TIME-DEPENDENCE OF ELECTROMAGNETIC TRANSFER FUNCTIONS AND THEIR ASSOCIATION WITH TECTONIC ACTIVITY

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Abstract. Laboratory experiments and theoretical considerations have suggested that anomalous dilatant regions can develop in the earth's crust during the period of strain accumulation prior to an earthquake. For moderate and major earthquakes such anomalous regions could be tens or even hundreds of kilometers in extent and should be detectable at the surface with appropriate survey or sounding techniques. Since electrical resistivity is one of the rock properties likely to be strongly modified in a dilatant zone, magnetotelluric impedance and geomagnetic transfer functions might be expected to show time-dependent precursory effects if monitored over a period of time above the focal region of an impending earthquake. Such experiments have been conducted in Japan and in other parts of the world and several examples of resitivity changes in the crust prior to earthquake occurrence have been reported. These results and their association with local seismicity are reviewed in this paper. The available evidence indicates that transfer functions and impedance can display significant time-dependent response to changing crustal conditions in some regions. However, the correspondence between these effects and earthquake occurrence is usually not very clear.

Introduction

During the last ten years important advances have been made in the study of earthquake precursors and the development of techniques for earthquake prediction. In seismically active regions many crustal properties are subject to change during the period of stress accumulation prior to the onset of an earthquake. Some of the properties in which important diagnostic changes have been observed are long-term tilt, strain, crustal uplift, seismic velocities, magnetic susceptibility and remanence, radon emission from ground water, earthquake recurrence and electrical resistivity. Most of the results achieved to date are only empirically related to earthquake occurrence. However, a physical model of stress-induced dilatancy in the crust has had some success in relating and explaining a number of independent observations of changing geophysical conditions preceding a seismic event.

Dilatancy in stressed rock is an inelastic volume increase which occurs prior to fracture. The effect has been observed and documented by Brace and his co-workers at Massachu-

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setts Institute of Technology during a series of laboratory experiments in the deformation of rock specimens under triaxial compression (e.g. Brace *et al.*, 1966). The volume increase is produced by cracks forming and propagating within the rock. The onset of the phenomenon depends not only on the applied stress, but also on the rate of stress accumulation. Dilatancy can begin in rock at stresses as low as half the breaking strength (Scholz *et al.*, 1973).

The volume increase in stressed rock leads to an increase in effective porosity. For fluid-saturated rock, this in turn can produce significant changes in electrical resistivity. Laboratory studies of the effect of pressure on the electrical resistivity of water-saturated

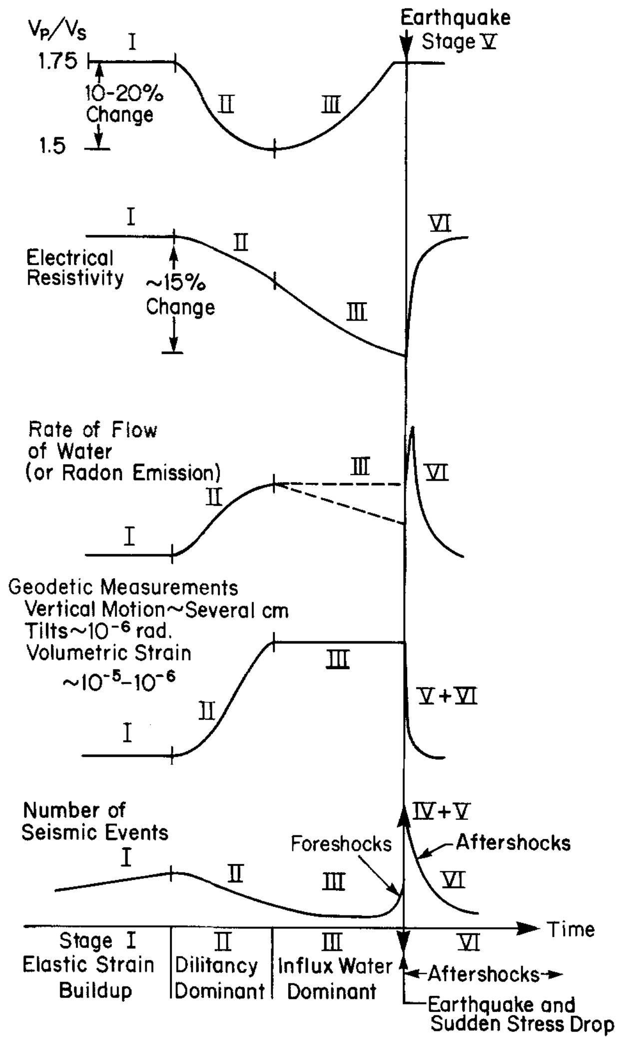

Fig. 1. Typical predicted changes of various physical parameters as a function of time based on the dilatancy model for an earthquake cycle. (After Scholz *et al.*, 1973).

rocks have been described by Brace *et al.* (1965), Brace and Byerlee (1967), Brace and Orange (1968a, b) and others.

General implications of earthquake prediction based on the development of a dilatant region in the earth's crust have been discussed by Nur (1972), Aggarwal *et al.* (1973), Scholz *et al.* (1973) and in a series of papers by Brady (e.g. Brady (1976)). Various types of precursory phenomena implied by the dilatancy model are depicted in Figure 1 from Scholz *et al.* (1973). Note that fairly prominent changes in electrical resistivity (15%) are predicted by the model in a dilatant region prior to the onset of an earthquake. The anomalous or dilatant region in which time-dependent effects are expected corresponds to the focal region of an impending earthquake (Brady, 1976).

Over 25 years ago time-dependent changes in electrical resistivity in the crust associated with tidal loading were observed in Japan at the Aburatsubo Crustal Movement Observatory. This early work, which has been reviewed by Rikitake (1976a) and Yamazaki (1977), led to the important conclusion that relative changes in earth resistivity ($\Delta\rho/\rho$) exceeded the linear strain ($\Delta L/L$) by a factor of about 300 for tidal loading in this area. It was therefore evident that earth resistivity might be a sensitive indicator of stress changes in the crust. Rikitake and Yamazaki (1970), using a sensitive instrument designed to measure changes in resistivity, recorded a stepwise change at the time of Tokachi-oki earthquake (M = 7.9) of 1968 at an epicentral distance of more than 700 km. Since then many similar abrupt changes in resistivity have been recorded simultaneously with major seismic events in Japan and some of these have been preceded by a precursory change of a few hours duration (Yamazaki, 1977; Rikitake, 1976a).

