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DEEP ELECTRICAL STUDIES ON THE SNAKE RIVER PLAIN

Final Report

01 May 1978 - 31 July 1979

Report No. DOE/ET/28422-1

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1. Introduction

During May and June, 1978, nine magnetometers were operated in south central Idaho to record small variations in the Earth's magnetic field. Each magnetometer recorded three components of the field, X (positive increase to magnetic north), Y (positive increase to magnetic east), and Z (positive increase downward). Persistent correlations between these components were used to detect areas of unusually high electrical conductivity near each station.

Magnetic variations recorded near the Earth's surface, both periodic variations and magnetic storms, are primarily due to currents flowing in the ionosphere and magnetosphere at least 60 km above the surface. These external fields induce eddy currents in the conducting Earth giving rise to an internal field. The internal field tends to enhance the horizontal variations of the external field and to suppress the vertical field. The external fields are usually uniform for hundreds of kilometers of horizontal extent in geomagnetic mid-latitudes. Magnetic observatories located over uniform conductivity structure will record very similar horizontal variations and weak vertical variations. Variations of electrical conductivity with depth do not change this phenomenon. Lateral changes in conductivity will produce anomalous current concentrations whose magnetic effects are superimposed on the normal field variations. The anomalous vertical variations are particularly notable since normal vertical field variations are small. If magnetic variations have a significant vertical component, then either the external source field is not uniform or anomalous currents are flowing through conductive bodies near the station. A network of recording magnetometers pro-

vides a way to detect and locate lateral heterogeneities in electrical conductivity.

Figure 1 illustrates that the vertical and horizontal variations due to a current in a conductor are related. The ratio of their amplitudes gives the tangent of the angle of the anomalous magnetic field at the recording station. An induction vector may be defined as having the direction in which vertical variations show a maximum correlation with horizontal variations. The vector will be perpendicular to the strike of a long conductivity anomaly. Its amplitude will be the ratio of the vertical to the horizontal variations.

Bodies of unusually high electrical conductivity in the crust may be due to composition, presence of ground water carrying ions in rock with connected porosity, or possibly elevated temperatures. All of these may occur in areas with potential for geothermal power generation. The most obvious example of a lateral increase in conductivity occurs at the seacoast. The elevation of the asthenosphere under the ocean from continental levels may add to the increase in conductivity going from crustal rocks to seawater to create the "coast effect," a strong vertical magnetic field anomaly associated with horizontal fluctuations perpendicular to the coastline. The induction vector at stations near the ocean is large and points out to sea. The coast effect has not been detected more than 1000 km inland on old stable continental shields or more than 500 km inland in tectonic areas such as the western U.S. The coast effect is not expected to bias magnetic observations in Idaho.

A long history of volcanic activity extending to recent times in the Snake River Plain of Idaho suggests the possibility of geothermal

Figure 1. Relation between current in a conductor, horizontal and vertical components of magnetic variations, and frequency. From Hyndman and Cochrane(1971).

heat sources and related electrical conductivity anomalies. In this study nine magnetometers were available to cover the area between Idaho Falls and Twin Falls. The geology of this area has been the subject of a recent conference(Greeley and King, 1977). Gravity and aeromagnetic surveys are discussed by Mabey(1978), and some elctrical soundings are presented by Zohdy and Stanley(1973) and Stanley et al.(1977). The Snake River Plain between Idaho Falls and Yellowstone National Park is also of interest for geothermal heat, and is the subject of another U.S. Geological Survey geomagnetic variation study.

It is tempting to assume that a long electrical conductivity anomaly may be found along the Snake River Plain by analogy to the Rio Grande Rift and the Kenya Rift Valley. In that case lines of magnetometers across the Snake River Plain would be the most efficient way to delineate the anomaly. However it was decided to place the magnetometers in as regular a pattern as possible over the area of interest since no geophysical data had yet suggested a linear anomaly along the Snake River Plain. In fact gravity and aeromagnetic trends(Mabey, 1978) and volcanic fissures(Greeley and King, 1977) are transverse to the axis of the Snake River Plain. Instrument locations are shown in Figure 2 and listed in Table 1.

