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Electrical Conductivity Structure by Geomagnetic Induction at the Continental Margin of Atlantic Canada

R. D. Hyndman and N. A. Cochrane

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Summary

Geomagnetic variations measured at 10 stations in Atlantic Canada show significant laterally inhomogeneous induction. Transfer functions giving the systematic dip angle and direction of the variation field lines have been computed for periods from 20 s to 120 min and the results numerically modelled.

High electrical conductivity exists starting at a depth of 15 km or less under the continental shelf off Nova Scotia and Newfoundland and perhaps under the Bay of Fundy. The apparent coast effect with a maximum at 30-min period results from the contrast between the highly conducting shelf structure and the more resistive inland rocks. The most likely explanation of the high conductivity is that there is highly saline interstitial water in the lower part of a 10 km sedimentary section associated with evaporite, salt layers, or that part of the crust is hydrated in this area.

Strong electric currents flow in the various arms of the Gulf of St Lawrence for short period (10 s to 10 min) inducing fields. Numerical models show that they can be explained by local induction in the shallow sea water. The details of the current flow indicate that significant conductive channelling must occur.

One station on the north shore of the St Lawrence River has large long period (30 min) anomalous vertical fields. They probably result from a contrast in deep conductivity between the Appalachian and Canadian Shield geological provinces.

1. Introduction

Geomagnetic induction studies of the crust and upper mantle have detected three main types of high conductivity zones: 1. The low velocity, partial melt, layer beneath lithospheric plates; 2. Deep crustal layers of partial melt or active metamorphic dehydration processes; 3. Surface sediments or bodies of salt water.

The plate tectonics theory postulates that a rigid plate 40–200 km thick moves over a weak zone (aesthenosphere, low velocity layer) which likely contains a few per cent partial melt (Anderson 1962; Anderson & Spetzler 1970; Ringwood 1969; Birch 1970; Press 1970). It is reasonable to expect this partial melt zone to have high electrical conductivity compared to the plate (e.g. Khitarov & Sluzky 1965) and magnetotelluric and depth sounding studies confirm the existence of high conductivity.

Seismic and thermal studies indicate different depths to the weak zone under oceans, tectonically active continental areas and stable continental areas (e.g. Press 1970; Sclater & Francheteau 1970). The same picture is becoming evident from geomagnetic induction studies (Uyeda & Rikitake 1970; Schmucker 1964; 1970; Caner *et al.* 1967; Swift 1967; Coode & Tozer 1965; Caner & Cannon 1965; Lubimova & Feldman 1970).

Geomagnetic induction measurement and analysis techniques are of two main types. (1) The vertical variation in electrical conductivity, assuming a nearly horizontally stratified structure, can be estimated by the magnetotelluric and the geomagnetic deep sounding methods. (2) The second type of approach is to look at lateral variations in electrical conductivity structure by comparing the magnetic and electric fields measured at different stations. Our study mainly involves the outlining of lateral variations in conductivity.

Only very recently was it realized that time variations of the Earth's magnetic field showed consistent geographical differences that could be ascribed to lateral non-uniformities in the Earth's upper layers. The coast effect is now well established and a number of inland anomalies have been discovered. In 1967 D. C. Tozer stated 'It seems probable that when observations are extended and refined more of these peculiar regions will be found, and that perhaps eventually quite small areas may be identified by their characteristic magnetic response' (Tozer 1967). We have recently analysed several tens of magnetic stations and find there are almost no 'normal' stations, all show some, and most, pronounced non-uniform induction due to lateral variations in electrical conductivity. In hindsight, this is reasonable considering the geological complexity of the Earth's crust and upper mantle and the presence of many inlets and inland bodies of salt water. It had not been realized that most magnetograms indicate non-uniform induction probably because of a lack of appropriate analysis.

The general presence of lateral induction anomalies has two important implications. Firstly, it suggests the wide applicability of the geomagnetic recording method to geophysical and geological problems. Secondly, the methods of determining the variations of electrical conductivity with depth by induction usually assume no lateral variations and thus frequently involve a large error.

The method of spherical harmonic analysis of field variations over the whole earth assumes no anomalous vertical field (produced by non-uniform induction). This error is particularly serious because of the large fraction of coastal stations that have been used in this type of analysis. A similar error is present in the magnetotelluric method (Cagniard 1953) and in the new and promising method of geomagnetic depth sounding (e.g. Caner *et al.* 1967).

The vertical field, in general, will be determined largely by the source field configuration and the vertical distribution of conductivity if the Earth's lateral conductivity variations have dimensions greater than those of the source field. It will be determined mainly by the lateral variations in conductivity structure if the dimensions of the structure are smaller than the dimensions of the source field.

Ideally, lateral conductivity variations are determined by formal separation of the fields of external and internal origin for an area. This requires large numbers of simultaneous stations and extensive analysis (eg. Porath *et al.* 1970; Reitzel *et al.* 1970).

Transfer function analysis (Schmucker 1964; Everett & Hyndman 1967) attempts to determine the laterally non-uniform induction by estimating the vertical component of the magnetic variation field due to the non-uniform induction. The results are used directly in geophysical interpretation and to determine at which stations the induction is sufficiently uniform for interpretation by spherical harmonics, geomagnetic depth sounding or simple magnetotellurics. At stations where the lateral variations are not too large, it may be possible to remove their effect before applying one of the above techniques (e.g. Cochrane & Hyndman 1970).

Our single station vertical transfer function gives the systematic dip angle or preferred plane of the magnetic variation field (with frequency and phase dependence).

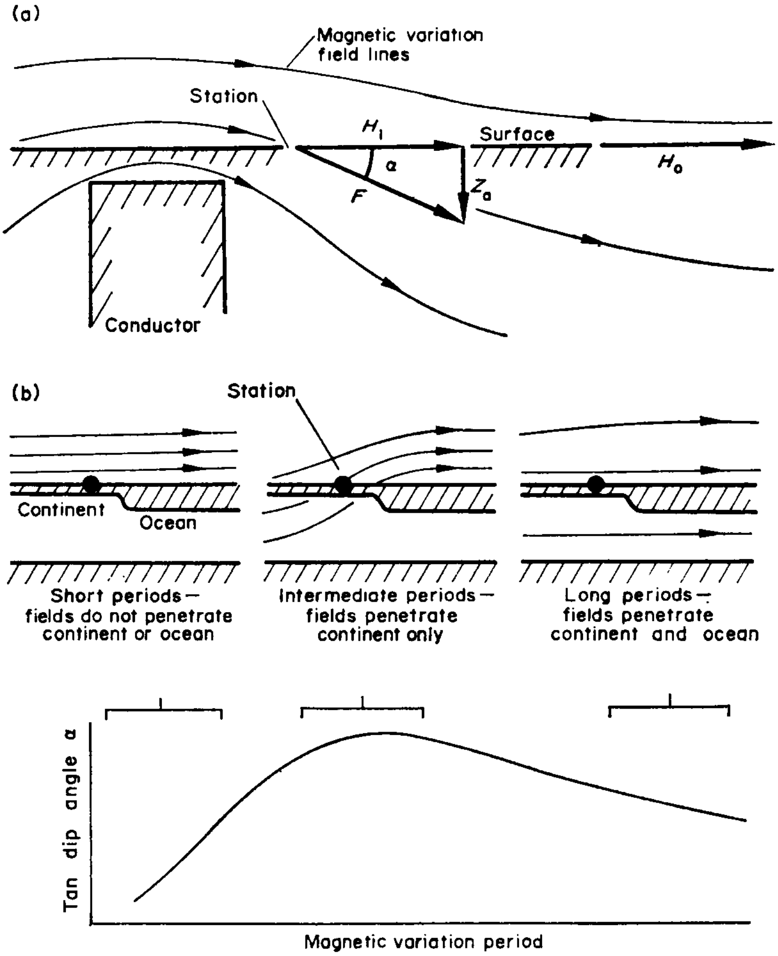

Fig. 1. A simplified representation of the transfer function.

