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10 Theodore R. Madden

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Abstract

The final six years of seventeen years of ONR sponsored research work at M.I.T. in geoelectricity and geomagnetism is reviewed. The specific areas included magnetospheric studies and crustal magnetotelluric studies. The magnetospheric studies involved Alfven wave damping in the plasmasphere and its effect on the ULF background noise spectrum. The magnetotelluric studies included a low frequency magnetotelluric survey of New England and a thin sheet analysis that incorporates the effects of a resistive crust on the telluric fields. A listing of personnel and a bibliography is also included.

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Introduction

This report summarizes the final 6 years of a 17 year association with the Office of Naval Research. The first decade was reviewed in a previous final report (Madden, 1971). During this last phase work was conducted in two areas, magnetospheric studies and crustal magnetotelluric studies. Two Ph.D. theses were completed and a third one was started. The principal investigator would also wish to repeat what he said in the previous final report that the support and encouragement of the Office of Naval Research was of immense benefit to his academic career.

In the first section we review the project work on Alfven wave damping in the magnetosphere. This damping has a very considerable effect on the ULF noise background at midlatitudes and also probably plays a not insignificant role in the phenomena taking place at the plasmapause. The theory, which seems to be in good accord with the observations, indicates that the damping is due to the outer radiation belt protons with additional contributions from ring current particles which penetrate inside the plasmasphere. This damping causes an exponential fall off of micropulsation energy with frequency with a typical damping factor of 30 cps^{-1}.

In the second section we review the project work on crustal magnetotellurics. This work comprises two parts. The first is a large scale magnetotelluric study of New England across New Hampshire and Vermont. Distinct differences between the upper crust electrical properties of New Hampshire and Vermont were observed and the study demonstrated the pronounced effect that the crustal geology has on the magnetotelluric fields even for very large scale measurements at very low frequencies. In the second part we began a theoretical development to model the effects of the crustal geology. This is a thin sheet analysis, but it is an extension of the usual thin sheet analysis which incorporates the effect of the vertical resistivity of the crust as well as its horizontal conductivity. This modification changes the nature of the solutions considerably and demonstrate the important effect that a resistive lower crust has on the magnetotelluric fields.

In the third section we list the personnel involved, and the degrees received with research done under ONR sponsorship. A bibliography is also enclosed.

I. Magnetospheric Studies

Alfven Wave Damping in the Plasmasphere

The source of the ULF background noise on the micropulsation spectrum is still not well understood. The shorter periods have dramatically less power and at midlatitudes there is a pronounced hole in the noise spectrum at the point where the lightning induced noise overlaps onto the micropulsation spectrum at around 1 hertz. Several lines of evidence from some of our previous studies led us to think that this reduction is not due to the source spectrum, but is instead an effect of the propagation down to the earth from the source region. First of all we see from our micropulsation monitoring a spectral peak at around 60-100 second period, and many people have reported a peak at around 20 seconds. The plasmasphere which encloses the midlatitudes has a sharp boundary and should make a good quarter wavelength resonator. The dimensions and Alfven wave velocities of the plasmasphere are also about right to give resonance periods for the two lowest modes of 60 and 20 seconds. If the Q of these resonances is the result of leakage out of the plasmasphere due to a less than unity reflection coefficient, higher harmonics should have increasing Q values, but these higher harmonics are essentially never seen. A damping mechanism in the propagation within the plasmasphere would reverse this trend, however, and discriminate against the higher frequencies.

Figure 1 shows calculated plasmasphere resonances using realistic plasma densities (including the ionosphere) and also show the effect of an assumed damping mechanism. The resonance spectrum obtained with damping included is quite reasonable, and the observed spectrum clearly cannot support an undamped propagation. The waves we are concerned with here are unguided Alfven waves with long horizontal wavelengths which are typical of the micropulsations observed at midlatitudes. These waves are capable of being damped by interactions with a hot plasma, which interaction is known as magnetic moment-wave magnetic field gradient interaction, and we presume such interactions must be taking place at the outer reaches of the plasmasphere.

The line of evidence presented above is somewhat indirect and, as our picture of unguided Alfven wave plasmasphere resonances is generally ignored in discussions of micropulsation spectra, might even be considered controversial. Another very different line of evidence exists, however, which strongly supports the damping hypothesis. This evidence consists of micropulsation events, which we call damping events, where there is a sudden loss of micropulsation energy. In general the source and propagation effects are as badly mixed in the time domain as in the frequency domain, but a large number of damping events are intimately associated with 'pearl'

Figure 1

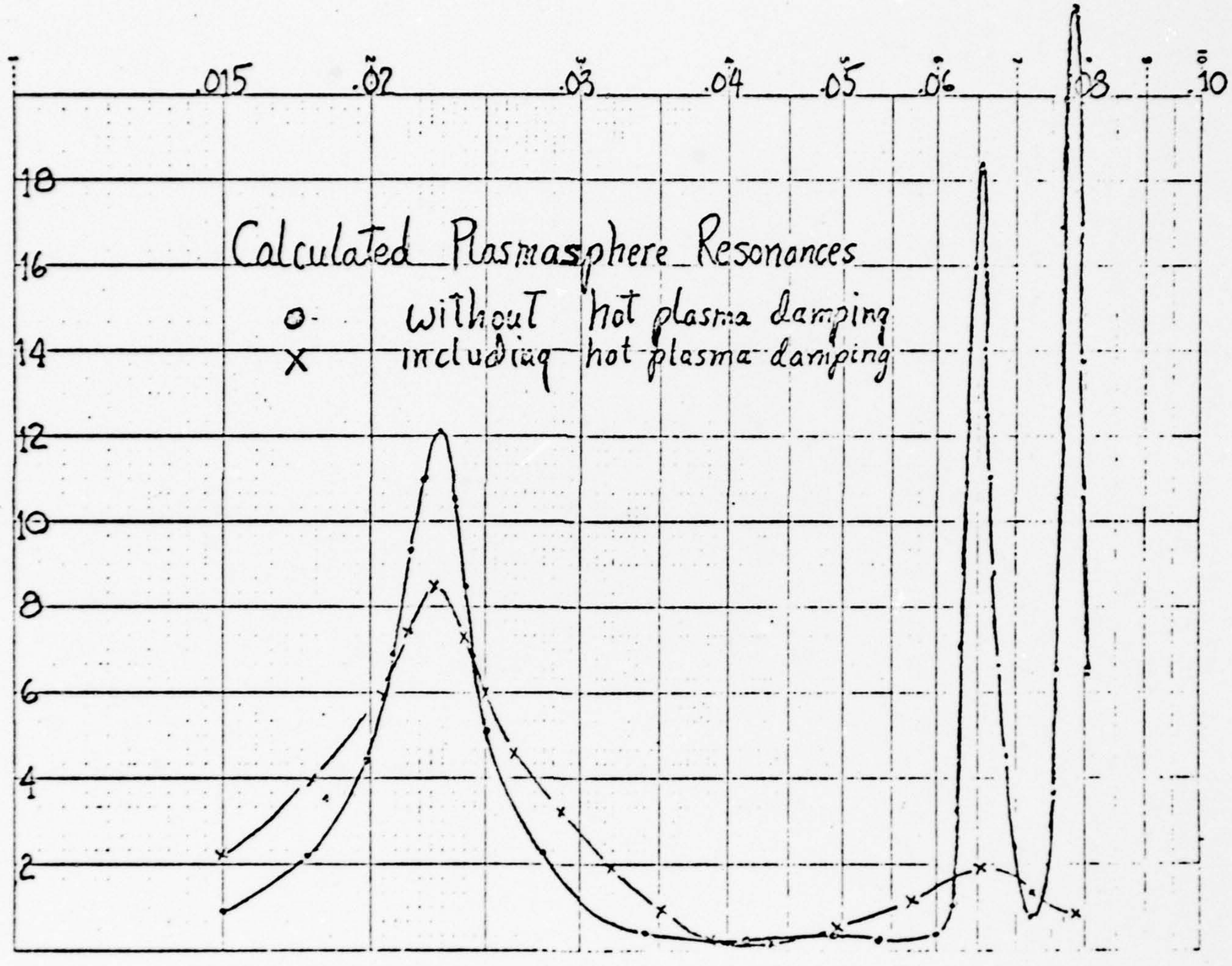
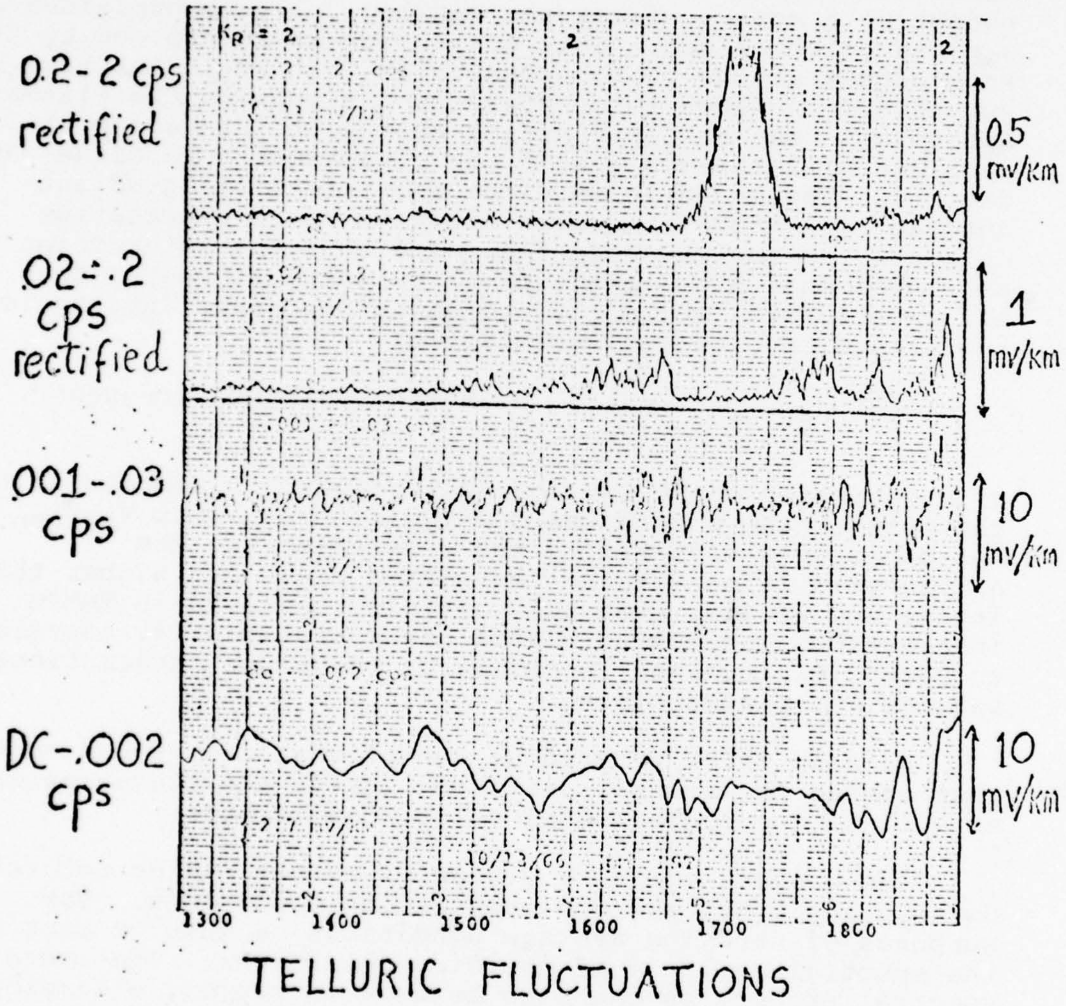

Calculated Plasmasphere Resonances
o· without hot plasma damping
x including hot plasma damping
18
16
14
12
10
8
6
4
2
.015
.02
.03
.04
.05
.06
.08
.10

Figure 2



TELLURIC FLUCTUATIONS
NEW ENGLAND 10/13/66

events which adds another dimension of information. Figure 2 shows such a damping event with the associated pearl event. The pearl events have been extensively studied and are known to be the result of proton cyclotron interactions with guided Alfven waves. There is general, but not universal, agreement that the interaction region for the pearl generation is close to but outside the plasmasphere. Since the pearl event is a spontaneous generation of micropulsation energy, the associated drop in the lower frequency micropulsation spectra cannot be a source effect and can logically be explained as a propagation effect. This conclusion is reinforced by the knowledge that the proton population that would interact with guided Alfven waves to generate pearls outside the plasmasphere also has the appropriate energy to interact with unguided Alfven waves inside the plasmasphere to cause wave damping. The magnetic movement-magnetic field gradient interaction (MMMFG) requires the wave to be propagating obliquely to the magnetic field and thus the interacting particles must have longitudinal velocities greater than the Alfven velocity, while the cyclotron resonance interaction requires a longitudinal velocity of

$$\left(\frac{\omega-\Omega}{\omega}\right) V_{Alfven} \quad \text{where } \Omega \text{ is the cyclotron frequency.}$$

ω is generally about $\Omega/2$ for the cyclotron resonance so that the interacting protons need velocities of about V_{Alfven} but oppositely directed to the wave velocity. The Alfven velocities outside the plasma pause are higher than inside and we find that the particles involved in MMMFG interactions inside the plasma pause have similar energies to particles involved in cyclotron resonance interactions outside the plasma pause.