Figure 2. Location of the magnetometer stations in south-central Idaho.

TABLE 1
STATION LOCATIONS

Symbol	Station Name	Latitude	Longitude
NRF	reactor facility	43.68°N	112.85°W
COM	Craters of the Moon (National Monument)	43.48°N	113.55°W
SIC	Shoshone Ice Cave	43.14°N	114.35°W
HHA	Hell's Half Acre	43.55°N	112.44°W
DTR	Dotson's Ranch	43.13°N	112.88°W
CTR	center	42.95°N	113.61°W
TWF	Twin Falls	42.66°N	114.28°W
FFA	Frazier Farm	42.79°N	112.40°W
RR1	Raft River 1	42.28°N	113.28°W

2. Instruments

Geomagnetic field variations were detected by an EDA FM-100B fluxgate magnetometer, and recorded digitally by a Sea Data 610 digital recorder on magnetic tape cassettes. The digitizer operated at a precision of 0.24 gamma per digital count. All three channels were recorded simultaneously with a sampling interval of 8.0 seconds. Time was provided by a quartz oscillator with a cumulative drift of a few seconds per week. Each cassette holds up to 21 days of data.

The fluxgate magnetometer responds to temperature variations with a sensitivity of approximately 1 gamma per degree Celsius. The magnetometer is buried to reduce the effects of temperature variation and tilt. The magnetometer sensor is mounted on a small support embedded in a concrete base poured in the bottom of a hole, and then covered with a plastic pail. The hole is then filled with soil. After initial settling no drift in the data due to tilt was observed on plots of recorded magnetic field components. After burial, temperature drift is expected to have a time constant of the order of several hours.

The magnetometer circuitry, recording electronics, and batteries are also buried in a watertight case at a small distance from the magnetometer sensor. Such an installation is almost immune from the effects of weather and can operate unattended for weeks at a time. Cassette tapes may be replaced without approaching the magnetometer sensor. The equipment was built by the Branch of Electromagnetism and Geomagnetism of the U.S. Geological Survey.

An attempt was made to measure telluric currents at four of the stations. Only a few hours of data were obtained due to an oscillation in the active long-period filter of the telluric circuit. This prevented magnetotelluric analysis at these stations which would have allowed

quantitative estimation of the conductivity under the stations.

3. Data Analysis Techniques

Data analysis in this study follows the Fourier transform methods developed by Everett and Hyndman (1967), Cochrane and Hyndman (1970), Hyndman and Cochrane (1971), and Edwards, Law, and White (1971), which are particularly suitable for interpreting data at a single station. The goal is to determine a correlation between observed horizontal and vertical variations, which indicates conductivity anomalies. The alternative is to treat all the stations as an array. The limited number of stations used in this study and the comparatively wide spacing compared to the size of possible conductivity anomalies makes array processing inappropriate.

Several weeks of data were recorded at each station, with only a few short breaks when tapes were changed. Plots of all the data were inspected and magnetic storms were selected for further analysis. At each station each storm was divided into a number of record sections or time series of 1024 points for further analysis. Each time series had a length of 8192 seconds or 2.275 hours at the 8.0 second sampling interval. A straight line was fitted to the mean value of each 10% end section of the time series, and that trend subtracted from the time series. The straight line was fitted to the 10% end sections to avoid an incorrect trend removal should an impulse occur just at the end of the time series. Fitting a straight line by least squares is also suitable. Any remaining mean value was then subtracted from the time series. Then a "cosine bell" taper (Kanasewich, 1975) was applied to each 10% end section of the time series to eliminate discontinuities at each end. These preliminary modifications of the time series were found by experiment to be essential for the correct estimate of spectral

parameters.

At this point the power spectrum of the X and Z components of the time series were automatically plotted on the consol of the computer to give an indication of data quality.

