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Controlled source time-domain electromagnetic methods for seafloor electric conductivity mapping[①]

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Abstract: Theoretical studies of some controlled-source electromagnetic methods, especially the horizontal coaxial magnetic dipole-dipole and horizontal collinear electric dipole-dipole electromagnetic methods, which are capable of accurately measuring the relatively low conductivity of the seafloor were reviewed. Marine electromagnetic instrumentations, especially the time-domain horizontal magnetic dipole-dipole system and horizontal electric dipole-dipole system which have been designed and constructed in the Geophysics Division of the University of Toronto, were provided with applications to geotechnical studies on the shelf and deep ocean surveys near the mid-ocean ridges.

Key words: seafloor resources; electric conductivity maping; instruments **Document code: A**

1 INTRODUCTION

Over three-fifths earth's surface is covered by oceans. Though petroleum is produced from huge deposits on the shallow continental shelf, the immense area of the ocean represents a largely unexplored and unexploited virgin ground reserving a store of mineral resources e.g. multi-metallic sulfide deposits.

The multi-metallic sulfide deposits on the seafloor were located visually with submersibles or using near-bottom survey tools, while they are not able to assess the actual extent of the deposits and the nature of the geological structures in which they are found. Seafloor conductivity mapping is one of the few geophysical tools suitable for this purpose, especially, in recent years, significant advances have been made in theory, methodology, and instrument for the marine electromagnetic (EM) methods. Many of the seafloor techniques are adaptations of standard terrestrial EM approaches, while others represent new directions. This paper summarizes the progress of marine EM methods over last 30 years, with emphasis on the controlled source time-domain aspect.

2 POSSIBILITY OF USING EM IN OCEANIC ENVIRONMENT

Although the highly conductive seawater layer reduces the amplitude of EM signals, it produces some compensatory benefits. Potential electrode noise is reduced because low impedence contact with seawater is easily established, and the ocean provides thermal and saline stability at a level never observed on land. Transmitter electrodes are also less of a problem than on land, where considerable labor is often required to obtain resistances to ground of 10 Ω. At sea, a grounding resistance of 0.1 Ω can be obtained merely by lowering a long, uninsulated cable or pipe into the water. Thus the measurement of the smaller signals is possible if correct advantage is taken of the marine environment.

Only magnetic sources and receivers can be towed over land by aircraft. In contrast, in the ocean both transmitter and receiver electrodes may be towed through the water and close to the seabed. Another advantage offered by the conductive ocean is its smoothing effect on electric fields. The uniformity and great electrical thickness of the water column dominate the effect of small-scale irregularities in the near-bottom rocks, yielding homogeneous electric field over large areas. On land, however, near-surface heterogeneity degrades the electric field coherence substantially, even when the distance between measurements is quite small.

Indeed, operating at sea does create special technical difficulties associated with maintaining equipment in a hostile environment. Seafloor equipment must be housed in watertight vessels capable of withstanding 10 ~ 100 MPa of hydrostatic pressure. Most receiving instruments are self-contained, operating off battery power and collecting data under the control of a small computer. Measurements are usually stored on magnetic tape or solid state memory. A means to orient the measurements with respect to the earth after instrument emplacement is sometimes necessary. The packages are buoyant to facilitate recovery, and attachment of a heavy anchor allows them to be lowered or dropped in free fall to the ocean bottom. When necessary, instruments may be located at the seafloor using standard acoustic ranging techniques. After data collection a timed or acoustically triggered release causes the instrument to part from the anchor and

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float to the surface, where it is recovered. Sometimes, people also use submersible to carry the instrument to the seafloor, and recover it after data collection.

In a word, it is possible to use EM in oceanic environment although there are some difficulties.

3 THEORETICAL DEVELOPMENT ON EM

For many years theoretical work on the response of EM systems on the seafloor has concentrated on frequency domain measurements. The elementary theory of the frequency-response of a crustal layer beneath a more conductive sea can be found in literatures[1~3].

