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"An interpretation of the Canadian Cordillera geomagnetic transition anomaly"

Montag, den 11.03.1974

Introduction

Over the past ten years, various geomagnetic depth-sounding and magnetotelluric studies have investigated the conductivity structure of the lower crust and upper mantle in western Canada. This work has established that a dominant feature for the Canadian Cordillera is the presence of a 'low-I' zone, where

$$I = |\Delta Z| / \{\Delta H^2 + \Delta D^2\}^{\frac{1}{2}}$$

This is a region where vertical field variations having periods between 5 and 30 min are greatly attenuated compared to vertical field variations observed further east (see Fig.1). The transition zone where the magnitude of I not only increases sharply but also shows a strong azimuthal dependence has been found to follow approximately a line along the western front of the Rocky Mountains from 49°N to at least 54°N latitude.

This large scale geomagnetic variations anomaly is made perhaps more interesting tectonically because of the presence of the Rocky Mountain Trench. Since this trench is a major physiographic feature lying within the I-transition zone, it is natural to speculate on a direct or indirect relation between the origin of both features. The primary purpose of this study was to investigate in greater detail the nature of the lateral conductivity changes encountered in the Canadian Cordillera geomagnetic transition zone.

1. Instrumentation

A geomagnetic depth-sounding profile of seven stations (see Fig.2) was operated for a period of two months during the fall of 1971. At the stations CLE, COC, and SUF, standard Askania variographs were employed. At the remaining stations, which were

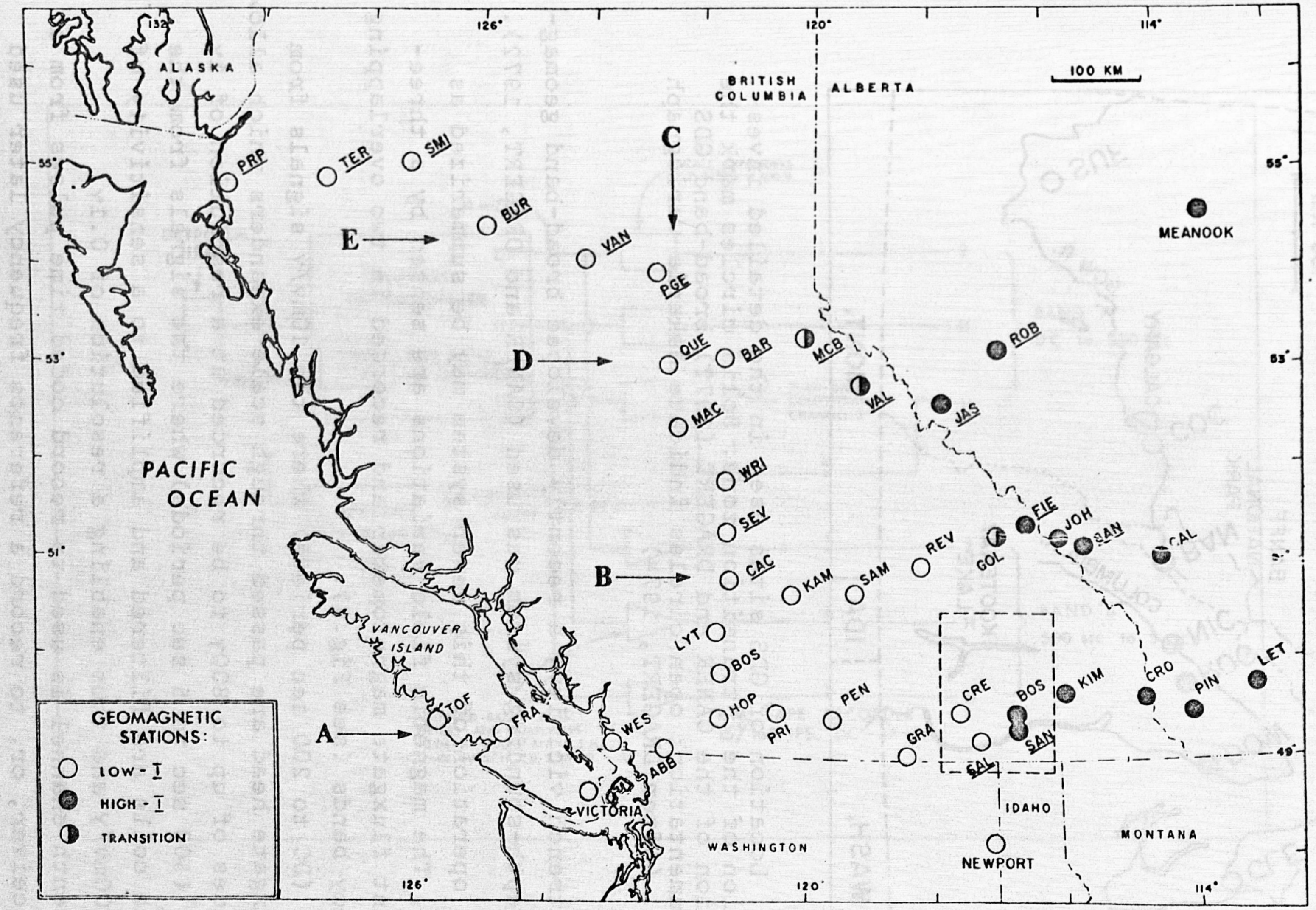


Fig.1: Location of GDS stations in western Canada up to 1970 defining the geomagnetic 'low-I' region. Profile A are stations of HYNDMAN (1963) and LAMBERT and CANER (1965); Profiles B and C are stations described by CANER et al. (1967); Profiles D and E are stations of DRAGERT (1970). The dashed rectangle identifies the area containing the 20-station network of LAJOIE and CANER (1970). (After CANER et al.,1971.)

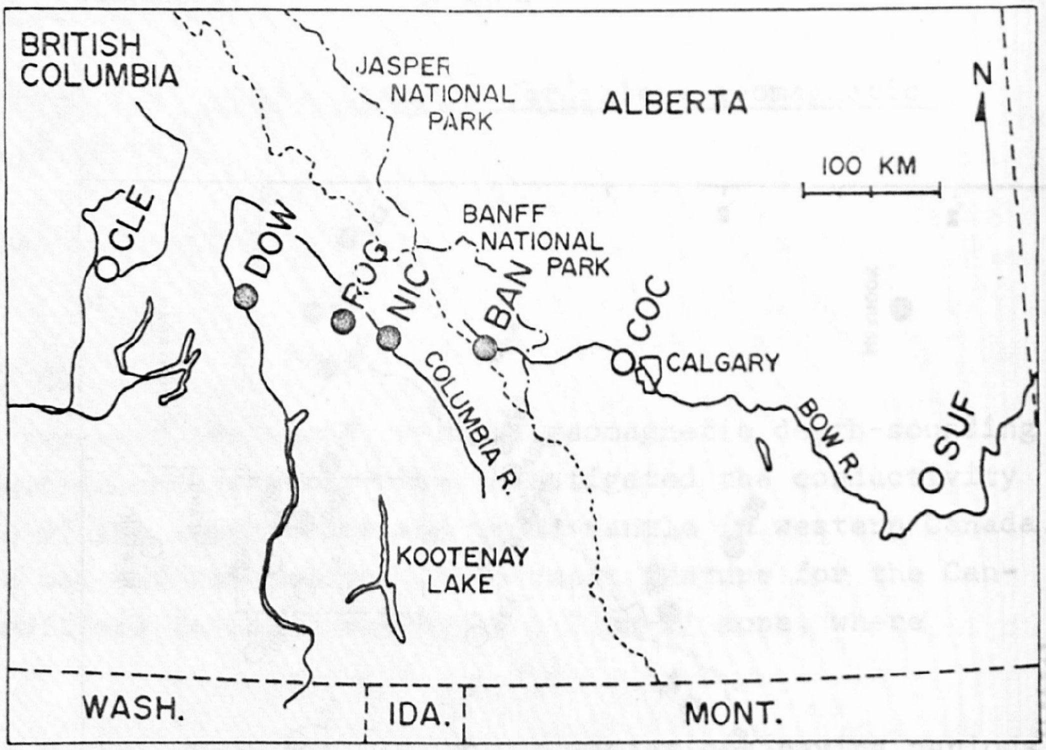


Fig.2: Location of GDS sites used in the detailed investigation of the I-transition zone. Solid circles mark the location of the CANER and DRAGERT (1972) broad-band GDS instrumentation; open circles indicate Askania variograph sites. (After DRAGERT, 1974)

in the trench vicinity, a recently developed broad-band geomagnetic depth-sounding system was used (CANER and DRAGERT, 1972).

The operation of this newer system may be summarized as follows. The magnetic field variations are sensed by a three-component fluxgate magnetometer and recorded in two overlapping frequency bands (see Fig.3):

BAND A: (DC to 200 sec periods) where the 10mv/γ signals from the fluxgate head are passed through scale expanders which allow amplitudes of up to 800γ to be recorded at a resolution of 1γ.

BAND B: (500 sec to 5 sec periods) where the signals from the fluxgate coils are filtered and amplified to a sensitivity of up to 200mv/γ and thus enabling a resolution of 0.1γ.

The seventh channel is used to record coded time pulses from a WWVB receiver, or, to record a reference frequency later used for flutter compensation on playback.

