Continental Drift

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Continental Drift

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Preface

Fifty years ago Alfred Wegener, the German meteorologist, published his theory of continental drift (*Petermanns Mitt.*, 1912, **58**, pages 185–195, 253–256, and 305–309; *Geol. Rdsch.*, 1912, **3**, pages 276–292). The first edition of his book "Die Entstehung der Kontinente und Ozeane" appeared in 1915. His theory that the continents of South America, India, Australia and Africa had formed one continent of Gondwanaland in the comparatively recent history of the earth was, like most ideas in science, not entirely new. Antonio Snider ("La Création et ses Mystères Devoilés", Librarie A. Franck, Paris, 1858) had produced maps that showed the supposed former contiguity of the two sides of the Atlantic, which are remarkable in their resemblance to some of Wegener's reconstruction. Also F. B. Taylor of the U.S.A. had suggested from tectonic consideration that a considerable redistribution of the continents had taken place in geological time. The development of the theory owed much to the discovery in the last half of the last century of the Permo-Carboniferous glaciation of the southern hemisphere.

The publication of Wegener's book gave rise to a vigorous controversy in the 1920s. Lack of a decisive test, however, and strong arguments against the theory on the part of geophysicists caused the idea of continental drift to be abandoned, at least by the majority of geologists in England and America. About ten years ago the development of studies of rock magnetism gave rise to new interest in this theory and has caused geophysicists in other fields to reconsider the ideas in relation to their own studies. It therefore seemed worth while to bring together within one volume a discussion of the geophysical evidence relating to horizontal movements in the earth's crust in its widest sense. This is not the time for a reappraisal of Wegener's work but it is hoped that this volume will stimulate a serious interest in a subject formerly considered by many earth scientists as already closed.

Newcastle-upon-Tyne S. K. Runcorn
July 1962

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Chapter I

Palaeomagnetic Evidence for Continental Drift and its Geophysical Cause

S. K. RUNCORN

The hypothesis of continental drift supposes that it is possible for the relative positions of the continents, and therefore their relation to the earth's axis of rotation, to have changed during geological time. Any method therefore by which the geographical meridian and the latitude of sites within continents can be determined at any time in the geological past will settle the question whether relative motion of the continents has taken place since that time. If the former longitudes of the sites were also known, the topography of the globe could be worked out for that time.

Palaeoclimatology has hitherto been the method by which geologists have attempted to fix the latitudes of the continents in the past. Nairn [1] has recently edited a book describing the latest position in this subject. Determinations of palaeowind directions provide the only method in this field of determining the orientation of the continents to the geographical pole [2, 3]. The latter method is restricted, of course, to the infrequent examples of aeolian sandstones and, because there is no satisfactory theory of the general circulation of the atmosphere, we cannot be absolutely sure that the latitude ranges of trade wind and westerly wind belts have not changed. The more general palaeoclimatic studies are handicapped by the somewhat subjective considerations by which interpretations of the geological record have to be made. The development of a precise physical method for the measurement of latitude and orientation, that of palaeomagnetism, has therefore, in the last ten years, revolutionized the discussion of continental drift.

The method is based on the supposition, suggested by its present distribution, that the mean geomagnetic field is that of an axial dipole at the geocentre. The field direction is conveniently specified by two angles. The angle of declination (D) is the angle between the field direction and the geographical meridian and is taken as positive eastwards. The angle of magnetic dip or angle of inclination (I) is the angle made by the field direction with the horizontal and is counted positive if the positive or north-seeking direction of the field vector dips below the horizontal and negative if it points above the horizontal. This is related to the angle of latitude (λ) and angle of colatitude (θ) by the expression

$$\tan I = 2 \tan \lambda = 2 \cot \theta \tag{1}$$

if the field is that of an axial dipole.