More recently, the rationale for a broad band time-domain electromagnetic system has been set out by Edwards and Chave[4], who computed the response of a crustal halfspace beneath a more conductive halfspace representing seawater to a transient electric dipole-dipole system. They showed that the transient collinear electric dipole-dipole (ERER) system in contact with the seafloor is useful for determining seafloor conductivity. And a little later, Cheesman and Edwards et al[5] showed that the HZHZ, HZHR and EPHIHZ systems shown in Fig.1 are to be unsuitable when the seafloor is resistive, because they do not show the separation of the signals from seawater only in the rare circumstance of the seafloor being locally more conductive than seawater are these systems sensitive to the conductivity of the seafloor.

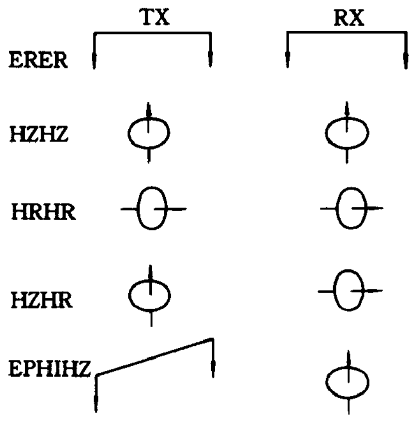

Fig.1 Different combinations of transmitters (TX) and receivers (RX) which might be used in a transient system of EM

Therefore, the collinear electric dipole-dipole (ERER) system and similarly the coaxial horizontal magnetic dipole-dipole (HRHR) system are two most appropriate transient EM systems used for seafloor conductivity mapping.

Many interesting seafloor structures are very complicated and cannot be represented simply by a double half-space model. For instance, beneath mid-ocean ridge crests with fast spreading rates shallow hydrothermal circulation is observed and a magma chamber with melt fraction greater than fifty percent has been detected[6]. A detailed knowledge of the spatial extent and physical properties of the magma chamber is crucial to the formulation of accurate geological models of active oceanic spreading centers.

The mid-ocean ridge may be approximated by a 2-D model. There is a defined local horizontal strike direction and the conductivity along strike is approximately constant. Everett and Edwards[7] computed numerically in 2-D model the response of a crustal magma chamber to excitation in two fundamental orthogonal modes, rise-normal (TE) and rise-parallel (TM) electric field. A finite element representation of the electromagnetic diffusion equations was solved in the Laplace domain and the results inverted into the time domain via the Gaver-Stehfest algorithm. A sequence of snapshots for each modes for the time range 0.1 to 15 s shows the complete progression of the eddy currents into, through and around the magma chamber. They used an infinite line as a 2-D source. Although the results may be used to assist with controlled-source data interpretation and experiment design, a major drawback is that they cannot represent the sources commonly used in real experiments, which are compact.

We thus investigate the response of an arbitrary 2-D structure to an artificial, compact source deployed on or near the seafloor, a case commonly described as having 2.5 dimensions. We transform the governing Maxwell equations into the Laplace and along-strike spatial Fourier domains. Two coupled linear-differential equations result whose dependent variables are the along-strike components of the electric and magnetic fields. The equations are solved by the finite element method. Responses in the space-time domain are recovered by a combination of inverse Laplace and Fourier transforms. We select the Gaver-Stehfest algorithm to compute the inverse Laplace transform because it requires the evaluation of responses at only a small number of real values of the Laplace variable, eliminating the need for any complex arithmetic.

Our purpose here is to present some transient responses of a 2-D mid-ocean ridge electrical model to a horizontal, compact electric-dipole excitation. Fig.2 shows the electric model representing the crustal and uppermost mantle sections of typical fast-spreading mid-ocean ridges. The model contains a uniform magma chamber of conductivity $\sigma = 0.05$ S/m (4.0 S/m), corresponding to 1 ~ 2 percent (60 percent) partial melt at 1 200 ℃[8], embedded in a layered model of young oceanic crust and upper mantle consisting of basalts, gabbros and peridotites. The shape of the magma chamber is fixed, consistent with the seismic reflection data[9]. Hydrothermal fluid circulation in fractured basalt near the ridge axis is modelled as a continuous band of enhanced electrical conductivity $\sigma = 0.3$ S/m above the lid of the magma chamber. The conductivity of seawater is $\sigma = 3.2$ S/m, consistent with the CSEM measurements of [10]. The horizontal electric dipole is located some 5 km off axis and is directed perpendicular to the strike direction.

