OCEANIC ELECTROMAGNETIC STUDIES: A REVIEW

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Abstract. The review covers the main results of the oceanic electromagnetic studies presented during last 4–5 years. Seafloor electromagnetic observations are dedicated to studies in solid Earth geophysics and oceanography. Thus, a large range of objectives and targets are under investigation. Technological and theoretical advances provide an increase of quantity and quality of the collected seafloor data. The host conductivity models for oceanic crust and mantle are being developed; the possibility of obtaining useful structural constraints in heterogeneous environment are discussed. Significant oceanographic results were derived from electromagnetic field observations; these appeared to be a new powerful method for study of long-term large-scale ocean variability.

1. Introduction

This review covers the main results on oceanic electromagnetic (EM) studies presented during the 4–5 years since Constable's (1990) review was published. The other recent reviews emphasizing oceanic EM studies were presented by Chave *et al.* (1992a), Brown (1992), Tarits (1992), Lilley (1993) and Lanzerotti *et al.* (1993a, 1993b). This selected list of review papers covers the background theory and previous results.

Oceanic EM studies are multifold: the methods and techniques as well as the objectives and targets are extremely varied. Artificial and natural EM fields in different spatial and frequency ranges and of different origin are studied. The conductivity structure of the oceanic crust and mantle, as well as large-scale, long-term ocean variability, can be studied with EM methods.

The following sections of this review consider controlled source electromagnetic (CSEM) methods, natural EM fields and technique used for measurements, magnetovariational (MV) and magnetotelluric (MT) soundings and motionally induced EM fields and their oceanographic applications; each section has a brief introduction followed by a review of recent activity and the main results obtained. A comprehensive review of the pertinent literature is included.

2. Controlled Source EM Methods

2.1. Introduction

A large number of CSEM methods utilizing time-varying electric and magnetic dipole sources to induce electric currents inside the conducting bottom are used

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in the oceans. Both frequency and time domain systems are in use. Since the penetration depth for these methods is limited; mainly the first two layers of oceanic crust can be studied (Edwards *et al.*, 1985; Edwards and Chave, 1986). Only deep CSEM frequency soundings utilising frequencies around 1 Hz allow investigation of the whole oceanic crust and lithospheric mantle (Cox *et al.*, 1986). Induced polarisation (IP), spontaneous polarisation (SP) and direct current (DC) methods are used for seafloor conductivity mapping and exploration of sulphide mineral and petroleum deposits (Brewitt-Taylor, 1975; Francis, 1985; Chave, 1990, Gramberg *et al.*, 1992; Vishnyakov *et al.*, 1992). The seafloor is a very different environment, because of the conductive seawater covering the seafloor and acting as a low pass filter for fluctuating EM fields. These peculiarities determine significant differences in theory and technique of EM studies that were described in detail by Chave and Cox (1983a) and Chave *et al.* (1992a).

Petrophysical properties of the oceanic crust differ from those on the continent as well. The main factor determining the physical properties of the oceanic crust is seawater saturating practically all the oceanic crust due to its high porosity and permeability (especially of the first two layers of the crust). As a result the small-scale near-surface conductivity inhomogeneties are significantly smoothed and the lithological composition of the crust is not the main factor determining it's in situ physical properties as it is within the continental crust.

The electrical conductivity of the oceanic sediments is highly dependent on the porosity as expressed through Archie's law (Archie, 1942). The sediments in the oceans are rarely thicker than a few hundred meters and are often water-saturated. The porosity is 40–80% near the seafloor and its value decreases with depth due to lithification and diagenesis; electrical conductivity of the sediments is 1.5–4 times smaller than that of seawater (Piskarev *et al.*, 1987). Pillow basalts are also water-saturated, especially in the spreading zone, and its conductivity is about 0.1 S m^{-1}, while underlying less porous basalts are much more resistive (from 0.03 to 0.001 S m^{-1}).

The porosity and permeability of the oceanic crust depends on the age of the lithosphere; hydrology geophysics implications are pretty important (Johnson and Semyan, 1994). The oceanic Moho is considered to be impermeable for water due to serpentinization processes and, as a result, only mantle fluids could exist below Moho (Anderson, 1989; Sorokhtin and Ushakov, 1993).

One more significant feature of the oceanic crust is anisotropy. In the vicinity of the ridge, basalts are extruded onto the seafloor within a narrow, fissured zone. The fissures are filled with the seawater and sediments that are better conductors than the host basalts. As a result, the anisotropy of electrical conductivity in the vertical direction and in the direction parallel to the ridge axis must be observed. As time progresses the cracks are filled with the more resistive products of low-temperature hydrothermal metamorphism (Shaw, 1994). Measurements of anisotropy in the lithosphere of varying age is an indicator of the tectonic activity at the ridge.

EM responses from the anisotropic oceanic crust models were analysed theoretically. The influence of vertical anisotropy was analysed by Yu and Edwards (1992a); they also suggest an algorithm for the computation of EM responses of multilayered, laterally anisotropic seafloor to arbitrary finite sources (Yu and Edwards, 1992b). Vanyan and Palshin (1996) discussed CSEM frequency sounding results for vertically anisotropic seafloor. It was shown that the influence of anisotropy on CSEM studies can not be neglected.

2.2. CONDUCTRVITY MAPPING OF THE SEAFLOOR

Several methods are intended for conductivity mapping of the seafloor mainly for prospecting sulphide mineral deposits. Starting from 1978 in Russian Geological Service (All-Russian Research Institute for Geology and Mineral Resources of the World Ocean, St. Petersburg) the direct electrical prospecting technique for petroleum and sulphide mineral deposits in the oceans has been developed. A number of deep-towed systems were designed for these purposes. The most recent one, named "Rift", consists of a multichannel streamer providing SP, IP and DC methods, among other hydrophysical and hydrochemical probes (Vishnyakov *et al.*, 1992).

Several towed CSEM systems were developed in Canada and the USA (see Figure 1). A towed EM transient system has been developed for measuring the conductivity of the uppermost 5–10 m of sediments on the seafloor. Transmitter and receiver are horizontal magnetic dipoles separated by 20 m (Cheesman *et al.*, 1987, 1990, 1991). A deep-towed EM transient system that is an adaptation of the above mentioned one, was developed for shallow electrical conductivity structures mapping in the deep sea. The transmitter and receiver are separated by 50 m and are sufficiently robust to survive continual contact with thinly sedimented, abrasive basalts. The average conductivity of the upper 25 m of the seafloor can be mapped using this instrument (Webb *et al.*, 1993). A towed frequency domain dipole-dipole system for EM surveying on the continental shelf was developed at Scripps Institution of Oceanography for mapping such resistive features as basalt flows.

2.3. DEEP CSEM SOUNDING

The Magnetometric Off-Shore Electrical Sounding (MOSES) method was developed for deep crustal sounding and mapping of sulphide deposits (e.g. Edwards *et al.*, 1985; Nobes *et al.*, 1986). Transmitter consists of a current transvertor connected at the output stage through a long vertical insulated cable to a source electrode at the seafloor. The current returns to an identical electrode at the surface that is in turn connected to the transvertor return stage. The magnetic response is recorded using a remote magnetometer consisting of two horizontal flux-gate sensors and encased in a pressure tight sphere (see Figure 2). The apparent resistivity, derived

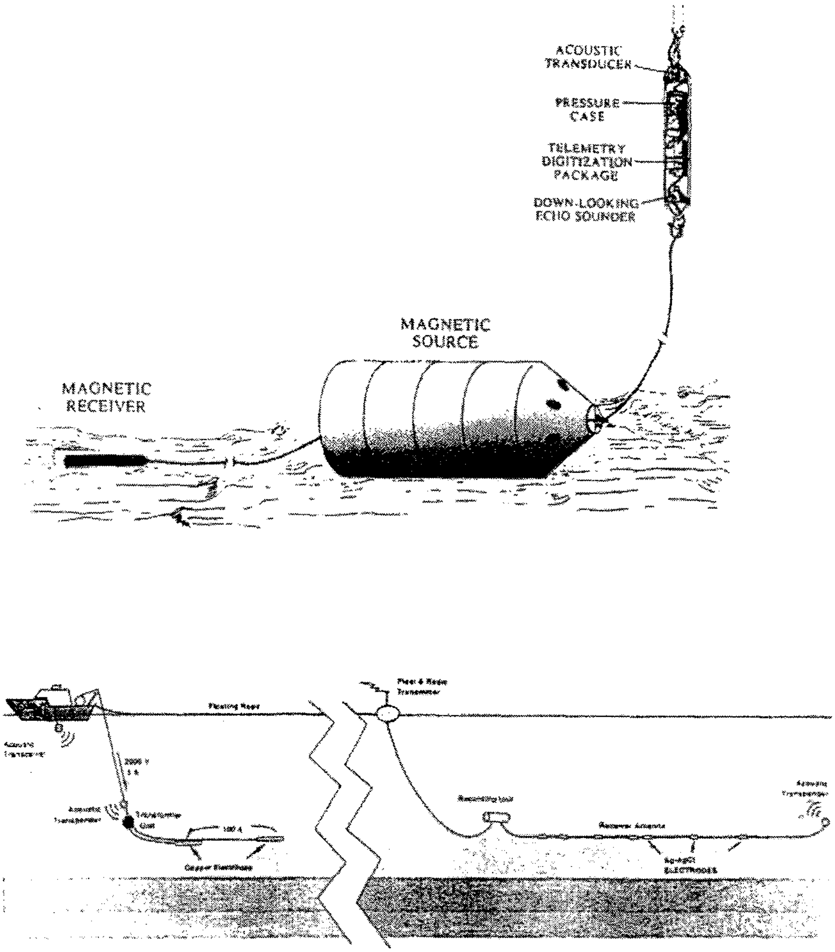
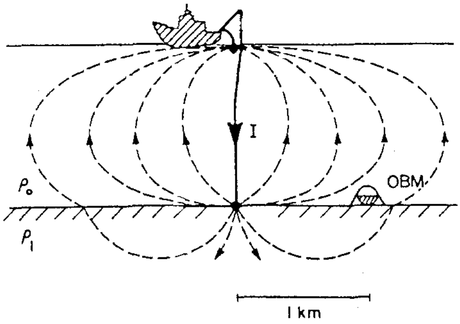


Figure 1. Deep towed EM systems for studying the uppermost part of the oceanic crust: transient deep electromagnetic (TDEM) system (top panel) and frequency domain profiling system developed at Scripps Institution of Oceanography (lower panel); from Webb *et al.* (1993) and Chave *et al.* (1992a).

from the magnetic field response, versus the source-receiver separation is used for modelling the electrical structure of the crust.

