OFFSHORE EMSLAB: objectives, experimental phase and early results

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Filloux, J.H., Law, L.K., Yukutake, T., Segawa, J., Hamano, Y., Utada, H., White, A., Chave, A., Tarits, P. and Green, A.W., 1989. OFFSHORE EMSLAB: objectives, experimental phase and early results. Phys. Earth Planet. Inter., 53: 422–431.

A large electromagnetic (EM) experiment dedicated to the exploration of lithosphere and asthenosphere associated with a spreading oceanic plate over its various tectonic regimes, from ridge accretion to subduction, was carried out during the second half of 1985 over an area extending from the Juan de Fuca Ridge, eastward across the coastal zone, the Cascade area and beyond. Referred to by the acronym 'EMSLAB', for 'EM Sounding of Lithosphere and Asthenosphere Beneath' the Juan de Fuca Plate, the experiment involved two principal arrays, one on land, the other on the adjacent seafloor. We report here on the outcome of the oceanic portion of EMSLAB, named OFFSHORE EMSLAB for convenience. The OFFSHORE EMSLAB array of seafloor instrumentation included 40 self-contained and free recording units including magnetometers, electrometers and other oceanographic devices. The latter were intended to provide information on the EM fields generated by the interaction of oceanic motions with the main Earth's field, so as (1) to decontaminate ionospheric signals prior to magnetotelluric interpretation, and (2) to illustrate the beneficial contributions that EM observations may provide to ocean studies. The collected database is described and assessed, and an early illustration of its information content is given.

1. Introduction

In an attempt to investigate the processes of mid-oceanic plate accretion, spreading and sub-duction beneath an adjacent continent, a group of scientists from four independent nations and a dozen institutions conceived project EMSLAB, acronym for 'Electro-Magnetic Sounding of Lith-osphere and Asthenosphere Beneath' the Juan de Fuca Plate. Several important factors contributed to the geographic location and the combination of institutions, namely (1) the geographic area to be examined is logistically of optimum accessibility to such a group of investigators, (2) the area constitutes one of a few attractive global settings that minimizes the total surface to be studied instrumentally so as to cover all tectonic phases between ridge crest, subduction and beyond, and (3) many of the individual research capabilities of the participating teams are complementary. Altogether the experimental zone extends on both sides of the North American west coast from 116
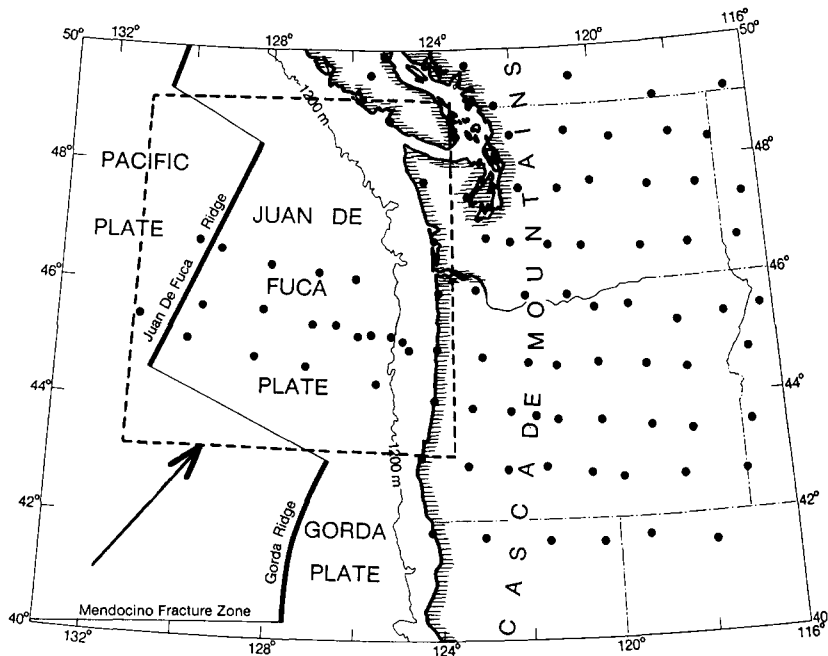
Fig. 1. Map illustrating the entire array of EM observation sites during the EMSLAB experiment. The dark arrow indicates the geographic area covered by OFFSHORE EMSLAB shown in greater detail in Fig. 2.

to 132° W and 41 to 50° N, that is, roughly 1300 km east–west and 1000 km north–south, thus encompassing at least in part, British Columbia (Canada), and the U.S. States of Washington, Oregon and California, in addition to a vast adjacent offshore territory (see map, Fig. 1).

