A NEW ROLE AND ANALYTICAL DESIGN FOR THE USE OF RESISTIVITY SURVEYING IN ARCHAEOLOGY

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ABSTRACT

In archaeological sites typical of North America, earthen archaeological features often are not easily distinguishable from their soil matrices with respect to their electrical resistivity. A statistical and geographical approach to the interpretation of archaeological resistivity survey data, in which the units of study are activity areas and larger geographical zones, rather than individual features and anomalies, is therefore proposed. Variability in resistivity data sets is first partitioned along the dimensions of depth and space into agricultural, natural pedological, and archaeological components using the Barnes Layer Method of resistivity data interpretation and spatial filter functions. Activity areas are then isolated and differentiated on the basis of the mean, variance, and pattern of variability of their resistivity values. The proposed analytical design is demonstrated on data from a Middle Woodland village in the lower Illinois River Valley.

INTRODUCTION

During the past fifteen years, archaeologists have become increasingly concerned with obtaining *statistically* adequate and representative samples of the artifacts, debris, and features contained within sites (e.g., Binford, 1964). To this avail, controlled surface pick-ups, geographical sampling designs for excavation, and the concept of the *activity area* have been applied (Binford, 1964, Binford et al., 1970; Redman, 1970; Struever, 1968). Electrical resistivity surveying methods, however, have been applied in archaeology traditionally for the purpose of locating and delimiting *individual* subterranean features of interest, such as trenches, walls, house depressions, etc., without regard to larger scale site structure. The purpose of this paper is: (1) to demonstrate that on earthen archaeological sites, the very nature of resistivity survey methods suggests that the activity area, rather than individual features, is often a more logical unit of analysis, and (2) to introduce the mathematical perspective and techniques with which resistivity data sets can be analyzed at such a scale.

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PROBLEMS IN TRADITIONAL METHODOLOGIES

Electrical resistivity surveying methods have been used with *consistent* success numerous times by archaeologists to locate individual *adobe* and *masonry* structures, and *hollow* chambers of tombs in America, and more particularly in Europe (Annable, 1958; Aiken, 1961: p. 70; Atkinson, 1946: p. 33, 1963: pp. 20-27; Chalabi, 1965: pp. 120-21, 132-33; Dunk, 1962; Hesse, 1966; Lerici, 1959; Lerici et al., 1959; Linington, 1967, 1968; Palerm, 1960: pp. 71-75; Rees et al., 1969; Kent A. Schneider, personal communication; Schwartz, 1961: pp. 67-69). In these cases, the features differ phenomenally in their conductance properties from their matrices. Traditional methods of data interpretation, in which outstanding local maxima or minima within the data set are isolated, are adequate to define such features. However, attempts to relate specific anomalies within a resistivity data set to specific *soil* disturbance in soil matrices more often than not have been met with failure, or with results which are unreliable (Clark, 1963: pp. 574-75; Dabrowski, 1963: pp. 86-87; Ford, 1969, personal communication; John Gansfuss, Richard Leary and Kent A. Schneider, personal communication).

Reasons for failure are varied, but there are some factors which reoccur consistently. First and foremost, the anomalies of interest tend to have low-contrast profiles. The anomalies differ too little in their *mean* resistivities from those of their matrices to be detectable at economic sampling intervals, given the fact that soils tend to show great *variability* in those of their physical and chemical properties which determine their electrical resistivities. This circumstance may be considered the *spatial* aspect of the problem of "high noise-to-signal ratios."

A second situation which prevents the location of individual features is the masking effect of highly variable layers above the subterranean target. In many soils, plowzone is the most variable horizon with respect to its physical and chemical attributes, as a result of spatially nonuniform plowing, liming, and fertilizing practices. Consequently, the resistivity of such a layer is highly variable. As this layer represents a part of the volume of soil which is measured for its resistivity, when surveying for subterranean features, it is an undesirable source of noise. Likewise, natural, surface and near-surface processes and factors, which occur in both cultivated and virgin soils, introduce undesirable, masking variability in the soil overlaying the feature of interest. These processes and factors include: differential effective precipitation, infiltration, and evaporation; small-scale topographic and drainage regimes; the kind and density of vegetational mats; soil water movements and variation of soil water ion contents and concentrations within the root zone; and temperature variation. All these factors, man-made and natural, contribute to a *depth-dependent* aspect of the problem of high noise-to-signal ratios.

Third, the problem of high noise-to-signal ratios is enhanced by the fact that the effect of any volume of soil upon the resistivity of the total volume of soil which is measured decreases with the depth of the contributing volume. Thus, in a typical situation where earthen features lay immediately below plowzone and the total volume of soil to be measured includes plowzone plus the anomalous feature and its matrix, it is plowzone and the zone of natural surface variation which most affects the resistivity value. Surface noise is magnified by the geometry of the resistivity method.

Fourth, in the Eastern Woodlands of North America, at least, many of the features of interest are too small to be easily detectable, within economic limits, by resistivity equipment. Given the low-contrast profile of many archaeological features and high variability of soil resistivity values, several measurements of the resistivity of an anomaly of interest and its matrix would have to be taken to distinguish the feature. If the average size of pits on a site to be surveyed is, for the sake of argument, one-half meter, the spacing between adjacent stations at which resistivity readings would have to be taken in order to discriminate those pits would be one-fourth or one-eighth meter. (Even the latter spacing would not result in four measurements of pit fill, but would include the matrix as well, within the volume of soil effecting the resistivity reading.) In a 5 X 5 m. square, 400 to 1600 resistivity measurements would be required in order to discriminate a pit. Clearly, the minimum sampling spacing necessary to distinguish most pits such as those in the Eastern Woodlands by the resistivity method is economically infeasible.

Fifth, features of round shapes, the most common form of pits and many types of houses in the Eastern Woodlands, are not as well distinguished by those electrode arrangements used in most resistivity surveys (four, collinear electrodes) as are features of linear and square shapes. Consider a graph (Fig. 1b) of standardized resistivity values against the location of the center of a Wenner electrode array (four, collinear, evenly spaced electrodes) as the array passes over a vertical electrical discontinuity of infinite depth and horizontal expanse (Fig. 1a). As the array crosses the discontinuity, the graph will trend toward the mean resistivity of the new medium being entered. In the midst of this trend, however, the graph will jut in the opposite direction. These "juts" are called "subsidiary peaks."

The clearness of the graph depends upon the magnitude of the difference in the resistivities of the two media on either side of the discontinuity, upon the electrode configuration and separation, and upon the angle which the array makes with the discontinuity. The more that the angle which the array makes with the discontinuity strays from ninety degrees, the more the graph starts to trend when the array is further from the discontinuity, and the smaller the subsidiary peaks become (Chalabi, 1969). If a rounded, vertical discontinuity and linear vertical discontinuity are both approached at the same angle, as described by the line of the array and the tangent to the perimeter, the *average* angle of approach with respect to the whole perimeter will be less for the circular discontinuity than the linear discontinuity. Consequently, resistivity equipment traversing over circular, vertical discontinuities, such as pits, will yield less distinctive resistivity graphs than will linear, vertical discontinuities, such as trenches.

Finally, there are numerous agricultural and natural features which can not be distinguished from archaeological features in their effect upon electric currents. Such features include infilled depressions from uprooted trees; roots, themselves; large animal burrows; natural stones; localized clay pans; drainage tiles; banded and other uneven distributions of fertilizers and lime; etc.

In summary, there are very clear, statistical, physical, chemical, and geometric reasons for expecting negative results for resistivity surveys which are performed on earthen archaeological sties and which have as their goal the isolation of individual archaeological features using economical sampling spacings between measurements.

STATISTICAL AND GEOGRAPHIC PERSPECTIVES

It is apparent that the problem of isolating individual archaeological features on earthen archaeological sites can be summarized as follows: (1) high variability in the resistivity of both natural and disturbed soils compared to the slight differences of their means; (2) the uneconomic distance between adjacent resistivity readings which would have to be used to resolve the difference in means; and (3) the indistinguishability of archaeological anomalies from natural and agriculturally-related anomalies. The first two difficulties are statistically different ends of the same problem, but I divide them to point out how the problem of resolution of archaeological anomalies can be solved from two directions. The first problem can be overcome by using the mathematical techniques of data interpretation which I will introduce, below. The second and third problems can be circumvented by increasing the scale of the anomalies of interest. I discuss the latter first.

If it is activity sets and activity areas (as both interpretive and sampling units) which are the interest of the archaeologist, there is no reason why resistivity surveying methods must first define the building blocks of activity areas—features of different functional classes—and then build these into activity sets and define spatial structuring of a site in terms of activity areas. While this is analogous to the method by which activity sets, activity areas and site structures are defined for artifact and debris classes, it is an unnecessary step in analysis, if feature-oriented activity areas can be defined directly.