This may be proved as is shown in Fig. 1, in which the axial dipole, M,

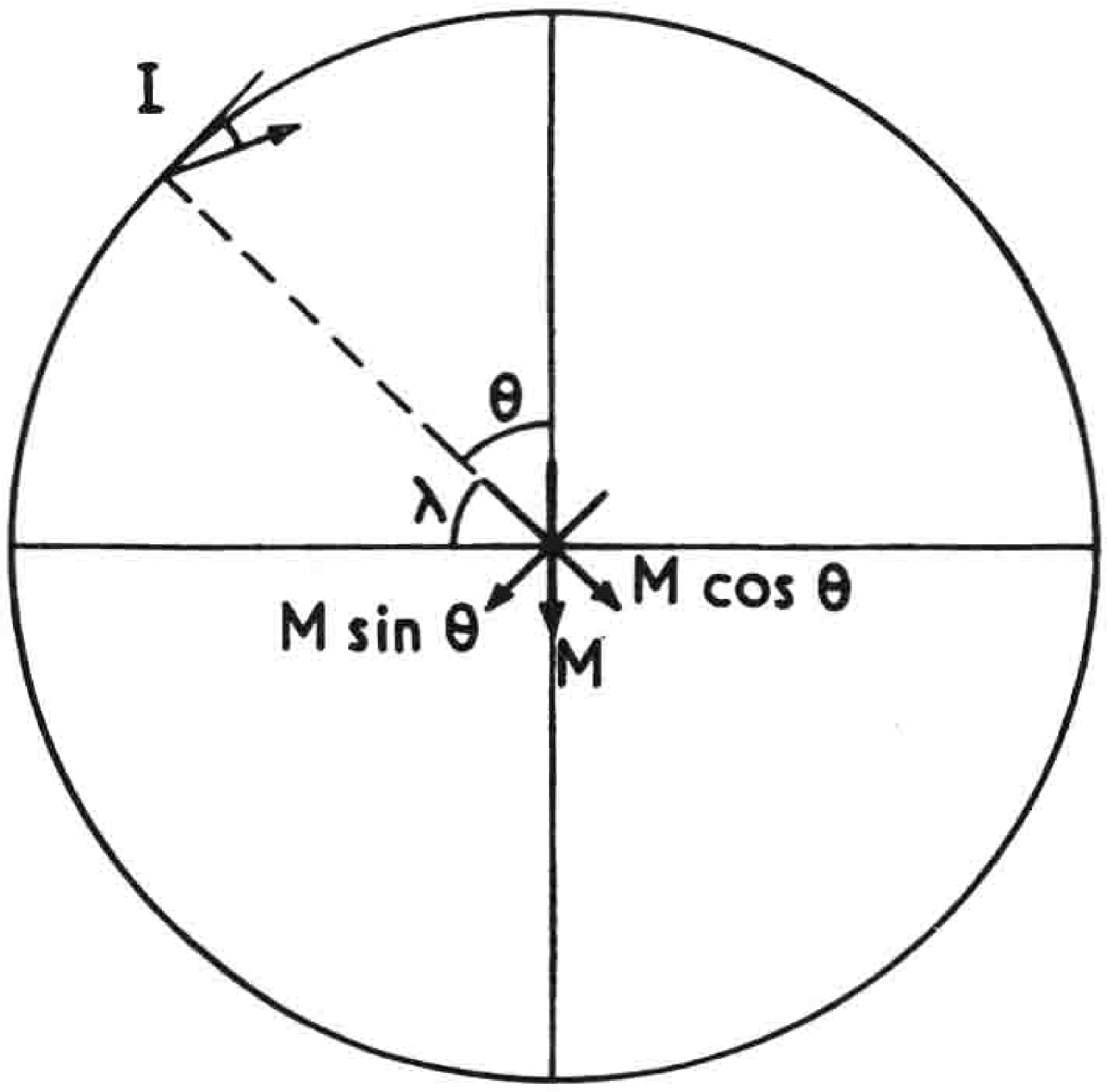

FIG. 1. Field of axial dipole.

being a vector, is resolved into a component $M \cos \theta$ along the radius vector through the surface site and a component perpendicular to the radius vector in the geographical meridian passing through the site. The former component produces a downward vertical field $Z = 2M \cos \theta/a^3$ at the site and the latter a horizontal field in the north direction $X = M \sin \theta/a^3$, where a is the radius of the earth.

