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Directions of Rapid Geomagnetic Fluctuations

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Summary

The vectors representing geomagnetic changes over intervals less than one hour tend to be confined to a plane at most temperate latitude stations. In many cases this plane is almost horizontal, but sometimes it is steeply inclined. This appears to be caused by currents induced asymmetrically in the Earth, possibly due to the highly conducting oceans.

1. Introduction

When the geomagnetic field changes, an electromotive force occurs within the Earth. Because the Earth has a finite conductivity, this electromotance gives rise to eddy currents, the magnetic field of which contributes to the total field measured at the Earth's surface.

The field due to eddy currents on a planetary scale has been studied in some detail by an analysis of the low order terms derived from the spherical harmonic analysis of the diurnal variation field. The fact that the greater part of the transient field of internal origin is due to eddy currents was first established by Schuster (1889). He showed that the ratio of, and phase angle difference between, the internal and external parts of the diurnal variation field can be explained approximately by electromagnetic induction in a uniform sphere of finite conductivity. The treatment has since been refined by considering the Earth to consist of a uniformly conducting "core" overlain by a non-conducting crust which in turn is capped with a thin, highly conducting shell (Chapman 1919, Chapman & Whitehead 1922). The shell is added to allow for the oceans. A further refinement was included by Lahiri & Price (1939), who considered the conductivity of the core to increase with depth. The last analysis indicates that the depth to the conducting "core" is about 600 km, and that the conductivity within it increases very rapidly. The conductivity of the core is at least 1 mho/m, which is almost indistinguishable from infinite conductivity. The outer shell appears to have a surface conductivity of 5 000 mho.

All these treatments consider the conductivity of the Earth to depend on depth only, i.e. surfaces of equal conductivity are spheres concentric with the centre of the Earth. On a planetary scale, this is probably essentially true, but on a regional scale irregularities in the crust may be expected to influence the magnetic field, especially the shorter period transient field. This was pointed out by Chapman (Chapman & Bartels 1940, p. 712). Some evidence of these influences has been reported recently from central Europe (Wiese 1954), and from Japan (Rikitake & Yokoyama 1955; contains references to earlier work on the subject by the same authors).

Results from Australian magnetic observatories show characteristics that seem to be connected with eddy currents induced in a non-uniform conductor. The importance of this fact lies in the possibility that the irregularities in conductivity are located not in the crust (in the geological sense), but in the upper part of the mantle. In this case their distribution over the Earth may have considerable geophysical significance.

2. Observed directions of geomagnetic changes

Let us define the geomagnetic difference vector for an interval of time T as the vector difference between the geomagnetic field at one instant and that at an instant T later. If T is a fraction of an hour, the magnitude of the difference vector is usually only a few gammas (1γ equals 10^{-9} weber/m^2), but during disturbed conditions it can be some tens of gammas, and in extreme cases it exceeds 100γ.

At non-polar stations, the directions of the difference vectors for intervals of about 20 minutes are not distributed at random, but generally show a tendency to occur on or near a plane. This plane may be called the "preferred plane", and the great circle in which it meets the unit sphere may be called the "preferred circle". In this paper changes taking a few minutes to one hour are called "rapid fluctuations" to distinguish them from the components of the diurnal variation which have periods of at least three hours.

Rapid geomagnetic fluctuations can be analysed by scaling the total change in the three magnetic elements (ΔH, ΔD, ΔZ) over a number of equal intervals. H, D and Z indicate respectively, horizontal intensity, easterly declination and downward vertical intensity. The direction of the difference vector for a given interval is specified by the two angles θ and ϕ. θ is the angle made by the vector difference with the upward vertical, and ϕ is the angle made by its horizontal projection with magnetic north. Then

$$\tan\theta = (\Delta H + k\Delta D)/\Delta Z$$

and

$$\tan\phi = k\Delta D/\Delta H$$

where

$$k = H/3440$$

if H, ΔH and ΔZ are expressed in gammas and ΔD in minutes of arc, H being the average value of the horizontal intensity.

Directions can be conveniently shown by a polar diagram such as Figure 2a in which polar co-ordinates represent θ and ϕ. The radial scale for θ is chosen so that areas in the circle are proportional to the corresponding areas on unit sphere. In the lower circle (for which $\frac{1}{2}\pi < \theta < \pi$), the radial distance from the centre represents $\pi - \theta$.