The most powerful tool for studying the electrical conductivity of the oceanic crust and lithospheric mantle is the CSEM frequency sounding method developed at Scripps Institution of Oceanography (Young and Cox, 1981; Webb *et al.*, 1985; Cox *et al.*, 1986). At present, the same technique is used by geophysicists from the University of Cambridge in the UK (Sinha *et al.*, 1990). The system utilises a long horizontal electric dipole with bared ends that is energised at frequencies of 1 Hz plus or minus a decade and a series of horizontal electric field receivers utilising Ag-AgCl electrodes to couple to seawater and separated from the transmitter at



MOSES

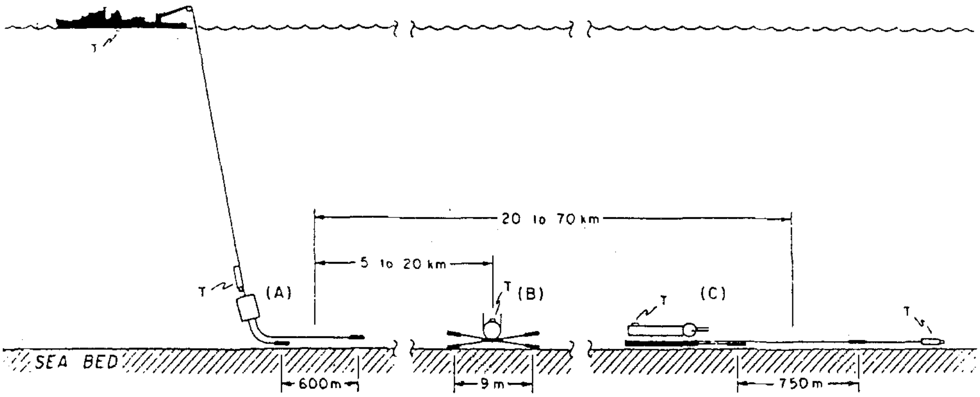


Figure 2. A sketch showing the principle of the Magnetometric Off-Shore Electrical Sounding (MOSES) system (top panel) and deep frequency sounding system (lower panel). A – seafloor transmitter, B – electric field recorder (range from 5 to 20 km) and C – long antenna EM recorder (range from 20 to 70 km); from Chave *et al.* (1992a).

1–200 km. The seafloor based-transmitter is connected to a surface (ussually a research vessel) power source by an insulated cable. The receivers are separate, self-contained horizontal electric field recorders (see Figure 2).

CSEM frequency sounding interpretation technique is under development; the inverse problem is solved usually by calculating the electric field as a function of separation between the transmitter and receiver for a set of 1D resistivity models to fit the experimental data (e.g. Cox *et al.*, 1986; Evans *et al.*, 1991). The resolving power of the method is now under investigation by several scientific teams.

Chave *et al.* (1990a) explored the seafloor-to-seafloor response to a horizontal electric dipole source for a reference model consisting of relatively conducting sediments and 6.5 km crustal layer overlying a resistive subcrustal (about 10^{-5} S m^{-1}) channel of 30 km thickness and terminating in a deeper conductive half-space. The response was explored as a function of frequency and range. The field enhancement due to trapping of electromagnetic energy in the resistive subcrustal wave guide was marked at frequencies other than 1 Hz. The results indicate that attempts either to model CSEM sources or to interpret controlled source data using half-space models for the Earth can be badly misleading.

Vanyan and Palshin (1993) analysed electric field of horizontal electric dipole on the seafloor and suggested to normalise it to the electric field corresponding to an insulated seabed. It was shown that the electric field attenuation depends mainly on range and an apparent resistivity as a function of range can be introduced. Vanyan and Jattieva (1996) utilised this approach for studying the depth resolution of seafloor CSEM frequency soundings and found that high-resistive layers screen the electric field and restrict the depth resolution of the method, especially in reference to underlying conductive layers.

Unsworth (1994) studied the response of such crustal targets as magma chambers and hydrothermal circulation zones, and estimated the effect of near-surface heterogeneity with a numerical modelling technique developed for a 2D conductivity structure excited by a 3D current source (Unsworth *et al.*, 1993). It was shown that near-surface heterogeneity effects could be large enough to prevent useful structural constraints being obtained.

Hence, the latest studies show that the resolving power of CSEM frequency soundings in reference to deep conductive layers and bodies is limited. Nevertheless, this method could be an efficient instrument for studying the geoelectric structure of the oceanic crust and lithospheric mantle if near-surface heterogeneities and anisotropy can be taken into account.

2.4. CONDUCTIVITY STRUCTURE OF THE OCEANIC CRUST

CSEM studies of the uppermost seafloor during the last 4 years were not very intensive. Cheesman *et al.* (1991) presented the results of porosity determination in the uppermost 5–10 meters of sediments on the seafloor from Knight Inlet, British Columbia. Porosity values determined by electrical conductivity average between 45–60%. Webb *et al.* (1993) reported the first results from a deployment of a deep-tow transient EM system near Cleft Segment of the Juan de Fuca Ridge. The electrical conductivity averaged over the upper 25 m of seafloor along an 8 km track, 15 km to the west of the Juan de Fuca ridge was found to vary from 0.1 to 0.4 S m^{-1}. The changes in conductivity could be explained with the variations in the thickness of the sediment layer or variations in the conductivity of the basalts. The results of these measurements reinforce the possibility of conductivity mapping of the uppermost seafloor in the axial part of the rift zone with transient CSEM deep-tow systems.

The latest studies of the oceanic crust show that the role that hydrothermal fluid circulation within crustal host rocks plays in controlling the physical properties of the crust, seems to increase in importance for understanding the evolution of the oceanic crust (Johnson and Becker, 1994). Thus studies of hydrothermal fluid circulation zones are one of the most important problems for CSEM in the oceans.

A good example of an electrical prospecting technique is detection and study of surficial sulphide mineral deposits. It is possible due to high conductivity of sulphides (5–10 S m^{-1}) and significant SP anomaly above it. A new hydrothermal vent field with sulphide mineralization on the Mid-Atlantic Ridge was discovered and mapped by a deep-towed system (Gramberg *et al.*, 1992).

Investigation of the embedded conductivity anomalies provided by hydrothermal circulation requires a CSEM technique with greater penetration depth. MOSES (magnetometric off-shore electrical sounding) is an example of such a technique that could be utilised for that purpose (Nobes *et al.*, 1986, 1992). Measurements with MOSES were carried out in Middle Valley, part of the northern Juan de Fuca complex, which is characterised by locally high heat flow, evidence of hydrothermal activity and near-surface mineralization. The background results yielded sediment conductivity of 1.2–1.5 S m^{-1} and basement conductivity of 0.12 S m^{-1}. The basement temperature and porosity were estimated to be 250 °C and 8–12%. Measurements carried out in an area with hydrothermal activity and high heat flow showed very high conductivity of the sediments (about 10 S m^{-1}). The sediments were found to be anisotropic; the degree of anisotropy is about 10. The results suggest that the horizontal conductivity is extremely high (of the order of 100 S m^{-1}), suggestive of sulphide mineralization, possibly occurring as thin layers interbedded with sediments saturated with hot fluids. The basement conductivity is 0.44 S m^{-1} and the porosity is estimated to be 10–14%. Data collected in this area suggest 2D or 3D structure summarised schematically in Figure 3. The presence of significant and probably widespread massive sulphide mineralization has been confirmed by ODP Leg 192:

CSEM frequency soundings carried out by Scripps in the north-eastern Pacific utilised frequencies around 1 Hz and transmitter-receiver separations up to 80 km. The results show that the host lower crustal conductivity is about 10^{-3} S m^{-1}, while the underlyng lithospheric mantle is characterised by extremely low conductivity that is estimated to be about 10^{-5} S m^{-1} (e.g. Cox *et al.*, 1986; Constable, 1990).

The first CSEM experiment aimed at detecting the presence of an axial melt body beneath a fast-spreading centre was conducted at 13° N on the East Pacific Rise (Evans *et al.*, 1991). A seismic low-velocity zone was discovered in this area at a depth of 1.25 km below the seafloor under the ridge axis. At around 4 km from the ridge, data indicate a normal oceanic crustal structure. The region is proposed to consist of a broad chamber, less than 6 km in width, of relatively low melt fraction

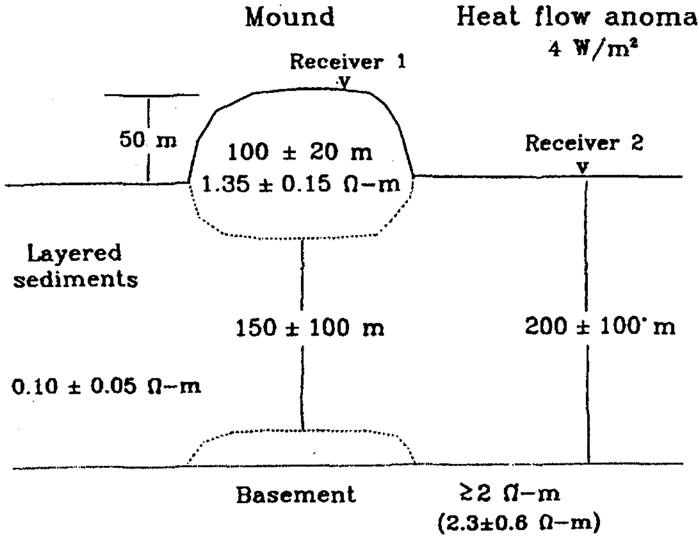


Figure 3. A conductivity model derived from MOSES studies at Middle Valley (part of the Juan de Fuca spreading center). The receiver locations are indicated; from Nobes *et al.* (1992).

(less than a few percent) surrounding a 1 km wide by a few hundred meter thick zone of higher melt fraction under the ridge crest at a depth of 1.25 km.

The results of the CSEM survey indicate a generally resistive crust at all depth to around 2 km and negate the possibility of a large volume of high melt fraction beneath the ridge crest. The results are consistent with a picture of axial structure that contains at most a few percent partial melt, most of which is in isolated crystallising pockets, with small pool of slightly higher melt fraction (about 10%) centred within 400 to 500 m beneath the ridge crust (Evans *et al.*, 1994).

Thus, the results of the CSEM suweys can be summarised as a reference host conductivity model of the ocean crust (see Table I). The physical properties controlling the electrical conductivity are age dependent (Johnson and Semyan, 1994; Carlson and Johnson, 1994), and hence the host conductivity of the oceanic crust is also proposed to be age dependent.

The hydrothermal circulation and sulphide mineralization zones, which are possible targets of CSEM surveys, are characterised by anomalously high conductivities which could be superimposed on the reference conductivity model background: the conductivity of sediments and fractured basalts are increased, due to the high temperature of pore fluids, high porosity and the presence of extremely conductive sulphides' layers; transverse anisotropy caused by interbedding of conductive and more resistive layers could be expected.