If x_n are the values of the time series representing the X field,

$$x_n = x(n \Delta t) \quad , n = 0, 1, \dots, N-1$$

where Δt is the sampling interval, then the discrete fourier transform is

$$X_k = \sum_{n=0}^{N-1} x_n \exp(-i 2\pi \frac{kn}{N})$$

where the first point is at $n = 0$, there are N points in the time series, and $k = 0, 1, 2, \dots, N/2$. The corresponding frequency values are

$$f_k = \frac{k}{T} = \frac{k}{N\Delta t}$$

Frequency components are equally spaced on the frequency axis with a separation of $1/N\Delta t$ hertz. The related power spectrum is

$$G_{xx}(f_k) = \frac{2\Delta t}{N} X_k^* X_k$$

X_k is a complex number and X_k^* is its conjugate. G_{xx} must be positive real number. In our case the Fourier transform and power spectrum is defined over the period range 8192 seconds to 32 seconds.

The process of digitizing introduces a random signal of 0.12 gamma peak amplitude into the actual signal. It was found in this case that the resulting power level due to the digitizing alone was near $0.7 \gamma^2/\text{Hz}$ at all frequencies. Spectral estimates were regarded as unreliable when

the power spectral value at that frequency component fell below twice this power level. The Z field is always weaker than X or Y so this component sets the limit on the highest frequency with usable data. In this study it was rare to find a Z field variation with power above the digital noise level at frequencies above 6 mHz (periods less than 160 seconds). This figure depends on the source field and conductivity structure of the earth near the instrument.

Because of the limited frequency range of the significant power of the Z field, an "S7-S9" filter (Kanamori, 1971) was applied to the data. This is a running average of 7 points (all points weighed equally) followed by a running average of 9 points. The first zero of the result is at $9 \times \Delta t = 9 \times 8 = 72$ seconds, and spectral values with periods less than 72 seconds are severely reduced (no point exceeds 0.033 times its original value). No phase shift is introduced. The half power point is at 200 seconds. Every fourth point of the time series may be now selected for further analysis. This sequence of filtering and selection of data can considerably reduce data storage requirements and computation time without loss of significant information. This processing is also applied to the X and Y time series.

The central process in data analysis is estimation of the transfer function (A,B) relating the horizontal components to the vertical component:

$$Z_k = A X_k + B Y_k$$

where X_k is the discrete fourier transform of the continuous field variation $X(t)$ and k is the index of the frequency component. (A,B) may have a different value at each frequency. If the power spectrum is defined as

$$G_{xx}(fk) = \frac{2\Delta t}{N} X_k^* X_k$$

and the cross spectrum as

$$G_{xy}(fk) = \frac{2\Delta t}{N} X_k^* Y_k$$

then the transfer function is estimated by

$$A = \frac{\langle G_{zx} \rangle \langle G_{yy} \rangle - \langle G_{zy} \rangle \langle G_{yx} \rangle}{\langle G_{xx} \rangle \langle G_{yy} \rangle - \langle G_{xy} \rangle \langle G_{yx} \rangle}$$

$$B = \frac{\langle G_{zy} \rangle \langle G_{xx} \rangle - \langle G_{zx} \rangle \langle G_{xy} \rangle}{\langle G_{xx} \rangle \langle G_{yy} \rangle - \langle G_{xy} \rangle \langle G_{yx} \rangle}$$

where $\langle \rangle$ indicates an ensemble average of the indicated quantity over a number of record sections. Note that A and B are estimated for each frequency component and that they are complex numbers.

The standard error of spectral estimates such as G_{xy} is 100% (Bendat and Piersol, 1971). An ensemble average of n points reduces the standard error by $\sqrt{n}$. It is necessary to perform an ensemble average to obtain a reasonable estimate of A and B. The standard error can also be reduced by band-averaging in the frequency domain. In this case all values of some spectral parameter such as G_{xy} centered on some frequency f_k are averaged, and the average value assigned to G_{xy} at f_k . The bandwidth increases by n and the standard error is reduced by $\sqrt{n}$ in this case, if n points are averaged.

