Reports

Measurements of the Large-Scale Direct-Current Earth Potential and Possible Implications for the Geomagnetic Dynamo

Abstract. *The magnitude of the large-scale direct-current earth potential was measured on a section of a recently laid transatlantic telecommunications cable. Analysis of the data acquired on the 4476-kilometer cable yielded a mean direct-current potential drop of less than about 0.072 ± 0.050 millivolts per kilometer. Interpreted in terms of a generation of the potential by the earth's geodynamo, such a small value of the mean potential implies that the toroidal and poloidal magnetic fields of the dynamo are approximately equal at the core-mantle boundary.*

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Magnetism is one of the most widespread attributes of astrophysical systems such as planets, stars, and galaxies (*1*), and the geomagnetic field is a fundamental feature of the earth. However, the geomagnetic dynamo and the conductivity structure of the deep earth can only be observed through seismic studies, careful, long-term measurements of the secular variation of the geomagnetic field, or paleomagnetic investigations. Studies of the secular variation, including the recently observed enhanced variations ("geomagnetic impulses"), provide the best understanding of the constraints on the conductivity at the core-mantle interface (*2, 3*).

Three decades ago Runcorn (*4*) proposed that, in addition to the magnetic field, another electrical property of the dynamo might be evident at the surface of the earth (or, more rigorously, at the crust-mantle boundary). Runcorn proposed that leakage from the current systems associated with the toroidal field in the core might be measurable at the earth's surface. Such a direct-current (d-c) component in telluric currents would not be related to other, non–d-c components.

Since $\mathrm{div}\mathbf{H}=0$, the dynamo magnetic field H has the form

$$\mathbf{H} = curl\mathbf{A} \qquad (1)$$

where the vector potential $\mathbf{A}$ can be expressed in terms of two different scalar functions

$$\mathbf{A} = \mathbf{r}\Phi_E + \mathbf{r}\times\nabla\Phi_M \qquad (2)$$

In dynamo theory, Φ_E and Φ_M describe the electric mode and the magnetic mode, respectively. The former consists of lines of force wrapped around spherical surfaces, and the latter has radial magnetic field components. These two fields are also known as toroidal and poloidal fields, respectively, and can be expressed in terms of the scalar functions as

$$H_E = \nabla\Phi_E\times\mathbf{r} \qquad (3)$$

$$H_M = curl(\mathbf{r}\times\nabla\Phi_M) \qquad (4)$$

A toroidal magnetic field that is confined to the highly conducting sphere of the core of the earth (or other planet) implies the existence of a poloidal electric current system that can extend into the mantle and the crust (depending on their relative conductivities).

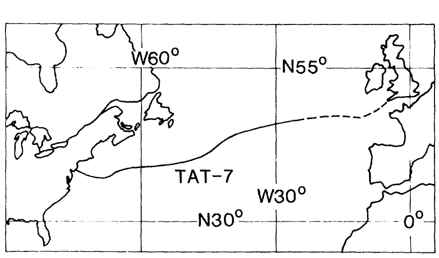

Fig. 1. Location of length of TAT-7 cable used in the experiment (solid line) and final segment to England (dashed line).

Runcorn tested his hypothesis by measuring the d-c current on two long segments of unused telecommunications cables in the Pacific Ocean (*5*) and established an upper limit for the leakage current from the core of approximately 0.1 mV/km. A decade later, using a different (and longer) segment of the same cable system, another group of investigators (*6*) reduced this upper limit to about 0.04 mV/km.

As Runcorn noted, long cables are essentially the only means available to measure d-c currents that may result from geomagnetic dynamo processes. Unfortunately, superimposed on any d-c currents are those induced by other processes in the geophysical environment, including ocean tides, possibly fluctuating and steady ocean currents, and geomagnetic variations (*7*). Furthermore, long cable systems are usually unavailable for making such measurements because they are always powered on present routes. However, we were able to monitor geomagnetically induced effects and to study d-c telluric currents on AT&T's TAT-7 cable when it was laid across the Atlantic (from Tuckerton, New Jersey to Lands End, England) for a 19-day interval (11 to 29 March 1983) before it was powered.

