CORROSIVE INFLUENCE OF NATURAL GEOELECTRIC CURRENTS

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A brief descriptions of natural geoelectric currents emancipating from earth's core, induced by ionospheric currents, magnetic crochets, magnetic storms, tidal movements and local earth currents due to spontaneous polarisation, junction potential, membrane potential, streaming potential, differential temperature cell action and lightning discharges have been given and the order of the currents due to these causes has been evaluated. The order indicates that the local earth currents due to physico—chemical causes in the earth may significantly add to the corrodibility of metals due to the physico—chemical nature of the soil. Longline telegraph cables may sometimes be damaged by corrosion due to the current induced by magnetic storms. The effect of all other geoelectric currents on the corrodibility of metals in soil is insignificant.

Electric currents in the earth's crust are one of the causes of corrosion of subterranean metal structures. In the earth electric currents produced because of certain electric installations are known as stray currents. Their corrosive influence has been extensively studied[1,2] and preventive methods have been successfully adopted in order to minimise the damage due to them. Important advances in the knowledge of the natural earth-currents have, however, been made only in recent years and an assessment of their corrosive influence has not been done. The causes of the natural electric currents manifesting in earth's crust, the order of their magnitude and the extent of their corrosive influence are summarised in this paper.

CURRENTS FROM EARTH'S CORE

The core[3] of the earth is a fluid mass of metals, about 6740 km in diameter. It is surrounded by a mantle consisting of solid rock. From the geophysical studies it is inferred that the electric currents of high magnitude flow in the earth's core and the inner part of the mantle. As the mantle is semiconductor in nature, a minute portion of the current may leak up to the crust. A schematic representation of such currents has been given by Runcorn[4,5]. Though these currents have not yet been identified at the surface of the earth, it is expected[5] that the potential gradient due to these currents may be of the order 0·1—1·0 mV/km. These currents continually operate for all time.

CURRENTS INDUCED BY IONOSPHERIC CURRENTS

The earth's magnetic field, having an average value of 0·5 gauss (50,000 γ), is never constant and varies geographically and chronologically. Ordinarily it is due to the effect of the interaction of actinic rays and the ionosphere [6,7]. Ionosphere is a region 80—360 km above the earth. Actinic rays react with the ionospheric gases to release vast swarms of free electrons. The electrons move in the form of electric dynamo currents. They flow in the ionospheric region in a vast circular and horizontal patttern. The magnitude of these currents is of the order 10^3 amperes. There are four main concentrations of ionospheric currents, each above the four quarters of the globe. The ionospheric currents cause rythmic fluctuations of magnetic intensity and direction on the earth. These fluctuations constitute annual solar cycle, diurnal solar cycle and diurnal lunar cycle. The daily variation in the magnetic intensity is of the order of 10 γ.

The variations in the magnetic field induce earth-currents. The mean current system at the earth's surface, induced by ionospheric currents, has been given by several workers[4,5,8,9]. A typical system is given in Fig. 1. There are four main groups of currents corresponding to four groups of ionospheric currents. This pattern of earth-currents rotates round the earth following the sun.

The paths of the earth-currents induced by each concentration of ionospheric current are of the order of 10^4 km. The change of magnetic flux during a day is about 10^{14} gauss × cm^2. Hence the rate of change of flux is 10^9 lines/sec. This corresponds to a voltage of 10 V round the circuit. Therefore the potential gradients[5] of the current is of the order of 1 mV/km.

CURRENTS DUE TO MAGNETIC CROCHETS

The magnetic crochets [10,11] are sudden small changes in all the three components of earth's magnetic field. They are connected with the more important solar flares believed to be due to an increase in the ionisation currents in the ionosphere. Some authors think that the currents causing magnetic crochets flow at a level different from ionospheric currents which produce normal diurnal variation in the geomagnetic field.