$$\therefore \quad \tan I = Z/X = 2 \cot \theta.$$

The directions of the mean magnetic field of the earth obtained for an epoch in the geological past are found to be different from those of the present but are still interpreted in terms of a dipole field by assuming that the relative positions of the continents and the axis of this dipole have changed. The palaeomagnetic data from any continent is therefore commonly displayed in one of the two ways:

(1) by plotting on a projection of the present globe the pole or axis of that dipole which would, at the site where the rocks were obtained, give a field coincident with the mean direction of magnetization

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of the rock specimens, after they have been returned, if necessary, to their original position by a geological dip correction. The poles refer, of course, to one continent, assuming that relative movements in the continent due to tectonics are not large enough to be taken into account at present. A map of the successive positions of the poles so calculated is known as a polar wandering path. The value of this method is that it provides a clear method of demonstrating the fact that the magnetic directions in one continent for one geological age are consistent. Also a discrepancy between the polar wandering curves for the different continents shows that relative movements have occurred up to the time when the curves become coincident.

(2) on an imaginary grid of lines of latitude and longitude with the dipole axis as centre, the successive positions of the continent throughout geological time are plotted. This has the advantage that it shows clearly the obvious point that the latitude and orientation of the continent, but not its longitude, can be determined—the latitude from equation (1) and the orientation from the palaeomagnetic declination which is the angle made by the longitude lines with the present meridian in the continents. Clearly the reconstruction of the topography of the globe in the past is accomplished by comparing such projections for the different continents.

The palaeomagnetic method of investigating continental drift therefore depends on two postulates: (1) that the mean geomagnetic field has always been dipolar and (2) that the rocks used in such studies have acquired a magnetization which, to within a degree or so, is coincident with the direction of the geomagnetic field at or soon after the time of their formation and which has been retained unchanged since.

We examine these two basic assumptions in turn. The former is at first sight contrary to our present day knowledge: the geomagnetic field at an epoch has considerable parts which are not representable by a dipole along the axis of the earth's rotation. Today it is better represented if the dipole is inclined by about 11° to the axis of rotation, but even then the difference between this field and that observed is considerable as is shown in Fig. 2. The deviations are greater than 0·1 oersted in many places. Further the field has a secular change. The longest series of measurements of the direction of the geomagnetic field are those for London and Paris, the angles of declination and inclination being shown in Fig. 3. When observations of the geomagnetic field were very sparse it was natural for it to be thought that the secular variation of the field was the result of a precession of the dipole about the earth's axis of rotation, which would of course cause the field at London and Paris to change roughly as shown in Fig. 3. However, it is now clear that this is a much too simplified picture. Vestine, Laporte, Lange and Scott [4] analyse the geomagnetic field for the epochs 1912·5, 1922·5,