It approximates the tangent of the dip angle α that would exist with a uniform horizontal source field. It assumes that the dip angle of the source field is random in direction and will be removed by averaging over a sufficiently long section of record. A horizontal transfer function can also be computed that estimates the horizontal field enhancement or reduction with respect to a reference station. For example, field lines are compressed or pinched together over a conducting body. A simplified representation is given in Fig. 1.

The variation of the transfer function with frequency can best be illustrated by an example. Let us consider the case of a station close to the edge of a thick two dimensional high conductivity layer. There is a thin conductive layer under the station (Fig. 1). The deep ocean edge with thin continental sediments may approach this model in some areas. The edge of a high conductivity deep crustal layer gives a similar response (e.g. the Kootenay Lake area of Cochrane & Hyndman 1970; Lajoie & Caner 1970). Qualitative results are obtained by examining the penetration of the field lines into the conductors. At high frequencies (5-min period) the depth of penetration is small in the deep ocean and in the continent so the dip angle of the field lines (or Z transfer function) is small. At intermediate frequencies (30 min) the fields penetrate the continent deeply but still hardly penetrate the deep ocean and the dip is large. At low frequencies (2 h) a large part of the field penetrates the deep ocean and the dip decreases. A highly conducting mantle under the ocean has the effect of damping the currents in the ocean and reducing the transfer function at long periods.

Our measurement area extends from Hauterive on the north side of the St Lawrence River to Sable Island, 200 kilometres off the Nova Scotia coast. These stations are from the Grenville province of the Canadian Shield across the Appalachian province to the deep offshore sedimentary trough. The Appalachian province has developed from a geosyncline through two major orogenies. The Gaspé peninsula and northern Newfoundland part were deformed in the Ordovician, Taconic orogency. Parts of these areas may rest on Precambrian Grenville basement. To the south-east in New Brunswick and central Newfoundland deformation occurred during the middle Devonian, Acadian orogeny (Zen *et al.* 1968). Bird & Dewey (1970) have suggested that the first Taconic deformation was associated with trenches across northern New Brunswick, the Gaspe peninsula and central Newfoundland that consumed a proto-Atlantic ocean. The Acadian orogeny was associated with the final continental collision. The present Atlantic breakup appears to have occurred along a new line considerably to the south (Wilson 1966). The southern areas comprising the Avalon peninsula of Newfoundland, Cape Breton and the Meguma trough of Nova Scotia were only slightly deformed at the times of the Appalachian orogenies.

The broad Nova Scotia shelf is underlain by at least 5 km of sediment at its outer edge (Barrett *et al.* 1964; Drake *et al.* 1959; Dewey & Bird 1970) and perhaps up to 10 km (*Oil and Gas Journal* 1970). They consist of a fairly continuous sequence to Cretaceous and perhaps Jurassic (Howie 1967). The inner part of the shelf is probably underlain by the Meguma shales and slates of Nova Scotia. The Meguma sediments have been very slightly metamorphosed and heavily intruded by Devonian granites.

The Gulf of St Lawrence and south-eastern New Brunswick are covered by Carboniferous sediments. Their maximum thickness is about 8 km under Prince Edward Island (Ewing *et al.* 1966).

Seismic refraction studies show P_n velocities of about $8{\cdot}0\,\mathrm{km\,s^{-1}}$ under both the northern edge of the Appalachians and the south-eastern margin but high $8{\cdot}5\,\mathrm{km\,s^{-1}}$ velocities under the central Appalachians. The crust is also thicker (45 km) and has an intermediate layer with velocity greater than $7{\cdot}0\,\mathrm{km\,s^{-1}}$. This interpretation appears to be consistent with gravity data (see Keen *et al.* 1971).

2. The coast effect

The coast effect associated with continental margins has been observed by many authors (Parkinson 1959, 1962; Rikitake 1959; Schmucker 1964, 1970; Schmucker *et al.* 1964; Lambert & Caner 1965; Everett & Hyndman 1967; Edwards 1969; Cochrane & Hyndman 1970; Srivastava & White 1971). The effect extends inland several hundred kilometres and is most pronounced at periods of about 1 hr. There has been considerable discussion as to whether this deep water coast effect can be explained by the highly conducting sea water alone or whether a contrast in mantle conductivity is required. Filloux (1967) and J. Greenhouse (personal communication) have made deep ocean floor magnetic recordings that exhibit strongly attenuated variations indicating high conductivity at shallow depth under the oceans.

We suggest that coasts of tectonically active continental areas will have only a small increase in depth to the high conductivity zone, going from ocean to continent so the coast effect is primarily produced by the highly conducting sea water (e.g. the California model of Schmucker 1970). The increase in depth is much greater across a stable margin. The step then makes a significant contribution to the coast effect which extends much further inland.

Shallow sea water estuaries and shelves exhibit effects that extend only a few tens of kilometres and that are most pronounced at periods of around 1 min (Mansurov

1958; Christoffel *et al.* 1961; Rokityanski 1963; Lokken & Shand 1962). It has been debated whether or not appreciable currents can be induced in small shallow seas or whether electric currents are channelled in from the ocean.

There have been two different approaches to the problem of induction in the ocean that produces the coast effect. One approach is to model the ocean by a thin flat sheet bounded by insulating continents and an insulating uppermost mantle underlain in turn by high conductivity. The other approach is to model the coast as an infinite two-dimensional boundary. Both approaches have serious inherent assumptions but we believe the latter model is the best approximation. A similar but even more complex problem is involved in trying to model inland conductivity structures.

The first approach uses analytic solutions for a conducting disc or strip (Ashour 1950, 1965; Roden 1964; Parker 1968; Edwards 1969; Bullard & Parker 1971). These authors generally argue that the oceans are too shallow for significant induction by the horizontal component of the source field so currents must be induced by the vertical component (in the disc model the pattern will be horizontal and circular with the currents concentrated near the circumference). This contention rests on there being no return circuit for a uniform sheet of electric currents in the ocean by connection of the ocean to the conducting mantle or around the Earth. However, complete circuits around the Earth are reasonable considering that two thirds of the Earth is covered by sea. And currents flowing down to the conducting mantle with little resistance are to be expected in many places such as the spreading ocean ridges and at the continental margins (e.g. Jones & Price 1970; Swift 1967). The question of currents flowing into the continents can be best resolved by measurements of the electric currents flowing perpendicular to the coasts (e.g. Madden & Nelson 1964).

The vertical field induction theory also predicts that the coast effect should fall off inland over a distance directly proportional to the width of the ocean (not allowing for different continental conductivities). The observed coast effects seem to be mainly dependent on the continental conductivity. The coast effect falls off more rapidly inland for western North America bordering the large Pacific Ocean than for western Australia or eastern North America bordering the smaller Indian Ocean, Atlantic Ocean and Labrador Sea. It is significant that the transfer functions for some inland conductors of small size compared to oceans give similar responses to the coast effect.

