ELECTROMAGNETIC RESEARCH IN THE OCEAN

G. A. FONAREV

The Institute of Geomagnetism, Ionosphere and Radiowave Propagation, U.S.S.R. Academy of Sciences, Moscow

Abstract. The results of electromagnetic researches at sea and in the oceans are considered. Those in the U.S.S.R. are given particular attention.

1. Introduction

Electromagnetic marine investigations increased greatly about 30 yrs ago due to the introduction of the geomagnetic electrokinetograph into oceanographic practice. Further investigations were related to the development of methods for electromagnetic sounding at the bottom of the ocean and with the introduction of new devices for the realization of these methods. The results of deep electromagnetic sounding have assumed great importance for global tectonics. At the present time there seems to be a good outlook for further use of electromagnetic fields of currents and waves for bottom sounding as well as for determining hydrodynamical source parameters.

A new aspect of electromagnetic investigations is suggested by certain species of fish who possess special organs capable of detecting electric signals. It would be of great interest to know how the natural electric fields influence the fish.

The electromagnetic field in the ocean is a combination of fields from different sources. Two independent contributions dominate the E.M. field actually observed namely (1) the magnetotelluric (ionospheric) field generated by electromagnetic processes in the ionosphere and magnetosphere of the earth, and (2) the hydrodynamic E.M. field resulting from the interaction of oceanic motions with the magnetic field of the earth. In the following we restrict our discussions to these two types of E.M. contributions.

The purpose of magnetotelluric research at sea is to study the structure of the earth beneath the bottom of seas and oceans. The objectives can be divided into two principal classes: (1) reconaissance research and (2) deep investigations. The first class is mainly concerned with the structure of the sedimentary layer on the bottom of inner seas on the oceanic shelf, this to depths ranging from tens of meters to several kilometers. Its major aim is the discovery of oil, gas and placer deposits. The second class relates to several aspects of deep geoelectric research with investigations down to several hundreds of kilometers. In principle, the technique used on land can be used over seas and oceans i.e. magnetotelluric sounding (MTS), magnetovariation sounding (MVS), magnetovariation profiling, etc. Measuring devices for these observations can be located within the water layer from the surface to the bottom. In the Arctic Ocean it is more convenient to place them on the surface, on ice floes; over most of the world oceans, measuring devices are

Geophysical Surveys 4 (1982) 501–508. 0046–5763/82/0044–0501$01.20.

better fixed on the bottom. Moreover, bottom installations have greater resolving power than surface ones. Peculiar features in the distribution of magnetotelluric fields in the water layer and the possibility of locating instruments at different levels provide opportunities for the application of gradient methods of sounding (Trofimov and Fonarev, 1972).

The effect of the ocean on a global scale was reviewed by Fainberg (1978). The results of local soundings in the oceans were described in another review (Cox, 1978).

In the wake of the new ideas and concepts of global tectonics, the number of problems that can now be solved by means of deep electromagnetic sounding is significant. The data from electromagnetic sounding should primarily reveal the thermal state and thermal history of the inner parts of the Earth. The distribution of electrical conductivity along the vertical is inferred directly from the observed data by means of M.T. soundings over an appropriate frequency range.

Electromagnetic sounding must be considered to constitute an essential part of asthenospheric studies. The asthenosphere under the oceans differs from that under the continent by variations in its thickness and by its depth of occurrence (Beloussov, 1968). If the seismic boundaries of the asthenosphere coincide with the boundaries determined by means of deep electro-magnetic sounding, then this is the evidence of the determining role of melts in the constitution of the asthenosphere itself. The inferred connection between the total integrated conductivity S of the asthenospheric layer and the age of ocean bottom is very promising, i.e. the more ancient the oceanic crust, the lower the conductivity of asthenospheric layer (Filloux, 1978, Vanyan, 1979).

