ELECTROMAGNETIC INDUCTION IN THE OCEANS AND INFERENCES ON THE CONSTITUTION OF THE EARTH

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Abstract. This review concentrates on the uncertainties surrounding interpretation of sea floor impedance measurements. Oceanic motionally induced signals prove to be 'noise' generators which limit the low frequency range of usable signals. At high frequencies the screening by a thick ocean and by the sediments and rocks of layer two present insuperable barriers to detection of poorly conducting rocks in the depth range 2 to 30 km below the sea bottom by usual methods. The conductivity of this layer is important for the interpretation of all ocean impedance measurements because it determines the width of a boundary zone at the continental margins of the ocean. If the conductivity is as low as 10^{-5} S/m the bounding zone begins to fill the whole ocean. It is suggested that use of an active, man-made EM source can provide signals at the sea bottom capable of resolving the uncertainty.

1. Introduction

There are two general reviews (Cox *et al.*, 1971; Bullard and Parker, 1971) which describe features of electromagnetic induction in the oceans relevant to deep sounding of the electrical conductivity within the earth below the ocean. Although these reviews are old, they bring out most of the difficulties of measuring and interpreting electromagnetic (EM) fields within the ocean. Mainly they need to be supplemented with a description of new apparatus and a list of measurements made since that time. Part of this task has been carried out by Bennett and Filloux (1975). The list is short because the techniques of measuring at sea have only just reached the state of development which is making possible EM measurements on a regular basis. The number of new measurements is increasing rapidly at present.

The two reviews mentioned above are inconsistent in one important detail. Cox *et al.* have assumed that the ocean is in effective conductive contact with the highly conductive, deeper parts of the earth, while Bullard and Parker have assumed that the oceans are effectively insulated. The uncertainty of which model is more nearly correct continues to this day and the different viewpoints of the two reviews reflect a discrepancy which has serious implications for interpretation of EM soundings.

If the oceans are insulated from deep underlying conductive matter, then the ordinary 'magnetotelluric' interpretation of EM impedance methods will be totally misleading because the electric current flow in the ocean (impeded by poorly conducting continental boundaries) must be greatly deflected, and generally reduced in intensity below the value it would have if the ocean were extended without boundaries. On the other hand, if the oceans are underlain by conductive enough rocks, electric currents flowing in the ocean in

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response to EM driving will be able to leave the ocean through the sea bed over a near shore boundary zone (of greater or less extent depending on the underlying conductivity). Within the zone the magnetotelluric impedance and its isotropy will be greatly affected by the continental interruption of current flow, but seaward of the zone the impedance will be scarcely affected and the usual 'one-dimensional' relation between impedance and directly underlying conductivity will become an adequate interpretational tool.

In this review I shall return to this uncertainty with some proposals for its resolution.

There are only a few physical measurements which can give us remote sounding information on the state and history of the earth's interior. Let us enumerate them:

(1) Rotation of the earth and its fluctuations. This provides information on moments of inertia of the earth.

(2) The gravity field. Although fundamentally non-unique in localizability, its observation constrains models of density and the strength of rocks in resisting deviatoric stresses within the earth.

(3) Distortions of the earth's surface. The past history of sea levels, the slow rebound of the crust after relief from glacial loading and the creep along faults provides insight into the anelastic behavior of the lithosphere. The rapid distortions, i.e., tidal, earth oscillations, and seismic vibrations provide increasingly detailed knowledge of the elastic properties and density of the earth's interior. Information on the rheological behavior is inferred from layers of low seismic velocity and from absorption of seismic waves.

(4) The heat flux through the earth's crust provides constraints on the temperature structure of the crust and upper mantle.

(5) Direct geochemical study of samples drilled from the interior, or carried up by tectonic or volcanic processes provides radioactive, chemical, crystallographic and pressure-temperature models for local regions of the uppermost layers of the earth. Speculation, based on hypothetical analogies with the composition of solar, meteoric and lunar material extends these models to the center of the earth.

(6) Magnetization of rocks. This has provided a wealth of information including constraints on the nature of the earth's core and a demonstration of rifting of the sea floor and drifting of continents. In conjunction with dating of rocks by biological and radiological methods, it has provided a time scale for evolution of the crust.

(7) Electromagnetic fluctuations. These can provide the conductivity structure within the earth; in principle the conductivity structure could be determined uniquely if enough observations could be made covering a wide enough band of frequencies (Bailey, 1970).

The purpose of enumerating these measurable physical variables is to illustrate how few they are and by inference how important it is to exploit them all. Among these broad classes there is probably no redundancy. For example, both elastic parameters and electrical conductivity depend on composition, pressure, and temperature. It is known however, that their dependencies are very different. When the needed measurements are available we can represent the multidimensional aspects of the interior of the earth along a few projections which correspond to the capability of the particular quantities measured. The projections are all different.

Measuring the electromagnetic impedances (or their equivalents) in the ocean is important because the ocean covers the majority of the planet. Some of the geophysical problems which can be examined by ocean EM measurements are the following:

(1) What is the structure of electrical conductivity in the vertical? For a proper global average one needs oceanic observations even more than continental ones. Seismic evidence suggests that major, pressure induced phase changes occur within the mantle. An olivine to spinel transition is believed to be a worldwide feature at a depth of 430 km. Since magnesium silicate compressed to spinel structure has greatly increased conductivity, this transition should be recognizable electrically. The latest global conductivity structure estimates are derived from a heterogeneous collection of magnetic variation observations at various land stations (Banks, 1969; Parker, 1970). It seems important to extend these observations to the sea bed to avoid possible systematic effects of continents.

(2) How does the electrical conductivity structure under continents differ from that under the oceans? According to modern ideas about plate motions, the sea floor tectonic processes consist mainly of horizontal motions – plates moving laterally on a shallow asthenosphere away from spreading centers – together with deep vertical motions in narrow subduction zones. Other vertical motions are more speculative. Thus some workers propose vertical movements from the core of the earth almost to the crust to explain mountain building processes (Artyuskov, 1972); others suggest filamentous convection leading to hot spots in the crust. Seismic evidence that mantle structures well below the asthenosphere are heterogeneous, with systematic differences between oceans and continental shields has been emphasized by Jordan (1978). The evidence is controversial (Okal, 1978). It would be especially useful to have reliable electrical conductivity information to complement the seismic data.

(3) What are the internal structures associated with spreading ridges, transform faults, subduction zones, island arcs, back arc basins, active and passive margins of continents? What is the variation of asthenospheric depth with age and location? These topics list some of the subjects which are becoming open to examination by EM methods and should be actively pursued in conjunction with modern methods.