Long baseline (6 km) d.c. resitivity measurements were made in the Garm seismic region of USSR over a number of years commencing in 1967. Some of the results have been reported by Barsukov (1972) and Sadovsky *et al.* (1972). Their data are shown in Figure 2 (adapted from Scholz *et al.* 1973). Apparent resistivity values are seen to be strongly time-dependent with values decreasing before the occurrence of an earthquake and increasing again afterwards. The strong correlation between resistivity minima and

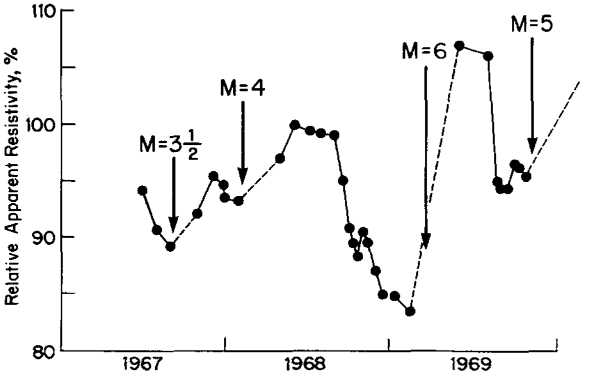

Fig. 2. Electrical resistivity changes and earthquakes observed at Garm, U.S.S.R. (After Scholz *et al.*, 1973 and Sadovsky *et al.*, 1972).

earthquakes is consistent with what one would expect from the dilatancy model. A decrease in resistivity of over 15% took place during the months preceding an event of $M = 6$. Mazzella and Morrison (1974) have also reported a large (24%) precursory change in apparent resistivity prior to a magnitude 3.9 earthquake in central California. They monitored resistivity with a dipole-dipole array with receivers located near the current dipole and at distances of 10 and 15 km. These experiments provide direct evidence that the electrical properties at depth in the crust can be strongly time-dependent in seismic regions. It is therefore reasonable to expect that natural geomagnetic and telluric fields should also contain a time-dependence related to seismicity which might be detected through the analysis of transfer functions. The purpose of this paper is to review variations which have been observed in geomagnetic and magnetotelluric transfer functions and to examine the manner in which these are associated with seismic events and a tectonic environment.

Transfer Functions and Crustal Structure

In studies of natural electromagnetic induction in the earth, the concept of a transfer function is associated with the observation that at many locations the three components of geomagnetic variation field show a persistent tendency of linear interdependence. Such a tendency was first demonstrated around the Australian coast by Parkinson (1959), and since then empirically derived relationships such as

$$Z = A\,H + B\,D \quad \text{or}\ Z = A'\,H_x + B'\,H_y \tag{1}$$

have been used by Everett and Hyndman (1967), Schmucker (1970), Lilley and Bennett (1973) and many others in the study of local induction anomalies and their structural implications. In these relations D is the magnetic declination and H, Z, H_x, H_y are the horizontal, vertical (downward), true north and true east components. The numbers A and B (or A', B') are called transfer functions. Generally speaking these numbers are complex and frequency dependent.

In magnetotellurics a similar linear dependence between horizontal components of electric and magnetic field measured at any point has long been known. In this case the transfer function is dimensionally equivalent to impedance and is defined by the relation

$$\begin{pmatrix} E_x \\ E_y \end{pmatrix} = \begin{pmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \end{pmatrix} \begin{pmatrix} H_x \\ H_y \end{pmatrix} \tag{2}$$

Here E_x and E_y are the north and east components of the telluric field and Z_{xx}, etc., are elements of the impedance tensor.

Transfer functions derived from geomagnetic or magnetotelluric fields have traditionally been regarded as parameters which are essentially controlled by – and therefore diagnostic of – the electrical conductivity of the crust and upper mantle. For interpretations of earth structure it is necessary to compute these functions over a fairly broad range of frequencies in such a way that time-dependent effects caused by varying distribution and intensity of ionospheric or spheric source fields are either eliminated or at least reduced to manageable proportions. This can usually be achieved by modern methods of time-series analysis or by very careful selection of individual events for analysis. The transfer function is considered to be meaningful at any point if it is found to be nearly invariant when computed from data collected at different times. Random time-dependent effects associated with the source fields are then assumed to have been averaged out in the analysis; these do, however, contribute to the errors associated with each computed value of the transfer function.

Transfer functions have found a wide application in the study of local or regional crustal features such as faults, dikes, grabens, land-sea interface, geothermal reservoirs, permafrost regions and prominent inhomogeneities in the lithosphere. All these features are associated with strong contrasts in electrical conductivity which influence the distribution of induced current in the crust and therefore affect the magnetic and telluric fields observed on the surface. In a seismically active region we have seen that quite profound changes in conductivity with time are predicted by the dilatancy model and, indeed, have been observed in long-line resistivity soundings. Transfer functions also have been found to be time-dependent in earthquake regions, particularly in Japan, and some of this experimental evidence will be reviewed in the next section.

Time-dependent Transfer Functions Observed in Japan

The earliest important study was that of Yanagihara (1972) in which 5-year mean values of transfer functions at Kakioka Observatory were computed over a 70 year interval from short-period magnetic variations such as sudden storm commencements and sudden impulses. At Kakioka these variations show a strong linear correlation between horizontal and vertical components and Yanagihara derived A and B values in Equation (1) using disturbances selected from the magnetograms between 1900 and 1970. His results, reproduced in Figure 3, indicate a remarkable secular variation in these computed coefficients. The A-value decreased until around 1920, increased to a maximum at about 1940 and has shown a decreasing trend thereafter. Even larger changes were found for the B-value but these are probably less significant since the geomagnetic variations used for analysis have in most cases a north-south polarization and therefore a small east-west component.