Because of the considerable differences existing in the application of 'natural source EM methods' to the solid Earth exploration over the oceanic province versus continental zones, it is convenient to visualize the EMSLAB program as made up of marine and continental parts, referred to for simplicity as OFFSHORE EMSLAB and INLAND EMSLAB. We report here on the oceanic experiment, OFFSHORE EMSLAB, at a time when the field work has been completed, when all data have been examined and when their early appraisal as well as preliminary tests on mutual consistency have confirmed the success of the most crucial and expensive phase of OFFSHORE EMSLAB. Nevertheless, because of the short time elapsed between the end of the experiment and the present reporting time, not all data ultimately to be availa-

ble can be presented here. The layout of the seafloor array is shown in detail in Fig. 2.

2. Theory of EM induction in the ocean

Natural EM fluctuations observable on the seafloor are generated not only by ionospheric–magnetospheric processes, but also by the interaction of oceanic motions with the main Earth's field (Longuet Higgins et al., 1954; Sanford, 1971; Chave and Filloux, 1984). In both cases, electric to magnetic relationships are affected by the electrical conductivity of the submarine basement and adjacent continent and, in the second case only, by the geometry and temporal character of the oceanic velocity fields as well. At the very low frequencies involved in EM exploration of the solid Earth and in investigations of oceanic water velocity fields, the balance of forces on electric charges can be simply written

$$-\Delta\phi - \frac{\mathrm{d}A}{\mathrm{d}t} - \frac{J}{\sigma} + V \times B = 0 \qquad (1)$$
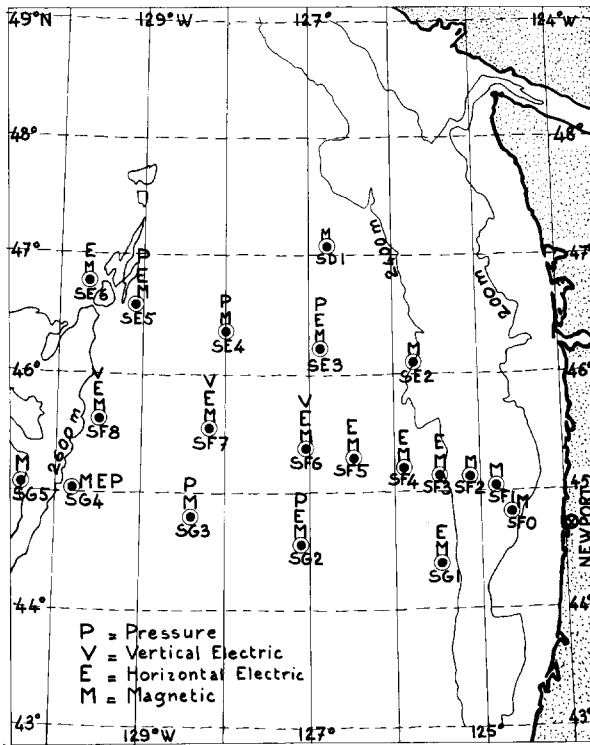
Fig. 2. OFFSHORE EMSLAB array of seafloor instrumentation. The geophysical parameters observed at each site are identified by letters defined in the lower left corner. Note the location of the continental shelf boundary (200-m depth contour), of the base of the continental slope (2400-m contour) and of the Juan de Fuca Ridge (rugged bathymetry at the extreme left). For information on the database collected, see also Table I.

where the first term represents the electrostatic field associated with the potential, ϕ, the second represents the electric field associated with temporal variations of the magnetic field (represented by the vector potential, A), the third is the resistive force opposed by the medium, of conductivity, σ, to the electric current with density, J, and the fourth term represents the motional or Lorentz electric field associated with the fluid motion, V, interacting with the main Earth's field, B.

In land magnetotellurics the motional term in (1) is nonexistent and it is generally assumed that the only EM induction process ocurring is one associated with ionospheric and magnetospheric variations, $-dA/dt$, alone. This assumption is

not necessarily correct in the vicinity of an ocean since the low-impedance oceanic generator may drive electric currents—contributing to the term J —into the land itself (see Harvey et al., 1977; Filloux, 1987). In fact, the coastal area of IN-LAND EMSLAB should be expected to be subject to a significant contamination of ionospheric fields by those of oceanic origins.