Edwards (1969) shows how correlated vertical and horizontal fields can be produced at coasts by vertical field induction. However, in his theory the part of the horizontal field that is correlated with the vertical field should be quite small. This is at variance with the observed large transfer functions which indicate that most of the horizontal field is correlated with part of the vertical field. It is also not in agreement with the very high coherence between measured horizontal magnetic fields and electric currents on the sea floor (Filloux 1967).

We conclude that the induction in the ocean which produces the coast effect is primarily by the larger horizontal part of the source field.

The second approach of a simple two-dimensional boundary requires similar assumptions to the theory for layered structures by Cagniard (1953) and Price (1962). We believe that for a realistic spherical earth largely covered by oceans, and with source fields with dimensions comparable or larger than the oceans, coasts can be approximated by plane two-dimensional structures with boundaries extending to infinity. The simple boundary conditions will be more closely approximated if the currents in the oceans readily leak down into the mantle near continental boundaries. In this theory, induction is assumed to be mainly by the horizontal component of the source field since it is generally much larger than the vertical component. Numerical solutions have been obtained for a number of two-dimensional structures (Schmucker 1964, 1970; Swift 1967; Madden & Nelson 1964; Madden & Swift 1969;

Jones & Price 1970; Filloux 1967; Wright 1969) and some approximate analytic (e.g. d'Erceville & Kunetz 1962; Weaver 1963; Ponomarvov 1960). Physical model studies have also been made that imply this sort of assumption (e.g. Dosso 1966). The validity of this kind of approximation needs more examination but it gives the correct form of the coast effect, and for the response of other structures.

3. Previous work in Atlantic Canada

Three component magnetograms have been analysed by Srivastava & White (1971) for Fredericton, New Brunswick, Halifax, Nova Scotia and Sable Island. They found that the horizontal field components were very similar at these stations and the vertical field was much larger at Halifax than inland at Fredericton as expected from the coast effect. However, their results unexpectedly showed very small vertical fields at Sable Island. They explained this result partly by the effect of highly conducting sediments and partly by high conductivity at depth under the Island. They suggested that the perturbation of the local electric currents by the island (island effect) should not be important. Electric fields were measured on the Island and on the ocean floor near the Island by Srivastava & White (1971). They indicated a strong polarization of the electric vector and low amplitudes indicative of high conductivity under the island.

Srivastava (1971) reported simultaneous total field measurements for daily variations at a number of stations around the Gulf of St Lawrence. The daily variations show almost no effect from the Gulf in contrast to the large effect at shorter periods discussed in this paper, and surprisingly very little coast effect along the continental margin. The amplitudes were largest near the coast (e.g. Dartmouth) and smaller at Sable Island and at inland stations. The effect is less but in general agreement with the results for higher frequencies presented in this paper. It is contrated to the significant effect found by Riddihough (1967) for the coast of Europe and the theoretical prediction of Roden (1964). These indications of an unusual structure under this coast provides some of the incentive for the work reported in this paper.

4. Measurements

Three component magnetograms were obtained from 10 stations in Atlantic Canada (Table 1, Fig. 2). Stevenville (SV) and Cape North (CN) were temporary field stations operated by the Division of Geomagnetism, Earth Physics Branch, Ottawa using fluxgate magnetometers and chart recorders. St Johns is a new Division of Geomagnetism permanent magnetic station. The remaining seven stations were recorded with a Sharp MFO-100 fluxgate magnetometer recording on a Honeywell multi-channel recorder (500 gamma full scale, 1·5 inches per hour) and in the case of Sable Island on a Hewlett Packard digital voltmeter and printer. For these stations the detector head was buried at a depth of 1 m to reduce temperature drift.

Table 1

The analysed magnetic variation stations in Atlantic Canada

1. Hauterive (HA),	49° 12′ N,	68° 16′ W	6. Dartmouth (DM),	44° 41′ N,	63° 37′ W
2. Matane (MA),	48° 51′ N,	67° 38′ W	7. Sable Island (SI),	43° 56′ N,	60° 03′ W
3. Charlo (CH),	47° 59′ N,	66° 20′ W	8. Cape North (CN),	46° 53′ N,	60° 30′ W
4. Newcastle (NC),	46° 59′ N,	65° 35′ W	9. Stephenville (SV),	48° 20′ N,	58° 20′ W
5. Moncton (MO),	46° 08′ N,	64° 54′ W	10. St. Johns (SJ),	47° 20′ N,	52° 25′ W

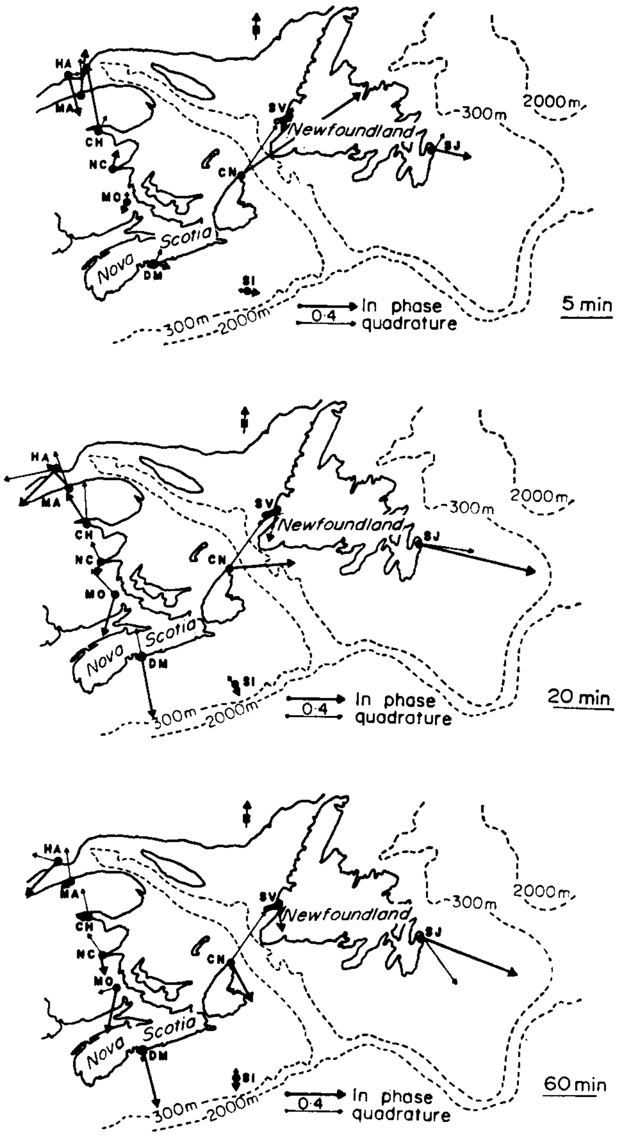

FIG. 2. Induction vectors for magnetic variation periods of 60, 20 and 5 min.

5. Analysis

Vertical (Z) transfer functions were computed in a manner identical to that described in detail by Cochrane & Hyndman (1970), which is similar to that used by Schmucker (1964), Everett & Hyndman (1967), and Edwards (1969). The part of the vertical field that is statistically correlated with the horizontal field is estimated as a function of frequency. The transfer function amplitude is the ratio of this correlated part of the vertical component to the amplitude of the horizontal components for the horizontal field in the direction of maximum correlation. It is usually assumed that the correlated part of the vertical component results from currents induced by the regional horizontal component (see above).