We also infer from these events that the proton surge that caused the events penetrated inside the plasmasphere as well as the region outside the plasmasphere.

The damping events are special events and do not tell us anything about average propagation conditions. For purposes of studying average conditions we must go back to the spectral analysis of the micropulsations. The average spectral properties can also be used to support a damping hypothesis. This is perhaps the weakest line of evidence, but once damping is accepted as being important, the spectra can be used to determine parameters of the damping. Noise sources generally follow power laws such as white light or 1/f. Damping, such as that produced by the magnetic moment-magnetic field gradient interaction, will superimpose an exponential decay on the source spectrum and should therefore cause a very pronounced jog in the resulting spectra. Our measurements of micropulsations are made on the telluric (horizontal electric) field. The telluric field is related to the magnetic field by the earth impedance, but this impedance again usually follows a power law. Because of the increasing conductance with depth inside the earth the impedance is close to a first power law behavior. Plotting the telluric spectra as power per octave generally leads to a rather flat spectra for the lower frequency micropulsations (this implies a power density spectra for the magnetic field going as ω^{-3}). At frequencies of around .02 hertz the spectra breaks away from this trend and falls off quite dramatically. As shown in figure 3 the spectrum can be well represented by the function

$f^n e^{-\delta f}$. We interpret this as evidence of damping

with f^n representing the source spectrum and $e^{-\delta f}$ representing the propagation effect. If magnetic field power density is plotted (which is the usual way micropulsation data is presented) the exponential fall off is much less apparent as seen in figure 4.

Taking all this evidence together we think makes a very strong case for plasmasphere damping being an important feature of the background electromagnetic noise spectra. Since damping factors as large as 50 hertz^{-1} are observed it is evident that the plasmasphere is responsible for a great reduction in the noise spectra, and that changes in the plasmasphere properties could profoundly influence ULF conditions. A study of the mechanism involved has, therefore, a practical importance. Such a study is also of interest for magnetospheric physics. The plasmasphere boundary is the separation between a denser, cool plasma corotating with the earth and the outer magnetosphere, a convecting, hot, tenuous plasma. The velocity shear across the boundary would be unstable, due to the Kelvin-Helmholtz instability, unless some stable stratification is present. Such a stabilizing factor is provided by the higher energy of the outer plasma despite its low number density. The penetration of this plasma into the plasmasphere which we inferred took place during damping events, is therefore destabilizing and probably plays an important role in the erosion of the plasmasphere that occurs during high magnetospheric activity. A quantitative theory of the damping together with observations of its magnitude should therefore lead to information of value in trying to understand the processes occurring in this region of space. Our own studies along these lines were not completed at the termination of our relationship with the Office of Naval Research, but significant progress was made which we report on here.

In order to make quantitative use of observations of the plasmapause damping of Alfven waves one must formulate the dispersion relationship of these waves in the

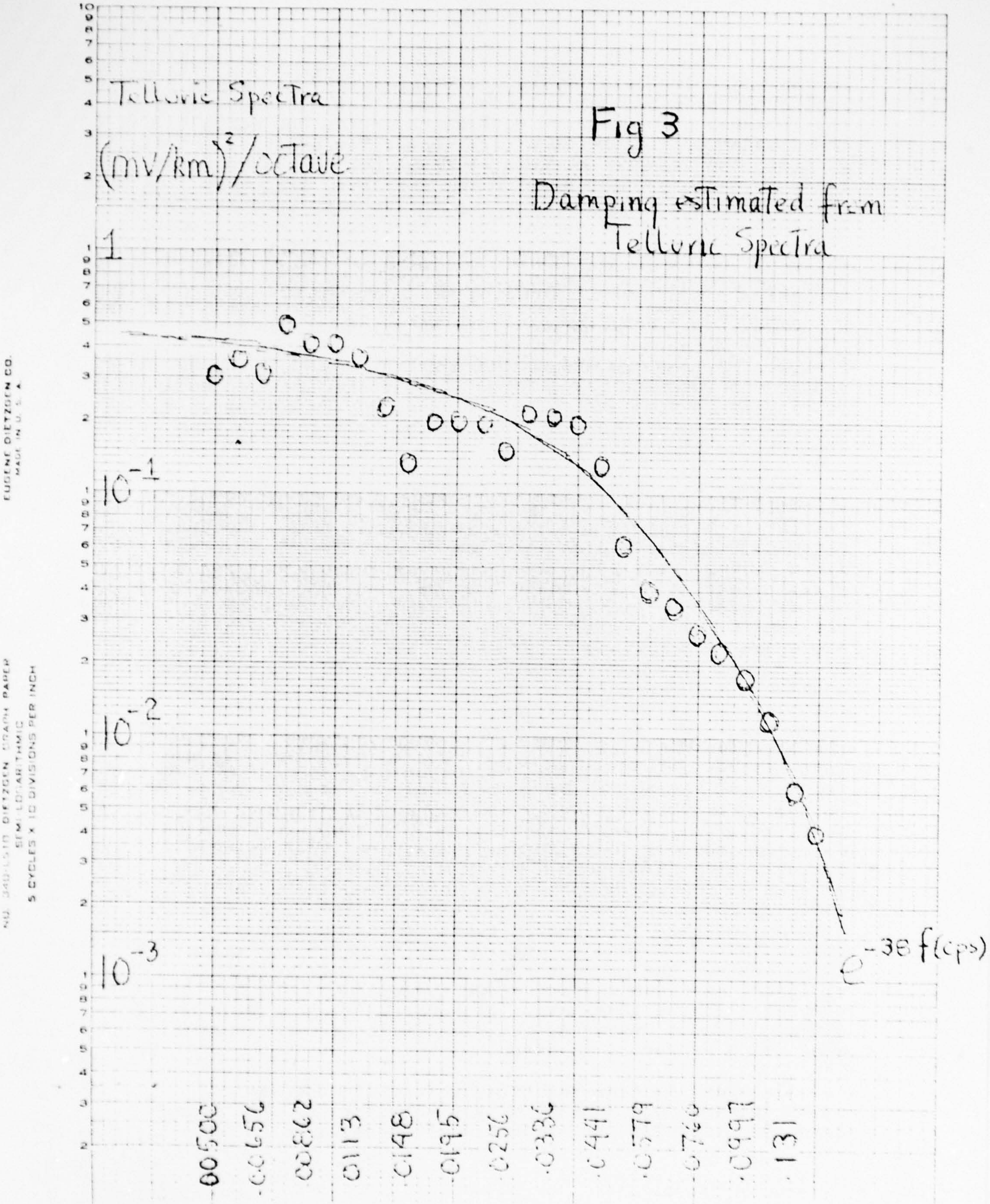


Fig 3

Damping estimated from Telluric Spectra

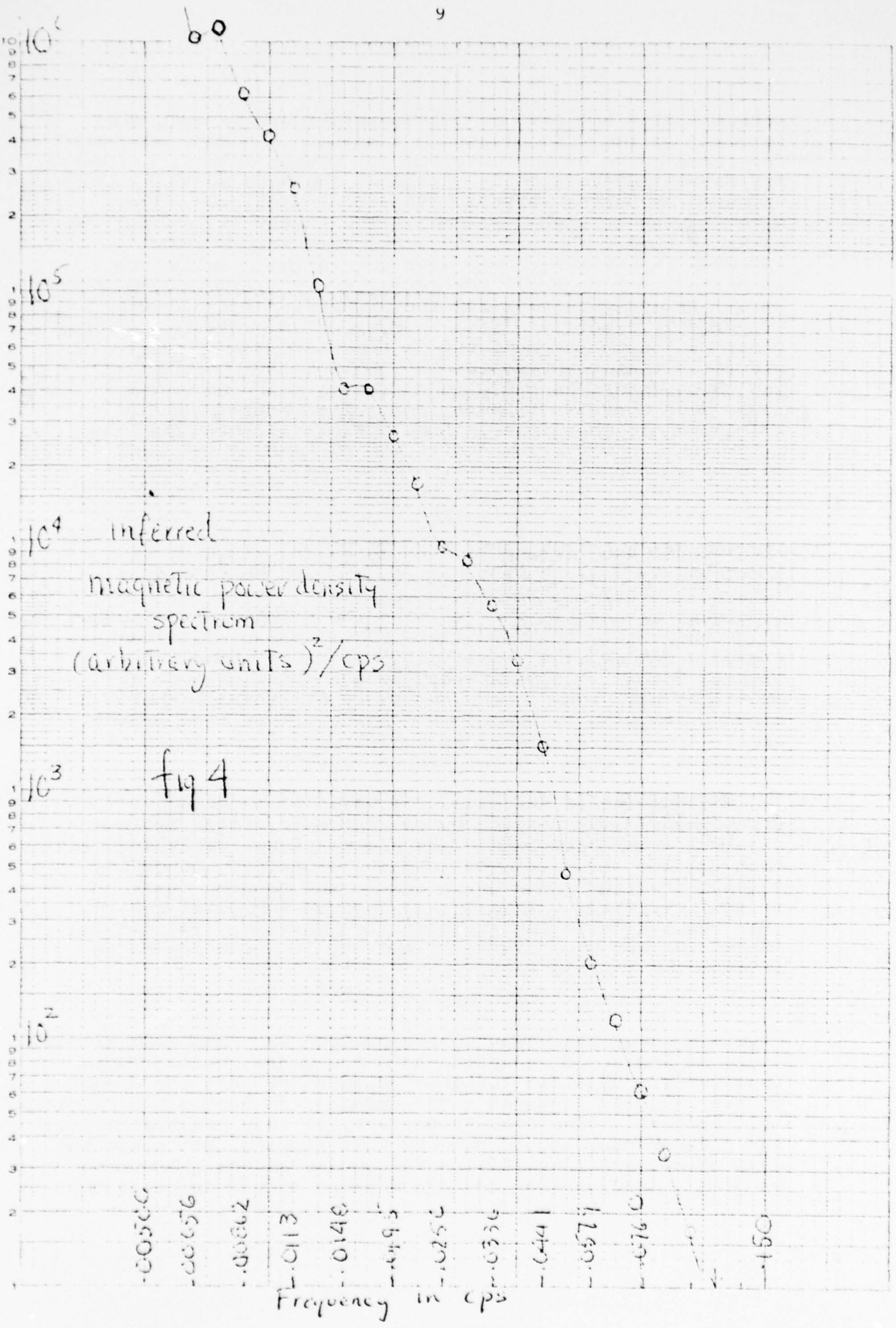

10^6
10^5
10^4
10^3
10^2
inferred
magnetic power density
spectrum
(arbitrary units)^2/cps
.00500
.00656
.00862
.0113
.0148
.0195
.0256
.0336
.0441
.0571
.0760
.150
Frequency in cps

fig 4

presence of a hot plasma. These relationships must also be valid in the case of strong damping. A theory adequate for these purposes was developed by Chandrasekhar, Kaufman, and Watson (Chandrasekhar, Kaufman, and Watson, 1957, 1958) and used by Barnes (Barnes, 1966) to investigate Alfven wave damping in high β plasmas. The theory is reviewed in Navato's thesis (Navato, 1973) and some errors that appeared in the references (but not in the results) are corrected, but we shall not repeat the voluminous algebra here. The calculations for the dispersion relationship are greatly simplified if a bi-Maxwellian particle velocity distribution is assumed, but in the plasmasphere the particles that comprise the main bulk of the population and which determine the Alfven wave velocity have much lower mean energies than the particles responsible for the damping. Therefore, a superposition of bi-Maxwellian distributions was assumed with the parameters adjusted to give reasonable fits to the observed particle energy distributions. These distributions were taken from King's (King, 1967) model AP5 for the low energy outer radiation belt protons, and Vette, Lucero and Wright's (Vette et al., 1966) model AE2 for the low energy outer radiation belt electrons as well as Chappell, Harris and Sharp's data (Chappell et al., 1970) on the thermal ($\sim$0.12 ev) component of the plasma. Solving the dispersion relationship numerically for conditions applicable to different L shells one obtains results such as those shown in figures 5 and 6. Similar results are obtained for calculations with real ω and complex k, and these latter results are used to compute the power transmitted across shells (treated as slabs) as a function of the angle of incidence. Figure 7 shows such a result.