The major thesis which I propose in this paper is that different kinds of activity areas, as whole geographic units, are statistically differentiable in their mean resistivity values, and/or the magnitude and patterning of variances. This thesis is based on the assumption (which I am presently in the midst of testing, [Carr, 1975]) that different human activities on earthen archaeological sites cause different kinds, magnitudes, and spatial patterns of physical and chemical alterations of natural soil profiles, which are reflected in their response to electric currents. Let me provide some examples of possible soil alterations. Different activity areas may differ in the areal density and the size of their features. The chemical composition of the feature contents, which determine the conductivity of the electrolyte soil water solution, may also vary between activity areas. The total amount of organic matter within the features, which determines the degree of granulation and porosity of the feature fill, and thus, the water-holding capacity and structure of the water films on the walls of pores within the feature fill, may also vary between activity areas. These human-caused, physical and chemical variations will, in part, determine the mean and variance of the distribution of resistivity values obtained within the activity area, and their spatial patterning. The means, variances, and spatial patterns of natural soil properties also will determine the statistical and spatial distribution of resistivity values, but can be sorted out through the mathematical techniques discussed below.

Thus, activity areas might be definable without differentiating the *absolute* location, morphology, and resistivity of *each individual* feature within the activity areas. The response of features to electric currents would play only a *statistical* role in the resolution of larger-scale activity areas. Emphasis upon statistical and geographical patterning of resistivity values would circumvent the problems of the uneconomic spacings necessary to characterize particular features, and the indistinguishability of particular natural and agricultural features from archaeological features.

Before I proceed to discuss the several mathematical techniques by which such a perspective can be realized, I do want to point out that I am not proposing an abandonment of traditional methodologies of resistivity surveying. Feature-oriented resistivity surveys are useful, reliable, and economical when the anomalies of interest are large and/or tend to be linear and when they contrast sufficiently from their matrices in resistivity. Defining the direction and limits of partially-excavated trenches, the areal limits of sites, and zones of previous excavation are all problems of importance, which traditional methods have tackled successfully. I wish to point out only that: (1) there are certain regular, definable circumstances in which feature-oriented strategies are unfeasible, and (2) when attempting to define site structure to guide excavation sampling procedures, a statistical and geographic perspective using the activity area as the basic unit of study is more economical. Both purpose and circumstance should be considered when choosing one of these two methodologies. A more detailed discussion of the matter of choosing between feature-oriented survey strategies and statistical, geographical survey strategies is given in Leith et al. (n.d.).

MATHEMATICAL METHODS

Soil resistivity is a single-dimensional measure of multiple soil properties. It is reasonable, then, to view a series of resistivity values across a landscape or over depth as a palimpsest, and to ask whether the summary series contains any meaningful information, either covert or apparent, of archaeological importance. Two summation processes can occur. In the one case, a single variable might produce two effects which completely neutralize each other. For example, addition of organic matter to soil might increase the number of chemical bonds between soil and water, but increased granulation resulting from the addition might also cause better drainage conditions. Over some drying regimes the effect of the added organic matter would be null. Information on such a soil change would not be reflected in a resistivity series. In the second case, two changes might have opposing effects with respect to the electrical response of the soil, but the spatial distribution of the two changes might not coincide. In this case, the pattern of destructive interference is not complete. Large-scale (low spatial frequency), natural soil variation in one factor, simultaneous with smaller-scale (high spatial frequency) human-caused soil variation in another factor, is an example of such a summation process. Information on both factors are extractable from the resistivity series.

The general area of applied mathematics which allows the separation of information about multiple variables from a series of data points tracing the behavior of a single, summary variable (e.g., soil resistivity) is time series analysis. Any linear series of data points can be envisioned as the sum of three components: (1) a trend, which can be obtained by fitting a curve through the data points using least-squares methods, (2) a periodic component, which can be obtained through Fourier series analysis, and (3) a random component, which can be described by Markovian matrices of probability (Davis, 1973; Rich, 1973). The periodic component, itself, may be considered the sum of multiple waves having different frequencies, amplitudes, and phase angles.

Resistivity data series may contain all three kinds of information: trends, periodicities, and random components. Natural soil variation, such as decreasing particle size with increasing distance from a stream, might be apparent in a major trend of decreasing resistivity away from the stream. Band fertilization and plowing might manifest themselves in the periodic components of the data series. Contact resistance between the electrodes and the soil (which raises resistivity values above normal), near-surface sources of noise, and measurement errors will appear as random and semi-random fluctuations in the data.

Importantly, however, these different kinds of information exemplified above segregate not only according to their *spatial* characteristics, but also with respect to *depth.* The effects of agricultural and near-surface, natural phenomena will be most apparent in the plowzone. Archaeologically-significant soil variation can be isolated at lower levels, while natural soil variation can be mapped in still lower horizons. The separation will seldom be perfect. For example, the effects of fertilizer leachates and near-surface, natural phenomena such as differential infiltration may extend into the levels of archaeological and natural character. Nevertheless, the structuring of different kinds of information over depth as well as over space should be recognized.

The aim of the mathematical techniques which I am proposing here is to partition the mean and variance of composite resistivity data series along both the dimensions of space and depth in order to maximize the quantity and clarity of information obtainable for each class of variables affecting composite soil resistivity measurements.

Division of resistivity data sets into component sets should first occur along the dimension of depth, in order to remove as much as possible of the effect of surface and near-surface noise and natural, subsoil variation upon the resistivity data. It is possible to mathematically subtract out the effects of such horizons and to isolate the response of those layers in which archaeological deposits occur by use of the Barnes Layer Method of resistivity data interpretation. This technique was invented by H. E. Barnes (1952, 1954, n.d.) and extensively tested and confirmed by the Michigan State Highway Department (Malott, 1964, 1965, 1967, 1968).

The theory of the Barnes Layer Method is based on Wenner's (1915) equation for determining the average apparent resistivity of a homogenous medium. Using a collinear array of four equidistant electrodes, the outer two supplying current and the inner two measuring the potential drop across the medium between them, the apparent resistivity of the medium is defined by:

$$(1) \qquad \rho_a = \frac{4\pi AR}{1+2A/((A^2+4B^2)^{1/2}) - (A/(A^2+B^2)^{1/2})}$$

where ρ_a is the average, apparent resistivity in ohm-centimeters for a volume of the medium extending to a depth of approximately A centimeters, where A is the equidistant electrode spacing in centimeters, where B is the penetration distance of the electrodes into the medium, and where R is the observed apparent resistance measured in ohms. The volume of the medium which affects the resistivity measurement has infinite lateral and vertical dimensions, lying between two hemispherical, equipotential bowls, as shown in Fig. 2a. The volume encompassing that portion of the medium having the most effect upon the resistivity measurement is shown in Fig. 2b.

Assuming a layered model with no lateral changes within strata, the hypothesis is then made that the apparent resistances of layers behave in a manner analogous to parallel electrical resistors. If a number of measurements are made with electrode separations $A_1, A_2, A_3, \ldots, A_n$, where the depth of the measured volumes of the medium are $A_1, A_2, A_3, \ldots., A_n$, then the measured apparent resistance, $R_1, R_2, R_3, \ldots, R_n$ will decrease such that

$$\frac{1}{R_L} = \frac{1}{R_N} - \frac{1}{R_{N-1}} \tag{2}$$

where R_N is the apparent resistance, in ohms, of a volume extending between the surface and a depth A_N, where R_{N-1} is the apparent resistance, in ohms, of a volume extending between the surface and a depth A_{N-1}, and where R_L is the apparent resistance, in ohms, of a layer of the medium, between depths A_{N-1} and A_N. The value of R_L may be used in Wenner's equation, along with the layer thickness (A in the numerator) and the average electrode separations and penetrations (A and B in the denominator) which were used to generate the two measured volumes, in order to calculate apparent resistivity values. The "layer" of influence which is generated by such a mathematical operation is shown in Fig. 3.

I should make it clear that the Barnes Layer technique is only a method of *interpretation* of resistivity, i.e., it allows the calculation of "apparent" resistivity values rather than absolute resistivity values. There are three reasons for this. First, the analogy between a profile of rock strata or soil horizons and a group of resistors hooked in parallel is not perfect. Parallel resistors are not contiguous and do not allow the flow of current between each other, while depositional strata and soil horizons are contiguous and do conduct current between each other. Second, the Barnes Layer Method assumes that (1) the strata do not change character horizontally, and (2) that the several strata in the new resistance-affecting material which is added to the sides of a measured volume when the electrode array is expanded (Fig. 3) contribute, relative to each other, to the measured resistivity in the same proportion as the strata within that originally measured volume. Neither of these assumptions is true, so the process of subtracting out the effect of overlaying deposits (equation 2) is only approximate. Barnes Layer Volumes, therefore, do reflect, to some extent, the resistivities of the strata above that being investigated. Finally, the Wenner equation itself is derived with the assumption that the conducting medium is totally homogenous, and that current flow lines follow a predictable, ellipsoid pattern. This assumption allows the calculation of the expected potential drop (and, therefore, resistance, by Ohm's law) between the two inner (potential) electrodes, given a specified amperage between the current electrodes and a specific resistivity of the conducting medium. The application of the Wenner equation to inhomogenous media for prospecting purposes (ironically) violates this assumption: current flow lines are warped around and through anomalies within the media. Thus, a calculated resistivity value for an inhomogenous medium does not represent the true resistivity of the medium, only an "apparent" one.

While the measurement of apparent resistivity rather than absolute resistivity is a true problem for geologists, who try to identify rock composition on the basis of resistivity value, it is much less of a concern to the archaeologist, who is interested in *relative changes* in resistivity patterns and values, and who is less concerned about the *true* resistivity of the medium he is investigating.