Table I
Host conductivity model of the oceanic crust.

Rocks	Conductivity, S/m	Thickness, km	Description
Sediments	0.75–2.0	≥ 0	Depends on porosity and temperature, isotropic
Fractured basalts	0.1–0.5	0.5–1.5	Depends on pososity and temperature, isotropic
Massive basalts	0.03–0.0003	≈ 5	Depends on cracks density and their direction and temperature, anisotropic?

3. Natural EM Fields in the Oceans

3.1. INTRODUCTION

Natural EM fields in the oceans are induced by two principal types of the sources: external – the ionospheric and magnetospheric current systems and internal – the dynamo interaction of moving conducting seawater with the Earth's magnetic field (core fields will not be considered here).

Thus, EM fields measurements in the oceans could be used for: (1) studies of the solid earth beneath the oceans by the magnetotelluric (MT) and magnetovariational (MV) methods, and (2) investigating the ocean variability. Excellent examples of such combined study are the EMSLAB and BEMPEX experiments: the first was focused on investigating the conductivity structure of the subducting slab and yet it yielded significant oceanographic results (Wannamaker *et al.,* 1989a, 1989b; Chave *et al.,* 1989) and conversely the second was intended to study barotropic water currents and allows in addition studies of the conductivity structure of the mantle in the central Northern Pacific (Luther *et al.,* 1987; Chave *et al.,* 1990b; Luther *et al.,* 1990).

The problem of separation of the EM fields induced by different sources has been studied by many geophysicists. Korotaev (1992) applied causal analysis to investigate the origin of EM fields on the oceans; the proposed procedure provides determination of the dominant type of source from a measured EM field (Korotaev *et al.,* 1993). This problem can be solved by studying the coherence between the magnetic field fluctuations measured on the continents, where motionally induced EM fields are presumably negligible, and EM fields measured in the ocean. The EM field spectrum is dominated by signals at tidal frequencies. Bindoff *et al.* (1988) analysed magnetic field fluctuations from the seafloor and on the continent during the Tasman experiment and demonstrated that the ionospheric dynamo and oceanic dynamo make comparable contributions to the horizontal fluctuations observed at the frequency of the M_2 tide. The horizontal electric and vertical magnetic fluctuation components at this frequency are almost entirely due to the oceanic dynamo.

For studying the deep conductivity structure beneath the oceans as well as for studying the long-period ocean variability, the tidal signals are a hindrance and must be excluded from the time series. The continuum spectrum is generated by fluctuations of the ring current at distances of 3–4 earth radii, auroral phenomena and ocean variability other than wide spatial and frequency range. Chave *et al.* (1989) analysed the spectrum of electric field fluctuations measured at the sea floor in the Pacific by ocean bottom electrometers and its coherence with the fluctuations of the magnetic field obtained at the continental observatories, and showed that beginning at frequencies of 1 cpd the electric field spectrum is dominated by motionally induced fields. The same analysis carried out for the electric field measured with long submarine cables California-Hawaii (Chave *et al.*, 1992b) and Australia-New Zealand (Vanyan *et al.*, 1994, 1995) showed that in this case the motionally induced fields dominate beginning from longer periods (about one week), due to significant spatial averaging of middle and small scale ocean variability (see Figure 4). Statistically meaningful correlation between the electric field measured by long submarine cables and on-land magnetic field exists up to periods of about 10 days in contrast to the point electric field measurements that are typically incoherent with the magnetic field at period greater than 2–4 days.

3.2. SEAFLOOR MEASUREMENTS

Ocean bottom magnetometers (OBM) and electrometers (OBE) are usually used to measure the fluctuations of natural EM fields in the oceans (Segawa *et al.*, 1983, 1986; Hamano *et al.*, 1984; Filloux, 1987; Sochelnikov *et al.*, 1992). The duration of the measurments should be at least several weeks for MT and MV studies and several months for oceanographic ones. The level of the signals to be measured is dramatically reduced by EM field damping in seawater. A salt-bridge chopper is used to remove the temporally time electrochemical potentials on the electrodes used in the receiving antennas in a OBE. Thus, ocean bottom instruments have to meet exacting requirements. Now, because of technological advances, the quality and quantity of data collected in the oceans is increasing, the multiyear deployments of OBM and OBE in the deep ocean become possible (Pettit *et al.*, 1992; Toh, 1993).

Over the last decade, several EM experiments were carried out by Japanese geophysicists. Beginning from 1984 geomagnetic variations were measured at six sites in total in the Ryukyu trench-arc system. The duration of the measurements varied from two weeks up to one and a half months (Shimakawa and Honkura, 1991). One more experiment was carried out on Tahiti Island in the south-east

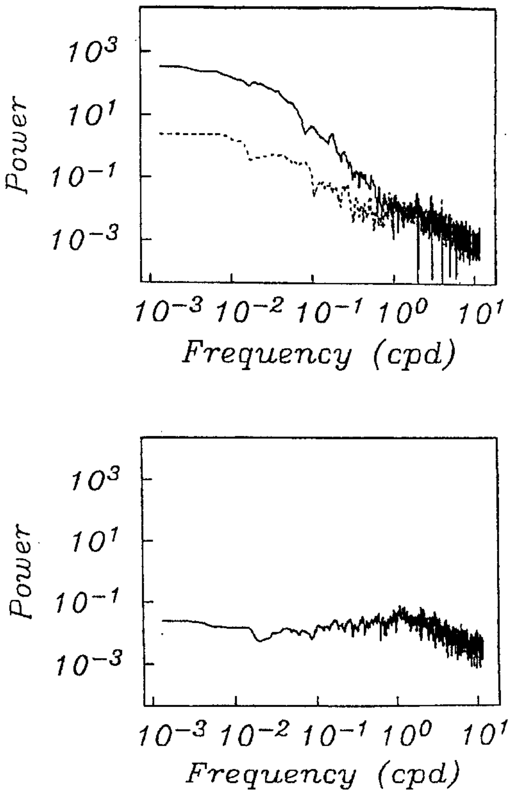


Figure 4. Power spectra (in (mV $\text{km}^{-1})^2$ cpd^{-1}) of hourly means of the electric field from the Hawaii-California I cable (lower panel) and for time series of the north electric component collected with point a sensor on the ocean bottom (top panel). In the upper panel, the solid line is for data taken under the Gulf Stream while the dashed line is for data acquired in a weak eddy variability region in the northern Pacific; from Chave *et al.* (1992b).

Pacific; the geomagnetic field variation was measured for about a month at two points (Yamaguchi *et al.,* 1992). One of the largest experiments was carried out at the Izu-Bonin Arc. Seafloor EM observations were conducted every year from 1986 through 1992 around one of the typical island arc-trench systems in the northwest Pacific. The observations were made by utilising both OBM (17 sites) and OBE (4 sites); the duration was from 1 to 4 months in each site (Toh *et al.,* 1991; Toh and Kitahara, 1993; Toh, 1993).

Several seafloor EM observations limited in duration were carried out by geophysicists from the FSU. In the Institute of Physics and Mechanics (Lvov, Ukraine) and South Department of Shirshov Institute of Oceanology (Gelendgik, Russia) an ocean bottom MT instrument was developed and tested in 1988 in the Bering Sea and South China Sea; the duration of the measurements was 27 and 20 hours, respectively (Sochelnikov *et al.,* 1992). In 1988 the simultaneous measurements of magnetic field fluctuations on the seafloor with three-component flux-gate magnetometer and near the surface with a proton magnetometer were carried out. The experiment was conducted in the Atlantic ocean at 9°01′3 N, 39°58′8 W in water 2932 m deep located at 50 miles from the Mid-Atlantic Ridge (Shneyer *et al.*, 1991). The same measurements were carried out in 1989 in the central part of the Tyrrhenean Sea (Palshin *et al.*, 1995). The duration of both experiments was about 5 days.

Indian geophysicists were conducting magnetic observations during three years (1988–1990) at Arabian, Andaman Seas and at the Bay of Bengal with Japanese OBM (D'Cruz *et al.*, 1991; Joseph *et al.*, 1991).

An OBE was installed on the landward slope of the Nankai Trough. This electrometer has 40 m long electrodes, which were extended with the aid of the manipulators of the submersible Nautile; 80 days of electric field variation comprising both north-south and east-west components were provided (Segawa and Toh, 1992).

A major international EM experiment, known as EMRIDGE, took place over the southern end of the Juan de Fuca Ridge, from the spreading ridge to the subduction zone. It was designed as a complement to EMSLAB (Wannamaker *et al.*, 1989a, 1989b). Collaboration between the groups from Japan, Canada and Australia led to eleven instruments (two OBE) being deployed on the seafloor, from July to November, 1988 (Heinson *et al.*, 1993).

From November 1992 to March 1993 a flux-gate OBM was deployed on the ocean floor approximately 200 km from the coast line of Southern California. Simultaneous magnetic field data were collected at a site next to the coast line; the duration of the measurements was about two months (Heinson *et al.*, 1994).

Most of the seafloor EM experiments were carried out (and are being carried out at present) in the USA; these experiments were aimed mainly for studying the ocean variability. The largest experiment, known as BEMPEX, was conducted in 1986–1987; 13 horizontal electrometers, 9 vertical electrometers, 12 pressure recorders and 7 three-component magnetometers were deployed for 11 months in an array covering about 1100 km east–west by 1000 km north–south, centred at 40° N, 163° W in the mid-latitude North Pacific. A second instrumental group, consisting of two magnetometers and a horizontal electrometer, was set near 31° N, 159° W as a remote reference site (Luther *et al.*, 1987).

A new scientific team was created in Woods Hole Oceanographic Institution (WHOI). Ocean bottom EM instruments, originally designed by Filloux, were modified (Petitt *et al.*, 1992). A new EM instrument for shallow (up to 1000 m) water was designed. These units record the vector electric horizontal field (without chopper), the vector variations of the magnetic field, pressure, temperature and two components of tilt at a nominal sample rate of 1 Hz for a month (Petitt *et al.*, 1993). Several large experiments were carried out by WHOI in the Atlantic ocean (personal communication with Chave, 1994):

- SYNOP (Synoptic Ocean Prediction). Four OBE were deployed for one year beneath the Gulf Stream off New Jersey. Electric field measurements were collected together with oceanographic measurements using current meters and inverted echo sounders (Luther and Chave, 1993),
- Antilles. 18 OBE and pressure recorders were deployed for 18 months along a 400 km line at 26.5° N off Abaco Island, the Bahamas.
- SEA (South–East Appalachies). An onshore-offshore geophysical transect along a line from south of Bermuda to about the 3000 m contour off South Carolina.