Table 1 shows the positions of magnetic observatories from which data are used in this paper. For the Australian stations the changes in each element over selected intervals were scaled from magnetograms. The intervals were selected without regard to time of day or season of the year. Only those intervals for which the magnitude of the difference vector exceeds 20γ were used. The initial epoch of each interval was chosen to coincide with a time mark on the magnetogram (i.e. at some multiple of 5 or 10 minutes after the hour), not necessarily at the beginning of a change in the magnetic field. For Darwin intervals always start on an hour or half-hour.

In general the intervals are not consecutive, although in some cases many were, e.g. for disturbed days at Macquarie Is. Very disturbed periods were avoided because a slight error in the time of beginning or end of the interval would cause a substantial error in the difference vector. Most intervals occur during bays on moderately quiet to moderately disturbed days.

Table 1

Positions of observatories and particulars of data

Observatory	Latitude	Longitude	interval mins.	data scaled from days	during	number of intervals	remarks
	° ′	° ′					
Darwin	12 26 S	130 50 E	30	17	July–Sept. 1957	98	
Alice Springs	23 47 S	133 51 E	20	9	June–July 1957	70	
Watheroo	30 19 S	115 53 E	20	12	Dec. 1951	71	
			60	22	Dec. 1951	58	
Gnangara	31 47 S	115 57 E	20	6	May–July 1957	47	
Toolangi	37 32 S	145 28 E	20	15	Apr.–Dec. 1955	131	
Macquarie Is.	54 30 S	158 57 E	20	4	Oct.–Nov. 1954	110	Dist.
			20	7	Nov.–Dec. 1954	60	Quiet
College	64 52 N	147 50 W					+
Sitka	57 04 N	135 20 W					+
Baldwin	38 47 N	95 10 W					+
Cheltenham	38 44 N	76 50 W					+
Tucson	32 15 N	110 50 W					+
Zi-ka-wei	31 12 N	121 20 E					+
Honolulu	21 18 N	158 06 W					+
San Juan	18 23 N	66 07 W					+
Amberley	43 10 S	172 44 E					+

+ indicates that values were not scaled; only qualitative information was obtained by inspecting published reproductions of magnetograms.

At Darwin northward and southward changes in the field are much more common than eastward or westward changes. To avoid crowding of points on Figure 2b many of the intervals containing principally northward and southward movements were deliberately ignored. Therefore the density of points in Figure 2b does not reflect the frequency of occurrence of directions of difference vectors at Darwin.

Australian Stations (Figure 1). Figures 2 and 3 show, on polar diagrams, the directions of the geomagnetic difference vectors scaled from magnetograms for the Australian stations. No account is taken of the magnitude of the difference vectors except that those less than 20γ have been omitted.

Macquarie Island differs from the other stations in being comparatively close to the auroral zone. On quiet days a downward change in the field is almost always associated with a southerly change, and an upward change with a northerly change. However there is no tendency for the directions to be confined to a plane.

FIG. 1—Locations of Australian stations.

This would be expected if the transient field is due to an overhead current flowing eastwards or westwards in the auroral zone south of the station. However on disturbed days this tendency almost disappears (see Figure 3d). This is probably due to the fact that on these days appreciable current flows to the north of the normal auroral zone, often being to the north of Macquarie Island. At such times the normal tendency is reversed and upward changes can coincide with southerly changes.

At each of the other stations there is a tendency for the difference vectors to lie in a plane. At Alice Springs (Figure 2c) the vectors are all almost horizontal. At Toolangi (Figure 3c) the vectors lie close to a plane which is almost horizontal, but is inclined slightly, the northern edge dipping downward.

At Darwin, Watheroo and Gnangara (Figures 2b, 2d and 3a) the plane containing the difference vectors is inclined quite steeply to the horizontal. At all