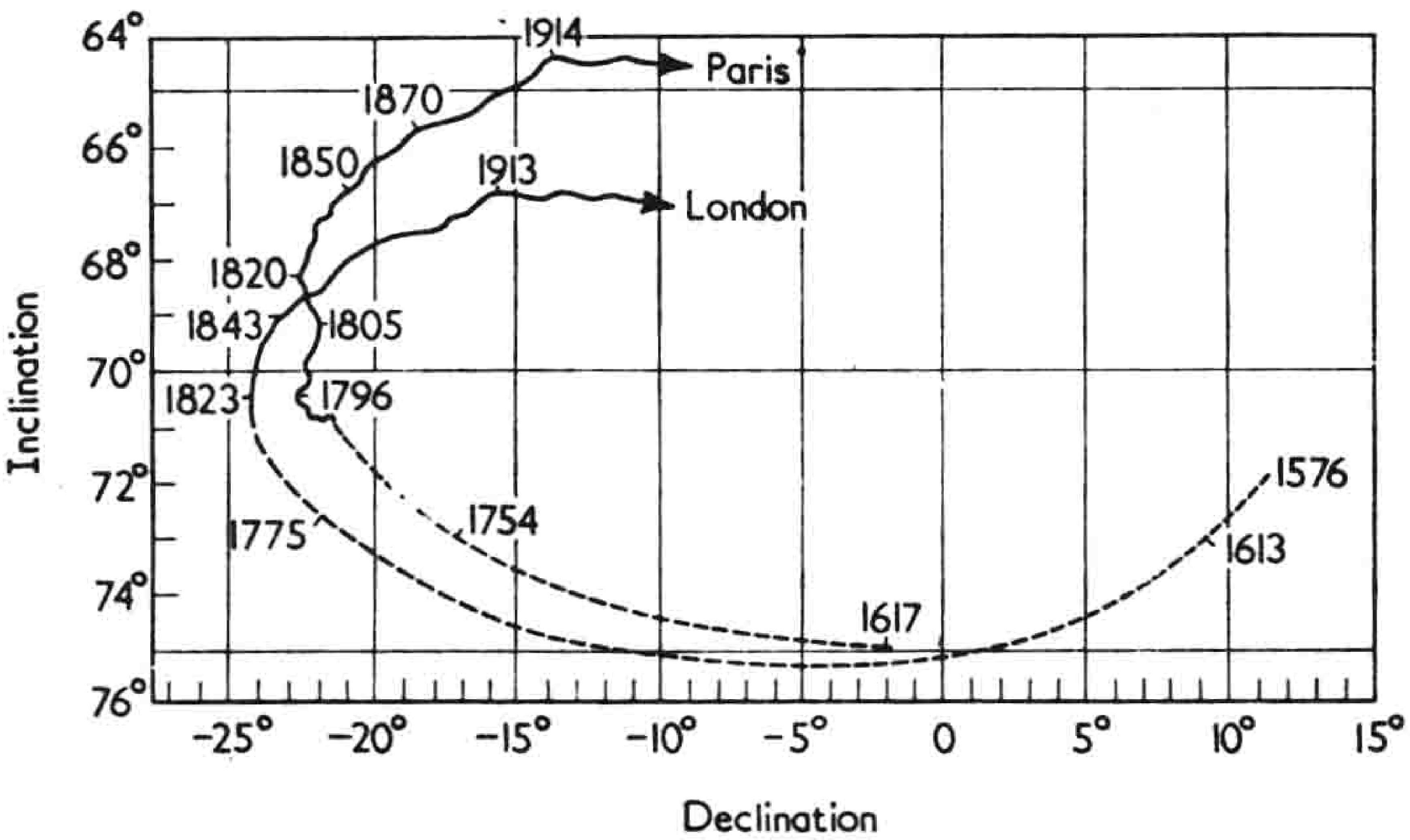

FIG. 3. Values of declination and inclination in London and Paris. After Gaibar-Puertas.

1932·5, and 1942·5 by the method of spherical harmonic analysis. They show, as others also have, that the field may be represented in terms of a scalar potential V, which can be expanded in the series

$$V = a\sum_{n=0}^{\infty} \sum_{m=0}^{n} (a/r)^{n+1} P_n^m(\theta) \left[g_n^m \cos m\lambda + h_n^m \sin m\lambda \right] \tag{2}$$

where a is the radius of the earth, r, θ, and λ are spherical polar co-ordinates and $P_n^m(\theta)$ is the associated Legendre function. Vestine *et al.* calculate the coefficients g_n^m and h_n^m and, using earlier spherical harmonic analyses, it is possible to plot the variation of the coefficients with time back to the early part of last century, when extensive surveys of the earth's magnetic field were commenced consequent on Gauss's discovery of the method of making absolute determinations of the field intensity by the deflection and vibration magnetometer. These results are shown in Fig. 4, the vertical scales being in 10^{-4} oersted and λ measured eastwards.

The periods decrease with the order: thus much of the secular change of the main geomagnetic field results from the westward drift of its non-axial components. Elsasser [5, 6] and Bullard and Gellman [7] have convincingly shown that the geomagnetic field is maintained by a process in the earth's fluid, electrically conducting core, which is similar to that of a self-excited dynamo, in which the electric current generated by induction in the rotor provides the necessary magnetic field. While the general problem of self-excited dynamos is still riddled