CURRENTS DUE TO MAGNETIC STORMS

The geomagnetic field is confined within a boundary known as magnetopause and intersects sun-earth line at about 10 earth radii. The region within this boundary is known as magnetosphere. The earth, surrounded by this magnetosphere, is immersed in interplanetary plasma stream known as solar wind, which always flows away from the

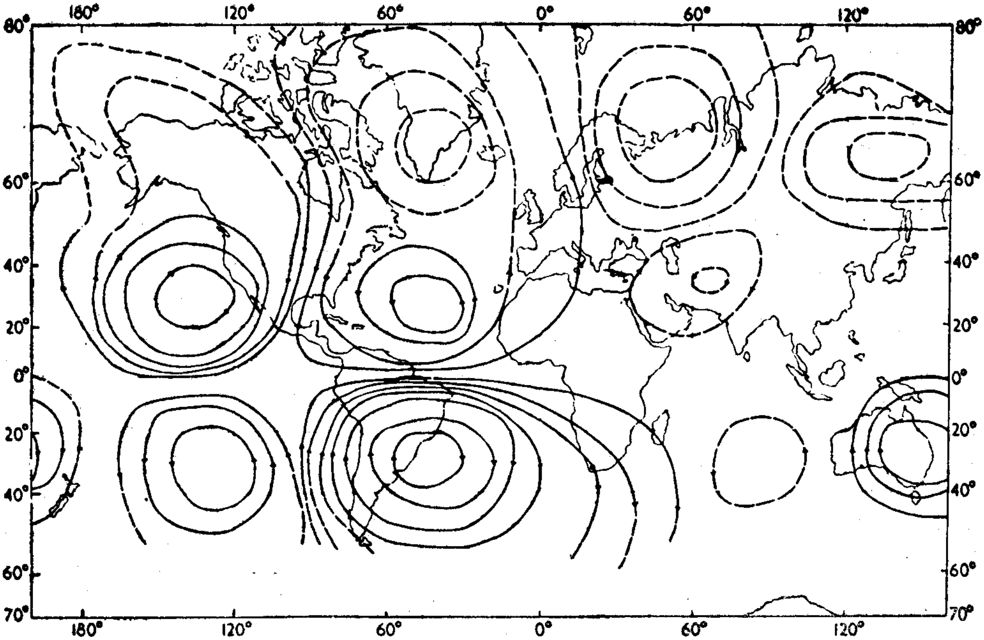


FIG. 1—World system of earth currents induced by ionospheric currents at 1800h GMT

sun [12]. The plasma consists of electrons and protons derived from hydrogen atoms emitted by solar flare [13]. It interacts with geomagnetic field in the regions of magnetopause[14]. The interaction is dependant on the intensity of solar wind. As a result, a cavity is produced in the magnetosphere and the distance of magnetopause from earth is reduced by a few earth radii on the sunlit side [15,16] on the other hand it extends to much greater distances on the night side. Occasional localised enhancements in the density and velocity are superimposed on almost a steady plasma stream which has the density of about 2·5 protons/cm^3 and velocity 1000—2500 km/sec. These superimpositions are often but not always associated with sunflares and other sudden events on the sun [17,18].

The interaction of enhanced solar wind with the geomagnetic field gives rise to the phenomenon known as magnetic storms on the earth [19,20]. Conclusions regarding the interaction of plasma stream and the geomagnetic field and the consequent effects on the geomagnetic intensity have been confirmed with the help of laboratory models [20,21]. Important investigations regarding the variations in the interplanetary plasma and its correspondence with the magnetic storm on the earth have been carried out with the help of artificial satellites [22 – 25]. For example, a geomagnetic storm commenced suddenly when Explorer—10 was at the distance of 22—32 earth radii. At this range the plasma density was found to be 10 protons/cm^3 and velocity 500 km/sec.