No evidence is known to support an external origin for such changes in transfer functions. Because Kakioka is located in the region of the Central Japan Induction Anomaly, Yanagihara suggested an internal origin for these effects and postulated a gradual alteration in the underground conductivity anomaly which gives rise to anomalous Z variations in this part of Japan. Since the A-value at Kakioka decreased steadily for at least 20 years prior to the 1923 Kanto earthquake of magnitude M = 7.9, and shows an increasing trend thereafter, Yanagihara further suggested that alteration in the under-

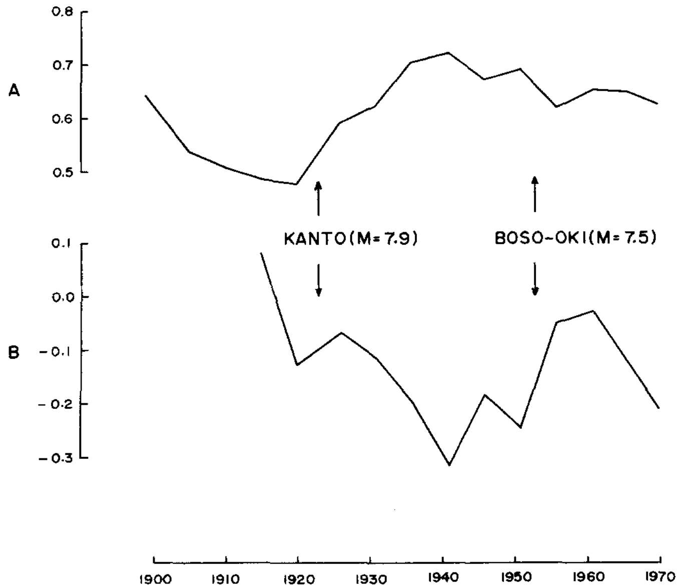

Fig. 3. Secular variations of short period transfer functions A and B at the Kakioka Magnetic Observatory. Arrows indicate the occurrence of the 1923 Kanto earthquake of magnitude 7.9 and the 1953 Boso-oki earthquake of magnitude 7.5. (After Yanagihara, 1972).

ground conducting structure might be associated with this large seismic event. The magnetic observatory is about 100 km distant from the focal region of the Kanto earthquake.

In Yanagihara's analysis, phase differences between the components and period dependence of transfer functions were not taken into consideration. However, Shiraki and Yanagihara (1977) calculated transfer functions from magnetic storm records by making use of the spectral analysis method put forward by Everett and Hyndman (1967). One storm record with 24-hour duration was chosen each year from 1917 to 1974 except for 1918 and 1919. Ten year running averages of both in-phase (Au, Bu) and quadrature (Av, Bv) transfer functions were obtained in this way for a period of 60 min. Though the error bars are quite large, particularly for data acquired before 1935, it was found that the in-phase Au values agreed well with Yanagihara's previous result for A-values. It seems clear that changes in transfer functions at Kakioka have actually taken place, though their correlation with the Kanto earthquake may be accidental.

If a change in electrical conductivity amounting to an order of magnitude actually takes place in the earth as suggested by the experiments of Brace and Orange (1968) it is not unreasonable to expect significant changes in transfer functions. However, a change in A-value at Kakioka amounting to as much as 0.2 seems difficult to explain by conductiivity changes at a distance of 100 km.

A high-seismicity zone exists to the south of the Kakioka Observatory and seismic activity there was very high before the Kanto earthquake. Honkura (in preparation) found from model calculations based on a two-dimensional approximation that an

A-value change of 0.1 at Kakioka (about a half of the observed change) is possible if a conductivity change of an order of magnitude occurs in the high-seismicity zone.

A correlation between changes in transfer functions at Kakioka and earthquakes of magnitude greater than 5 which occurred between August 1973 and May 1975 in the high seismicity zone was reported by Yanagihara and Nagano (1976). In their analysis isolated bay-type disturbances were used to compute Fourier transforms of D, H and Z components corresponding to a period of 80 min. The in-phase values Au and Bu computed over the 22-month interval are shown in Figure 4. Yanagihara and Nagano did not provide a detailed discussion of the errors associated with these computed values, but the data clearly imply that quite rapid changes in transfer functions can occur over a period of a few days immediately before and immediately following an important seismic event. Ten earthquakes occurred for which $M \geqslant 5$ and with epicentral distances less than 110 km from Kakioka. It is reasonable to suppose that the observed changes in transfer functions are directly related to the on-going process of strain accumulation and strain relaxation in this tectonically active region as is suggested by the dilatancy model.

Transfer functions as previously defined imply a linear dependence between various components of geomagnetic or magnetotelluric fields at a given location. In this review we will broaden the definition to include as well the ratio of similar magnetic (or telluric) field components recorded at two different locations. If we impose the condition that the separation between the two recording stations is much less than the scale length of the external source field, such ratios can be diagnostic of internal resistivity structure and therefore have properties in common with the geomagnetic and magnetotelluric transfer functions previously discussed. For example, it is well known that the amplitude of the horizontal component of short-period geomagnetic variations is enhanced over a conducting body as a result of concentration of induced electric currents. It is therefore

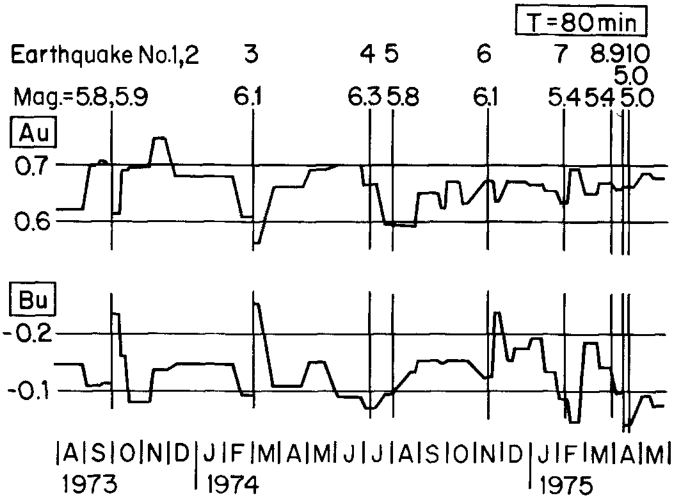

Fig. 4. Transfer function changes and earthquakes observed at Kakioka Observatory. (After Yanagihara and Nagano, 1976).

useful to monitor horizontal magnetic variations at two or more locations as a means of detecting an underground conductivity anomaly. Transfer functions derived from experiments of this kind have been investigated for time-dependence at some locations in Japan.