Both frequency-band averaging and ensemble averaging were used in data reduction in this study. Based on previous geomagnetic variation anomaly studies, a period range of 2 hours to 2 minutes was selected as most suitable. This range was broken into 15 frequency bands. The parameters

of the bands are listed in Table 2. The bands are separated by an approximate multiplicative factor of 1.3 which leads to uniform data separation on logarithmic frequency plots. Such logarithmic frequency steps characterize the response of physical systems more efficiently than a linear frequency scale. Ensemble averages of four to ten record sections were used for each magnetic storm, depending on length of the storm and data quality. In most cases seven or eight record sections were included.

As indicated in the Introduction, current flowing in conductive part of the earth near a station will produce an anomalous Z field variation which is correlated with some horizontal variation. The transfer function (A,B) can be used to represent the degree and direction of the correlation.

A is a complex number of the form

$$A = A_R + iA_I ,$$

and B is of the form

$$B = B_R + i B_I .$$

The real induction vector is defined as

$$\vec{M}_R = A_R \hat{i} + B_R \hat{j} ;$$

its magnitude is

$$M_R = (A_R^2 + B_R^2)^{1/2}$$

and its azimuth is

$$\tan \theta_R = B_R / A_R ,$$

TABLE 2

FREQUENCY BANDS

center frequency (mHz)	center period (sec)	no. of frequency estimates averaged
0.122	8192.0	1
0.244	4096.0	1
0.366	2730.7	1
0.488	2048.0	1
0.610	1638.4	1
0.732	1365.3	1
0.977	1024.0	3
1.343	744.7	3
1.831	546.1	5
2.441	409.6	5
3.174	315.1	7
4.150	240.9	9
5.371	186.2	11
6.836	146.3	13
8.545	117.0	15

measured clockwise from magnetic north.

The magnitude of the real induction vector is the ratio of the correlated vertical field to the horizontal field component in the direction of maximum correlation.

The imaginary induction vector is

$$\bar{M}_I = A_I \hat{i} + B_I \hat{j} ;$$

with magnitude $(A_I^2 + B_I^2)^{1/2}$ and azimuth $\tan^{-1} (B_I/A_I)$. The correlated horizontal component M_I is in quadrature (90° phase shift) with the vertical field variation. The magnitude and azimuth of the real and imaginary induction vectors were calculated at each frequency band for each magnetic storm. Standard errors of these parameters were estimated from the scatter in values between individual storms. The scatter is usually larger at long periods due to the smaller number of frequency components included in the band averages, and due to source effects (Everett and Hyndman, 1967).

If (A,B) is largely imaginary then anomalous vertical field variations are about 90° out of phase with the correlated horizontal variation. If the imaginary part of (A,B) is small compared to the real part, the anomalous vertical field is almost in phase with the correlated horizontal field. In that case θ_R is usually a smoothly varying function of frequency and θ_I is irregular. In virtually all cases in this study the imaginary induction vector was smaller than the real vector.

Strictly speaking the name Weisse vector should be applied to the vector $\bar{M}_R$; it points away from the higher conductivity regions carrying the current inducing the anomalous vertical variations. Conventionally 180° is added to the azimuth θ_R to define the induction vector which then points towards the higher conductivity regions. The imaginary

vector was not reversed in this study.

4. Directional Magnetic Variations caused by Induction

The azimuth and magnitude of the real induction vectors are shown in Figures 3 through 11. The mean value and standard error bars are based on a collection of transfer functions, each transfer function representing a magnetic storm by ensemble average of several shorter data record sections as outlined above. No data was included in the final summaries unless the vertical field power in each frequency band exceeded twice the noise power introduced by digitizing. Much of the data in the higher frequency bands was eliminated for this reason. To correct for the deviation of magnetic north from true north, 17° has been added to the calculated azimuths at each station. Better estimates of the deviation could be made at each location to account for local static magnetic fields.

