MARINE ELECTROMAGNETIC RESEARCH

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Abstract. All aspects of Marine Electromagnetic Research have made important advances over the last few years: theoretical studies, instrument design and data from equipment on the bottom of the ocean. The seafloor results show that the depth to the conducting asthenosphere is greater under older lithosphere and thus the thickness of the lithosphere increases with age. To obtain greater resolution of the electrical conductivity structure of the upper layers, several controlled source systems were developed. The first observations indicate a decrease in conductivity a few kilometers below the seafloor. Improved theoretical response curves for the electromagnetic fields at an ocean-continent boundary are now available. The theoretical curves, combined with land and seafloor data from coastal regions, allow the effects of the electric currents induced in the seawater to be separated from those caused by currents in the tectonic structure at the continental margin. Of growing interest is the application of electromagnetic methods to determine oceanographic wave parameters. Recent studies have investigated meanders in ocean current patterns, the response of internal edge waves and the tidal effect. With the forseeable improvements in seafloor instrumentation it will be possible to investigate the conductivity structure of offshore basins and the hydrothermal deposits associated with spreading ridges.

1. Introduction

At the preceeding workshop on electromagnetic induction in the earth and moon, Fonarev (1982) presented an overall perspective of marine electromagnetic research and listed its purposes: (1) to determine the thickness of the lithosphere, which relates to its thermal state; (2) to determine the electrical conductivity structure of the seafloor, particularly of the sedimentary layers in offshore basins with hydrocarbon potential; (3) to determine the effect of the oceans on the geomagnetic field; (4) to determine hydro-dynamical source parameters; and (5) to determine the influence of the natural e–m fields on fish and other sea fauna. Many of these purposes have been comprehensively reviewed with extensive bibliographies within the last few years.

At the fourth workshop in Murnau 1978, induction in the ocean was reviewed by Fainberg (1980) and by Cox (1980). In 1979 the International Union of Geodesy and Geophysics meeting convened in Canberra, review papers were presented on the electrical conductivity of the oceanic lithosphere (Cox, 1981) and on deep geoelectric models (Vanyan, 1981). The fifth workshop, Istanbul 1980, had reviews on induction methods (Mosnier, 1982), the conductivity structure of the lower crust (Gregori and Lanzerotti, 1982) and the previously mentioned, electromagnetic research in the oceans, paper by Fonarev (1982). In the last few years there were also reviews on the geomagnetic coast effect (Parkinson and Jones, 1979) and electromagnetic soundings (Filloux, 1979a).

This selected list of review papers covers the background theory and previous results and the bibliographies contain the important earlier references. This paper highlights a few of the many recent results from the last few years.

Contribution of the Earth Physics Branch No. 1071.

Geophysical Surveys **6** (1983) 123-135. 0046-5763/83/0062-0123$01.95.

1.1. PURPOSE #1. THE THICKNESS OF THE LITHOSPHERE

Developments in instrumentation now permit electromagnetic data to be obtained more routinely from the seafloor. Magnetometers with suspended magnets (Filloux, 1979a), fluxgate elements (Law, 1978, White, 1979) and proton precession sensors (Tomoda *et al.*, 1981) have been successfully deployed. To date all but one of the soundings were in the Pacific Ocean. The early results were seaward of California (Filloux, 1979b) and north-east of Hawaii (Filloux, 1980; Chave *et al.*, 1981). Analysis of these data sets suggested that the depth to the conducting layer increased with the age of the lithosphere. The results from near the Juan de Fuca Ridge (Law and Greenhouse, 1981) provided additional support for this conclusion. Oldenburg (1981) re-analysed these data sets and provided an explanation for the increasing depth to the conducting layer in terms of partial melting. Measurements were later obtained at two locations in the Mariana Island Arc region (Filloux, 1982a) and from the East Pacific Rise in the Rose area (Filloux, 1982b).