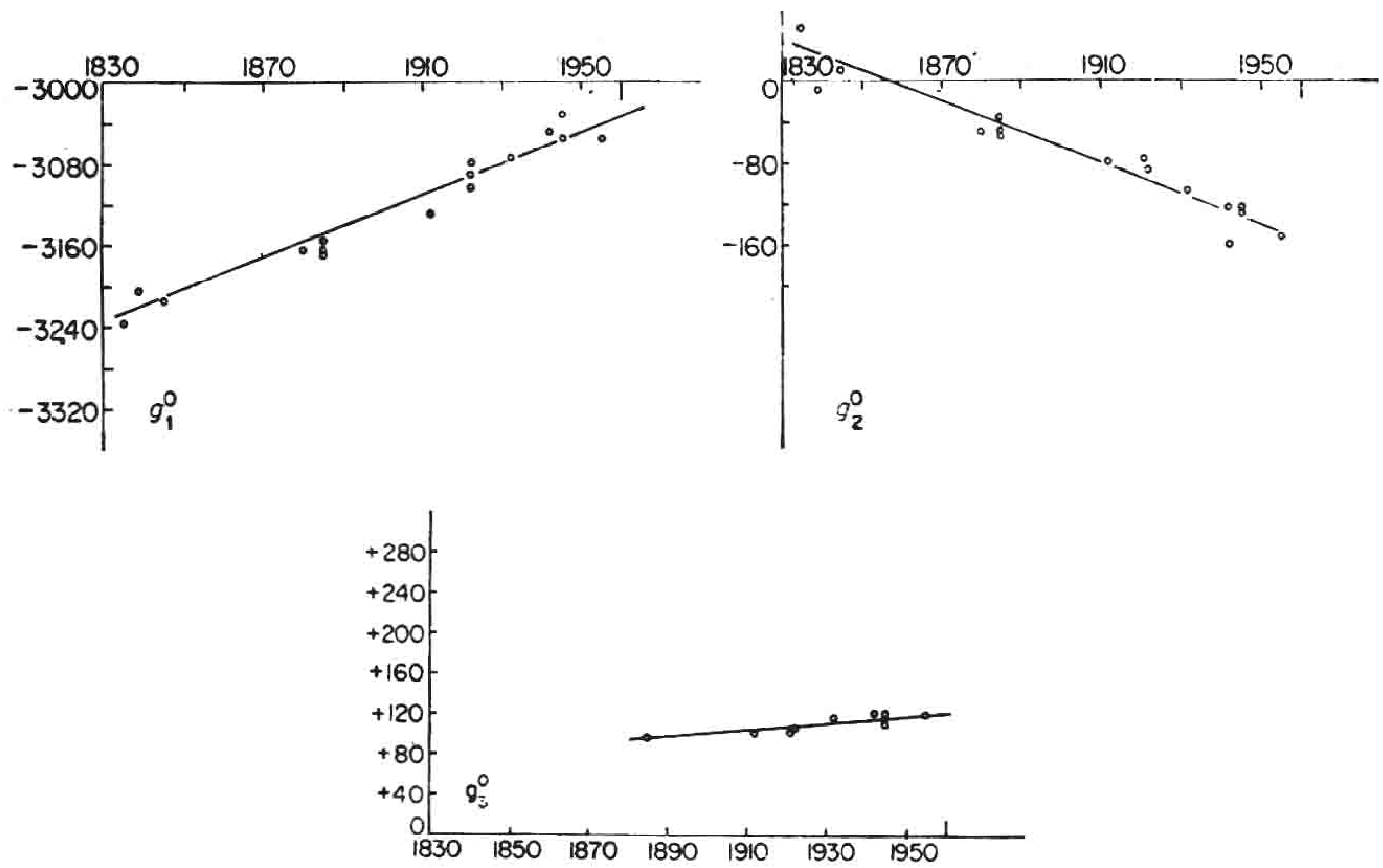

FIG. 4a. Values of spherical harmonic coefficients g_1^0, g_2^0, and g_3^0 since 1830.

with mathematical uncertainties, the physical picture of the earth's core is clear. Radioactive heating and possibly potential energy released by the settling of iron towards the earth's centre provides the kinetic energy of the convection currents. Electromagnetic induction causes the transfer of some of this energy into magnetic energy. The problem of the earth's magnetism is therefore part of the subject of magneto-hydrodynamics. To gain a physical insight into this subject it has been found useful to return to the Faraday-Maxwell concept of visualizing a magnetic field by supposing the lines of force to be elastic strings having a tension but also repelling one another. By Lenz's law there is a tendency for the lines of force to remain attached to the fluid particles—they would have no relative motion at all if the fluid had infinite electrical conductivity. Most modes of motion will stretch the lines of force and therefore increase the magnetic energy per unit volume. In a fluid with finite electrical conductivity and with no motions the magnetic field decays, lines of force diffusing through the fluid The

