

EVALUATION OF ARCHAEOLOGICAL RESISTIVITY AND
MAGNETIC TECHNIQUES IN SURVEYS OF ARID REGIONS

by

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ABSTRACT

The essential background to archaeological and near surface geophysics is discussed, with special emphasis on the use of magnetic and resistivity surveying in arid regions. Soil magnetic susceptibility forms an important aspect in the magnetic detection of near surface features. The mechanisms which influence the magnetic susceptibility of soil are discussed as well as recent research into an alternative enhancement mechanism based on certain bacteria which scrounge iron from water and synthesize it into magnetite. The magnetic detection of features mainly relies on the existence of a contrast in magnetization between the sought after feature and its surroundings. This can either be caused by a difference in susceptibility, TRM or magnetic viscosity. In practice magnetic surveying is best suited to the detection of soil features and traces of occupation such as pits with special relevance to burnt clay (kilns, hearths) and iron.

With resistivity the emphasis will be on the location of walls and earthworks. Little work has been done into shallow soil conductivity. Relevant studies into the effects of precipitation and sun exposure are discussed, as related to the season and the variation in temperature, on the detection of local features. An evaluation is given of the performance of the various electrode configurations based on their sensitivity and resolution. Only one detailed resistivity model study has been made on buried near surface features. The results are discussed with the pertinent profiles.

Adequate enhancement and presentation of the results can significantly increase the signal to noise ratio of geophysical data. In image analysis, regional, local and micro anomalies are extracted from data by means of spatial frequency analysis either directly by the use of Fourier transforms or indirectly by convolution. A number of filtering procedures have been examined and a computer programme was written for their implementation. Data can be effectively presented in the form of two-dimensional dot density images. A comprehensive computer programme was compiled for this purpose.

In surveys of very dry sites in the Middle East, resistivity provided useful results without the necessity of probe watering. Depth penetration was, however, limited to circa 1 m as the current was effectively short-circuited by a highly conductive saline overburden. Under similar conditions magnetic surveys suffered from the considerable variation in soil thickness with lithology and geomorphology. Trials were also undertaken using VLF EM. These proved unsuccessful.

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CHAPTER 1

AN INTRODUCTION TO ARCHAEOLOGICAL AND NEAR SURFACE GEOPHYSICS

1.1. Introduction to Applied Geophysics

Geophysics refers to the physics of the earth and its surrounding atmosphere. Pure geophysics mainly concerns itself with the earth's physical properties and its internal constitution as based on a study of associated physical phenomena. In applied geophysics the main object is the search for minerals, oil and gas, which generally occur beneath the surface. Their detection relies on specific characteristics which distinguish them from the surrounding medium. These usually appear in the form of distinct, relatively small and shallow features such as geological faults, magnetic ore bodies, anticlines of oil in sedimentary rocks and water-bearing strata. Therefore investigation centres around measuring their physical properties such as density, magnetism, elasticity and electrical conductivity, combined with geological information. Accordingly the various techniques can be divided into four main categories:

- a) static methods - distortions of a static physical field are detected and accurately measured enabling the source of disturbance to be determined. The static field can either occur in the form of a natural field such as the geomagnetic field, gravitational field and thermal gradient field or as an artificially produced field e.g. electric potential gradient.
- b) dynamic methods - these rely on signals being put into ground and receiving them. Measurements are made of their time of arrival and magnitude. In seismics the time of wave arrival is the main factor whereas in electromagnetics the frequency or phase difference

assumes importance.

- c) relaxation methods - these lie between static and dynamic methods; of relevance here is the time required by a disturbed medium to reach its normal state. This includes the overvoltage or induced polarization methods.
- d) integrated effect methods - with these the measured signal will be the statistical average over a specific area or volume. This applies to radioactive methods.

The choice of technique will depend on various factors, such as the nature of the sought-after feature and its surroundings and whether the feature can be directly inferred as with magnetic ores or indirectly by ascertaining whether local conditions favour the existence of a given mineral.

The results of some methods are more suited to quantitative as opposed to qualitative interpretation. Techniques such as gravity and magnetic surveying rarely necessitate the measurement of absolute values of the respective fields, but are more interested in determining the effect a feature has on these fields.

In practice the application of seismic methods will be preferred for layered strata which are not too complex. The results readily enable precise and detailed as well as unambiguous information to be obtained.