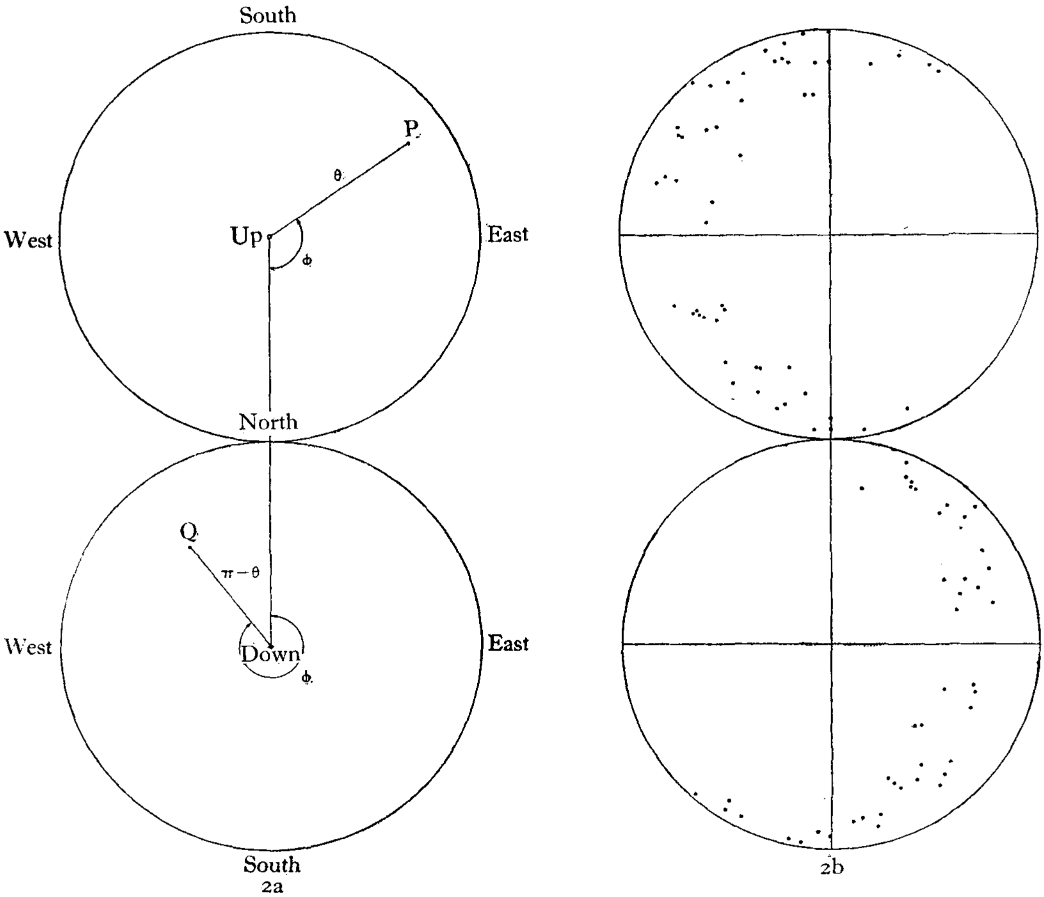


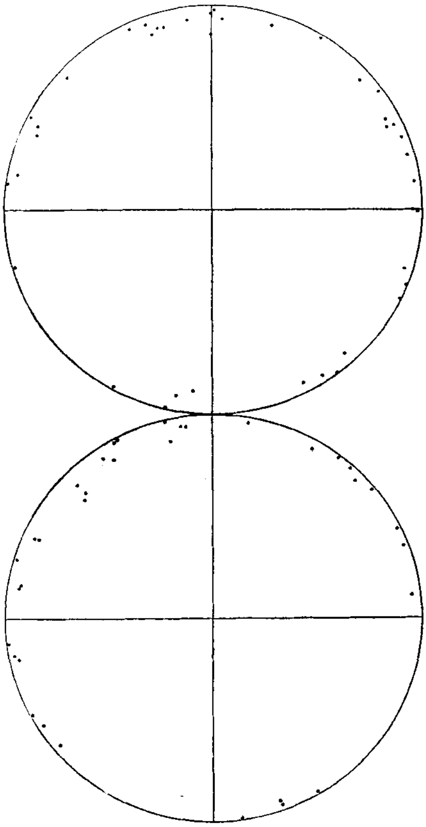
FIG. 2a—Explanation of polar diagrams. P represents a direction in the south-east-up octant, and Q a direction in the north-west-down octant.

FIG. 2b—Polar diagram showing directions of change vectors at Darwin.

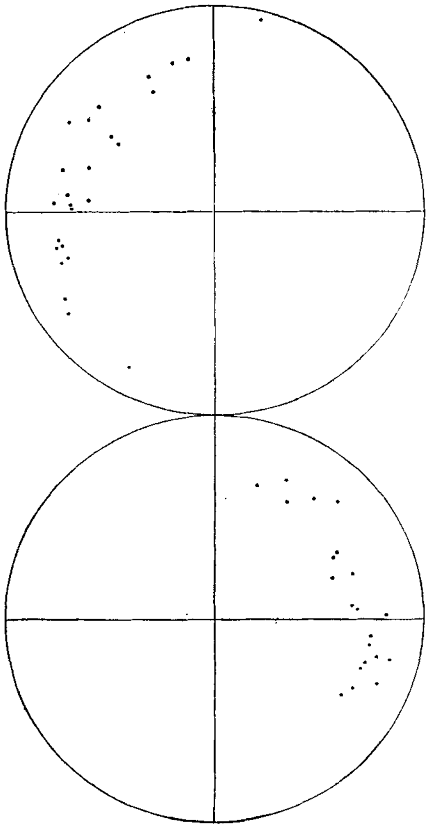
three stations the plane dips downward to the east. This tendency is very strong at Watheroo. In fact only 13 per cent of the vectors lie more than 10° from the plane which has its normal at $\theta = 39°$, $\phi = 67°$. The pattern for Gnangara, which is only 110 miles from Watheroo, is almost identical with that for Watheroo.