In Figure 1 the depth to the conductor as determined by Filloux for his four data sets are plotted as triangles; the three sites with depth as re-analysed by Oldenburg are shown as circles and the square is from the analysis of M–T data north-east of Hawaii by Chave *et al.* (1981). The trend of increasing depth with age is apparent. The differences in depth for the same data sets are partially a product of the analysis techniques, with discrete layers versus a smoothly varying conductivity structure.

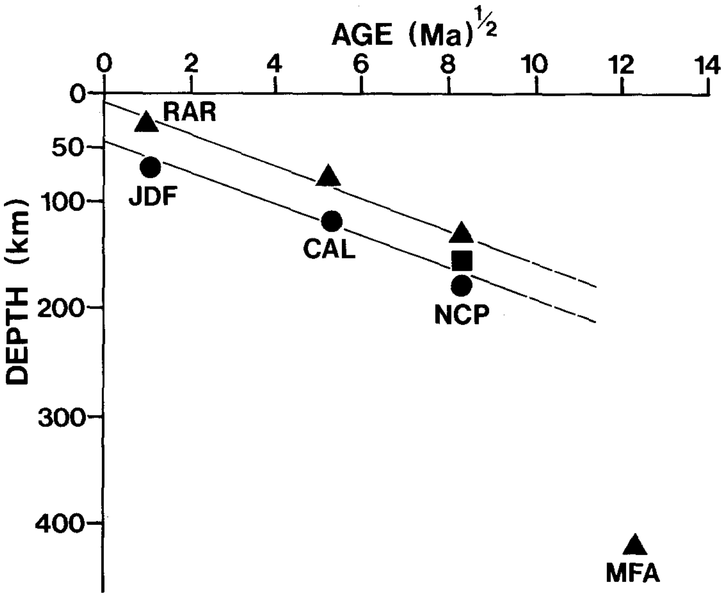

Fig. 1. Depth to a conductive layer as a function of age of the lithosphere from ocean bottom soundings. RAR – Rose Area Ridge, JDF – Juan de Fuca Ridge, CAL – west of California, NCP – North Central Pacific (north-east of Hawaii), MFA – Mariana fore arc basin.

Considerable effort is directed toward firmly establishing the increase in depth to the conductor with age of the lithosphere and placing limits on the depth estimates. These few results have also raised other important issues. Is the greater than expected depth to the conductor in the Mariana's area related to the sinking slab and the cooled region adjacent to it (Filloux, 1982a)? Both data sets from near spreading ridges (Law and Greenhouse, 1981; Filloux, 1982b) show no significant enhancement in the vertical field or phase reversal across the ridge; this implies that there is no long continuous linear conductor associated with these ridges. Also, the horizontal field transverse to the ridge is somewhat larger at both locations. Is the transverse conductivity higher and caused by fractures produced as the new crust cools?

Additional data are now available from the southern Vancouver Island region (Law *et al.*, 1981) and across the Japan Trench (Filloux and Yukutake, 1982). These experiments are both across active margins but with different subduction rates and thickness of the slab. The similarities and differences in results should establish the effect of the conducting layer below the lithosphere at the coast. For the Pacific plate the conductivity structure is being determined point by point.

In contrast, there is only one sounding in the Atlantic (Cox *et al.*, 1980). The results from this experiment in the north-west Atlantic on 130 Ma old seafloor showed sharp increases in conductivity at 70 and 250 km. It is important that many more soundings be made on the Atlantic plate if we are to understand the nature and form of the lithosphere–asthenosphere boundary.

The work of Trofimov and colleagues working on the sea ice has provided several soundings of the lithosphere in the Arctic Ocean region (Trofimov, 1979). The geoelectric section for the Lomonosov Ridge is similar to many continental results, whereas the area near the Chukchi Plateau and the northern margin of the Canadian Basin have much higher conductivity profiles. Although there are major logistic difficulties, soundings of the lithosphere under the Arctic Ocean provide valuable data for comparison with the ocean bottom soundings on the Pacific plate. The sea ice also offers a unique opportunity to measure the electromagnetic components at the surface and with ocean bottom instruments on the seafloor at the same location.