At each station the auto and cross spectra were computed for 3 to 6 record sections, each of from one half to one day in length. To effectively cover the period range from

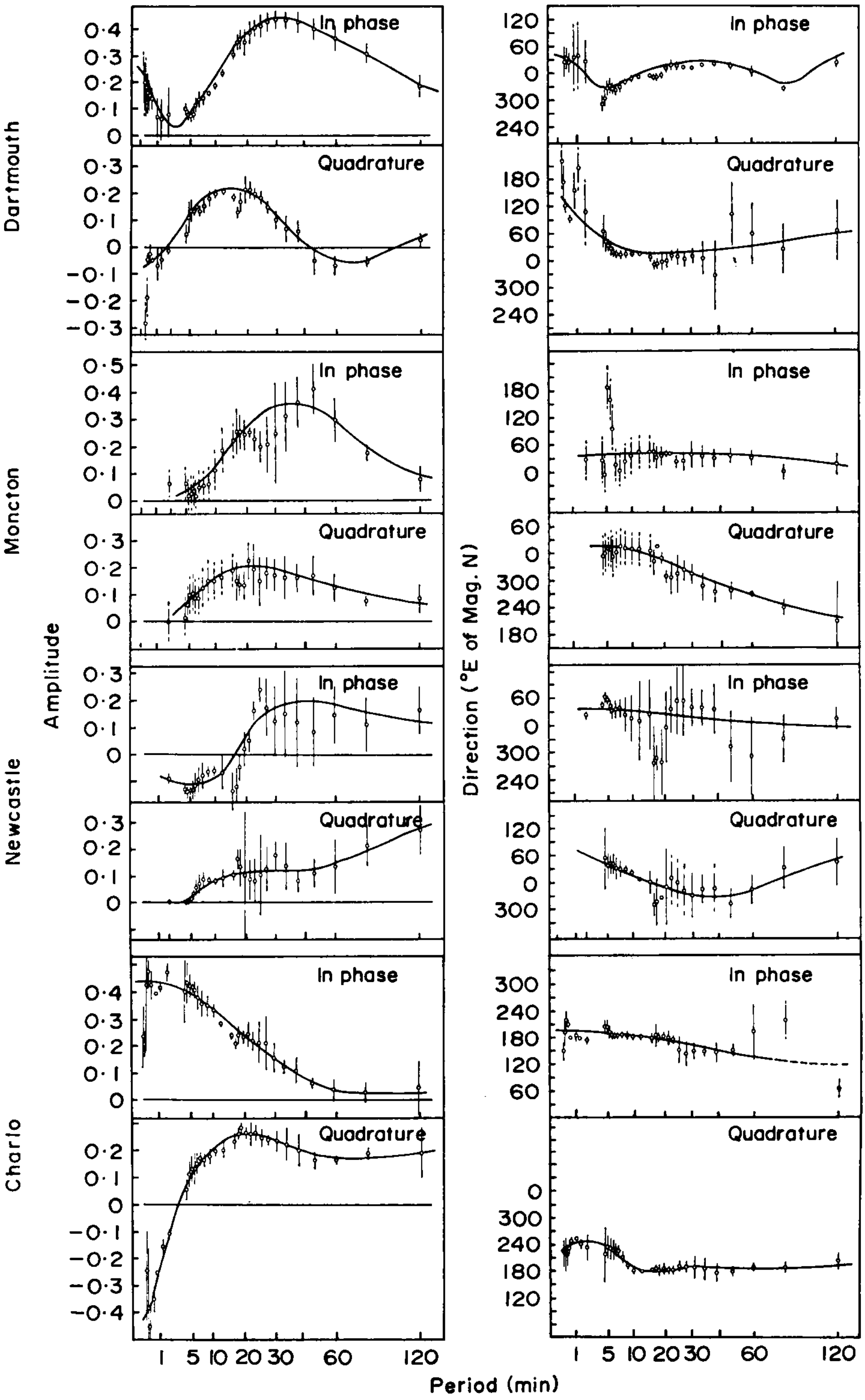

FIG. 3(a)

FIG. 3.(a), (b) and (c). The amplitudes and directions with frequency of the single station Z transfer functions.

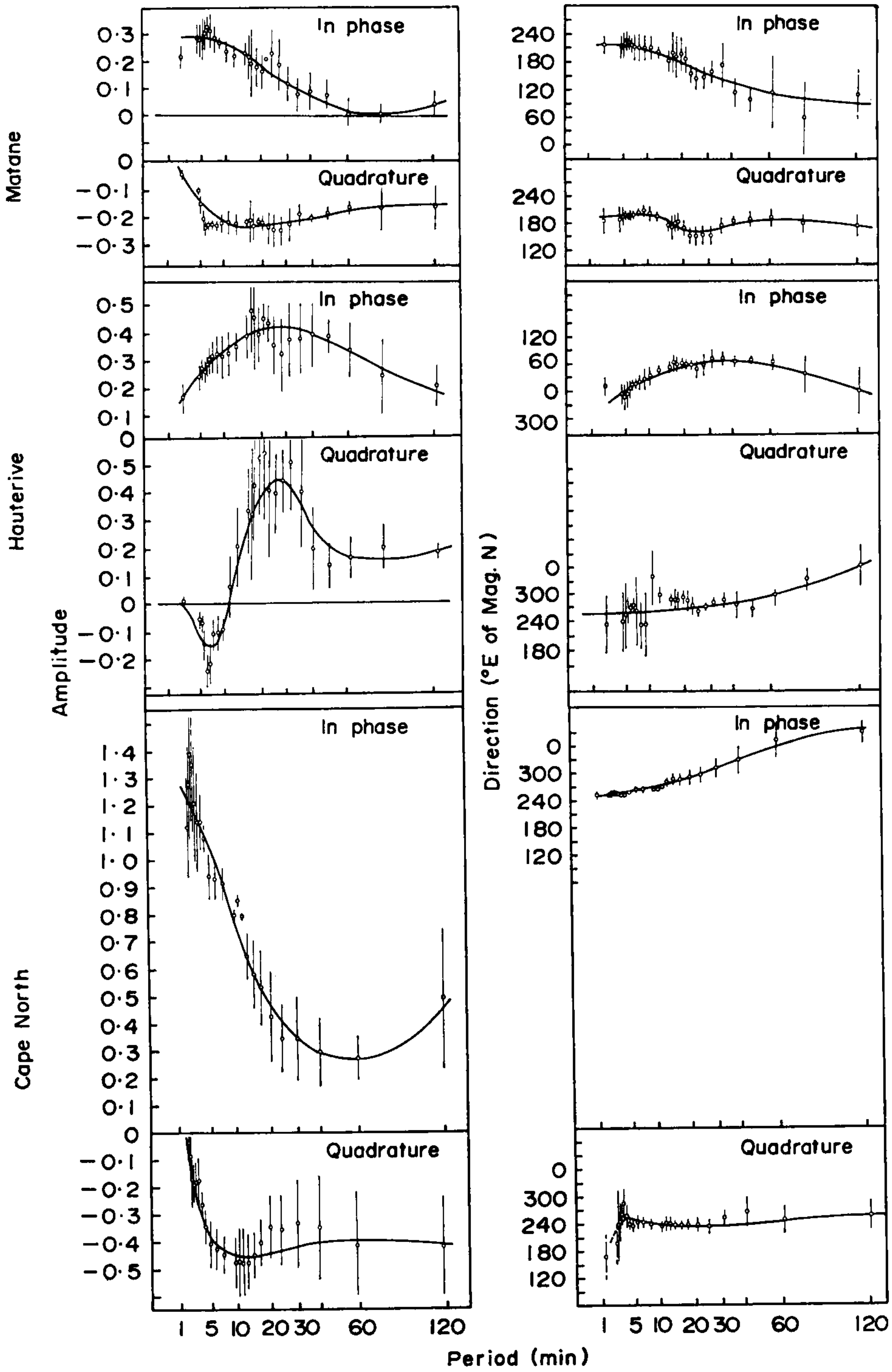
Matane
Hauterive
Cape North
Amplitude
Direction (°E of Mag. N)
In phase
Quadrature
0·3
0·2
0·1
0
−0·1
−0·2
−0·3
0·5
0·4
1·4
1·3
1·2
1·1
1·0
0·9
0·8
0·7
0·6
240
180
120
60
300
1 5 10 20 30 60 120
Period (min)