All the polar diagrams of Figures 2 and 3 apply to 20 or 30 minute intervals. It is interesting to see how this pattern changes with the length of the interval. Watheroo data have been analysed for longer and shorter periods. For an interval of one hour the vectors tend to lie on the same plane as for 20 minute intervals, but they scatter much more. This is shown in Figure 3b.

It is not convenient to use the same method of analysis for shorter periods, but an idea of the behaviour can be obtained from an analysis of the more rapid variations recorded by a rapid run magnetograph, with a time scale of 18 cm per hour. These often take the form of more or less sinusoidal variations with periods between 1 and 4 min. It is found that variations in D and Z are in phase to within a quarter of a minute. The ratio of the amplitude of the Z wave to that of the D wave (considered as a variation in the magnetic east component) has an average



2c



2d

Fig. 2c—Polar diagram showing directions of change vectors at Alice Springs.

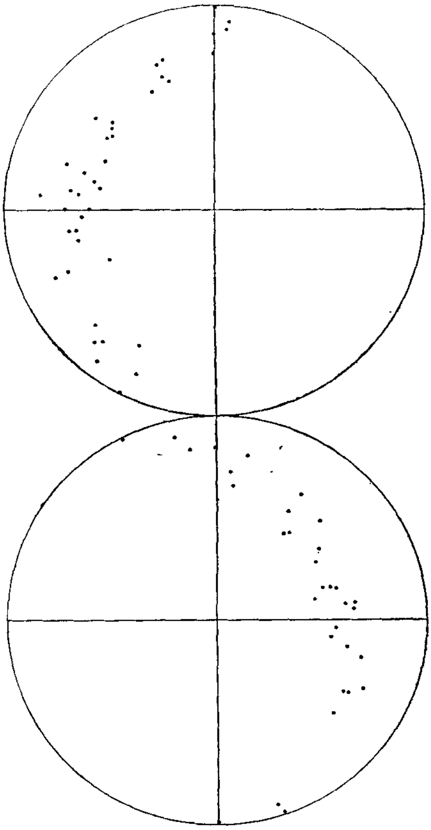
Fig. 2d—Polar diagram showing directions of change vectors at Gnangara.

value 0·5, with a tendency to become smaller for the shorter periods. The corresponding ratio for 20 min periods is 0·8.

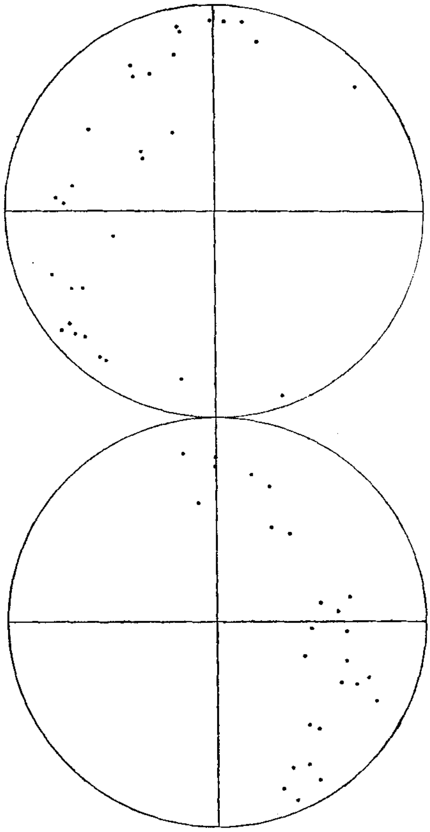
It appears, then, that much the same thing happens for more rapid fluctuations as for fluctuations of about 20 min period, except that the preferred plane tends towards the horizontal for shorter periods.