Geomagnetic variation measurements on islands have been used to determine the conductivity structure which is assumed representative of the nearby ocean areas. Results from Minami-Daito Island (Honkura *et al.*, 1981) in the Northwestern Philippine Sea show a conducting layer exists at a depth in the range of 80 to 120 km on 60 Ma old lithosphere. This depth lies above the upper line in Figure 1. The use of this method for islands in other regions, would provide important additional soundings for comparison.

1.2. PURPOSE #2. THE ELECTRICAL CONDUCTIVITY STRUCTURE OF THE SEAFLOOR

As noted in the previous section, the magnetotelluric and geomagnetic depth soundings on the ocean floor have revealed regions with higher conductivities at depths greater than 20 km. The natural magnetic fields used in these studies originate above the earth's surface and are screened by the conductive sea water and temporal variations with

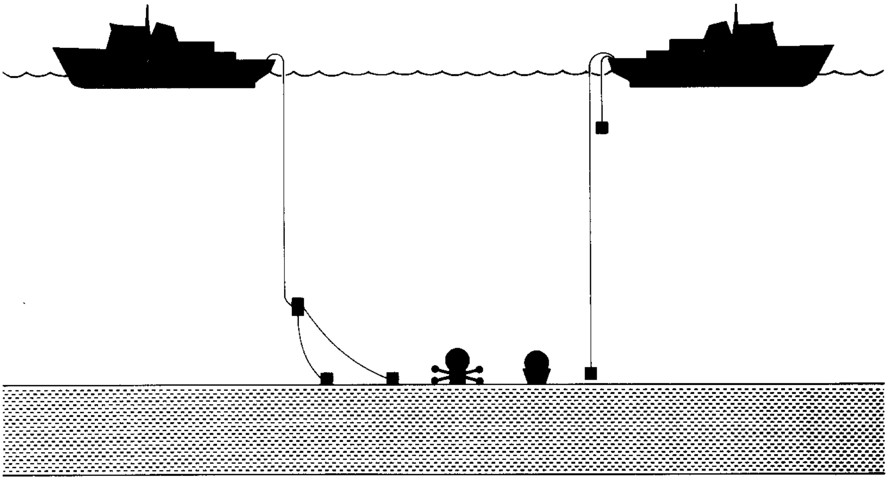

Fig. 2. Controlled source systems with horizontal and vertical electric dipole transmitters powered from the ships and electric and magnetic ocean bottom receivers.

periods shorter than a few minutes cannot be observed. To determine the electrical structure of the seafloor requires an active source electromagnetic technique. There are four fundamental source types, vertical and horizontal orientation of electric and magnetic dipoles. Both the vertical and horizontal electric dipole source have been developed (Edwards *et al.*, 1981; Cox *et al.*, 1981).

A recent paper by Chave and Cox (1982) presents expressions for the electromagnetic induction fields produced by active sources in the conducting ocean overlying a one-dimensional earth.

Figure 2 is a cartoon depicting the horizontal and vertical electric dipole transmitters and the respective electric and magnetic field receivers. Present technology permits measurements to be made to a maximum horizontal range of 50 km. The depth of penetration is of the order of half the transmitter-receiver separation and, depending on the conductivity of the lithosphere, the electrical structure to depths of more than 20 km can be determined. The first controlled source results were obtained by Young and Cox (1981) near the East Pacific Rise with a horizontal electric transmitter and an electric field receiver separated by almost 19 km. Models fitting this data set are shown in Figure 3. The results clearly reveal a decrease in conductivity at a depth of less than 2 km apparently related to the depth of fracturing and penetration of seawater into the crust. The electric log results from the D.S.D.P. hole 504B provide strong support for this conclusion.