FIG. 3(b)

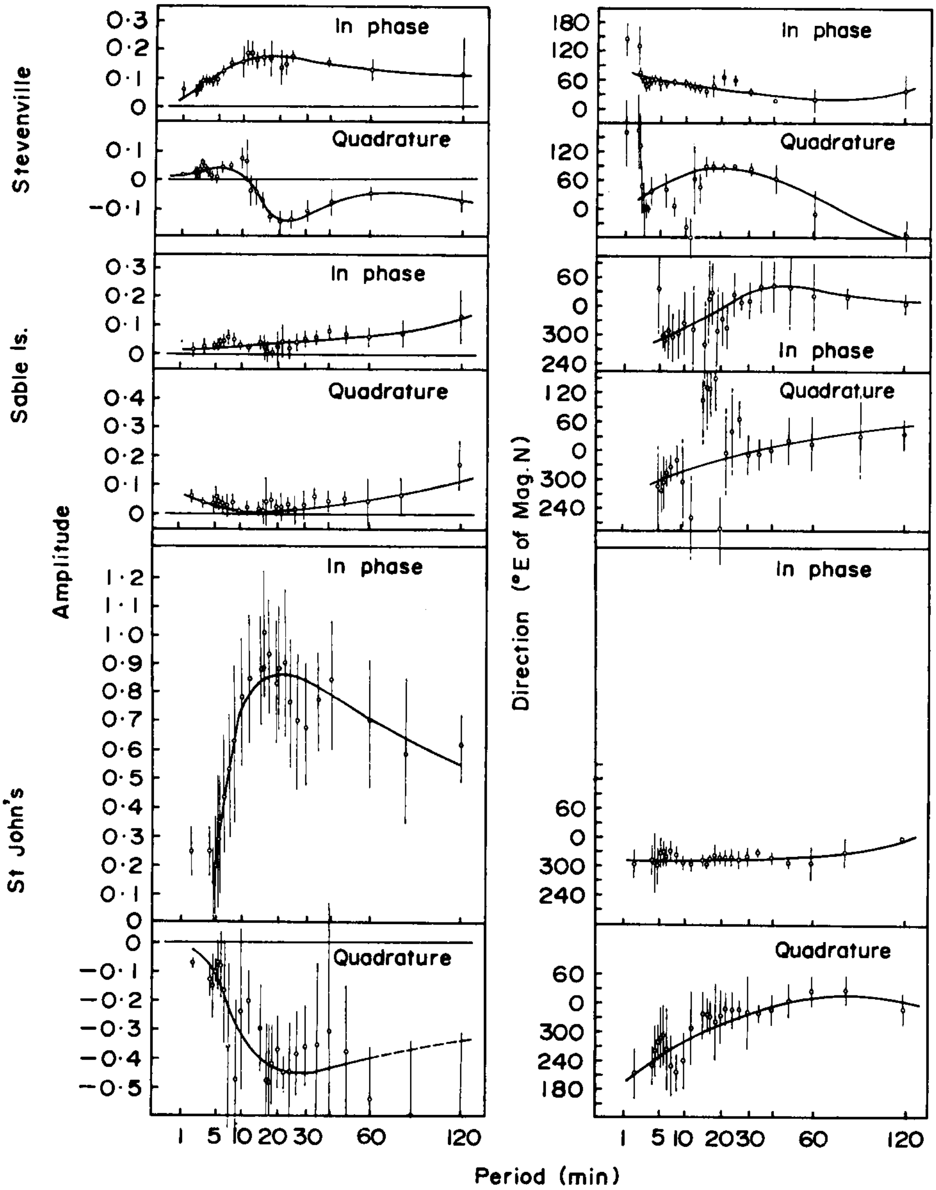

FIG. 3(c)

2 to 120 min spectra were obtained for frequency intervals of 0·00833 and 0·0333 cycles/min. At Charlo and Dartmouth where there was high speed recording, 0·50 cycles/min intervals were also used. Transfer functions were computed from the average spectra at each station and error estimates by also computing the transfer functions for each individual record length. The amplitudes and directions of the transfer functions are shown in Fig. 3. Fig. 2 shows the induction vectors (similar to those of Parkinson, 1962) for periods of 60, 20 and 5 min. Their lengths are proportional to the absolute amplitude of the transfer function, and their directions are those of maximum horizontal to vertical correlation (the negative for the in phase part and positive for the quadrature part). The arrows will generally point toward electric current concentrations.

Horizontal transfer functions (see Schmucker 1964; 1970) were computed for Sable Island using Dartmouth as a reference.

6. Results

The main features of the transfer functions (Figs 2 and 3) are: Firstly, a pronounced continental margin effect, largely in phase, with maximum amplitudes for periods between 20 and 60 min that is still significant 500 km inland from deep water. Secondly, a shallow water effect. Comparatively strong current concentrations are indicated in Cabot Strait between Nova Scotia and Newfoundland, in the lower St Lawrence River, Bay of Chaleur, and Atlantic coast shelf water. The maximum amplitudes are for periods of 20 s to 5 min. At these periods the transfer functions are mainly in phase but they become more in quadrature at longer periods.

At stations such as Cape North (CN) and Stevenville (SV) the transfer function arrows (Fig. 2) show an apparent deep ocean coast effect (pointing perpendicular to the coast) at longer periods (60 min) and gradually swing around perpendicular to the local sea water channel at higher frequencies (5 min). At the higher frequencies the coast effect is smaller and the currents in the local channel are more intense.

The transfer function arrows at Charlo (CH) and Newcastle (NC) point toward the Bay of Chaleur and at Matane (MN) toward the lower St Lawrence River which indicates strong electric currents flowing through these shallow conductors and into conducting continental sediments. The frequency responses at these stations are similar to that at Cape North (CN) resolved perpendicular to the deep water channel of Cabot Strait. Hauterive (HA) shows a local channel effect at high frequencies (1–10 min) similar to Matane (MN) across the river and Cape North (CN), but also shows a low frequency transfer function which is puzzling. The low frequency effect is probably related to the geological boundary at depth between a higher conductivity Appalachian and lower conductivity Canadian Shield (Grenville) geological provinces along the lower St Lawrence River channel. Additional data is required to outline this structure. Its existence is confirmed by recent measurements by R. N. Edwards (personal communication).

Sable Island (SI) shows a very small transfer function at all frequencies. This must be explained by very high conductivity within the crust or by a deep structure that counteracts the normal coast effect. The Sable Island horizontal amplitudes are very similar to those recorded similtaneously at Dartmouth. Sable Island has amplitudes from 5 to 20 per cent lower than Dartmouth for period between 2 and 120 min.