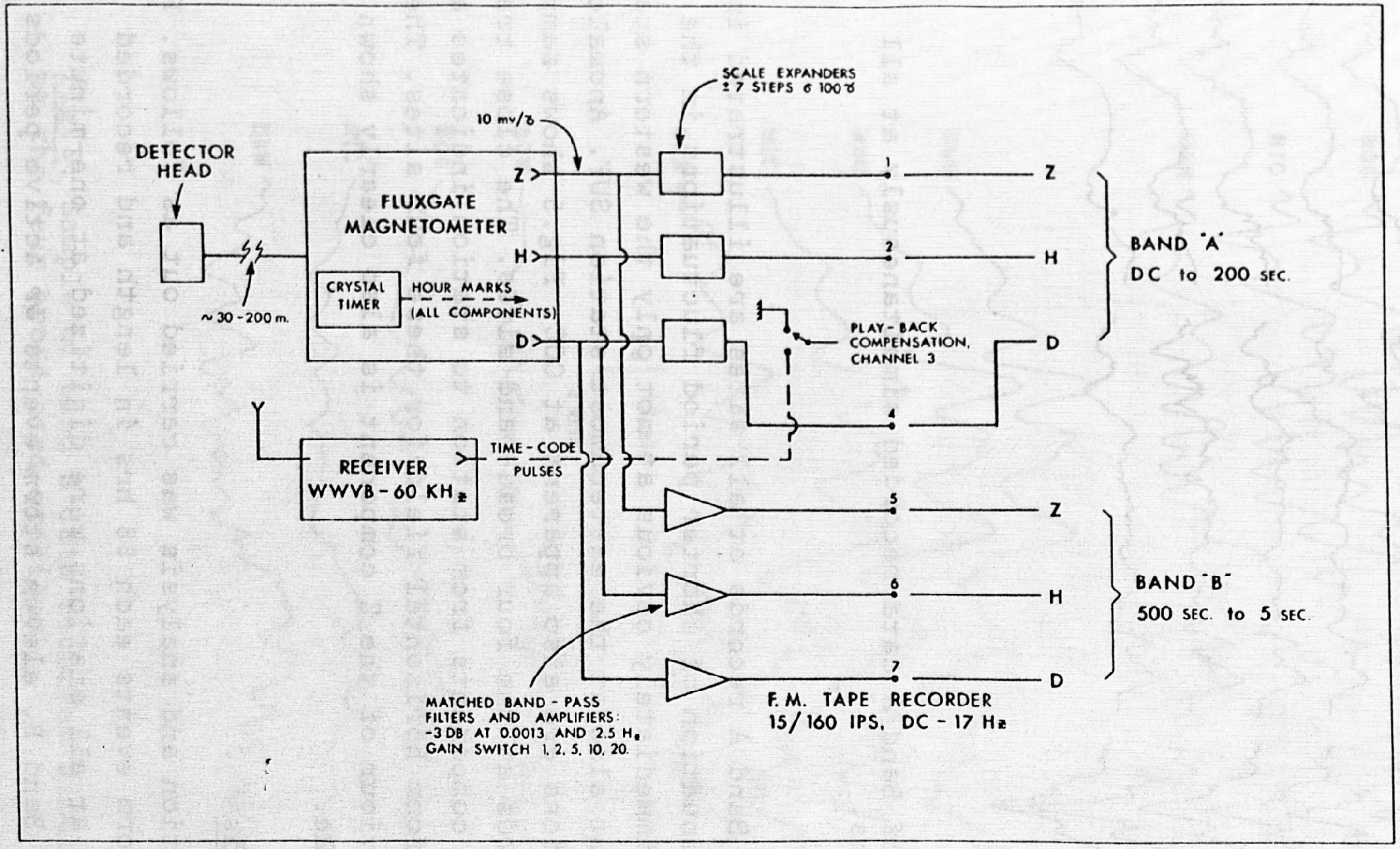


Fig.3: Block diagram of the system circuitry for the broad-band GDS instrumentation. (After CANER and DRAGERT, 1972)

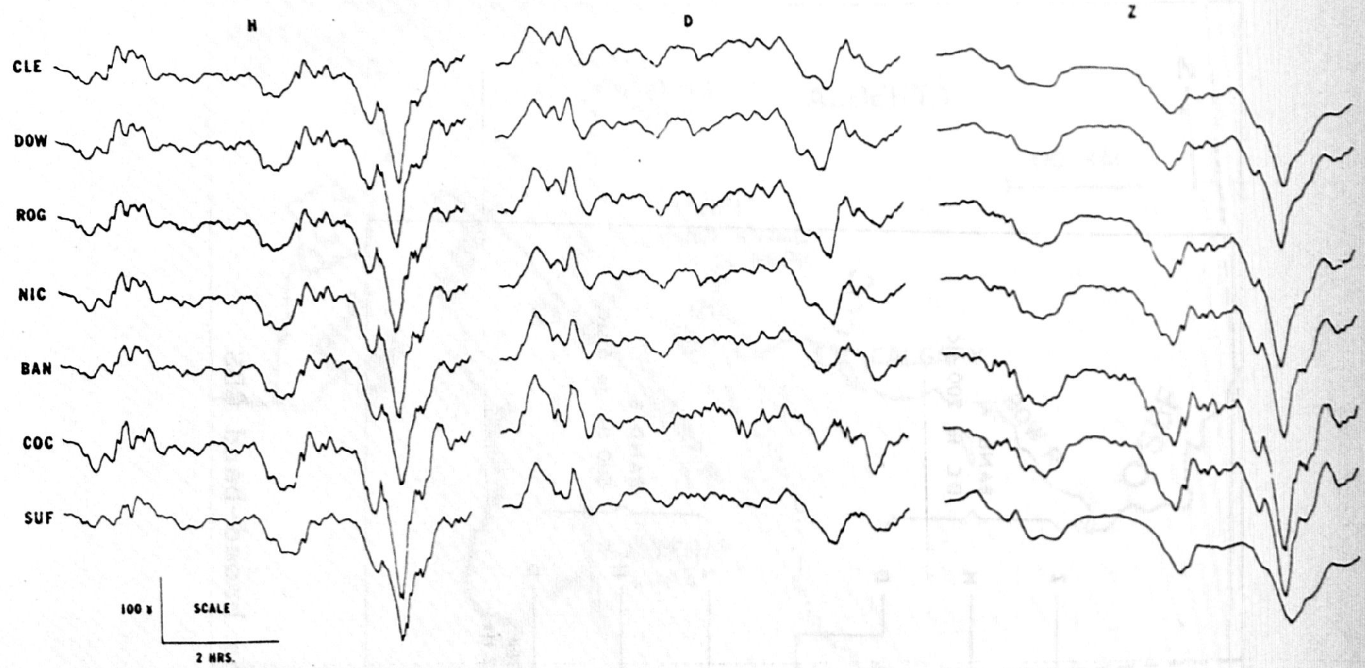


Fig.4: Sample of Band A data recorded simultaneously at all profile stations.

Samples of Band A records at all sites are illustrated in Fig.4. The attenuation of shorter period fluctuations in the Z component are immediately obvious at not only the western stations CLE and DOW, but also at the easternmost station SUF. Anomalous H and D variations are also apparent at COC. Fig.5 shows samples of Band B records at the four broad-band sites. The close tracking of the H and D components from station to station indicates a reasonably uniform horizontal field for these four sites. The anomalous behaviour of the Z component is also clearly shown by this data sample.

2. Data Analysis

Data reduction and analysis was carried out as follows. For Band A, six storm events each 36 hrs in length and recorded simultaneously at all stations were digitized at one-minute intervals. For Band B, eleven storm events or active periods each 100 min in length were digitized at 2.5 sec intervals. The resultant discrete time series were frequency analyzed using a periodogram technique which employed the Fast Fourier Transform