Oceanic motional fields are produced by a vast range of processes that cover a broad frequency band. Of these, the tidal motions produced by the gravitational tide generating potential associated with the motions of Earth and Moon are the most energetic because of their narrow band width. Internal waves and internal motions also constitute an energetic continuum spanning the interval from the Brunt–Väisälä or natural buoyancy frequency of a few cycles per hour, to the local inertial frequency

$$f = 2\Omega \sin \lambda \qquad (2)$$

near 1 cycle d^{-1} at mid-latitudes (where Ω is the angular rotation frequency of the Earth and λ the latitude; see Chave and Filloux (1985)). Other readily observable oceanic processes include those associated with coastal and equatorial trapped waves and a variety of planetary motions with frequencies as low as only a few cycles per year. The oceanic portion of EMSLAB, 'OFFSHORE EMSLAB', therefore, is concerned with two important problems of geophysics: one dealing with exploration of the solid Earth—lithosphere and upper mantle—and another related to large-scale oceanic velocity fields. In fact, since oceanic signals—a significant component of the noise in seafloor magnetotelluric data—are large, then an effective treatment of OFFSHORE EMSLAB data must exploit both aspects simultaneously.

The opportunity to study the ocean—an important though secondary subject here—is well worth the challenge, for EM methods offer new and attractive observational approaches to physical oceanography for which no satisfactory alternative and economical oceanographic technique exists at present (Filloux, 1987). Thus, toward fulfilling this new objective the OFFSHORE EMSLAB array also included, in addition to magnetometers and electrometers, two other types of

seafloor recorders: namely, pressure recorders sensitive to changes in the weight of the local oceanic water column (Filloux, 1983), and vertical electric field sensors extremely sensitive to seafloor zonal velocities while nearly unaffected by ionospheric signals (Chave and Filloux, 1985; Filloux, 1987).

TABLE I

Specific information on the OFFSHORE EMSLAB experiment: station identification, participating institution, instrument identification, date installed and recovered, geographic position, depth, asessment of data quality

Station	Instrument	Installation date	Recovery date	Location		Depth (m)
				Latitude	Longitude	
SF0	USGS					400 G, ND (25%)
SF1	PGC-OBM6	04-08-85	01-10-85	45:03.5	125:07.6	652 VG
SF2	FUA-M	–	01-10-85	45:08.1	125:07.6	1568 VG
SF3	SIO-E84-2	–	02-10-85	45:09.0	125:34.9	2635 G, ND (1%)
SF3	SIO-M8	–	02-10-85	45:09.0	125:35.1	2634 VG
SE2	PGC-OBM5	03-08-85	02-10-85	46:07.2	125:56.0	2557 VG
SF4	SIO-E2	05-08-85	02-10-85	45:09.2	125:55.3	2663 VG
SF4	SIO-M9	–	02-10-85	45:09.1	125:55.3	2663 VG
SF5	SIO-E84-1	04-08-85	03-10-85	45:16.6	126:25.1	2699 VG
SF5	SIO-M5	–	03-10-85	45:19.7	126:25.1	2699 VG
SF6	TUJ-OBMS1	31-07-85	03-10-85	45:20.2	126:59.4	2818 G, cassette noise
SF6	SIO-V84-1	–	03-10-85	45:20.1	126:58.7	2815 G, ND (5%)
SF7	SIO-M6	–	04-10-85	45:34.4	128:09.2	2758 G
SF7	SIO-E8	–	04-10-85	45:33.8	128:09.3	2761 VG
SF7	SIO-V84-2	–	04-10-85	45:33.9	128:10.2	2765 G, ND (2%)
SE4	TUJ-OBMS5	02-08-85	04-10-85	46:20.0	127:59.6	2743 VG
SF8	TUJ-OBMS4	27-07-85	05-10-85	45:36.8	129:35.8	2647 VG
SF8	SIO-E9N	–	05-10-85	45:37.0	129:36.0	2730 G
SF8	SIO-VE2	–	05-10-85	45:36.7	129:35.6	2730 G, occasional noise
SG5	PGC-OBM3	25-07-85	05-10-85	45:24.9	131:07.1	2815 VG
SG4	SIO-M4a	26-07-85	05-10-85	45:01.5	129:55.6	2712 VG, occasional spikes
SG4	SIO-P77-4	–	06-10-85	45:01.5	129:55.7	2712 VG
SG4	SIO-E4	–	06-10-85	45:01.4	129:55.7	2712 G, slight noise
SG3	TUJ-OBMS3	28-07-85	07-10-85	44:44.7	128:19.2	2813 G, cassette noise
SG3	SIO-P84-4	–	07-10-85	44:44.9	128:19.2	2813 VG
SG2	SIO-P83-1	29-07-85	08-10-85	44:36.7	127:07.4	2838 VG
SG2	SIO-M2-75	–	08-10-85	44:37.2	127:07.4	2838 G, drift
SG2	SIO-E7-75	–	08-10-85	45:37.1	127:07.7	2838 VG
SG1	SIO-M1	31-07-85	09-10-85	44:19.1	125:30.8	2898 VG
SG1	SIO-E6	–	09-10-85	44:18.7	125:31.5	2901 G, occasional high noise
SE3	SIO-M3	03-08-85	11-10-85	46:15.0	126:49.4	2677 VG
SE3	SIO-P84-5	–	11-10-85	46:15.0	126:49.4	2677 VG
SE3	SIO-E84-3	–	11-10-85	46:15.0	126:49.4	2677 G, ND (1%)
SE6	PGC-OBM4	01-08-85	12-10-85	46:41.9	129:45.6	2700 VG
SE6	SIO-E1A	–	12-10-85	46:41.7	126:45.6	2700 VG
SE5	SIO-P84-2	02-08-85	13-10-85	46:36.5	129:11.6	2603 G, some noise
SE5	SIO-M7	–	13-10-85	46:36.4	129:11.6	2603 VG
SE5	SIO-E5	–	13-10-85	46.36.4	129:11.6	2603 G, some noise
SE4	SIO-P84-6	–	14-10-85	46:20.1	127:59.6	2743 G, occasional misses
SD1	PGC-OBM2	24-07-85	14-10-85	47:05.1	126:44.7	2507 not recovered