Non-Australian stations. If the difference vectors for short intervals are confined to the horizontal plane, this is shown in the magnetograms by the absence of rapid variations in Z. The behaviour at Watheroo or Darwin is characterized by a correlation between variations in D and Z. Since the preferred circle at Watheroo is inclined about an axis running NNW and SSE, and not N and S, the correlation is not perfect. In fact it can be reversed when the difference vectors are directed almost north or south. This is the case for the few points in Figure 3a in the south-east-up and north-west-down octants.

In this way some qualitative idea of the behaviour of the difference vectors for a station can be obtained simply by looking at typical magnetograms. The following notes have been made from an inspection of reproductions of magnetograms published in the references mentioned:—



3a



3b

FIG. 3a—Polar diagram showing directions of change vectors at Watheroo for 20 minute intervals.

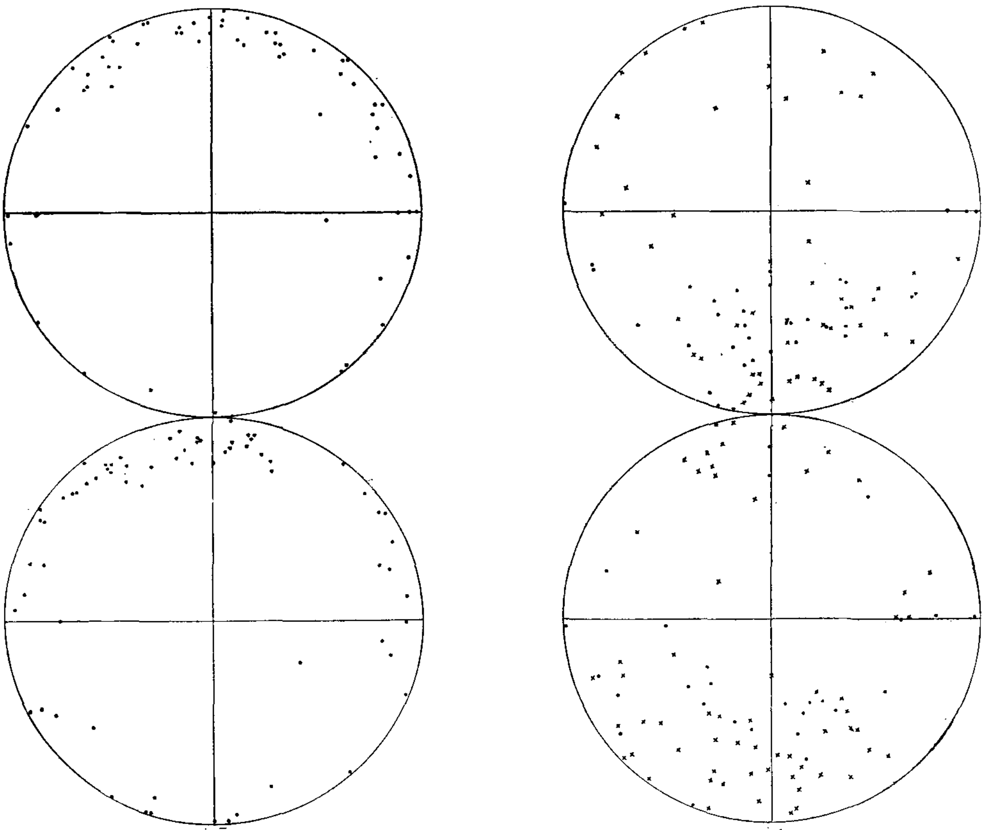
FIG. 3b—Polar diagram showing directions of change vectors at Watheroo for 60 minute intervals.

Amberley, New Zealand; (N.Z.D.S.I.R. 1940) there is a positive correlation between downward movement of Z and westward movement of D. The correlation is not perfect, and appears to be influenced by movements in H. The ratio $\Delta Z/\Delta Y$ is about 0·65 (cf. 0·8 at Watheroo). The pattern is generally similar to that at Watheroo, but the preferred plane is tilted in the opposite direction, and not quite as far from the horizontal.

San Juan, Puerto Rico (U.S. Department of Commerce 1953a); Short time changes in Z are small. There is a slight positive correlation between downward changes and westward changes, but the ratio $\Delta Z/\Delta Y$ is only about 0·18, i.e. the preferred circle is inclined at some 10° to the horizontal. The pattern is similar to that for Toolangi, but with the preferred circle tilted up towards the east.

Tucson, Arizona, U.S.A. (U.S. Department of Commerce 1955a). Rapid movements in *Z* do not occur at this station. The difference vector is confined very closely to the horizontal plane (except for comparatively long period variations such as diurnal variation). The pattern of difference vectors is similar to that for Alice Springs.