Global magnetovariation sounding allowed the collection of data on the distribution of electrical conductivity over the globe. The initial material of the soundings was obtained at magnetic observatories situated only on continents. Global oceanic E.M. sounding should be regarded in perspective as one of the most attractive objectives of marine geoelectrics at present. In general a deep electromagnetic sounding allows the determination of the position of the boundaries between layers with an accuracy greater than the determination of the electrical conductivity. Nevertheless a more accurate determination of the electrical conductivity of the Earth's crust and upper mantle is a most desirable goal. The review of Cox (1978) deals with this aspect. Electromagnetic fields of hydrodynamical origin should perhaps be used as a contribution to the solution of this problem. The possibility of using the electromagnetic fields associated with oceanic water currents in S determinations of the sedimentary layer has, in fact, been solved (Trofimov *et al.*, 1978). The authors used the impedence principle and suggested an experimentally verified method of determination of the total integrated conductivity of sedimentary layer by using measurements (on the bottom) of all three components of the magnetic field, of the two horizontal components of the elctrical field, and also of the average local current velocity. The possibility of performing deep induction soundings by means of the fields of oceanic currents is restricted by the small value of the vertical velocity component in the open sea (Leibo and Semenov, 1978). As follows from the paper (Poehls and Herzen, 1976), at least in some of the regions of the world oceans, the electrical resistance of the crust and upper mantle is small. This conclusion is obtained from a new evaluation of deep soundings by taking account of galvanic connection of current fields with the geoelectrical section. As in the case of galvanic sounding at constant current, the deep sounding of current fields is impossible in the presence of high-ohmic intercalation under the sediments. Therefore, the results obtained by Poehls and Herzen (1976) shows the means for deep sounding of fields of currents, large-scale vortexes and long-period waves.

It is necessary to know how to distinguish between ionospheric and motional fields, so as to effectively use the electromagnetic field observed in the oceans. The electromagnetic fields of currents and waves are the noise of magnetotelluric sounding. In turn, the magnetotelluric field brings about essential restrictions on the possibility of using electromagnetic methods to study the parameters characteristic of currents and long-period waves. The effectiveness of the geomagnetic electrokinetograph (GEK), for example, depends on the consideration of the effect of telluric currents. This is particularly true for the long-period range of variations. The electrical fields of sea-surface waves are much greater than short-period variations of telluric currents. The towed electrode line of the GEK can be used to determine the parameters of waves during the movement of the ship in the open sea (Fonarev, 1976). A two-dimensional progressive wave model is used. On legs parallel to the crests of waves, the elements of the measuring base together with water particles make orbital movements in planes perpendicular to the course of the ship. In this case the meter records the signal:

$$\Delta V_{/\!/} = (V_z \cdot H_x - V_x \cdot H_z) . l \,,$$

where V_x, V_z are velocity components of water particles; H_x, H_z are, respectively, the horizontal component of the magnetic field of the Earth perpendicular to the course, and the vertical component; l is the length of the measuring base. The measuring base experiences high tension during towing. It is assumed that on legs perpendicular to the crests of waves the elements of the measuring base cannot make oscillatory movements together with water particles. In this case the signal recorded is as follows:

$$\Delta V \perp = H_v \int_{l_1}^{l_2} V_z \, \mathrm{d}X \,,$$

where H_y is the magnetic field component; l_1 and l_2 are the distances from the ship at which the electrodes are towed. If our suppositions are true, there is a possibility of measuring electrical fields of waves during the movement of the ship and of determining the following parameters: period of waves, height and length of wave. Experimental verification produced positive results (Novysh *et al.*, 1979). This example again demonstrates the possibility of using the electromagnetic fields observable in the ocean for oceanographic research.

There is still another example of the useful application of electrical fields; Korotaev (1979) gives an estimation of the electromagnetic field generated by the sea water that percolates through the sea floor. The electromagnetic field of this source is determined mainly by filtration processes; its magnetic field contribution corresponds to tens of nT, while its electric field contribution is in the hundreds of mev m^{-1}. It is suggested that such an electrical field could be used for reconnaissance, compilation of charts and determination of discharge rate of ground waters through the sea floor. Corresponding experiments were made in the Barents Sea, the Sea of Japan and the Caspian Sea (Korotaev, 1979; Korotaev *et al.*, 1979).

