PART VIII : GEOPHYSICS

THE GEOPHYSICAL INTERPRETATION OF CHANGES IN THE LENGTH OF THE DAY AND POLAR MOTION

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ABSTRACT. The data on the irregular fluctuations in the length of the day and the motion of the pole is of great significance in the geophysicist's task of constructing a model of the earth's interior.

Short term instabilities in the dynamo generating the earth's magnetic field produce what is observed at the surface as the secular variation. These changes induce currents in the lower mantle and the resulting torques appear to be the cause of the irregular fluctuations in the length of the day, although some quantitative problems remain.

The excitation of the Chandler wobble could result from impulsive torques applied to the mantle by very short period (a year or less) local magnetic field disturbances coming to the surface of the core. The alternative mechanism by earthquakes has been much investigated and the possibility of this is still obscure. A test however is available in the polar motion data: a disturbance in its path displaces the subsequent centre of its Chandler motion in the latter theory, but only its amplitude on the former theory. The behaviour of the pole around 1968 supports the core theory, but much more analysis of the polar motion is required.

1. THE LENGTH OF THE DAY.

Spencer Jones (1939) demonstrated from the observed discrepancies in the sun, moon and inner planets that the irregular fluctuations in the length of the day have a time scale of tens to hundreds of years. This is only paralleled in geophysics by that of the geomagnetic secular variation. At that time, not enough was known of the generation of the geomagnetic field and its secular variation for any understanding of the mechanism of these enigmatic changes in the earth's rotation. Their origin had been very puzzling since de Sitter (1927) clearly demonstrated that they could not occur through crustal processes: to change the moment of inertia by the amount to increase the length of the day by 3 m sec, observed just before 1900, would require the raising of another Himalayas.

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The discovery by Vestine et al (1947) - or rediscovery as the phenomenon had been known to Halley (1692) and to Bauer (1895) - of the westward drift of the geomagnetic field (about $1/5^{\circ}$ per year) provided the important clue. Alfven's fruitful idea that, on the cosmic scale, lines of force move with a conducting fluid provides a simple interpretation: the earth's core is at present rotating more slowly than the mantle, about 1 cm/s at the interface, a speed similar to that of the convection in the liquid iron core needed to generate the geomagnetic field by the dynamo process. Clearly a change in the rotation of the core could explain the irregular fluctuations of the length of the day, for assuming conservation of angular momentum of the earth, Runcorn (1955) showed that the change in the length of the day (dT) in sec and the change of the westward drift ($d\omega$) expressed in $^{\circ}$/yr are related by

$$dT = 0.067/d\omega$$

The largest change in the length of the day referred to above could be brought about by a 20% change in the westward drift of the core.

Different ways of measuring the westward drift give roughly the same values, except for the rotation of the equatorial dipole which is much smaller and is not really understood. Thus Vestine (1953) was able to trace the variation of the westward drift back to 1820 by determining, from the spherical harmonic analyses of the field from Gauss onwards, the longitudes of the off-centre dipole commonly used to represent the quadrupole term in the field. The latest comparison of the length of the day and the westward drift (Kahle et al 1969) shows a good correlation, supporting the theory that the irregular changes of the length of the day arise from transfers of angular momentum between the core and the mantle. It is not surprising that the exact theory of the nature of the coupling mechanism is still controversial, except that viscous coupling fails by many orders of magnitude.

Recently a new and most interesting correlation has been found by Cazenave & Lambeck (1976) between the irregular changes in the length of the day and the angular momentum of the atmosphere, as determined from surface pressure observations. This has planted doubt in some minds as to the correctness of the above theory, but quantitative considerations suggest that it is unlikely that the changes in atmospheric circulation could be responsible. Further, rather sudden changes in the rotation of the earth's mantle would alter the atmospheric angular momentum as viewed from the earth and would appear to be a satisfactory explanation of the correlation found. The sign predicted by these two alternate theories are opposite and should supply a decisive test: an increase in the westward flow in the atmosphere should be associated with a decrease in the length of the day on the hypothesis that the atmosphere is responsible and with an increase in the length of the day if the core is responsible.