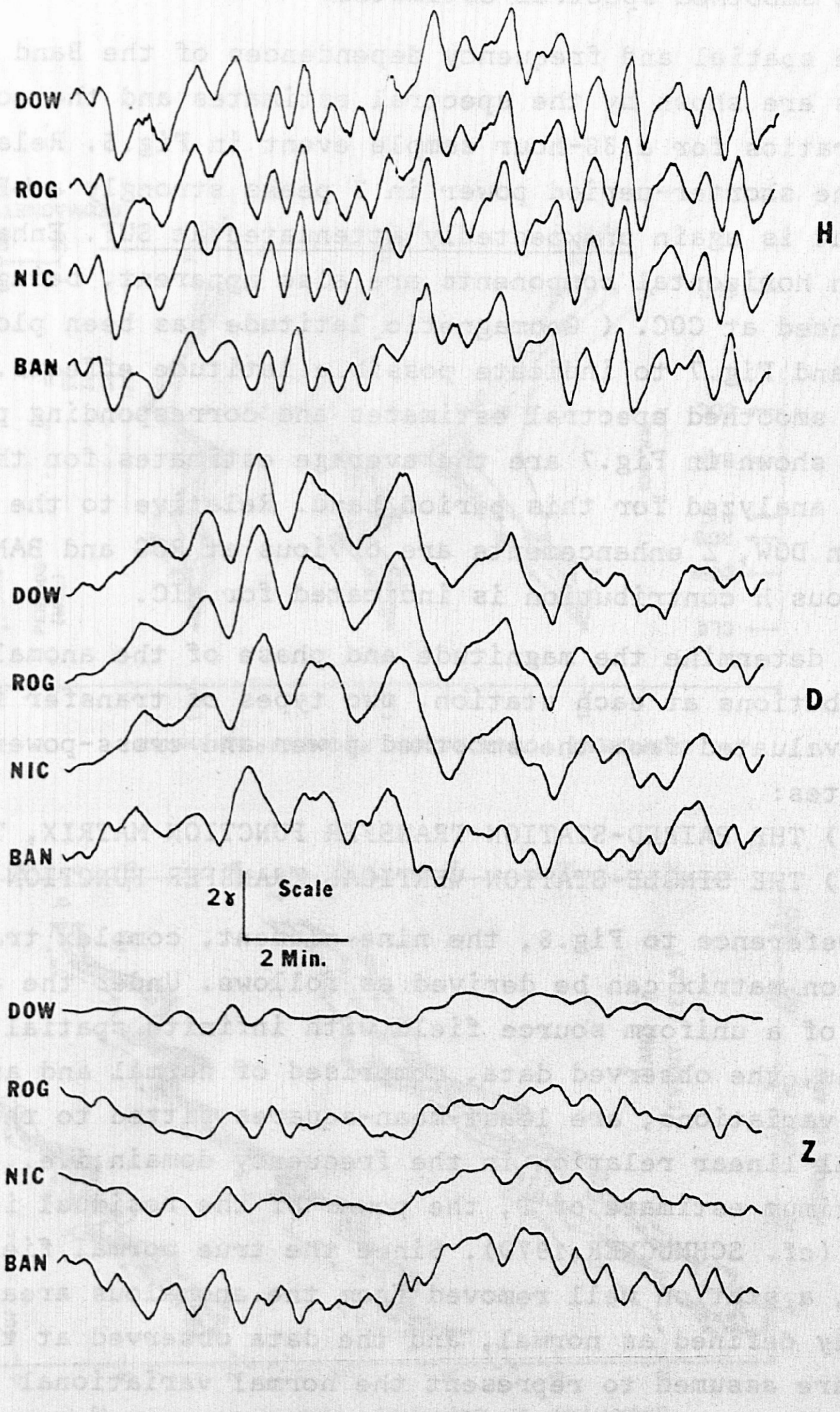


Fig.5: Sample of Band B data recorded simultaneously at the four broad-band stations.

(COOLEY and TUKEY,1965) and a frequency-dependent Parzen window for the smoothed spectral estimates.

The spatial and frequency dependences of the Band A components are shown by the spectral estimates and the component power ratios for a 36-hour sample event in Fig.6. Relative to CLE, the shorter-period power in Z peaks strongly at BAN and COC, but is again unexpectedly attenuated at SUF. Enhancements of both horizontal components are also apparent, being especially pronounced at COC. (Geomagnetic latitude has been plotted in Fig.6 and Fig.7 to indicate possible latitude effects.) The Band B smoothed spectral estimates and corresponding power ratios shown in Fig.7 are the average estimates for the eleven events analyzed for this period band. Relative to the reference station DOW, Z enhancements are obvious at ROG and BAN, and an anomalous H contribution is indicated for NIC.

To determine the magnitude and phase of the anomalous field contributions at each station, two types of transfer functions were evaluated from the smoothed power and cross-power spectral estimates:

1.) THE PAIRED-STATION TRANSFER FUNCTION MATRIX, T;

2.) THE SINGLE-STATION VERTICAL TRANSFER FUNCTION, T_Z;

With reference to Fig.8, the nine-element, complex transfer function matrix can be derived as follows. Under the assumptions of a uniform source field with infinite spatial wavelengths, the observed data, comprised of normal and anomalous field variations, are least-mean-squares fitted to the shown general linear relation in the frequency domain;i.e., to obtain an optimum estimate of T, the power of the residual is minimized (cf. SCHMUCKER,1970). Since the true normal field is not known, a station well removed from the anomalous area is arbitrarily defined as normal, and the data observed at this single site are assumed to represent the normal variational field for the entire region; hence the name 'paired-station' transfer function matrix. Needless to say, this reference field may still be affected by the anomaly in question, or contain other unrelated anomalous contributions, or even be characteristic of a normal conductivity structure that is quite different from

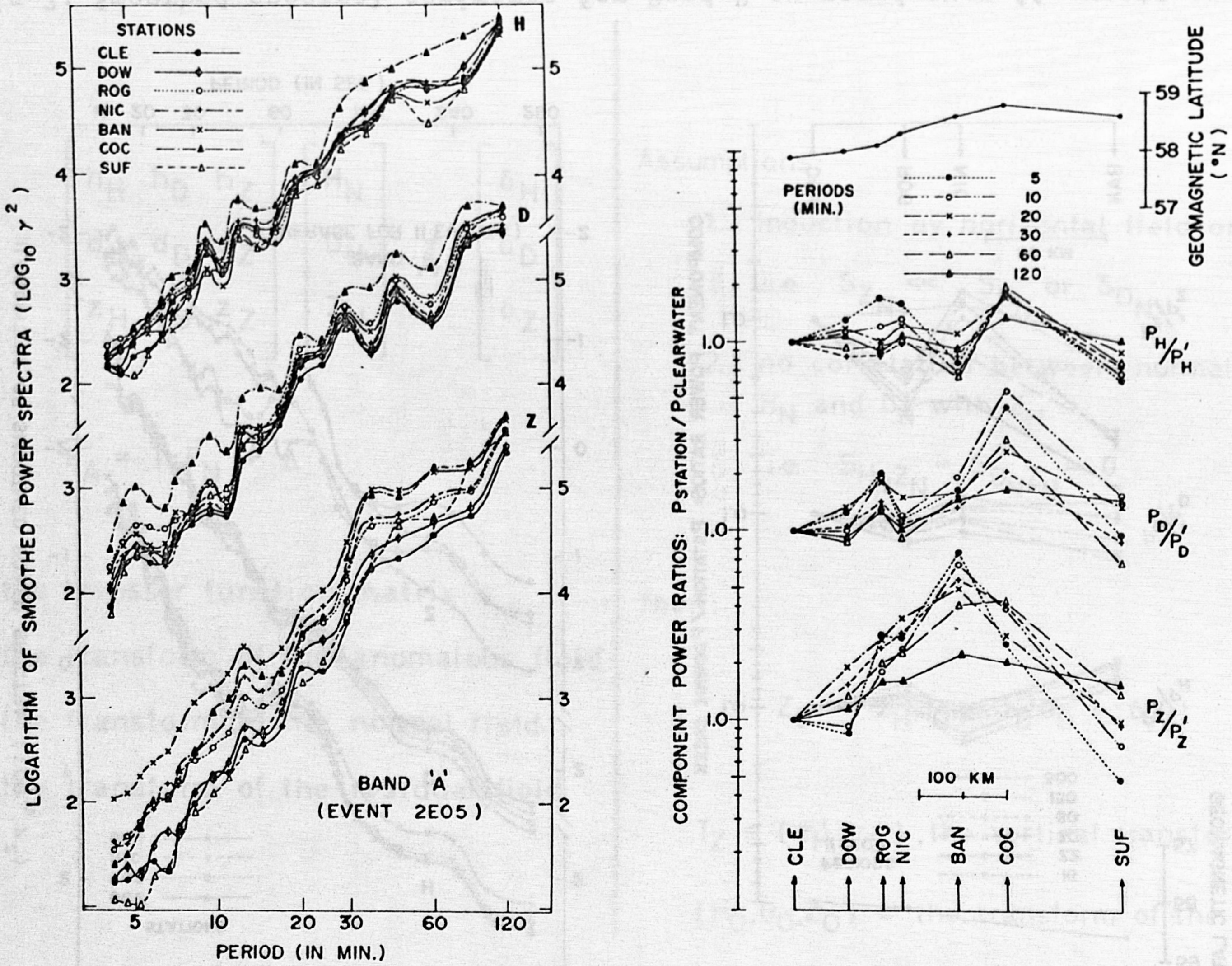


Fig.6: Smoothed spectral estimates for Band A for a sample event of 36 hours. Component power ratios are also shown for selected periods. The graph of geomagnetic latitude indicates possible latitude effects.

