life of 5568 years shows values too low, mainly between 3000 and 4000 years.)

We can conclude that the fluctuations in the radiocarbon production rate seem to correlate inversely with the changes in the Earth's magnetic moment. Some differences between the courses of both curves *a*, *b*, in figure 8 are due to imprecise dating of archaeological samples used for archaeomagnetic analysis. If this correlation applies then increasing the original Libby value (Libby 1955) of 15.3 to 15.8 disintegrations per minute per gramme of carbon in the biosphere would result in decreasing the magnitude of the deviation between Libby's original dates and the carbon-14 values obtained on dendrochronologically dated wood samples (Suess 1969; Ralph & Michael 1969). For instance at 3300 B.C. a deviation of *ca.* 12 % (i.e. 960 years) would be reduced to *ca.* 5 %.

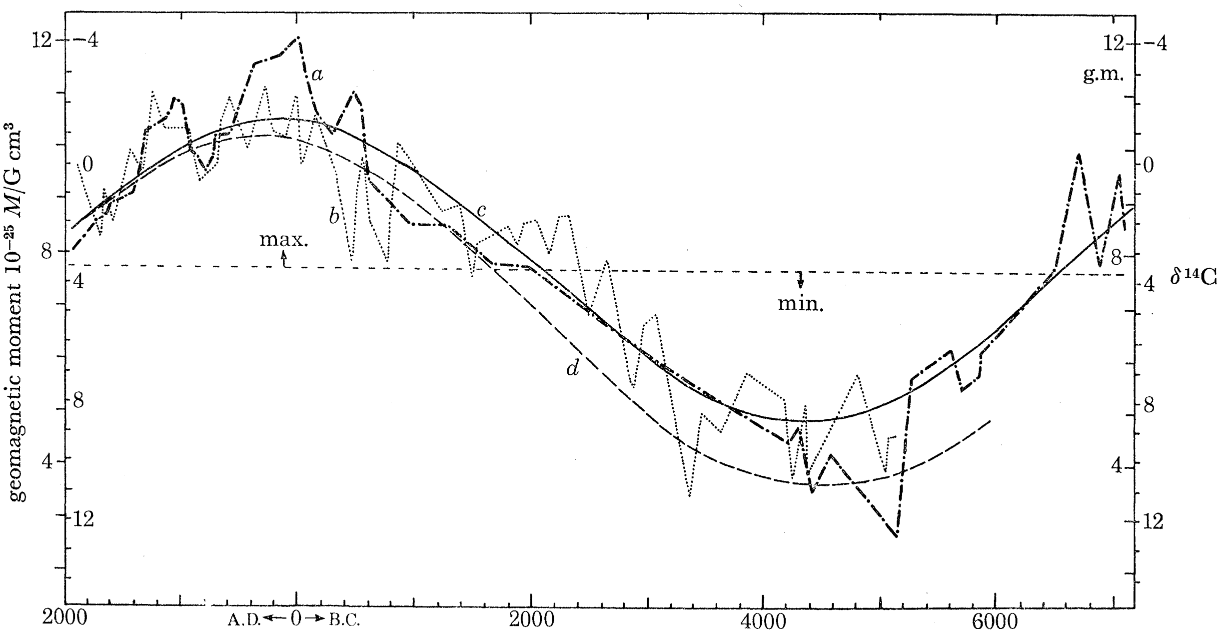

FIGURE 8. Comparison of ^{14}C deviations for the half life of 5730 years according to Suess (1969) (curve *b*) with the geomagnetic moment changes (curve *a*); *c*, smoothed sinusoidal curve for magnetic moment changes and ^{14}C deviations (5730 half life); *d*, sinusoidal curve for ^{14}C deviations (5568 half life).