The vertical electric dipole system with magnetic field sensors was successfully tested in July 1982 and the preliminary results were presented at this workshop (Edwards *et al.*, 1982). Signals were recorded at distances of more than 10 dipole lengths in water depths of almost 200 m over a basin area on the continental shelf of western Canada.

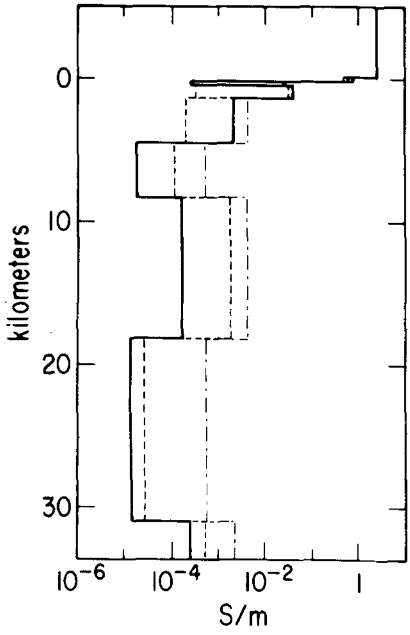

Fig. 3. Three fitted model profiles of electrical conductivity as a function of depth beneath the seafloor. The solid line is the 'best fit' model. (after Young and Cox 1981).

Active source electromagnetic sounding is the best method to locate relatively small scale targets such as magma chambers beneath the spreading ridges and polymetallic sulphide deposits associated with hydrothermal flow near the ridges. The controlled source method also has the capability to resolve the conductivity structure of the offshore basins and instrumentation could be developed for hydrocarbon exploration.

1.3. PURPOSE #3. THE EFFECT OF THE OCEANS ON THE GEOMAGNETIC FIELD

The most notable effect of the ocean is the well known edge or coastal anomaly where the vertical field variations are enhanced near the coast. A series of theoretical results on the currents induced by Sq variations on a global scale were published, e.g. Beamish *et al.* (1980). The latest, five-island model produces current distributions considerably better than the earlier simpler models. On a more regional scale, the calculations of Hobbs and Dawes (1980) for vertical component induction by Sq for a simple model of the Pacific Ocean are in qualitative agreement with observations near the coast of California. Improved theoretical response curves for the electromagnetic fields at an ocean continent boundary were derived by Fischer (1979) and re-examined by Raval *et al.*, (1981). These theoretical studies, combined with land and sea floor data from coastal regions, allow the effect of the electric currents induced in the ocean to be separated from those caused by currents in the tectonic structure at the continental margin.

Analogue model studies of the coast effect, such as the paper by Dosso *et al.* (1980) on the eastern coastal region of North America, have proven useful. The model fields for these areas were strongly influenced by induced currents which were deflected and channelled by the coastline and ocean bathymetry and were dependent on the polarization of the source field. A detailed analogue model study of a coastline with capes and bays (Chan *et al.*, 1981) shows the large variability in response produced by the local geometry of the coast. In some of the coastal regions studied, although the model responses are in general agreement with field observation, there are differences in amplitude at periods greater than 40 min. This suggests that a more complex structure is required for the lithosphere than the uniform layer of the model.

The field observations on land provide one side of the response curve near the land-sea boundary and are obtainable over a variety of tectonic settings. Additions to the earlier measurements areas include a study in Cuba (Abramova *et al.*, 1979), in Scotland (Hutton *et al.*, 1981) and in Scandinavia (Jones, 1981). All of these studies observed large effects at the coastal sites. A comparison of the Scandinavian results to a thin sheet model showed that the responses are adequately described by the conductivity contrast between the land and sea water and do not require a lateral variation in the lithosphere between the ocean and continent.