PGC, Pacific Geoscience Center, Canada; FUA, Flinders University, Australia; SIO, Scripps Institution of Oceanography, U.S.A.; TUJ, Tokyo University, Japan; USGS, U.S. Geological Survey. G, Good; VG, Very Good; ND (10%), No data—10% of the time spent by instrument on seafloor.

In that sense, OFFSHORE EMSLAB constituted a stepping-stone for the large-scale and long-term, principally oceanographic program BEMPEX (for 'Barotropic EM and Pressure Experiment' see Chave et al., 87).

3. Experimental phase of OFFSHORE EMSLAB

The OFFSHORE EMSLAB research team included participants from four countries: the U.S.A., Canada, Japan and Australia. As a result
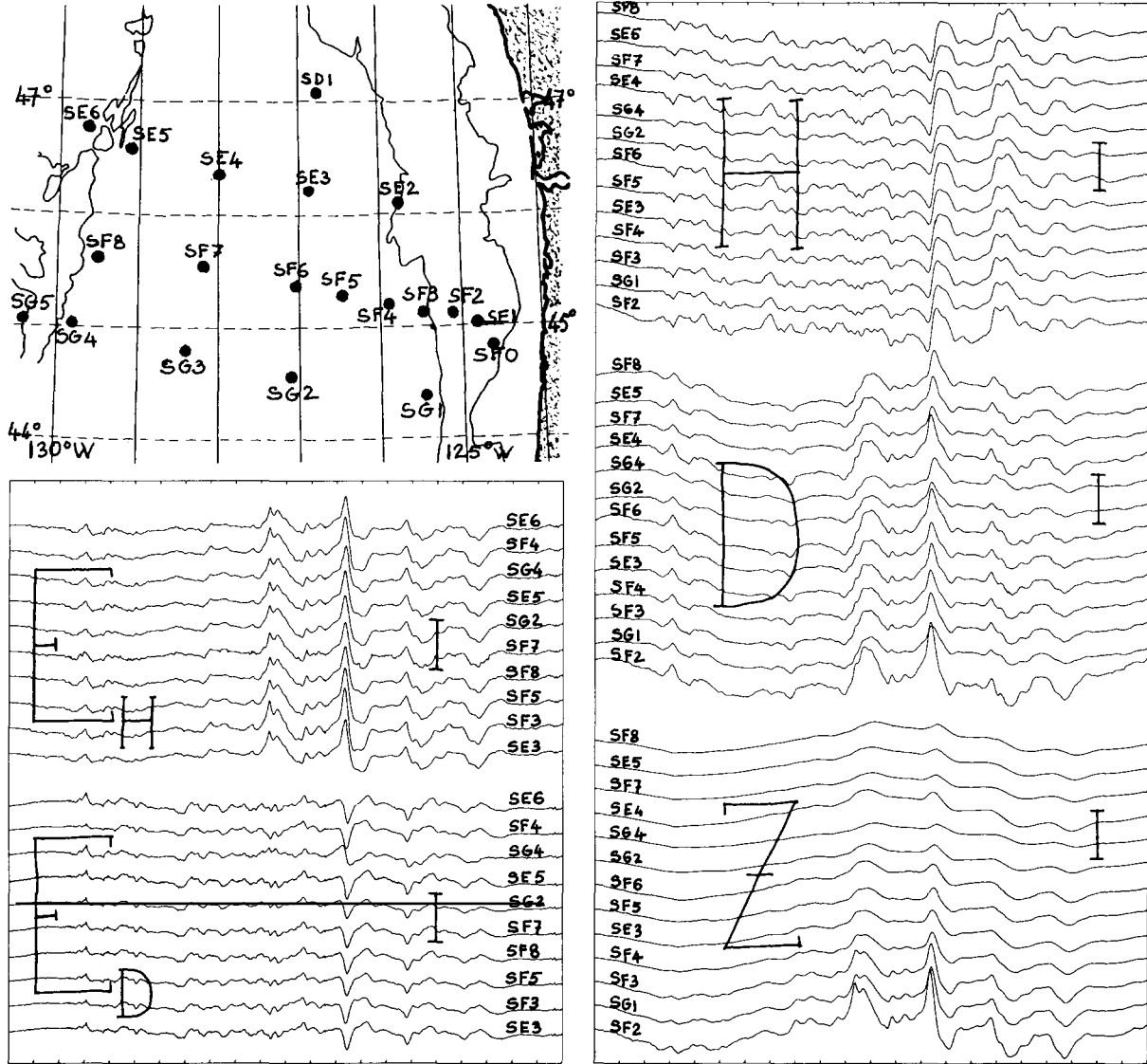