College, Alaska (U.S. Department of Commerce 1955b). The *Z* trace moves violently, sometimes being correlated with movements in *D*, sometimes with those in *H*, but more often independently of both. This might be expected for a station so close to the Auroral Zone.



3c 3d

FIG. 3c—Polar diagram showing directions of change vectors at Toolangi.

FIG. 3d—Polar diagram showing directions of change vectors at Macquarie Island. Quiet days are indicated by dots, disturbed days by crosses.

Sitka, Alaska (U.S. Department of Commerce 1954). This station is much the same as College. During the quieter periods there is a tendency for upward movements to correlate with southerly movements, which is the counterpart of the pattern for Macquarie Island.

Cheltenham, Maryland U.S.A. (U.S. Department of Commerce 1952). There is a tendency, although not a very strong one for difference vectors to lie on a plane inclined upward to the north west by about 10°.

Baldwin, Kansas, U.S.A. (Hazard 1909). At times a fairly good positive correlation between easterly and downward movement is shown, the ratio $\Delta Z/\Delta Y$ being about 0·5. However, often no correlation at all is evident. Rapid movements in Z occur although they are smaller than in the other elements. This station is clearly not the same type as are Alice Springs and Tucson.

Honolulu, Hawaii (U.S. Department of Commerce 1953b). There is a fairly definite positive correlation between downward and eastward movements, with $\Delta Z/\Delta Y$ about 0·7. This applies to movements occupying a major fraction of an hour. The situation is complicated by another correlation, which appears to apply only to very rapid movements such as sudden commencements. This is a positive correlation between northward and downward movements. A good example occurs just after 22h (local time) on 1950 April 12. The apparent time constant of recovery in Z is only one or two minutes.

Zi-ka-wei, China (Zi-ka-wei 1905). Rapid movements in Z are small, being only about 1/10 of those in H. Upward movements generally accompany northward movements.

A good idea of the behaviour at European stations can be obtained from a paper by Wiese (1954), at least for a particular instance. Two maps are presented, each showing synoptically the changes in Z at a number of European observatories. There are two centres of Z-movement. In the northern one, which includes Rude Skov, Wingst, and Lerwick there is a positive correlation between downward and eastward movements. In the southern region, which includes Niemegk, Pruhonce and (possibly) Fuerstenfeldbruck, there is a positive correlation between upward and eastward movements. The line along which changes in Z are small lies close to Castellaccio, Chambon-la-forêt and Potsdam. In western Europe, downward movements accompany eastward movements, but become smaller towards the west.

A similar summary of Japanese stations is given by Rikitake & Yokoyama (1955). In Honshu, downward movements are accompanied by northward movements. The ratio $\Delta Z/\Delta H$ is about 0·6 in the south-east of the island, but decreases rapidly in a north-west direction, being almost zero along the north-west coast.

In both Japan and Europe the network of stations is sufficiently dense that some kind of regional distribution of the behaviour of the vertical component can be deduced. Maps of these regions showing this distribution give the impression that there exist anomalies within which rapid changes in Z are positively correlated with changes in some horizontal direction, and outside which rapid changes in Z are small. This would lead us to conclude that Watheroo, Darwin, Amberley, possibly Baldwin and Honolulu are on or near such anomalies. In view of the total number of observations considered here, it seems probable that such anomalies are quite common.

3. Deductions from Watheroo data

Both Wiese (1954) and the Japanese workers (Rikitake & Yokoyama 1955) attributed the intensity of vertical intensity fluctuations to the effects of eddy currents beneath the Earth's surface. In fact they were able to separate the transient field into parts due to underground and overhead sources. This is impossible in the case of an isolated station. However it seems safe to attribute the behaviour at Australian stations to the same cause.

Let us concentrate on Watheroo, since this shows a closer correlation between the elements than do other stations. To explain the behaviour shown in Figure 3a by the form of the external field only, would require that the north or south flowing currents are confined to the east of Watheroo at all times of the day and seasons of the year. This is quite untenable. We must seek an explanation in the form of the internal field.

The behaviour can be summarized by saying that the total field cannot change rapidly in a direction north 67° east 51° up. This would result if the plane normal to this direction were the boundary of a semi-infinite body of considerable conductivity. This is clearly a physical impossibility, but the same effect may be caused by some physically possible configuration of conductivity underground. It would be interesting to know the time constant of the system of eddy currents causing the behaviour of the difference vectors at Watheroo. It is impossible to derive any precise information on this without knowing more about the primary field. However it is significant that the distribution of difference vectors for 60 minute intervals is not greatly different from that for 20 minute intervals. This suggests that the time constant of the eddy currents is at least of the order of one hour, and possibly greater. If, for instance, the primary field is nearly horizontal and the time constant of the eddy currents is considerably less than one hour, the points of Figure 3b should lie generally closer to the horizontal than those of Figure 2d.