3.3. LARGE-SCALE ELECTRIC FIELD MEASUREMENTS

Submarine analog telecommunication cables are an alternative and very effective tool for measuring electric fields; both retired and in-service cables can be utilised for this purpose and in some cases special submarine cable could be installed for electric field measurements (Runcorn 1964, 1993; Bloom, 1964; Larsen 1985, 1992; Lanzerotti, 1992; Lanzerotti *et al.*, 1993b).

The use of submarine cables as long horizontal antenna coupled at one or both ends to the seafloor provide long-term, large-scale, low-cost onshore systems for measuring the electric field induced in the oceans. The advantages of a long cables are evident: the longer the receiving line, the greater is the level of signal while the electrode noise does not change. Moreover, transoceanic cables give a unique possibility to study electric potentials over very large spatial scales. In particular, measurements of quasi-steady telluric currents could yield information on dynamo processes withm the Earth's core.

Many transoceanic cables are now retiring from commercial service as they are replaced by fiber optic technology. In order to generate scientific community interest and support, several workshops on the scientific use of submarine cables were hold in USA and Europe (Honolulu, January 1990, Edinburgh, April 1992). Larsen (1991) showed that in-service submarine cables could also be used for electric potential difference measurements.

Electric potential difference measurements were carried out with the following cables (see Figure 5): several cables crossing the Florida Current (100–150 km), Sydney to Auckland (about 2600 km), Suva to Auckland (about 2250 km), Suva to Bamfield (about 9660 km), Tuckerton to Lands End (about 4471 km), California to Hawaii (about 3900 km) and other Pacific cables.

In addition Russian and Japanese geophysicists are planning to start measurements with Nakhodka (Russia) – Naoetsu (Japan) cable crossing the Japan Sea in 1995 (personal communication with Vanyan and Utada).

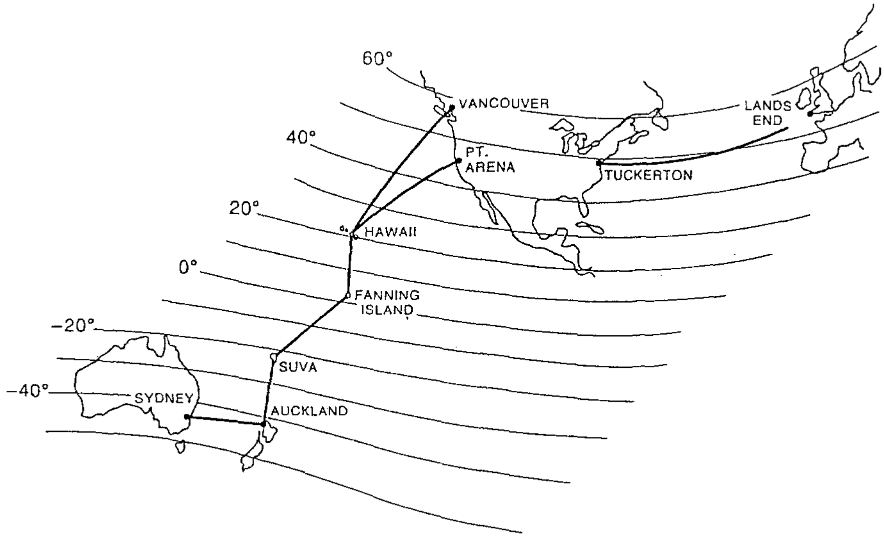


Figure 5. Locations in the Atlantic and Pacific oceans where DC potential measurements have been made using long cables; from Lanzerotti *et al.* (1993).

4. Magnetovariational and Magnetotelluric Studies

4.1. INTRODUCTION

The total amount of experimental data in the oceans is still limited, thus 2D inverse procedures cannot be applied in most oceanic studies (EMSLAB is the only exception). The most comprehensive approach is constructing a starting conductivity model using all available a priori information and then applying the trial-and-error method for modifying the model in order to fit experimental data. Another possibility is de-distortion of experimental responses or selecting quasi-1D data set with the help of 2D or quasi-3D thin-sheet numerical forward modelling (Sheinman, 1947; Price, 1949; Wiedelt, 1975; McKirdy *et al.*, 1985) and inverting the derived responses with 1D procedures like Parker's and/or Constable's algorithms (Parker, 1980, 1981; Constable *et al.*, 1987). This interpretation technique was developed in the late 80's and is widely used in Russia (e.g. Palshin, 1988; Berdichevsky *et al.*, 1989).

Vanyan *et al.* (1992b, 1994 and 1995) suggested a new approach for studying the TM mode measured by long submarine cables together with magnetic field variation obtained from nearby on-shore observatories for deep MT sounding of the oceanic mantle. As was mentioned above, the long cables average small-scale ocean variability as well as near-surface geoelectric inhomogeneties, and gives the possibility to estimate an impedance in the frequency range from 0.1 to 10 cpd. Most transoceanic undersea cables are directed across the coast lines and the electric field measured by such a cable corresponds to the TM mode (assuming a 2D structure) and thus is influenced by coast effect. Conductivity model parameters determining the coast effect could be estimated with the help of numerical modelling and the trial-and-error method.

4.2. OCEANIC MANTLE CONDUCTIVITY MODELS

One of the best examples of MT method application on the regional scale is the EMSLAB experiment held in the late eighties off the Pacific coast of the USA across the Juan de Fuca plate subduction zone. A rich collection of MT data of unprecedented breadth and quality has been collected here as a result of wide international cooperation (Wannamaker *et al.*, 1989a). The most representative subset of the EMSLAB MT data was obtained on the Lincoln Line transect along the 45th latitude. Interpretation of these data has given a detailed structure of subsurface resistivity and a general view of conductive asthenosphere beneath the ocean and low resistivity crustal inclusions on the continent (Wannamaker *et al.*, 1989b).

Varentsov *et al.* (1996) reported the results of the study of the existence of continental conducting asthenosphere and its relation to the oceanic one and the continental conducting crust structures (including the slab structure). A number of alternative models have been studied together with the original EMSLAB group model. The model verification was held mainly by 1D and 2D interactive graphical inversion codes (Varentsov and Golubev, 1996). The final EMSLAB group collection of broad band MT transfer functions (Wannamaker, 1990) together with processing estimates were used to form data sets for this joint inversion (namely, impedance phases, magnetic transfer functions and low weighted apparent resistivities). The main result of this study is the comparison of 2D geoelectric models inverted from the same data but with different starting models. The model with two laterally separated conducting asthenospheric half layers looks to be one of the best in this comparison (see Figure 6). However the difference in the quality of fit in relation to other models is rather slight, and the authors are going to search for more long period estimates and to reconsider weights of various data components for a new round of inversion solutions before reaching final conclusions.

The main island-arc systems in the vicinity of Japan were intensively studied in the last years; two new conductivity models were presented (see Figure 7). Shimakawa and Honkura (1991) developed a 2D model of Ryukyu Trench-Arc system. The comparison of transfer functions derived from observations and calculations yields a model showing two conducting zones in the mantle wedge; one at the depth range from 20 to 60 km in the forearc region and the other at the depth range from 60 to 130 km or more beneath the northwest region of the Okinawa Trough behind the arc. Toh (1993) presents a conductivity model of the Izu-Bornin arc determined from a complete dataset connected on east–west traverse lines from the subducting Pacific plate. The conductivity structure of the oceanic plates on both sides of the Izu-Bonin arc are characterised with the different thickness of

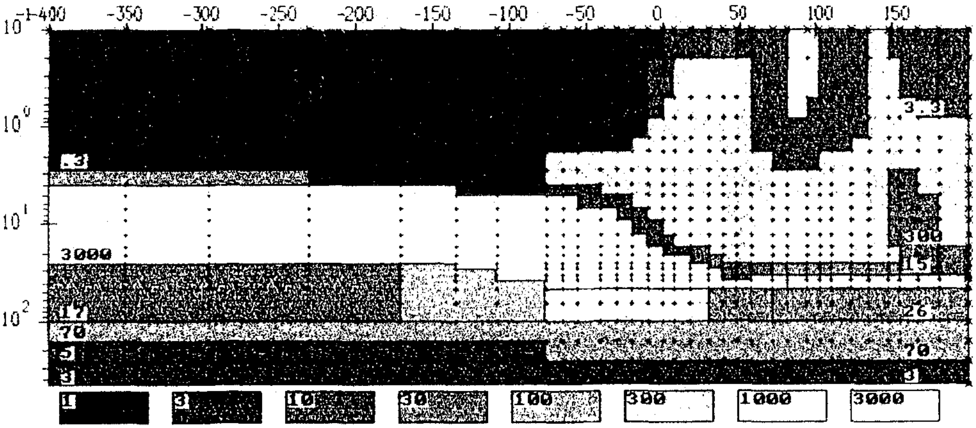


Figure 6. Geoelectric model with two asthenospheric structures inferred from 2D inversion along the Lincoln line (TE-mode); from Varantsov *et al.* (1996).

the lithosphere; the Pacific plate is thicker than that of the Philippine sea plate. The uppermost parts of the plates, corresponding to layer I and II of the oceanic crust, are conductive due to the large amount of water in these layers. After several trials and error a 2D conductivity structure was constructed. A forearc conductor was introduced in order to explain the small amplitudes of the observed transfer functions. The presence of the forearc conductor was also verified by 2D modelling using attenuation of the horizontal magnetic component between the sea surface and the seafloor for the TE mode.

The role of thin a conductor, interconnecting the near-surface (i.e. ocean) and deep conducting zones, is very important and can be interpreted as a fluid reservoir for the postulated dehydration process, and the forearc conductor may directly correspond to the hydrous column in Tatsumi's model (Tatsumi, 1989).

Heinson *et al.* (1993) presented the results of a major EM experiment known as EMRIDGE. The principal objective of this experiment was to investigate the migration and accumulation of the melt, hydrothermal circulation, and the thermal evolution of the oceanic lithosphere. Changes in the bathymetry, as it was found with the help of quasi-3D thin-sheet numerical modelling, have a major influence on seafloor EM observations. Furthermore, if the influence of the bathimetry is removed from the observations, then no significant conductivity anomaly is required at the ridge axis. A one dimensional inversion of MT data suggests that the top 50 km is electrically resistive, and that there is a rise in the conductivity at approximately 300 km. A high conductivity layer at 100 km depth is also a feature of 1D inversion, but its presence is less well constrained (see Figure 8).