2. Recent Impedance Measurements

The review of Bennett and Filloux (1975) can be brought up to date by a summary of recent developments. More details are available in reports by Filloux (1977a, b).

Direct observations of both electric and magnetic fluctuations at the sea bed have been made increasingly convenient by instrumental developments. Filloux (1974) describes a method of electrical recording with short span instruments in which errors due to electrode drift are removed by 'chopping' the salt bridges which conduct oceanic signals to the electrodes. An early version of this instrument was used in the MODE oceanographic experiment together with sea bottom magnetometers by Von Herzen. The measurements were conducted simultaneously with electric and magnetic measurements on adjacent

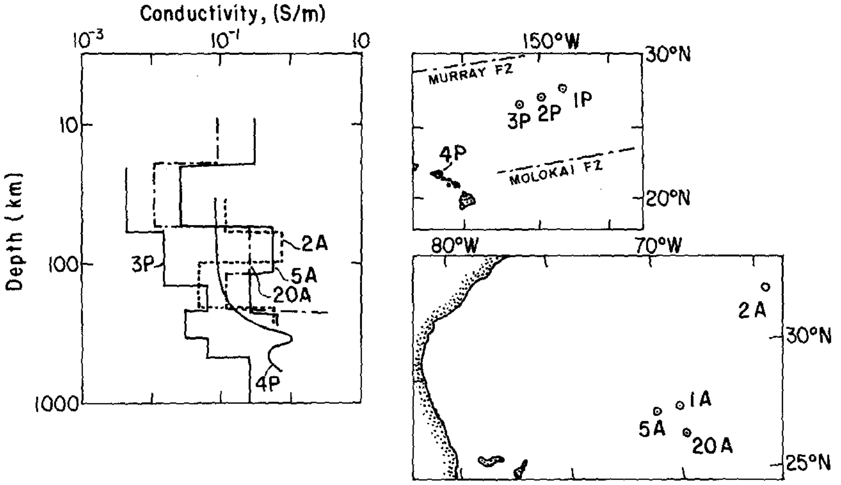

Fig. 1. Conductivity profiles derived from Atlantic and mid Pacific impedance measurements. Inset shows locations where observations were made. In the Atlantic 2A is on Bermuda. Numerals on the impedance profiles identify the corresponding locations.

islands by Larsen and Gough. Later versions of Filloux's instruments, including magnetometers have been used by him to measure the electromagnetic impedance of the deep Pacific floor.

These recent Atlantic and Pacific measurements are discordant: the Atlantic ocean lithosphere appears to be more conducting than the Pacific at depths of 70–100 km (Figure 1).

In the Atlantic the first analysis was made by Poehls and Von Herzen (1976). They used differences between the magnetic field on Bermuda and on the deep seafloor in effect to infer the electric currents in the ocean and thereby to infer the impedance at the seafloor. The method suffers from uncertainty engendered by the poorly known effects of the island and on spatial inhomogeneity in the incident fields. The direct approach of using the seafloor EM fields and also the fields recorded on Bermuda is reported by Cox *et al.* (1977). These results (also shown in Figure 1) provide fuller information. While they disagree in detail with Poehls and Von Herzen, they emphasize the highly conducting structure of the Atlantic upper mantle.

Electromagnetic impedance measurements on the floor of the mid-Pacific are reported by Filloux (1977a, b, c). The lower conductivity, which his analyses require, is supported by observation on the Hawaiian Islands (Larsen, 1975; Klein, 1978). Whether the apparent difference between the upper mantle beneath the Atlantic and Pacific is a fundamental and large-scale feature or merely a result of the particular choice of observation sites remains to be learned. It could also be an artifact of imperfect instrumental calibrations and errors of timing although this explanation seems unlikely because of the agreement between multiple and independent instruments used in both oceans. Another possibility is a systematic effect of the varying horizontal scale of overhead ionospheric sources.

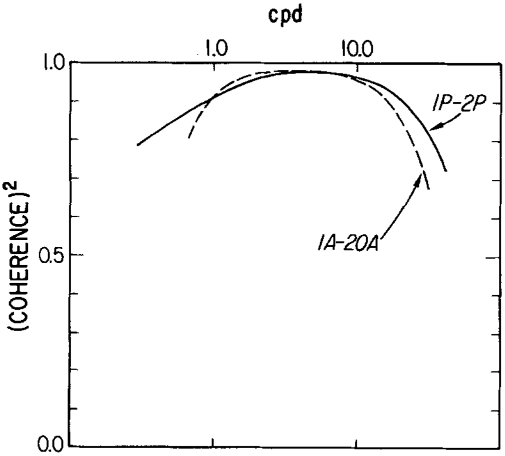

Fig. 2. Typical squared coherences observed between pairs of seafloor electric observation stations. The east component of the electric fields has been compared for stations identified by numerals on the map of Figure 1.

Since the Atlantic observations were conducted much closer to the auroral zone than the Pacific, one may reasonably expect the former to have been exposed to smaller scale sources than the latter. The dip latitude of the MODE area in the Atlantic is 43°; the Pacific observations extend over a range from 20° to 30°. This feature will lead to estimates of conductivity systematically too high under the Atlantic because no allowance was made for the source scale.

The limited horizontal scale of sources should lead to a decrease in spatial coherence of the seafloor fields. In Figure 2, we illustrate the effect by a comparison of Atlantic and Pacific coherences of the electric field. At both locations the coherence diminishes with increasing frequency. In agreement with expectations, the fall of coherence is more rapid in the Atlantic (for stations separated horizontally by 100 km) than in the Pacific even at a larger separation. Some of the loss of coherence is caused by imperfect relative timing between the independent recording systems; another part could be caused by the induction by water motions of small horizontal scale.

In the frequency range above 1 cpd, these motions are probably mainly internal gravity waves. According to Garrett and Munk (1975) such waves are of uniform intensity within a factor of two throughout the deeper parts of the ocean wherever they have been surveyed. Furthermore, internal waves should make a rather unimportant contribution to the measured fields (see below). Hence we tentatively ascribe most of the contrast of coherences in the Atlantic and Pacific to the smaller scale of overhead Atlantic ionospheric sources relative to the Pacific.

A fall of coherence squared to 0.5 for stations separated by 100 km is consistent with the existence of source horizontal wave numbers k extending from small values up to $k_0 = (100\ \mathrm{km})^{-1}$. In the Atlantic the coherence squared of 0.5 (100 km separation) occurs at $f_0 = 2.4$ cph. The estimation of conductivity at shallow depths in the earth will be seriously affected only for conductivities comparable with $k_0^2/(2\pi f_0 \mu) = 3 \times 10^{-3}$ S/m.