Once a resistivity data set has been partitioned into stratigraphically, semi-independent data series, largely of either agricultural, archaeological, or natural pedological character, each series can be further analyzed using the methods of time series analysis. A standard approach (e.g., Rich, 1973) would involve: (1) removal of trends (e.g., long-frequency, natural soil variation) found with least squares methods, (2) performance of spectral analyses to determine those frequencies which account for the greatest variability of the data series, (3) removal of such periodicities (presumably of agricultural origin in this case), and (4) examination of residuals for archaeologically significant attributes. On the basis of my work in resistivity surveying at the Crane Site (see next section), however, I would not recommend this standard analytical design. There are two major reasons. First, I have found that areas of human disturbance, whether at the activity-specific scale of analysis or at larger geographic scales (e.g., the extent of midden deposits) can be characterized best when means and variances are jointly examined in relation to *local* norms. Areas of human disturbance are characterized jointly by means and variances lower than the natural, local norm in raw data series. Removal of long-frequency, natural soil trends prior to examination of the data simply removes an interpretive frame of reference—the local norms for resistivity magnitudes. Second, trend removal is often used as a preparatory manipulation for spectral analysis. I would not, however, recommend the use of this tool unconditionally either. When soil resistivity is sampled at intervals which are of the length appropriate to the definition of activity areas (ca. 0.5-1.0 m.), the the total variance of the resistivity series is largely accounted for by the highest frequencies. These frequencies are, by definition, those which contain the most information about activity areas, because of the relative magnitudes of the sampling interval and activity areas. They should not be removed. In spectral analyses of such data sets, variability of low-frequency periodicities of the agricultural type is so completely overwhelmed by that of the first several harmonics (of archaeological importance) that the analysis is of little aid in sorting out those low frequencies which should be removed.

In place of such a standard, analytical design, I would suggest the use of filter functions (Holloway, 1958) which are specifically designed to bring out particular attributes of the resistivity series. First, prior to interpretation of the resistivity series by the Barnes Layer Method, those points which are too high or low to represent subsidiary peaks and which probably represent noise should be replaced by the average of their adjacent points. The limiting values defining "too high" and "too low" can be calculated by: (1) finding average local maxima and minima over a short interval; (2) knowing the electrode spacing and configuration; and (3) assuming a vertical discontinuity, which separates two media having resistivities equal to the maxima and minima, is being approached in a direction perpendicular to the array (that orientation which would yield the largest subsidiary peaks). Such an operation would remove from the series those data points which can be attributed to only contact resistance or random measurement error. It is important to define the points to be removed on the basis of local variability in resistivity values rather than by a specific pair of upper and lower threshold levels with respect to the whole series, particularly when there are very low frequency trends running through the data. The latter approach will inconsistently remove or pass by noise and subsidiary peaks, depending on the local mean resistivity. This is undesirable because subsidiary peaks are apparently important diagnostics: the borders of activity areas and general debris zones are usually demarcated (in my data sets from the Crane Site, at least) by high local variance which can be explained most easily by the phenomenon of subsidiary peaking. Locations which are the borders of several coterminating activity sets or zones having generally high debris densities have "subsidiary peaks" of greater amplitudes than those at the borders of single activity sets. It is thus possible to distinguish multipurpose activity zones within a site from more special-purpose, activity-specific zones by the relative amplitudes of their "subsidiary peaks" at their borders. One should be careful to avoid removing such diagnostics and use the local operator defined above, instead of series-wide threshold values. It should also be noted that the replacing value should be an average over not more than one tier of surrounding points, so as to avoid the introduction of artificial polarity reversals.

Second, the data series can be partitioned into any number of bands of different frequencies and widths, using a normal filter function. An operator of this type replaces each data point in the series by a weighted average of the points surrounding it, the weighting values being the ordinates of a normal curve. The operator has the advantage of maintaining the mean and phase angle of the series without introducing polarity reversals characteristic of a simple, equally-weighted, running average. The smoothed series is then used to obtain high-frequency components of the raw data series, by subtracting the smoothed (low-frequency) series from the raw data series. Intermediate bands of frequencies can be obtained by performing the operation twice, using filtering intervals of different widths, and then subtracting the well-smoothed series from the less well smoothed series. This method is appropriate for only one-dimensional data series. When operating in two dimensions, using an analogous ring filter, response is poorly defined in directions oblique to the principle axes of the data set, and it is more appropriate to filter in the Fourier domain (Scollar, 1970: p. 15).

The purpose of this second operation is to locate regions having different magnitudes and patterns of variability at similar and different frequencies. The different frequency-specific responses can be taken as indicators of the kinds, intensity, and geographic scale of agricultural, archaeological, or natural phenomena. In my resistivity work at the Crane Site, I have found that activity areas of different types can be differentiated from one another by examining several different bands of frequencies (1-m. wide bands between the frequencies of 0 and 10.5 m., for a resistivity series where measurements were made every 0.5 m.). At any one band, some activity areas are similar in the magnitude of the variance and patterning of the variance of their resistivity values, while at other bands, they may differ. This is an expectable outcome, if one assumes that the soil changes in different kinds of activity areas are of different intensities, and have different spatial structures.

To aid in the objective examination of magnitudes of variance at particular frequencies, another operator can be used, which replaces each data point in the filtered series by the local standard deviation of the points surrounding it within a set interval width. I have found an interval width of five data points (2.5 m.) to be optimal in my data sets, as it yields a series which is neither too erratic nor too smoothed to study. Similarly, an operator could be designed to emphasize those locations within the filtered series where there occur runs of adjacent resistivity values within particular ranges of each other. Other pattern-locating operators could also be designed.

Before such a fine analysis of magnitudes and patterns of variability is undertaken, however, it is wise to remove low-frequency periodicities, first. Such periodicities can be isolated by subjecting a smooth resistivity series to spectral analysis. Having removed the overwhelming effects of high-frequency variability from such series, those periodicities lower than the smoothing interval used to obtain the series now will be apparent. It is useful to perform such an analysis on the agricultural, archaeological, and subsoil horizons so that interpretation about fertilizer leaching and changes in the soil chemistry of the archaeological strata can be made and resultant effects upon the electrical response of the archaeological layer can be estimated.

In summary, by designing particular spatial operators to bring out specific attributes of resistivity data sets over specific geographic intervals and within specific frequency bands, it is possible to objectify the search for those locations in which particular agricultural, archaeological, and natural phenomena occur. The extent of success will depend on the extent to which the phenomena and their effects are understood, and the appropriate operator is designed.

To conclude this section, agricultural, archaeological, and natural pedological phenomena, when viewed from a statistical, geographical perspective, can be segregated over two dimensions, by use of both filter operators over space and the Barnes Layer Method over depth. These two kinds of data manipulations are by no means equivalent; use of filter operators on resistivity data which are interpreted by Wenner's equation for volumes of soil extending from surface, agricultural horizons, through layers of archaeological interest, and into the subsoil will not yield the same results as when the Barnes Layer Method is used to make such separations and filter operators are applied to the separate series. For example, I have noted that archaeologically-significant information from survey data which are collected with sampling intervals appropriate to the resolution of activity areas (0.5-1.0 m.) naturally occurs in the highest frequencies. These are the same frequencies in which random noise resulting from surface and near-surface natural variation occurs. Use of spatial filtering instead of the Barnes Layer Method to remove superficial noise for resistivity volumes extending into archaeological deposits will also remove and waste important high-frequency information about human-caused soil variability. Thus, the Barnes Layer Method and spatial filtering are complementary, mathematical techniques which, when used together, allow the extraction of much more archaeologically-significant information from a resistivity palimpsest than could spatial filtering, when used alone.

AN EXAMPLE OF THE PROPOSED METHODOLOGY

During the summers of 1974 and 1975, I directed a resistivity survey and correlative soil survey on the Crane Site (Fig. 4), a Middle Woodland (ca. 200 B.C.-400 A.D.) village located on the banks of precanalized Macoupin Creek, a primary tributary of the lower Illinois River. Various portions of the site have been farmed since 1819, but intact subplowzone middens (up to 40 cm. deep), pits, hearths, and post molds still remain. The village is located within alluvially-redeposited, loessic parent material of Winsconsinian age, upon which has developed a degraded Stark (forest) soil (Soil

Conservation Service, 1974) showing some variability in the development of its *B* horizon.

Soil resistance was measured using a Wenner configuration every 0.5 m. along a number of transects which were oriented so as to perpendicularly crosscut the major topographical trends and concentrations of surface archaeological debris (Fig. 4). At each location, the Wenner array was expanded four times, allowing the separation of the apparent resistivities of five layers. The resistivity profiles of three of these layers along Transect 4 will be exemplified below: a layer encompassing all of *plowzone,* from the surface to 26.4 cm. below surface; a level including *midden deposits,* when present, from 26.4 to 42.5 cm. below surface; and a level from 64.7 to 75.0 cm. below surface, including largely the natural *B horizon* with infrequent intrusions for deep pits from above. Using a notation reflecting the Barnes Layer subtraction procedure, these layers will be called *BL*1-0, *BL*3-1, and *BL*5-4. The volumes of soil extending from the surface to the base of these layers will be called "whole volumes" *WV*1 (equivalent to *BL*1-0), *WV*3, and *WV*5.