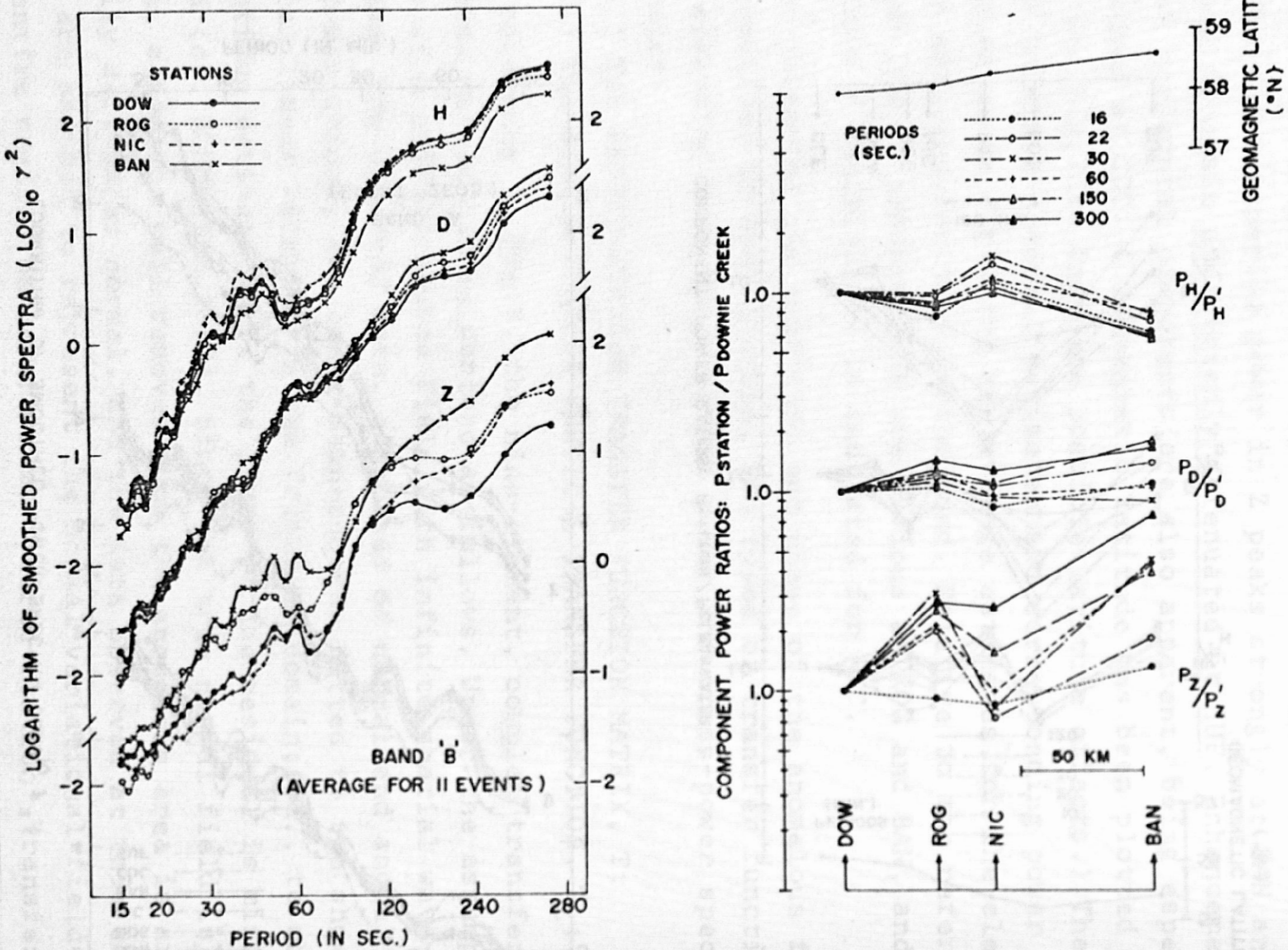


Fig.7: Smoothed spectral estimates for Band B averaged over 11 events each 100 min in length. Component power ratios are also shown for selected periods. *The graph of geomagnetic latitude indicates possible latitude effects.*

THE PAIRED-STATION TRANSFER FUNCTION MATRIX

$$\begin{bmatrix} H_A \\ D_A \\ Z_A \end{bmatrix} = \begin{bmatrix} h_H & h_D & h_Z \\ d_H & d_D & d_Z \\ z_H & z_D & z_Z \end{bmatrix} \begin{bmatrix} H_N \\ D_N \\ Z_N \end{bmatrix} + \begin{bmatrix} \delta_H \\ \delta_D \\ \delta_Z \end{bmatrix}$$

or $\quad \bar{F}_A = T \cdot \bar{F}_N + \bar{\Delta}$

T = the transfer function matrix

$\bar{F}_A$ = the transform of the anomalous field

$\bar{F}_N$ = the transform of the normal field

$\bar{\Delta}$ = the transform of the residual field

THE SINGLE STATION VERTICAL TRANSFER FUNCTION

Assumptions:

1.) induction by horizontal field only

i.e. $S_{Z_N} << S_{H_N}$ or S_{D_N}

2.) no correlation between normal components H_N and D_N with Z_N

i.e. $S_{H_N Z_N} = S_{D_N Z_N} = 0$

Then:

$$Z_O = z_H' H_O + z_D' D_O + \delta_Z$$

$T_Z = (z_H', z_D')$, the vertical transfer function

(H_O, D_O, Z_O) = the transform of the observed field

Fig. 8: The formulation of the two types of transfer functions used to estimate the anomalous parts of the observed variation field.

the normal structure in the vicinity of the investigated anomaly (cf. DRAGERT, 1973). Summarily, as formulated here, the transfer matrix T linearly relates the anomalous field to an estimated normal field, allowing for arbitrary directions in the inducing field and for coherencies between normal field components, but not for finite spatial wavelengths.

The formulation of the single-station vertical transfer function, T_Z, as used by COCHRANE and HYNDMAN (1970), is based on two further simplifying assumptions. First of all, only the vertical anomalous field is analyzed, and, assuming that induction is primarily by horizontal field variations and that there are no long term $H_N Z_N$ or $D_N Z_N$ correlations, then the data can be fitted to the simpler relation with only two unknown complex terms, z_H' and z_D', as shown in Fig.8. Under these assumptions, a normal field need not be estimated, and the observed Z variations are fitted to the horizontal variations observed at the same station; hence the name 'single-station' vertical transfer function. T_Z is therefore seen to be a general linear transfer function relating the observed vertical component at each station to the horizontal field observed at the same station, allowing for horizontal induction only, and taking neither finite spatial wavelengths nor correlations between normal field components into account.

Because of spatial non-uniformity of source fields, instabilities encountered in complex-matrix inversion, and the multiplicity of numerical errors accumulated by the elements of T, no meaningful paired-station transfer matrices could be evaluated for the short-period band. On the other hand, for Band A, stable mean transfer matrices could be derived, although they were still marked by a high experimental scatter ranging from 20% to 60%. Such a high error level precluded the quantitative interpretation of the matrix elements. However, the following qualitative observations were deemed significant:

(i) For periods greater than 15 min, the diagonal elements of T, shown in Fig.9, generally reflect a behaviour expected for the case of a reference site located over an overall more conductive horizontally-layered medium (DRAGERT,1973), and only

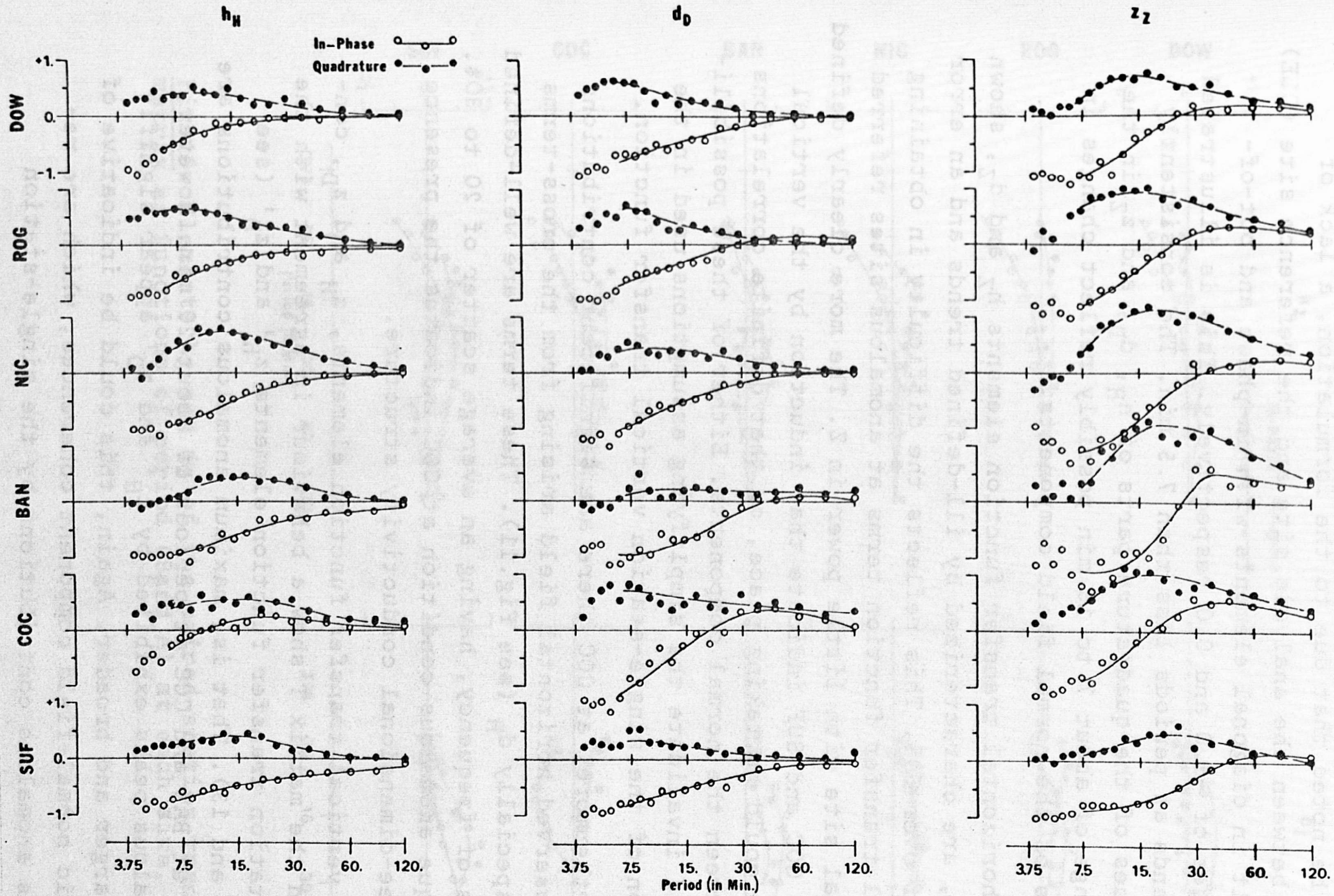


Fig.9: Diagonal elements of the paired-station transfer matrix as functions of period (Band A) at each site.

at BAN and COC does it appear necessary to invoke anomalous contributions to account for the changed pattern of the curves. It should be noted that due to the formulation, a lack of coherence between the analysis site and the reference site (CLE) will result in diagonal elements with in-phase and out-of-phase values of -1.0 and 0.0 respectively. This is illustrated by the trends at periods less than 7.5 min. The consistently large values of the quadrature parts of h_H, d_D, and z_Z in the period range of about 7 to 15 min possibly reflect changes in the phases of the normal field components.