On the basis of Thellier's work archaeomagnetic measurements of materials dating from the last 2000 years (Thellier & Thellier 1959), Elsasser *et al.* (1956) have suggested large deviations in the carbon-14 values for older periods. However, according to our results the Earth's magnetic moment during the past 9000 years has not exceeded its present-day value by more than 60 %. It seems most probable that no deviations larger than 5 % will appear along Libby's original curve when adjusted to a half life of 5730 years. To obtain more precise age determinations, it would be necessary to apply Suess's calibration curve (Suess 1969). According to our recent palaeomagnetic investigations into dated sedimentary rocks this can be applied most probably also for older time intervals, except for suspected shorter events of reversed geomagnetic field polarity where positive deviations could be higher. Indeed, our preliminary results show (figure 9) that short reversals probably took place approximately sometime between 10000 and 20000 B.C., as well as between 30000 and 40000 B.C. Negative inclination indicates reversals of geomagnetic polarity. The solution of this important problem—examination of changes of the geomagnetic field during the past 40000 years—would need, however, more detailed palaeomagnetic investigation of both archaeological objects and rocks as well as much more accurate dating of sedimentary rocks used, before precise conclusions are possible.

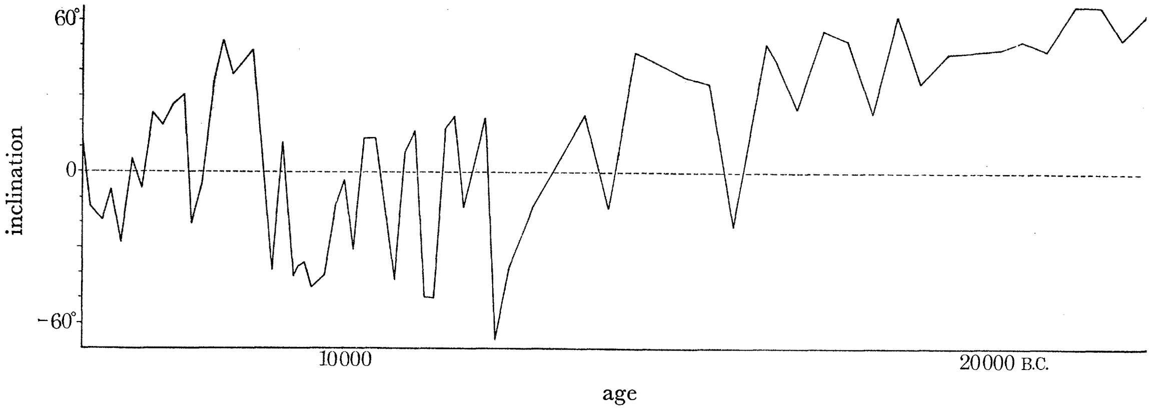

FIGURE 9. Palaeomagnetic measurements of inclination into dated sedimentary rocks of age between 10000 and 20000 B.C.

From the above results it can be deduced that the Earth's magnetic field has shown significant changes not only during the last centuries, as has been determined by direct geomagnetic measurements, but also in the pre-historical and geological past including reversals of geomagnetic polarity.

Financial support for a part of this work from the National Science Foundation through NSF Grant GA-1641 is gratefully acknowledged.

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Discussion

H. E. SUESS (*University of California, San Diego*). Many archaeologists must have received the impression, from what we heard this morning, that radiocarbon ages are exceedingly unreliable, and often wrong. Therefore, I would like to summarize the situation as I see it, and would like to show that it is perhaps not quite that bad. There is no question now that the so-called conventional radiocarbon dates need corrections. As you have heard, the magnitude of the corrections depends upon the age of the samples only. For the past 2000 years these corrections are relatively small, and rarely amount to more than 100 years. They become more significant for the first millennium B.C., and reach values of about 300 years at around 800 B.C. For the second millennium B.C. the necessary corrections are increasing, until during the fourth and fifth millennium B.C. they are of the order of 800 years, and can at times even reach 1000 years. Going farther back in time, it seems that the corrections are presumably decreasing, but their precise values are not yet known, because the tree-ring chronology has not been established beyond 5300 B.C. The magnitude of the corrections is not a steady function of time; the curve shows many wriggles that increase the uncertainty range for the individual dates. For the archaeologist, therefore, these wriggles will, in general, represent a nuisance in spite of their great interest to the geophysicist and geochemist. In certain special cases, however, the wriggles can be of great help in the determination of precise data. This is true in cases for which 'floating' tree-ring sequences are available. Sufficiently large logs of wood, which themselves contain a large number of rings, can be used for establishing such 'floating' tree-ring sequences. Dr Bannister has mentioned our work on the Swiss neolithic site of Auvernier, for which radiocarbon data accurate to perhaps 50 years could be determined by comparing the trends of the carbon-14 values as a function of time in such tree-ring sequences, with those of the bristlecone pine wood from the same period (H. E. Suess, June 1970, *Antiquity*). Clearly, the corrections will affect most noticeably our picture of the chronology of the neolithic. For earlier periods of time the corrections will not be quite as important. Also, the chronology of the glacial times will not be changed by the corrections, because in the time range before 10000 years the corrections of less than 1000 years will not appear too significant. In any case, I would like to repeat my suggestion that every effort be made to secure logs with a large number of rings, from as many archaeological sites as possible, because the radiocarbon method will usually give dates of optimal precision only if sequences of rings are available that can be used to obtain a series of successive radiocarbon values.