Figs. 5 through 13 exemplify various stages of analysis of the resistivity data collected along Transect 4, for both the cumulative and separated layers. On each resistivity graph, I have marked the limits of the features which this transect crosscuts: a gulley, two locations having high debris densities at the site surface and associated with subsurface midden deposits, and the extent of debris and tool sets (numbered 1 through 8) representing different types of activity. Activity areas in the southern debris density zone are multipurpose (contain several debris and tool sets) and are associated with the Middle Woodland village, itself, while activity areas in the northern high debris density zone are more specialized (contain only one or two debris and tool sets) and are peripheral to the village area.

I wish to make it clear that the precise function and limits of the activity areas are not known at present. Both are based solely on the distributions of different classes of debris and artifacts which were picked up in 6 X 6 m. squares from the site surface. The problem of border definition should be borne in mind when comparing the resistivity data to controlled surface pick-up data; it should not be expected that "subsidiary peaks" will occur *exactly* on activity area borders defined by the surface pick-up data, which have a lower resolution (ca. ± 3 m.) than that of the resistivity data (0.5 m. sampling interval).

The first analytical step I have suggested is the separation of variability in a resistivity series by depth. Figs. 5, 6, and 7 show the resistivity of cumulative "whole volumes" *WV*1 (plowzone), *WV*3 (plowzone and archaeological levels), and *WV*5 (plowzone, archaeological, and subsoil levels), while Figs. 8 and 9 show the resistivity of the segregated layers, *BL*3-1 (archaeological) and *BL*5-4 (subsoil). A comparison of these data sets reveals the advantages of using the Barnes Layer Method to interpret resistivity data and to remove the effects of surface areas. Plots of *WV*1, *WV*3, and *WV*5 show that as more soil to a greater depth in the profile is encompassed within the volume effecting resistivity measurement, apparent resistivity decreases. The total-series means for these three data sets are, respectively, 16,905 ohm-cm, 9,724 ohm-cm, and 5,005 ohm-cm. This decrease is expectable, in view of known increases in soil moisture with depth. As *WV*3 and *WV*5 encompass the highly resistant surface layer, *WV*1 (*BL*1-0) as well as the lower, less resistant layers, the resistivity values of *WV*3 and *WV*5 should be greater than those of *BL*3-1 and *BL*5-4, which theoretically encompass a much smaller percentage of the surface layer. Thus, we find the total-series means for *BL*3-1 and *BL*5-4 are only 7,749 ohm-cm and 3,369 ohm-cm—less than the total-series mean resistivity values for *WV*3 and *WV*5. It can be argued that the difference in means of the corresponding Barnes Layers and Whole Volumes reflects only the mathematical process of subtraction, and not improvement in the estimation of layer resistivity. A second comparison of the two methods of interpretation is therefore provided. If the Barnes Layer method does allow segregation of layer resistivities, then a sequence of *layers* should be statistically more independent in their resistivity values than is a sequence of successively encompassing and nesting *whole volumes.* This proves to be the case. When the data series for *WV*1 was correlated with *BL*3-1, the correlation coefficient, R^2, which was obtained (0.03196) was less than that obtained when *WV*1 and *WV*3 were correlated (0.2654). Similarly, the R^2 value obtained when *WV*3 and *BL*5-4 were correlated (0.06410) is less than that obtained when *WV*3 and *WV*5 were correlated (0.29319). These differences in R^2 values were significant at the 0.00002 and 0.01 levels, respectively, using a one-sided test, as outlined in Olkin (1967). Application of the Barnes Layer method, thus, has allowed the discrimination of the different *spatial patterns* of the resistivity values of the separate strata, as well as their different means.

Once the variability of a resistivity data set has been partitioned over depth, definition of archaeological features can be undertaken. In Fig. 8, a normal filter with a smoothing interval of 10.5 m. has been used to locate areas of generally low resistivity (dotted line). Three are apparent, corresponding to the northern zone of high debris densities, the gulley, and the southern zone of high debris densities. By plotting the smoothed curve over the unsmoothed series, the relatively low variability of the three locales and the tendency of adjacent locations to have similar resistivity values (i.e., the continuity of the graph) is also noticeable. The anomaly associated with the gulley can be regarded as a result of topographically-enhanced moisture, and ignored in the archaeological interpretation of the resistivity series.

Within the two low-mean, low-variance anomalies of archaeological origin, areas of high variability, which might be explained by the phenomenon of subsidiary peaking, are found. The peaks tend to be located at or near the borders of activity areas, as defined by controlled surface pick-up data (ca. locations 4567, 4581, 4590, 4602, 4625, 4646, 4763, 4776, 4791, 4806, 4840, 4887, and 4920). A few locations which were not defined as the borders of activity areas by the controlled surface pick-up do have peaks, which may reflect the grosser sampling interval of the controlled surface pick-up. Those few locations in which activity area borders have been defined by surface pick-up data but which are not demarked by peaks in part occur between two activity areas of similar mean resistivity (4817, 4829), but not always (4610). Examination of patterns of variability by frequency (below) allow the discrimination of those patterns which are not delimited by peaks.

Peaking also is useful in defining zones of general high debris density from areas of lower debris density, and multipurpose activity zones from specialized areas. In Fig. 8, proveniences 4567, 4590, 4806, 4840, 4887, and 4920 are all locations where the distribution of several tool sets coterminate and where resistivity peaks are unusually large. Locations marking the limit of the distribution of singular activity sets are not characterized by such high peaks (except 4625 and 4856). It would seem that the greater the number of activities which coterminate at a location, the larger is the peak at that location. The lesser magnitude of the peaks in the northern debris concentration, where more specialized activity areas occur, compared to the southern debris concentration, where multipurpose village activities are carried out, supports this conclusion.

The association of peaks with activity area borders is also supported by an examination of the Barnes Layer resistivity series for the subsoil (*BL*5-4, Fig. 9). The pattern of peaking is almost completely different at this depth. The exceptional locations (4590, 4602, 4840) which show large peaks in both layers might be explained by the extension to greater depths of those chemical alterations of the soil caused by human activity.

Up to now, I have defined areas of interest and distinguished different kinds of areas—multipurpose and specialized—using the Barnes Layer series alone. Further differentiation of the resistivity series into activity areas of particular types, as well as the definition of activity areas which are not distinguishable by their "subsidiary peaks," can be achieved by examining the magnitude and patterning of local variability in the resistivity series. Fig. 10 plots the high-frequency component of *BL*3-1 (Fig. 8), found by subtracting a series which has been smoothed with a normal filter (2.5 m. smoothing interval) from the original series. In Fig. 11, the local standard deviations of the high-frequency series have been plotted using a kernel operator with a 2.5 m. filter width. These plots show that at a particular frequency, different activity areas may vary in the magnitude of their variance and the patterning of their variability (degree of continuity in the values of adjacent points).

At different frequencies, different activity areas will be characterized by high or low variability (Fig. 11) and greater or lesser continuity between the values of adjacent points (Fig. 10), relative to other activity areas. Compare, for example, Figs. 11 and 12, which are plots of the local standard deviations of bands of frequencies in series *BL*3-1 (Fig. 8) found using two different normal filter smoothing intervals of 0 to 2.5 m. and 8.5 to 10.5 m. Comparing Fig. 11 to Fig. 12 shows that at high frequencies the activity area between locations 4790 and 4803 is characterized by a low variance relative to other activity areas, while in a band of lower frequencies, the area is characterized by relatively high variability. If a wide spectrum of frequency bands is examined, all the activity areas can be distinguished by their variability relative to other areas, regardless of whether or not they are defined by "subsidiary peaks." Subsidiary peaking is a phenomenon dependent on change of *mean* resistivity, while frequency analysis examines changes in the *variability* of resistivity values.

Finally, using frequency analysis, periodicities of agricultural origin can be located. Fig. 13 is a plot of the local standard deviations of a band of frequencies obtained by using normal filter smoothing functions with widths of 8.5 and 10.5 m. on series *BL*5-4. A period of 5 locations (2.5 m.) is evident. This periodic component was also evident in plowzone and the level of archaeological interest and is most probably related to the pattern of application of fertilizers and lime which have alluviated through the soil profile. Such periodicities should be removed from the resistivity series of the archaeological level *before* a frequency analysis of activity areas is undertaken, although this has not been done here for demonstrative purposes.

In summary, the Barnes Layer Method and spatial filtering are mathematical techniques which make feasible the interpretation of resistivity data sets within a geographic and statistical framework. Such a framework is consistent with economic sampling designs which make resistivity surveying a practical technique, and with current archaeological perspectives for the interpretation of intra-site structure.