When an earthquake of magnitude 6.2 named the Southeastern Akita earthquake took place in 1970 in the northeastern part of Japan, some temporary magnetic recording stations happened to be in operation near its epicentral area. Honkura (in preparation) has examined amplitude ratios in horizontal magnetic variations between stations MA and HI and between IS and HI. MA and IS lie within 20 km of the main shock epicentre, while HI at distance of 43 km is used as the reference or normalizing station. Ratios for these pairs of stations were calculated for both H and D components and the results are shown in Figure 5. At MA the amplitude of the H component seems to be enhanced at

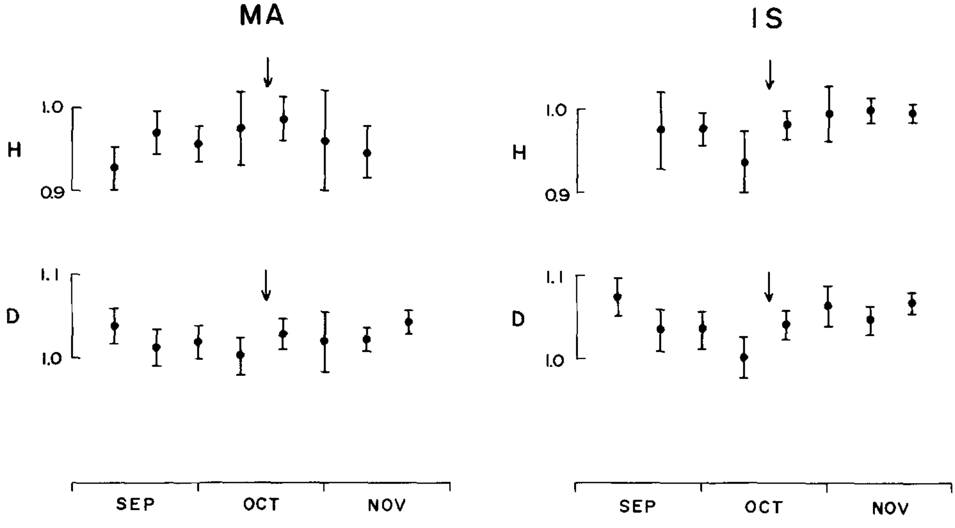

Fig. 5. Changes in the amplitude of the H and D components of short-period geomagnetic variation at MA and IS, respectively. Arrows indicate the occurrence of the 1970 Southeastern Akita earthquake of magnitude 6.2 Error bars denote two standard errors.

the time of earthquake occurrence, while the amplitude of D is slightly depressed. However, these changes are not very significant at the 95% confidence limit. At IS, depression in amplitude is recognized for both components. Honkura has shown that the observed changes at MA and IS are consistent with an increase in conductivity beneath the active zone.

Honkura and Koyama (in preparation) conducted similar research in another area where anomalous crustal uplift and anomalously high micro-earthquake activity had been observed. Three components of short-period geomagnetic variations were measured with a fluxgate magnetometer at station NKZ (Figure 6) beginning in July, 1976. In August, 1976, about one and a half months later, an earthquake of magnitude 5.4 occurred approximately 15 km south of the station. The Yatsugatake Magnetic Observatory, which is about 140 km from NKZ, was chosen as the reference station. Amplitude

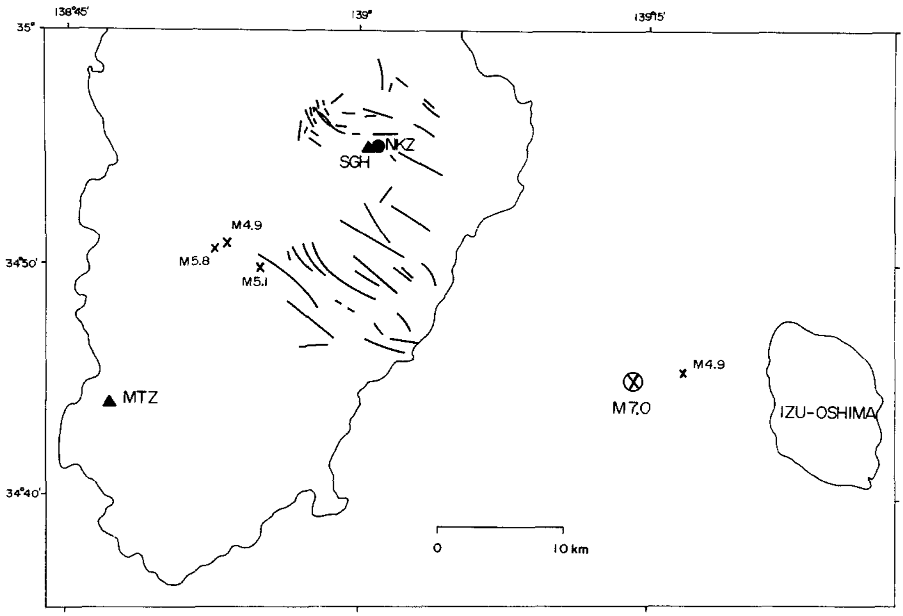

Fig. 6. Localities of stations: NKZ for observations of short-period geomagnetic variations and the natural electric field, SGH and MTZ for measurements of the geomagnetic total intensity. A circle with a cross shows the epicenter of the main shock, while small crosses denote the epicentres of foreshocks and aftershocks (After Tsumura, personal communication). Solid lines indicate active faults in the northeastern part of Izu Peninsula (After Matsuda, 1977)

ratios were determined every half month for both H and D components. The results suggest that slight changes may have occurred in association with the earthquake as shown in Figure 7, although they are not very significant at the 95% confidence limit. The large error bars (two standard errors) are due partly to a simple method of analysis; a maximum amplitude is read for individual disturbances having a duration of 10–40 min.