It would seem reasonable to assume that a conductivity anomaly might be found along the center of the Snake River plain, judging from the volcanic features and overall linear trend. Such a case was found in the Kenja Rift Valley (Banks and Ottey, 1974). In that case induction vectors on the sides of the rift valley pointed towards the center and ones in the center were small. However, aeromagnetic anomalies in the eastern Snake River Plain typically trend across the plain (Mabey, 1978). The most recent volcanic eruptions on the plain vented from fissures transverse to the axis of the plain, such as the great rift from Craters of the Moon to the Wapi Lava field, and Hells Half Acre (LaPoint, 1977; Greeley and King, 1977). So conductivity anomalies of any orientation may be anticipated. The calculated induction vectors divide neatly into three groups based on both geographic location of the stations and character of the induction

Figure 3a. Magnitude of the real induction vector at station NRF.

Figure 3b. Azimuth of the real induction vector at station NRF.

Figure 4a. Magnitude of the real induction vector at station COM

Figure 4b. Azimuth of the real induction vector at station COM.

Figure 5a. Magnitude of the real induction vector at station SIC.

Figure 5b. Azimuth of the real induction vector at station SIC.

Figure 6a. Magnitude of the real induction vector at station HHA.

Figure 6b. Azimuth of the real induction vector at station HEA.

DTR

Figure 7a. Magnitude of the real induction vector at station DTR

Figure 7b. Azimuth of the real induction vector at station DTR.

Figure 8a. Magnitude of the real induction vector at station CTR.

Figure 8b. Azimuth of the real induction vector at station CTR.

Figure 9a. Magnitude of the real induction vector at station TWF.

Figure 9b. Azimuth of the real induction vector at station TWF.

Figure 10a. Magnitude of the real induction vector at station FFA.

Figure 10b. Azimuth of the real induction vector at station FFA.

Figure 11a. Magnitude of the real induction vector at station RR1.

Figure 11b. Azimuth of the real induction vector at station RR1.

vectors. The three groups are those on the northern edge (stations NRF, COM and SIC), those near the center of the Plain (HHA, DTR, CTR, and TWF), and those south of the Plain (FFA and RR1).

The northern stations show strong induction at all frequencies, the magnitude of the induction vector exceeding 0.3 at long periods (0.244 mHz), and falling to 0.1 at 3.15 mHz (COM). The decrease of magnitude with increasing frequency is typical of induction vectors observed at many stations both in this study and by previous workers. At short periods the induction vectors at all three northern stations point directly into the Snake River Plain, but at longer periods they gradually shift to due south.

At the three center stations HHA, DTR, and CTR good induction is also observed, though it is weaker than at stations on the northern margin of the plain. Nowhere does the magnitude of the induction vector significantly exceed 0.2. The induction vector is very small for frequencies over 1.0 mHz, especially at stations HHA and DTR. The induction vector points consistently SW at station DTR at all frequencies. At HHA the induction points SW at the lowest frequency and swings west with increasing frequency. At CTR the induction vector points approximately to the south at the low frequencies but swings to the SE at higher frequencies.

The magnetic variations at station TWF are unlike those at the other stations near the center of the plain. Except at the two lowest frequencies the induction vector is very small. It is not surprising in such a case to find that the standard errors on azimuth are large compared to data from other stations. At the longest period (0.122 mHz) the induction vector is fairly large and points southerly.

Induction at station FFA southeast of the Plain is large, nearly comparable to those on the northern margin. However the induction vector points southwest throughout the entire frequency range, rather than towards the plain, which lies northwest of FFA.

Induction at station RRI has the unusual property of increasing in magnitude as frequency increases, continuing to increase up to the highest frequency measured, 8.54 mHz (117 seconds). The real induction vector points southerly at the longest period and gradually swings to due west with increasing frequency. Note the small standard errors on the real induction vector at this station.

5. Attenuation of the Normal Vertical Field

The normal vertical field is the part of the vertical field that would be observed if no vertical field variations due to internal current concentrations were present. The normal vertical field is entirely due to the source modified by the the conductivity structure of the earth just under the station. Attenuation of the normal vertical field is an indication of higher conductivity than usual under the station.

Caner, Cannon, and Livingston (1967) used the total observed field as an estimate of the normal field. This is correct only in the case of no lateral conductivity variations leading to induction. Cochrane and Hyndman (1970) developed a formula for the power spectral density of the normal vertical field which is correct when the anomalous vertical variations due to induction are small compared to the normal field. We here present an estimate for the power in the normal vertical field which should be appropriate for all cases.