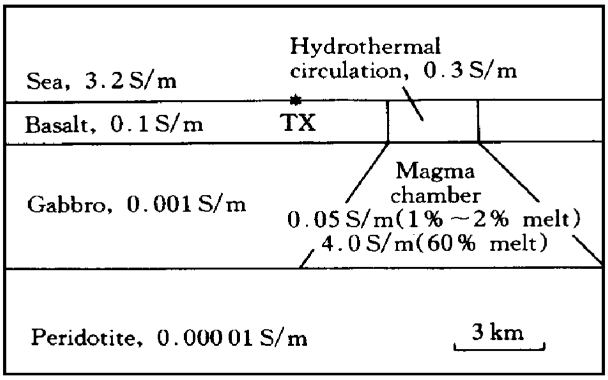

Fig.2 2-D electrical model of an active mid-ocean ridge segment
* —Location transmitter (TX)

As an example, Figs.3(a) ~ 3(d) show contours of the along-strike electric field 1 s after swith on, for several distances along strike. The magma chamber conductivity is 0.05 S/m. The presence of a magma chamber has a significant effect on the signal, especially at distances along-strike 1 km or more. For the 0.05 S/m magma chamber, the signal at these times and distances is enhanced in the magma chamber with respect to the surrounding gabbros. For the more conductive magma chamber, the signal is excluded from the magma chamber because electric currents prefer to flow along strike, i.e. out of the vertical plane, lends the electric and magnetic fields their distinctive 3-D character. It is also the major feature distinguishing 2.5-D forward solutions from their 2-D counterparts. In the 2-D problem, electric currents are always confined to the vertical plane.

Some theoretical work has been also done to investigate the suitability of the time-domain EM methods for the exploration of active hydrothermal sulfide mound structures. Evans & Everett[11] constructed 2-D electrical models of a volcanic-hosted sulfide mound and computed the EM fields created by a compact transient electric dipole source deployed on the seafloor. The time it takes for fields to diffuse between the source and receiver is diagnostic of the intervening electrical conductivity. YU & Edwards[12] examined the response of a conductive axi-symmetric sulfide mound to a transient in-line electric dipole-dipole seafloor system. However, theoretical studies of the time-domain electromagnetic responses of 3-D seafloor structures to the compact sources are still in the infancy. To our best knowledge, no reults have been published with respect to this kind of true 3-D problems.

4 INSTRUMENTATION AND APPLICATION

Controlled source frequency-domain marine EM systems have been developed at Scripps Institution of Oceanography for deep sounding of the oceanic lithosphere whereas controlled source time-domain EM systems have been developed at the Geophysics Division of the University of Toronto.

4.1 Coaxial horizontal magnetic dipole-dipole (HRHR) system

The prototype of a time-domain HRHR system has been constructed and tested at the University of