In January, 1978, another large earthquake of magnitude 7.0 occurred below the sea about 30 km southeast of NKZ. In Figure 6 are shown epicentres of the main shock, a large foreshock (M4.9) which occurred near the main shock, and large aftershocks (M4.9, 5.1, 5.8). About two months before the main shock, the amplitude of H at NKZ increased by about 5% and gradually returned to the previous level as shown in Figure 7. On the other hand, the amplitude of D began to decrease gradually about three months before the main shock. After this event the amplitudes of both H and D appear to have undergone oscillatory changes.

It is not clear whether or not these changes reflect an underground conductivity change. However, there are some indications which support the assertion that the amplitude enhancement in the H component around the middle of November, 1977 reflects a precursory change in the conductivity of the crust near the station. First, the natural electric field at NKZ began to decrease around November 10, the change amounting to

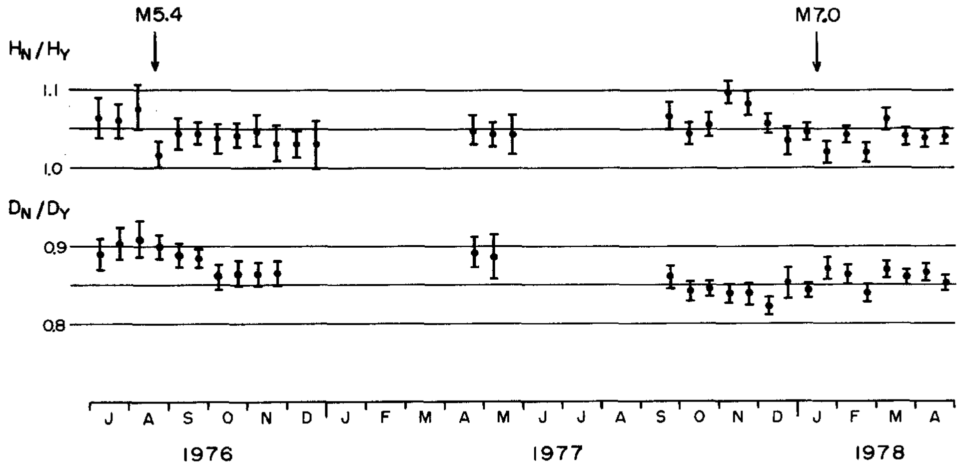

Fig. 7. Secular variations of the amplitude of the H and D components, respectively, of short-period geomagnetic variation at NKZ relative to Yatsugatake. Arrows indicate the occurrence of the 1976 Kawazu earthquake of magnitude 5.4 and the 1978 Izu-oshima earthquake of magnitude 7.0, respectively. Error bars denote two standard errors.

30 mV/km or so. Second, the magnetic total intensity at SGH (very close to NKZ) relative to MTZ (about 30 km southwest of SGH) decreased by about 5 nT (Kawamura, personal communication, 1978). These two effects were very similar to each other not only in time but also in form. Third, the radon content also changed in early November at a well station near NKZ (Wakita, personal communication). Most of these changes are probably precursory effects related to fluid flow along active faults having a nearly NWW–SEE trend as shown by solid lines in Figure 6.

Time-dependent Transfer Functions in North America and Elsewhere

Reddy *et al.* (1976) conducted magnetotelluric measurements over a period of eight months in or near the Los Angeles basin in Southern California and gave a well documented account of the experimental procedure and data analysis they used in an attempt to detect significant time-dependence in the measured impedance functions at frequencies near 0.04 Hz. They concluded that there were no significant changes in tensor apparent resistivities or phases during the recording periods at their three stations. No earthquakes of magnitude greater than 4 occurred in this interval within 50 km of any of the sites though there were a few events with $M \leqslant 3$. However Phillips *et al.* (1977) have continued monitoring magnetotelluric signals in southern California in the 0.03–0.04 Hz band and in the 7–8 Hz band. Their new results indicate crustal resistivity changes with time which significantly exceed the uncertainty of their estimates. They comment that the nature of the association between these resistivity changes and the tectonic environment remains uncertain and requires further study.

A magnitude 7.2 earthquake occurred near Sitka, Alaska on July 30, 1972. Wyss (1975) found evidence for anomalous secular variation in the horizontal component at Sitka Magnetic Observatory commencing 7½ years before the earthquake. Shortly after the earthquake the mean value of the H-field returned to its normal or expected value. Encouraged by this result, Rikitake (1978) analysed short-period ($\sim$ 10 min) geomagnetic variations at Sitka Observatory to see if the transfer functions A and B (as defined by Equation 1) were subject to any unusual behaviour prior to the earthquake. The focal region was located only about 40 km west of the observatory. The transfer functions were estimated by scaling individual selected events on the magnetograms and, as in Yanagihara's 1972 analysis, no account was taken of phase and frequency dependent effects. Transfer function A increased by about 0.1 in 1971 and then returned to its normal level before the earthquake occurred. At this latitude (60°N geomagnetic) it is difficult to be certain that the transfer functions have not been influenced by the effect of overhead currents in the auroral electrojet. Rikitake selected his events carefully in order to avoid this influence and the maximum A value in 1971 should be significant in the sense that it reflects precursory changes in crustal resistivity rather than a source effect.

In Canada, magnetotelluric fields have been monitored for nearly 4 years at a few stations near the centre of seismicity in a well confined active region on the north shore of the St. Lawrence River about 80 miles downstream from Quebec City. This zone is contiguous with a major thrust fault, Logan's Line, which underlies the river and separates the Precambrian shield to the north from the Appalachian region to the south. The seismicity occurs at or near the intersection of a large Palaeozoic impact crater (the Charlevoix Crater) and Logan's Line. The most recent important earthquakes occurred in 1935 (M = 5.8) and 1925 (M = 7). Focal depths average about 10 km for current microearthquake activity in the region.