Fig. 3. Sample of EMSLAB offshore data for a 22-h period starting August 12, 1985 at 1630 UT and for 13 magnetic and 10 electric stations. The various traces are arranged in the order of increasing offshore distances, upward from lower trace. Reference to geographic position is easily made from identification symbols on both the reduced map and on individual traces. The letters H, D, Z, refer to the traditional directions, namely: positive toward magnetic north, east and downward. E refers to the electric field. The scale bars correspond to 100 nT and 20 μV m^{-1}. The coast effect is particularly conspicuous in the Z and D components. (For additional information on the complete data set see Table I).

of this co-operation, a total of 40 instruments were deployed on the seafloor according to the array geometry of Fig. 2, for a duration of 60–70 days. Of these 40 seafloor recorders, 39 were recovered and the data return was exceptionally favorable in terms of both continuity and quality. Table I provides complementary information giving details of many aspects of the experiment and of its outcome.

All instruments deployed were of the free-fall type, that is, unconnected at any time to mooring tackles or surface markers (Filloux, 1987). The relatively light individual capsules returned under their own buoyancy following the release of their ballast-support triggered at the time of recovery, either by means of preset timers or by coded acoustic signals. On the surface they were sometimes located immediately following their return simply by visual sighting or, more commonly, by accessory means such as flashing lights, or by tracking their small radio beacons from the recovery research vessel in use. Digital data logging was either on Phillips cassettes or on low-power solid-state memories.

The instrumentation included 20 three-component magnetometers, 11 two-component horizontal electric field, six pressure and three vertical electric field recorders. Typical least-count was 0.1–0.2 nT for the magnetometers, 18×10^{-9} V m^{-1} for the electric recorders and 0.02 cm water head equivalent for the pressure instruments.

4. Data base

The scope of seafloor magnetotelluric data collected during OFFSHORE EMSLAB is best visualized by means of Figs. 2 and 3, with further reference to Table I. The data sample shown on Fig. 3 covers 22 h of an ionospherically active period selected from roughly 65 days of simultaneous recording. The set of recordings presented here is still incomplete. During their operation on the seafloor a few instruments developed malfunctions that complicated data transcription or that required readjustment of scales, compensation for imperfect initial adjustment of clock frequency, or other corrections. The affected data, fully recover-

able, will be corrected but have not been included in this figure. The data from at least another four magnetometers will eventually complete the set illustrated on Fig. 3.

As indicated earlier, physical oceanographic data were also collected by six pressure sensors, and three vertical electric field recorders (Filloux, 1983, 1987). Although one pressure record contains occasional digital recording defects (station SE4) the data return from this group of instruments is essentially complete (for economy of space no oceanographic data sample is presented at this time).

5. Preliminary investigations

Because of the large size of the data set and of the crucial importance of best preserving the integrity of the data as they are transferred and processed from their initial, compactly recorded format, analysis and interpretation have proceeded only slowly. Nevertheless, several tests on analytic ideas and procedures are now available to help confirm the high quality and vast information content of OFFSHORE EMSLAB seafloor observations.