An interesting area to investigate both the coast effect and any differences in the ocean-continent lithosphere is the active margin off of Vancouver Island. The tectonics of this region, with the Juan de Fuca Plate subducting under the North American Plate,

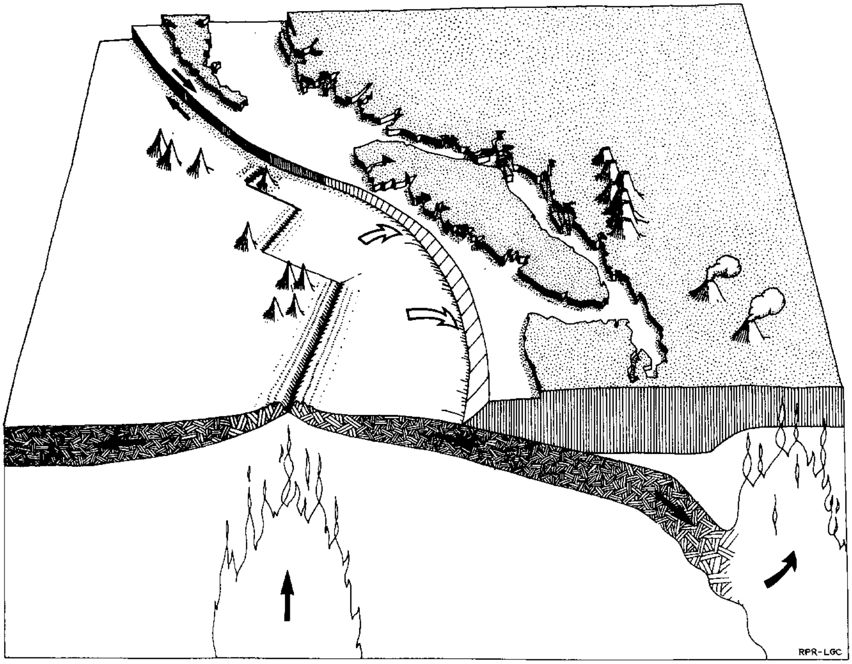

Fig. 4. Cartoon depicting the tectonics of the Juan de Fuca plate area. (after Riddihough, 1978).

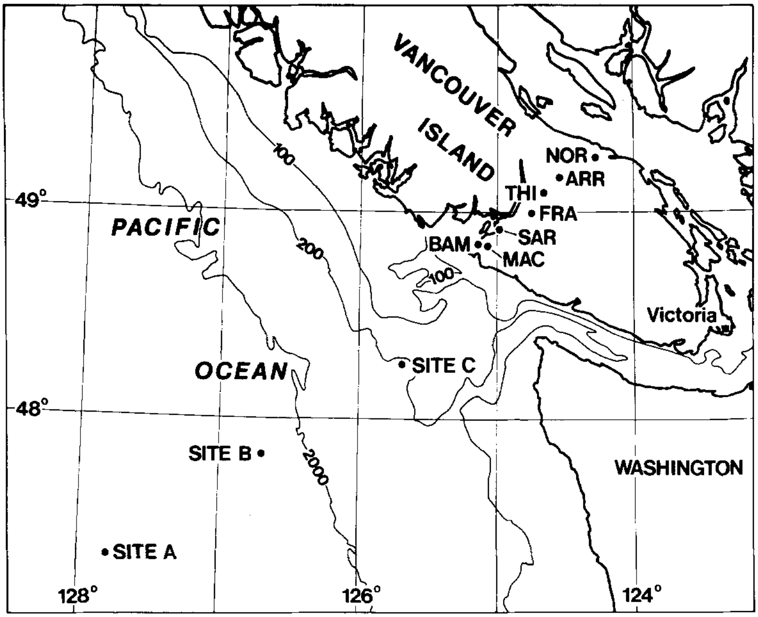

Fig. 5. Location of magnetometers – Vancouver Island project.