(ii) The horizontal transfer function elements h_Z and d_Z, shown in Fig.10, are characterized by ill-defined trends and an error scatter of over 50%. This reflects the difficulty in obtaining horizontal transfer function terms at anomalous sites referred to a normal site with little power in Z. The more clearly defined trends at COC and SUF indicate that induction by the vertical component could be taking place, or that definite correlations exist between the normal components. Either of these possibilities would invalidate the simplifying assumptions used in the evaluation of the single-station vertical transfer function.

(iii) Furthermore, at COC there are significant contributions to the observed horizontal field arising from the cross-terms h_D and especially d_H (see Fig.11). These terms are well-defined functions of frequency, having an average scatter of 20 to 30%. This unique anomalous condition at COC indicates the presence of a three-dimensional conductivity structure.

(iv) The vertical transfer function elements, z_H and z_D, contained in the matrix T show a behaviour in agreement with the single-station transfer function elements z_H' and z_D' (see Figs. 12 and 13). That is, maximum anomalous contributions are apparent at BAN and COC at periods of about 20 min. However, the anomalous peaks exhibited by z_H' and z_D' appear significantly larger and broader. Again, this could be indicative of systematic normal-field component coherences, which are regarded as anomalous contributions by the single-station vertical transfer function.

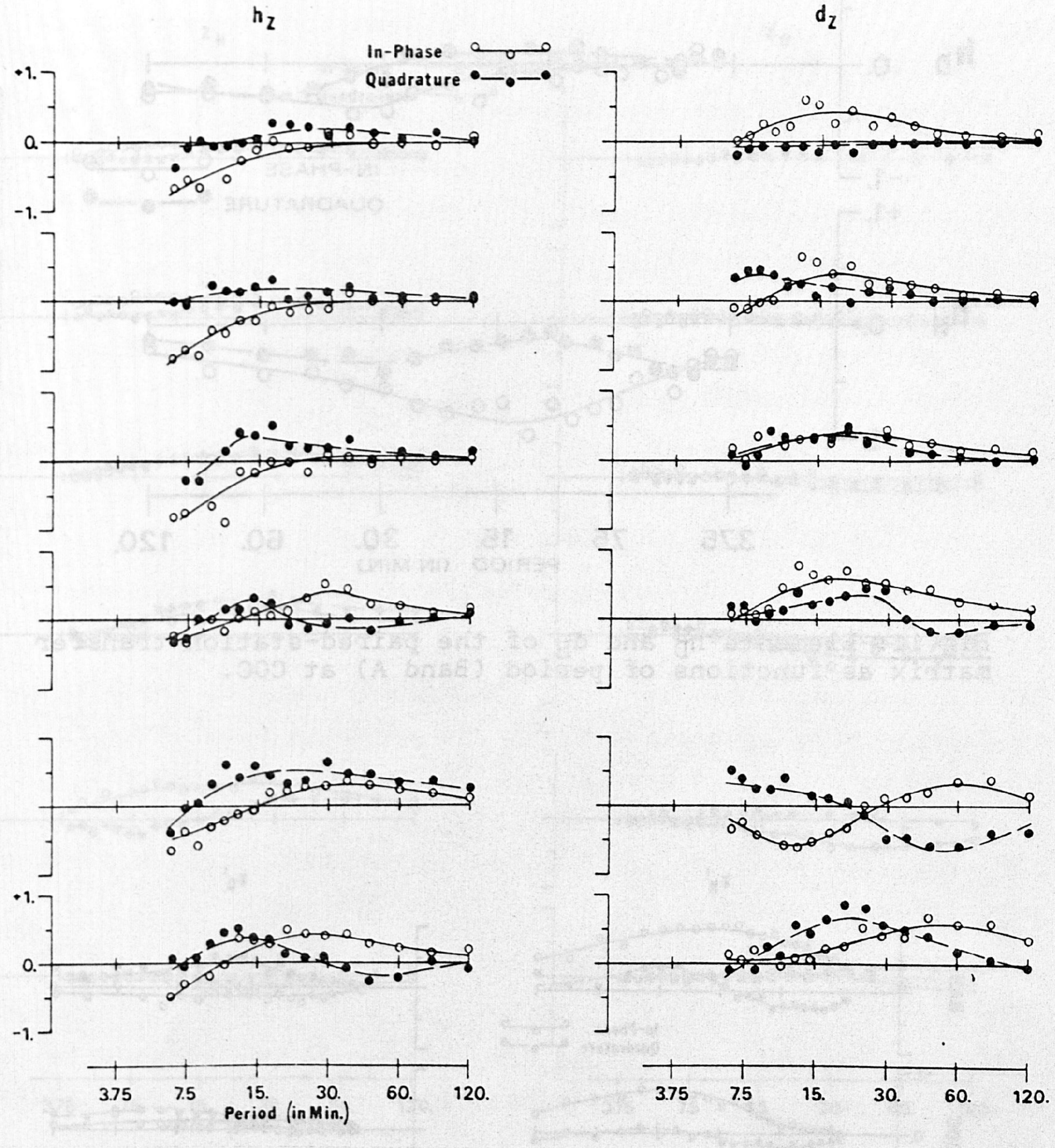


Fig.10: Elements h_Z and d_Z of the paired-station transfer matrix as functions of period (Band A) at each site.

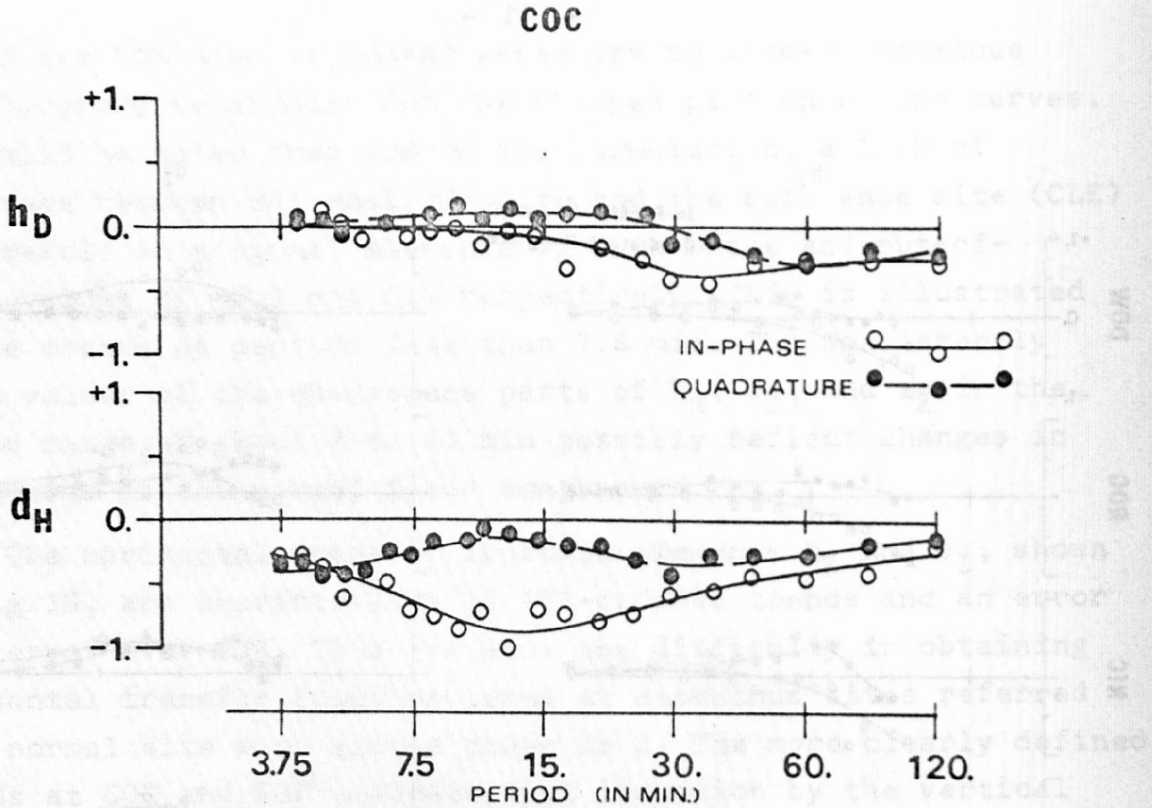


Fig.11: Elements h_D and d_H of the paired-station transfer matrix as functions of period (Band A) at COC.