Heinson and Lilley (1993) presented the results of thin-sheet numerical modelling and interpretation of MT data observed on the seafloor of the Tasman sea. MT responses were 'de-distorted' and then appeared to be isotropic, and were inverted using 1D procedures. MT data is diagnostic of a lithosphere conductivity of less

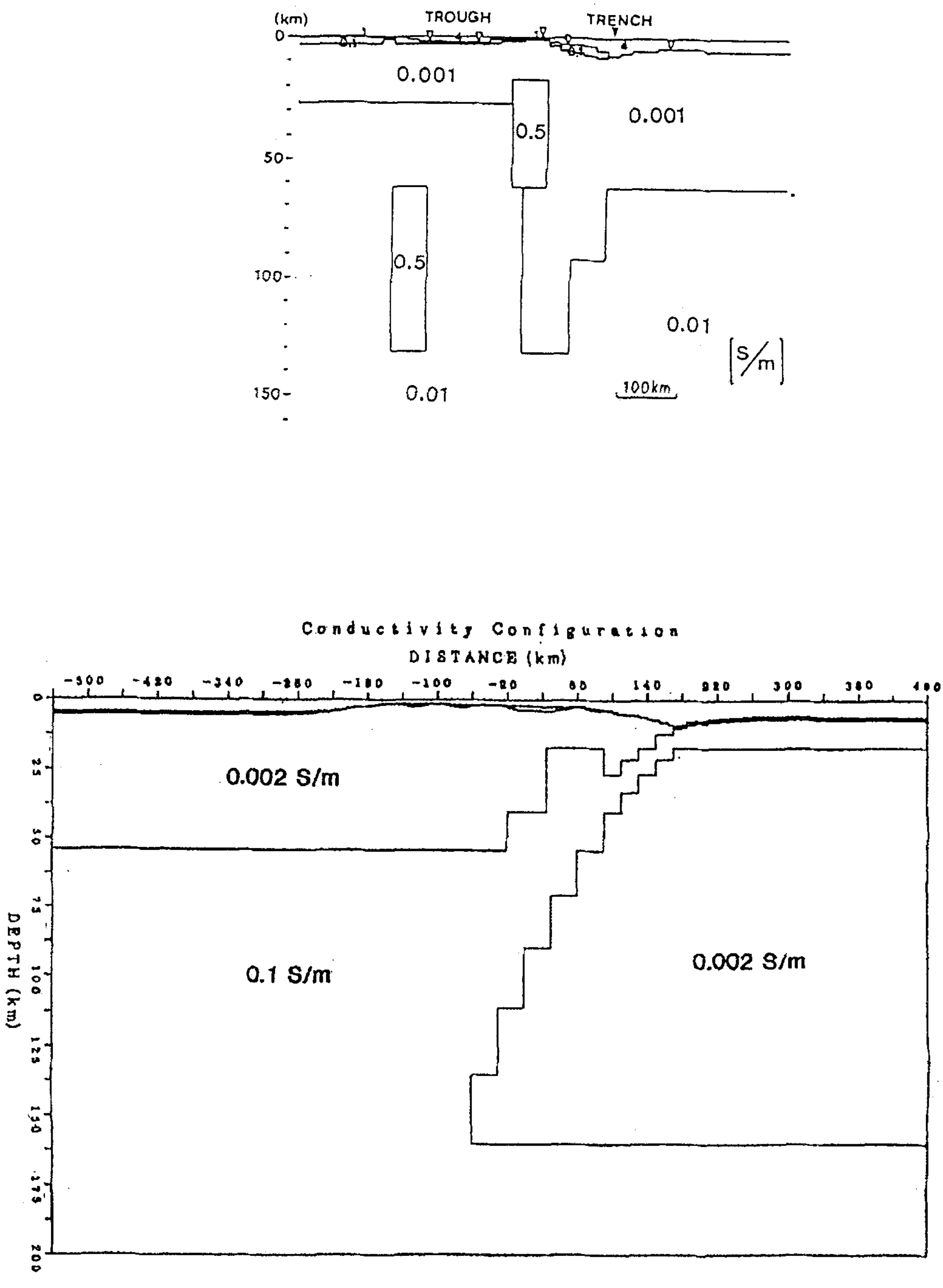


Figure 7. 2D models of the conductivity structure beneath the Ryukyu (top panel) and Izu-Bonin (lower panel) trench-arc systems; from Shimakawa and Honkura (1991) and Toh (1993).

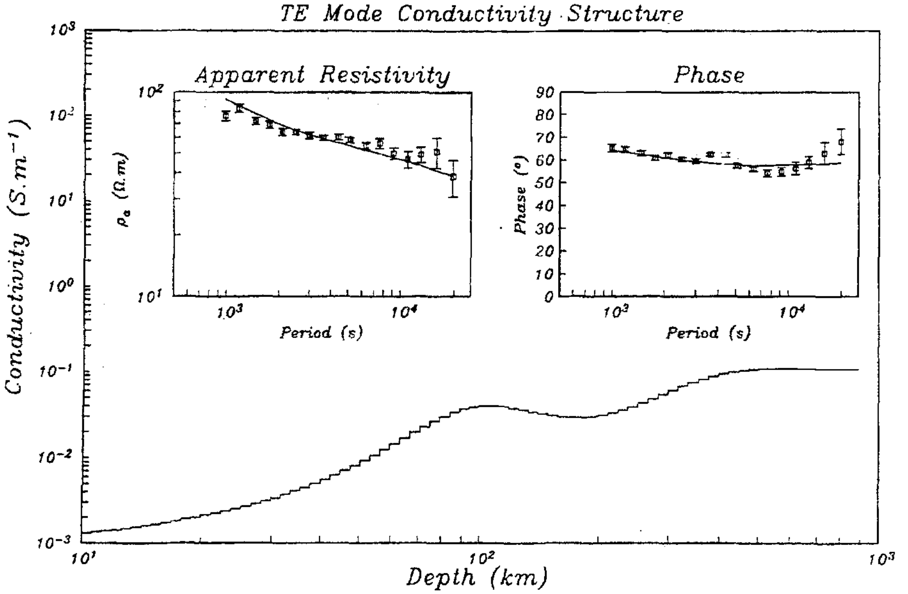


Figure 8. Occam's inversion of a subset of the EMBRIDGE TE mode MT estimates. The inset boxes show the apparent resistivity and phase data with one standard error, and the modelled MT response is shown as a solid line; from Heinson *et al.* (1993).

than 10^{-4} S m^{-1} (the estimation of integral resistivity of the lithosphere is $5 \cdot 10^8$ Ohm m^2). Conductivity rises by two orders of magnitude below 80 km, to greater than 10^{-2} S m^{-1}, and is probably related to an asthenospheric layer in the upper mantle. At a depth of approximately 400 km, the conductivity is approximately 1 S m^{-1}, consistent with global estimates for the lower mantle (see Figure 9). There is a little evidence for major change with age in the structure across the Tasman sea.

Heinson *et al.* (1994) constructed a 2D conductivity model of the Californian margin inferred from the coast effect (see Figure 10). The continental lithosphere was found to be less resistive than the oceanic one. The integral resistivity values are, consequently, $2.5 \cdot 10^7$ Ohm m^2 and $5 \cdot 10^8$ Ohm m^2. Below the lithosphere, the modelled electrical conductivity rises at a depth of 60 km, which marks the boundary with the asthenosphere.

A 1D conductivity model for south-east Pacific was estimated by Yamaguchi *et al.* (1992) through comparison of observed response functions and the predicted ones from a number of thin-sheet numerical models. A four-layer model is summarised as follows: (1) the first layer is highly conductive (oceanic crust) at the depth 5–10 km with conductivity of 1 S m^{-1}. (2) The second layer is less conductive (lithosphere) with conductivity of 0.05 S m^{-1} and is 40–50 km thick. (3) The third layer has a characteristic high conductivity (asthenosphere) of 0.1–0.2 S m^{-1} and is 9–10 km thick. (4) The bottom layer was assumed to be uniform with a conductivity of 0.06 S m^{-1}.

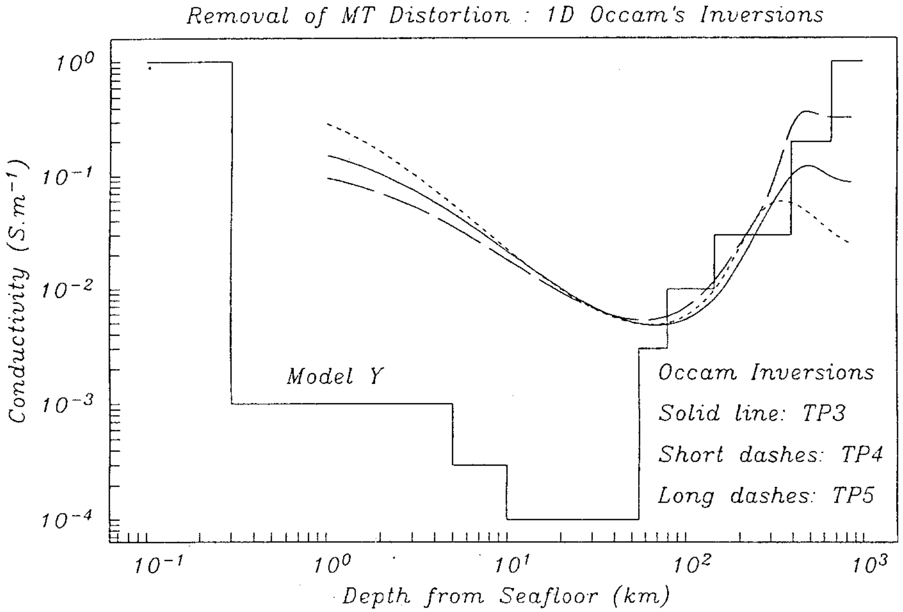


Figure 9. Occam's inversion of the corrected TM mode estimates from the MT responses obtained at the Tasman sea. Model Y has been shown to be the 'optimum' forward model in reproducing the observed data; from Heinson and Lilley (1993).

4.3. COAST EFFECT

The coast effect influence on MT and MV responses was estimated with both laboratory analogue and numerical modelling (e.g. Moroz, 1991; Dosso and Meng, 1992; Agarwal and Dosso, 1993) in order to remove the latter from the responses.

EM field anomaly analysis revealed that the coast effect plays a key role in MT and MV data interpretation; the coast effect is an additional source providing information on deep conductivity structure, especially on integral resistivity of the lithosphere, rather than a distortion effect (e.g. Chave and Cox, 1983b; Palshin, 1988; Vanyan and Palshin; 1990; Vanyan *et al.*, 1992a).

Berdichevsky and Yakovlev (1989) (see also Cox (1980)) obtained analytical expressions for impedance behaviour for the three layered 2D model (uppermost inhomogeneous conductive layer and the second uniform resistive layer underlaid by conductive half-space) which are convenient to use for analysing the coast effect. It was shown that the attenuation of TM mode impedance with the distance from the coast line depends on the galvanic constant $G = 1/\sqrt{S_1 \cdot R_2}$ where S_1 is conductance of the first layer (conductance of water layer and bottom sediments) and R_2 is the resistance of the second layer (integral resistivity of the lithosphere); the amplitude of the impedance jump at the coast line is determined by the relation between the conductance of the first layer at the oceanic and continental sides.