5.1. Parkinson arrows

The Parkinson arrows have been calculated for three frequencies ranging from 0.5 to 2.3 cycles h^{-1} for which the maximum EM energy in the signals ensured minimum noise contamination, according to the relation

$$Z = \left[-A_r (\cos \theta_r \cdot H + \sin \theta_r \cdot D) - A_i (\cos \theta_i \cdot H + \sin \theta_i \cdot D) \right] \tag{3}$$

where H, D and Z represent the three components of the magnetic variations to magnetic north, east and downward, A_r and A_i are the modulii of the real (in phase) and imaginary (in quadrature) parts of the Parkinson arrows, θ_r and θ_i are their spatial orientation referred to north, increasing eastward, and $i = (-1)^{1/2}$. The results are mapped on Fig. 4, and the orientation of the arrows is such that the arrow points toward the most significant
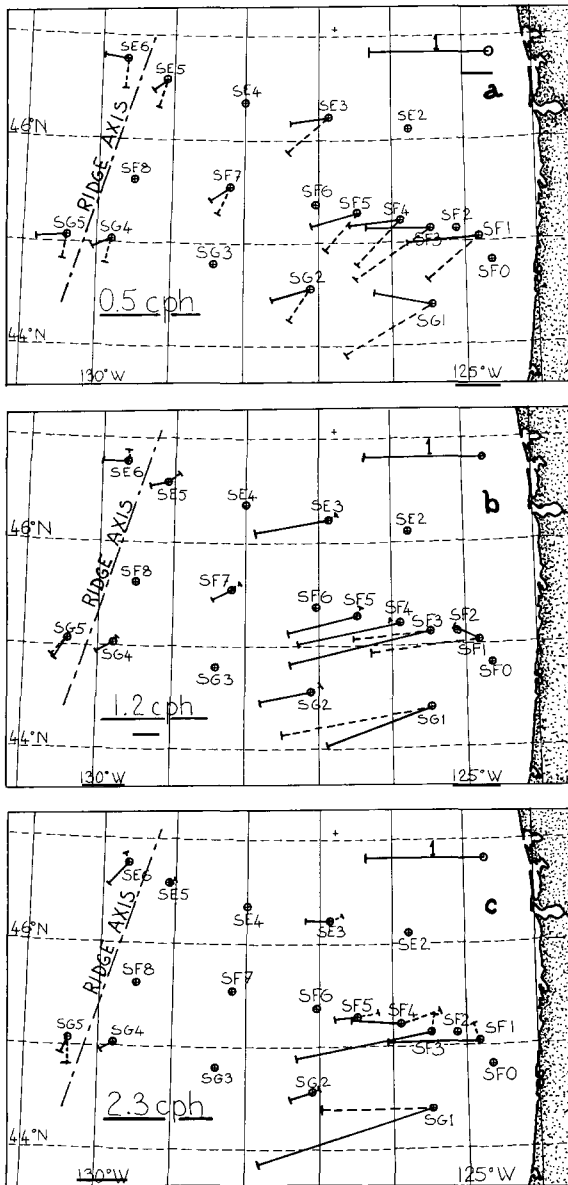
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Fig. 4. Parkinson arrows at 12 magnetic stations for frequencies of 0.5, 1.2 and 2.3 cycles h^{-1} (boxes a, b, and c, respectively). Real part: continuous line; imaginary part: dashed line. For scale see unity segment at upper right. Note the smooth variability over space at all three frequencies and the strong frequency dependency. Suggestion of a distinct EM signature associated with the Ridge occurs only at the highest frequency of 2.3 cycles h^{-1}. We expect it to become more pronounced when analytic improvements permit us to extend the frequency range upward.

local conductor sensed at that frequency. The correlations implied in eqn. (3) above were established without taking advantage of the powerful noise reduction scheme based on remote referencing (Gamble et al., 1979a, b). When all EMSLAB data become properly reduced, simultaneous magnetic field coverage from INLAND EMSLAB will provide a sophisticated test of the merits of the remote reference technique and, because of the availability of a large number of alternate referencing time series, usable individually or in combination, it should also cast new light on the mode of operation, hence on the optimum applicability of noise reduction by remote reference approaches. Nevertheless, despite the benefits from this procedure, a comforting consistency exists between all Parkinson arrows shown for the three frequencies considered in Fig. 4. Their large size near the base of the continental slope—sometimes larger than unity—constitutes a conspicuous expression of a strong 'coast effect', although the large size is due in part to the attenuation by the ocean of H and D on the seafloor being greater than the attenuation of Z. Another question to be addressed is whether or not the influence of the Juan de Fuca Ridge crest is detectable. If such a tectonic feature does imply the existence of an elongated and shallow zone with high temperature and extensive magma infiltration, then one would expect rotation toward the Ridge, as frequency increases, of the Parkinson arrows for stations located westward of it. At 2.3 cycles h^{-1}, there is a suggestion that this effect appears to begin to take place (see Fig. 4). A more sophisticated treatment of the data should help extend the useful frequency range of sufficiently well resolved transfer functions, and, in turn should enhance the expected rotation.