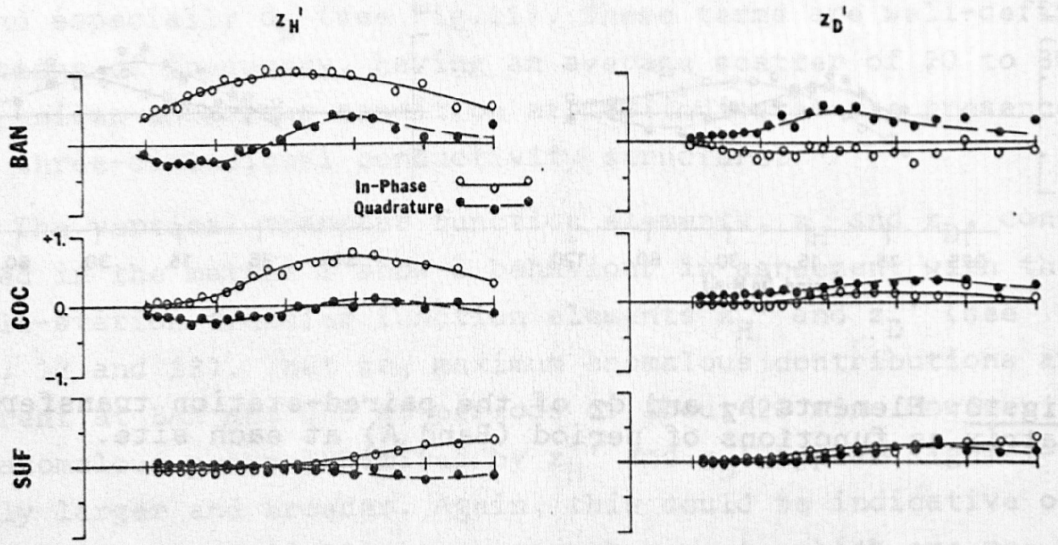


Fig.12: Elements z_H' and z_D' of the single-station vertical transfer function as functions of period (Band A) at the three western stations.

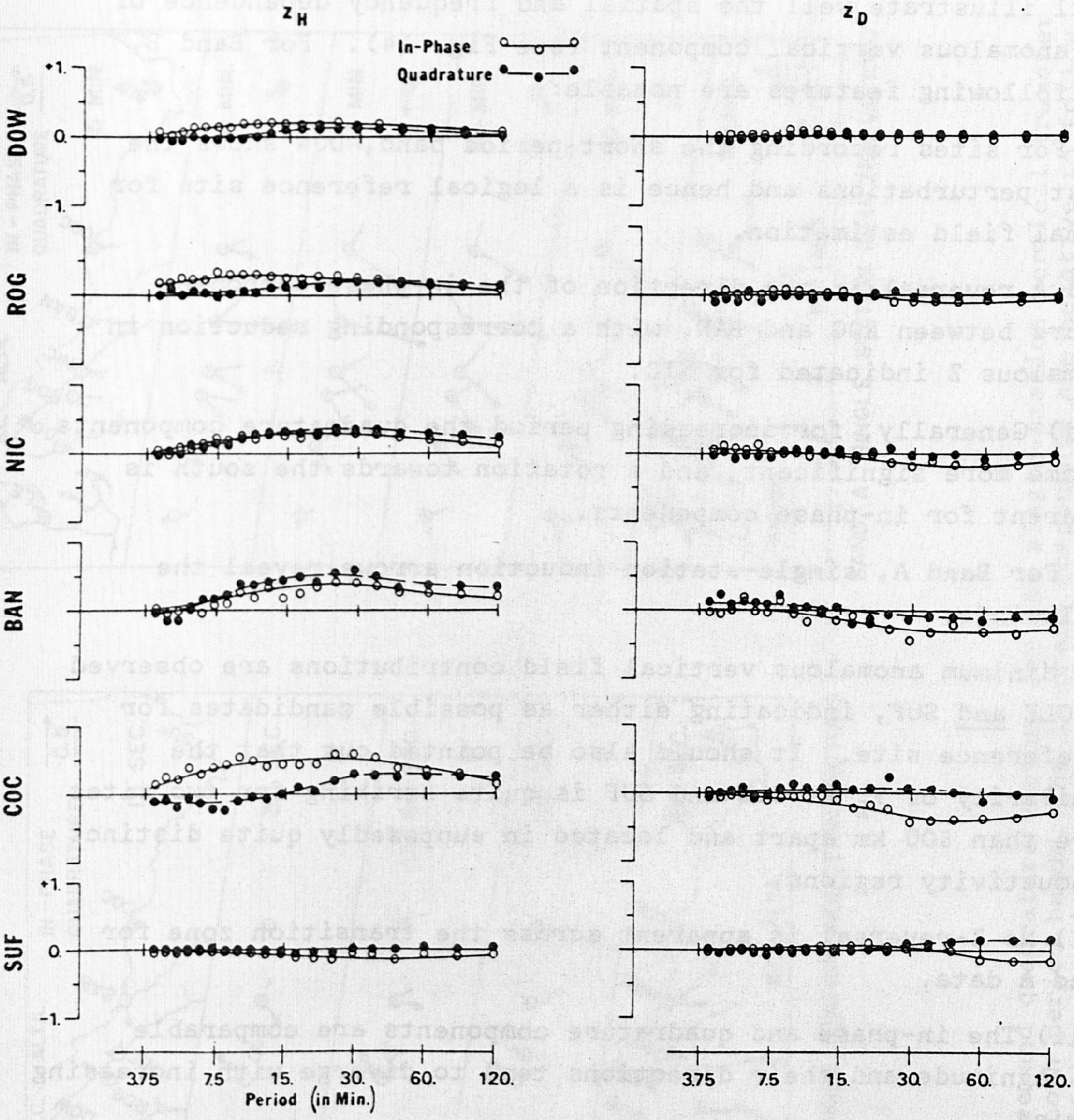


Fig.13: The vertical transfer function elements z_H and z_D contained in the paired-station transfer matrix as functions of period (Band A) at each station.These two elements are analagous to the single-station transfer function pair of z_H' and z_D'.

Although subject to more restrictive and perhaps questionable assumptions, the in-phase and quadrature vectors derived from the simpler, single-station vertical transfer functions still illustrate well the spatial and frequency dependence of the anomalous vertical component (see Fig. 14). For Band B, the following features are notable:

(i) For sites recording the short-period band, DOW shows the least perturbations and hence is a logical reference site for normal field estimation.

(ii) A reversal in the direction of the in-phase component occurs between ROG and BAN, with a corresponding reduction in anomalous Z indicated for NIC.

(iii) Generally, for increasing period the quadrature components become more significant, and a rotation towards the south is apparent for in-phase components.

For Band A, single-station induction arrows reveal the following:

(i) Minimum anomalous vertical field contributions are observed at CLE <u>and</u> SUF, indicating either as possible candidates for a reference site. It should also be pointed out that the similarity of T_Z at CLE and SUF is quite striking for two sites more than 600 km apart and located in supposedly quite distinct conductivity regions.

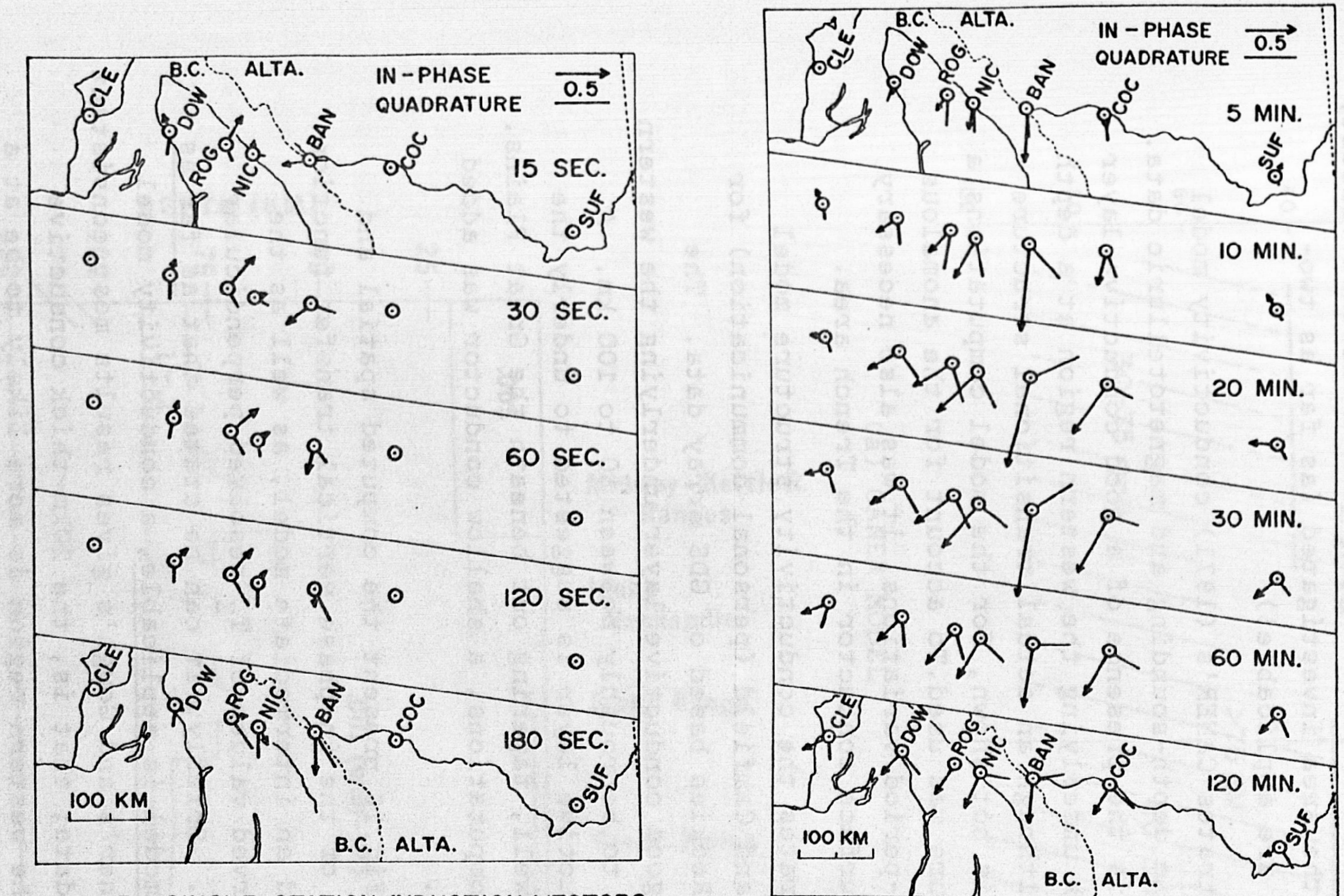
(ii) No Z-reversal is apparent across the transition zone for Band A data.