With the commencement of the magnetic storm, rapid irregular fluctuations in the magnetic field are observed all over the world. The fluctuations occur mainly in the horizontal component of the magnetic field. The vertical component is much less affected. The period of each fluctuation extends to several hours or days. In the first phase of the storm a sudden enhancement in the horizontal field is observed. The enhancement is of the order of 10 γ in weak, 10^2 γ in medium and usual, and 10^3 γ in severe storms. In severe storms, the geomagnetic field at higher latitudes may increase to $2{\cdot}5\times10^3\gamma$. This occurs in the course of a few minutes. Usually the period is about an hour. Then the field decreases and remains above its normal value for 2—4 hours. The decrease continues for several hours until the minimum is reached at the end of about 15 hours from the commencement of the disturbance. The depth of the minimum field is usually greater than the height of the maximum field. Several irregularities and alterations in the magnetic intensity are also associated with this drop. Thereafter the phase of recovery extends to several days during which gradual return to normal value occurs [5,13].

Variations in the field are strongest in those zones of the earth where aurora is best developed. In general, the disturbances are much greater in polar regions above 60° than in middle and lower latitudes. The polar regions are constantly disturbed even at periods when geomagnetic field at lower latitudes is free from any disturbances [26 – 28]. The magnitude of such disturbances is of the order of 10 γ.

Weak storms occur with a frequency of several times per month, medium storms at an approximate interval of 27 days [29,30] and severe storms average less than one per year. The magnetic storms are more frequent specially when sun spots are numerous [31] because the solar flare is closely associated with the occurance of sun spots. It is well known that the frequency of sun spots varies according to an eleven year cycle [13]. A close correlation between cycles of change in the number of sun spots and in the intensity of magnetic disturbance has been observed [32].

There is definitely a physical relationship between the geomagnetic variation and the earth-current or potential gradient but its exact nature is not yet known because of the inadequate knowledge of sub-surface structure of the earth, which is also involved in the correlation. As the structure is varying and complicated, the correlation is not expected to be simple, more so because the magnetic variations induce earth-currents which in turn react with magnetic field to modify it still further [33]. Some attempts have been made to derive theoretically a correlation between the changes in magnetic flux and the earth potential gradient [34] but only a rough qualitative agreement is found to exist between the calculated and observed field results [35]. A schematic diagram of earth-current induced by magnetic storm is given in Fig. 2.

At middle and lower latitudes, the earth currents induced by a change in the geomagnetic flux travel round the globe more or less is east-west direction [36]. At polar regions, two loops of currents of comparatively higher density exist. The order of the current during usual magnetic storms is expected to be 5×10^3 amperes. In severe storms, a potential gradient of 0·1—0·2 V/km has been recorded at several stations in middle latitudes[33]. At polar stations, higher values have been recorded. In extreme cases potential gradient of the order of several V/km is observed [37]. For example, 800 V has been recorded to be induced in 600 km of a subterranean cable [5]. In transatlantic cables 1000—2500 V have been observed to be induced during magnetic storms.

CURRENTS DUE TO TIDAL WAVES

Periodic rise and fall of water level of ocean due to the combined effect of sun and moon is termed as tide [38,39]. The water level varies with time in the form of a sine curve having a period of about 12·5 hours. The saline water of ocean, estuary or a tidal river functions as a moving conductor cutting the lines of force of the vertical components of the geomagnetic field. Thus the tidal movement induces voltage across the bank and current flows between the banks through the conducting bed in one direction and the intervening water in another. The chronological behaviour of the voltage induced by tidal movements has been measured across transpacific lines[5]. There is a very good correspondence between the variation in voltage and tidal movement. The effect of tidal