2. CORE MANTLE COUPLING

Two forms of core-mantle coupling have been discussed: electromagnetic couples produced by induced electric currents in the lower mantle, which is a semiconductor, and hydrodynamic coupling produced in the core by hypothetical undulations on the core mantle boundary of some 10 km high and 100-1000 km in wavelength. The latter suggestion, due to Hide (1969), arises from an attempt to explain a correlation between the geomagnetic non-dipole field potential and the geoid, both cut off above the 4th degree, and the geoid displaced through 160°. The electromagnetic coupling encounters some quantitative problems as pointed out by Roden (1963), Rochester (1960) and Roberts (1972), but in extrapolating the known surface field to the core boundary, the strength of the varying fields in the lower mantle produced by changing eddies in the core may be underestimated. Runcorn (1970) has pointed out that rapidly changing fields may arise from the core, as Alfven wave velocities of magnetodynamic disturbances (about 100 m/sec) divided into the length scale of core eddies (100 km) yield time scales of a month. The lower mantle below 1000-2000 km, which is likely to have conductivities of $100\Omega^{-1}\ m^{-1}$, would screen such rapidly changing fields and they would be undetected at the Earth's surface.

In understanding the theory, much depends on the analysis of the observations. De Sitter (1927) represented the discrepancy between the observed and theoretical longitude of the Moon (where time was measured in subdivisions of the day) as a series of straight lines, Brouwer (1952) by a series of parabolic arcs: the former require impulsive torques to cause discontinuities in the Earth's rotation and the latter abrupt changes in the magnitude of torques, neither being physically plausible. Smoothing techniques inevitably remove any sharp changes, even if they are present and a new method of analysis to determine the time scale over which changes take place is needed. The geomagnetic secular change is a regional phenomenon, the areas of rapid change establishing themselves in a few tens of years, last for a few hundred years drifting westwards, and disappear to be replaced by other isoporic centres - Elsasser's analogy to meteorological charts is apt. Interpretation by a number of eddies each generating a growing or decreasing dipole field in the outermost core has been made. Supposing a dipole growing, induced current loops in the mantle would develop in a time equal to σa^2, where σ is the lower mantle conductivity and a the size of the eddy, or about 1 month - 1 year, and then would remain constant until the dipole growth ceased. This would yield a constant torque over the lifetime, say some tens of years, of the eddy. If, however, a constant field surfaced in the core an impulsive torque would be produced with time scale of about 1 year. Examination of the length of day variations suggests that both are present.

3. THE CHANDLER WOBBLE

The course of the impulses which generate the Chandler wobble is puzzling and earthquakes and the atmosphere have been suggested. Yet if electromagnetic torques must be invoked to explain the changes in the length of the day and if some are impulses, then, bearing in mind the complexity of the secular variation, it is not reasonable to suppose the electromagnetic torques on the mantle are axial torques. Components in the equatorial plane will generate the Chandler wobble. As Runcorn (1970) pointed out, there is a considerable difference in the physics between constant and impulsive torques: the former generate a forced nutation and as Mintz & Munk (1951) showed these must be negligible contributions to the polar motion, but the latter, supposed of the same order as the impulsive torques along the earth's axis required to explain the sharper changes in the length of the day, e.g. that just prior to 1900, would be effective in exciting the Chandler wobble.

Again the analysis of the data is the key to a decision between the different mechanisms, as Runcorn (1969) showed. To generate the Chandler wobble, consider the axis of figure F, the axis of instantaneous rotation I and the axis of angular momentum M to be at first coincident. If an earthquake excites the Chandler wobble, F is suddenly displaced and I and M, which are very close together rotate in a circle around a new centre F, see Fig. 1(ii). If an impulsive torque is applied in the equatorial plane to the mantle, F remains fixed and M (and I) are suddenly displaced and then move in a circle around the same centre. This is shown in Fig. 1(i). What is needed is an analysis of the Chandler component of the polar motion to examine whether disturbances in the path are of the former or latter type. Guinot (1972) using a method to remove the 12 monthly term in the polar motion due to atmospheric excitation finds a case in 1968 when the polar path sharply diverges and then continues in a circular path round the same centre. This is clearly explicable only in terms of an impulsive torque (with a time scale of at most a few months), and is not what would be expected from an earthquake. It seems unlikely that the atmosphere could provide such an impulsive torque.