It is hard to imagine any crustal feature with sufficient size and conductivity to support a system of eddy currents with a time constant as long as one hour. The only feature likely to have these properties is an ocean. It is important to try to decide whether, in fact, the oceans are the locations of the eddy currents controlling the directions of the difference vectors.

4. Effect of the oceans

The oceans can be considered as an irregularly shaped shell on the surface of the Earth, of infinitesimal thickness and of surface conductivity proportional to the depth. They have sufficient conductivity to influence greatly the direction of rapid fluctuations in the geomagnetic field. In fact Lahiri & Price (1939) showed that an ocean covering the whole Earth to a uniform depth of one kilometre would have an appreciable effect on the comparatively slowly varying diurnal variation field, although its effect on the still more slowly varying disturbance field is negligible.

It is very difficult to compute even a reasonable approximation to the effect of an actual ocean on the magnetic field at a nearby station. The difficulty is that almost any model sufficiently simple to yield numerical results must be greatly idealized. Probably the simplest model would be that consisting of a uniform ambient field and a flat semi-infinite ocean occupying half of the $Z = 0$ plane. It can be shown, however (Price 1950), that such a problem is indeterminate. Either the conductor or the imposed field must be considered to be of finite extent.

If the conductor is a finite horizontal lamina, a purely horizontal ambient field will not induce eddy currents, but only cause a separation of charge. When the dimensions of the conductor are sufficiently small that the ambient field can be considered uniform, some idea of the expected behaviour can be obtained from the treatment of Ashour (1950).

The Indian Ocean is about 3 000 km in radius and has an average depth of 4 km and a conductivity of 3 mho/m (Sverdrup, Johnson & Fleming 1942, p. 15 and 72). It would therefore have a time constant of 3 h if its depth were uniform. Considering irregularities in depth, and the fact that the primary field is not uniform over such an area, one hour is not an unreasonable value for the effective time constant.

When the dimensions of the ocean are large compared to the extent of the field, it may be considered as an infinite conducting sheet, and the method of Maxwell (1904, p. 294) may be applied. In this case, the behaviour depends on the form of the source of the primary field and its location. If the ocean is assumed to be 3 km deep, the eddy currents due to a sudden change in an overhead dipole at a height of 100 km decay to $1/e$ of their initial value after 5 minutes, those due to a line current at a height of 100 km in 23 minutes, and those due to a strip of uniform current density 1 000 km wide in 105 minutes. According to this theory, those from an infinite sheet of current should persist indefinitely. This is one aspect of the indeterminacy mentioned above.

Solutions in which the ambient field has a periodic structure have been studied by Price (1949), but the solutions depend critically on the length periodicity, and it is difficult to estimate this in the geomagnetic case.

It is not unlikely that the effect of a large ocean, at a point near its edge, will be to deflect the magnetic field upward if it is directed towards the ocean and downward if it is directed towards the land. This is the effect observed at Watheroo, in fact the direction of slope of the preferred plane is perpendicular to the coastline within a few degrees. Darwin has a smaller body of water to the west of it and has generally the same kind of behaviour (although the nearest deep water is the Banda Sea 300 miles to the north west). Alice Springs, far away from any ocean has almost no rapid change in Z. Toolangi has only small rapid changes in Z but it is reasonable to regard this as an inland station, for it is at least 250 miles from the nearest 100 fathom line. The effect of the comparatively shallow water over a continental shelf can be neglected compared to that of the deep ocean when considering intervals of the order of 20 minutes.

The behaviour of rapid fluctuations in other parts of the world, however, does not always agree with that to be expected if eddy currents in the oceans are the controlling influence. For instance the anomalous regions in Europe (Wiese 1954) have no apparent connections with coastlines or the edges of continental shelves. However it is interesting to note the situation at Coimbra in Figure 3 of that reference. The primary field is directed to the west, and a vertically upward induced field coincides with it. Coimbra is close to the western edge of the continental shelf.

The Japanese data are not quite what would be expected from eddy currents in the ocean (Rikitake & Yokoyama 1955 etc.) although it may be significant that the region where $\Delta Z/\Delta H$ is greatest is along the coastline which runs more nearly east–west than any other in the Japanese Islands.

Let us summarize the stations mentioned in Section 2; the direction in brackets below is that associated with an upward change in Z.

