Reports

Motions of the Earth's Core and Mantle, and Variations of the Main Geomagnetic Field

Abstract. *Theoretical work on the magnetohydrodynamics of the earth's liquid core indicates (a) that horizontal variations in the properties of the core-mantle interface that would escape detection by modern seismological methods might nevertheless produce measurable geomagnetic effects; (b) that the rate of drift, relative to the earth's surface, of nonaxisymmetric features of the main geomagnetic field might be much faster than the average zonal speed of hydrodynamic motion of core material relative to the surrounding mantle; and (c) why magnetic astronomical bodies usually rotate. Among the consequences of (a) and (b) are the possibilities that (i) the shortest interval of time that can be resolved in paleomagnetic studies of the geocentric axial dipole component of the earth's magnetic field might be very much longer than the value often assumed by many paleomagnetic workers, (ii) reversals in sign of the geomagnetic dipole might be expected to show some degree of correlation with processes due to motions in the mantle (for example, tectonic activity, polar wandering), and (iii) variations in the length of the day that have hitherto been tentatively attributed to core motions may be due to some other cause.*

The interpretation of a variety of phenomena at the earth's surface in terms of hydrodynamic and magnetohydrodynamic motions in the earth's interior is an important problem in modern geophysics.

Through their work on the "homogeneous dynamo" theory of the earth's magnetism, Bullard, Elsasser, and others have convinced most geophysicists that the main geomagnetic field is due to magnetohydrodynamic motions, at rather less than 0.1 cm/sec, occurring in the earth's liquid core, and that fluctuations in the main field are best regarded as manifestations of the fluctuating component of these motions. Core motions are responsible not only for the creation and destruction of lines of force of the earth's magnetic field, but also for their rearrangement. Field changes on time scales of years to centuries—the geomagnetic secular variation—may be largely due to the rearrangement process (*1, 2*), but the creation and destruction of magnetic field lines cannot be ignored in the theory of slower field variations, including reversals in the sign of the dipole component of the main field. [Extensive lists of pertinent references can be found in two recent review articles (*3, 3a*).]

In addition to *material* motions in the core, magnetohydrodynamic *wave* motions there may contribute to the distortion and displacement, including the well-known "westward drift" (*3–4*) of the geomagnetic field pattern at the earth's surface. Although wave motions have not been considered seriously in most theoretical work on the geomagnetic secular variation, a recent study of free magnetohydrodynamic oscillations of the core (*1*) suggests that such motions may be quite important. The characteristics of these free oscillations depend on the earth's angular velocity of rotation about its axis, the (unknown) strength, B, of the toroidal magnetic field in the core, and the size and shape of the core (*1*). The "free oscillations" model accounts for the general time-scale of the geomagnetic secular variation if B has the reasonable value of 100 gauss, and it may also account for the westward drift (see, however, *4* and *5*). If the westward drift of nonaxisymmetric features of the geomagnetic field *is* largely a manifestation of wave motions in the core, then the observed rate of drift—0.03 cm/sec—could be much faster than the *average* speed of hydrodynamic motion, relative to the overlying mantle, of the material of the core (see *1*); the "available" angular momentum in the core might, therefore, be much less than the value that is usualy assumed in discussions of the effects of core motions on the rotation of the mantle (*6, 6a*).

Core motions are very strongly influenced by Coriolis forces due to the earth's rotation (see *1, 3, 6a, 7*). These forces align core eddies, thus giving the geomagnetic field its approximate symmetry about the earth's axis of rotation. Less obvious, but probably very important, is the role played by Coriolis forces in ensuring that, irrespective of the size of the *energy-producing* eddies in the core, the *largest* eddies that occur there are comparable in size with the dimensions of the core (*1*); thus may be achieved the low degree of symmetry necessary for the "homogeneous dynamo" mechanism (*7*) to work efficiently (*3a*). These large eddies gain kinetic energy by nonlinear interactions with smaller eddies—a process which, though impossible in isotropic homogeneous turbulence (where energy cascades in the opposite direction, from large to small eddies), should be quite common in large-scale natural systems, where anisotropy (due to the earth's rotation in the case of the core) is the rule rather than the exception (*1, 3a*). This type of mechanism may underlie the observational result that magnetic astronomical bodies (stars, planets) usually rotate.

It has recently been recognized that, owing to the earth's rotation, quite weak horizontal temperature variations at the boundaries of the core, and horizontally extensive topographical features of the core boundaries that are so shallow [vertical dimensions about a kilometer or so, possibly even less (*8*)] that they would escape detection by modern seismological methods, might nevertheless produce pronounced hydrodynamical effects throughout the core (*1, 9*). Consequently, it is conceivable that the conditions prevailing at the core-mantle interface could be reflected in the main geomagnetic field. Gravitational effects at the earth's surface due to the presence of such topographical features at the core-mantle interface, and concomitant stresses within the earth, could be significant, but would not be excessive.