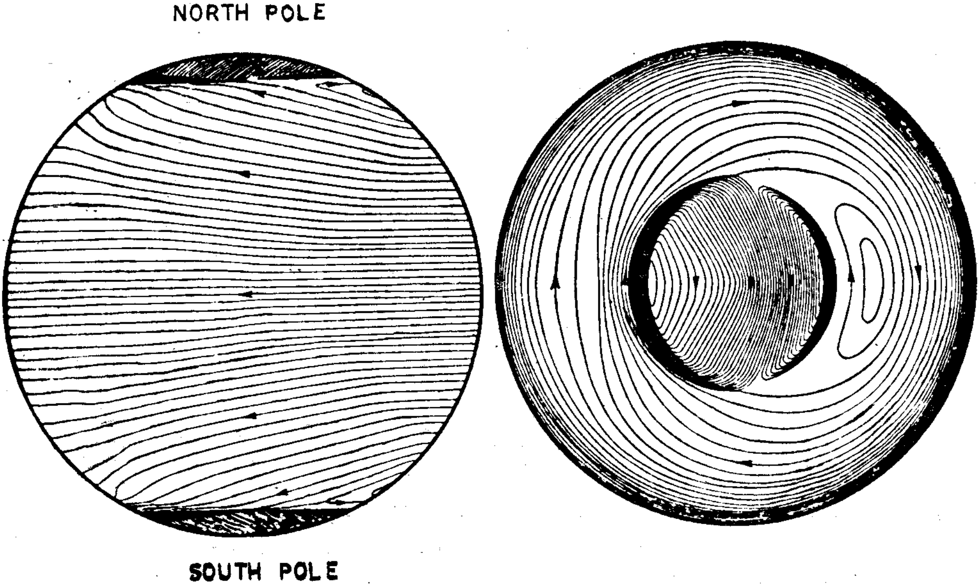


FIG. 2—World system of earth currents induced by geomagnetic storm. The centre of the figure on the right hand side represents the north pole of the earth.

motion on the regular diurnal geomagnetic variation has been observed and confirmed at several stations situated at coastal areas [40 — 44]. Diurnal geomagnetic variations upto the extent of 20% at such areas are attributted to this cause[40].

The e.m.f. induced across a water system is given by

$$e = H_z \,.\, v.\ l.\ e.m.u.$$
$$= H \,.\, v.\ l. \times 10^{-8}\ V$$

where e is the induced e.m.f.; H_z, the vertical component of geomagnetic field; v, the horizontal velocity of the tide and l, the length of water system.

By differentiation

$$\frac{de}{dl} = H_z \,.\, v \,.\, 10^{-8}\ V/cm$$

The velocity of the tide is approximately 50 cm/sec. (about a knot) and the order of geomagnetic field is 0·5 gauss. Therefore the order of the potential gradient is 10 mV/km per knot.

The velocity of tidal waves in estuaries and tidal rivers, depends on the depth of water. The relation is given by

$$V = 0{\cdot}61\sqrt{D}$$

where V is the velocity in knots and D, the depth of water in meters. Therefore at such spots the induced voltage and the earth current become correspondingly less.

The resistivity of sea-water is approximately 21 ohm cm. If the resistance of the path of the current through the earth is considered to be negligible, the maximum current is given by

$$I_{max} = \frac{de}{dl} \cdot 1/\rho$$
$$= H_z \,.\, V.\ 10^{-8} \,.\, \frac{1}{21} \,.$$

By substituting the values as above the order of the maximum current density is found to be 10^{-8} amp./cm^2.

LOCAL EARTH CURRENTS

At several sporadic spots on the earth, potential gradients are established due to several physio-chemical causes [45] other than those mentioned above. The paths of the currents due to these potential gradients are comparatively very short and because of this reason, these currents are generally not included under the term earth-current. Therefore, they are designated as local earth currents. The various causes of such currents are given below.

Spontaneous polarisation

Chemical reactions at some spots establish distinctive potential patterns around some ore bodies in earth[46]. The phenomenon is most important around the sulphide and graphite ores where comparatively large potentials are observed [47]. In the case of sulphide ores, oxidation occurs mainly above the water table and corresponding reduction at the lower end of the ore which is submerged in water and is low in oxygen concentration. Consequently a current flows from one end of the ore to the other through the intervening soil. The differential mechanism cannot be considered to operate in the phenomena over graphite ores which do not undergo significant oxidation. Hence an alternative mechanism has been proposed for the development of such potential differences[48]. Oxidation potential difference exists between the substances in solution above and below the water table because of differential concentration of oxygen at two zones. The ore body functions merely as a good conductor and serves to transport electrons from the zone of reduction at depth to the upper zone of oxidation and does not take part in the electrochemical action. Schematic diagram showing the local earth current systems due to sulphide and graphite ores are given in Fig. 3.