The magnetotelluric experiments in this region have been described by Kurtz and Niblett (1979) and Honkura *et al.* (1976). Locations of the recording stations are shown in Figure 8. The station designated Charlevoix lies within the zone of seismic activity and near the centre of the impact crater. It has been operating more-or-less continuously since October 1974. Lac la Batture is a control station about 70 km to the northwest where recording began about a year later. It is outside the active zone and remote from the St. Lawrence River. The MT stations at Dufour and Ste-Mathilde were established in the spring of 1977 for comparison with the other stations.

From the data recorded at these locations the impedance has been computed along the principal direction of anisotropy. Time sequence plots of the principal impedance, of electric field polarization and of the in-phase geomagnetic transfer function $(A^2 + B^2)^{1/2}$ are shown for Charlevoix in Figure 9 for 5 and 10 min periods. The plotted principal impedance values are normalized to their arithmetic mean so that the observed variations may be viewed as percentage changes. Figure 9 also shows earthquake occurrences and epicentral distances from the Charlevoix station. When the 3½ year sequence of normalized impedances at this station is compared to similar data from the control station at Lac la Batture it is clear that significant time-dependence has occurred only at Charlevoix. At

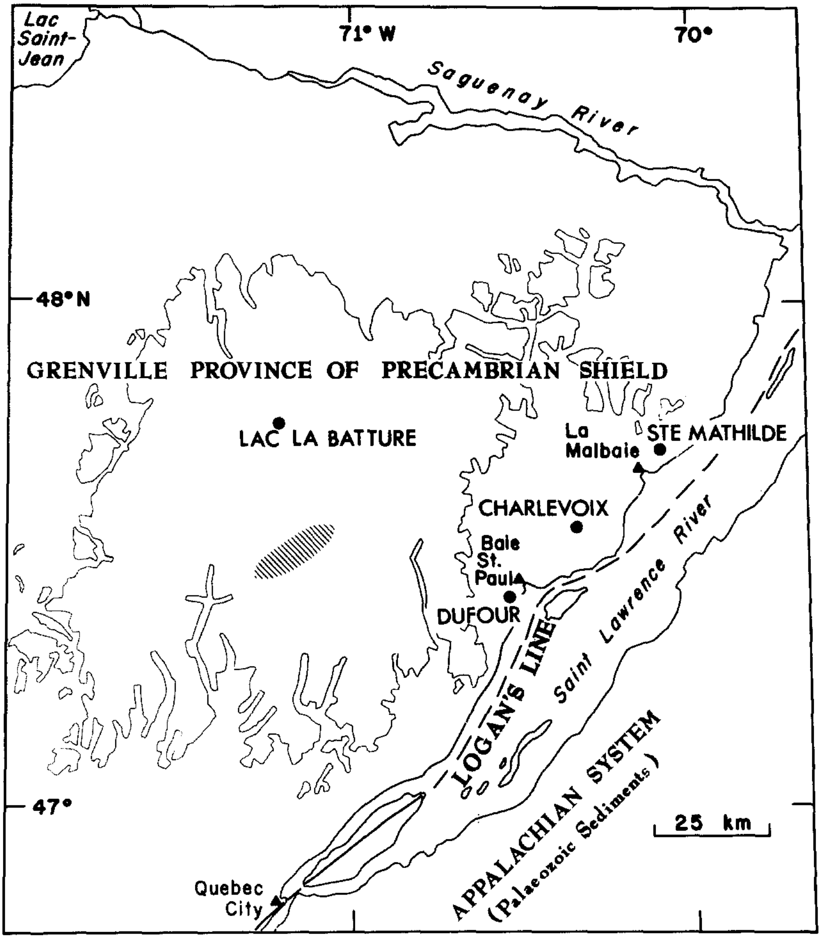

Fig. 8. Location of four magnetotelluric recording stations in the St. Lawrence-Saguenay region of Quebec.

5-min and 10-min periods the most important part of this time-dependence is caused by a trend increase of 14% per year though a statistically significant portion remains which is quasi-periodic or non-linear. In sharp contrast to the magnetotelluric results the geomagnetic transfer functions are very stable at both Charlevoix and Lac la Batture. These data suggest that electrical conductivity changes in the crust are strongly localized and confined to the zone of seismicity. They also indicate that electric fields are much more sensitive than magnetic fields in detecting localized time-dependent effects in this region.

Over the 3½ year recording interval the Charlevoix region has experienced fairly continuous low-level seismicity indicative of on-going crustal instability. The non-linear part of the variable impedance determined from the MT data at Charlevoix suggests that electrical conductivity at some depth within the crust may be changing in response to this instability. This conclusion is supported by the absence of both seismicity and