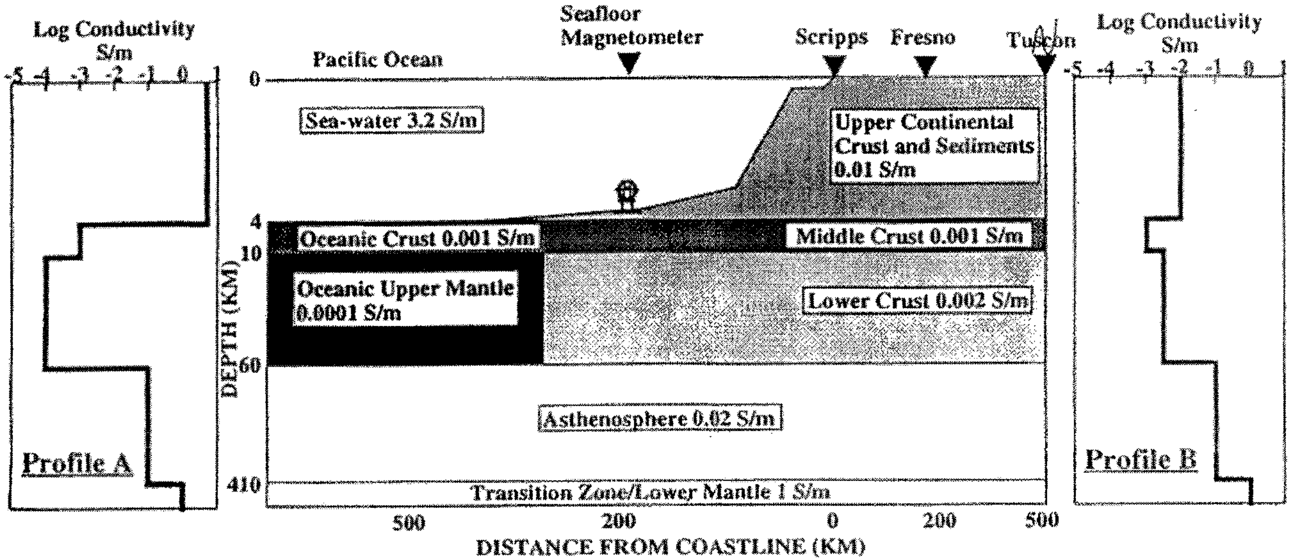


Figure 10. 2D conductivity model across the margin of southern California, based on a priori constraints and forward modelling to minimise the misfit with the observed data. 1D sections A and B show the conductivity structure beneath the ocean and continent respectively; from Heinson *et al.* (1994).

Thus, the main factor controlling the TM mode coast effect and hence the main parameter being studied with the TM mode coast effect, is the integral resistivity of the lithosphere (the TE mode is not as sensitive to coast effect as the TM one). The integral resistivity of the lithosphere is determined by the uppermost 20–40 km of the mantle, or in other words by the conductivity of the lithospheric mantle.

It would appear reasonable that well-known thermal models of plate behavior (e.g. McKenzie, 1967; Parker and Oldenburg, 1973; Sorokhtin, 1973; Parsons and Sclater, 1977) combined with laboratory studies of the electrical conductivity of the mantle material (e.g. Constable and Duba, 1990; Constable *et al.*, 1992; Duba and Constable, 1993) can be used to calculate the dependence of the oceanic mantle conductivity on the age of the lithosphere. Heinson and Constable (1992, 1993) constructed such a petrological model; the uppermost mantle parameters were based on CSEM results obtained in the north-east Pacific. The integral resistivity of the lithosphere according to the model ranges from $5 \cdot 10^8$ Ohm m^2 for the 10 m.y. lithosphere to $2 \cdot 10^9$ Ohm m^2 for ancient lithosphere (100 m.y.). Heinson and Constable also tested the one-dimensionality of MT data with Parker's D+ algorithm and claimed that two of three data sets fail a test for independence of residuals. Re-inversion of these MT data produced models that are incompatible with their petrological model of mantle conductivity. The authors explained the discrepancy by a pervasive 3D coast effect. Indeed, the estimates that can be obtained with both analytic expressions and 2D or quasi-3D thin-sheet numerical modelling show that an integral resistivity of lithosphere of 10^9 Ohm m^2 will cause the coast effect to extend over all the Pacific ocean (Vanyan and Palshin, 1990; Heinson and Constable, 1992; Constable and Heinson, 1993).

These propositions were argued by Tarits *et al.* (1993). They pointed out that the presence of electrical connections between the ocean and deep mantle in subduction zones (and elsewhere) have a strong effect on the MT response in the basin interior by substantially reducing the influence of coast lines. Response functions reexamined by Heinson and Constable are arithmetic and geometrical means of the off-diagonal components of the response tensor (that is TM and TE mode combination is this particular case; the interpretation of means, as it was shown by Palshin (1988), is intolerable). Furthermore, one data set is not the true MT response, but rather a vertical gradient sounding, which makes the discussion on dimensionality of this data set irrelevant.

Several estimates of the integral resistivity of the lithosphere were inferred from the TM mode MT responses distorted by coast effect in the north-eastern Pacific (Chave and Cox, 1983b; Palshin, 1989; Vanyan *et al.*, 1988; Vanyan, 1989, Vanyan *et al.*, 1992a). All of these estimates are in the range 10^7–10^8 Ohm m^2, that is at least one order of magnitude less than those inferred from the petrological model. The TM mode MT response inferred from the electric potential difference measurements by submarine a cable crossing the Tasman Sea results in integral resistivity estimates of the lithosphere of $2 \cdot 10^7$ Ohm m^2 (Vanyan *et al.*, 1994a, 1994b). The same technique, being applied to Hawaii–California cable data, gave a value $5 \cdot 10^7$ Ohm m^2, which is close to previous estimates.

Furthermore, MT soundings, carried out on the north-east of Hawaii (Palshin 1988), at Juan de Fuca Ridge (Heinson *et al.*, 1993) and those inferred from BEMPEX data (Chave *et al.*, 1990b) are characterised by the virtual absence of response tensor anisotropy; the observed moderate anisotropy could be explained by the influence of bathymetry. Thus the coast effect seems to be limited to ranges of about 1000 km from the coast line, which means that the integral resistivity of the lithosphere does not exceed 10^8 Ohm m^2. Thus, we are faced with the fact that all the estimates of the integral resistivity of the lithosphere inferred from the TM mode coast effect are more than one order of magnitude less than those calculated from the petrological model.

Palshin (1988) proposed that oceanic lithosphere is characterised by large-scale vertical anisotropy of electrical conductivity; in other words, there exist subvertical conducting zones that can be treated as vertical electrical current leakage paths. The axial parts of the mid-oceanic ridges are the most probable candidates; there is some direct evidences for the existing of such weakened subvertical zones at the spreading centres (Geli *et al.*, 1994; White and Clowes, 1994). Transform faults and zones of interplate tectonic activity could provide an additional electrical current leakage paths from the ocean to the conductive mantle. Therefore, the TM mode in the oceans is controlled by the "apparent" or "effective" integral resistivity of the lithosphere which is proposed to be significantly reduced, due to spatial averaging of subvertical conducting zones.

MT studies on the continents showed that MT responses in many cases are less distorted than can be derived from models with uniform and resistive lithosphere. This incompatibility is also explained by the smoothing influence of deep conducting fluid-saturated faults; the behaviour of the MT response in the presence of vertical conductive paths were studied in detail both analytically and numerically for a set of typical conductivity models (Berdichevsky *et al.*, 1993; Berdichevsky and Kulikov, 1994). The contribution of subvertical conducting zones seems to be a decisive factor in understanding the nature of EM anomalies both at the continents and the oceans.

4.4. ASTHENOSPHERIC CONDUCTING LAYER AND REFERENCE CONDUCTIVITY PROFILE

Another very important feature of the oceanic conductivity structure is the increase of the electrical conductivity in the "asthenospheric" depth range which is usually interpreted as a partial melt zone; some other or additional candidate mechanisms responsible for conductivity increase have also been discussed (e.g. Constable and Heinson, 1993), but it is quite clear that "dry" mantle material cannot satisfy the experimental seafloor MT responses.

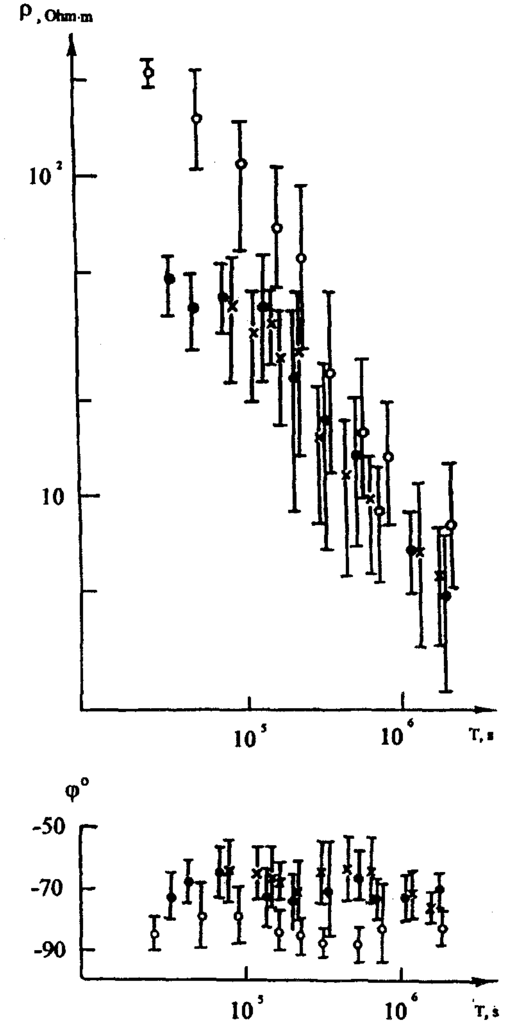


Figure 11. Comparison of the global MV soundings obtained from MAGSAT data for three sectors. Euroafrican sector – open circles, Pacific sector filled circles and American sector – crosses; from Abramova (1994).