7. The ocean coast effect and general conductivity structure of the margin

Large amplitude transfer functions are observed at all of our stations near the coast except for Sable Island. Observations of the coast effect have been largely ascribed to induction in the deep ocean (e.g. Schmucker 1964; 1970). To compare our data with other coasts we have plotted the amplitudes of the in phase part of the transfer function at 60-min periods with distance from the shelf edge (taken at about 400 m depth) (Fig. 4). Given for comparison are the curve for the south-western Australian shield and a curve derived from the results of western North America and eastern Australia (Schmucker 1964; Everett & Hyndman 1967; Cochrane & Hyndman 1970). St Johns is at a nearly right angle corner of the coast but to a first approximation the coasts of the North Atlantic and Labrador Sea can be treated separately.

Sable Island plots well off either curve. Offshore island results of Schmucker (1970) and sea floor measurements on the continental shelf (J. G. Greenhouse, personal communication) show that the amplitude remains large to the edge of the continental shelf off California. Thoeretical results for the deep ocean coast effect also show this

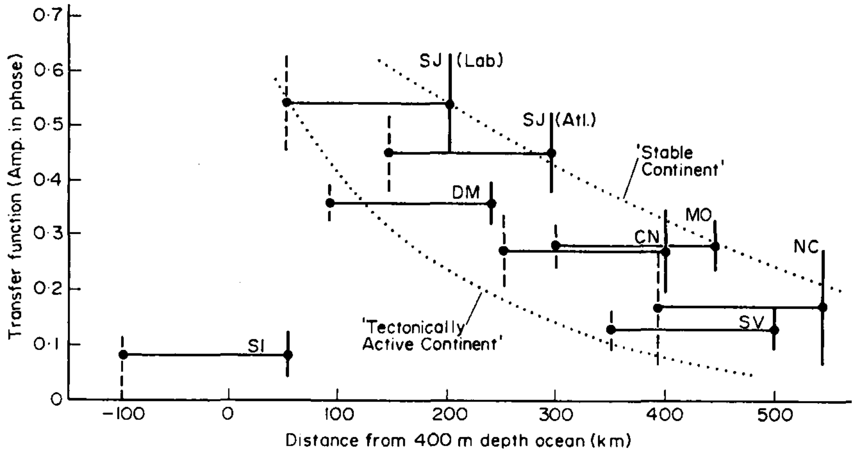

FIG. 4. Amplitudes of the in phase part of the Z transfer functions at 60-min period. The solid bars are for distance taken from the shelf edge. The broken bars are for distance taken from the edge of the postulated high conductivity continental shelf block.

(e.g. Schmucker 1970; Roden 1964). We conclude that the continental shelf off Nova Scotia is underlain by a conducting layer with a depth integrated conductivity comparable to the deep ocean. (This layer is discussed further below.) Thus, the transfer functions we have observed inland are not strictly coast effect. They must result primarily from the inland edge of this conductive layer. A similar but less pronounced effect was observed over the coastal sedimentary basin of western Australia by Everett & Hyndman (1967).

If the conductive shelf layer is assumed to behave in the same way as the deep ocean or as an extension of the ocean the amplitudes away from the edge are near to but slightly higher than our curve for tectonically active continental areas (Fig. 4). The general deep conductivity of the Appalachian geological province thus appears to be lower than the shield although slightly higher than western North America or eastern Australia. This is in general agreement with the results for example by Cantwell (1960) and Swift (1967).

We have computed transfer functions for Cheltenham and Fredricksburg on the Maryland and Virginia coasts and at Weston near the Massachussetts coast and found very small values (Parkinson 1959, also found only a small coast effect at Cheltenham). This can be explained if the shelf in that area is not highly conducting. The main long period coast effect will then occur at the shelf edge. It will have fallen to small values at the coast.

8. Transfer function types

The electrical conductivity structures indicated by our transfer functions can be classed into four types, each with a characteristic frequency and spatial dependence. Three represent the edge of a high conductivity layer and one a uniform high conductivity layer. Examples have been taken from this study, from data from western Canada by Cochrane & Hyndman (1970), and from the Australian shield by Everett & Hyndman (1967), and several unpublished results.

(a) *Shallow seawater channel*

Stations just off the edge of a shallow inland body of salt water (Charlo; Matane; Cape North; Stevenville). The transfer function amplitude is large at periods less than

5 min and falls rapidly at longer periods. The amplitude falls off rapidly with distance from the edge to be quite small at a distance of 50 km. Inland basins of high conductivity may behave in this way.

(b) *The edge of a conductive layer over a highly conducting mantle*

Stations off the edge of the deep ocean or of a high conductivity crustal layer, overlying a high conductivity mantle (Dartmouth; Kootenay Lake; and British Columbia coast stations). The amplitude is small for periods below 5 min and rises sharply to a maximum at about 30 min then falls off for longer periods. The in phase and quadrature parts are about equal at short periods. At long periods, the transfer function is nearly in phase. The amplitude falls off to half its maximum at about 200 km from the edge.

(c) *The edge of a conductive layer over a resistive mantle*

Stations off the edge of the deep ocean or a high conductivity crustal layer, overlying a low conductivity (stable) mantle (Lethbridge, Alberta; Australian shield coast stations; Ottawa and Agincourt, Ontario). The frequency response is similar to the above structure except that the amplitude does not fall off at long periods (2 hr). The amplitude falls off slowly with distance from the edge being half its maximum at a distance of about 400 km.

(d) *Uniform high conductivity layer*

Stations located over a high conductivity layer at shallow depth (Sable Island; western North American stations away from the coast such as Grand Forks; and the Mould Bay area in the Arctic). The transfer function is small at all periods even if lateral conductivity variations within several hundred kilometers are known. The normal or source field vertical component is also strongly attenuated. These are the 'low I' stations of Caner *et al.* (1967).

9. Inland shallow sea anomalies

The electric currents in the Lower St Lawrence River, Gulf of St Lawrence and Cabot Strait could be produced by: 1. Currents induced in the ocean that are channelled through the Gulf (leakage currents). 2. Currents produced by local induction.

We feel that local induction by the horizontal component of the source field is responsible for the currents in these areas. There is no obvious return circuit to the ocean for leakage currents entering the Gulf of St Lawrence and lower St Lawrence River so it is difficult to explain the large transfer function amplitudes observed inland in this way. Also currents channelled in from the ocean require all inland transfer function arrows perpendicular to the ocean coast, the direction that produces maximum ocean currents. Arrows perpendicular to the local channels are observed at every station.

Currents channelled from the ocean could produce transfer function arrows perpendicular to the local channel only if the channel currents produced a local horizontal field greater than the general source horizontal field. We believe that the horizontal field at land stations produced by shallow water current sheets is small. Comparison of simultaneous records from these stations and from Agincourt (near Toronto, Ontario, 1000 km to the south-west) shows no systematic difference in horizontal amplitudes. As an additional check, the vertical transfer function at Charlo was computed using the vertical component from Charlo but the horizontal components from Agincourt. The transfer function is virtually unchanged. This shows that the anomalous vertical field is correlated with the regional rather than local horizontal field. We conclude that local induction by the horizontal component of the source field is required for the currents in the channels.

Induction by the horizontal component in the inland channels has the same problem of return currents as in the ocean. The problem is more difficult because the source field dimensions are much larger than the body of water so currents must spread out into the less conducting land and down into the conducting mantle. The fact that large currents do flow through the lower St Lawrence River, Bay of Chaleur and areas like the Eskdalemuir anomaly in the British Isles (Osemeikhian & Everett 1968) shows that salt water bodies cannot be considered as isolated conductors. Significant currents do flow into the land. In the cases of the lower St Lawrence and Bay of Chaleur, currents flow into sedimentary basins.