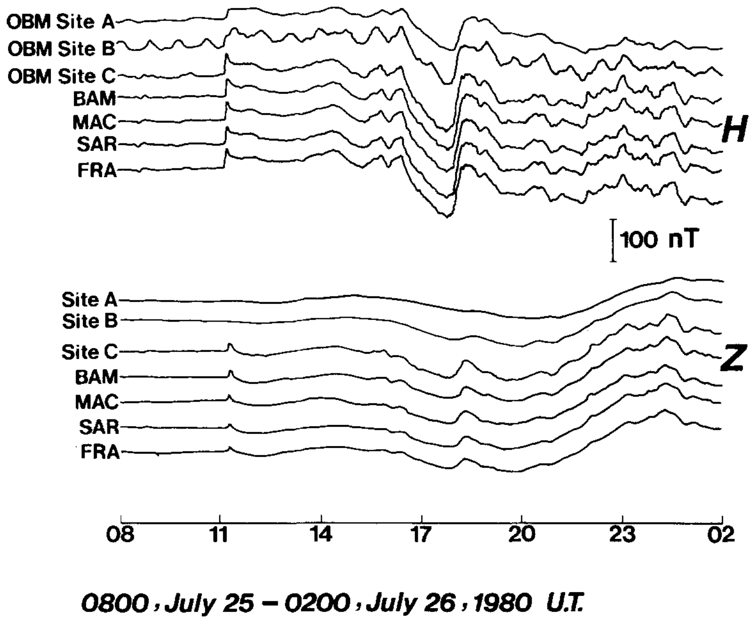

Fig. 6. Magnetograms from the OBM's and the westerly land sites illustrating the coast effect.

are depicted in the cartoon, Figure 4. A line of three component magnetometers, extending from the deep ocean across the continental shelf and across southern Vancouver Island, was located as shown in Figure 5. The ocean bottom magnetometer sites were at the top of the continental slope (290 m depth) at the base (2200 m) and 100 km further out in the ocean (2705 m). Magnetograms for the 3 OBM sites and the four western land sites are presented in Figure 6. Note that the direction of the horizontal magnetic field H is approximately 22° E of north and therefore almost perpendicular to the coast.

This example illustrates all the main features of the coast effect: the similarity of the horizontal field for all land sites and site C, the increase in amplitude for the vertical component from the inland sites toward the coast and to the top of the slope,and the attenuation in the fields at the deep ocean sites A and B. The signal on the H component at site B will be discussed in the following section on oceanographic applications. These magnetograms show that the currents for periods greater than 10 min are concentrated along the continental slope in the deep ocean. For comparable response, 2-D models require a wedge of sediments at the shelf and a good conductor below the lithosphere. Further results from this data set are contained in the paper by DeLaurier *et al.*, (1983).

1.4. PURPOSE #4. OCEANOGRAPHIC APPLICATIONS

Electromagnetic methods are capable of determining oceanographic parameters related to the spatial and time variation of the water velocity. Conventional current meters measure at a point in space; in contrast, ocean bottom e–m instruments sample over a region dependent on the scale, on the type of water motion and on the conductivity of the seafloor. This regional coverage is advantageous in determining mass transport or current meanders which normally require an array of current meters. Theoretical studies of barotropic and baroclinic waves have been published (Zhmur and Lapshin, 1980; Cox, 1980). The predicted power spectral levels of magnetic induction caused by ambient external waves are sufficiently large to be measured by existing ocean bottom instrumentation (Petersen and Poehls, 1982). A thorough treatment of the theory for using ocean currents as sources of electromagnetic fields for induction sounding has been given by Chave (1983). This paper contains the response functions of the electromagnetic field of gravity waves and a Kelvin wave along the California coast.

Electromagnetic fields produced by tides have been observed at many observatories on islands and on the seafloor (Filloux, 1980). During the MODE-1 oceanographic experiment in the western Atlantic, the electromagnetic response of the mesoscale current patterns were recorded on the seafloor and are discussed by Cox *et al.*, (1980).