5.2. Oceanic EM tidal signals

Because of the generally large horizontal scale of oceanic motions compared with the oceanic depth, h, it can be shown (Sanford, 1971) by vertical integration of eqn. (1) from the ocean bottom to the surface that, in the absence of ionospheric activity, the horizontal electric field in a reference frame fixed to the seafloor, when

properly scaled, is a close measure of the local oceanic water mass transport, Vh (where V is the average horizontal water velocity and h the oceanic depth). Specifically, over a non-conducting seafloor in which $J = 0$, thus ensuring through the non-divergence of J that the integral of J from bottom to surface vanishes, we have

$$E_{x,y}/B_z = -\overline{V^*_{-y,x}} \qquad (4)$$

with

$$\overline{V^*_{-y,x}} = \frac{\int_{-h}^{0} V_{-y,x(z)}\sigma_{(z)}\,\mathrm{d}z}{\int_{-h}^{0} \sigma_{(z)}\,\mathrm{d}z} \qquad (5)$$

where $\overline{V^*}$ is the conductivity weighted average of the horizontal velocity, $V_{-y,x}$, in the horizontal directions $-y$ and x, and B_z is the vertical component of the main magnetic field of the Earth. Since the ocean floor is not a perfect insulator, the electric current J generated by the motional field does return in part through the seafloor. Thus, to ensure vanishing of the vertical integration of J it is necessary to extend the integration limit to a greater depth where J vanishes. It is thus clear from eqn. (4) above that conduction of the seafloor does result in a reduction of $\overline{V^*}$, hence in an underestimate of $\overline{V}$. This situation is not too detrimental for two reasons: (1) at the specific characteristic dimensions of the problem, electric current return through the seafloor is limited by the high seafloor impedance and (2) a first-order correction can be made when magnetic observations are available from the seafloor, which was the case here (see Tarits et al., in preparation) since they are closely proportional to electric current leakage through the seafloor. There are other small errors involved; in particular, one resulting from equating $\overline{V^*}$ to $\overline{V}$, as is done when the variations in seawater conductivity with depth are neglected; see eqn. (5). This error is generally quite small, however, as discussed in Sanford (1971) and illustrated in Filloux (1987), because significant conductivity variations are restricted to the thin surface layer above the thermocline.

Application of the above concepts to tidal motions over the EMSLAB area have resulted in a most illuminating illustration of the usability of seafloor EM observations in the investigation of large-scale oceanic motions (see Tarits et al., in preparation).

Briefly summarized, the seafloor data from OFFSHORE EMSLAB permit us to derive two completely independent estimates of tidal velocities over the area, one based strictly on seafloor EM data, the other on seafloor pressure data.

Estimates of the tidal barotropic velocity or average horizontal velocity over the entire oceanic water column have been made according to the above guidelines, using both electric and magnetic observations. For this purpose, electric and magnetic time series were separated into (1) components correlated with the gravitational tide producing potential, (2) others representing solar daily variations, and (3) those representing uncorrelated noise. Despite the extensive contamination of the strictly gravitational tide signals by those associated with the magnetospheric daily variation and harmonics of same frequencies, both electric and magnetic fields tidally generated are surprisingly well resolved, as illustrated by the spatial consistency of the ellipses, representing their temporal variations in size and orientation (see the example for the main semidiurnal constituent M2, in Fig. 5a). From these electric and magnetic data, corresponding estimates of the tidal barotropic V, were also made and are shown in Fig. 5a.

Alternatively, observations of tidal pressure fluctuations on the seafloor over an appropriate space can be used to simulate mathematically the modal structure of tidal fields over the area. The pressure observations made during the OFFSHORE EMSLAB experiment (see Figs. 2 and 5b), augmented by data previously obtained at sites not shown on the map of Fig. 5b, can be closely reproduced by the combination of a Kelvin wave mode and a single Poincaré mode with optimum incidence parameter (for illustration of method, see Munk et al. (1970)). From the resulting simulation, the tidal flow can be calculated at each recording site. The corresponding tidal velocity ellipses for M2 (continuous lines) are compared in Fig. 5b with those inferred from the thoroughly independent EM observations (dashed lines).