Junction potential or diffusion potential

Wherever two solutions in the form of ground waters having different ion activities and mobilities are in contact, an electrochemical diffusion potential is established [49]. The magnitude of such a potential difference is given by

$$E_j = \frac{(v - u)}{(v + u)} \cdot \frac{G \cdot T}{n \cdot F} \; ln. \; \frac{a'}{a''}$$

where v is cationic mobility; u, anionic mobility; G, gas constant (8·314 joules/°C); T, absolute temperature; n, ionic valency; F, Faraday (96,000 coulombs); a' and a'' mean activities of the two solutions and ln the natural logarithm.

Membrane potential or mounce potential

If the solutions are separated by ion-active earth materials, an additional potential known as mounce potential is also observed [49]. The magnitude of the potential for a simple case of two different concentrations of a univalent ($n = 1$) salt like sodium chloride is given by

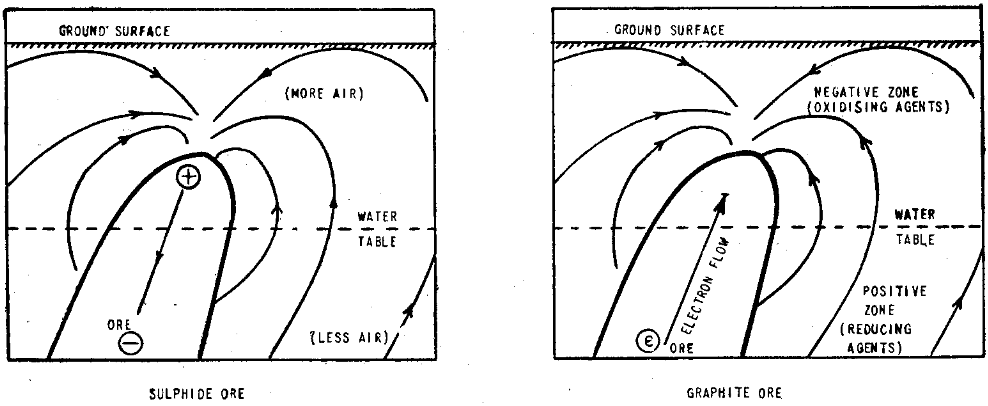
$$E_m = \frac{GT}{F} \; ln \; \frac{a'}{a''}$$

The total potential is obtained by the addition of diffusion and mounce potentials.

Streaming potential

The potential generated by the flow of solutions through permeable beds is known as streaming or electrofiltration potential[46]. Its magnitude is given by

$$E = \frac{U.P.\,k}{4^{\pi}\gamma_f\sigma_e}$$



SULPHIDE ORE GRAPHITE ORE

FIG. 3—Schematic diagram showing the local earth current system due to sulphide and graphite ores

where U is the adsorption potential existing between the double layer of charge on the walls of capillaries. Its magnitude is a function of ionic concentration. P is the difference in pressure between the points where E is measured; k, the dielectric constant; γ_f, the viscosity and σ_e, the conductivity of the solution.

The potential gradient developed due to the above causes operates continuously at spots where the necessary conditions for their development exists. The maximum potential gradient of the order of 0·1 V/m is often developed by the above mentioned causes at various spots on the earth.

Differential temperature cell action

Voltages of very small magnitude are developed due to the different temperatures at two points in the earth even though otherwise they may be electrochemically identical. The magnitude of the electric currents due to this cause is always insignificant.

Lightning discharges

Surges of high magnitude of electric current are produced in the earth because of the dissipation of the potential through the crust[50,51]. In quiet weather the density of vertical earth-current is of the order of 10^{-16} amp/cm^2, but during thunder storms it increases[52] 10^5 fold. Potentials of the order of 10^6 V and currents of the order of 10^5 amp are associated with the travelling surges passing through conducting towers. Therefore, very high density of current exists at the spot of lightning discharge. The density decreases gradually with the distance from the point of discharge. These currents are transient in nature having a period of existence of the order of 10^{-5} sec. Therefore the amount of electricity flowing in surge is of the order of 1 coulomb.