The Fourier transform of the part of the z field due to induction is

$$Z_a = A X + B Y$$

where (A,B) is the transfer function determined as above and X and Y are the Fourier transforms of the horizontal field variations. Then a residual or "normal" z field may be defined as

$$z_n(t) = z(t) - F^{-1} \{ Z_a \}$$

and the transform of this "normal" field is

$$Z_n = Z - Z_a$$

where Z_a is determined above and Z is the transform of the total observed z field. The power spectral density of this normal field is

$$\begin{aligned}
 G_{znzn} &= Z_n^* Z_n = (Z - Z_a)^* (Z - Z_a) \\
 &= Z^* Z - Z^* Z_a - Z_a^* Z + Z_a^* Z_a \\
 &= G_{zz} - Z^* (AX + BY) - (AX + BY)^* Z \\
 &\quad + (AX + BY)^* (AX + BY) \\
 &= G_{zz} - 2 \operatorname{Real} (A G_{zx}) - 2 \operatorname{Real} (B G_{zy}) \\
 &\quad + |A|^2 G_{xx} + |B|^2 G_{yy} + 2 \operatorname{Real} (A^* B G_{xy}) .
 \end{aligned}$$

As in the case of the transfer function (A,B), the parameter G_{znzn} is actually computed using both frequency-band averages and ensemble averages of the terms that compose it.

As a test of this parameter the ratio G_{znzn}/G_{zz} (power ratio of "normal" field to total observed z field) was computed for each ensemble average. Theoretically the ratio should equal unity if the observed Z field is totally normal, and should be less than unity if induction is present. The ratio is plotted for each station in Figures 12 through 20. The results for a single representative magnetic storm are shown. For stations where good induction was observed (NRF, COM, SIC, CTR, FFA) the ratio is consistently less than unity in some part of the frequency range. For stations with weak or no induction (HHA, DTR, TWF) the ratio is near unity. The results for TWF are particularly encouraging since that is the station showing the smallest induction, and the power ratio is consistently close to unity throughout the frequency range. The ratio at station RRI seems too high but it is lowest where induction is largest, at the high and low frequency ends. This example suggests that G_{znzn}

Figure 12. Power ratio of normal vertical field to total vertical field at station NRF.

Figure 13. Power ratio of normal vertical field to total vertical field at station COM.

Figure 14. Power ratio of normal vertical field to total vertical field at station SIC.

Figure 15. Power ratio of normal vertical field to total vertical field at station HHA.

Figure 16. Power ratio of normal vertical field to total vertical field at station DTR.

Figure 17. Power ratio of normal vertical field to total vertical field at station CTR.

Figure 18. Power ratio of normal vertical field to total vertical field at station TWF.

Figure 19. Power ratio of normal vertical field to total vertical field at station FFA

Figure 20. Power ration of normal vertical field to total vertical field at station RR1.

properly estimates the power in the actual normal field to within a factor of two, taking into account the standard errors expected in this sort of analysis. The reference magnetic storm was not recorded at stations HHA and DTR so mean values from other storms are plotted.

Since G_{znzn} seems to be a reasonable estimate of the normal vertical field, it may be used to study the attenuation of the normal vertical field. An example of the attenuation of the vertical field is shown in Figure 21 where the ratio G_{znzn}/G_{xx} is plotted for station NRF for the same magnetic storm as in the previous figures. A similar rapid decay of normal vertical field power is observed at the other stations.

The ratio of the value (G_{znzn}/G_{xx}) at a pair of stations indicates differences in conductivity structure under the two stations. (G_{znzn}/G_{xx}) at a test station is divided by (G_{znzn}/G_{xx}) at a reference station. If the result is near unity the two stations have similar conductivity structures. If the result is less than unity the test station overlies a region of higher conductivity than the reference station. This technique has been used by Caner et al. (1967) and Cochrane and Hyndman (1970) to compare different regions in western Canada.