In the U.S.S.R. magnetotelluric reconnaissance is conducted in the Baltic, Caspian and Black Seas (Sochelnikov, 1979). Magnetovariation profiling has been conducted in the South-Caspian mega-depression with the purpose of verifying the position of inhomogeneities in the geoelectrical section (Schneier *et al.*, 1979).

The method of local magnetovariation sounding was used in the Arctic Ocean. Here, variations of the vertical component of the magnetic field observed on the Earth's surface are of smaller amplitude than the primary H_z variations. The greater the conductivity of the Earth, the less are the observed H_z. The rate of decrease of H_z variations at different frequencies is actually the source of information on the geoelectric section. It is necessary to know the location and kind of variation sources to make local MVS. In that case suitable formulas are obtained for simple models of the source (dipole, filament, filament with spreading current, etc) in asymptotic cases; these formulas connect the relation of the vertical and horizontal components of magnetic variations with impedance.

The Arctic Ocean is within the auroral zone; the polar ionospheric electrojet stretches along it perimeter and is the most powerful source of variations in high latitudes. The polar electrojet is modelled as a raised arc with spreading current. The magnetic field components depend on the position of the arc in relation to the observation point, which changes during the day. A local MVS is made by using one baylike disturbance with allowance for a specific position of the source. The arc-sharped source can be replaced with a dipole with spreading current by introducing effective distance from the observation point to an equivalent dipole (Volkomirskaya, 1978). This technique of local MVS was tested on the known geoelectric section in the Arctic Ocean by Volkomirskaya and Fonarev (1978). The determination of the effective distance to the source is one of the important operations in the local MVS method. The relation of the horizontal electrical component of the electrical field to the vertical magnetic component of the magnetic field was used for this purpose. This relation is independent of geoelectrical parameters and permits the determination of the effective distance to the source:

$$d_{\mathrm{eff}} = |E_x/H_z| \cdot T/\mu_0 \Pi,$$

where T is the period of variations (Volkomirskaya and Fonarev, 1978).

New results of deep sounding in the Arctic Ocean have been obtained in recent years. Though not large, this ocean has almost all kinds of oceanic and suboceanic structures. The Arctic Ocean is characterised by geological, geomorphological and geophysical inhomogeneity best manifested in its deepwater part, i.e. in the Arctic Basin. The western portion of the Arctic Basin (Eurasian sub-basin) is the polar fragment of the North Atlantic mega-basin with its typical spreading structure and with a crust of oceanic type. The Gakkel Ridge belongs to the Mid-Arctic Ridge. It is believed that part of the boundary between the Eurasian and North American plates passes along the ridge (Zonenshain *et al.*, 1978). In the western part a sounding was made at a single point in the southern part of the Gakkel Ridge (Trofimov and Fonarev, 1976). The results of this sounding still need interpretation, for they did not reveal the features typical of oceanic geoelctric sections. There are certain circumstances that may possibly explain these results. The rates of crustal spreading in this region are less by a factor of ten than those in the mid-oceanic ridges in other oceans. The banded structure of the anomalous magnetic field is already absent in the southern part of the ridge (Bogolepov and Chikov, 1976) A complicated transformation of the oceanic rift system into continental rifts is possibly taking place in this part of the ridge. Moreover, this MTS result may reflect the process of attenuation of mobile masses in the interior of the Earth in near-pole regions (Liubimova *et al.*, 1976).