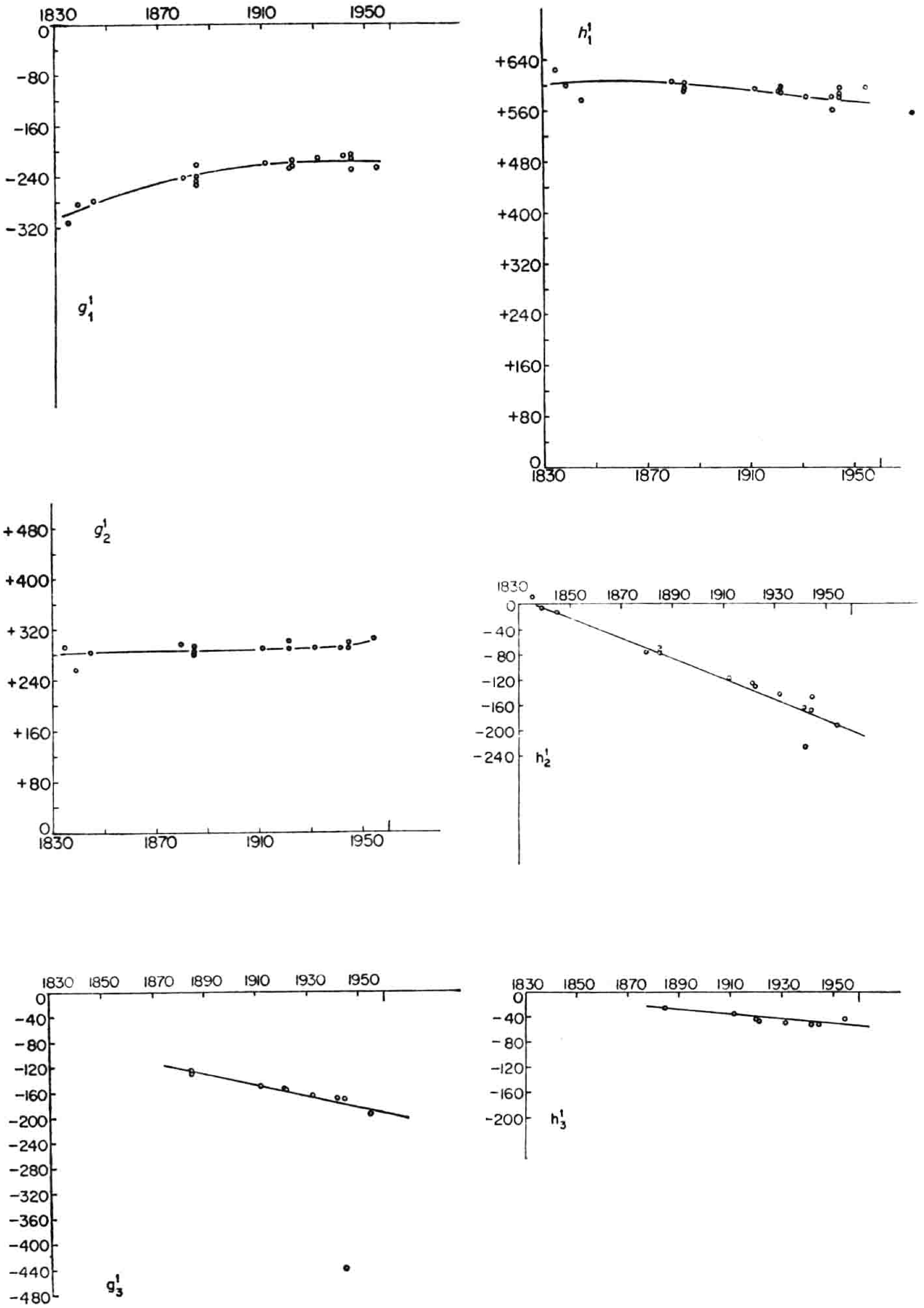

Fig. 4b. Values of spherical harmonic coefficients of first order since 1830.