The damping is maximized for waves propagating at steep angles with respect to the magnetic field. Because of the low velocity within the plasma pause, waves arriving from outside are refracted into steep angles. Cascading results from the different L shells and keeping track of the refraction allows one to compute the total damping that results for waves arriving from outside. The damping depends on the wave frequency but can be expressed as an attenuation factor,

$$\text{wave energy} \sim e^{-\delta f}.$$

Figure 8 shows the computed attenuation as a function of the angle of incidence on approach to the plasmapause. These results were obtained for quiet conditions when the magnetosphere is fully expanded. The damping was due to the radiation belt protons. Ring current protons, if they penetrated into the plasmapause, should enhance this damping, but since the damping depends inversely on the square of the Alfven wave velocity, eroding away the plasmapause should decrease the

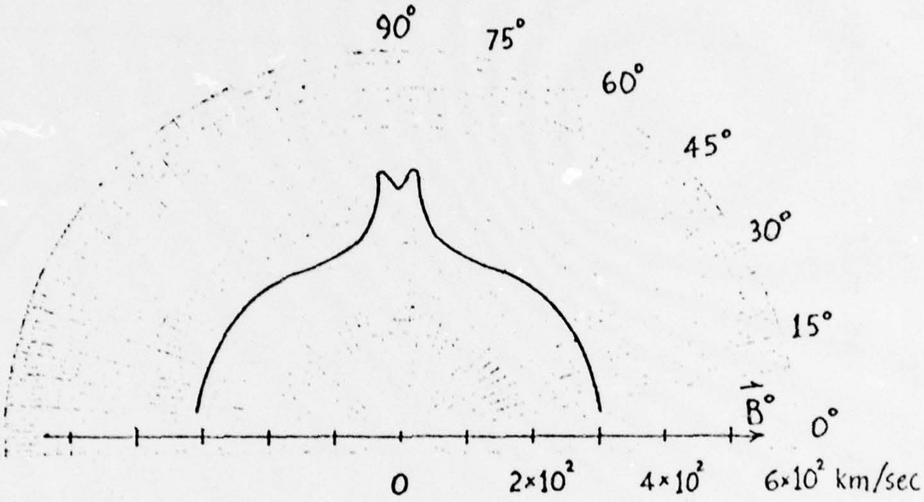


Figure 5

Phase Velocity Diagram

Real $\vec{k}$, complex w, $|\vec{k}|$ = .642E-09 cm^{-1}

L = 4.6 Re, lat. = 0° (geomagnetic),

long. = 288° E(midnight), $K_p < 1^+$

Figure 6 Damping Rate Diagram

Real $\vec{k}$, complex w, $|\vec{k}| = .642\text{E-09}\ \text{cm}^{-1}$

L = 4.6 Re, lat. = 0° $\left\{\begin{array}{l}\text{(geomagnetic), long.} = 288^\circ\ \text{E}\\ \text{(midnight)}\quad ,\ K_p < 1^+\end{array}\right.$

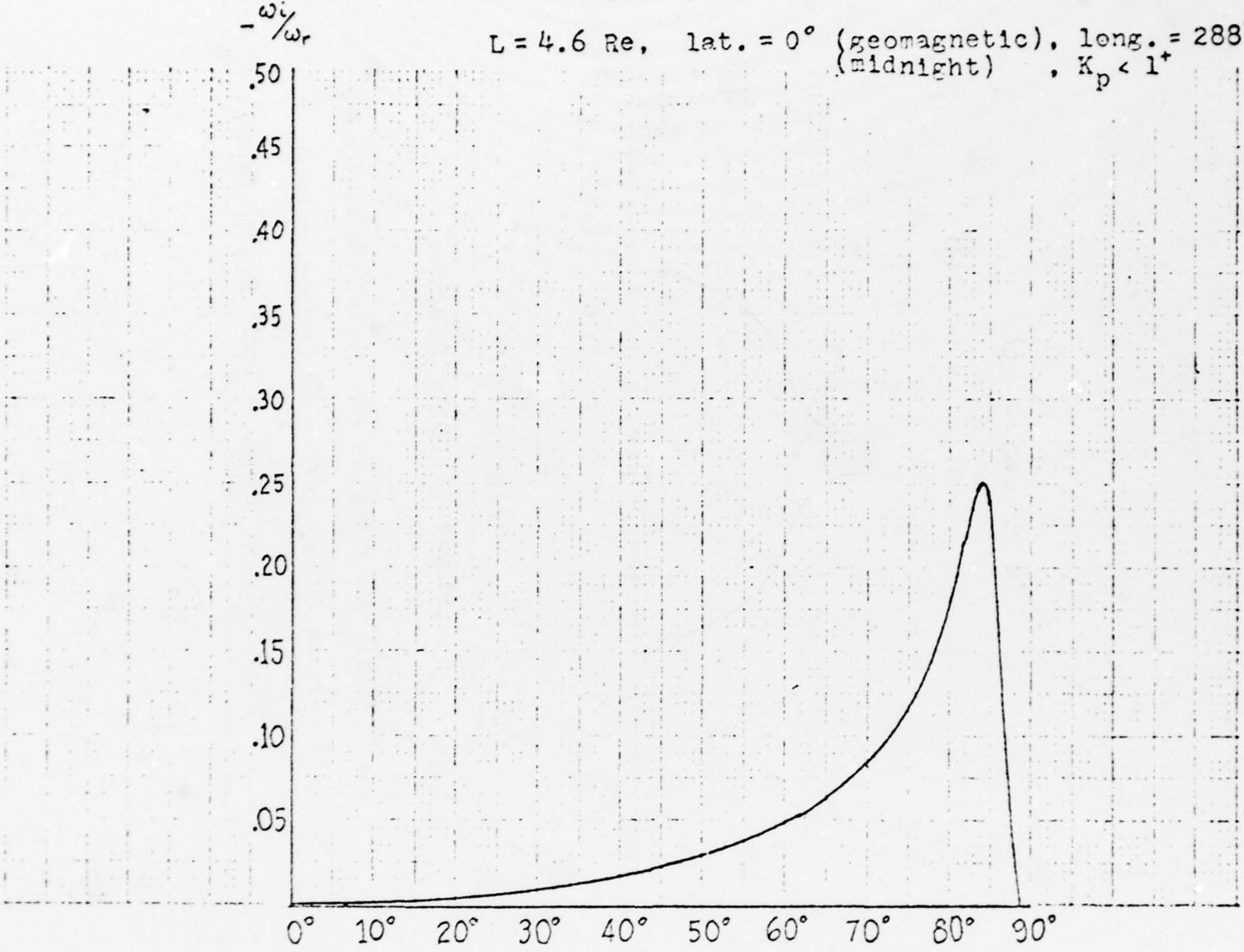


Figure 7   Relative Transmitted Power Below 1 Re Slab

Real w, complex $\vec{k}$, frequency = .02 cps
L = 4.6 Re, lat. = 0° (geomagnetic)
long. = 288° E (midnight), $K_p < 1^+$