Magnetotelluric sounding in the central part of the Arctic Basin (the Lomonosov Ridge, the Podvodnikov depression, the East Siberian Sea) has produced a geoelectric section almost identical in parameters to sections on shields and platforms (Trofimov and Fonarev, 1976). This result is understandable since the central part of the Arctic Basin is expected to be the broken remnant of the continental margin of Eurasia (Heezen, 1975). The eastern part of the Arctic Basin (Amerasian sub-basin) cannot be as definitely characterised as its western and central parts owing to the unknown nature of the Mendeleiev-Alfa Ridge (Demenitskaya, 1975). The magnetic field of this ridge is different from the typically oceanic one; its crust is thinner than that on the continent and the bottom topography and some other features exclude the continental origin of the sub-basin. Only one region in the eastern part, the Chutkotka Cupola, was covered by sounding during the first investigations in the Arctic Ocean (Trofimov and Fonarev, 1976). In this region the depth to the conducting mantle was found to be 200 km. Later magnetovariation soundings were made at two points on the Mendeleiev Ridge (south-western and north-eastern parts), as well as magnetotelluric sounding in the Canadian depression, in the region adjoining the Mendeleiev Ridge (Trofimov, 1979, Baglaenko *et al.*, 1980). Figure 1 shows MVS curves (the Mendeleiev Ridge) and MTS curves (the Canadian depression). The curves differ only in the S range, the difference being accounted for by the conducting oceanic layer. As compared to the global MVS curve, these curves show lower ρ_T values. If from a certain depth the Earth is supposed to be spherically homogeneous, then any of the

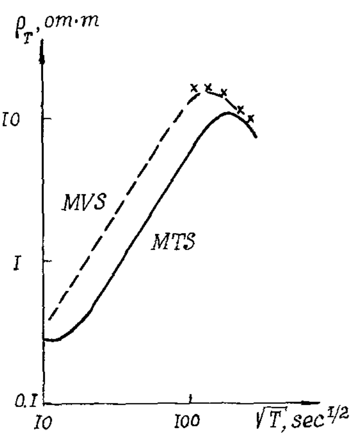

Fig. 1. Comparison of MVS and MTS curves.

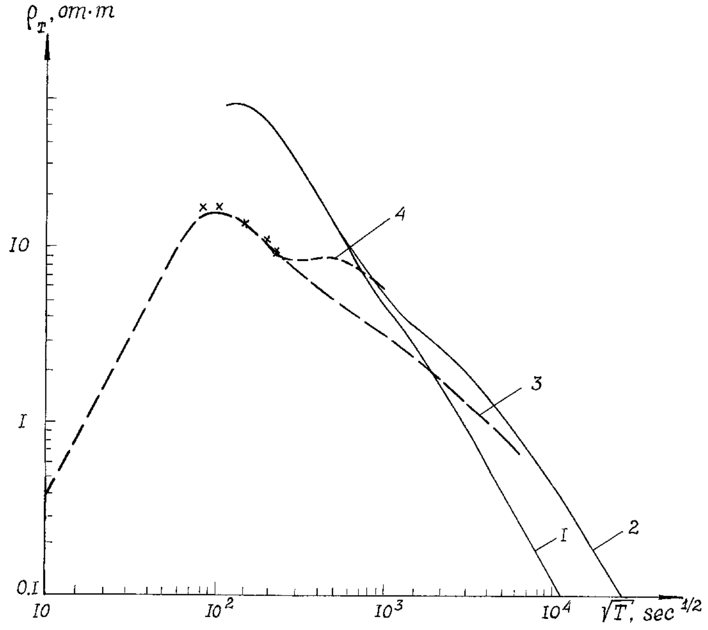

Fig. 2. Sounding curves: (1) global gradient; (2) global stratified; (3) calculated gradient; (4) calculated stratified

curves of local or regional sounding should transform into the global curve. In Figure 2 the local MVS curve (the Mendeleiev Ridge) is shown together with the gradient and stratified curves of global sounding (Dmitriev *et al.*, 1978). Calculations of the direct problem were made for two types of section: stratified and gradient. Their parameters are given in Table I.

TABLE I

d km	2,5	8	15	20	40	10	50	50	100	100	∞
ρ_T ohm m^{-1}	0,4	4000	15 000	6000	2000	800	600	500	2,5	10; 1,5	0,4

Calculated results are also shown in Figure 2. The basic difference between the gradient and stratified models is in the period range of $10^5 - 10^6$ s. Therefore, the point where the local curve appears on the global MVS curve is unknown. The depth of the highly conductive level is estimated to be 200 km. We can now state, with a certain degree of reliability, that the eastern part of the Arctic Ocean has a low-Ohmic geoelectric section.