The upper level conductivities shown for the Atlantic in Figure 1 are well above this figure and therefore probably not greatly affected. On the other hand, conductivities at great depth are ascertained primarily by the impedance measured at frequencies much lower than f_0 and here the coherence is high. On this basis we tentatively regard the Atlantic measurements as free from serious distortions even though the source fields are of rather small horizontal scale. It is clear, however, that further analysis and measurements of the source field variability are needed before the results can be accepted without reservations.

3. Some Characteristics of Oceanic EM Measurements

The measurements have technical difficulties because of the difficulty of emplacing and operating unattended instruments in stable but retrievable positions in the ocean. (This requires generally that they be placed on the sea floor, but some attempts have been made to moor them in mid-water or at the surface.) At the same time there are advantages and disadvantages for interpreting measurements in the ocean. Let us concentrate on the difficulties first.

3.1. INFLUENCE OF MODAL STRUCTURE

EM deep soundings can be carried out with magnetometers alone. Some recent work has been carried out by Law (1978) and Law and Greenhouse (1978). For quantitative results we must deduce the spatial scale of the EM fields. A more powerful technique combines electric and magnetic measurements. The latter are usually analyzed in terms of the sea floor impedance tensor, that is the linear vector function which relates the horizontal components of the electric and magnetic fluctuations.

In a horizontally layered medium all field distributions can be classified into independent modes TE and TM. The transverse E mode has the electric field strictly horizontal while the magnetic field vibrates in various directions but constrained in the vertical plane which is normal to E (if the conductivity is anisotropic, somewhat more complicated conditions can occur). In the transverse magnetic mode, the magnetic field is horizontal and E vibrates in the vertical plane. The relationship between the electromagnetic impedance at the sea floor to the conductivity structure below can be very different for the two modes, and even can vary for a single mode if the horizontal wavelength of the fields changes.

On the other hand, if the horizontal wavelength is sufficiently large, the impedance of both modes tends to the same limit, that for 'normal incidence'. These facts have been illustrated by model calculations of various authors (Price, 1962; Srivastava, 1966; Cox *et al.* 1971). Two results emerge from these model studies: (1) Interpretation of impedance in terms of the underlying conductivity is, in general, impossible unless there is some knowledge of the horizontal scale of the generated fields. (2) Detailed knowledge of scale for the TE mode is far less important than for the TM mode provided the scales are sufficiently large.

We note that the actual impedance is larger than the normal incidence impedance for the TM mode. The degree of increase depends critically upon the minimum conductivity which isolates the ocean from deep underlying structures.

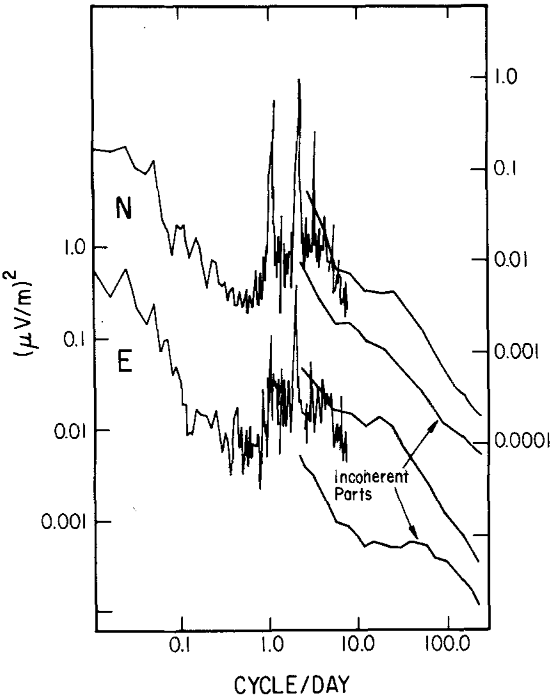

Fig. 3. The spectra of horizontal electric components N and E on the sea floor at MODE station 1 (28°N, 69°W, 5500 m water depth). The graphs show the spectral density times frequency plotted as functions of frequency. The broad dip in each spectrum separates the low frequency parts generated by mesoscale eddy motion from higher frequencies generated mainly by the upper atmosphere. Prominent peaks due to the solar daily variation are evident. The smoothed spectra extending from 2 to 200 cpd were completed from 20 days segments of the entire 3 months record (April through June 1973) used for the lower frequency analysis. The electric field is only partly coherent with the sea floor magnetic record as shown.

3.2. INTERFERENCE BY LOW FREQUENCY WATER CURRENTS

Most of the low frequency fields (say less than 2 cph) generated in and above the atmosphere and which reach the sea bottom are of the TE mode. This is shown by the fact that the corresponding *vertical* electric field in the atmosphere just above the sea surface is observed to be small (Cox *et al.*, 1971) whereas the TM mode would produce very large vertical E in dielectric media. Furthermore, in regions which are far from the auroral or equatorial electrojets, it is reasonable to expect large scale EM fields. This circumstance is favourable for ready interpretation of the EM impedance in terms of the basement conductivity. But there are fields in the ocean which are of small scale and of the TM mode. They act as a noise source which tends to obscure the desired signals. The major source of TM and short wavelength TE modes in the ocean is induction from water currents. The horizontally nondivergent flows which characterize the barotropic part of the steady state and mesoscale eddies in the ocean produce predominantly TM mode fields (Appendix). The mesoscale eddies, with typical horizontal scales near 50 km and frequencies which extend downwards from 1/2 cpd, are particularly troublesome because they can completely dominate the electric field spectrum (Figure 3). The observations summarized in this figure were made in the western Atlantic (28°N) where mesoscale activity is high.

The electric fields induced by water motions can be related to the water currents in this case because the observations were made as part of a program in physical oceanography called Mid Ocean Dynamic Experiment (MODE). Figure 4 shows a comparison between the electric fields observed at the sea floor (low pass filtered to remove 1 cpd and above) with the horizontal components of $U \times F$. Here U is the horizontal velocity at mid depth measured with neutral buoyant floats and F is the geomagnetic induction. According to the results shown in the Appendix, the electric field would be reduced in magnitude below $-U \times F$ if there were appreciable leakage of electric current into the sea floor. The observations suggest that the leakage is negligible and therefore the effective conductivity is less than a certain amount which depends on the ratio of ocean depth to horizontal scale of the water current flow. (The limit is about 0.25 S/m).