maintenance of the geomagnetic field is therefore a balance between the magnetic amplifying process of the fluid motions and the process of free decay. Paradoxically, if the core were infinitely conducting there would be no observable magnetic field: it would be entirely enclosed within

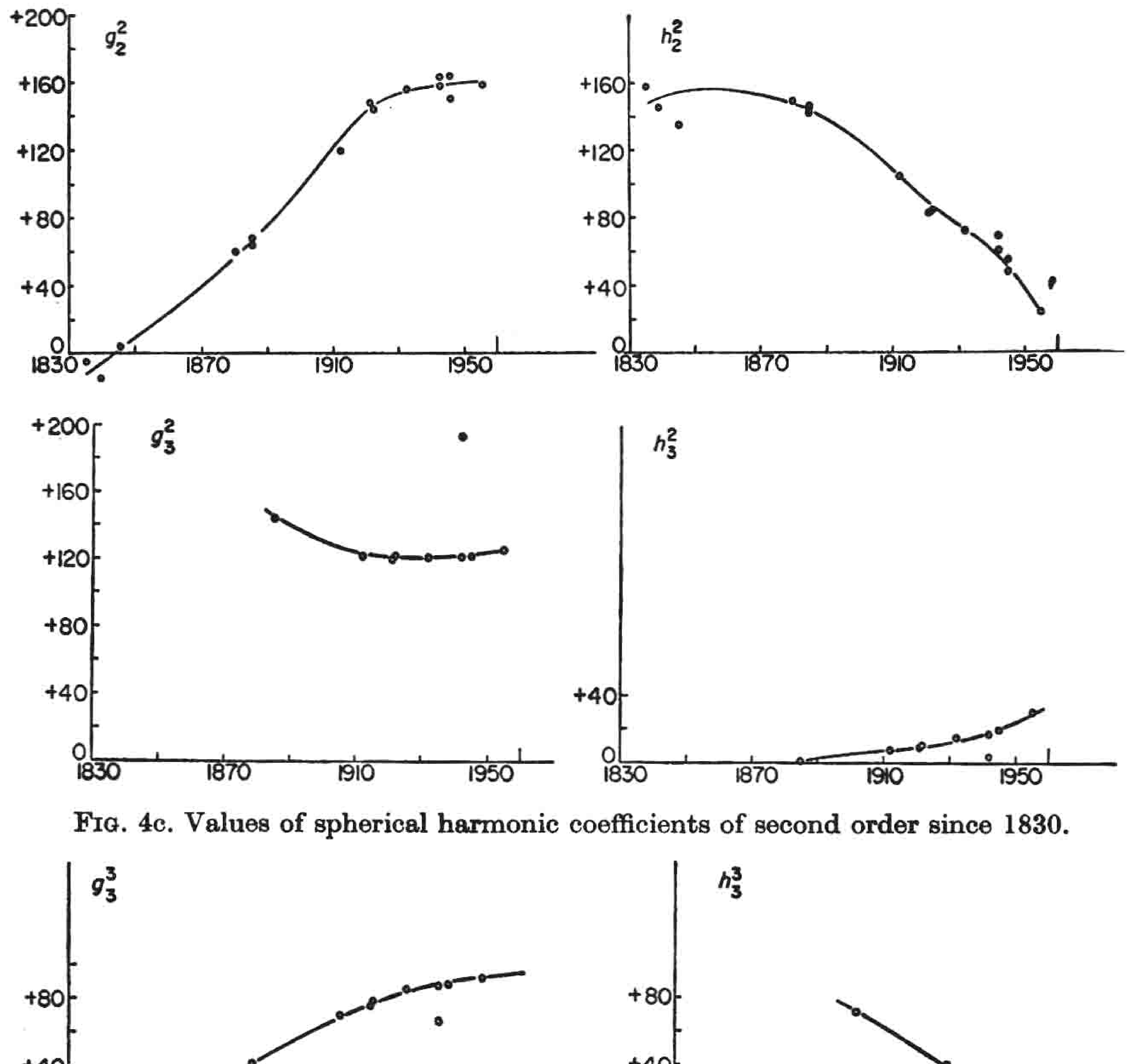

FIG. 4c. Values of spherical harmonic coefficients of second order since 1830.