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University of Michigan

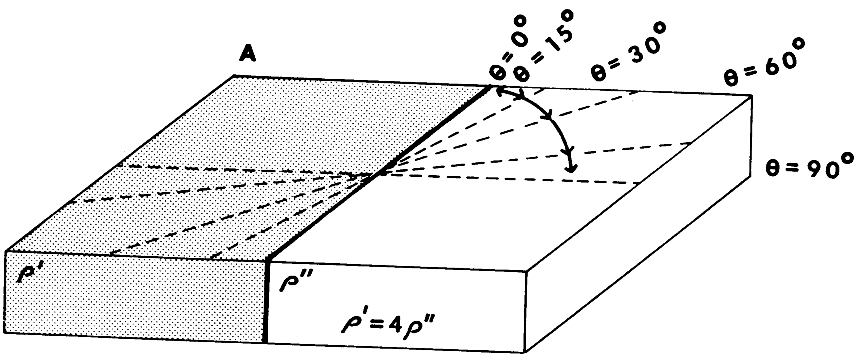
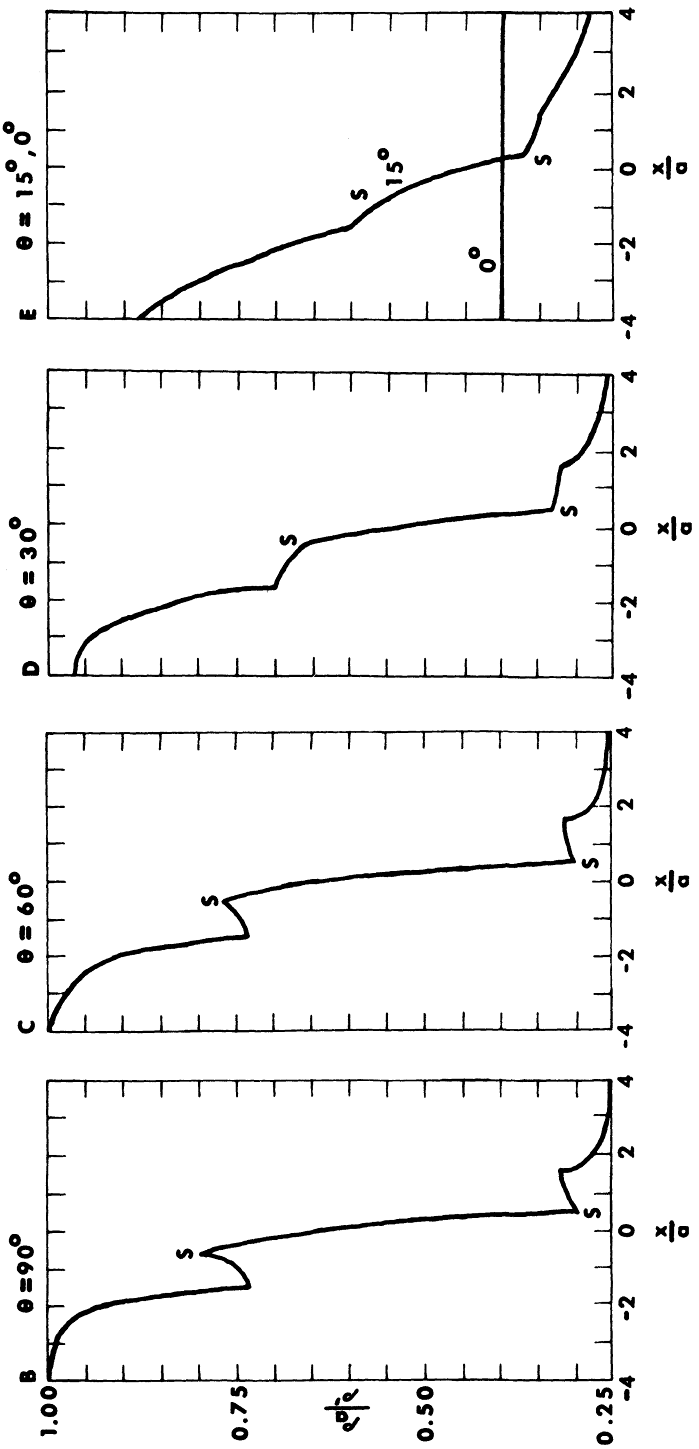


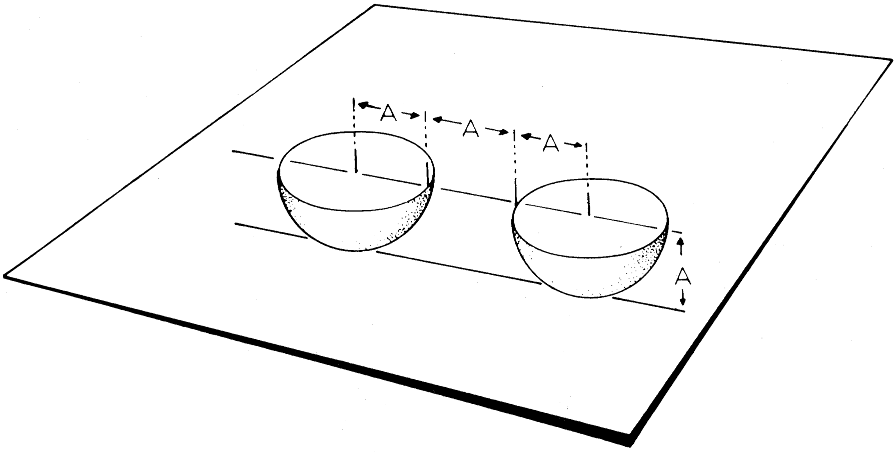
Fig. 1. Theoretical resistivity values as a Wenner electrode array crosses a vertical discontinuity of infinite depth and horizontal expanse. Traverses are made at angles of 90° (B), 60° (C), 30° (D), and 15° and 0° (E), with respect to the discontinuity. $\rho'/\rho'' = 4$. ρ_a = apparent resistivity. x = the distance of the center of the array from the discontinuity. a = the electrode spacing, s = subsidiary peaks. Adapted from Van Nostrand and Cook (1966: p. 120).

(Figure continued on next page)



(Figure 1 continued)

A



B

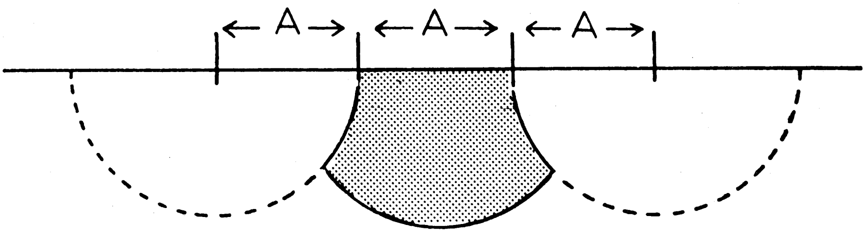


Fig. 2A. The volume of a medium which is encompassed in a resistivity measurement lies between two equipotential bowls. Adapted from Malott (1963: p. 3).

Fig. 2B. Profile of Fig. 2A, showing depth of investigation.

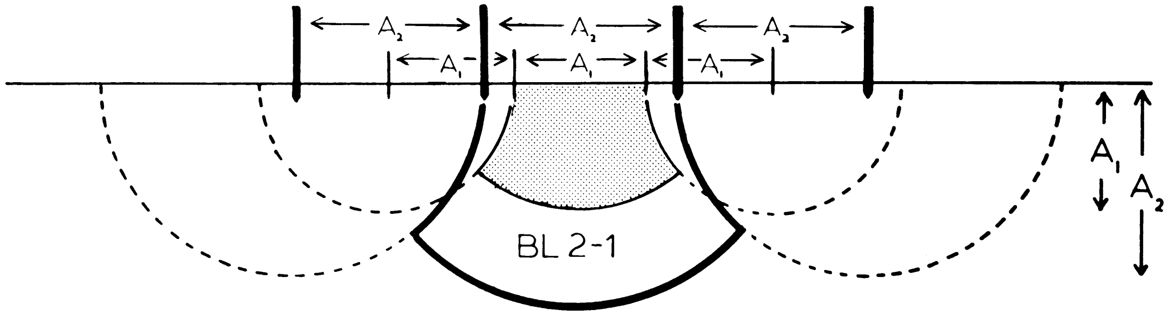


Fig. 3. Generation of a Barnes "layer" as a Wenner array is expanded.

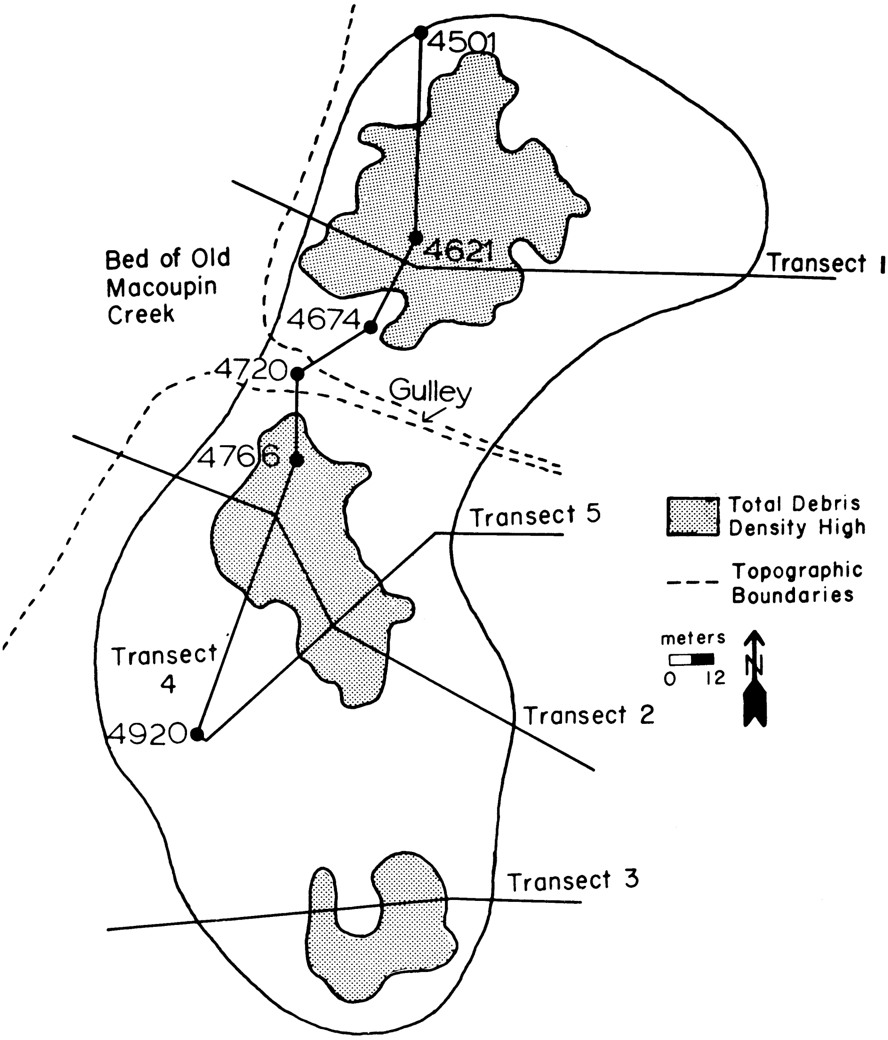


Fig. 4. Crane Site. Numbers along Transect 4 are locations graphed in Figs. 5-13.