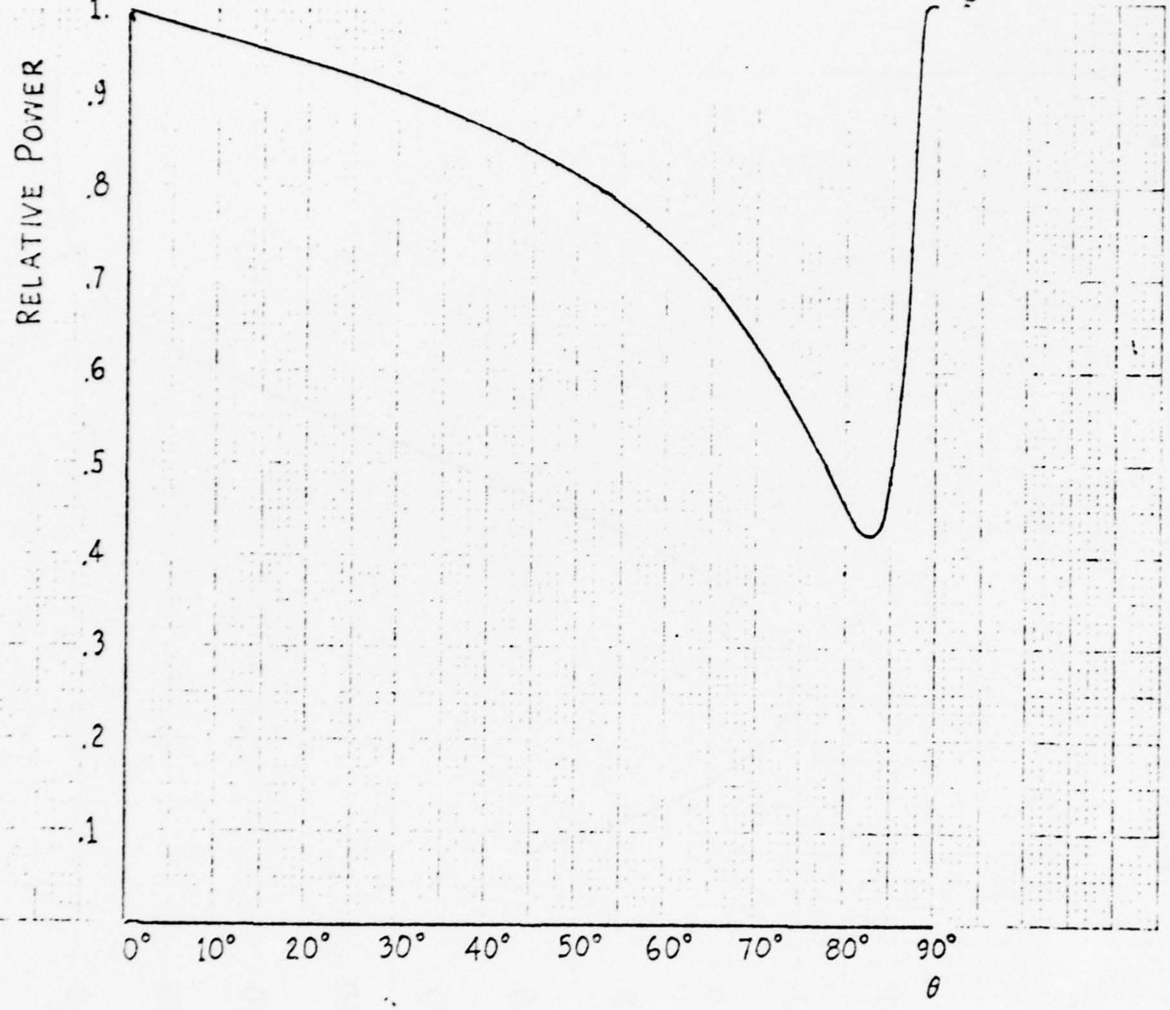
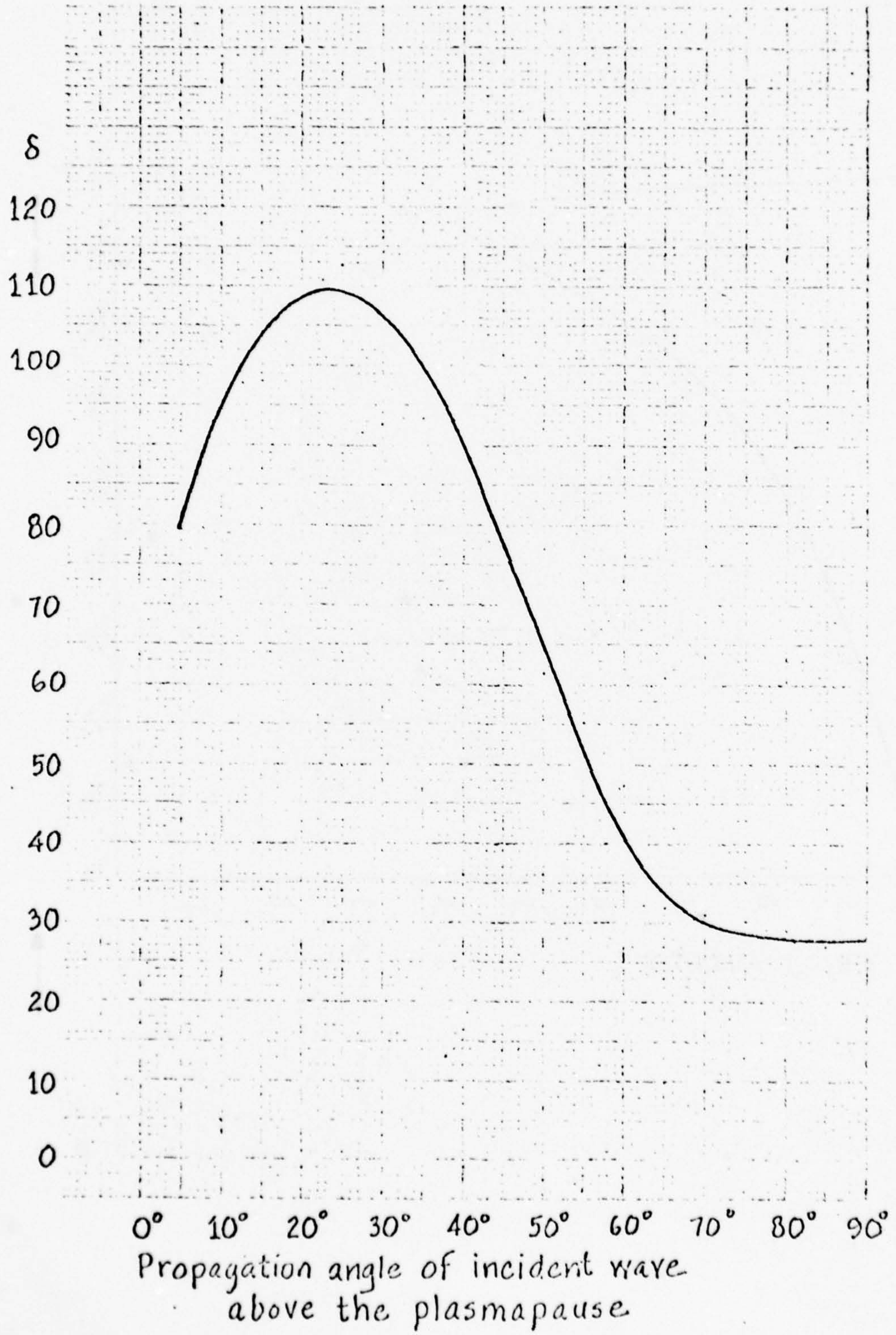


Figure 8 Power attenuation factor δ when source is above the plasmapause
Lat. = 0° (geomagnetic), Long. = 288°E, $K_p < 1^+$



damping. Thus it is still unclear how the damping will behave with varying magnetic activity and more work is needed to sort the various effects out.

The temperature assumed for the thermal plasma ($\sim$3000°K) was too low to allow the thermal electrons to contribute much, but this could be greatly changed if higher temperatures are obtained. The fact that the predicted damping is of the rightorder of magnitude and the coincidence of damping events with pearl events, which are proton events, appears to uphold the use of these low temperatures, which relegates the damping to the hot protons.

We attempted to catch damping events by using a pearl event trigger to activate a tape recording of the telluric fluctuations. The spectra during these events could then be obtained by digitizing the recorded data. Figures 9, 10, and 11 show three such examples. In figure 11 the normal spectra was so depressed we believe all the energy shown is actually propagated from higher latitudes down the F_2 layer waveguide, and no estimate of the plasmapause damping was possible.

Older digital data of micropulsation spectra was also available from which estimates of damping factors could be made and these results are summarized in figure 12. The median damping factor is about 32 which is very close to the theoretical results shown in figure 8 for waves approaching the plasmapause at steep angles of incidence. These results encompass a range of different magnetic activities, however, and probably require the additional effects of ring current particles penetrating inside the plasmapause. Our study of the effect of these particles is incomplete and we think worthy of further investigation.

```
CONCORD-LINA, N.H., TELLURIC FLUCTUATIONS, SEPTEMBER 10, 1971
23:43 - 00:10 EST, 27.3 MINS. DURATION
ELECT., NW.  SAMPLING INTERVAL=0.20 SEC, FUND. FREQ=.0006 CPS.
FREQ. CPS.          POWER/OCTAVE, ((MV/KM)**2)/OCTAVE
A=.1E-04, B=.1E-03, C=.1E-02, D=.1E-01, E=.100, F=1.00, G=10.0
```

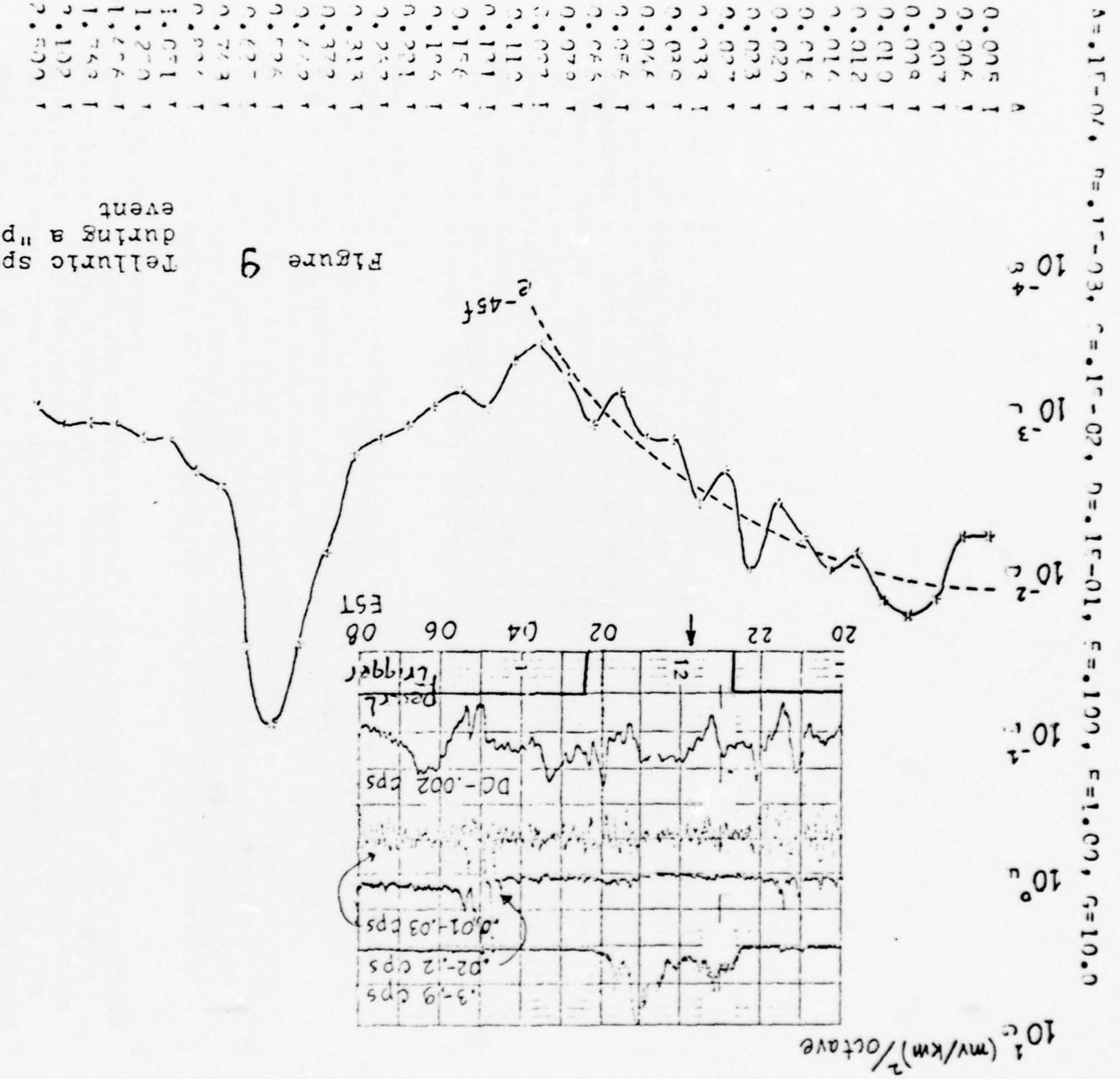
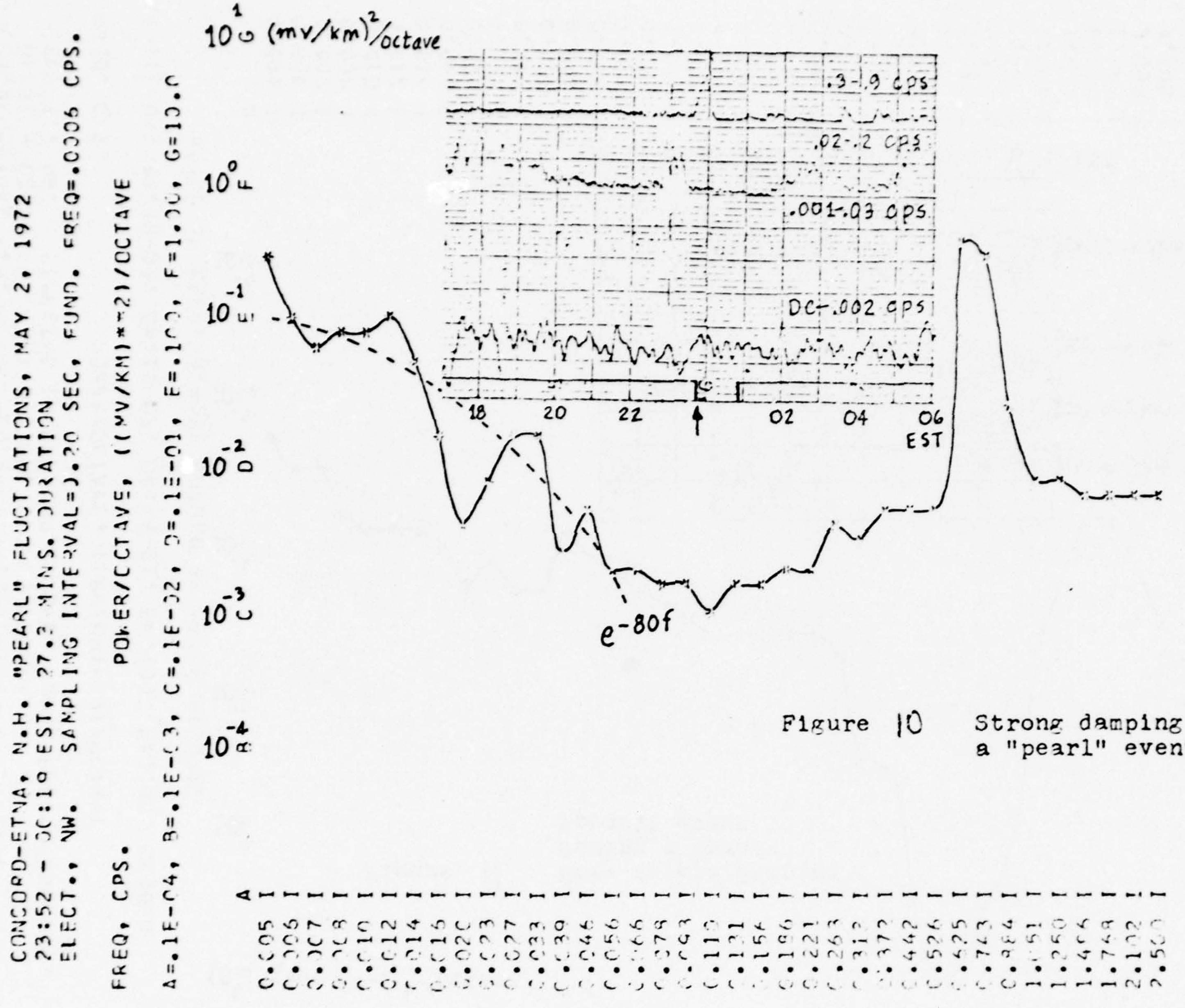