The calculation of this limit is only possible because the horizontal scale of the eddies in the Atlantic was measured (at a cost on the order of 10^7 dollars). It is unlikely to be a frequently used method! If at some future time it should become possible to measure the magnetic as well as electric fields of mesoscale eddies and at the same time their horizontal structure, then a more exacting limit will be possible. The magnetic fields will be a measure of the electric current flow, hence of the leakage through the sea floor.

There is evidence that mesoscale motions are most intense near the western boundary of the oceans (Bernstein and White, 1977 and Figure 5; Wyrtki *et al.*, 1976). Therefore deep EM impedance soundings, which utilize low frequency signals, will be much more limited in these noisy regions.

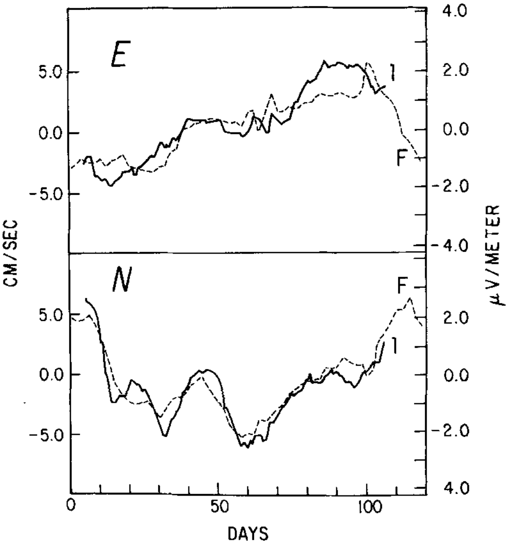

Fig. 4. The sea floor electric field (low pass filtered) is compared here with the EMF $-u_b \times F$ generated by barotropic flow. The flow was estimated by the motion of neutral buoyant floats at 1500 m depths (Freeland and Gould, 1976), where baroclinic motion is small. F is from the float data; 1 is the electric field at Station 1.

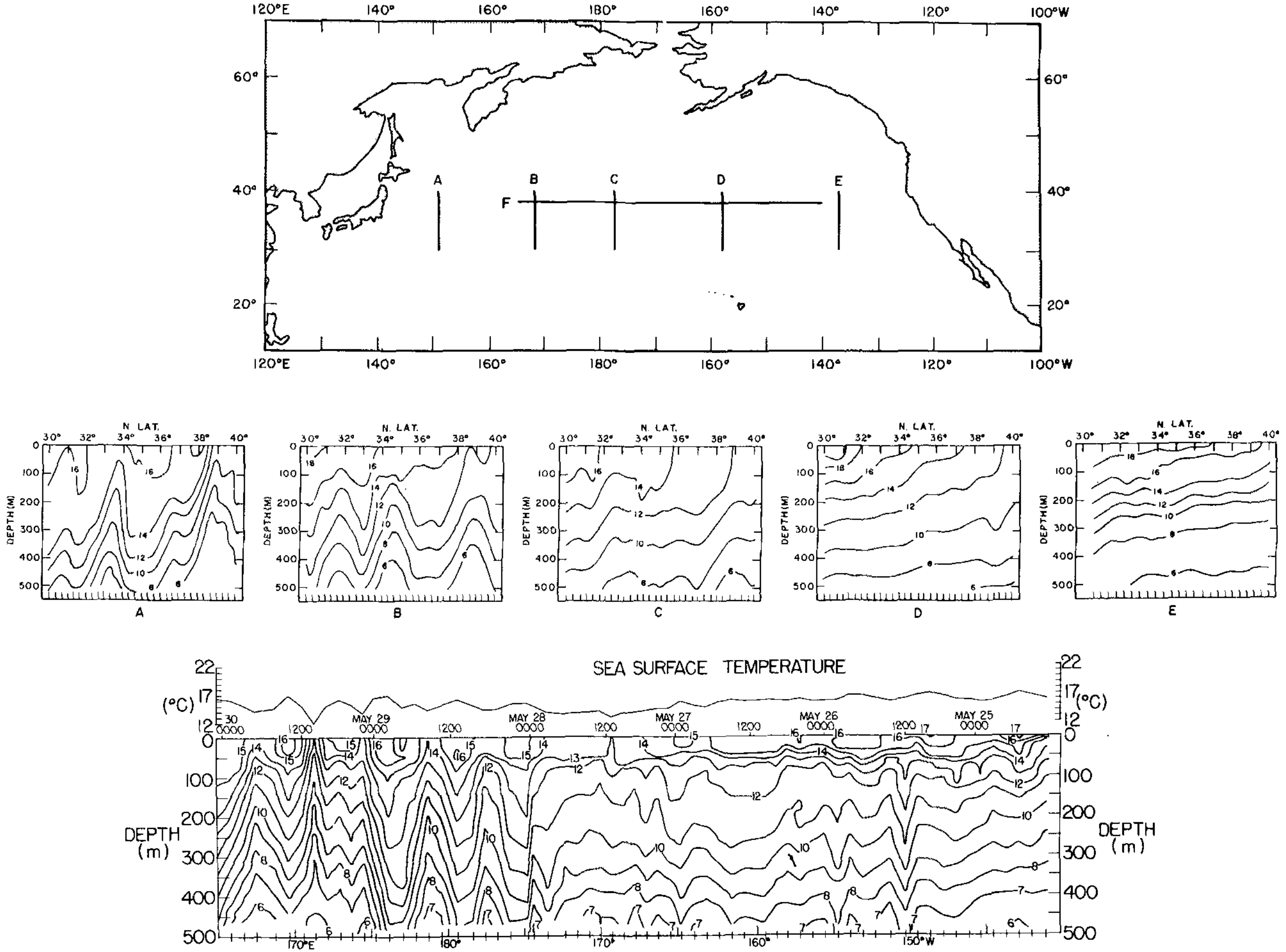

Fig. 5. Evidence for an increase of eddy intensity from east to west in the North Pacific. The data shown are five north-south and one east-west sections showing isotherm depths. The marked fluctuations of depth west of 175°W longitude are the signature of strong eddies or meanders in the North Pacific current system.

3.3. MID FREQUENCY OCEANIC EM GENERATION: TIDES AND OTHER GRAVITY WAVES

In the ocean, gravity waves exist as surface and internal waves. Except for some exceptional phenomena (e.g. tsunami) the surface waves consist of tides and wind waves. Tides as electromagnetic generators have been discussed by Larsen (1968) with the conclusion that they will become useful deep sounding sources only when their horizontal spatial variability has been established on a global scale. This time is rapidly approaching (see, for example, Gordeev *et al.*, 1977). Recent work by Parke (1978) has produced by semi-empirical methods a fairly good map (Figure 6) of global tides. Tidal currents of barotropic mode have a large horizontal scale in the deep sea and should therefore be a useful source of deep sounding data. The application of this new knowledge in conjunction with the increasing information on the concomitant electric and magnetic fluctuations (e.g. Richards, 1977; Larsen and Cox, 1966) may present a fruitful new approach to deep soundings.