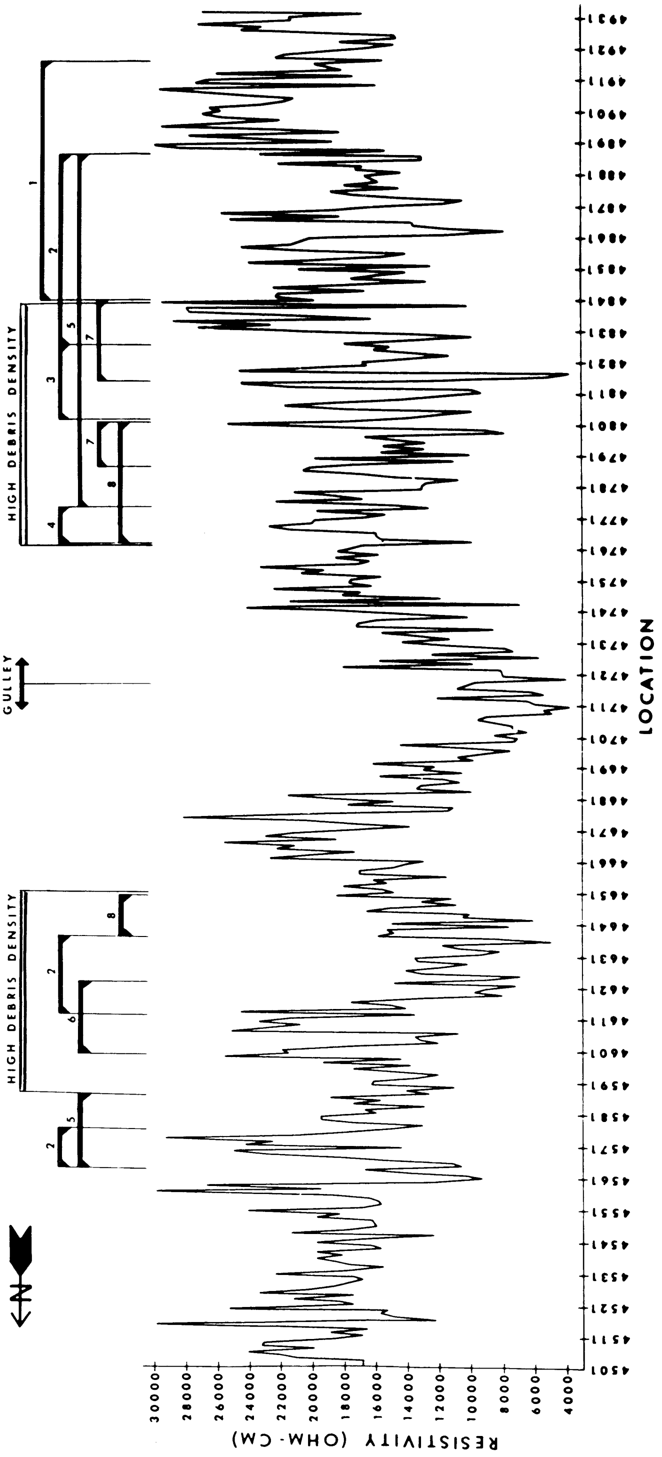


Fig. 5. Apparent resistivity along Transect 4, Whole-Volume 1 (plowzone).

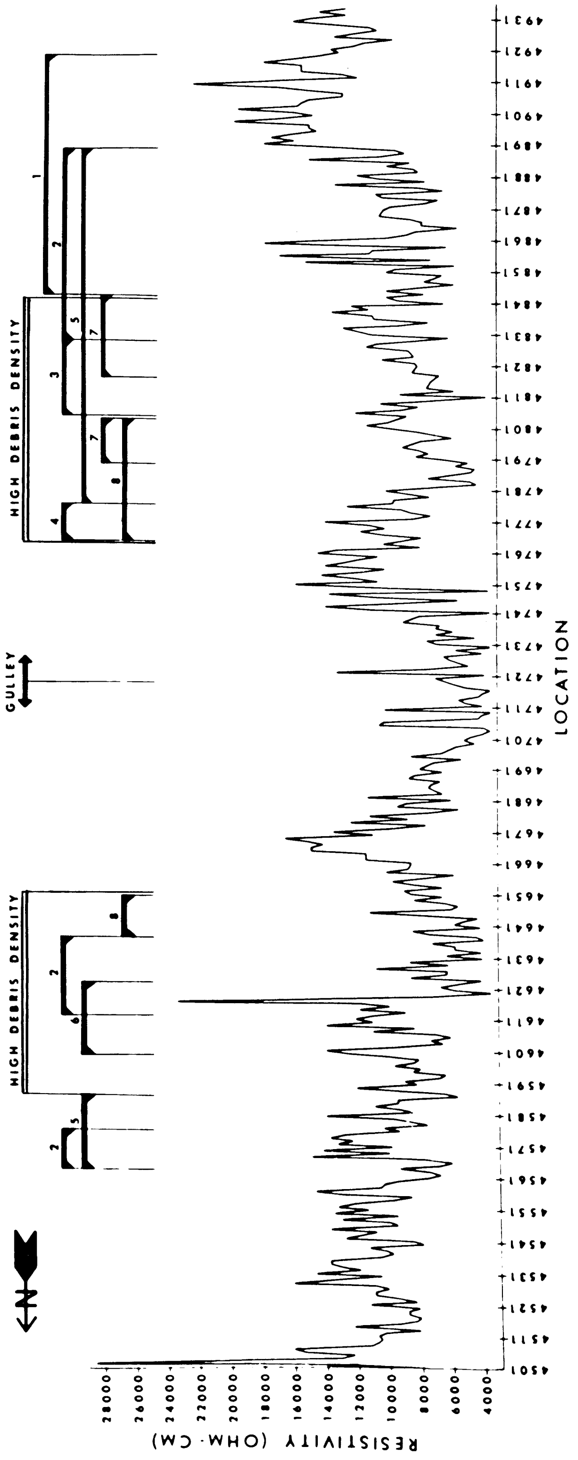


Fig. 6. Apparent resistivity along Transect 4, Whole-Volume 3 (plowzone plus levels containing archaeological deposits, when present).

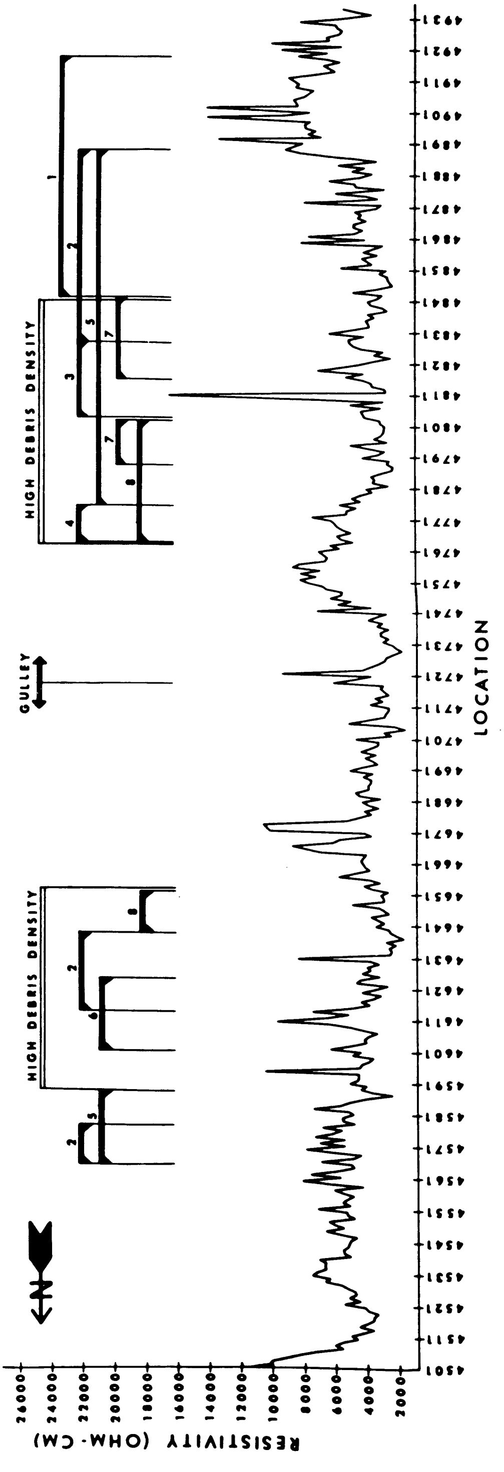


Fig. 7. Apparent resistivity along Transect 4, Whole-Volume 5 (plowzone, archaeological levels, and natural soil *B* horizon).