Figure 9 Telluric spectrum during a "pearl" event



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CONCORD-ETNA, N.H. "PEARL" FLUCTUATIONS, MAY 2, 1972
23:52 - 00:19 EST, 27.3 MINS. DURATION
ELECT., NW.     SAMPLING INTERVAL=0.20 SEC, FUND. FREQ=.0006 CPS.

FREQ, CPS.            POWER/OCTAVE, ((MV/KM)**2)/OCTAVE

A=.1E-04, B=.1E-03, C=.1E-02, D=.1E-01, E=.100, F=1.00, G=10.0
```

Figure 10 Strong damping during a "pearl" event

```
CONCORD-ETNA, N.H. PEARL FLUCTUATIONS, SEPTEMBER 22, 1971
  01:51 - 02:19 EST,   27.3 MINS. SAMPLE LENGTH
  ELECT., NW.    SAMPLING INTERVAL=0.20 SEC, FUND. FREQ=.0006 CPS.

FREQ, CPS.              POWER/OCTAVE, ((MV/KM)**2)/OCTAVE

A=.1E-04, B=.1E-03, C=.1E-02, D=.1E-01, E=.100, F=1.00, G=10.0

          POINT AT FREQ= 0.5255 SHOULD BE ABOVE FIGURE.
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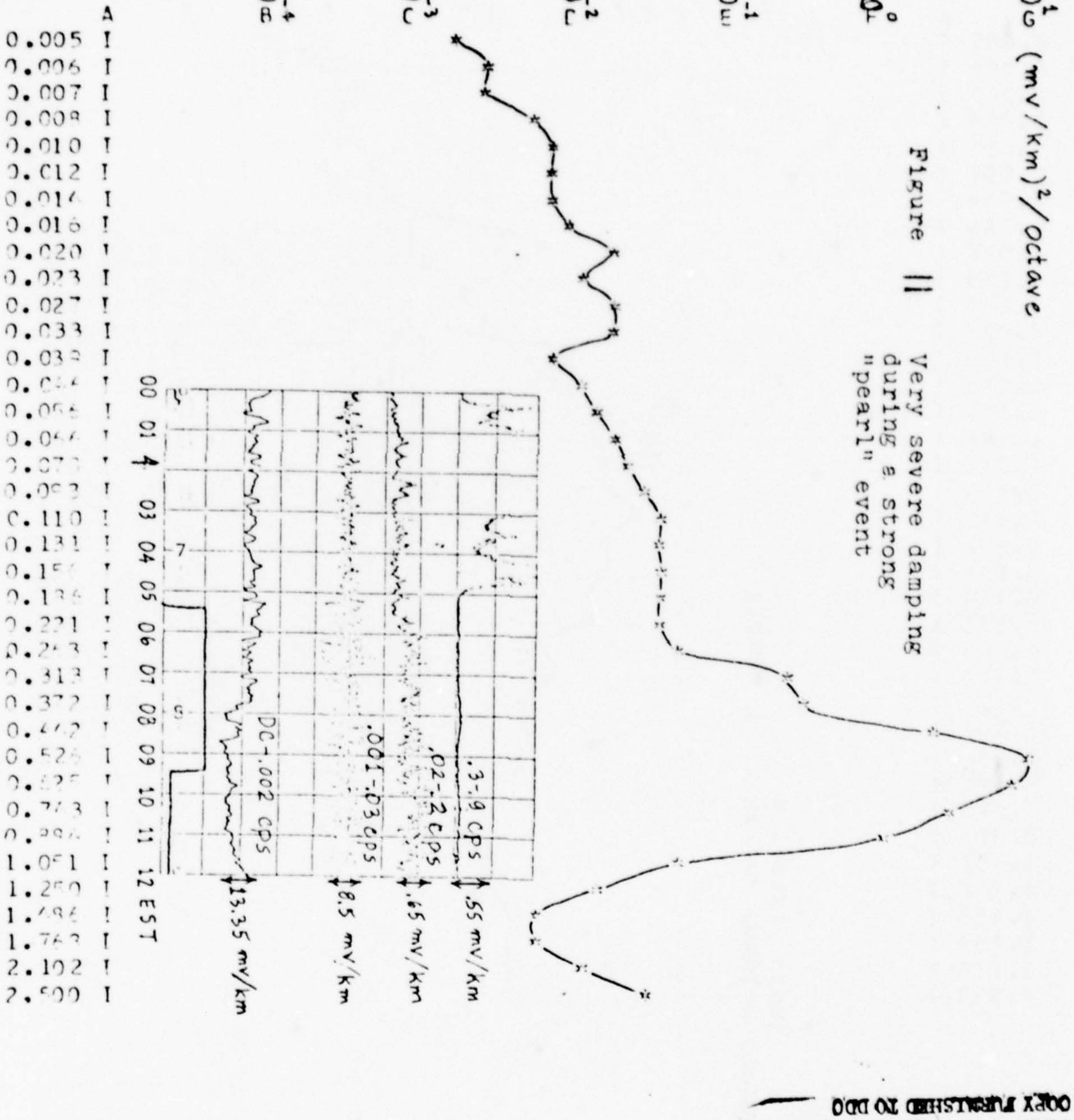


Figure 11 Very severe damping during a strong "pearl" event

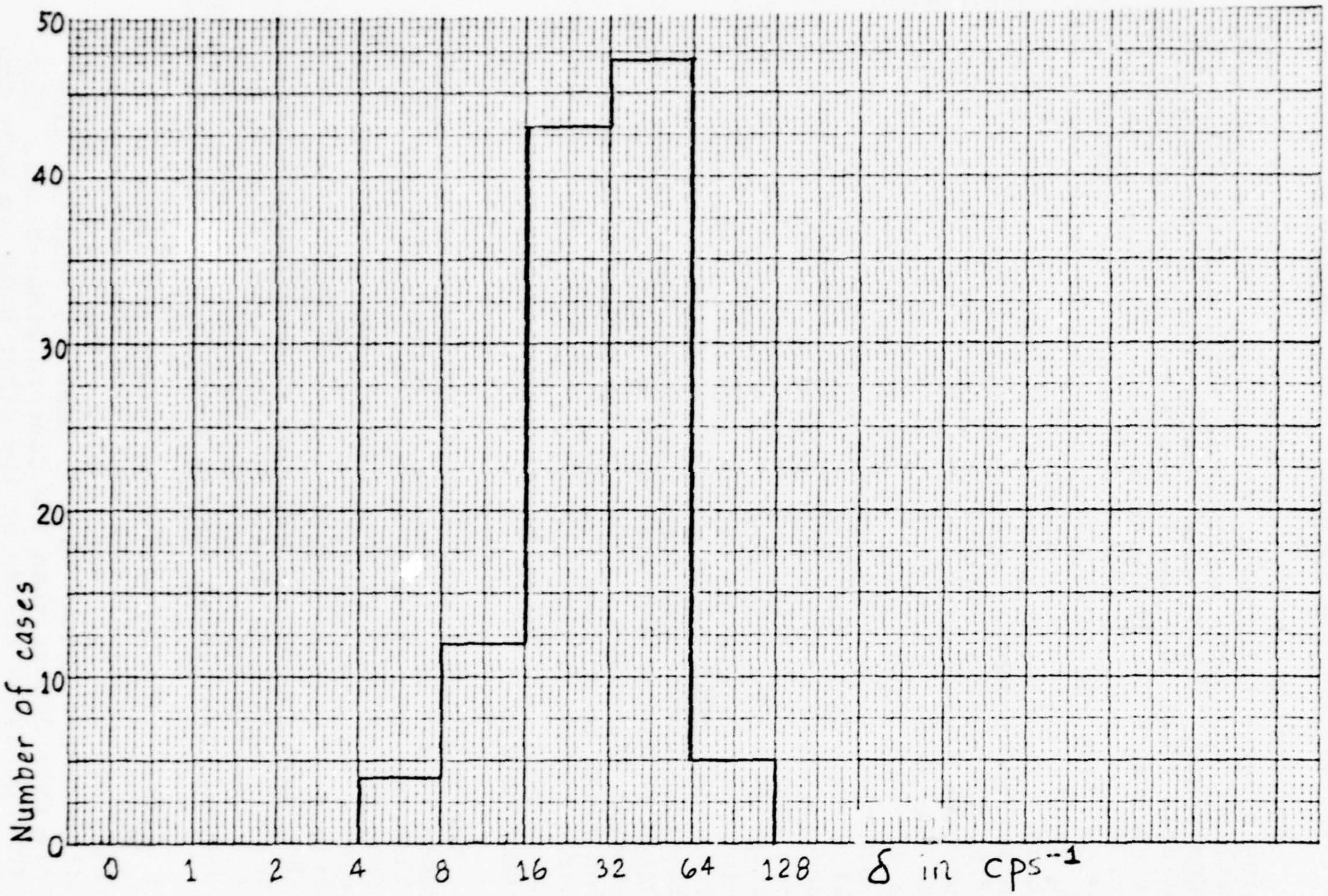


Figure 12 Histogram of attenuation factors δ from New Hampshire spectra

II. Crustal Magnetotelluric Studies

A. New England Magnetotelluric Survey

Studies of the magnetotelluric response of New England using a large telluric array and very long periods were initiated under NSF sponsorship and completed under ONR sponsorship. The original concept was to use long contiguous telluric lines in order to avoid the effect of local geologic variations on the telluric signals and to go to longer periods in order to better understand ocean boundary effects and to allow the interpretations to penetrate deeper into the mantle. Figure 13 shows the telluric array that was set up. The dipoles shown were leased all-metal telephone lines. The magnetic data was obtained from recordings made off of the Weston Geophysical Observatory three component flux gate magnetometer, supplemented with standard recordings from the magnetic observatory at Fredericksburg, Maryland. The data was hand digitized off of the records for analysis. In order to lessen the dynamic range limitations of the analog recording, the data was electronically filtered into three separate bands before recording. These bands were DC-40 hour, DC-30 min, and 30 min-1 min periods. Despite this prefiltering the errors introduced by digitizing the analog records was one of the principal noise sources. Another important noise source was drift on the low pass telluric channels due either to electrode potential variations (buried Pb electrodes were used) or amplifier drift. Paul Kasameyer (Kasameyer, 1974) in his thesis study went to great pains to analyse the effect of such noise on the impedance estimates and this effort represents an important contribution, but we will not report on it here in any further detail.