Larsen (1976), among the most important problems affecting sounding, emphasised the need to study the effect of natural electromagnetic fields on fish. We now know that electromagnetic fields do have an important influence on the behaviour of fish. The paper (Protasov *et al.*, 1975) demonstrates how the catch depends on magnetic activity, and describes certain ideas about the mechanism of orientation of fish by the electrical fields. The possibility of perception of telluric currents and electrical fields of sea waves was experimentally proved (Brown *et al.*, 1978, 1979) by placing sharks in an aquarium electrically connected with the coastal sea zone in such a way that the intensity of the electrical field in the aquarium was equal to that in the sea. The frequency variations of the nerve impulses in response to fairly small variations of the electrical field (0.6 mcv m-s) were recorded in the process of this experiment.

Conclusions

At the present time the general outlines of three trends may be seen:

(1) Application of magnetotelluric fields for sounding the ocean bottom. The study of deep electroconductivity under the oceans has already given useful results.

(2) Electromagnetic fields of hydronamical origin may be perfectly well used to investigate the parameters of waves and streams. Except for the use of GEK, the work in this field is only just beginning.

(3) The study of the influence of natural electric fields on the life conditions of fish is developing into a new domain of science in which marine geoelectricity borders on ichthyology.

References

Baglaenko, N. V., Volkomirskaya, L. B., Dmitriev, V. I., Rotanova, N. M., and Fonarev, G. A.: 1980, 'Interpretation of Magnetovariational Probing Curves in the Eastern Part of the Arctic Ocean'. *Dokl. Akad. Nauk S.S.S.R.* 249.

Beloussov, V. V.: 1968, *The Earth's Crust and Upper Mantle of the Oceans*, Nauka, Moscow.

Bogolepov, K. V. and Chikov, B. M.: 1976, *The Geology of the Ocean Bottom*, Nauka, Moscow.

Brown, H. R., Ilynsky, O. B., Muravejko, V. M., Gorshkov, E. S., Skriabin, S. A., Tiulenev, A. I. and Fonarev, G. A.: 1978, 'Perception of Telluric Currents, Due to the Geomagnetic Variations, by the Electroreceptors of Lorenzini Ampullae of Shark Fishes', *Dokl. Akad. Nauk S.S.S.R.* 241.

Brown, H. R., Ilynsky, O. B., Muravejko, V. M., Gorhkov, E. S., and Fonarev, G. A.: 1979, 'Evidence that Geomagnetic Variations Can Be Detected by Lorenzinian Ampullae', *Nature* 277.

Brown, H. R., Ilynsky, O. B., Muravejko, V. M., Morozov, P. A., Fomenko, V. P., and Fonarev, G. A.: 1979, 'Perception of See Wave Electric Fields by Lorenzini Ampullae Electroreceptors', *Dokl. Akad. Nauk S.S.S.R.* 248.

Cox, C. S.: 1978, *Electromagnetic Induction in the Oceans and Inferences on the Constitution of the Earth.* Preprint, Murnau, F.R.G.

Demenitskaya, R. M.: 1975, *The Earth's Crust and Upper Mantle*, Nedra, Moscow.

Dmitriev, V. I., Rotanova, N. M.; and Balikina, O. N.: 1978, 'About Geoelectrical Interpretation of Results of Global Magnetovariation Sounding', *Geomagn i Aeron.* 18.

Fainberg, E. B.: 1978, *Electromagnetic Induction in the World Ocean*, Preprint, Murnau, F.R.G.

Filloux, J. H.: 1978, *Magnetotelluric Soundings over N.E. Pacific May Reveal Spatial Dependence of Depth and Conductance of Astenosphere*, Preprint, Scripps, Inst. of Oceanogr., U.S.A.

Fonarev, G. A.: 1976, 'On the Nature of Wave Interference with the Electromagnetic Current Meter Recordings'. *Oceanology* 3.

Heezen, B.: 1972, *Inland and marginal seas. The upper mantle*, A. R. Ritsema (ed.).

Korotaev, S. M.: 1979, 'Filtering Electromagnetic Field of Submarine Sources', *Izv. Akad Nauk S.S.S.R., Ser. Fiz Zemli* 8.