(iii) The in-phase and quadrature components are comparable in magnitude and their directions tend to diverge with increasing period.

(iv) The directions of the in-phase components are dominantly south to southwest for all periods.

3. Interpretation

The three-dimensional structure suggested by the transfer functions for the observed anomaly ruled out the derivation of



BAND B : SINGLE STATION INDUCTION VECTORS

BAND A : SINGLE STATION INDUCTION VECTORS

Fig.14: In-phase and quadrature vectors for the single-station vertical transfer functions for both period bands. The in-phase components are negative to follow PARKINSON's (1962) convention.

an unambiguous, independent, equivalent two-dimensional conductivity model. Consequently, two previously proposed models were used to generate model transfer function curves which were then compared to observed data to establish a relative validity of each model for the area investigated (as far as two-dimensional models are applicable!)

Fig.15a illustrates CANER's (1971) conductivity model based on geomagnetic depth-sounding and magnetotelluric data. The major feature is the presence of a good conductive layer roughly 20 km thick underlying the western region at a depth of 15 to 20 km. Although an actual transitional structure from west to east is not shown, for the model computations a simple step structure was used.To account for the anomalous response for short-period variations, it was also necessary to add a shallow surface conductor in the Trench area.

Fig.15b illustrates the conductivity structure model proposed by Gough and Camfield (personal communication) for the northern U.S. Rockies based on GDS array data. The mean depth of the good conductive layer underlying the western region is proposed to be roughly between 50 to 100 km. A slightly less conductive layer is suggested to underly the eastern region as well, tapering out beneath the Great Plains. Again, for model computations, a shallow conductor was added in the Trench area.

The curves of Fig.16 present the computed spatial and frequency response of the in-phase vertical transfer function for both models and an intermediate model, as well as the corresponding observed values of T_Z resolved perpendicular to tectonic strike. Briefly, it can be stated that <u>as far as a two-dimensional model is applicable</u>, a conductivity model intermediate to Caner's and Gough's gives results most consistent with the observed data; that is, the 20km-thick conductive layer underlying the western region is more likely to be at a depth of 40 to 50 km in the Trench area. Although such an intermediate model would be more consistent with observed data, it must be noted that it can only account for barely one-half

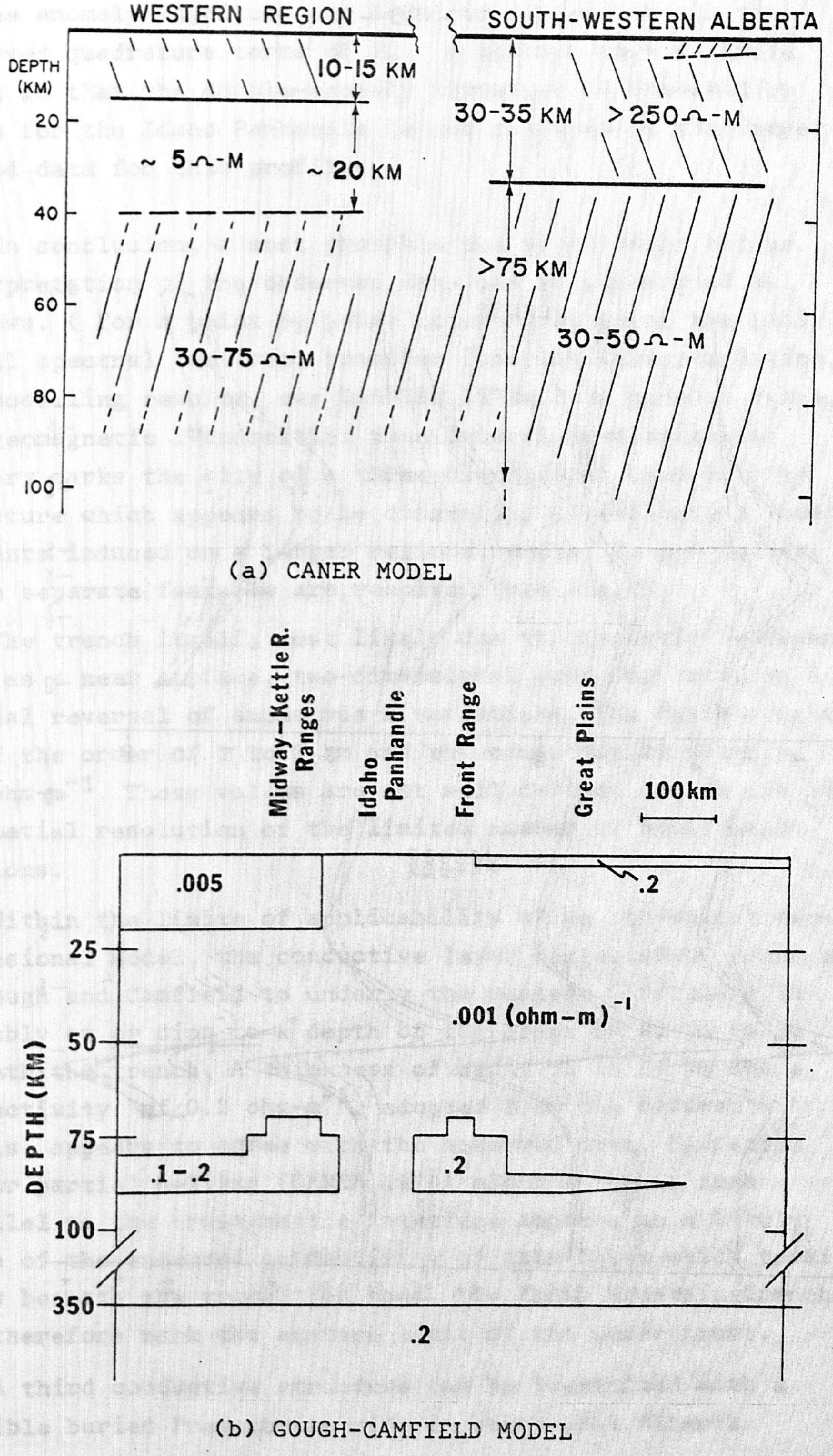


Fig.15: Conductivity structure models suggested for south-west Canada (Caner) and for northern U.S. Rockies (Gough and Camfield).

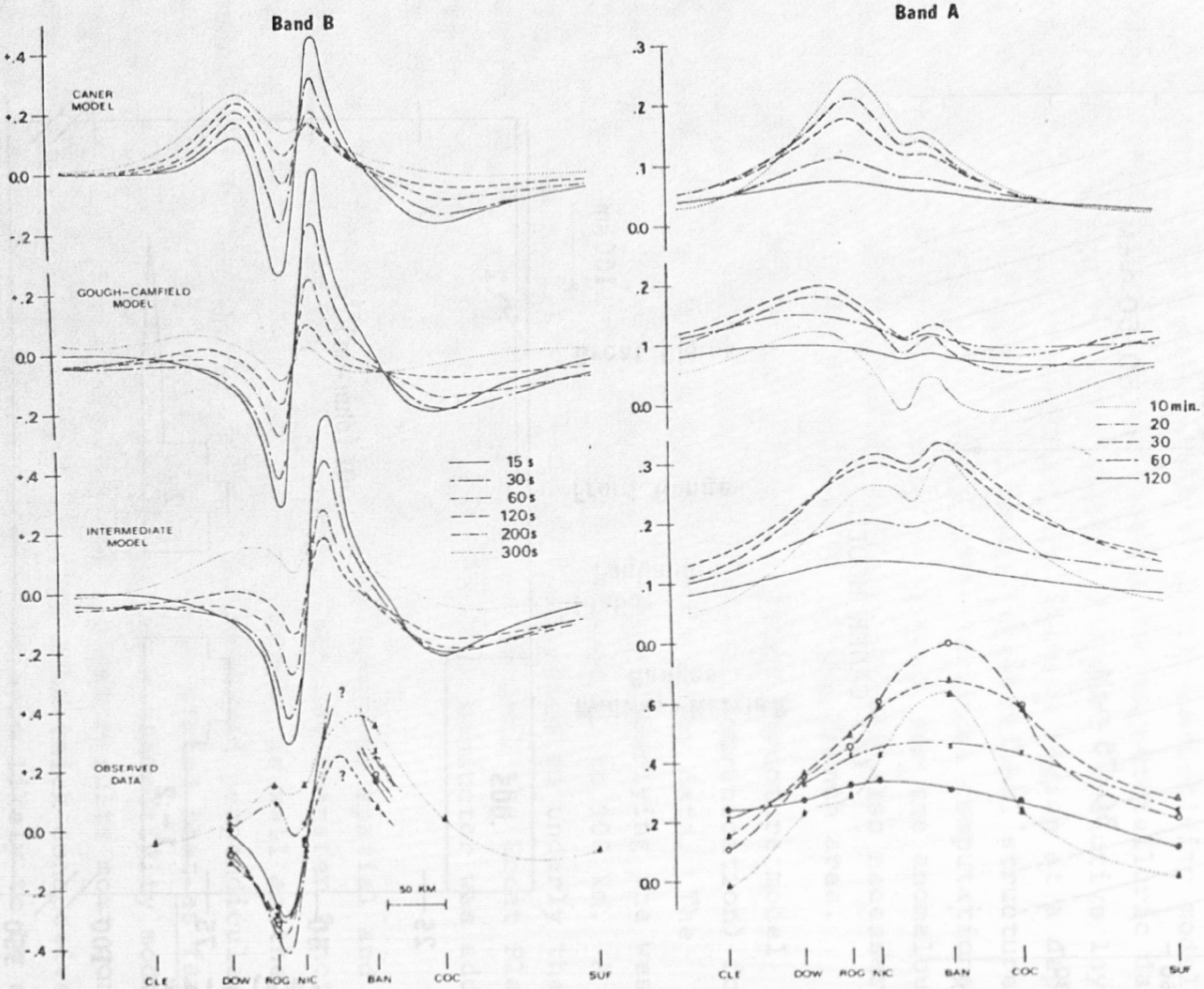


Fig.16: The in-phase vertical transfer function computed for the Caner model and the Gough-camfield model. The observed values of T_Z resolved perpendicular to tectonic strike and the response of an intermediate model are also shown.

of the anomaly magnitude and does not explain at all the observed quadrature terms of T_Z. A perhaps more definite point is that the double-anomaly structure as observed by Gough for the Idaho Panhandle is not resolved by the longer period data for this profile.