The more simple and less expensive electrical methods are suited to small-scale exploration of simple structures. In many instances more than one method will be applied. This allows the location of suitable areas for detailed work as well as improving the interpretation by removing spurious anomalies as well as strengthening others. Having decided on an appropriate method or methods, the choice of suitable instrumentation will usually be based on the purpose of the survey and the minimum amount of data required to obtain adequate interpretation as well as on cost effectiveness. The main problem centres around noise and

any measurements will be a compromise between this and the signal.

Numerical analysis forms an important part of interpretation, as well as theoretical studies in which real situations are simulated by models based on computation or by means of analogue models based on scaled-down versions of a feature. In such cases correlation between theory and practice can generally be established by combining geological and geophysical information.

1.2. Archaeological and Near Surface Geophysics

Archaeological geophysics refers to the use of geophysical surveying techniques in the detection of archaeological remains such as buried walls, kilns, graves, pits and ditches associated with past agricultural, occupational, industrial or funeral activities. Erosion, either through natural processes or caused by human activity, will have resulted in the collapse and decay of these remains generally leading to an amorphous collection of features covered by a layer of soil. The thickness of this layer will vary from area to area with .3m being a representative figure for this country.

In the Middle East one will frequently be dealing with an increased depth of overburden, sometimes up to several meters or more. With tell sites the problem is further complicated by the superimposed stratification of hundreds and often thousands of years of human occupation.

A large amount of visual information can be furnished by aerial photography. Sites are sometimes visible as crop marks caused by variations in soil moisture content. Other indicators are soil marks, snow marks and shadow marks, the latter are of special relevance to oblique-angle photography. Attempts are being made to use satellite photography but this does at present not offer a high enough resolution.

Resistivity was first used in archaeology in 1946 (Atkinson, 1953) followed by magnetics in 1958 (Aitken et al, 1958). Since then many other

geophysical techniques have been applied with varied success. Experience coupled with research has led to a distinctive approach in survey methods and in interpretation with the emphasis on resolution, cost effectiveness and rapid site coverage. The use of these techniques has varied widely and may also apply to on-shore pipeline, site investigation and other near surface applications. A summary of the principal methods and their applicability is given in the table of Fig. 1.1.

The aim of this thesis has been threefold:

- (1) to provide an overview of current methods in archaeological geophysics;
- (2) the use of the two main techniques, magnetics and resistivity in surveys of archaeological sites in the Middle East;
- (3) to develop an integrated programme package enabling the processing and presentation of survey results with the emphasis on methods of graphical display.

Chapter layout has been as follows. In chapter 1 a general outline is given of existing techniques used in archaeological prospection, excluding the magnetic and resistivity techniques. Chapter 2 discusses the magnetic method and mentions the latest developments in research on soil magnetism with chapter 3 concentrating on the resistivity method. Relevant image processing techniques and methods of data display are mentioned in chapter 4. This is followed by a description of computer programmes developed for this project in chapter 5 with the final chapter 6 describing the use of magnetics and resistivity on a number of archaeological sites in the Middle East. In certain cases a comparison has been drawn with other geophysical techniques. Relevant conclusions are mentioned at the end of the chapter.

1.3. Electromagnetic Surveying

1.3.1. The pulse induction meter (PIM) forms a sophisticated variant of the common 'metal detector'. It was developed in 1964 by Colani (1966) and consists of a primary and a secondary coil arrangement. Unipolar current pulses of 350 microsecond duration and a repetition rate of circa 11 pulses per second induce small eddy currents in a material, caused by the sudden switching-off of the primary pulse. The induced currents in metallic objects will be proportional to the rate of change of the magnetic flux, and their rate of decay will depend on the sensitivity of the metal. In-phase conductive components will also be involved. The relationship between in-phase (I/P) and out-of-phase (O/P) components is discussed further on (section 1.3.2). In practice the decays vary between 100 microseconds to 1000 microseconds. The voltage detected by the secondary coil is sampled every 50 or 100 microseconds at the end of each transmitter pulse, and the difference between the signals is integrated (Fig. 1.2). Highly magnetic or good conductors will give a strong reading (slow decay) with non-to weakly magnetic conductors as well as bad conductors giving a weak one (fast decay). Signal magnitude relates to the conductivity of a material, its size and relative orientation to the induced magnetic field. Depth response falls off as d^{-6} . The pulse induction method enables the use of differing coil sizes. These can be held vertically or horizontally with the latter position providing the best results. A smaller-diameter coil will increase instrument resolution but decrease the depth response with the converse applying to a large coil diameter. By relating the different values obtained with both coil sizes, the depth of an object can be estimated (Foster and Hackens, 1969).