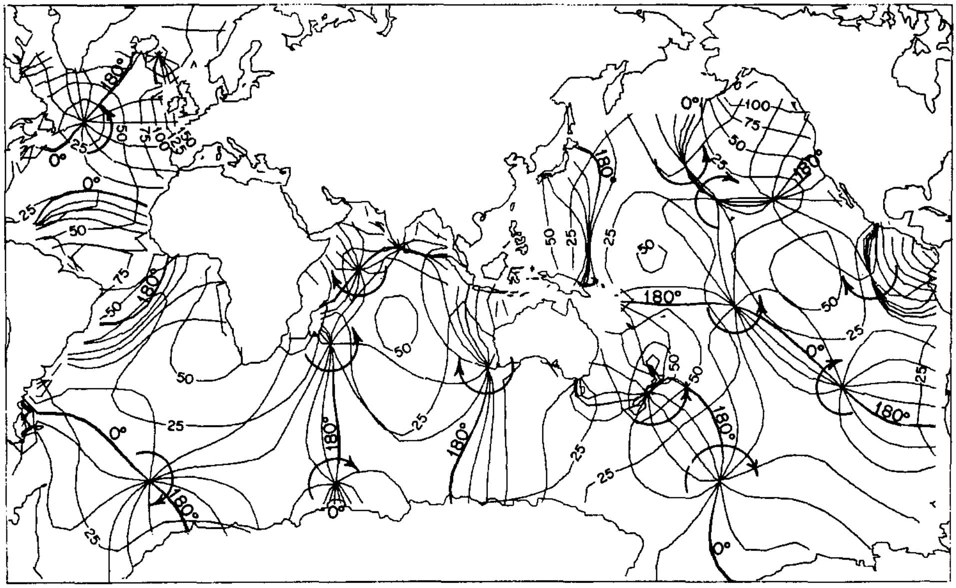

Fig. 6. The M2 tide according to Parke (1977) from a semi-empirical fit of analytic modes to open sea island station data. Amplitudes are in cm, phases in degrees relative to passage of (M2) moon over Greenwich.

Heretofore, the tidal fluctuations in the EM spectrum have had to be regarded as unwanted noise because the impedance exhibited by their generated EM fields is significantly different from EM fields at normal incidence.

Because of their high frequency, the EM effects of surface wind waves are largely confined to shallow water (Weaver, 1965). It has been shown by Cox *et al.* (1978) that wind wave EM effects can be detected in deep water through a nonlinear interference mechanism which is related to the Longuet–Higgins mechanism by which they also generate microseisms. The EM fields generated in this way have twice the frequency of the wind waves and a spatial scale of about the water depth (Figure 7).

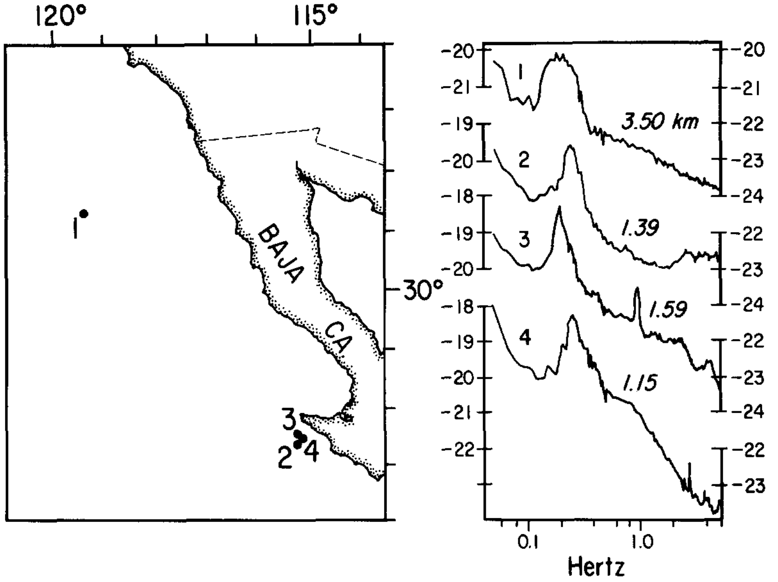

Fig. 7. Spectra of horizontal E on the sea bottom show the peak at 0.2 Hz thought to be caused by a nonlinear interference between opposing trains of wind waves. Locations of stations are shown at the left; water depth is marked on each spectrum. The spectral ordinate is the logarithm (base 10) of the intensity in $(V/m)^2/Hz$.

Internal waves are a ubiquitous feature of the ocean. According to Garrett and Munk (1972; 1975; 1978) their intensity and spectral form is remarkably uniform (within a factor of 5 or better) in time and space. Watson (1979) has examined the electromagnetic fields to be expected from a Garrett and Munk internal wave spectrum on the deep sea floor. Fortunately there is little effect because the water motions and induced electromotive forces are in opposition from level to level in the ocean and the overall result is a high degree of cancellation at the sea floor as far as the magnetic and horizontal electric fields are concerned. In magnetotelluric impedance methods these are the relevant field components. The vertical electric field is, however, very nearly $U \times (F_2 \hat{e}_2)$ where U is the bottom water current, F_2 the northward geomagnetic induction. It can happen that the electric field measuring equipment is not well aligned with the sea floor so that to some degree the *vertical* electric component is erroneously combined into the horizontal measurement. This can produce substantial noise as shown by the estimate (Table I) of Watson (1979).