EM field distortion and relatively poor resolution of the high conducting layer present severe problems in studying the spatial distribution of the asthenospheric conductive layer parameters. Nevertheless, the parameters of this layer were estimated by many scientists (Filloux, 1980; Oldenburg, 1981, 1984; Tarits 1986; Palshin 1988; Vanyan *et al.*, 1988; Vanyan, 1989). As was mentioned above, some of them used geometrical and arithmetical mean apparent resistivities, calculated from TM (minimum) and TE (maximum) MT responses in the north-east Pacific. The TM mode apparent resistivity is significantly reduced by the coast effect, while the TE mode is distorted only in a narrow zone along the coast (about 500 km);

thus, utilising geometric or arithmetic means may induce artificial dependence of mantle conductivity on the distance from the coast line. This dependence could be mistakenly treated as a function of the age of the lithosphere. An attempt to estimate the coast effect and 'de-distort' the MT responses leads to disappearance of the presumed age dependence; the conductive layer conductance and depth to its centre can be estimated to be of 8000 S and 120 km for the north-eastern Pacific (Palshin, 1988). A high electrical conductivity zone at approximately 100 km depth was revealed beneath the Juan de Fuca Ridge; its conductance was found to be about 3000 S (Heinson *et al.*, 1993), which is similar to the conductivity modelled at a similar depth beneath the Juan de Fuca plate by Wannamaker *et al.* (1989b). Heinson and Lilley (1993) found the conductivity rising by two orders of magnitude below 80 km, to greater than 10^{-2} S m^{-1}, and interpreted it as a probable asthenospheric layer.

The use of the "normal" or reference combined MT and MV response and corresponding conductivity profile can improve the invertion on deep MT soundings (Berdichevsky *et al.*, 1989). The latest global MV results inferred from MAGSAT data (see Figure 11) show that the mantle conductivity model for the Pacific and American sectors are close, but both of them differ significantly from that for the Eurasian sector (Abramova, 1994). These data, combined with the MT response calculated from electric field measured with cables that are located far from the continents (e.g. Auckland-Suva) and those inferred from long time series obtained in oceanographic experiments (e.g. BEMPEX), could provide the reference MT response for the Pacific ocean. With this aim in mind re-processing of old time series with new robust procedures and quasi-3D thin-sheet numerical modelling for realistic conductivity models of the oceans also could be extremely useful.

5. Motionally Induced EM Fields

5.1. INTRODUCTION

The existence of motional electric currents was postulated many years ago; Faraday (1832) made an attempt to verify it experimentally in the Thames near the Waterloo Bridge. The first oceangraphically valuable results were obtained more than a hundred years later (e.g. Bloom, 1964).

The theoretical investigation, presented by Sanford (1971), formed among other things the basis for the successful interpretation of submarine cable measurements in terms of transport. Chave and Luther (1990) re-examined the motional induction problem; the EM field was expanded mathematically in poloidal and toroidal modes based on Helmholtz decomposition; approximate solutions were constructed for the low-frequency limit. The introduction of geophysically reasonable conductivity models yielded a spatially smoothed proportionality between the horizontal electric field components and the vertically-integrated, conductivity-weighted horizontal

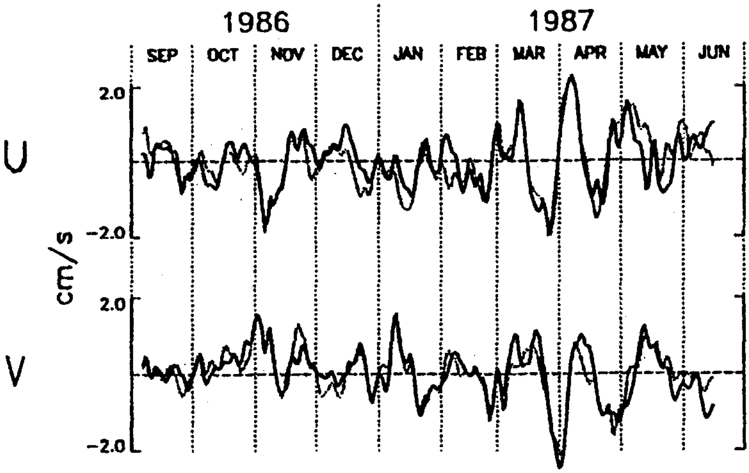


Figure 12. Comparison of the components of the barotropic velocity at the centre of the BEMPEX array – U is eastward, V is northward, respectively – estimated from moored current meter data (solid line) and inferred from the horizontal electric field in the orthogonal direction observed on the seafloor at the same site (dotted line). In both cases, time variations with periodicities shorter than 4 days have been filtered out; from Luther *et al.* (1991).

water velocity. Because vertical variations in the conductivity of the seawater are weak beneath the thermocline, the horizontal electric field is a spatially filtered version of the true water velocity that strongly attenuates the influence of baroclinity and accentuates the barotropic component.

The theoretical relationship between the motional electric field and the water transport was supported by seafloor measurements of horizontal water velocity collected in the central North Pacific (Luther *et al.*, 1991). It was shown, that in the BEMPEX area, conductivity weighting results in very little baroclinic contribution to the electric field, thus the latter is an accurate measure of transport at periods greater than 5 days. Furthermore, the actual transport divided by depth is nearly identical to the barotropic component of the water motion (see Figure 12).

Vanyan *et al.* (1992c) developed a quasi-3D thin-sheet numerical modelling procedure for simulating the quasi-steady motionally induced electric field and calculated the electric response of the Gulf Stream for a realistic spatial vertically integrated velocity distribution and conductivity structure beneath the Atlantic ocean and the continent. The electric field was found to be some 10 mV km^{-1} both at the continent, near the coast line, and within the Gulf Stream in the Atlantic ocean (see Figure 13). Palshin *et al.* (1996) applied numerical quasi-3D thin-sheet modelling to study the possibility for on-shore monitoring of the Norwegian Coastal Current. Calculations show that the electric field should be measurable on-shore (see Figure 14).

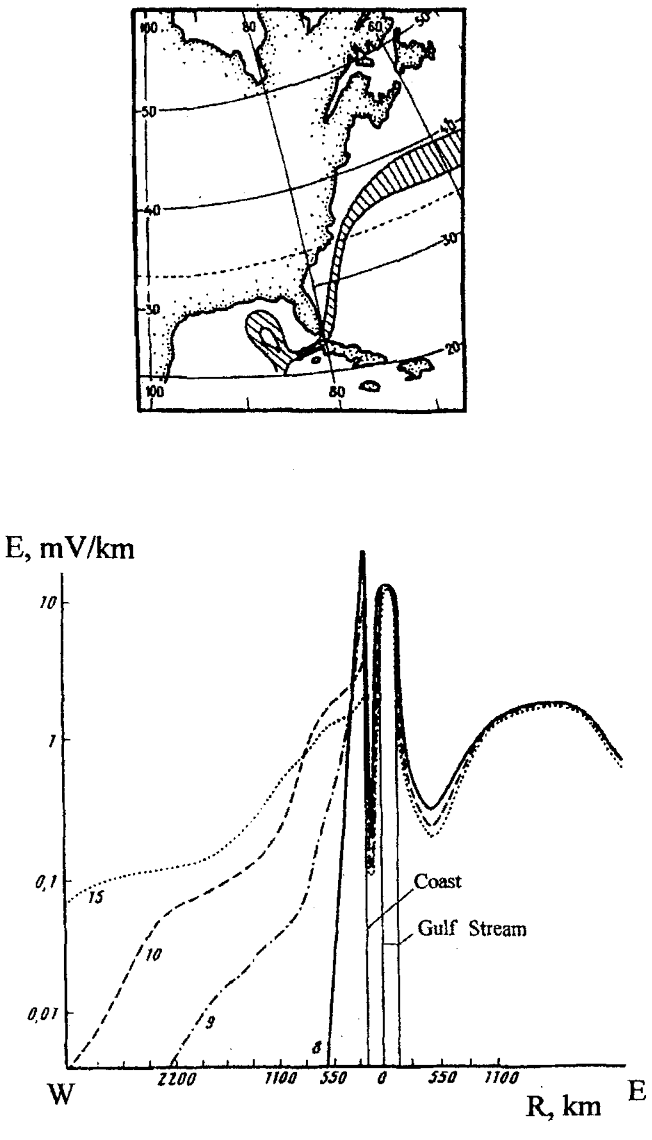


Figure 13. Numerical modelling of the electric field induced by the Gulf Stream. Location map showing the modelled area (upper panel). Shaded region indicates the main path of the Gulf Stream. The electric field modulus (lower panel) along the line crossing the Gulf Stream at 34° N (dashed line in the upper panel) for varying integral resistivity of the lithosphere; figures are the logarithm to the base 10 of the integral resistivity of the lithosphere in Ohm m^2; from Vanyan *et al.* (1992c).

5.2. OCEANOGRAPHIC APPLICATIONS

Larsen (1992) reported the results of the 14 years cross-stream voltages measurements using an abandoned cable between Florida and Bahamas as well as the procedures used for deriving the oceanographic information from the measured

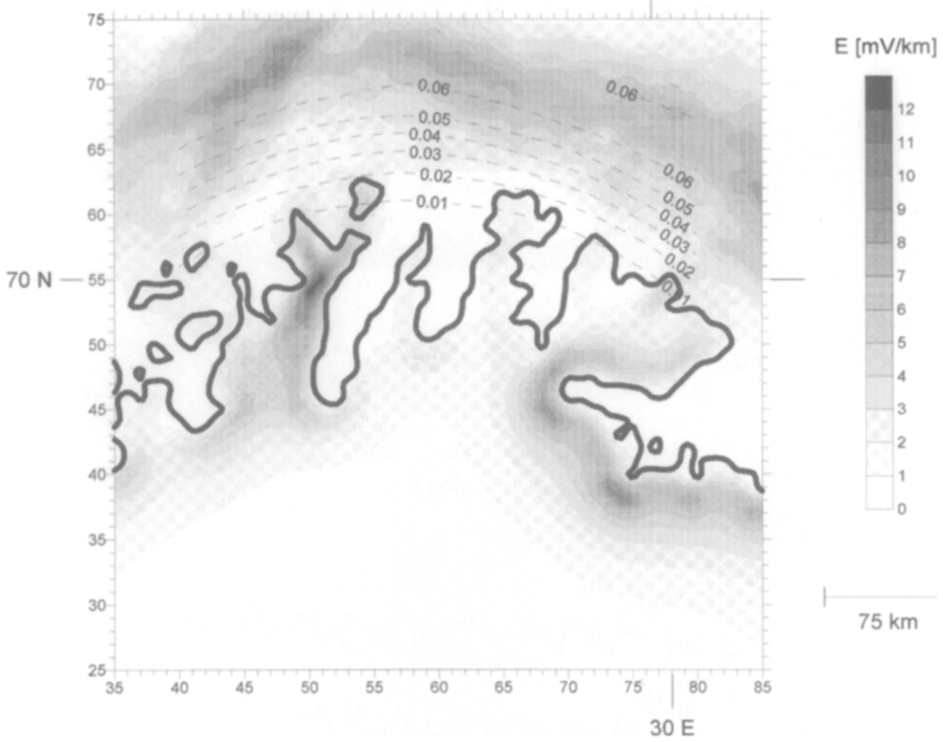


Figure 14. Numerical modelling of the electric field induced by Norwegian Coastal Current. The electric field modulus is shown in mV km^{-1} for the central part of the mesh. The direction of the electric field at the land is perpendicular to the coast line. Solid line is the 100 S isoline running approximately along the coast line. The dashed lines show the isolines of the modulus of the sea current velocity in cm s^{-1}. The direction of the sea current is parallel to these isolines. Numbers depict nodes in the mesh used in numerical modelling. Node distance is 7.5 km in both directions; from Palshin *et al.* (1996).

voltages. Observations yield estimates of the transport variations with an accuracy of 2.5%. The excellent agreement found between the transport variation derived from the voltages, the velocity profiling data, and current meter data show that the voltage variations caused by meandering of the Florida current at 27° N are not important (see Figure 15). The mean voltage-derived transport is 32 Sv based on 4862 daily mean values from 1969 to 1990. The seasonal and month-to-month changes in the transport were studied; the heat flux was estimated as well.