Rather more problematic would be estimates of the size of an object based on the decay rate of the induced eddy current. Such an assessment could perhaps be made when one is dealing with objects of the

same type e.g. good conductors of varying size.

The instrument reacts to ferrous and non-ferrous metals. Measuring the phase separation of the decaying signals can enable differentiation between the two.

Soil magnetic viscosity (see Chapter 2) also influences the results obtained with a pulsed induction meter. The response from a soil decays proportional^{ly} to time. For metal the decay time is typically proportional to $t^{5/2}$ (Colani and Aitken, 1966). Therefore soil viscosity causes a delay in response to the induced signal resulting in a phase lag or difference between the driving current and the voltage induced in the secondary coil. This leads to various phase angles which makes it difficult to determine the exact nature of a buried object. Furthermore, the voltage as measured by the PIM was found to lie within 20% of the soil magnetic susceptibility, illustrating the link between magnetic viscosity and susceptibility (Tite and Mullins, 1969).

Mullins (1974) subsequently suggested using the PIM for magnetic viscosity measurements, claiming an accuracy of 4% and coming up with a minimum detectable viscosity value of 30×10^{-6} emu/cc for current instrumentation. However, Graham and Scollar (1976) pointed out that this could not be substantiated owing to calibration requirements. They suggested that as a method it would be more useful in obtaining preliminary results of viscosity with long-term constant-field measurements providing more accurate and reliable results.

When surveying with the PIM a good procedure is to use a grid with a set measurement spacing related to the required definition. At first a large diameter coil should be applied as this will enable greater depth penetration and site coverage. A smaller coil can then be used for a more detailed search of areas of specific interest as well as for anomaly pinpointing.

Survey procedure can also rely on sweeping the coil in wide arcs

across an area. This has to be done very carefully as the instrument's response is rather slow. Best survey results will be obtained against a uniform background. A high soil viscosity can mark^s any small metal items such as coins. The thermoremanence of tile and potsherd rubble may also cause problems. Badly corroded metal objects will be difficult to detect owing to the electrically non-conductive oxidation.

Mullins (1974) calculated the depth penetration of the PIM based on model studies of a spherical pit with uniform volume magnetization due to the transmitter. (Fig. 1.3). The results indicate that when the susceptibility of a feature equals that of the topsoil, the maximum depth response is 30 cm. This figure will be increased to 38 cm (37.5% increase) if the susceptibility value for the pit is twice the relevant value for the surrounding topsoil. These figures apply to a transmitter coil diameter of 0.5 m. A larger diameter coil clearly improves these values.

A similar table relevant to the proton magnetometer (see chapter 2) is also shown (Fig. 1.4). The signal response of the proton magnetometer falls off less with depth, providing better results for high susceptibility features. However, the PIM provides increased depth response for low susceptibility features indicating its usefulness in detecting such features at shallow depths.

1.3.2. The soil conductivity meter (SCM) consists of two electrically coupled coils placed at right angles to each other ('zero' coupling). One coil forms the transmitter, the other the receiver. A high energy sinewave of circa 4 kHz transmitted from the vertically aligned coil induces eddy currents in a material, the magnitude of which depends on the strength of the magnetic flux and on the geometry of the object with respect to the coil, as well as on the resistivity of the material. Best values will be obtained if the largest surface faces the transmitter coil.

The reverse applies to magnetic material. It is worth considering the following cases:

- (1) response to a non-magnetic conductor (e.g. copper, silver, brass, gold) - the magnitude of the eddy currents will depend on the electrical conductivity (σ) of the material, the shape of the object and its concentration with respect to the transmitter coil. A combination of these factors causes the induced voltage and induced current to be out of phase with each other. With a highly conducting material the phase shift (Q) will tend towards 90° .
- (2) response to a magnetic but non-conducting object (e.g. clay, burnt rock) - the magnetic flux from the transmitter coil will magnetise the object depending on its magnetic permeability (μ), its size and position relative to the coil. The induced magnetisation generates a magnetic flux density which will be in phase with the voltage induced in the secondary coil.
- (3) response to a magnetic and conducting object (e.g. soil, iron) - clearly a combination of the abovementioned factors occurs resulting in arbitrary amplitude and phase.