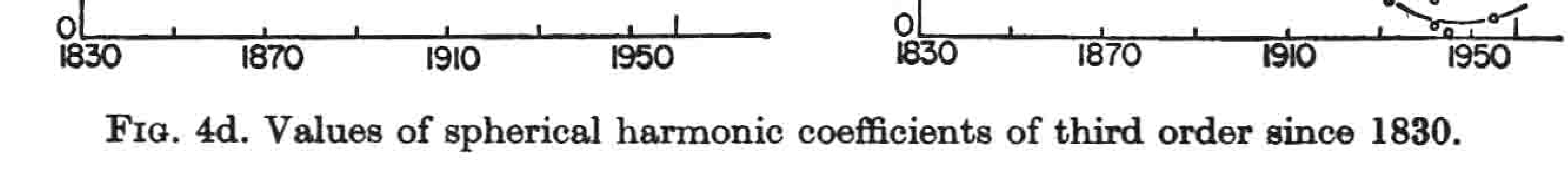

FIG. 4d. Values of spherical harmonic coefficients of third order since 1830.

the core, the lines of force lying parallel to the velocity vector at every point. The existence of a field outside the earth and its change relative to the core are therefore consequences of the finite conductivity of the latter. It therefore appears entirely fundamental to interpret the westward drift of the geomagnetic field as a motion of the core as a whole relative to the mantle at the rate of about 1/5° per year.

The electrical conductivity of the lower mantle is known to be much smaller than that of the core, but it is estimated to be about 1 ohm^{-1}

cm^{-1} and is the result of intrinsic semiconduction. Were the mantle a perfect insulator, one might well wonder why the angular velocity of the core and mantle should be so nearly the same (about 1 part in 10^8) for it is easy to show that the viscous friction between the core and mantle is exceedingly small. The eddy currents induced in the mantle through the relative rotation of the non-axial parts of the magnetic field generated in the core are sufficient to keep the core and mantle rotating at nearly the same speed. However, the changes of the field relative to the core induce currents in the mantle which will give torques of either sign and consequently speed up or slow down the rate of westward drift of the core relative to the mantle. Conservation of angular momentum implies that the mantle's angular velocity will change with a time scale similar to that of the secular variation of the geomagnetic field—an effect long known by astronomers as the irregular fluctuations in the length of the day. An exceedingly important result follows from this: the exact equality of the rate of rotation of the core and mantle is seen to be an unusual state of affairs and one not likely to persist over many periods of the secular variation, i.e. more than about a thousand years.

Thus although at any epoch the geomagnetic field may have, as it has today, a considerable part not symmetrical about its axis, it is certain that, on the average, over times greater than a few thousand years, the mean geomagnetic field is axial [8]. An observer on the surface will follow the field around a line of latitude on the core and, when a mean is taken, the axial field will be left. Returning to equation (2) the potential is given by

$$V = a \sum_{n=0}^{\infty} \sum_{m=0}^{n} (a/r)^{n+1} P_n^m(\theta) \left[g_n^m \cos m(\varphi + \Omega t) + h_n^m \sin m(\varphi + \Omega t) \right]$$

where Ω is the westward drift and t the time. The mean potential vanishes for $m \neq 0$ for whole numbers of complete relative rotations of core and mantle.

In rock magnetism, directions of magnetization are determined from a number of rock samples collected over a sufficient stratigraphical thickness in order to ensure that many times the secular variation period is being examined. Order of magnitude calculations on the rates of deposition of deltaic deposits indicate that some hundreds of feet of sandstone will in general suffice [9]. Even intensive sampling of rocks which have essentially been formed at a point in time such as a single lava flow will clearly not satisfy this vital criterion. The directions of magnetization from one geological formation are each given unit weight and their vector mean calculated. This is not quite the same as averaging the scalar potential and if there were only one spherical harmonic term

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