CORROSIVE INFLUENCE

The agencies inducing potential gradient in the earth, also induce a potential gradient in the subterranean metal structure. In a subterranean structure, a considerable part of the induced potential gradient is lost in the form of eddy currents within the metal structure. They do not produce any corrosive influence. Only a small portion forms a part of the earth-current system which dissipates out into the soil. The same phenomenon occurs if such a metal structure is situated in the path of non-induction type of earth-current. The magnitude of this current is principally dependent on the permeability of the covering towards ions and water and the frequency and area of the occurance of vulnerable points on the structure. Wherever the current leaves the metal structure and enters the soil, the corrosion of metal occurs.

The minimum order of the currents associated with corrosion due to the physico-chemical properties of soil may be taken as 0·1 V/m. The order of the potential gradient developed due to the leakage currents from earth's core, ionospheric currents, magnetic crochets and usual magnetic storms is 1 mV/km. The maximum potential gradient due to the tidal waves is 10 mV/km. Therefore, the corrosive influence of all these currents in terms of corrosion loss per unit area per unit time is insignificant as compared to that of the physico-chemical properties of the soils.

In very long structures lying parallel to the direction of the potential gradient, the current enters at several vulnerable points extended over a large area but leaves at small limited area which suffers significant corrosion[5] with deep penetration. Such type of effect by severe magnetic storms has been observed[5] in long line telegraph cable of the order of 10^3 km. A uniformly good insulated covering free from vulnerable points offers a good protection against any such damage.

The local earth-currents due to the physico—chemical causes in the earth have the maximum potential gradient of the order $0 \cdot 1$ V/m. This is the minimum order of the currents associated with corrosion processes due to the electro-chemical factors of the soil. Therefore the corrosive influence of the currents due to these causes is comparatively far more than that due to the afore-mentioned currents. At several spots these currents may significantly add to the corrosivity due to the physico-chemical nature of the soil. The protective methods adopted against the corrosity of soil due to its physico-chemical nature suffice for the protection against the corrosive influence of the local earth-currents.

The currents due to the lightning discharge, though heavy but transient in nature, do not significantly add to the soil corrosivity.

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REFERENCES

1. UHLIG, H.H., "Corrosion and Corrosion Control", (John Wiley and Sons, Inc., New York) 1963, p. 175.
2. WATERS, F.O., "First Internat. Cong. on Metallic Corrosion, London, 1961", (Butterworths, London) 1962, p. 355.
3. JACOBS, J.A., "The Earth's Core and Geomagnetism", (Pergamon Press, Oxford), 1963.
4. RUNCORN, S.K., *Scientific American*, **193** (1955), 152.
5. ——————, *Discovery*, **25** (1964), 8.
6. FEGER, J.A., *Rev. Geophys.*, **2** (1964), 275.
7. ——————, *J. Geophys. Res.*, **69** (1964), 123.
8. CHAPMAN, S., *Terrest. Magnetism, Atmos. Elect.*, **40** (1935), 349.
9. SILSBEE, H.B. & VESTINE, E.H., *ibid.*, **47** (1942), 195.
10. BYRNE, F.N., ELLISON, M.A. & REID, J.H., *Space Sci. Rev.*, **3** (1964), 319.