The open circuit–induced voltage on the length of cable available to us (4476 km; Fig. 1) was measured between the center conductor and ground at the New Jersey shore terminal. The grounding system near the terminal (referred to as ocean ground) consists of an array of six electrodes composed of 5-foot lengths of silicon-iron rods (diameter, 3 inches) buried in salt marshland. The Atlantic Ocean end of the cable was grounded through saltwater contact with the large surface area of the copper-beryllium housing of the last repeater casing (*8*). The total impedance of the cable and the 486 unpowered repeaters and 16 equalizers was 58,500 ohms. The voltage drop between the cable center conductor and ocean ground as well as the local magnetic field (three components) was monitored at Tuckerton at 10-second intervals and was digitally recorded on computer-compatible cassette tapes. A voltage drop of approximately 0.7 V between the measuring point in the terminal building and ocean ground was due to a ground return current of about 0.7 A from the powered TAT-3 and TAT-4 cables; this current was passing through the 1-ohm resistance of the common cable to ocean ground (*9*).

The data were subjected to statistical analysis to determine daily variations and to verify data quality. The 10-second

Table 1. Long-distance d-c Earth potential measurements.

Cable parameters: Shore terminals	Cable parameters: Length (km)	Time interval (days)	Data points (number)	Electric field (mV/km)*	Reference
Suva to Auckland	~2250	4	96	<0.1	(5)
Sydney to Auckland	~2600	4	96	<0.1	(5)
Suva to Bamfield	~9660	85	40 × 10³	<0.03	(6)
		19† (all data)	15 × 10⁴	−0.076 ± 0.067§	This work
Tuckerton to Lands End	4476	5† (quiet data)	42 × 10³	−0.028 ± 0.063§	This work
		19‡	15 × 10⁴	−0.072 ± 0.050§	This work

*Variance estimates are not reported for voltage values taken from earlier sources because it is difficult to assign uncertainties to them. †Arithmetic mean. ‡Karhunen-Loève estimate (11). §Standard errors correspond to the 95 percent confidence limit. Allowance for ±30 percent uncertainty on the estimated values from unknown sources of error would increase these values to ±0.081, ±0.078, and ±0.068 mV/km, respectively.

voltage data points on each day were averaged over 5-minute intervals, and the individual variances were computed (Fig. 2). The means and variances of each 5-minute interval over the 19 days were then computed after first removing the overall 19-day mean of the voltage time series. The corresponding means and variances were also calculated for a subset of the data from the 5 days that were the most geomagnetically quiet (Fig. 2). The data show evidence of a diurnal variation in the voltage signal characteristic of that expected from the ionosphere current pattern (10). The 19- and 5-day mean voltages (electric fields) (Table 1) indicate a net current from the mid-Atlantic toward North America.

The mean of the data set was also determined by spectral analysis (11). The 5-minute averaged data were low-pass filtered to a bandwidth of 5 cycles per day by means of the zero-order discrete prolate spheroidal sequence [Slepian sequence (12)] of length 72 (5-minute data points) and bandwidth parameter 3/72. Alias terms from the previous averaging were thus suppressed by more than 80 dB. A spectrum of the resulting 180 data points was then computed by means of a multiple window technique (13). Five windows were used, each with the same bandwidth parameter of 3.5/180. The spectrum was reshaped about the three most significant line components. The mean value obtained by this method was −0.068 mV/km after subtracting the constant 0.7-V drop. From the Karhunen-Loève expansion (11), a value of −0.072 ± 0.050 mV/km (mean ± standard deviation) was obtained (Table 1).