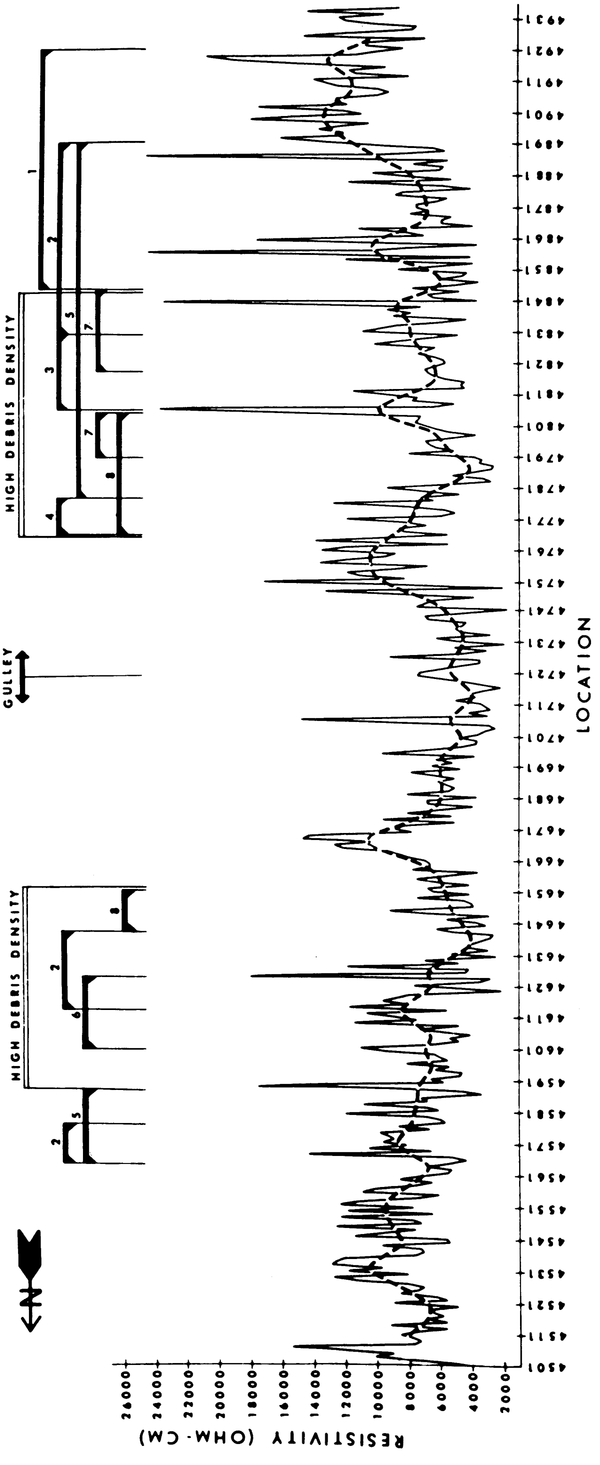


Fig. 8. Apparent resistivity along Transect 4, Barnes Layer 3-1 (archaeological levels). The gentle curve (dotted line) is derived from the more variable (solid line) curve using a running normal filter with a smoothing interval of 10.5 m. (21 locations).

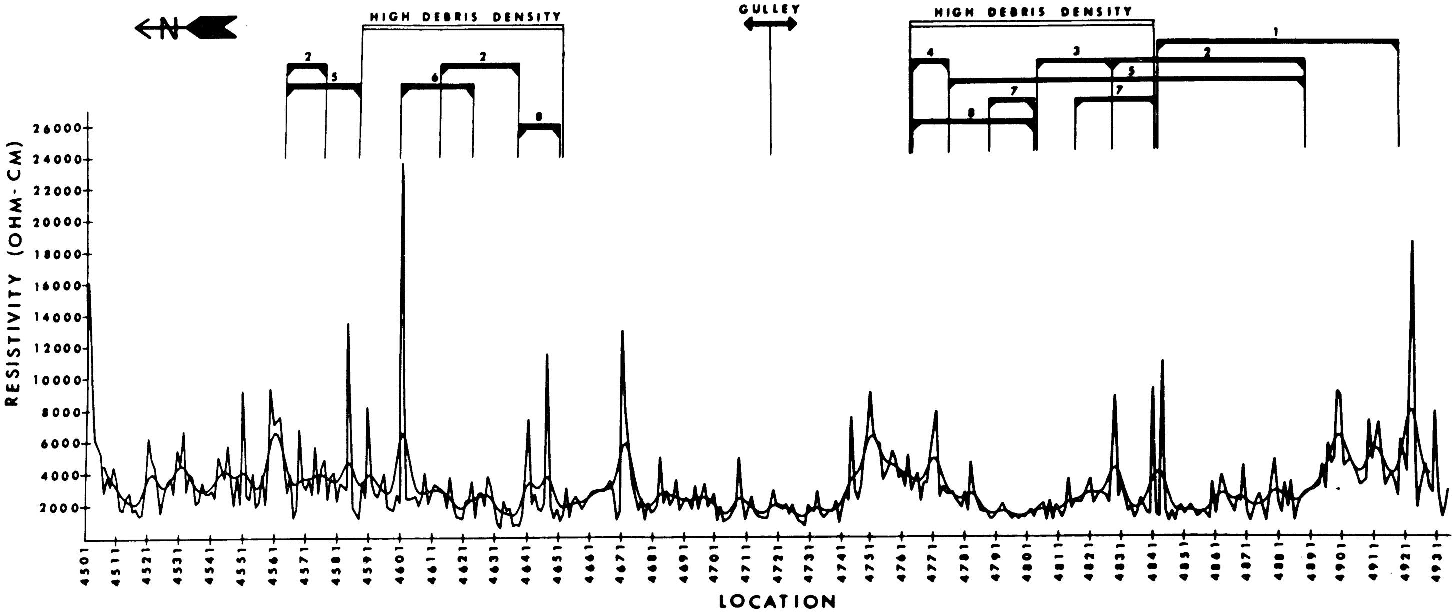


Fig. 9. Apparent resistivity along Transect 4, Barnes Layer 5-4 (natural soil *B* horizon). The gentle curve is derived from the more variable curve using a running normal filter with a smoothing interval of 10.5 m. (21 locations).

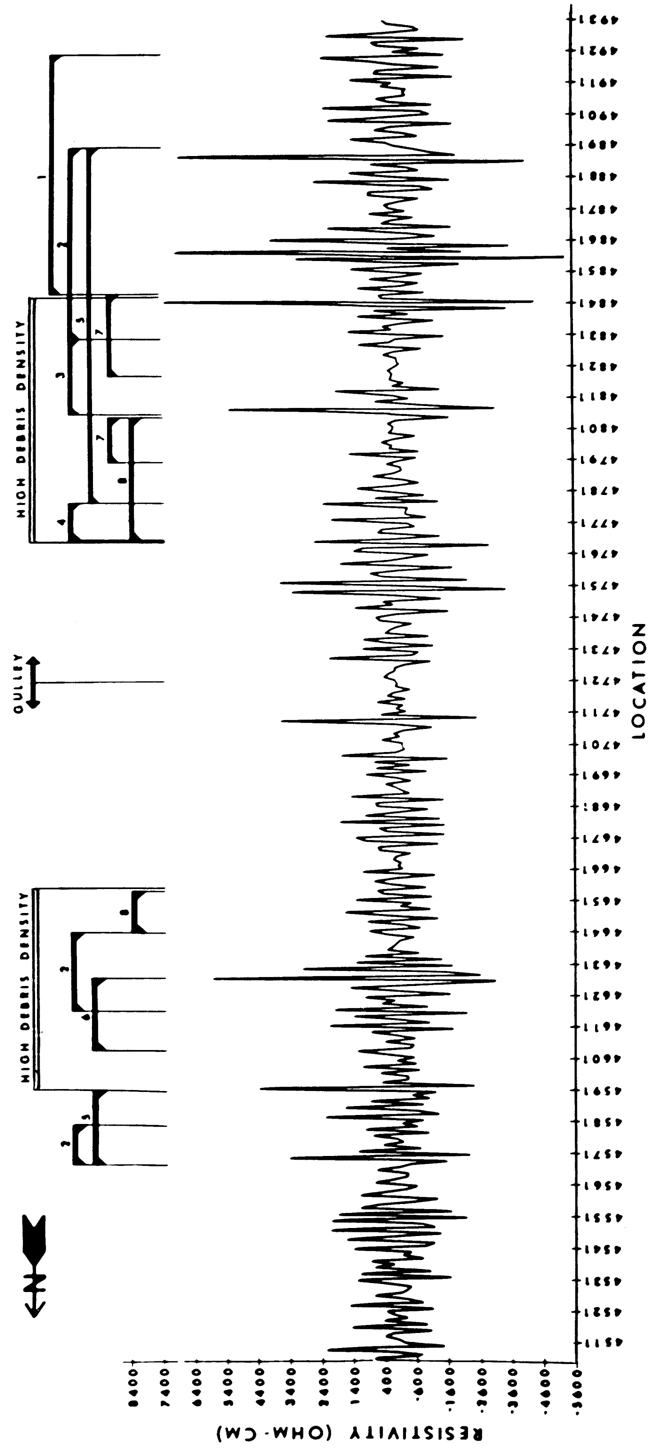


Fig. 10. High frequency component of apparent resistivity along Transect 4, Barnes Layer 3-1. A normal filter with a smoothing interval of 2.5 m. (5 locations) was used to obtain the series.