3.4. HIGH FREQUENCY NOISE

At frequencies above 10 cph the decline in intensity of EM signals from above the atmosphere coupled with increasing screening of the sea floor by the deep overlying blanket of sea water work together to weaken usable EM fields seriously. Even the comparatively weak noise signals induced by turbulent flow and electrode instabilities conspire to make

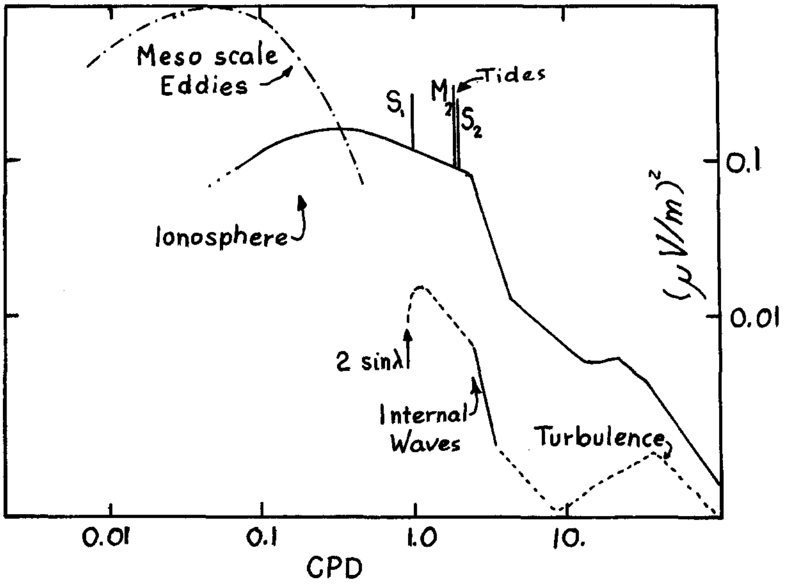

Fig. 8. Contributions to the north horizontal electric field spectrum on the sea floor at MODE station 1. The curves show frequency times intensity as a function of frequency. The MODE area has strong mesoscale eddies. Internal waves induce signals beginning at the local inertial frequency, 2 sin latitude (cpd). Internal waves generate mainly vertical E but irregularities in the sea floor can couple this to a horizontal recorder. The turbulence is computed from the observed coherence of E with B and corresponds to a root-mean-square turbulent speed of a few mm/sec.

electric measurements ineffective. This put an effective upper frequency limit to impedance methods of EM sounding. Little is known of the magnetic noise in this frequency interval. It is possible that an extremely sensitive magnetic variometer would be able to extend the upper frequency limit slightly. However the oceanic screening will ultimately prevail thus putting an upper limit to the frequency range where natural EM signals from above the ocean are usable. The range of useful frequencies for impedance measurements on the deep sea floor is summarized in Figure 8.

3.5. FAVORABLE FEATURES OF EM SOUNDINGS ON THE DEEP SEA FLOOR

The foregoing paragraphs have outlined some of the limitations to impedance methods using natural EM sources. There are also outstandingly favorable circumstances which encourage the use of this method for geophysical studies. They are connected with the high and uniform conductivity of ocean water and its almost unchanging temperature and salinity.

At first sight, it seems unfortunate that the ocean is very conducting because this makes the electric fields weak. A counterbalancing advantage is that it is possible to make low resistance contact to the ocean and thereby couple abundant electric energy to the recording apparatus. This feature, coupled with the thermal and saline stability of the

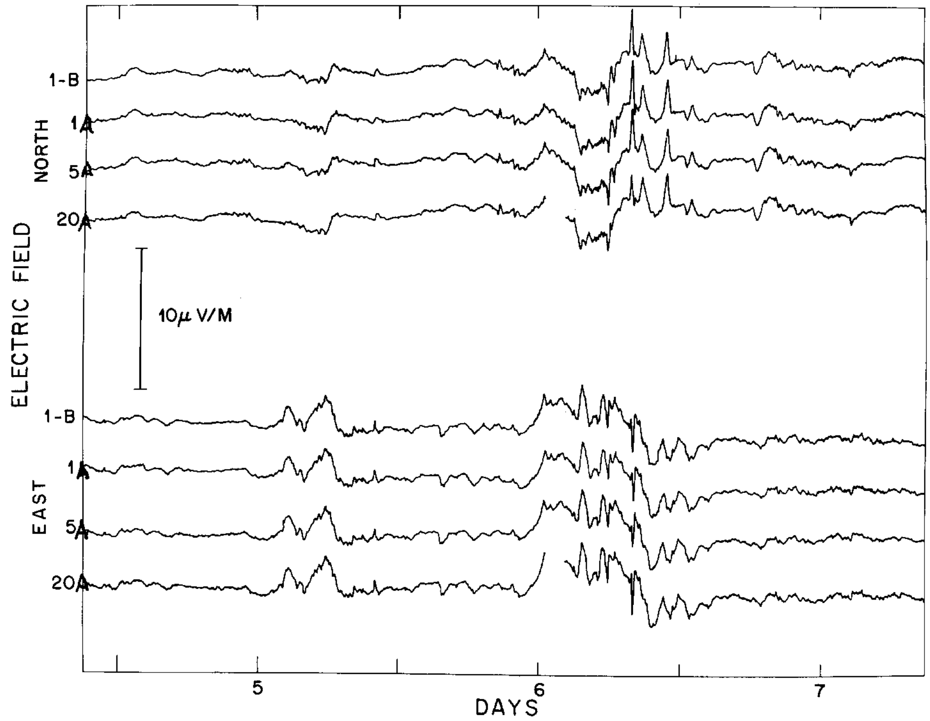

Fig. 9. Horizontal components of the electric field in the MODE area of the Atlantic illustrating the spatial homogeneity of fields. Station locations are those indicated in Figure 1. The traces labelled in 1 B were measured at a station 8 km east of 1 A.

oceans makes possible a very low noise of recording of the electric field. For the small scale apparatus (6 m antenna spread) of Filloux (1974), the noise level seems to be so small that it is undetectable even with the extremely low field intensity at the high frequency end of Figure 8. A very low noise has also been achieved at still higher frequencies by use of a 1 km antenna (Cox *et al.*, 1978; and Figure 9).

The uniformity of the ocean depth (in regions of subdued bottom relief) is also a great advantage because the thick layer of homogeneously conducting water dominates small irregularities of conductivity in crustal rocks and makes the electric field homogeneous over large areas. Figure 9 illustrates the similarity of horizontal electric components observed across the MODE array. The electrical field is remarkably consistent across a span of more than 100 km. The consistency is even more striking in the lower latitude Pacific observation (Figure 2). This circumstance is to be contrasted with electric recordings on land where the spatial scale of electrical variability is dominated by irregularities in crustal rocks to such a marked extend that it is often difficult to make impedance measurements.

4. What is the Maximum Resistivity which Isolates the Ocean from the Body of the Earth?

We now return to the question of the uncertainty about electrical continuity between the seafloor and deep underlying matter where the conductivity is high.