The power ratio from station NRF is used as a reference in this study because the values for G_{znzn}/G_{xx} are generally higher at NRF than at other stations, and because of interest in geothermal heat sources near NRF. The power ratios are plotted in Figures 22 through 29.

Stations HHA, DTR, and CTR show somewhat greater attenuation than at NRF at all frequencies. Stations CTR, FFA, RR1, and TWF all have notably greater attenuation than at NRF at the three lowest frequency bands, 0.122 mHz through 0.366 mHz. All these stations are located in the southern part of the study area. The station TWF has the greatest

Figure 21. Power ratio of normal vertical field to north-south horizontal field variations at station NRF.

Figure 22. Comparison of power ratio (G_{ZnZn}/G_{XX}) at COM to NRF.

Figure 23. Comparison of power ratio (G_{ZnZn}/G_{XX}) at SIC to NRF.

Figure 24. Comparison of power ratio ($G_{ZnZn}/G_{XX'}$) at HHA to NRF.

Figure 25. Comparison of power ratio (G_{ZnZn}/G_{xx}) at DTR to NRF.

Figure 26. Comparison of power ratio (G_{ZnZn}/G_{XX}) at CTR to NRF.

Figure 27. Comparison of power ratio (G_{ZnZn}/G_{xx}) at TWF to NRF;
 • note vertical scale is ten times smaller than in pre-
 ceeding figures.

FFA

Figure 28. Comparison of power ratio (G_{ZnZn}/G_{XX}) at FFA to NRF.

Figure 29. Comparison of power ratio (G_{ZnZn} / G_{XX}) at RR1 to NRF.

attenuation of any of the stations at all frequencies. The high frequency attenuation at TWF is particularly noticeable, being much greater than at any other station at frequencies near 1.5 mHz.

6. Discussion of Results

The measurements of this study provide two separate indications of the locations of high electrical conductivity in the crust of south central Idaho. Induction vectors indicate the direction from stations to current concentrations flowing in conductivity anomalies. The attenuation of the normal vertical field indicates relative conductivity under each station.

Geographical plots of the real and imaginary induction vectors are shown in Figures 30 and 31. The induction vectors at a period of 4096 seconds (Figure 30) may be responding to electrical conductivity anomalies as deep as the upper mantle. Induction vectors at 410 seconds (Figure 31) represent the short period results and probably respond to conductivity structures in the upper crust.

At most of the stations the induction vectors point nearly due south at the longest periods, the only exceptions being at stations HHA, FFA, and DTR where the long period induction vectors point west of south. The largest long period induction vectors are at stations NRF, COM, and SIC on the north edge of the Plain. The southerly vectors at other stations are smaller than those on the northern edge (except at FFA). This pattern suggests a broad increase of deep conductivity, partly lying under the Plain but even more pronounced south of the Plain.

The data from stations HHA, DTR, and FFA suggest that the largest increase in conductivity lies southwest of those stations. The greater attenuation at long periods of the normal vertical field (Figures 21-29) at stations in the center of the Plain and south of it compared to the three stations on the northern margin reinforces the conclusion the

Figure 30. Real and imaginary induction vectors at 0.244 mhz (4096 seconds).

Figure 31. Real and imaginary induction vectors at 2.441 mHz(409.6 seconds).

conductivity in the lower crust and upper mantle is higher under the Plain and south of it than on the northern margin.

The long period induction vectors may be indicating a transistion in properties of the lower crust and upper mantle from fairly typical continental crust in central Idaho to the Basin and Range type crust of Utah and Nevada. The north-south valleys and ranges in Idaho south of the Snake River Plain indicate Basin and Range structure extends to the south edge of the Snake River Plain. The Basin and Range is characterized by high heat flow, thinner crust, lower crustal and mantle P velocities, and higher seismic wave attenuation, all suggesting higher than normal temperatures and increased electrical conductivity in the lower crust and upper mantle.