Korotaev, S. M.: 1979, *Submarine Sources' Electrical Field in the Caspian Sea. Fundamental Problems of Marine Electromagnetic Investigations*, Nauka, Moscow.

Korotaev, S. M., Shneer, V. S., and Gurevich, V. I.: 1979, 'Submarine Sources' Ascending Velocity Estimates from Filtering Electric Field Data', *Sovetskaya geologiya* **6**.

Larsen, J. C.: 1976, 'Marine Electromagnetic Studies', *Acta Geod., Geoph. et Montanist. Acad. Sc., Hungary* **11**.

Leibo, A. B. and Semenov, V. Ju.: 1978, 'Conditions of the Current Origin on the Sea Bottom, Induced by Water Motion', *Geomagn. i Aeron.* **18**.

Liubimova, E. A., Nikitina, V. N., and Tomara, G. A.: 1976, *Thermal fields of the U.S.S.R. Inland and Marginal Seas*, Nauka, Moscow.

Novysh, V. V., Smagin, V. P., and Fonarev, G. A.: 1979, *On Wave Electric Field Measuring by Means of Towed Electrodes. Fundamental Problems of Marine Electromagnetic Investigations*, Nauka, Moscow.

Poehls, K. A. and von Herzen, R. P.: 1976, 'Electrical Resistivity Structure Beneath the North-West Atlantic Ocean',*Geoph. J. Roy. Astron. Soc.* **47**.

Protasov, V. R., Fonarev, G. A., and Shneer, V. S.: 1975, 'On Natural Marine Electric Field Influence on Fish Behaviour and Distribution', *Zoologichesky Jurnal* **47**.

Shneer, V. S., Finger, D. L., Dubrovsky, V. G., Piatibrat, O. M., Pukhomelin, A. F., Bobrov, V. N., Gaydash, S. P., and Ignatov, I. I.: 1979, *Preliminary Results of Magnetovariational Measurements at the Southern Caspian Water Area. Fundamental Problems of Marine Electromagnetic Investigations*, Nauka, Moscow.

Sochelnikov, V. V.: 1979, *Basic Theory of the Natural Marine Electromagnetic Field*, Hydrometeoizdat, Leningrad.

Trofimov, I. L.: 1979, 'Magnetotellurical Sounding in the Canadian Hollow', *Geomagn. i. Aeron.* **19**.

Trofimov, I. L. and Fonarev, G. A.: 1972, 'About the Applicability of the Sounding Gradient Methods on the Ocean', *Geomagn. i. Aeron.* **12**.

Trofimov, I. L. and Fonarev, G. A.: 1976, *Deep Magnetotelluric Surveys in the Arctic Ocean. Geoelectric and Geothermal Studies, KAPG Geophys.* Monogr., Budapest.

Trofimov, I. L., Shneer, V. S., and Korotaev, S. M.: 1978, 'Definition of Summary Longitudinal Conductivity of Sea Sediments and Full Streams on Electromagnetic Field of Streams', *Geomagn. i. Aeron.* **18**.

Vanyan, L. L.: 1979, *Deep Geoelectrical Models: Geological and Electromagnetic Principles. Simp. Electr. Cond. and the Charact. of the Astenosphere*, Australia.

Volkomirskaya, L. B.: 1978, 'Mathematical Source Modelling in the Auroral Zone Serving to Estimate the Potentialities of the Local MVS'. *Izv. Akad. Nauk S.S.S.R., Ser. Fiz. Zemli* **11**.

Volkomirskaya, L. B. and Fonarev, G. A.: 1978, 'Experience of Local Magneto-variations Sounding in the Region of the North Arctic Ocean', *Geomagn. i. Aeron.* **18**.

Volkomirskaya, L. B. and Fonarev, G. A.: 1978, 'About Experimental Determination of the Distance to the Source of Variations for Purposes of MVS', *Geomagn. i. Aeron.* **18**.

Zonenshain, L. P., Natapov, L. M., Savostin, L. A., and Stavsky, A. P.: 1978, 'Recent Plate Tectonics of North Atlantic and Arctic Basins', *Oceanology* **5**.