The previously noted OBM experiment off of Vancouver Island provided a clear example of the ability of ocean bottom instruments to record the e–m fields produced by oceanographic waves. Figure 7 shows magnetograms from the 3 OBM sites for a magnetically quiet interval: almost no signal is observed at the deep site A; a quasi-sinusoidal signal of about 50 min period and 20 nT amplitude is present at the base of the slope, site B; and there appears to be a signal of longer period and less amplitude on

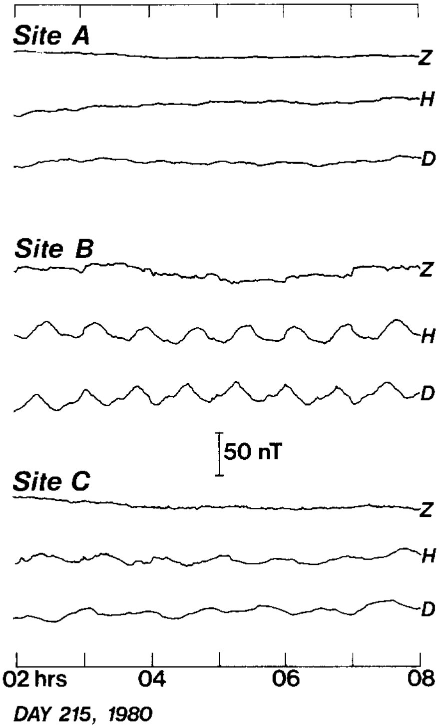

Fig. 7. Magnetograms from the OBM's illustrating the oceanographic wave response.

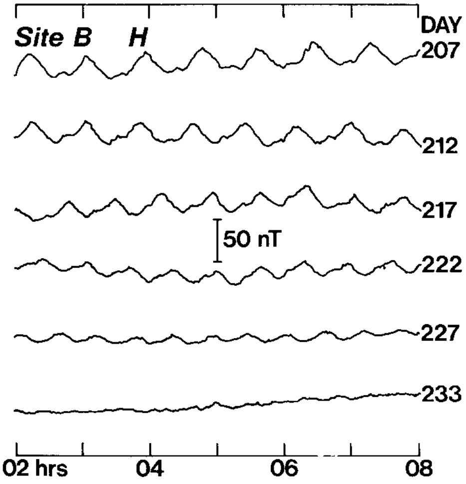

Fig. 8. Magnetograms from the OBM at Site B illustrating the decay of the oceanographic wave.

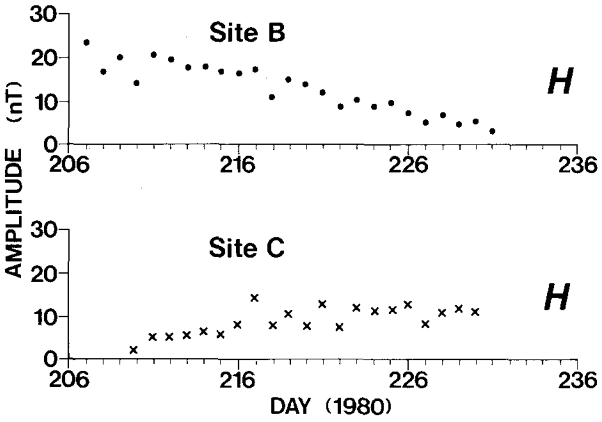

Fig. 9. Amplitude of the oceanographic wave signal at OBM sites B and C.

the shelf at site C. The decrease in amplitude and period of the signal at Site B, which persisted for over 20 days, is illustrated in Figure 8 by the 6 hr record sections selected at times of low geomagnetic activity. Figures 9 and 10 show the amplitude and period for sites B and C from a Fourier analysis of record sections one day in length (1440 points).