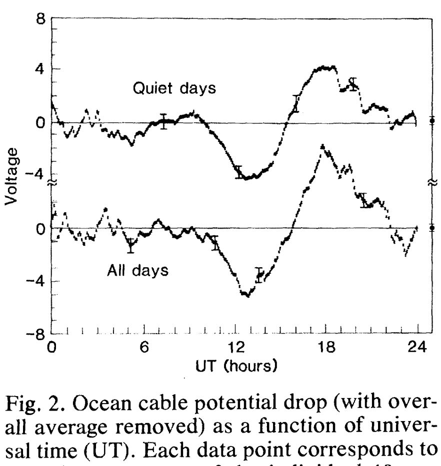

Fig. 2. Ocean cable potential drop (with overall average removed) as a function of universal time (UT). Each data point corresponds to a 5-minute average of the individual 10-second data points for each day averaged over five geomagnetically quiet days (upper trace) or over all days of data collection (lower trace). Representative standard deviations on 5-minute averages are shown. Overall standard errors corresponding to the 95 percent confidence limits (t-test) are shown on the right-hand axis for each of the two data sets. Because the data are serially correlated from point to point, and are not independent, such an estimate of error is slightly optimistic.

The interpretation of the measured d-c electric field in the context of Runcorn's original hypothesis depends on the conductivity of the core-mantle interface and the dominant magnetic toroidal mode in the core. For several exactly calculable models of the mantle conductivity $\sigma(r)$, all of which decrease monotonically with increasing radius r, Roberts and Lowes (14) determined the poloidal electric field that would be associated with a toroidal core magnetic field and that should be observed at the earth's surface (or, rigorously, at the mantle-crust boundary). They showed that the tangential component, $H_n(r)$, of a magnetic field of spherical harmonic order n at the core-mantle boundary could be related to the magnitude of the tangential component, $E_n(r)$, of the poloidal electric field of order n at the top of the mantle as

$$N_n = \frac{1}{c\sigma(c)} \frac{|H_n(c)|}{|E_n(a)|} \quad (5)$$

where $r = a$ and $r = c$ correspond to the radius of the mantle and of the core, respectively (see Fig. 3).

Two experimental uncertainties can complicate the interpretation of a measured potential drop: electrochemical potential effects from the grounding procedures at each end and steady ocean currents. Grounding of the cable ends was done according to AT&T standards and provided a stable reference in that no drifts were seen in the voltage values

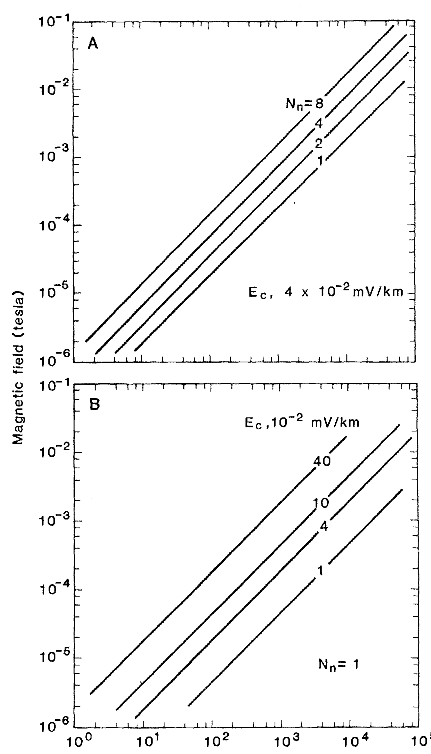

Fig. 3. Toroidal magnetic fields at the core-mantle boundary as a function of the lower mantle conductivity, $\sigma(c)$, for (A) an electric field of 0.04 mV/km (see Table 1) for different harmonics (order n) of the toroidal field and (B) different values of the tangential component of the poloidal electric field.

from day to day and no sudden offsets appeared in the data, as was reported, for example, for a broken cable off the coast of Florida used for ocean transport studies (*15*). A potential drop less than about 0.5 V might be expected between the iron and copper electrodes (*16*). Such an electrochemical potential would not alter the basic conclusion that the natural potential drop measured in the experiment was near zero, so that the results in Fig. 3A are representative. For example, the voltages expected for values of $E(c)$ ranging over a factor of about 40 around the measured value for $N_n = 1$ are plotted in Fig. 3B. For reasonable estimates of $\sigma(c)$ of about 10^2 to 10^3 S/m, values of the toroidal magnetic field are still of the order of 10^{-5} to 10^{-3} T (Fig. 3B).