Segawa and Toh (1992) reported a relatively large effect of the motionally induced electric field on the long-period variations measured at the Nankai trough due to strong western boundary ocean current, the Kuroshio.

The motionally induced magnetic field has not yet been investigated well enough despite long-standing interest. During the Tasman experiment favourable conditions appeared due to the passage of an active ocean eddy across a line of OBM and

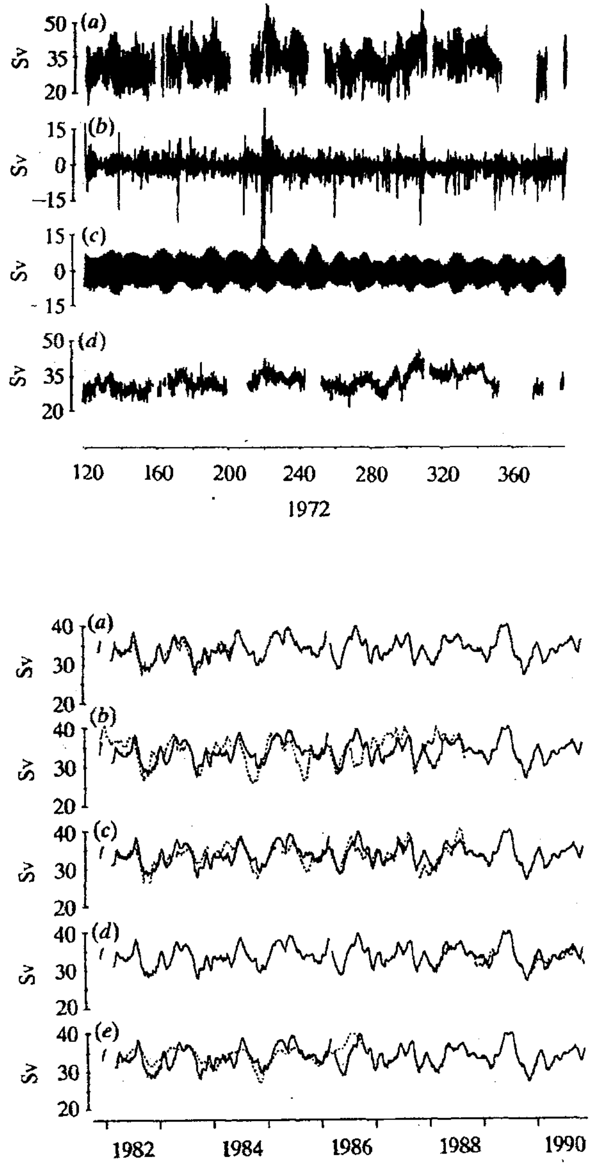


Figure 15. Hourly mean Florida – Cuba voltages in transport units: (a) Uncorrected values. (b) Geomagnetic-induced variation. (c) Tidal variation. (d) Corrected values (upper panel). Monthly mean transports (lower panel) derived from the Florida-Bahamas voltages (solid curve) compared with the monthly mean transport derived from: (a) mooring data; (b) and (c) sea level data at different sites; (d) another Florida-Bahamas voltages; (e) NORDA model driven by monthly winds; from Larsen (1992).

OBE and the presence of 1 km thick porous sediments. The magnetic signal was clearly identified and was some 30 nT in amplitude; the corresponding electric field signal was of some 30 mkV m^{-1}. Applications of the basic theory for quasi-steady rectilinear flow give a seafloor conductance of about 900 S. An agreement with independent estimation supports the application of quasi-steady theory (Lilley *et al.*, 1993).

Except in the vicinity of strong ocean boundary current, most barotropic fluctuations observed in the ocean at periods longer than several days are directly, atmospherically forced. The coherence between barotropic velocities derived from single point measurements of the motionally induced horizontal electric field collected during BEMPEX and air pressure, wind stress and wind stress curl derived from the Fleet Numerical Oceanographic Centre data product (Chave *et al.,* 1991) were examined over the 1–200 day period band (Luther *et al.*, 1990; Chave *et al.*, 1992c). Nonlocal coherence with the wind stress and the wind stress curl at periods greater than a week, and local coherence with the wind stress at shorter periods, was found to be statistically significant. Significant coherence was found between the barotropic velocities and one or more surface variables over the North Pacific. Some of the observed patterns of squared coherence are very similar to those predicted by simple models of atmospherically forced currents; more commonly, distinct forcing locations were found. The influence of topography on the barotropic velocity observations was suggested by the observations. A suitable numerical model that incorporates real topography and real winds must be constructed for the quantitative understanding of these effects Luther and Chave, 1993).

As was mentioned above, the EM field spectrum is dominated by periodic signal at the tidal frequencies; thus the electric field approach to estimation of the tidal velocity seems to be very promising. Junge (1988) studied the time variations of the telluric field measured at six sites in the northern Germany for at least 2 months, together with variations of the magnetic field at Gottingen, and found that the direction and phase of the telluric field that was uncorrelated with the magnetic at tidal frequency M_2 coincides with the assumed motionally induced electric current in the Northern Sea. Filloux *et al.* (1991) compared the tidal velocity for M_2 at the central BEMPEX site derived from a theoretical global tide simulation with that derived from electric data, and found the experimental one was only slightly smaller (see Figure 16). This reduction was explained by electric current leakage through the seafloor. This effect appears to be small, and suggests that a resistive zone must separate the oceanic basement from the asthenosphere beneath. Thus, assuming the theoretical tidal velocity computations to be accurate, tidal velocities derived from electric data provides us with a new mode of exploration of the oceanic basement as well as with a means to study open ocean tides.

Thus, seafloor electromagnetic (EM) observations initially dedicated to studies in submarine solid earth geophysics and geology have been shown to contain information of considerable importance to the study of large-scale, long-term ocean variability. The broad spatial averaging properties of EM data justify their place alongside more conventional techniques of large-scale physical oceanographic research in forthcoming investigations of the global ocean circulation and its secular variability.

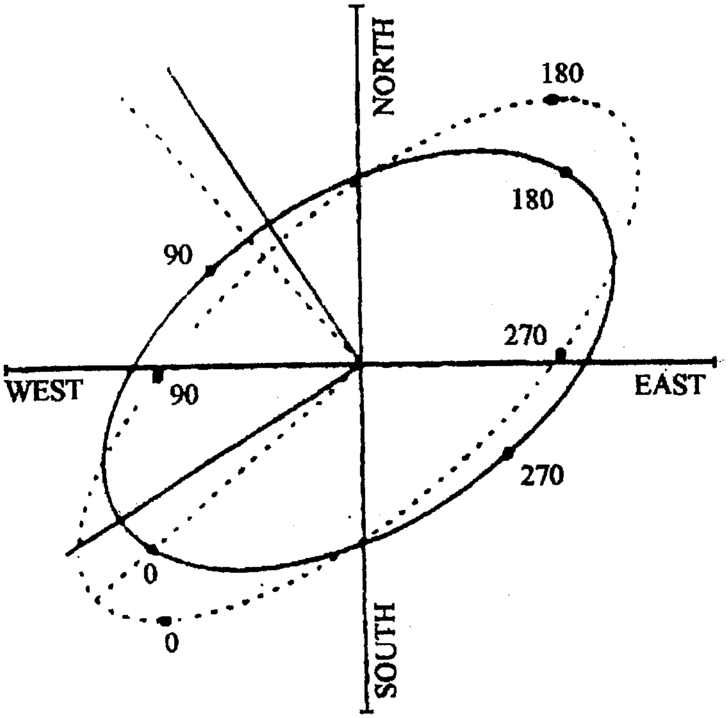


Figure 16. Tidal velocity hodographs for the semidiurnal lunar constituent M2 from electric field data at station EB of BEMPEX (continuous line) and from theoretical model predictions (dashed line). Semi-axis sizes correspond to 1.5 cm s^{-1}; from Filloux *et al.* (1991).

6. Conclusions

Recently the quantity and quality of EM data collected in the oceans are increasing, because of technological, data processing and interpretation advances.

CSEM methods in the ocean, faced with a very different environment, are characterised by significant peculiarities in theory and technique. The results of CSEM surveys can be summarised as a host conductivity reference model of the oceanic crust that is supposed to be age dependent. The anomalies of conductrvity caused by the hydrothermal circulation, sulphide mineralization and local embedded conductive bodies such as magma chambers can by studied by CSEM methods with the understanding that such factors as anisotropy of crust conductivity, the effect of near-surface helerogeneities and topographic effects are to be taken into account.

MT and MV studies carried out at the eastern and western margins of the Pacific ocean make it possible to construct well-constrained conductivity models of the subducting plate; a conductor interconnecting the near-surface and deep conducting zones was found to be a characteristic feature of these models. The result of MT and MV studies cite as evidence that the EM response in many cases is less distorted than can be derived from models with a uniform and resistive lithosphere; the contribution of the subvertical conducting zones seems to be a decisive factor in understanding the EM field anomalies at the continents and oceans.

The separation of the enhancement of the conductivity, known as asthenospheric conducting zone, on the background of increasing conductivity with depth is a serious problem that needs special studies for the purposes of constructing a reference EM responses and corresponding reference conductivity profiles.

The seafloor EM observations initially dedicated to studies in solid earth geophysics and geology have been shown to contain information of considerable importance to the study of large-scale, long-term ocean variability. The theoretical relationship between the motional EM field and the water transport was supported with seafloor measurements of horizontal water velocity collected during major oceanographic EM experiment in the central north Pacific.

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