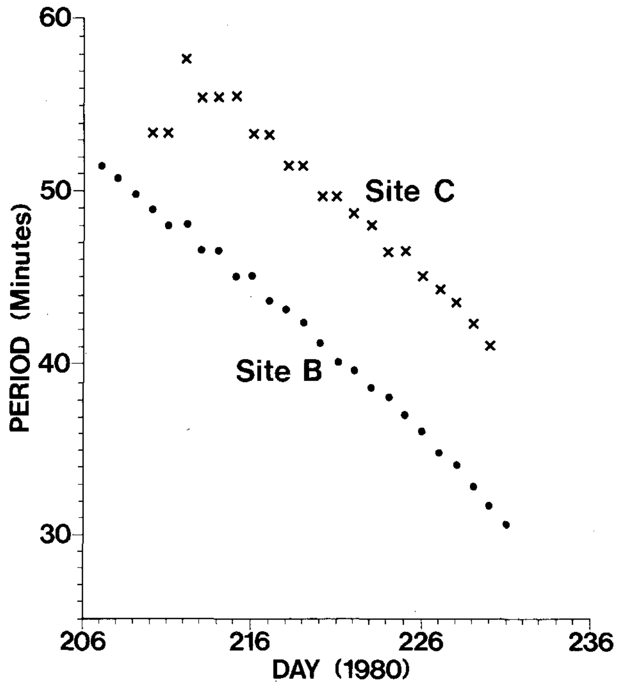

Fig. 10. Period of the oceanographic wave signal of OBM sites B and C.

There was no comparable signal at site A. As the period at both site B and C are less than one hour, this signal is unlikely to be caused by either a tidally driven wave or an internal shelf wave. The decrease in period indicates a dispersive wave and it is suggested that the signal is produced by a type of edge wave caused by a large slump of material somewhere along the continental slope. Unfortunately, there were no current meters in the area sampling at a short enough time interval to detect this wave. The result illustrates the potential for electromagnetic observations of oceanographic phenomena and the need for theoretical studies of the electromagnetic response of complex wave motions in the ocean.

The determination of the transport of the Florida Current by electromagnetic methods (Larsen , 1983) is another oceanographic application. A submarine cable that makes contact on opposite sides of the stream was used to measure the cross-stream voltage potential. The theory, techniques and a method to eliminate the geomagnetic noise using the horizontal geomagnetic fields from reference stations are presented.

1.5. PURPOSE #5. THE INFLUENCE OF THE NATURAL ELECTROMAGNETIC FIELDS ON MARINE FAUNA

In his review paper, Fonarev (1982) emphasized the need to study the influence of natural electromagnetic fields on fish. The interest in biomagnetism is evident by an American Geophysical Union symposium in the fall of 1981 with 14 papers – the abstracts are in *EOS* **62**, 349–351. Pals and Schoenhage (1979) measured marine electric fields in estuaries and found the gradients of sufficient magnitude to be detectable by electro-sensitive fish. An experiment by Quinn (1980) has convincingly demonstrated the role of the earth's magnetic field for lake migrating sockeye salmon fry. Quinn speculates that it would be unlikely for sockeye salmon to have a compass mechanism to guide their movements in lakes and not in the oceans. This intriguing field of study will undoubtedly receive more attention in the future.

2. Future Directions

An imminent advance in instrumentation is the development of ring-core fluxgate sensors for ocean bottom magnetometers. These will increase the sensitivity of the magnetometers to at least 0.01 nT (10 pT) and permit measurement of shorter periods in the deep ocean. But most importantly it will greatly increase the usefulness of electromagnetic methods for oceanographic purposes.

Unfortunately, the measurement of the electric field on the seafloor remains difficult and no innovative improvements are forseeable at this time.

More advanced controlled source systems will be developed for both deeper penetration of the ocean floor and as an exploration technique in offshore sedimentary basins. Controlled source experiments will be carried out to determine the conductivity structure of the oceanic lithosphere and of areas of particular interest near the ridge crests.

As noted, all but one of the deep soundings were in the Pacific Ocean. Co-operative programs between institutions are required to investigate other areas, such as ridges with different spreading rates, passive margins of different ages, and other active margins.

From an experimentalist's viewpoint great progress was achieved in marine electromagnetic research over the last few years and with the above anticipated advances the next years should be just as productive.

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