Therefore there are three different ways of exciting the receiver coil:

- a) eddy current caused by the induced voltage in a specimen e.g. conducting metals;
- b) magnetisation effect e.g. piece of burnt clay;
- c) combination of the above two effects e.g. piece of iron, soil.

The effects on the received signal are related to phase and magnitude (Fig. 1.5).

The magnetic susceptibility of the topsoil also affects the readings. As such the instrument acts more as a soil susceptibility meter, and its results closely resemble those taken with a proton magnetometer. The latter, however, has greater depth penetration (d^{-3}) as the depth response of the SCM falls off as d^{-6} . Current instrumentation enables a minimum

sensitivity of 60×10^{-6} emu/cc to soil susceptibility. The real (in-phase) component of the SCM response is approximately proportional to the soil susceptibility with the imaginary component only assuming minor importance. This changes in sea water, where the imaginary component becomes predominant.

No correspondence has been established between instrument response and soil resistivity (Mullins, 1974). Increasing the transmitter frequency to above 100 kHz causes the instrument to react equally to soil conductivity and susceptibility. However, this would decrease the depth penetration to less than 30 cm (Tite and Mullins, 1969).

In very dry conditions where it becomes very difficult to apply resistivity techniques, an SCM tuned to microwave frequencies and therefore specifically reacting to soil conductivity, would be of use. Unfortunately the depth penetration decreases to 10 cm which is too shallow for archaeological purposes (Aitken, 1974). Aspinall (1973) mentions the use of a long wire with the ends grounded as a new technique common to general geophysics, but does not elaborate on its application in future field trials.

Survey procedure is generally in the form of a grid. As the instrument provides a continuous response readings can either be taken at meter intervals (depending on the required resolution) or plotted on an x-y plotter. Instrument height above the ground should be between 3 - 8 cm, and kept as accurate as possible in view of the instrument's sensitivity to height variations. This impairs its use on bumpy or uneven terrain. Wind can be another problem. It will make it difficult to keep the instrument steady and adversely affect the mechanical rigidity of the staff supporting the two coils, resulting in changes in transmitter-receiver coil alignment. Anomaly location is approximately halfway between these two coils.

Earlier versions of the SCM (Howell SCM) also suffered from a high battery drain which caused a steady decrease in measured values during a survey (Mousson, 1968).

Mullins (1974) carried out similar model experiments to those mentioned earlier, on the SCM. The following table provides an indication of its depth response (Fig. 1.6). Best results will be obtained on sites with a low magnetic contrast and shallow features.

High susceptibility soils, which can have a masking effect on any underlying metal objects, are best surveyed with a proton magnetometer. When using the instrument purely for metal detecting, ferrous metals will provide the strongest response owing to the secondary currents generated within the metal. Overall the PIM will, however, provide the greatest sensitivity to ferrous and non-ferrous metals.

In igneous areas, such as the Highland zones of Britain, the SCM should prove useful for archaeological detection as it tends to be less severely affected by very strong magnetic fields, already present in the ground material.

1.3.3. Underwater Application

The PIM is best suited for such purposes as it is small, light and compact, and is not strongly affected by sea water conductivity (known as the 'sea water effect'). Furthermore, magnetic viscosity is not known in marine sediments and will therefore have no influence on the results (Foster, 1970).

Underwater use of the SCM would necessitate suppressing the imaginary component of the signal as the instrument would otherwise strongly respond to water conductivity. Also, the mechanical link between both coils would have to be made very rigid indeed to prevent coil coupling problems.

In underwater surveying, the emphasis is on metal detection, for which the PIM is eminently suited. Therefore the discussion will be limited to this instrument. Prior to commencing a survey the PIM is set

up by positioning it on the sea bed and selecting an appropriate gain switch position. Readings are then either taken by slowly sweeping the instrument in wide arcs along a traverse or by noting the meter deflection at fixed intervals. Instrument height should be kept in the region of 10 cm. Anomalies are pinpointed by changing the gain to a lower value and checking the supposed location again. Signal strength and anomaly size are noted on a clip-board and the anomaly position marked with a non-metallic rod or other suitable object. Its depth can be determined by increasing the height of the instrument and taking a new reading which is then compared with the initial value.