Edwards (1969) has argued for conduction or leakage from the deep ocean for most of the currents observed around the British Isles. There are direct circuits through the Irish and North Seas between the Atlantic Ocean and Norwegian Sea. He also found significant differences in the amplitudes and directions of transfer functions if the horizontal field components were taken from other stations (the test that gave no change at Charlo).

10. Thin sheet and image current model

The amplitude and frequency response for the inland stations located near shallow sea water estuaries can be estimated using a simple sheet and image current model. The anomalous fields resulting from the sea water channels are computed assuming induction in a uniform thin conductive sheet. The change in the normal current flow under the sheet because of its presence (shielding) is accounted for by an image current flowing in the opposite direction at some depth under the sheet. This is the type of model used by Van'Yan *et al.* (1970) for conductive sedimentary basins (neglecting the image current).

The current density J in a sheet of conductivity σ can be estimated from the Cagniard (1953) impedance $Z_1 = E/H$ characteristic of an infinite sheet current. $J = \sigma E = \sigma Z_1 H$. For a sheet of finite width (E polarization) the impedance Z_1 will not be strictly uniform across the sheet but for this approximate theory we will assume it uniform. The variation of Z_1 with depth in the sheet was computed and found to be negligible at the frequencies studied.

The perturbation of the normal current flow under the sheet because of the sheet's presence is simulated by placing an equal but opposite sheet current at a depth h, where $h = \sqrt{2}\beta$ (β = skin depth in the underlying region). The anomalous vertical and horizontal field at a station are then computed and from them the single station transfer function.

The stations Matane (MN), Charlo (CH) and Cape North (CN) have very similar frequency responses although their amplitudes vary considerably. The structures at Charlo and Cape North are complicated, the former being on a bay connected to a sedimentary basin and the latter on a narrow strait connecting two large bodies of water. Matane on the lower St Lawrence River is closest to being on a two-dimensional structure. The cross-section of the River was approximated by seven blocks varying in thickness from 20 to 300 m. The impedance over the river was taken to be that at the surface of a 250 m deep layer of sea water (0·25 ohm/m) over a half space with the Cantwell–MacDonald conductivity structure (Madden & Nelson 1964). At Matane the effect of the image current is small for periods down to 15 s because the river is only about 50 km wide and the station within 1 km of the edge. The image is much more important at stations such as Stevenville (SV) that are further from the main current flow. The importance of the image current is also critically dependent on the conductivity structure under the water.

The frequency response, absolute amplitude and directions of the model transfer functions are in remarkable agreement with those observed considering the simplicity of the model. The observed and computed transfer functions are shown in Fig. 5.

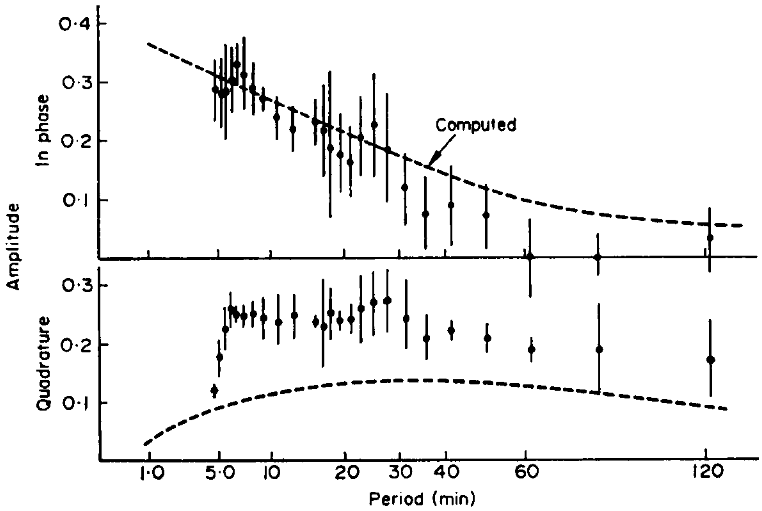

FIG. 5. The observed and computed transfer function with frequency at Matane on the lower St Lawrence River.

This agreement substantiates the conclusion that the currents are produced by local induction. Where do the currents go inland? The end boundary conditions are those of *H* polarization (Jones & Price 1971; Swift 1967; Wright 1969). If a conduction current is to flow, it must go downward into the highly conducting mantle. The path to the mantle would have about the same resistance per unit length as the River if the lower St Lawrence River was connected upstream to a conductive sedimentary area of about 10^4 km^2 in area with material of 10^3 ohm m between the sediments and high conductivity mantle. Inland sediments can also provide the path to the mantle for currents in the Bay of Chaleur (Charlo).

11. Numerical models by the transmission line analogy

For two dimensional conductivity structures, solutions for magnetotelluric *E* and *H* fields may be obtained numerically from transmission line theory (Swift 1967; 1971; Madden & Swift 1969; Wright 1969). We have computed the response of two dimensional conductivity structures for infinite wavelength, horizontal inducing magnetic fields perpendicular to the structure (*E* polarization). A two dimensional structure is a reasonable approximation for the Canadian coast of the North Atlantic. Except where induction in shallow inland water is important our induction arrows tend to point perpendicular to the coast and to the strike of the Appalachian system. There may be a high conductivity structure under the Bay if Fundy which we have attempted to include in our model. Assuming an infinite wavelength source field may result in small systematic errors in conductivities and depths but the general structure should be correct.

Simple Cagnaird (1953) solutions were used for the boundary conditions on the inland and seaward boundaries. The models used an irregular 19 × 24 grid extending 3000 km inland 1000 km seaward of the coastline. The upper boundary was a uniform field 5000 km above the Earth's surface. The transmission line equations were solved by standard Gauss–Siedel over-relaxation. The non-uniform vertical and horizontal magnetic fields were obtained from the calculated horizontal and vertical impedance gradients respectively. About 4 min was required for a solution at each frequency on an IBM 360/50. Satisfactory solutions were required to approximate both the spatial and frequency dependence of the observed transfer functions.

12. Model of the continental margin of Nova Scotia

The major restraints on the model of the continental margin were: 1. The low vertical transfer functions at Sable Island only 60 km from the deep ocean. 2. The Dartmouth frequency response, particularly the sharp fall off at short periods and the fall off at long periods. 3. The effect of the coastal structure extending inland about 400 km from the coast.

Attempts to model these results showed that the apparent coast effect in this area was actually the effect of a shallow high conductivity layer under the continental shelf at crustal depths. This layer is required by the response at Sable Island. Transmission line numerical solutions show that the Dartmouth frequency response can only occur near the edge of a high conductivity layer at crustal depths underlain by high uniform conductivity (i.e. Type 2 above). The best model solution was obtained with high uniform conductivity at a depth of about 120 km. At short and intermediate periods the fields are only influenced by the shallow layer. At longer periods the currents in the shallow layer are damped by the underlying conductor. A simple case was analytically examined by Rikitake & Whitham (1964). It is also likely that the finite dimensions of the ocean reduce the amplitude of the currents at long periods.

We have thought of four possible explanations for the high shallow continental shelf conductivity. They are the thick shelf sediments in general; widely distributed salt in the older sediments; carbonaceous schists; or water saturation in the lower crust. Older seismic measurements indicated that there were about 5 km of sediments under the outer shelf (Officer & Ewing 1954; Drake *et al.* 1959; Berger *et al.* 1965; Keen & Loncarevic 1966; Emery *et al.* 1970). However, recent drilling and seismics have indicated that the sediments are some 10 km thick (e.g. *Oil and Gas Journal* 1970). To explain the observed data by 5 km of sediments the average resistivity needs to be 1 ohm m or less. This is rather high for sediments and the Mobil Oil Sable Island test well (see Monro & Brusset 1968) electrical logs showed resistivities of 2 to 10 ohm m to a depth of 5 km.