Strong Z movement	*Slight Z movement*	*No Z movement*	*Irregular*
Watheroo (W)	Toolangi (S)	Alice Springs	College
Gnangara (W)	San Juan (E)	Tucson	Sitka
Amberley (E)	Cheltenham (NW)		Macquarie Is.
Darwin (W)	Zi-ka-wei (N)		
Kakioka (S)			
Baldwin (W)			
Honolulu (W)			

Directions associated with the upward movements are roughly those to the nearest large ocean in the case of the first five of the first group and the first two of the second group. Both of the stations where Z is almost constant (over short time intervals) are well inland. However many features of this table cannot be so explained. For instance Darwin is several hundred miles from an ocean of appreciable depth and so should be influenced much less than Watheroo. The effect at Cheltenham is in the wrong direction, and the Pacific ocean is east of Zi-ka-wei (ignoring the continental shelf which extends to the Ryukyu Islands) not north of it. Baldwin is even further inland than Tucson. It is difficult to explain either of the effects observed at Honolulu by the presence of the ocean; in fact rapid changes in Z would not be expected to occur at all there, considering the extent of the surrounding ocean.

The question of whether the direction of rapid geomagnetic fluctuations are controlled by eddy currents flowing in the oceans, must be left unanswered for the moment. There seems to be little hope that calculations can be made sufficiently exact to settle the question. The best approach appears to be the setting up of temporary recording stations at well chosen locations, taking into account the edges of continental shelves rather than coast lines.

5. Non-oceanic causes of directional effects

The directional asymmetry of rapid geomagnetic fluctuations in many places requires the conductivity to be non-uniform in a horizontal plane below the surface of the Earth. If it can be shown that the oceans cannot explain the geographical distribution of these effects, we must look for a region of non-uniform conductivity in the upper part of the mantle. The Earth as a whole behaves as if there is a very rapid increase of conductivity to a value of at least 1 mho/m at a depth of the order of 600 km.

Two possibilities exist. Either there are conducting bodies above the 600 km level, or the boundary of the conducting "core" is not spherical, 600 km being an effective depth.

The simplest conducting body to consider is a sphere. In a uniform ambient field, this is equivalent to a dipole situated at the centre of the sphere and anti-parallel to the ambient field.

The dipole equivalent to the Kakioka anomaly has been calculated (Rikitake, Yokoyama & Hishiyama 1953). It turns out to be at a depth of about 150 km. The authors have assumed that it is located beneath a point north of Kakioka, in which case the sense of the dipole is parallel to the ambient field. This corresponds to a sphere of negative conductivity, or less conductivity than the surrounding material. If the dipole is placed south of Kakioka, the corresponding sphere would have a conductivity greater than the surrounding medium.

It is interesting to see what the maximum effect of a buried sphere is. The ambient field can be considered to be uniform. This problem is dealt with in text books (e.g. Smythe 1950 p. 397). If the ambient field is horizontally northwards and the surface of the ground is tangent to the sphere, the resultant field is inclined upward south of the sphere and downward north of the sphere. The maximum inclination of the resultant field is $21^\circ.5$ at a distance equal to $0.62\,R$ (R being the radius of the sphere).

The distribution of vertical intensity over a buried sphere would be something like that shown in Figure 2 of the paper by Wiese (1954). The centres of the inclination maxima are about 830 km apart, which indicates a depth of the equivalent dipole of 670 km. However this distribution apparently occurs with an eastward ambient field, so is probably not associated with an underground conducting sphere.

It is worth noting that the maximum inclination of the resultant field ($21^\circ.5$) is considerably less than that observed at Watheroo (40°).

6. Conclusion

The vectors representing the change experienced by the geomagnetic field during short (about 20 minute) intervals have a strong tendency to lie on a plane at non-polar stations. At some places this plane is inclined to the horizontal by as much as 40°. This phenomenon is almost certainly due to some form of electromagnetic damping which inhibits rapid changes in the field in a certain direction (normal to the preferred plane).

The eddy currents causing this damping must flow either in the oceans or quite deep in the Earth, probably in the upper part of the mantle. If the latter is the case, a study of the directions of geomagnetic vectors could become a powerful method of exploring the upper part of the mantle, which in turn may throw some light on the large scale tectonic systems of the Earth. At present not enough is known of the regional distribution of the effect, nor of the theoretical interpretation. With modern geomagnetic recording instruments the collection of data should not be difficult. The theory, however, is complicated. It may be necessary to use model experiments to solve certain problems associated with irregularly shaped conductors.

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