In conclusion, a most probable but by no means unique interpretation of the observed data can be summarized as follows. (For a point by point interpretation of the individual spectral features, transfer function characteristics, and modelling results, see DRAGERT,1973a.) In general terms, the geomagnetic I-transition zone between Revelstoke and Calgary marks the site of a three-dimensional conductivity structure which appears to be channeling or deflecting internal currents induced on a larger regional scale. In particular, three separate features are resolved (see Fig.17):

1.) The trench itself, most likely due to conductive sediments acts as a near surface, two-dimensional conductor causing a spatial reversal of anomalous Z variations. The depth extent is of the order of 1 to 2 km and the conductivity roughly 0.1 $ohm\text{-}m^{-1}$. These values are not well defined due to the lack of spatial resolution of the limited number of broad-band stations.

2.) Within the limits of applicability of an equivalent two-dimensional model, the conductive layer suggested by Caner and by Gough and Camfield to underly the western Cordillera is probably at <u>or dips to</u> a depth of the order of 40 to 50 km beneath the trench. A thickness of about 15 to 20 km and a conductivity of 0.2 $ohm\text{-}m^{-1}$, adopted from the reference models, appears to agree with the observed data. Hydration and/or partial melting (CANER,1970) along a thrust zone parallel to the crust/mantle interface appears as a likely cause of the enhanced conductivity of this layer which terminates beneath the transition zone. The Rocky Mountain Trench may therefore mark the eastern limit of the underthrust.

3.) A third conductive structure can be identified with a possible buried Precambrian rift in south-west Alberta

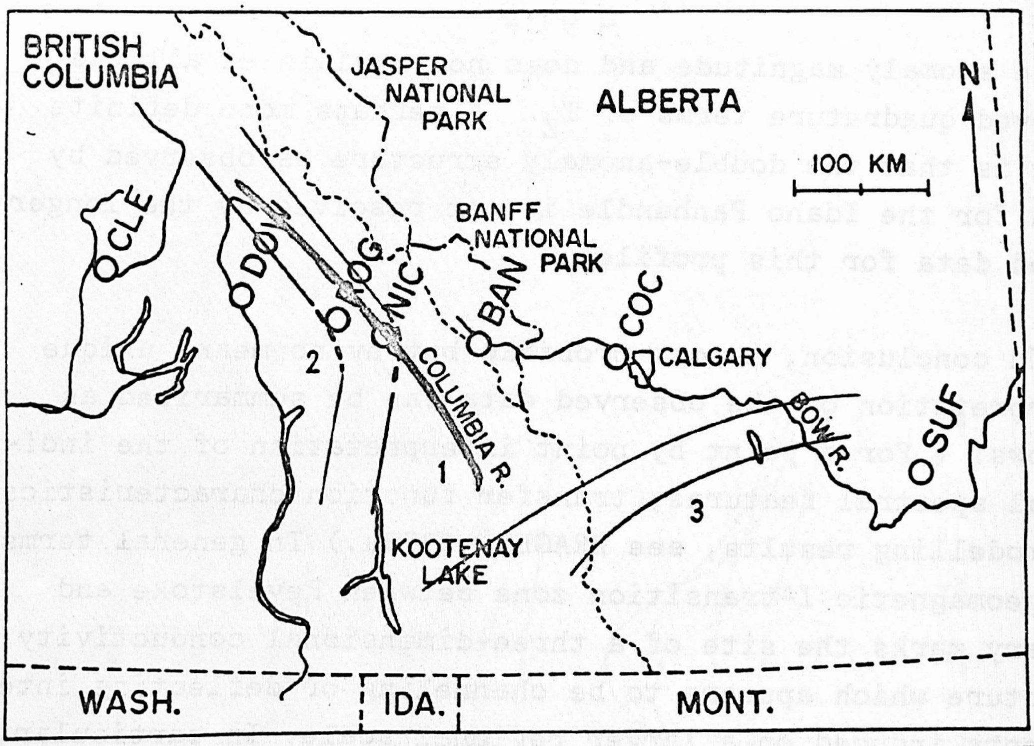


Fig.17: Conductivity structures suggested for the interpretation of the Canadian Cordillera geomagnetic I-transition zone. (See text for the description of the three indicated structures.)

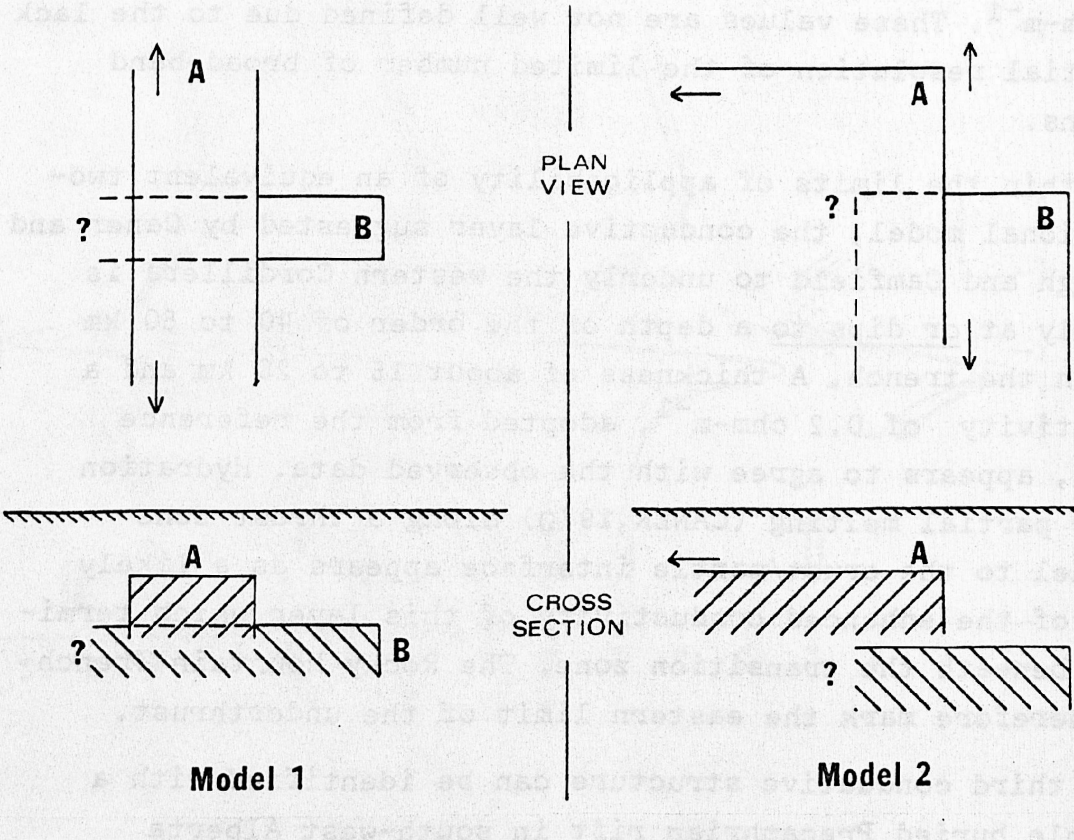


Fig.18: Examples of simple three-dimensional models which would be suitable first-approximation models for the observed longer-period anomaly.

(KANASEWICH,1968), which strikes almost perpendicular to the I-transition zone. The observed anomalous field directions in this study and from COCHRANE and HYNDMAN's (1970) study indicate that this anomaly connects with the Kootenay anomaly along a line following this rift from Alberta into B.C. This implies that the Kootenay anomaly is not strike-slip caused as suggested by LAJOIE and CANER, (1970) but more likely associated with enhanced conductivities of evaporites suggested by Kanasewich to have been generated within the rift by syngenetic and/or hydrothermal deposition. Furthermore, it is possible that this rift marks the northern extent of a moderately conductive layer suggested by Gough and Camfield to underly the Front Ranges and the Great Plains in the northwestern United States. The exact interrelation of the two deeper conductivity structures is not resolved, but a conductive connection appears likely.

From this summary it can be seen that the type of model required to represent the I-transition zone must be at least a simple three-dimensional model as suggested by the schematics in Fig.18. A model, such as the illustrated Model 2, could certainly account for most of the observed features of the transfer matrix elements, as well as resolving the differences in the T and T_Z estimates.

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