At all stations in this study (except RR1) the induction vectors, and hence the vertical field variations, are largest at long periods. Since the long period induction vectors all point in roughly the same direction, no reversals in vertical field are observed. Such reversals have been used by several previous investigators to infer the location of linear conductivity anomalies crossing their arrays. The data from this study shows no such anomaly at long periods, except for the broad increase in conductivity to the south. No indication of an increase in electrical conductivity in the lower crust or upper mantle colinear with the Snake River Plain is found in the data, as is found in the Kenya Rift Valley and the Rio Grande Rift.

With increase in frequency the induction vector at the three stations on the north edge of the Plain (NRF, COM, SIC) swing to the southeast; that is, perpendicular to the axis of the Plain (Figures 3 to 5). The short period magnetic variations at these periods are probably responding to currents flowing along the plain in a shallow conductive layer only 1 to 2 km deep (Stanley et al., 1977; Zohdy and Stanley, 1973).

At frequencies above 1.0 mHz the magnitude of the real induction vector is very small at stations near the axis of the plain (HHA, DTR, CTR, TWF). This phenomenon is expected at stations overlying shallow conductive structures. The direction of the induction vector in this case will only indicate the location of local current concentrations in the regional current sheet. Consistent directions are not expected or observed at these stations at these frequencies.

As well as the small size of the induced vertical field, the attenuation of the normal vertical field is larger at the stations on the Plain than at the stations on the northern edge (Figures 24 to 27). This observation also supports the idea of a shallow electrically conductive layer underlying the stations on the Plain.

The short-period induction vector is also small at station FFA, and points west (Figure 10). Attenuation of the normal vertical field at this station is lower than at NRF at the highest and lowest frequencies. The magnetic variations at this station are not markedly different from those observed near the center of the Plain north of FFA.

Station RRL, located near the Raft River Geothermal Area, has the most unusual short-period magnetic variations of any station in this study. The magnitude of the real induction vector increases with frequency (Figure 11) whereas the reverse is true at all other stations in this study

and in many other similar studies (Everett and Hyndman, 1967; Cochrane and Hyndman, 1970). Starting pointing south at the longest periods (as at the other stations) the real induction vector swings to the west and reaches its maximum magnitude at the shortest period studied, 117 seconds. This indicates the presence of a good electrical conductor at shallow depths west of station RR1.

7. Conclusions

The magnetic variations in south-central Idaho observed in this study can be largely produced by two features in the electrical conductivity structure of the crust and upper mantle. There appears to be an increase in electrical conductivity in the lower crust or upper mantle starting near the north edge of the Snake River Plain and extending south from there to well south of the southern edge of the array of stations used in this study, which lies south of the Snake River Plain. Short period variations at most stations are consistent with a shallow conductor co-extensive with the Snake River Plain which may be the shallow conductor identified by Stanley et al. (1977) with magnetotellurics and by Zohdy and Stanley (1973) with d.c. resistivity soundings.

Short period variations at station RR1 indicate a shallow, highly conductive body west of that station, perhaps in the area of aeromagnetic highs detected by Mabey (1978) under the Albion mountains. This area lies a few kilometers north of the present Raft River geothermal power test station. Low conductivity structures underlie the station RR1 itself.

The combination of high electrical conductivity, aeromagnetic highs, and adjacent geothermal heat sources suggest the area west of station RR1 may have high temperatures near the surface. The location of this electrical conductivity anomaly could be improved by an array of magnetotelluric and geomagnetic variation stations west of RR1. The array would probably not have to extend as far as stations TWF and CTR since those stations apparently did not record magnetic variations due to current flow in the Raft River area.

Present desire to locate geothermal heat sources for the Idaho National Engineering Laboratory focuses interest on stations NRF and HHA. As indicated in this report induction at NRF is typical of stations on the northern edge of the Snake River Plain; conductivity anomalies lie towards the center

of the Plain. Short period attenuation of the normal vertical field, an indication of shallow electrical conductivity, is intermediate between that of station COM and stations such as HHA which are closer to the center of the Plain. This is consistent with the position of NRF which is not actually on the north edge of the plain (as is COM) but is a few kilometers towards the center. Short period induction at NRF and HHA is not notably different from other stations on the northern and central Plain, and does not suggest any significant elevations of high temperature isotherms near the Idaho National Engineering Laboratory.

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