A very simple model will suffice to indicate the importance of high resistivity underlying the ocean. Suppose induction processes have generated an electric current J (integrated vertically) within the ocean and that this current is flowing towards a continental boundary at some distance from the shore. As a consequence of the poorly conducting continental boundary this current is deflected either parallel to shore or downwards into the mantle of the earth. Let L denote the distance offshore within which the currents are deflected. Within this boundary zone the current is unsupported by induction processes and must therefore be driven by an electrostatic potential of the order of magnitude

$$V = J L/(\sigma_0 h) \tag{1}$$

where σ_0 is the conductivity and h the depth of the ocean. The potential will also drive current flow through the sea bed towards the highly conducting core of the earth which we take at zero potential. If the integrated leakage current through the sea bed is also of order J then

$$J = \sigma_r (L/H) V \tag{2}$$

where σ_r, H are the conductivity and vertical extent of the high resistive layer. The implication found by eliminating J/V from (1) and (2) is that $L^2 = (\sigma_0/\sigma_r) h\, H$. This expression is valid only for the very low frequency fields for which the ocean is much less than one skin depth deep.

The order of magnitude calculation has been verified by detailed calculation of the boundary zone by Pistek (1977). An analytical expression for the shoreward edge of the boundary zone has been found for an infinitely conducting ocean (Nicoll and Weaver, 1977).

The high resistitivity layer will certainly be limited in depth by rising temperatures. The geothermal profile has been estimated for oceanic conditions by Chapman and Pollack (1977). Taking 500°C as an upper limit for insulating rocks, the depth H will be about 30 to 50 km in regions of normal heat flow. I estimate H = 50 km. Choosing h = 5 km corresponding to typical deep ocean depths and σ = 3.3 S/m, the following relation between L and σ_r is found:

σ_r (S/m)	L (km)
10^{-2}	2.9×10^2
10^{-4}	2.9×10^3
10^{-6}	2.9×10^4

If the conductivity is as low as 10^{-5} S/m the 'boundary zone' fills the largest ocean and normal impedance interpretations are useless. Clearly it is of great importance to learn the conductivity of the near bottom rocks.

It is useful to review present knowledge and speculation about the structure and temperature of the oceanic crust and upper mantle. Direct knowledge from core samples obtained by the Deep Sea Drilling Project extends through the sediment layers and 600 m into the igneous rocks of oceanic 'layer two', found to be highly fractured basalt lava flows. The conductivity of solid samples of the basalt and related rocks is known through the work of Hyndman and Drury (1976). There are also electromagnetic logs which provide an estimate of *in situ* conductivity of the fractured rocks. It is very high; about 0.03 S/m on average. The conductance is clearly caused by sea water within cracks and fractures.

Below the drilling depth our knowledge is uncertain. The ophiolite rock sequences found exposed on land at many places surrounding present and past ocean basins are thought to represent contorted slices of ocean crust and upper mantle (Coleman, 1977). With due regard for uncertainties associated with their ancient and specialized provenance, and the changes they have undergone since leaving the ocean floor, they are still the most informative materials available to instruct us about the state of deep lying materials. A remarkable study of mineralogy and seismic velocities has been made of the ophiolite exposed on Blow-Me-Down Mountain, Bay of Islands, Newfoundland (Salisbury and Christensen, 1978). It appears that massive water penetration during the formative stages of the rocks was limited to the basaltic layer. Deeper materials have increasing crystal sizes, indicating slow cooling. The evidence from mineralogy is ambiguous because many water altered minerals are present but probably were produced by metamorphism after the rocks were cooled below the solidus temperature. I think it will be important to measure electrical conductivities of these materials under various conditions of water saturation, temperature and pressure.

It is known from the work of Watanabe (1970) that a slight trace of water will greatly increase the conductivity of basalt at moderately high temperatures. The oceanic mantle is thought to have basaltic minerals mixed with olivine. Hence the amount of volatiles within the mantle is crucial to our understanding of resistivity.

5. Methods of Detecting High Resistance Layers under the Ocean

EM induction experiments of various types suggest themselves as possible methods of progress towards this understanding. (1) Improvements to electric and magnetic measurements may allow impedance measurements to be extended into higher frequencies than now possible. This procedure will permit better resolution of poorly conducting material near the sea bed but is certainly limited in capability. It is difficult to learn about the conductivity of strata, the integrated conductivity of which is less than (say) 10% of the conductivity of the overlying layers. If the water saturated basalt layer has integrated conductivity $2 \text{ km} \times 3 \times 10^{-2}$ S/m = 60 S then a deeper stratum of thickness 30 km will only be detectable if its conductivity averages $>2 \times 10^{-4}$ S/m. (2) Since the impedance is greatly altered and rendered anisotropic within the zone bounding poorly conducting continents, one might attempt to infer the sea floor leakage by observing the impedance within the zone. This method will be difficult because of possible complicating features: the continent-ocean transition may well have a deep seated conductivity anomaly itself. Such an explanation is suggested by the variability of the Parkinson (1962) induction anomaly found at continental margins. (3) Two attempts have been made to detect sub-audio frequency signals which penetrate into the rocks of a continental massif then diffuse *under* the adjacent ocean. The frequencies examined are so high that propagation through the ocean is excluded. The method was first suggested by Soderberg (1969). The first attempt was a search for coherent, naturally occurring fields on land and on the sea bed. It was carried out adjacent to the Baja California coastline (Pistek, 1977; Cox *et al.*, 1978). A later attempt using an artificial source on the shore near the strait of Juan de Fuca, (Washington State) is reported by Bostick *et al.* (1978). Both attempts were unsuccessful and place effective lower limits to the conductivity of near bottom rocks of about 10^{-2} S/m. The possibility of deeply buried, more resistive oceanic layers however cannot be excluded because the nature of the rocks at the continental margin may have extinguished the signals which would otherwise have propagated them. (4) An active method may be used in which artificial signals are injected directly into the sea floor. In the simplest method a horizontal electric dipole source could be lowered to the sea floor and caused to radiate electromagnetic signals in the sub-audio frequency range. The skin depth for EM penetration is very short in the sea water (270 m for 1 Hz). Consequently signals which propagate in the sea will be rapidly absorbed. A small amount of energy will enter the solid rocks below the sea, where it will penetrate more effectively. Consequently if a very sensitive receiver is able to detect the signals at distances of tens of kilometers, these signals will have penetrated through the rocks. There will of course be major losses of signal strength within the ocean sediment and water saturated basalt layers.