Another phenomenon in polar motion data of interest to the geophysicist is the slow secular change in the mean pole, determined by averaging out both the Chandler and the annual term. Markowitz (1968) finds a motion in a generally similar direction since 1900 of about 0.006"/year. This is of the order of the rate of polar wandering found from palaeomagnetic date ($1/5^{o}$/year). Of course the observed palaeomagnetic pole wandering curve from any one continent (or microplate) results from continental drift relative to other continents as well as from polar wandering. A meaning can be attached to the latter, but in any case both phenomena are caused by slow flow in the solid earth's mantle resulting from solid state creep. Studies of sea floor spreading resolves the motion of the continents on the 10^5 y - 10^7 y time scale, and the palaeomagnetic date from the continents has even less time resolution. Thus the mean motion of the pole as determined by astronomical and other sensitive methods in historic time are an important contribution to the yet poorly understood mechanism of plate motions.

The study of the earth's rotation throws a unique light on the dynamics of the earth's interior and is an important contribution to the geophysicist's programme which in the last quarter of a century has replaced the classical static model of the earth's interior by a dynamical one.

When the motion of the Moon in longitude is expressed in dynamical time, it is found to be a parabolic function of time. There is thus a real acceleration of the Moon. Until recently the results for this acceleration obtained from observatory data over the last 300 years and from ancient and medieval eclipse and other observations were thought to differ. However, revaluation of both methods gives essentially the same value. Thus Morrison and Ward (1975) deduced an acceleration of ("/cy^2) - 26 $\pm$ 2 (corresponding to a rate of retreat of the Moon from the Earth of about 4.9 cm yr^{-1}) from transits of Mercury since AD 1677. Muller (1976) in his revision of the analysis of the ancient and medieval data by Muller & Stephenson (1975) obtained - 30.0 $\pm$ 3.0 (4.4 cm yr^{-1}). Daily, monthly and annual growth increments are seen on skeletons of marine creatures. However, further developments in the use of fossils for counting the ratios between these increments is required if these parameters are to be of use in the evolution of the Earth-Moon system (Rosenberg & Runcorn, 1975).

Tidal friction appears adequate to provide the decelerating torque required by the astronomical observations (Lambeck 1978). However, this torque cannot have remained over the earth's life, and it is still doubtful whether it has remained constant over Phanerozoic times in view of changes in oceanic and continental distribution (Pannella 1975).

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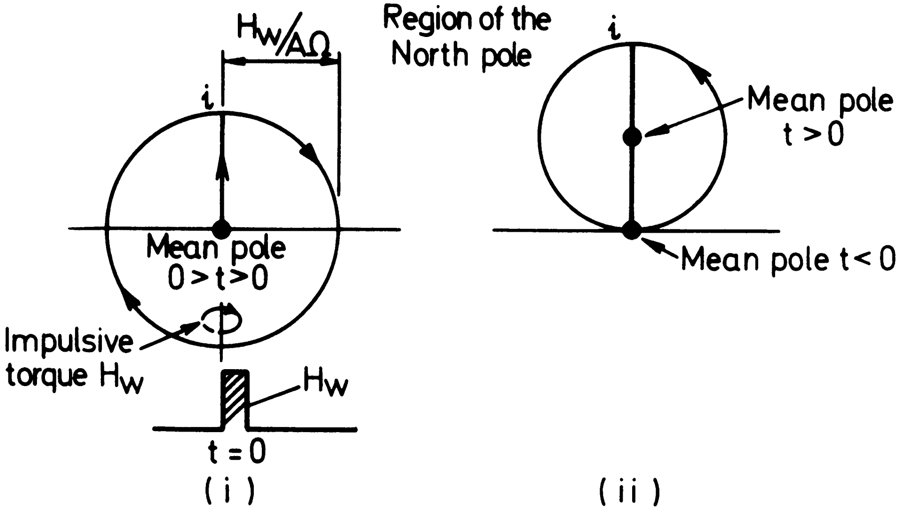

EXCITATION OF CHANDLER WOBBLE

(i) Impulsive torque from core. (ii) Mass displacement by earthquake.

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