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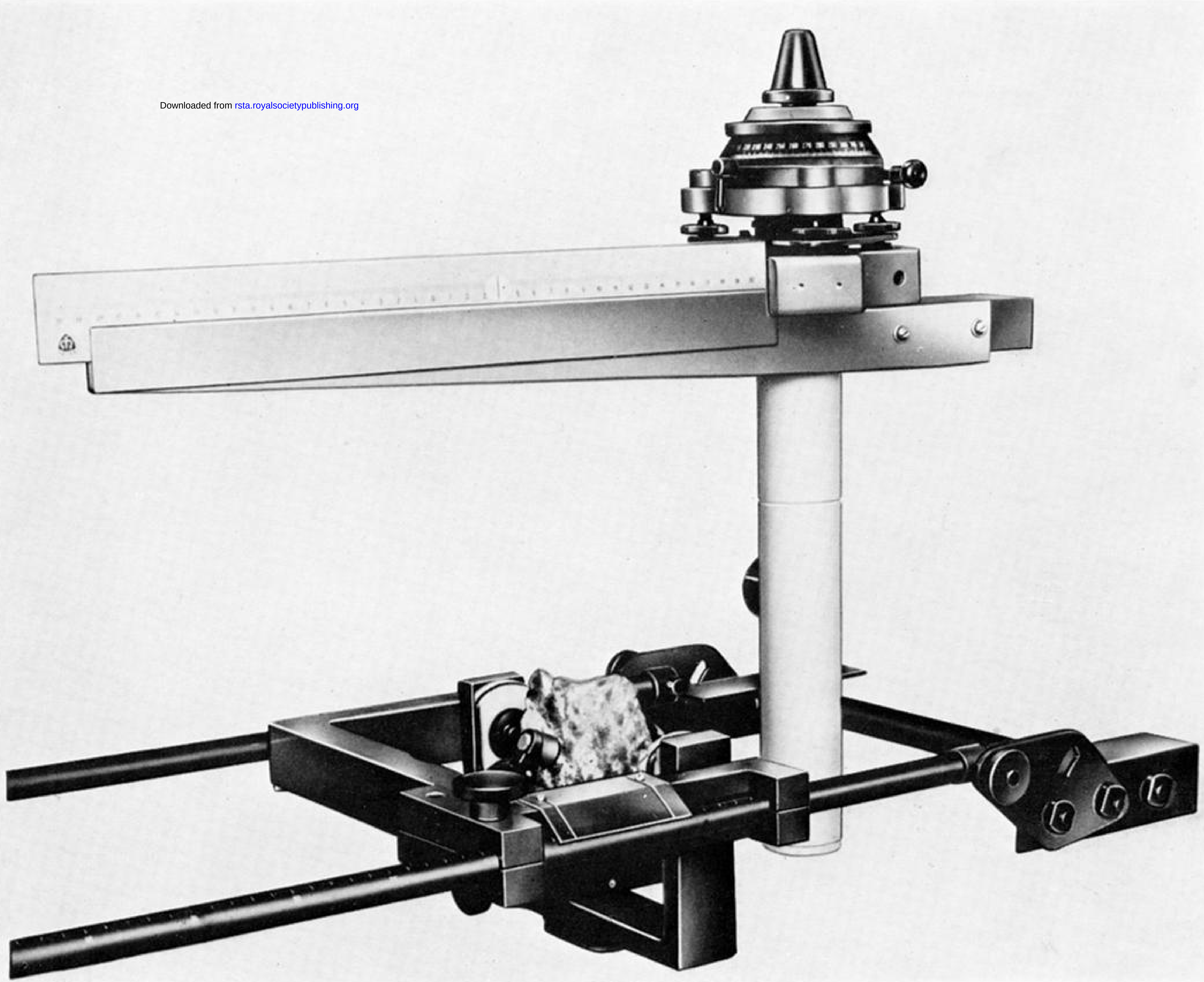

FIGURE 2. Astatic magnetometer of Pesina.