The magnetotelluric impedances obtained are shown in figures 14 and 15. A remarkable feature of these results is that the long dipoles and low frequencies did not free us from the effects of the crustal geology and this is an important warning concerning the dangers of simple interpretations of magnetotelluric data. The N-S lines such as Rut-Ben gave impedances slightly less than the predictions of Swift's mantle conductivity model (Madden and Swift, 1969). The E-W lines, however, were dramatically different. The Concord-Georgetown line gives very high impedance values. This is more or less expected due to the ocean-continent edge effect. The Concord-Etna values are lower as one would expect being further away from the ocean continent boundary but the fall off is slow. The Rutland-Etna and Brattleboro-Bennington values, however, jump up again and are even higher than the Concord Etna-values. The Jaffre-Bennington values on the other hand are very low. These results are all strongly correlated with the crustal geology. The Jaffre-Bennington line lies mostly in the Littleton formation which includes a great deal of pyritic-

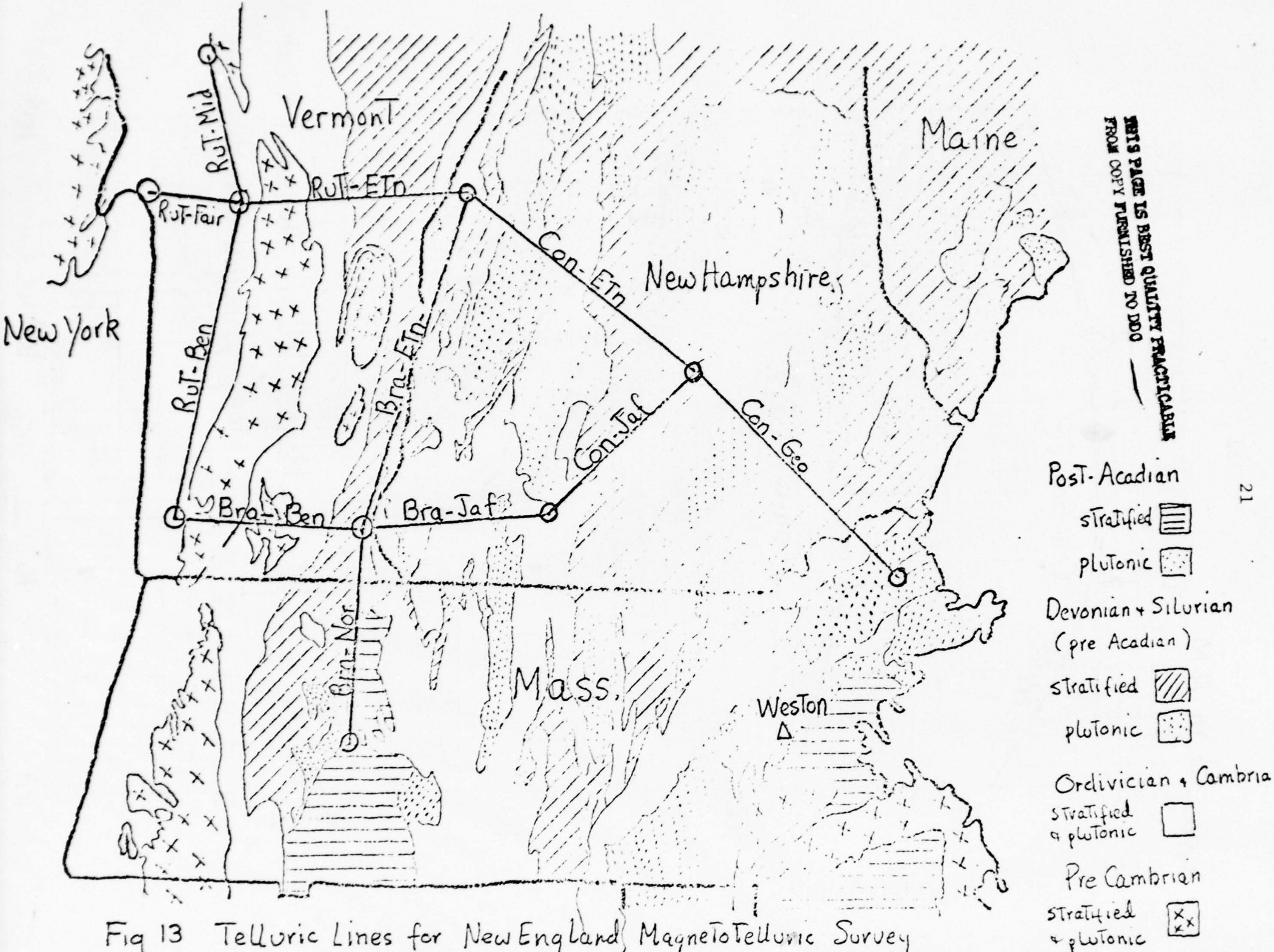


Fig 13 Telluric Lines for New England MagnetoTelluric Survey

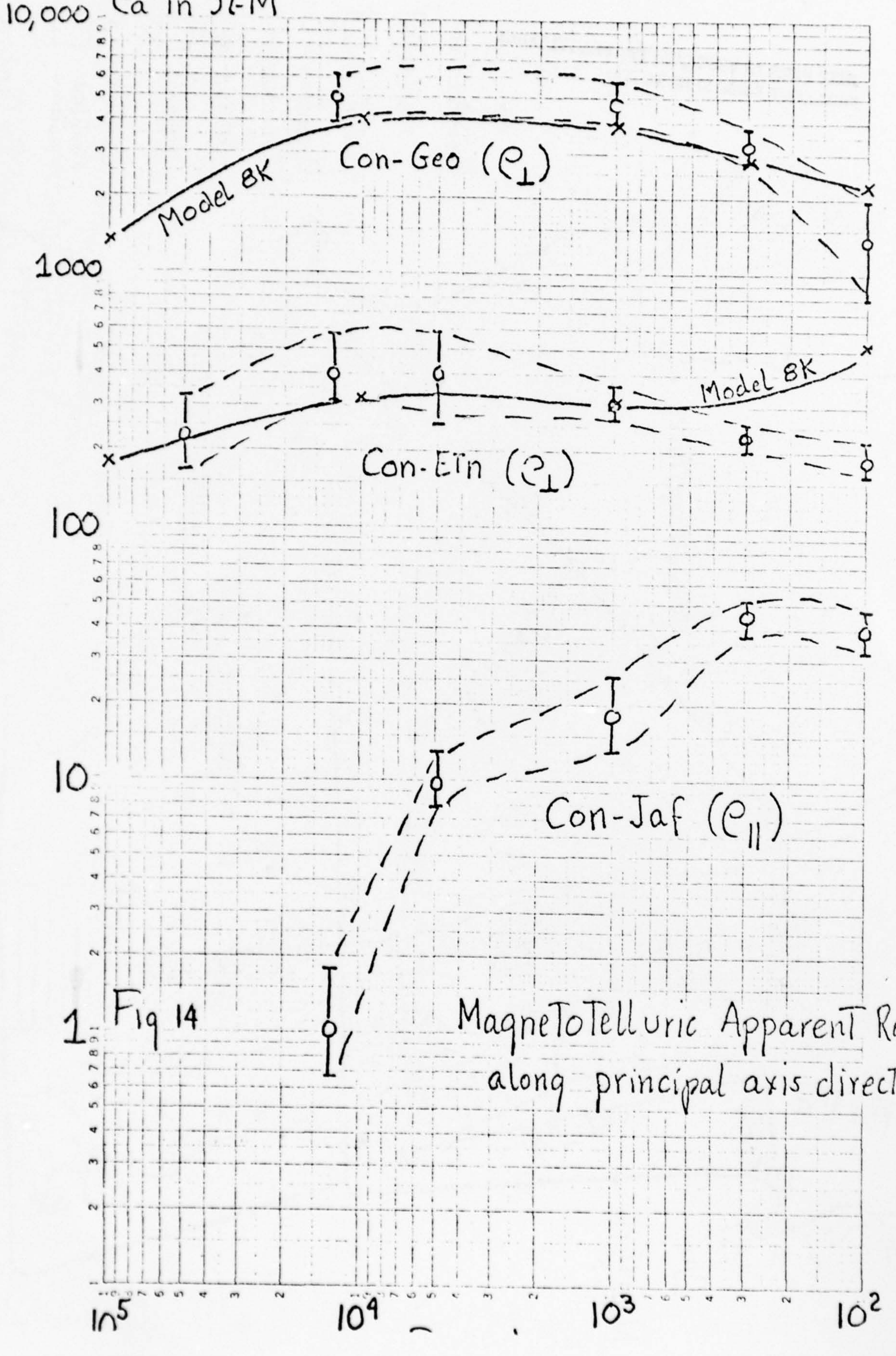


Fig 14

MagnetoTelluric Apparent Resistivitie
along principal axis directions

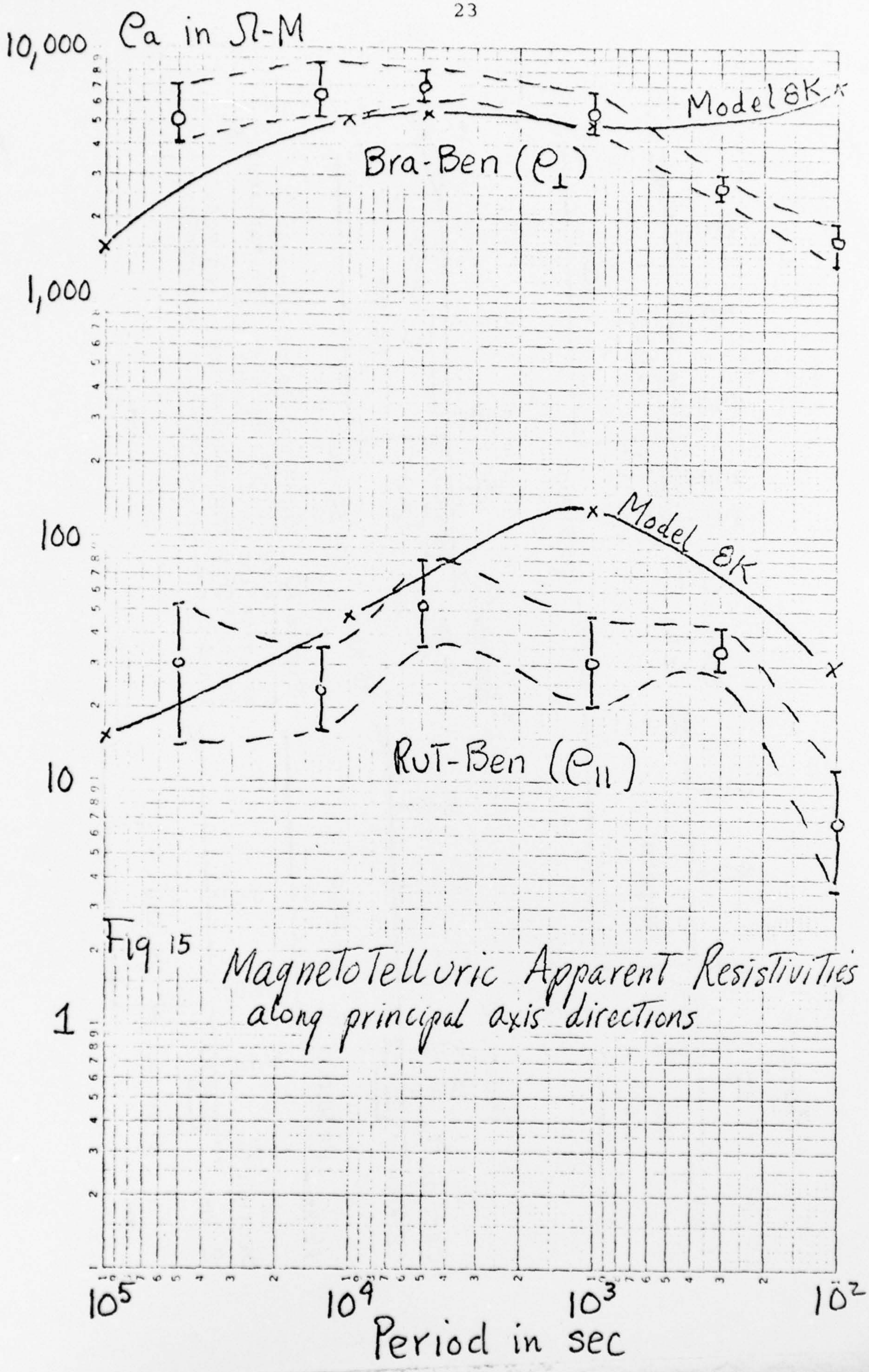


Fig 15 MagnetoTelluric Apparent Resistivities along principal axis directions

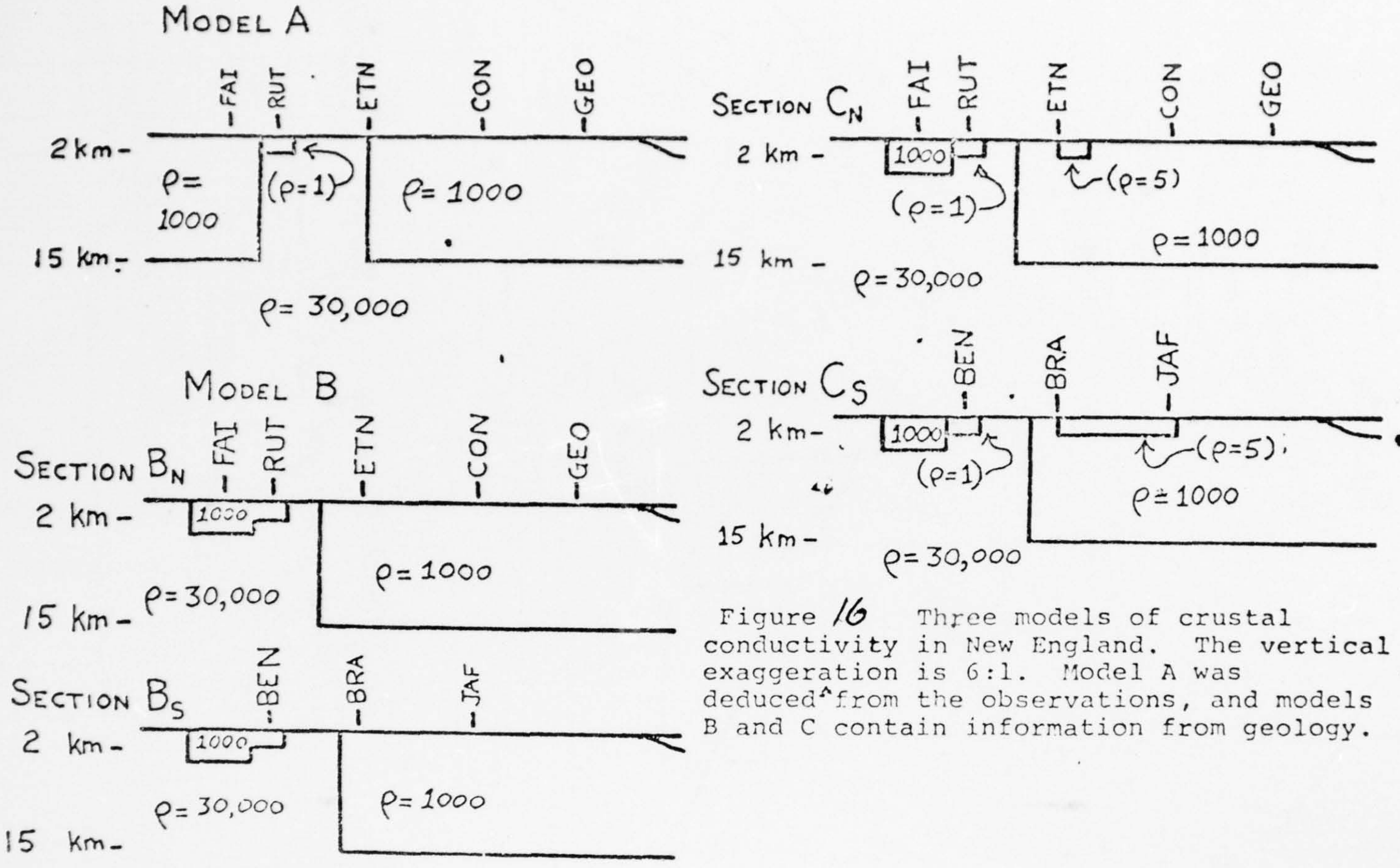


Figure 16 Three models of crustal conductivity in New England. The vertical exaggeration is 6:1. Model A was deduced from the observations, and models B and C contain information from geology.

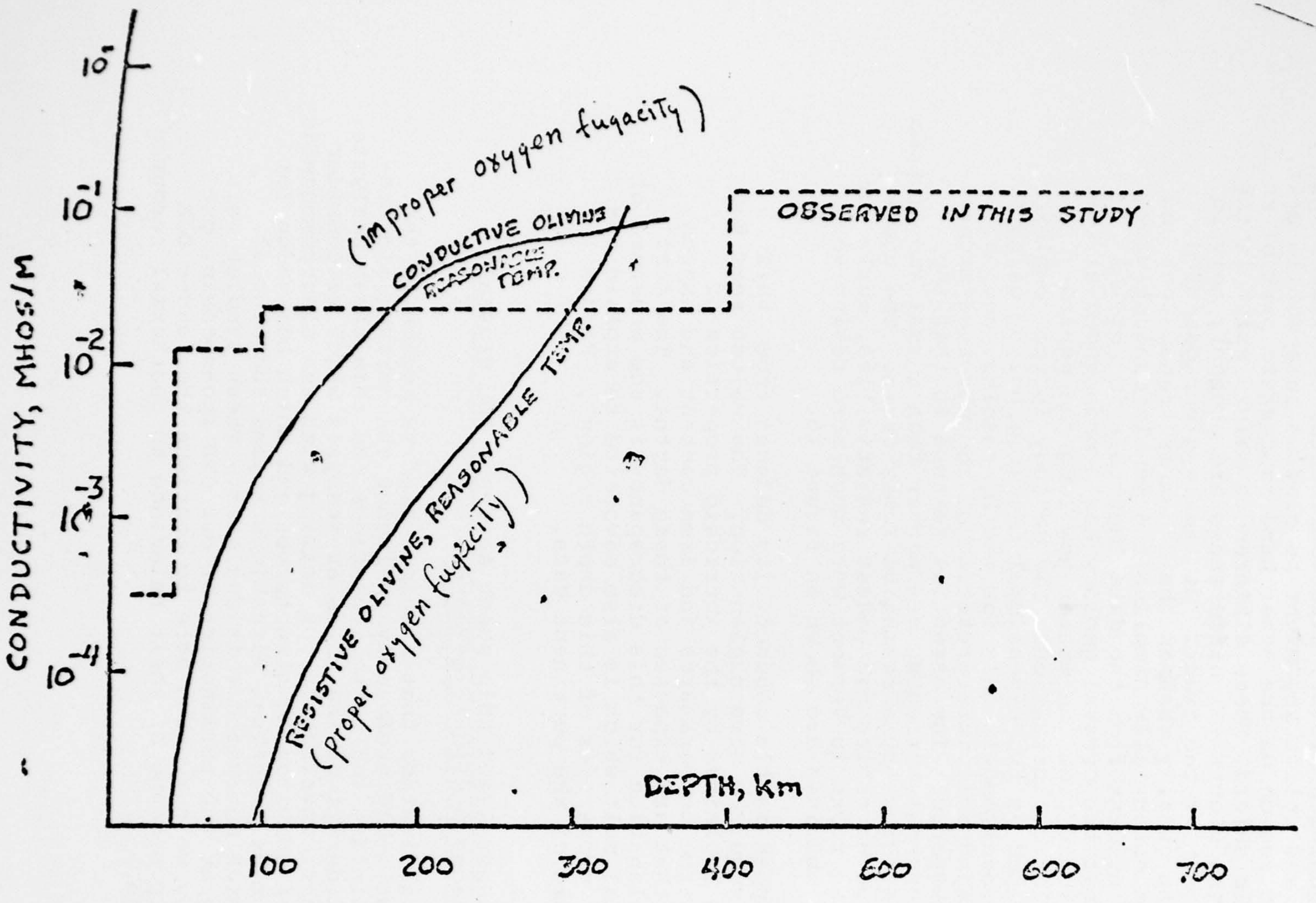


Figure 17 Two conductivity profiles deduced from gectherms and measurements of olivine conductivity.

graphitic shists which are very conductive.

The New Hampshire region is believed to have undergone a complex geologic history with continental collisions and subduction and uplift and might be classed as a mobile belt. The Vermont region on the other hand represents part of an older stable shield. These differences mainly exist in the crust and the electrical differences are probably only in the upper part of the crust. At the long periods used, however, one usually assumes the crust is transparent and that we are essentially sampling the mantle conductivity. It is very evident from the data that this is not the case and that the crustal geology has a pronounced effect on the telluric field no matter how long the period of the telluric fluctuations. The geology is too complex to be modelled as two dimensional features, but by using two dimensional models only for the $E_{\perp}$ results, one can obtain a reasonable interpretation of the observed magnetotelluric response. The essential feature is that the east-west crustal currents are higher than normal and trapped in the upper crust by a resistive lower crust. The upper crust of New Hampshire had modest resistivities, while the pre Cambrian rocks in Vermont were much more resistive. The models obtained are shown in figure 16.