Various lines of geological and geophysical evidence suggest that relative motions of the order of 1 cm/year (3×10^{-8} cm/sec) occur in the earth's upper mantle, but the cause and vertical extent of these motions are still highly controversial (*10*). Relative motions in the lower mantle, if they occur, could produce horizontal variations in the properties of the core-mantle interface. Vertical displacement velocities of parts of this interface relative to other parts might amount to 1 km in 10^5 or 10^6 years if the speed of lower-mantle motions is between 10^{-1} and 1 cm/year (3×10^{-9} to 3×10^{-8} cm/sec).

Doell and Cox (*11*) have adduced paleomagnetic evidence that the secular variation over the Pacific hemisphere has been systematically weaker than elsewhere on the earth's surface for the past 10^6 years, and I have attempted to account for this and related observations by invoking the interaction of core motions with hypothetical "topographical features" of the core-mantle interface (*1*). If such interactions are important, then a typical interval of time, τ, over which nonaxisymmetric features of the geomagnetic field can safely be assumed to average out to zero at a point on the earth's surface will be governed not by the secular variation—time-scale, years to centuries—as has often been assumed in the interpretation of paleomagnetic data (*12*), but by the dynamical processes affecting the core-mantle interface—time-scale, 10^5 to 10^6 years (?). The observational and theoretical bases for taking τ as low as 10^3 years should, therefore, be reexamined. Further tests of Doell and Cox's conclusions concerning the geomagnetic secular variation over the Pacific hemisphere, and the careful study of the relationship, if any, between features of the earth's magnetic field and features of its gravitational field, will be particularly important.

Because only minor variations in core motions are required to reverse the sign of the dipole field (*7, 13*), it would not be surprising to find that "reversals" are correlated to some extent with other phenomena that may be affected by motions in the mantle, such as tectonic activity (mountain building, ocean-floor spreading, continental drift, and so forth) and the movement of the earth's poles of rotation relative to the earth's surface ("polar wandering") (*9*). The search for such correlations might, therefore, lead to results of direct theoretical importance.

RAYMOND HIDE

Department of Geology and Geophysics and *Department of Physics, Massachusetts Institute of Technology, Cambridge 02139*

References and Notes

1. R. Hide, *Phil. Trans. Roy. Soc. London Ser. A* **259**, 615 (1966).
2. E. H. Vestine and Anne B. Kahle, *J. Geophys. Res.* **71**, 527 (1966); P. H. Roberts and S. Scott, *J. Geomag. Geoelect.* **17**, 137 (1966).
3. T. Rikitake, *Electromagnetism and the Earth's Interior* (Elsevier, Amsterdam, 1966).

3a. R. Hide, *Planetary Space Sci.* **14**, 579 (1966).

4. E. C. Bullard, C. Freedman, H. Gellman, J. Nixon, *Phil. Trans. Roy. Soc. London Ser. A* **243**, 67 (1950).
5. T. Rikitake, *J. Geomag. Geoelect.* **18**, 383 (1966); D. W. Allan and E. C. Bullard, *Proc. Cambridge Phil. Soc.* **62**, 783 (1966); W. V. R. Malkus, *J. Fluid Mech.*, in press; K. Stewartson, *Proc. Roy. Soc. London Ser. A*, in press.
6. E. H. Vestine, *Proc. Nat. Acad. Sci. U.S.* **38**, 1030 (1952); W. H. Munk and G. J. F. MacDonald, *The Rotation of the Earth* (Cambridge Univ. Press, New York, 1960); B. G. Marsden and A. G. W. Cameron, Eds., *The Earth and Moon System* (Plenum Press, New York, 1966).

6a. S. K. Runcorn, in *Handbuch der Physik*, J. Bartels, Ed. (Springer, Berlin, 1956), vol. 47, p. 469.