We can estimate the signal strength from the classical analysis directed towards the solution of the 'ground wave' problem where radio waves are transmitted through the atmosphere over a finite conductance earth. (In my application, the problem is inverted: the atmosphere becomes the poorly conducting rock half space while the earth becomes the conducting ocean). Let the horizontal electric dipole source be in the contact plane of these two half spaces and radiate with dipole strength

$$P = P_0 \exp(i\omega t).$$

The radial electric field, also in the contact plane and in a direction along the axis of the dipole source is

$$E_r = (2\pi\, \sigma_0\, r^3)^{-1}\, P_0\, F(\gamma_r r)\exp(i\omega t) \tag{3}$$

where r is the horizontal separation of source and receiver, σ_r, σ_0 are the conductance of rock and sea water and

$$\gamma_r = \sqrt{i\,\omega\,\mu\,\sigma_r}\,, \qquad \gamma_0 = \sqrt{i\,\omega\,\mu\,\sigma_0}$$

are the propagation constants within the rock and ocean, respectively. The expression is a near field approximation valid when

$$|\gamma_0| \gg |\gamma_r|\,, \qquad |(\gamma_r^2/\gamma_0)\,r| \ll 1\,, \qquad |\gamma_0\,r| \gg 1$$

(Kraichman, 1970). The asymptotic expression for F (Figure 10) is

$$F(z) = (1 + z + z^2)\exp(-z).$$

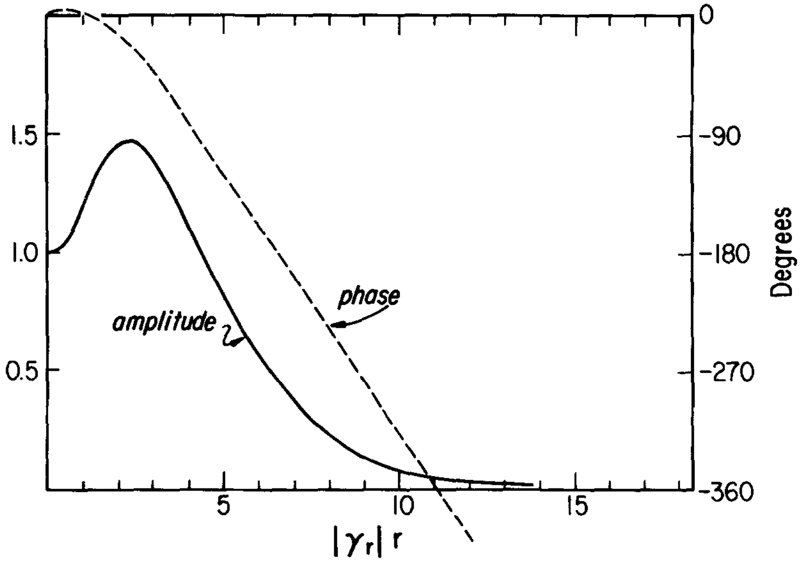

Fig. 10. The function $F(\gamma_r r)$.

Expression (3) is valid for two homogeneous layers, water over rocks. The effect of sediment and high conductivity basalt layers will roughly introduce an additional attenuation

$$\exp\,(-2\,h_s\gamma_s - 2\,h_b\gamma_b) \tag{4}$$

because the signals must diffuse twice through each layer. (The thickness and propagation constant of each layer are indicated by h and γ respectively. The subscripts s and b refer to sediment and basalt.) With average oceanic values: $h_s = 300$ m, $h_b = 2$ km, $\sigma_s = 1$ S/m, $\sigma_b = 0.03$ S/m, the magnitude of the attenuation factor (4) is 0.08 at a frequency of 1 Hz. Suppose the underlying rock has a conductivity 10^{-4} S/m, a source dipole of strength $P_0 = 10^5$ A m is used, and the receiver noise level is comparable to that shown in the top trace of Figure 7. Then it would be possible to detect the source to a distance of 150 km provided the bandwidth can be narrowed to 10^{-4} Hz by prolonged observations. (A signal-to-noise ratio of 20 dB is assumed). This distance is certainly adequate to explore much of the region where conductivity is uncertain. This method looks promising and furthermore will give primary emphasis to the high *resistivity* layers below the sea. The most effective mode propagating from a horizontal electric dipole is TM: the electric field is nearly vertical in the poorly conducting rocks. It is fortunate that the effective vertical conductivity is precisely the knowledge needed for interpretation of oceanic impedance measurements.

Appendix

We compute the electric field induced by low frequency motions of the ocean through the geomagnetic field. In this computation we assume that the ocean is of uniform depth, has a poorly conducting basement and that the horizontal scale of the motion is large compared to the ocean depth.

The electric current density j is related to the electric field measured by a stationary observer by Ohm's law for a moving medium

$$j = \sigma(E + \boldsymbol{u} \times F) \tag{A1}$$

where σ, $\boldsymbol{u}$ are the conductivity and velocity of the water and F is the geomagnetic induction.

We integrate the horizontal components of (A1) vertically through the ocean (of depth h) to obtain

$$J = \Sigma(E + U \times \hat{e}_3 F_3) \tag{A2}$$

In this notation J is the integrated electric current, Σ is the vertically integrated conductivity of the ocean $\hat{e}_3$ is a unit vertical vector and

$$\bar{E} = \frac{1}{\Sigma}\left[\int_0^h \sigma E \,\mathrm{d}z\right]_{\text{horizontal}} \qquad \bar{U} = \frac{1}{\Sigma}\left[\int_0^h \sigma \boldsymbol{u} \,\mathrm{d}z\right]_{\text{horizontal}}$$

are the vertically averaged (conductivity weighted) horizontal components of E and $\boldsymbol{u}$. Because we consider only low frequency and large scale variations we may assume that curl E and therefore $\partial E_1/\partial x_3 = 0$, $\partial E_2/\partial x_3 = 0$. Consequently E is the same as the horizontal electric field measured at the seafloor. U is practically equal to the barotropic component of water flow.

With very good accuracy one can neglect the curl of $\bar{E}$ for the very low frequency water motions which constitute mesoscale eddies and other moderate and large scale water motion. Consequently one can derive from (A2) the relation

$$\nabla \times (J/\Sigma) = \hat{e}_3 \nabla \cdot (F_3 U) . \tag{A3}$$

Furthermore, if electric leakage through the sea floor is completely negligible, the continuity of electric charge requires that

$$\nabla \cdot J = 0. \tag{A4}$$

From (A3) and (A4) one concludes that J will vanish when Σ and F_3 are sufficiently uniform and the flow is divergence free. The latter is indeed a characteristic of quasi-geostrophic flow. We conclude that the simple relation

$$\bar{E} = -U \times \hat{e}_3 F_3 \tag{A5}$$

is a good approximation when the flow field is sufficiently large in scale compared to the water depth but at the same time not so large that the horizontal variation of vertical magnetic force F_3 needs to be included in (A3). A more refined analysis indicates that the right hand side of (A3) remains acceptably small even for the largest scale flows. The correctness of (A5) in this latter case depends critically on electrical leakage to the seafloor.

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