11. SUBRAMANYAN, R.V., *J. Atmos. Terres. Phys.*, **26** (1964), 1119.

12. NEUGEBAUER, M. & SYNDER, C.W., *Science*, **138** (1962), 1095.

13. STRAHLER, A.N., "Tne Earth Sciences", (Harper and Row, New York), 1963, p. 142.

14. OBAYASHI, T., *J. Geophys. Res.*, **69** (1964), 861.

15. MEAD, G.D. & BEARD, D.B., *ibid*, **69** (1964), 1169.

16. MEAD, G.D., *ibid*, **69** (1964), 1181.

17. NEWTON, H.W., *Monthly Notices of the Roy. Astronom. Soc.*, **103** (1943), 244; 104 (1944), 4.

18. SMITH, H.J. & SMITH, E.V.P., "Solar Flares", (The Macmillan Co., New York) 1963, p. 641.

19. SPRETER, J.R., *I.C.S.U. Rev. Worl l. Sci.*, **6** (1964), 1783.

20. KAWASHIMA, N. & FUKUSHIMA, N., *Planetary Space Sci.*, **12** (1964), 1181.

21. CLADIS, J.B., MILLER, J.D. & BASKETT, J.R., *J. Geophys. Res.*, 69 (1964), 2257.

22. HIRSBERG, J., *ibid.*, **68** (1963), 5917.

23. BONNETTI, A., BRIDGE, H.S., LAZARUS, A.J., ROSSE, B. & SCHERB, F., *ibid.*, **68** (1963), 4017.

24. NISHIDA, A., *ibid.*, **69** (1964), 2243.

25. SMITH, E.J, SONETT., C.P. & DUNGEY, J.W., *ibid.*, **69** (1964), 2669.

26. FUKUSHIMA, N., *Report on Ionosphere and Space Research in Japan*, **16** (1962), 37.

27. FUKUSHIMA, N., *J. Phys. Soc., Japan*, **17** (Suppl. A.-1) (1962), 70.

28. BOBROV, M.S., "Results of Researches of the I.G.Y. Program, Moscow," Section IV, (1) (1961), p. 36.

29. PETERS, W.J. & ENNIS, C.C., *Terrestrial Magnetism*, **31** (1916), 57.

30. ROONEY, W.J., "Terrestrial Magnetism", Edited by Fleming, J.A., (Dovar Publications, New York) 1949, p, 270.

31. WINCKLER, J., *Discovery*, **24** (1963), 21.

32. CHAPMAN, S. & BARTELS, J., "Geomagnetism", (Oxford University Press, London), 1951, p. 173.

33. "Earth Current", *Encyclopedia Britannica*, **7**, 837.

34. GISH, O.H., *The Scientific Monthly*, **43** (1936), 47.

35. CHAPMAN, S. & WHITEHEAD, T.T., *Trans. Phil. Soc.*, **22** (1922), 463.

36. HOWELL, B.F., "Introduction to Geophysics", (McGraw Hill Book Co., New York), 1959, p. 349.

37. JACOBS, J.A., RUSSEL, R.D. & TUZO WILSON, J., "Physics and Geology" (McGraw Hill Book Co., New York) 1959, p. 153.

38. DEFANT, A., "Physical Oceanography, Vol. II" (Pergamon Press, London) 1960, p. 320.

39. STRAHLER, A.N., "The Earth Sciences", (Harper and Row, New York). 1963, p. 92.

40. Roden, R.B., *Geophys, J.*, **8** (1964), 375.

41. HILL, M.N. & MASON, C.S., *Nature*, **195** (1962), 365.

42. PONOMAREY, E.A., *Akad. Nauk S.S.S.R.*, 3rd, Sess. I.G.Y., Program, No. 4, Geomagnetic Disturbances, (1960), 35.

43. ZIGALOV, L.N., *ibid*, (1960), 30.

44. NAGATA, T., *Rep. Ionos. Res.*, **5** (1951), 134.

45. CHAPMAN, S. & BARTELS, J., "Geomagnetism", (Oxford University Press, London), 1951, p. 432.

46. HEILAND, C.A., "Geophysical Exploration", (Prentice Hall, New York), 1940.

47. PARASNIS, D.S., "Principles of Applied Geophysics", (Mathuen and Co. Ltd., London), 1962, p. 64.

48. SATO, M. & MOONEY, H.M., *Geophys.* **25** (1960), 226.

49. WYLLIE, M.R.J., *J. Petrol. Technol.*, **1** (1949), 17.

50. SHRIER, L.L., "Corrosion, Vol. I", (George Newness Ltd., London), 1963, p. 2.

51. HATAKEYAMA, H., "Recent Advances in Atmospheric Electricity" Proceedings of the Second Conference on Atmospheric Electricity, New Hampshire, (Pargamon Press, London), 1958, p. 289.

52. BARTELS, J. "Terrestrial Magnetism and Electricity" edited by Fleming J. A., (Dovar Publications, New York), 1949, p. 430.