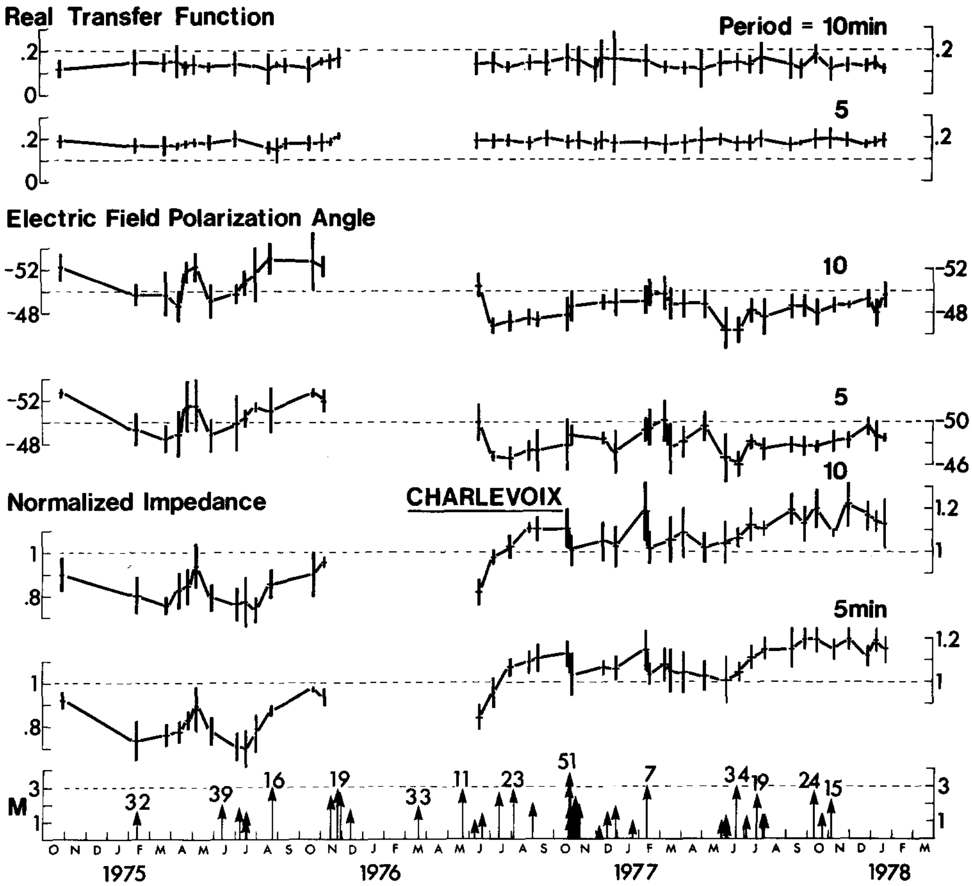

Fig. 9. Impedance and transfer function changes at Charlevoix. Lower two graphs: Normalized impedance values measured in the direction of the major axis of anisotropy for 5 and 10 min periods. Middle two graphs: Azimuth clockwise from magnetic north of the major axis of the polarization ellipse of the telluric fields. Upper two graphs: In-phase transfer function. Error bars are two standard deviations in length. Earthquakes of magnitude greater than 2 within 50 km of the Charlevoix station are shown along with their approximate epicentral distances.

comparable impedance variations at Lac la Batture and other recording sites. Though the possibility that seasonally changing conditions in the St. Lawrence River might influence the telluric field at Charlevoix is as yet unresolved, it seems most unlikely that the long-term increasing trend in impedance could be explained by either superficial surface features or by variable source fields. The evidence therefore supports the hypothesis of changing electrical conductivity at depth in the crust in a localized region which has been accumulating strain. With the data presented here it has not been possible to demonstrate a direct correspondence between impedance change and a specific earthquake occurrence. The absence of premonitory effects is likely due to the fact that the largest earthquake to occur in the immediate vicinity of the station during these experiments had a magnitude of 3.2. Earthquakes of this size probably do not produce premonitory effects large enough or of sufficient duration to be detected by observations made here.

Miyakoshi (1975) analysed magnetograms at Tashkent and Askhabad in Central Asia with special reference to the 1966 Tashkent earthquake of magnitude 5.5 and the 1970 Askhabad earthquake of magnitude 6.6. No notable change in transfer function was found in association with the Askhabad earthquake, but at Tashkent a significant maximum in yearly mean values of $(A^2 + B^2)^{1/2}$ occurred about a year before the seismic event. The focal region of the Tashkent earthquake was about 30 km from the magnetic observatory. The duration of the anomaly is in harmony with a precursory change in radon content at a well station in Tashkent (Sadovsky *et al.*, 1972). Miyakoshi concluded that his observation might be explained by a conductivity increase in the focal region of the earthquake in such a manner as described by Scholz *et al.* (1973).

Shapiro and Ivanov (1974) discovered very unusual behaviour of the geomagnetic field near the town of Butka on the eastern slope of the Urals. A very deep tectonic active fault is believed to exist nearby. The secular variation of the total force field has been found to differ by as much as 30 nT/year over a distance of less than 50 km. Shapiro and Pjankov (1977) have pointed out that there is evidence for an anomaly in electrical conductivity in the deep crust or upper mantle in this region and that the anomalous secular variation is probably caused by local irregularities in electromagnetic induction. Accordingly they decided to examine geomagnetic transfer functions (Wiese vectors) at a pair of temporary recording stations near Butka. For magnetic variations in the 10–20 minute period range the Wiese vectors at both stations were found to change in orientation by approximately 90° over a period of only 3 months. The magnitude of the vectors were much less severely affected. This appears to be one of the most remarkable changes in transfer functions so far reported. Shapiro and Pjankov concluded that their observations could be explained by changing electrical conductivity in the crust but they did not present any evidence suggesting an association between these temporal changes and tectonic activity.

Remarkable successes in earthquake prediction have been reported in the People's Republic of China. The city of Haicheng was nearly destroyed by a magnitude 7.3 earthquake which occurred in February 1975. However the event was predicted accurately enough to permit massive evacuation of the local population a few hours before the main shock. A description of the investigations leading up to this successful prediction is given by the Haicheng Earthquake Study Delegation (Bennett *et al.*, 1977). Included in the program were difference measurements between magnetic field components recorded at Darien and Peking, the latter station being 215 km from the epicentre. Precursory changes of about 20 nT in Z between these stations, which occurred about 8 months before the earthquake, have been reported. Xu *et al.* (1978) have reported time-dependent geomagnetic transfer functions at Lanchow Observatory located in a zone of geothermal and seismic activity in Kansu Province. Changes in transfer function A were found to correlate well with earthquakes of magnitude 5.1 (1970), 6.5 (1973) and 7.2 (1976).

At Alibag Observatory in India large changes in scalar transfer functions A and B have been reported by Arora and Singh (1979) which appear to be associated with the occurrence of an earthquake in the vicinity.

Discussion

Rikitake (1976b) has used two-dimensional model calculations to examine whether any detectable change in short-period geomagnetic variations could be expected in association with appearance of a conductivity change in the crust amounting to an order of magnitude. A fairly large change, up to 100%, in the horizontal field was obtained for a certain combination of the period of geomagnetic variation and the spatial extent of the anomalous area. Changes amounting to several tens of percent appear to be possible above an underground dilatant zone. The horizontal component is more strongly affected than the vertical with this model.