Steady ocean currents that do not complete a closed circuit loop across the length of a cable, such as tidal components with periods greater than the time interval of data, could produce a potential drop across the cable that would mimic a d-c potential over the time interval of analysis. However, analysis of the data for the entire time interval, as well as for five separate days within the total interval, revealed similar, small potentials within the calculated variances (Table 1). Furthermore, the spectrum estimation procedure has sufficient resolution to isolate all but the low-amplitude monthly lunar and semiannual solar tides (*17*). Extrapolating from the K_1, K_2, and S_2 tidal amplitudes in the data, the lunar and solar tides should not appreciably influence the d-c estimate.

The measured electric field from this experiment places some severe constraints on the toroidal field magnitude at the core-mantle boundary, if values of the lower mantle conductivity [10^2 to 10^3 S/m (*18*)] inferred from analyses of the secular variation are used. This would suggest a toroidal field at $r = c$ of about 10^{-4} to 10^{-3} T, which is comparable to the poloidal field.

A complicating matter in alternative attempts to arrive at values of σ in the lower mantle is the sudden ("impulse") changes in the geomagnetic secular variation (*19*). Although a straightforward interpretation of a change with a 2- to 4-year period would imply a low conductivity ($\sim 10^2$ S/m) at the core-mantle boundary, treating the mantle as a filter is not inconsistent with a value for $\sigma(c)$ of approximately 10^2 to 10^3 S/m (*20*). Interpreting such a geomagnetic impulse as a purely internal process (in contrast to external processes, such as solar cycle–dependent geomagnetic activity) has been called into some question (*21*).

On the basis of the work of Roberts and Lowes (*14*) and assuming that the conductivity at the core-mantle boundary is of the order of 10^2 to 10^3 S/m, our result for the large-scale d-c potential is consistent with the toroidal and poloidal fields being of approximately the same magnitude at $r = c$. However, a theoretical complication may exist in that Backus has recently used a singular perturbation method for estimating the electric field produced in the mantle by the core dynamo (*22*). Backus shows that, assuming that the conductivity has only one local minimum in the mantle, the resulting critical layer will screen out any internal-origin electric field except for the case where the critical layer occurs at the earth's surface. A null result, such as that obtained here, would be consistent with such a model. Further work is required to investigate the validity of such model considerations.

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A Unique Symbiosis in the Gut of Tropical Herbivorous Surgeonfish (Acanthuridae: Teleostei) from the Red Sea

Abstract. *Herbivorous surgeonfish (*Acanthurus *species) in the Red Sea harbor gut symbionts that include bacteria, trichomonadid flagellates, and a peculiar putative protist that attains densities of 20,000 to 100,000 cells per milliliter of gut contents. The structure, mode of reproduction, and within-gut distribution of the latter are described. This may be the first report of an organism of this type and the first evidence of a consistent endosymbiosis in the gut of a herbivorous marine fish.*

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Symbiotic relations between organisms are often the products of coevolutionary processes (*1*), may exhibit close interactions on ecological, anatomical, physiological, or biochemical levels, and involve a broad array of taxa (*2–4*). In most instances of gut endosymbiosis involving herbivorous organisms, the gut flora and fauna either participate in the digestion of plant material on which the host feeds or provide important micronutrients to the host (*3, 4*).

Such well-defined symbiotic relations have not been described for marine fish. Although obligate anaerobic bacteria from freshwater fish have been recorded (*5*), studies of gut microfloras and faunas of fish leave the impression that there are few obligate relations of this sort and that gut microbes often reflect microbial populations in the water or the food. Furthermore, most studies have been performed on carnivorous or omnivo-