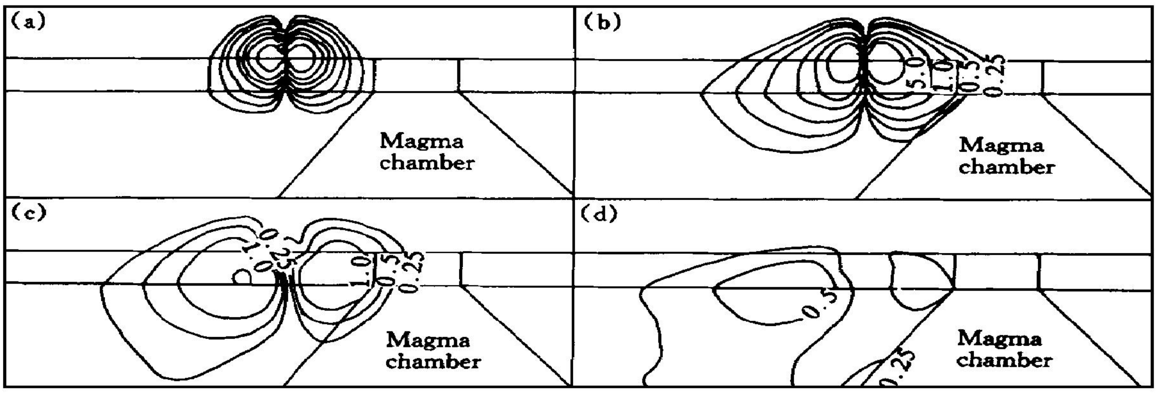

Fig.3 Contours of electric component E_y(unit: V/km) showing diffusion into mid-ocean ridge electrical model with electrical conductivity of magma chamber $\sigma = 4.0$ S/m and $t = 1$ s after source switch on
(a) —$y = 0.1$ km; (b) —$y = 1$ km; (c) —$y = 2$ km; (d) —$y = 5$ km

Toronto[15]. The magnetic dipole transmitter consists of a fiberglass cylinder, 2 m long and 1 m in diameter, in which 100 turns of wire are embedded and evenly spaced along its length. The cylinder is open ended. The front end is tapered slightly to prevent scooping of bottom sediments from occurring as it is dragged forward. The receiver coil consists of 10 000 turns of wire wound in five sections on a 1.2 cm diameter ferrite core, 20 cm long. The receiver coil is enclosed within a fiberglass pressure vessel, which is in turn enclosed in a polycarbonate shell for protection from abrasion. It is joined to the transmitter by a cable. The entire array is towed along the seafloor by heavy wire spooled on a winch so that its length may be varied with the water depth, as illustrated in Fig.4. In order to eliminate noise produced by motion of the receiver coil through the earth's magnetic field, measurements are made with the system stationary intermittently, while the ship proceeds slowly along the measuring line. This is accomplished by paying out wire during the measurement and recovering wire between measurements. Current to the transmitter coil is supplied by a transmitter and transformer on the ship which is powered by a pair of 12 V automotive batteries. The polarity of the current is reversed every 5 ms by an electronic switch to provide the EM transient. A transformer is used to supply 1.5 A at 120 V. The signal detected in the receiver coil is amplified, then sent back through the tow cable to the ship, where it is digitally sampled, stacked and stored. The current supplied to the transmitter, and the signal returned to the surface from the receiver, are carried in separate conductors in the tow cable.

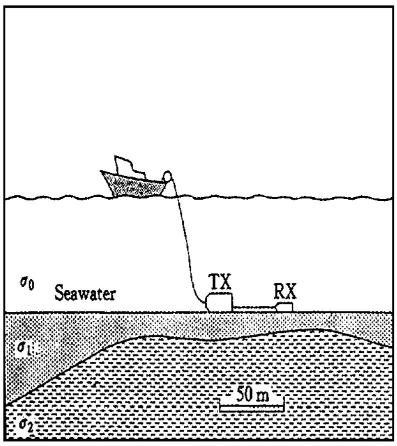

Fig.4 HRHR system deployed on seafloor from a research vessel

The first field test of the prototype HRHR system was conducted in January, 1988, in the Trincomali Channel near the southeast end of Vancouver Island at about 48°55′ N, 123°27′ W where the water depth ranges from 30 to 100 m. The seafloor consists of bedrock overlain by varying thicknesses of mud, ranging from zero to tens of meters, so that the response of the system to varying thicknesses of sediment could be ascertained. A total of 38 measurements were made at 19 sites along 3 lines. These lines in the survey were chosen with reference to the local bottom conditions. All measurements are consistent with a model in which a varying thickness of 10 Ωm mud overlies rock with a resistivity of about 60 Ωm[16].