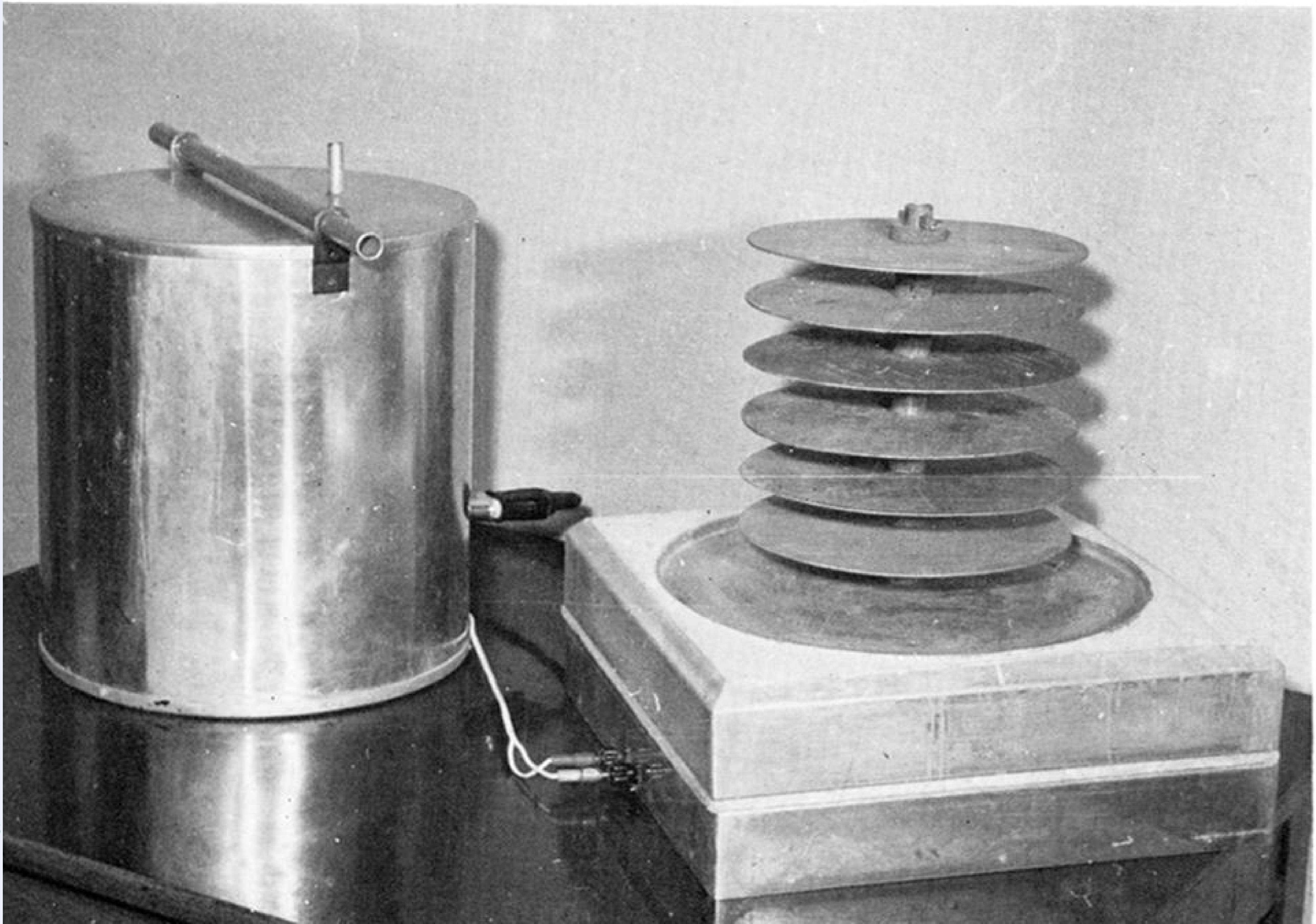

FIGURE 3. Non-magnetic oven for archaeomagnetic double-heating method.

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