Although the fit between the two sets of tidal estimates is most pleasing, further improvements are possible. Two important geophysical subjects
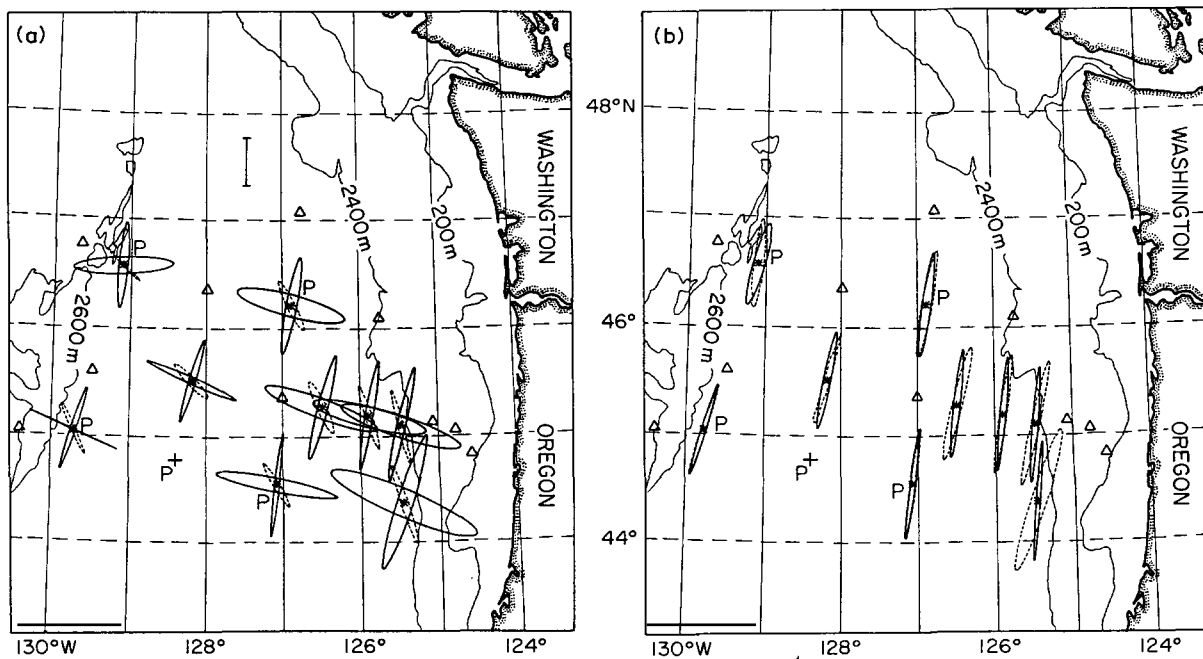
Fig. 5. (a) The east–west trending ellipses (continuous line) represent the horizontal electric field variations associated with the semidiurnal lunar constituent M2 at those nine stations where both electric and magnetic fields were recorded. The dashed line ellipses represent the magnetic variations, also for M2. The north-south trending ellipses (continuous line) combine both electric and magnetic information to construct estimates of the tidal barotropic velocity for M2 tide. The scale segment, up-center, corresponds to 10^{-6} V m^{-1} (electric field), 5×10^{-9} T (magnetic field) and 2.5 cm s^{-1} (velocity). (b) The continuous ellipses represent independent estimates of the barotropic tidal velocity for M2 derived from seafloor pressure. Data from stations P (see text and Fig. 2). The dashed line ellipses represent the EM estimates of the barotropic velocity. The agreement between both is most rewarding, and could be improved by modeling of the electrical conductivity of the seafloor (see text).

can be enlightened in the process of this optimization. First, the current density, J, is extremely dependent on the Kelvin–Poincaré mode mix, thus its adjustment allows great constraint of the tidal structure, with considerable information on tides gained in the process. Second, knowledge of J, together with further optimization of the fit between the two independently obtained velocity fields in terms of electrical conductivity models of lithosphere and mantle, should expose important constraints on the variability of conduction and, indirectly, on the solid Earth structure locally (see discussion of this subject in Larsen (1968)).

6. Conclusion

OFFSHORE EMSLAB, with an array of 40 seafloor recording instruments, of which 39 were

recovered with a remarkably high data return, is the largest electromagnetic oceanic experiment carried out to date with the dual, simultaneous and mutually beneficial objectives of (1) solid Earth exploration beneath the seafloor and (2) the investigation by novel techniques of large-scale oceanic velocity fields.

The experiment was made possible by the harmonious association of researchers from four countries and six independent institutions, illustrating the benefits of co-operative work in a project where wide spatial coverage and high density of observations are of determinant importance.

Above all, the true value of OFFSHORE EMSLAB will result from its being part of the overall EMSLAB project in which well over a hundred EM observation stations operated simultaneously over an area of considerable geophysical

significance, representative of a variety of tectonic processes at present under intense scrutiny for purposes of theoretical as well as applied science.

Acknowledgments

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