The second field test of the system was conducted in March, 1990, in Knight Inlet, which is located on the British Columbia coast at about 51°N. In this test, the electrical conductivity of the uppermost 5 ~ 10 m of sediments on the seafloor were first measured, then they were interpreted on the basis of the Archie's law to give porosity and likely texture of the bottom sediments. The interpreted results were in good agreement with seafloor samples from this area[17]. Applications for the HRHR system also include the rapid identification of sediment types for dredging operations, geotechnical surveys, or reconnaissance mapping of Quaternary geology.

4.2 Collinear electric dipole-dipole (ERER) system

In a typical controlled source ERER experiment, a horizontal electric dipole transmitter is positioned on the seafloor, while a receiver capable of measuring small variations in the horizontal components of the electric field is stationed some distance away. A transient variation in the current through the transmitter causes a correlated variation in the EM field at the receiver. This field includes a component which diffuses through the seafloor, undergoing diffusive dispersion as it interacts with conductive material along its path. The recorded signal therefore contains broadband information about the conductivity distribution in the seafloor, which may be recovered through inversion using suitable models.

The first field test was conducted in June, 1988, in the Strait of Georgia, British Columbia. The transmitter electric dipole is 1 650 m long and is installed in shallow water at the coast perpendicular to the shoreline. The independent receiving system consists of three identical electrodes which are joined to each other by 50 m cables. The transmitter is energized with an 1 Hz, 3.5 A square wave current supplied by an onshore power supply. The frequency and rise times of the transmitted signal are controlled by an accurate clock. At the beginning of each square wave, a synchronized clock aboard the ship triggers data collection from the receiving array. Once a measurement is completed, the receiver system is towed to the next location. The data collected is in the form of potential differences between pairs of electrodes. The array is towed in the direction away from the source, passing first over the Sechelt Trough where the sea depth is 170 m and overlies a thick layer of sediment. At about 4.5 km from the centre of the source dipole the Sechelt Trough gives way to the MacCall Bank where sea depths are only 110 ~ 130 m and the sediments are much thinner. The test results fairly reflect the seafloor structure.

The second field test was conducted in May, 1993, to study the internal structure of the Trans-Atlantic Geotraverse (TAG) active sulfide mound. The TAG hydrogthermal field is located at 26°08′ N and 44°49′ W and situated in water depths between 3 620 m and 3 670 m at the juncture between the floor and the east wall of the rift valley of the Mid-Atlantic Ridge. The TAG active mound is about 200 m in diameter, 35 m high, and may contain 5 million tons of surface sulfide ore. The entire mound is probably constructed of massive sulfides precipitated from hydrothermal solution[18, 19].

The electric dipole-dipole system consists of two autonomous transmitter/receiver units which are carried to the seafloor and deployed by submersible. Each instrument has 2 transmitter and 2 receiver channels and runs under microprocessor control. Program development is done in C^{++} on a Macintosh computer.

The submersible ALVIN carried the instruments to the measuring site and deployed the receiver on a flat location of the mound at first, and the pull-out electrode was extended perpendicular to the orientation of the PVC dipole. ALVIN then went to the northern edge of the mound, from where it carried the transmitter on a survey route which circled the receiver at a radius of approximately 70 m. Care was taken to move slowly and stay close to the bottom during the logging bursts. At the end of the dive, ALVIN retrieved the receiver and carried the instruments to the surface. The survey lasted 4 hours. Measurements made at 12 sites were initially interpreted in terms of an apparent conductivity of a uniform seafloor. A more complex model in which the seafloor has two layers is then used. Apparent conductivities range from 1.4 to 15.9 S/m, generally higher than that of seawater. The results suggest possible focusing of hydrothermal convection in the northern quadrant of the mound, adjacent zones of anhydrite accumulation and fluid convection in the north-eastern quadrant, heterogeneity and layering in the Kremlin zone, and unexpected spatial variability in the western quadrant. The data from several sites show evidence of distortion attributed to 3-D anomalies.

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