7. E. C. Bullard and H. Gellman, *Phil. Trans. Roy. Soc. London Ser. A* **247**, 213 (1954); W. M. Elsasser, *Rev. Mod. Phys.* **28**, 135 (1956).
8. An entirely satisfactory criterion for the occurrence of pronounced interaction between core motions and topographical features of the core-mantle interface has not yet been given; rough theoretical arguments suggest that a typical horizontal dimension of a topographical feature multiplied by its average height above (or depth below) the surrounding mean level must exceed the radius of the core multiplied by a typical hydrodynamical flow speed divided by the angular speed of rotation of the earth [see R. Hide, *Nature* **190**, 895 (1961); *Mem. Soc. Roy. Sci. Liège* **7**, 481 (1963); *Bull. Am. Meteorol. Soc.* **47**, 873 (1966); and in *Magnetism and the Cosmos*, W. R. Hindmarsh, F. J. Lowes, P. H. Roberts, S. K. Runcorn, Eds. (Oliver and Boyd, Edinburgh, 1967); ——— and A. Ibbetson, *Icarus* **5**, 279 (1966)].
9. R. Hide, "Free and forced reversals of the earth's magnetic field," Scientific Note No. 5 (Geophysical Fluid Dynamics Laboratory, M.I.T., Cambridge, Mass., Feb. 1966).
10. S. K. Runcorn, *Nature* **193**, 311 (1962); W. M. Elsasser, in *Earth Science and Meteoritics*, J. Geiss and E. D. Goldberg, Eds. (North-Holland, Amsterdam, 1963); ———, in *Advances in Earth Science*, P. M. Hurley, Ed. (M.I.T. Press, Cambridge, Mass., 1966); various papers in *A Symposium on Continental Drift*, P. M. S. Blackett, E. C. Bullard, S. K. Runcorn, Eds. (Royal Society, London, 1965).
11. R. R. Doell and A. Cox, *J. Geophys. Res.* **70**, 3377 (1965).
12. T. Nagata, *Rock Magnetism* (Maruzen, Tokyo, 1953); P. M. S. Blackett, *Lectures on Rock Magnetism* (Weizmann Science Press, Jerusalem, 1956); S. K. Runcorn, *Handbuch der Physik*, J. Bartels, Ed. (Springer, Berlin, 1956), vol. 47, p. 498; A. Cox and R. R. Doell, *Bull. Geol. Soc. Amer.* **71**, 645 (1960); ———, *Bull. Seismolog. Soc. Amer.* **54**, 2243 (1964); E. Irving, *Paleomagnetism* (Wiley, New York, 1964); *J. Geophys. Res.* **71**, 6025 (1966); A. Cox, R. R. Doell, G. B. Dalrymple, *Science* **143**, 351 (1964); ———, *ibid.* **144**, 1537 (1965).
13. S. K. Runcorn, *Ann. Geophys.* **11**, 73 (1955).
14. My interest in mechanisms that might possibly give rise to correlations between geomagnetic and geological phenomena was aroused by a paper presented by Professor P. M. S. Blackett at the N.A.T.O. Advanced Study Institute on "Planetary Magnetic Fields" held at Newcastle in April 1965 [see *Magnetism and the Cosmos*, Hindmarsh, Lowes, Roberts, and Runcorn, Eds. (Oliver and Boyd, Edinburgh, 1967)]. Owing to lack of detailed information about the properties of the core and lower mantle, the subsequent suggestion, namely, that mantle motions might affect conditions both at the earth's surface, where geological events occur, and at the core-mantle interface, where effects on the geomagnetic field may arise, must, of course, be regarded as speculative. The favorable reaction of Dr. D. W. Strangway and Dr. E. Irving convinced me that the suggestion might not be entirely farfetched and was at least worth bringing to the attention of other paleomagnetic workers (*9*). The work of the Geophysical Fluid Dynamics Laboratory, Department of Geology and Geophysics, M.I.T., is supported by NSF (Atmospheric Sciences Program) under grant No. GP5053. This is Paper No. 25 of that laboratory.

23 March 1967

Romeriscus, the Oldest Known Reptile

Abstract. *The description of* Romeriscus, *a new genus of limnoscelid reptile, is based on a partial skeleton from the Early Pennsylvanian (Westphalian A) of Nova Scotia. Although it is the earliest and most primitive reptile yet known, it is probably already too late and too specialized to be ancestral to the more advanced Carboniferous and Permian captorhinomorphs and pelycosaurs.*

The most primitive described genus that is also unquestionably reptilian is *Limnoscelis* (*1, 2*) from the Lower Permian of Texas. Both Romer (*2*) and Watson (*3*) have indicated that, morphologically, *Limnoscelis* is more or less intermediate between anthracosaur amphibians and typical captorhinomorph reptiles and not far from the ancestry of pelycosaurs. Two other genera of the family Limnoscelidae are known from the Lower Permian (*4*). A somewhat earlier genus, based on very incomplete material from the Middle Pennsylvanian of Nova Scotia, is being described elsewhere (*5*).

Numerous other reptiles are known from the Pennsylvanian (*6*), the earliest being two romeriid captorhinomorphs and one pelycosaur from the Lower Pennsylvanian of Joggins, Nova Scotia (*7*). All of these forms are more advanced in their morphology than is *Limnoscelis* and show little evidence of affinity with anthracosaurs. This indicates that forms related to *Limnoscelis* must have been living throughout the Pennsylvanian and possibly even in the late Mississippian.

A single specimen that evidently represents an early member of the limnosceloid lineage is described here. It was found in 1959 by D. Baird and W. F. Take near Port Hood on the northwest shore of Cape Breton Island, Nova Scotia, Canada. Its source