The upper mantle conductivity deduced from this data also requires some explanation. The values seem too high to be explained by the intrinsic properties of olivine at the temperatures and iron content and oxygen pressures that are expected at these depths. The most likely explanation for this discrepancy is the presence of some partial melt which is also advocated to explain the mechanical properties of this depth region . Figure 17 reviews some of the pertinent data.

B. Generalized thin sheet analysis for crustal magnetotelluric effects

The realization that a thin resistive region in the lower crust could profoundly influence the surface electromagnetic fields, led us to reconsider the thin sheet analysis. These considerations led us to an analysis which we consider an important contribution for dealing with the electromagnetic response of complicated structures, and which has value for analysing many practical situations beyond the crustal studies which motivated this analysis. These studies were incomplete at the termination of our ONR sponsorship, but fortunately we have been able to continue them under DOE sponsorship because of their relevance to geothermal resource exploration.

Price (1949) had introduced to the geoelectric literature a useful approximation to model the effects of variable surface conductivities on low frequency electromagnetic fields. In his original analysis, the underlying regions were treated as insulators, but later modifications modelled the mantle conductivity by including a perfect conductor at some depth below the thin sheet. An excellent review of these concepts which includes practical methods of carrying out the calculations is given by Bullard and Parker (Bullard and Parker, 1970).

Treating the lower crust and upper mantle as a perfect insulator allows one to describe the magnetic field as the gradient of a simple potential field, which simplifies the numerical calculations, but also eliminates one possible electromagnetic mode. This mode is the mode responsible for current interchange between the mantle and the upper crust. The lower crust is usually a poor conductor, but not poor enough to completely eliminate current interchange, and therefore plays an important role in the determination of the current levels that exist in the upper crust. Modelling the effect of the lower crust is thus as important as modelling the effect of the upper crust. Since for many problems the lower crust can also be considered as thin, one should be able to incorporate its influence in a thin sheet analysis. Such an analysis we call a generalized thin sheet analysis. It consists of two extensions of Price's original analysis. First the boundary conditions are generalized to allow the thin sheet to contact a layered medium of arbitrary resistivity. This generalization is not a basic modification of Price's analysis but it does allow both electromagnetic modes to operate. One can model some of the effects of a resistive lower crust by including such a crust in the layered medium below the thin sheet.