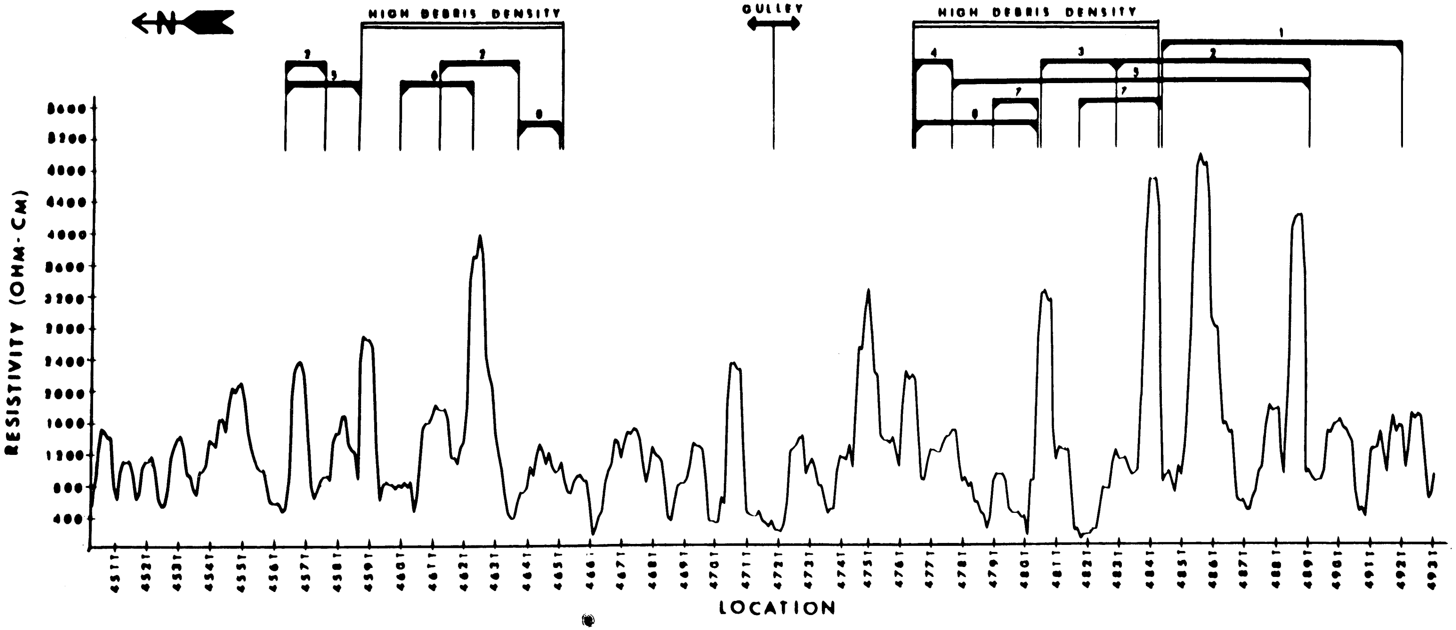


Fig. 11. Local standard deviations of the high frequency component of apparent resistivity along Transect 4, Barnes Layer 3-1, shown in Figure 10. The interval over which variability was assessed was 2.5 m. (5 locations).

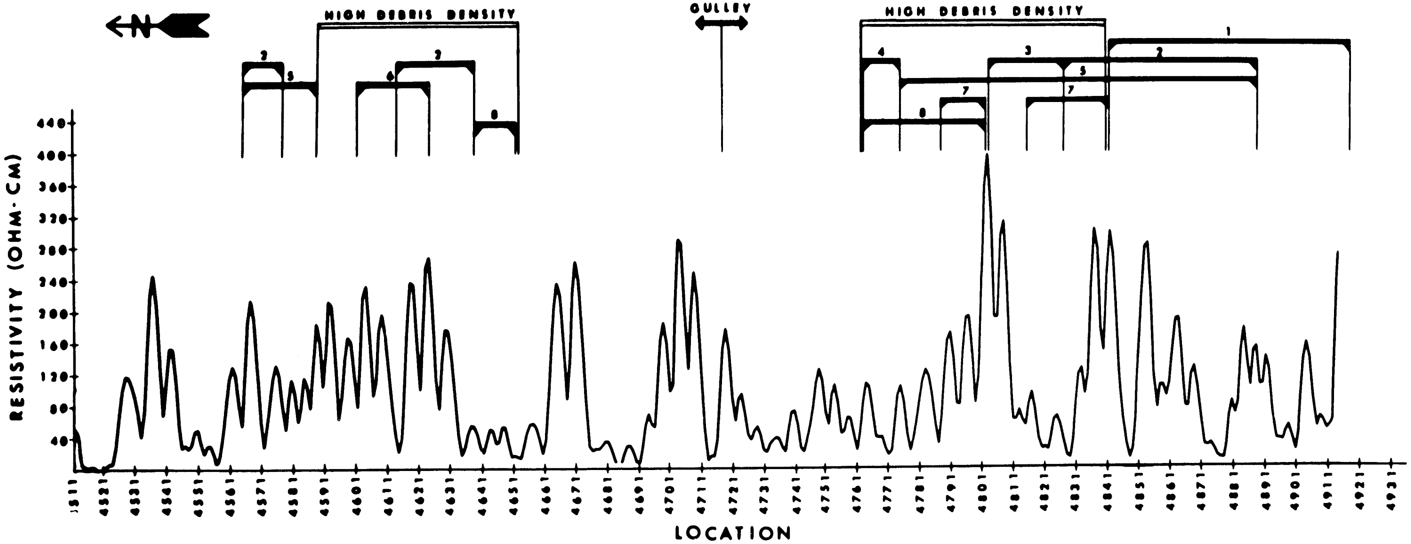


Fig. 12. Local standard deviations of a band of frequencies composing the apparent resistivity along Transect 4, Barnes Layer 3-1. The band was obtained using two normal filters with smoothing intervals of 8.5 m. (17 locations) and 10.5 m. (21 locations). The interval over which variability was assessed was 2.5 m. (5 locations).

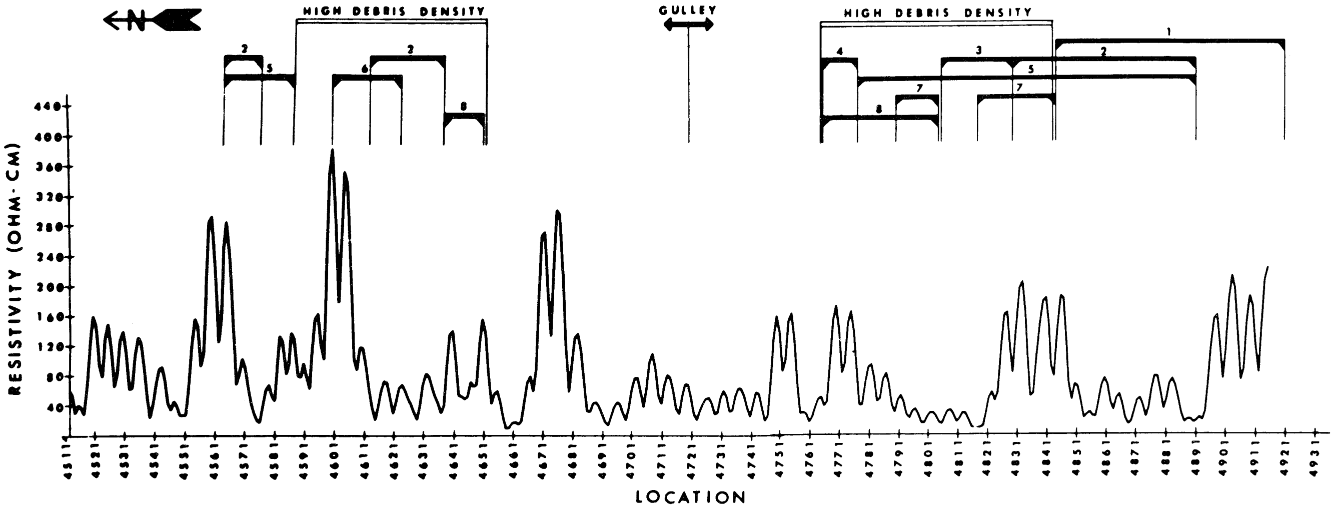


Fig. 13. Local standard deviations of a band of frequencies composing the apparent resistivity along Transect 4, Barnes Layer 5-4. The band was obtained using two normal filters with smoothing intervals of 8.5 m. (17 locations) and 10.5 m. (21 locations). The interval over which variability was assessed was 2.5 m. (5 locations).

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