The conductivity of the deeper sediments could be high if there is high concentration of salt. Evaporites are indicated by the frequent diapirs on the shelf (Pautot *et al.* 1970; King & MacLean 1970; *Oil and Gas Journal* 1970; Swift 1967b). A considerable amount of water would also need to be present since dry salt has a very high resistivity. High conductivity probably of this origin appears to be the explanation for the 'North German Anomaly'. Vozoff & Swift (1968) found conductivies in the north German basin of about 1 ohm m and a depth integrated conductivity of about 5000 ohm^{-1}. These values are just what is required for the Scotian Shelf. High conductivity has also been found in Triassic and Paleozoic sediments in northeastern British Columbia by A. Densmore (see Pamenter 1971). It is attributed to the presence of salt water.

Carbonaceous (graphite) schists have high conductivity and have been suggested as the explanation for the near surface Eskdalmuir anomaly in Scotland (Edwards 1969) and the North American central plains anomaly (Camfield *et al.* 1971). We do not think this explanation is likely for the Scotian shelf but it cannot be discounted.

The final explanation is water saturation in the lower crust. Hyndman & Hyndman (1968) and Berdichevski *et al.* (1969) have suggested that in young geosynclinal areas of high temperature, part of the lower crust may be water saturated. Metamorphic processes will have dehydrated older areas. This explanation is more reasonable in areas of high heat flow. The Nova Scotia area has normal heat flow for a stable area 1·1 to 1·5 $\mu\text{cal cm}^2\text{ sec}$ (Jessop 1968; Jessop & Judge 1971; Rankin & Hyndman 1971). The temperature gradient measured by A. Jessop and ourselves in the Sable Island hole to 1000 m depth was approximately 30°C km^{-1}. This gradient is quite high but without thermal conductivity estimates we cannot extrapolate to the

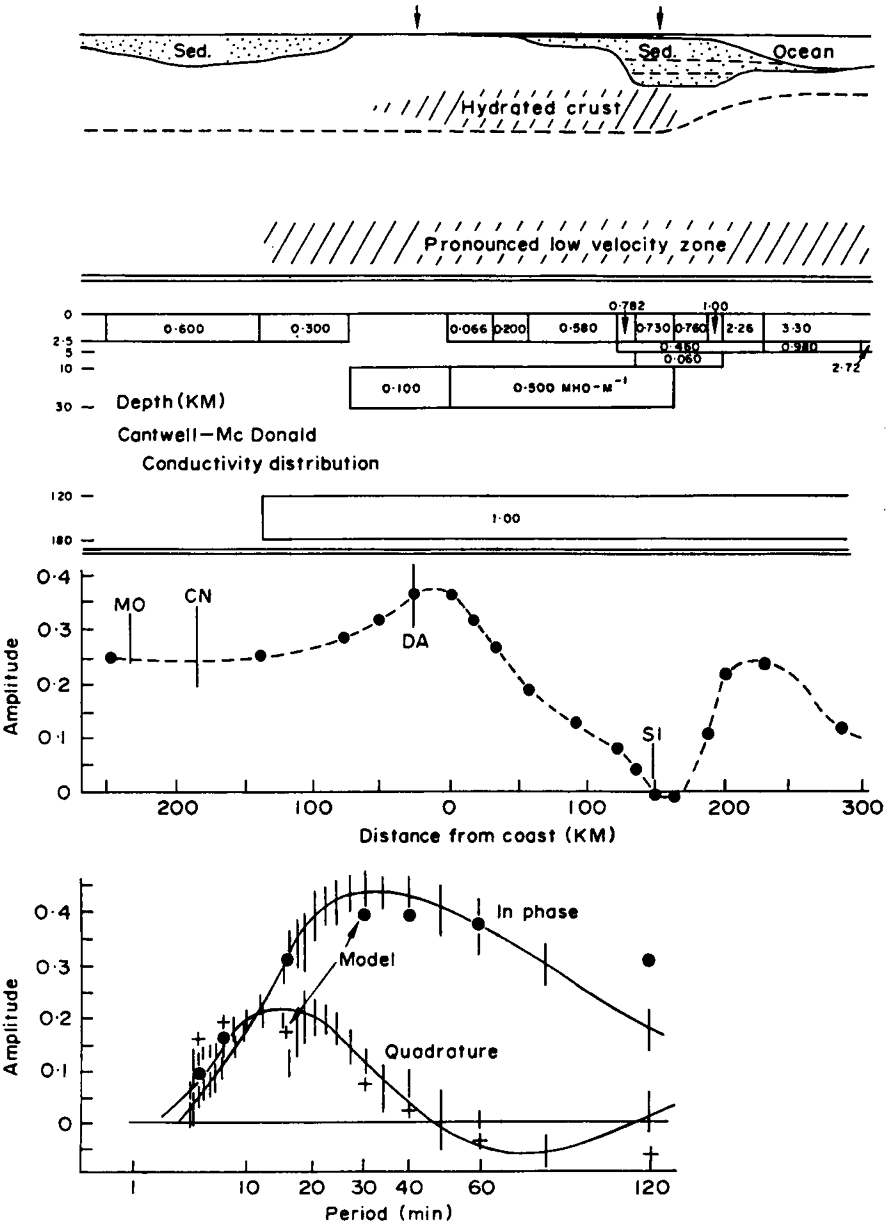

FIG. 6(a). The computed and observed amplitude of the transfer functions at 60-min period across the continental marin. (b) The computed and observed frequency response at Dartmouth.

lower crust with any certainty. In Fig. 6 a model giving a reasonable fit to the data is shown. The model has high crustal conductivity due to hydration. The computed and observed transfer functions for a number of stations are given for 60-min period along with the computed and observed frequency response at Dartmouth. Representative sediment conductivities were taken from an oil exploration hole drilled on Sable Island by Mobil Oil Ltd. In the unmarked regions we have used the Cantwell–McDonald (Madden & Nelson 1964) conductivity distribution.

We have not been able to obtain a satisfactory theoretical response with a model having just high sediment conductivity. However, we feel that the data can probably be explained without crustal hydration if the sediment conductivity is very high.

13. Conclusions

High electrical conductivity has been found under the continental shelf off Nova Scotia and Newfoundland. The apparent coast effect actually results from the contrast between the highly conducting shelf structure and the more resistive inland rocks. There is little contrast between the shelf and deep ocean. The high conductivity must occur at a depth of 15 km or less. The two most likely explanations are that there is highly saline interstitial water in the lower part of a 10 km sedimentary section associated with salt or evaporite layers (this is a similar explanation to that now given for the 'North German Anomaly'), or that part of the crust is hydrated in this area. High conductivity may also exist under the Bay of Fundy.

Numerical, network analysis using the transmission line analogy has produced a two-dimensional model across the Nova Scotia continental margin in reasonable agreement with computed transfer functions.

Strong electric currents flow in the various arms of the Gulf of St Lawrence for short period inducing fields. A simple model of the lower St Lawrence River shows that they can be explained by local induction in the shallow sea water. However, the details of the current flow require significant conductive channelling effects.

One station on the north shore of the St Lawrence River has large, long period anomalous vertical fields. We suggest that they result from a contrast in deep conductivity between the Appalachian and Canadian Shield geological provinces.

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R. D. Hyndman:
Institute of Oceanography

N. A. Cochrane:
Department of Physics
Dalhousie University
Halifax, Nova Scotia

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