When the electric and magnetic fields are essentially horizontal we have from Maxwell's equations for the change in E and H across a thin sheet

$$\Delta E_s = -i\mu\omega\Delta z\hat{\imath}_z x H_s \qquad \text{1a}$$

$$\Delta H_s = -\sigma\Delta z\hat{\imath}_z x E_s \qquad \text{1b}$$

Since $E_s/H_s = (-i\mu\omega/\sigma_{ap})^{1/2}$ the relative changes in E_s and H_s are given as

$$\Delta E_s/E_s \simeq (-i\mu\omega\sigma_{ap})^{1/2}\Delta z \qquad \text{2a}$$

$$H_s/H_s \quad \frac{\sigma}{\sigma_{ap}}(-i\mu\omega\sigma_{ap})^{1/2}\Delta z \qquad \text{2b}$$

When the layer is thin compared to the depth of penetration of the wave in the mantle, $\Delta E_s/E_s$ is small, but for a conductive surface layer $\Delta H_s/H_s$ can be appreciable. Thus Price set up his analysis assuming ΔE_s was zero. He also assumed the layer was underlain by a perfect insulator which allowed him to describe the magnetic field outside the thin sheet as the gradient of a potential. This is not a necessary part of Price's analysis and one can treat the case of a general layered medium under the thin sheet.

If H_s^L and E_s^L are the fields at the bottom of the thin sheet and Y^L the conductance of the layered medium below, we have

$$H_s^L = Y^L E_s^L \qquad 3a$$

At the surface all the wavelengths other than the source wavelength are outgoing and therefore we again have a known relationship between H and E

$$H_s = Y'^u E_s + H_s^o \qquad 3b$$

Here Y'^u is the H·E relationship for upgoing waves in the air above the thin sheet, but exclusive of the source wavelength and H_s^o is the field at the source wavelength.

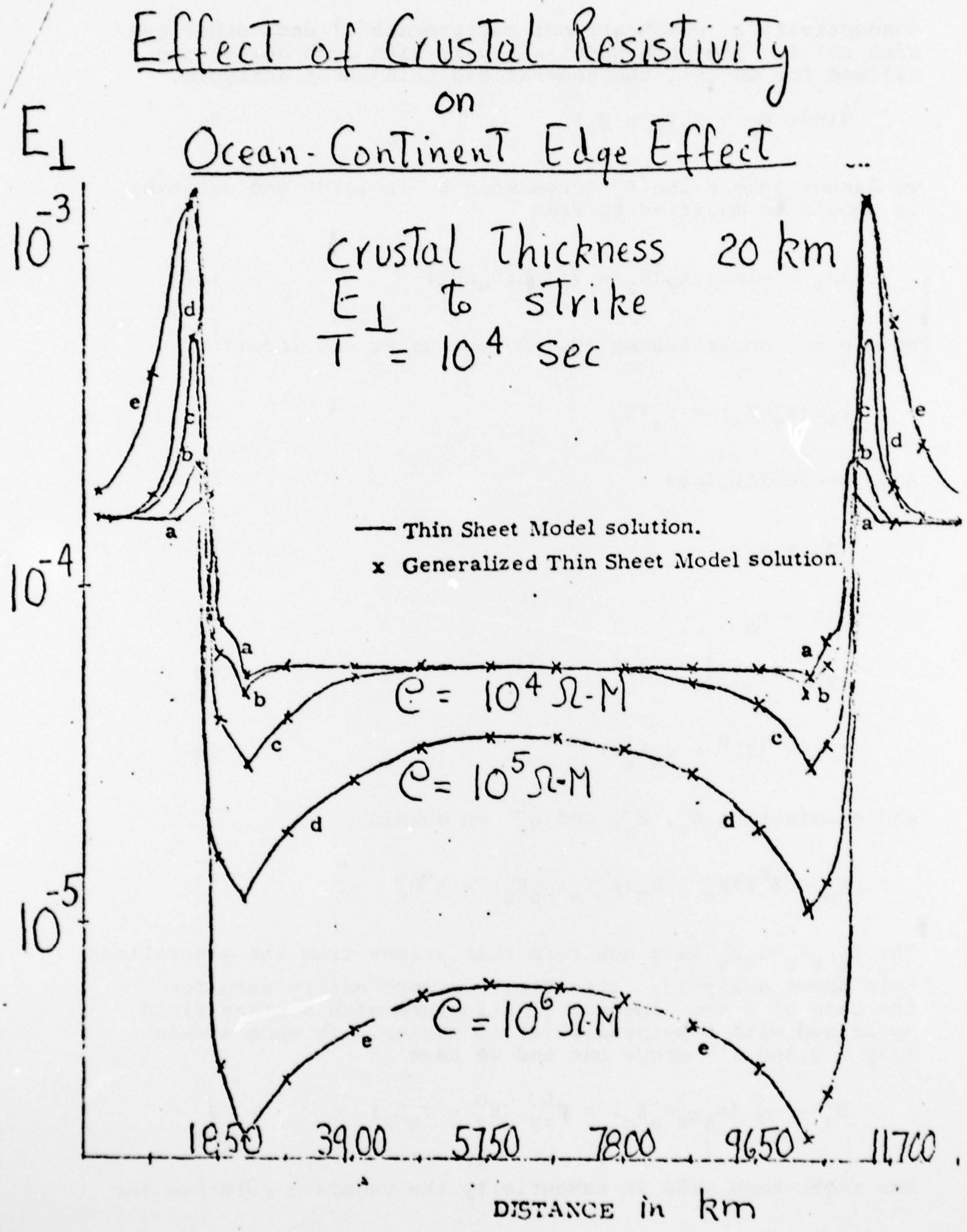
Using (1) and (3) and assuming $\Delta E_s = 0$, we have

$$(Y^L - Y'^u)E_s + \sigma \Delta z i_z x E_s = H_s^o \qquad 4$$

Y and σ must be treated as operators and equation (4) can be solved either in the space domain or in the wavenumber domain.

If the layered medium below the thin sheet contains a resistive layer and if there are conductivity contrasts in the thin sheet, the resistive layer strongly influences the resulting electric field distribution as shown in figure 18. Obviously modelling the resistivity variations is as important as modelling the conductivity variations and since the resistive layers can also often be considered thin one should be able to incorporate it into a thin layer analysis.

The presence of conducting layers and resistive layers overlying each other in a thin sheet makes the sheet highly anisotropic with a vertical resistivity ρ and a horizontal



Effect of Crustal Resistivity on Ocean-Continent Edge Effect

Fig 18

conductivity σ which are not reciprocals of each other and with $\rho\sigma >> 1$. The thin sheet analysis with such anisotropy allowed for we call the generalized thin sheet analysis.

Since $E_z = \rho(\nabla_s \times H_s)$ $\qquad$ 5

we cannot ignore the E_z terms when ρ is large and equation 1a should be modified to read

$$\Delta E_s = -i\mu\omega\Delta z \hat{1}_z x H_z + \nabla_s(\rho\Delta z \nabla_s x H_s) \tag{1a.1}$$

We can no longer assume $\Delta E_s = 0$ but using the identity

$$\nabla_s x (1_z x E_s) = \nabla_s \cdot E_s \tag{6a}$$

and the definitions

$$\sigma\Delta z \equiv \sigma_s \tag{6b}$$

$$\rho\Delta z \equiv \rho_s \tag{6c}$$

$$(Y^L)^{-1} \equiv Z^L \tag{6d}$$

$$Y^* = (Y'^u - \sigma_s i_z x) \tag{6e}$$

and eliminating H_s, H_s^L, and E_s^L we obtain

$$E_s - Z^L Y^* E_s - \nabla_s(\rho_s \nabla_s \cdot \sigma_s E_s) = Z^L H_s^o \tag{7}$$

The $\nabla_s \rho_s \nabla_s \cdot \sigma_s E_s$ is a new term that arises from the generalized thin sheet analysis. Its effect is most easily seen for the case of a two dimensional structure with a plane field polarized with E perpendicular to strike. In such a case $\partial/\partial y = 0$ and Y'^u drops out and we have

$$E_x - \frac{\partial}{\partial x}\left(\rho_s \frac{\partial}{\partial x} \sigma_s E_x\right) = Z_{xy}^L \left(H_y^o - \sigma_s E_x\right) \tag{8}$$

The right hand side is essentially the Cagniard solution for a layered medium with the same conductivities as the local structure, E_x^o. For a uniform region where ρ_s and σ_s are constant we can therefore write

$$E_x - \rho_s \sigma_s \frac{\partial}{\partial x^2} E_x = E_x^o \qquad 9$$

$$\text{with solutions } E_x = E_{xo} + A_\pm e^{\pm \frac{x}{\sqrt{\rho_s \sigma_s}}} \qquad 10$$

Such solutions can be patched together to represent a sequence of zones by maintaining continuity of $\sigma_s E_x$ and continuity of $\rho_s \sigma_s (\partial E_x/\partial x)$ at each zone boundary. The $\sigma_s E_x$ continuity gives us continuity of H_y and the $\rho_s \sigma_s (\partial E_x/\partial x)$ continuity gives us continuity of E_z across the contact. Such solutions show the behavior seen in figure 18. On the conductive side the $E_\perp$ field drops to very low values at the contact and recovers exponentially away from the contact with an adjustment distance given by $(\rho_s \sigma_s)^{1/2}$. The field on the resistive side rises at the contact and falls off to normal values away from the contact with its own adjustment distance. When the σ_s contrast is large there is a modification to the adjustment distance, but this is usually not very significant.

The $E_\parallel$ solution in this example is not influenced by the ρ_s term, but for a finite wavelength source, it too is considerably modified, although the boundary effects are less dramatic than those for $E_\perp$.

The magnitude of $(\rho_s \sigma_s)^{1/2}$ for crustal environments is often 100 km or more and therefore one cannot interpret magnetotelluric results without taking into account the resistivity structures of a considerable region around the measurement sites.

These extensions of the thin sheet analysis are also important if one wishes to attack three dimensional modelling by cascading thin sheets together. It is necessary, however, to develop efficient computational methods as the modelling must include the effects of a large region around the point of interest.

III. Project Personnel and Publications

Principal Investigator

Theodore R. Madden	Professor in Geophysics

Student Investigators	Degrees received on ONR sponsored research	
F. Navato	Ph.D.	1973
P. Kasameyer	Ph.D.	1974
R. Ranganayaki	Ph.D.	1978
A. Figueroa		

For the entire seventeen year period of ONR sponsorship nineteen students were involved in the research work and 14 degrees (10 Ph.D., 3 M.S., and 1 B.S.) were granted on thesis work developed in these studies.

Publications

ONR Reports

Geoelectric and Geomagnetic Studies, final report Nonr-1841(75), 1961-1970, 1971.

Transmission systems and network analogies to geophysical forward and inverse problems, 1972.

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Ranganayaki, R.P., 1978. Generalized thin sheet approximation for magnetotelluric modelling, Ph.D. thesis, Department of Earth and Planetary Science, M.I.T.

Ranganayaki, R.P., and T.R. Madden, 1979. Generalized thin sheet analysis in magnetotellurics: an extension of Price's analysis, submitted to Geophysical Journal of R.A.S.

In addition one thesis study on the Plasmapause Stability is still in progress.

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The final six years of seventeen years of ONR sponsored research work at MIT in geoelectricity and geomagnetism is reviewed. The specific areas included magnetospheric studies and crustal magnetotelluric studies. The magnetospheric studies involved Alfven wave damping in the plasmasphere and its effect on the ULF background noise spectrum. The magnetotelluric studies included a low frequency magnetotelluric survey of New England and a thin sheet analysis that incorporates the effects

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cont. of a resistive crust on the telluric fields. A listing of personnel and a bibliography is also included.