From a relation between the magnitude of an earthquake and the spatial extent of an anomalous area, the period of geomagnetic variation for which changes are most effectivily observed can be estimated for various magnitudes. In the case of magnitude 7, for instance, variations having a period of 30 sec or so should give the best result. For magnitude 8, a period of a few minutes is the most suitable period for detecting changes. If the period is too long or too short for a certain size of anomaly, large changes are not expected from Rikitake's model.

Some of the precursory changes reported so far are fairly large even at periods of a few minutes to several tens of minutes. The model calculations suggest that shorter periods would be more effective in revealing time-dependent effects. However, inductive or conductive response of the crust and upper mantle depends on the local conductivity structure. The important point derived from the model calculations is, therefore, that it is quite possible to detect changes in short-period geomagnetic variations if the conductivity changes appreciably in association with earthquakes.

Changes in magnetotelluric parameters were estimated by Honkura (1976) on the assumption that the induced electric field is approximately uniform in the crust and the effect of secondary induction is negligibly small. This assumption is valid only for periods which are sufficiently long for the penetration depth to be deeper than the crustal depth. Calculations were made for three cases corresponding to anomalies associated with very shallow, shallow, and deep earthquakes, respectively. Except for deep events, changes can be expected in the amplitude and direction of the induced electric field, although these will be small unless the station is located within the anomalous area. For short periods, the above result will not be applicable. If the penetration depth of the varying field is comparable to the depth of an anomalous area, much larger changes in the induced electric field and in the impedance are to be expected. Since many earthquakes have focal depths of about 10 km or less it is clear that short-period data approriate for penetration depths of this order will usually provide the best MT response to time-dependent dilatancy effects.

Thus the bulk of the experimental and theoretical evidence accumulated so far suggests that electromagnetic transfer functions can display a measurable response to changes in stress at some depth within the crust or upper mantle. Long-term secular trends have been found by Yanagihara (1972) and Kurtz and Niblett (1979). Shorter term effects which appear to be significant have been seen by Yanagihara and Nagano (1976), Miyakoshi

(1975), Rikitake (1978), Phillips *et al.* (1977), Honkura (unpublished), Shapiro and Pjankov (1977), Kurtz and Niblett (1979) and Xu *et al.* (1978). In all this work there are uncertainties concerning the significance of the measured time changes because of errors associated with computations of the transfer functions. In most cases an improved reponse might have been obtained if shorter periods had been studied. While the dilatancy model provides a general expectation that apparent resistivity should be time-dependent in an active zone, there are insufficient data at this stage to derive empirical relationships between precursor times indicated by transfer functions and earthquake magnitude (M), or between the linear dimension of the anomalous (dilatant) zone and M. Rikitake (1976a) has shown that for many long-term precursory phenomena associated with earthquakes the empirical relation

$$\log_{10} T = 0.76\,M - 1.83$$

applies fairly well. Here T is the time-duration of the precursory effect measured in days. This gives $T \approx 15$ days for $M = 4$ and $T \approx 8$ years for $M = 7$. With the experimental techniques used in most of the above analyses the detection of precursory transfer function effects for earthquakes of $M \leqslant 4$ would be either unlikely or impossible. The resistivity measurements by Yamazaki (1977), Barsukov (1972), Mazella and Morrison (1974) and others have provided evidence of time-dependent apparent resistivity with direct correspondence between resistivity changes and seismic events. Such unambiguous correlations have not yet been achieved through analysis of transfer functions.

The work of Yanagihara and Nagano (1976) illustrates one of the difficulties in studying transfer function effects in a very active region. In a period of only 22 months they observed 10 events of $M \geqslant 5$ within 110 km of Kakioka along with many more events of smaller magnitude or greater epicentral distance. So much activity in one region is almost certain to lead to a complex response at any given observing site and to obscure to some extent any direct correlation between transfer function changes and a single seismic event.

With controlled source or d.c.-resistivity methods it is possible to measure apparent resistivity with substantially higher precision than has so far been obtained in the measurement of transfer functions. Naturally occurring sources allow 'seeing' to much greater depths, especially in resistive terrain, but their uncertain distribution in space and time contributes to errors in the computation of transfer functions and impedances which can easily exceed 10%, even with high quality data and sophisticated statistical techniques of analysis. Until these quantities can be determined with higher precision transfer function methods are likely to remain inferior to active methods of estimating earth resistivity for the purpose of studying earthquake precursors.

In experimental studies in the field it is important to compare geomagnetic or magnetotelluric data at two or more stations, some of which are located near the centre of tectonic activity and some of which are remote. When this is done one is in a much better position to distinguish between time-dependent effects caused by varying source fields and those related to internal (and presumably stress-induced) changes. Accurately recorded difference fields between pairs of geomagnetic or magnetotelluric recording stations should allow a very substantial reduction in the errors associated with transfer functions, and therefore a better assessment of their time-dependence. For periods less than 1 minute telemetering of data to a single recording site would probably be required to achieve satisfactory results (Babour and Mosnier, 1977).

Brady (1976) has discussed three distinct classes of earthquake precursors. Class I precursors refer to long-term manifestations of impending failure and may include crustal uplift anomalies, long-term tilt, and the seismic velocity ratio v_p/v_s. These effects have been seen to precede major shallow earthquakes by several years and their development is controlled by a logarithmic relationship such as the one given above. Class II precursors are short-term indicators which develop several hours prior to major shallow earthquakes. These include S-bend tilt, vertical and horizontal crustal displacements, electrical and magnetic effects, and changes in water level. Class III precursors are very short-term phenomena which precede major shallow earthquakes by only a few seconds. Brady has examined the theory of rock failure in detail and has shown how these various classes of precursors might be related to the development of inclusion zones within a dilatant or anomalous region. It is interesting to note that apparent resistivity has shown variations typical of each of the three classes of precursors. The transfer function and impedance results reviewed in this paper, despite their lack of precision, show convincing evidence for long-term class I resistivity changes. Class II and possibly class III changes have been observed with the sensitive resistivity variometer developed by Yamazaki (Rikitake and Yamazaki, 1970). Magnetotelluric measurements at Schumann band frequencies should also be capable of detecting class II precursory effects.

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