Most metal objects tend not to be too deeply buried. Ships' cannon have been successfully located at depths ranging from 2 - 5 m.

Ideally the results of a metal detector survey should be linked to other surveying techniques: a photogrammetric survey which delimits the visible remains, a probe survey to ascertain the depth of the silt layers as well as any buried features, and a proton magnetometer survey (Hall, 1972) which will provide greater depth penetration.

1.4. Induced Polarization

This technique relies on the phenomenon that when a direct current applied to a medium is suddenly stopped, a gradual decay of the voltage takes place. It is known as the transient or overvoltage and its decay will depend on the amount and concentration of electrolyte in the medium. When a current flows through a medium a certain amount of energy will be stored within that medium. Energy storage will be mainly in the form of chemical energy. This can be divided into:

- a) membrane or electrolytic polarization - this is brought about by differences in ion mobility in rock fluids and is the cause of the background or normal IP effect. It forms the predominant factor in most rocks which lack metallic minerals, being especially pronounced

in soils which contain clay minerals.

- b) electrode overvoltage - metallic minerals within a rock may more or less hinder electric conduction owing to differences in electronic and ionic conductivity. This effect is usually larger in magnitude than electrolytic polarization and can be enhanced in disseminated ores as it is basically a surface phenomenon.

Therefore different soils will exhibit varying degrees of polarization with the transient voltage lasting from 1/2 sec to 10 sec or more. Its magnitude depends on the external current source, the mineral concentration and distribution within a soil and the soil porosity and water content. It is also roughly inversely proportional with the current density, and decreases with increasing source frequency when using an a.c. supply.

Two different methods are available to determine the decay characteristics of induced polarization. The first method, known as frequency-domain IP, measures the apparent resistivity at two or more different frequencies (e.g. 0.1 Hz and 10 Hz), after which the induced polarization is expressed as a percentage change (per cent frequency effect) in conductivity.

When measuring in the time domain, a sample is taken at different intervals along the decay curve or the decay is extrapolated to zero time (Fig. 1.7):

$$M = \frac{1}{V_c} \int_{t_1}^{t_2} V(t) dt \quad (1.1)$$

where M is the chargeability in milliseconds, V(t) the residual voltage at time t after the current is cut off and V_c the steady voltage prior to cut-off.

One can also integrate the decay time over a given period ($t_2 - t_1$).

Field measurement is basically the same as used for resistivity (see Chapter 3) except that non-polarizable electrodes are used for the potential electrodes. A suitable electrode has been designed for near-surface surveys and is employed similar^{ly} to normal steel electrodes (Aspinall and Lynam, 1970).

First the probes are arranged according to the required configuration and a reading is made at the existing selfpotential. This is subsequently automatically subtracted from the second reading which measures the induced polarization after an energising current has been applied. At first IP was seen as a complementary technique to be used when resistivity failed (Aspinall and Lynam, 1968). Subsequent field trials on a ring ditch structure came up with promising results which clarified those obtained with resistivity (Aspinall and Lynam, 1970). Unfortunately the application of IP has as yet not shown a considerable gain in the resolution of near-surface features. It also takes longer to obtain a reading and requires reasonably sophisticated and expensive equipment. Therefore it has so far only been of limited use in archaeology.

1.5. Gravity Surveying

In certain instances gravity surveying has been applied to archaeological sites (Linington, 1966b). Its use has been mainly restricted to locating subsurface cavities and chamber tombs (Samson, 1979), and is based on the supposition that such features will suitably influence the gravity field as to allow measurement. The basis of the method is formed by Newton's Law of Gravitation which states that the force of attraction between two particles is proportional to the product of their masses and inversely proportional to the square of the distance between them:

$$F = \frac{\gamma m_2 m_1}{r^2} \quad (1.2)$$

where F is the force between the two particles of mass m_1 and m_2 at separation r , and γ the universal gravitational constant.

At its simplest the bodies of interest are assumed to be spheres or point masses. In practice the gravitational attraction can be expressed as the acceleration, a , of a body of mass m_1 due to the attraction of a mass m_2 given by

$$a = \frac{F}{m_1} = G \frac{m_2}{r^2} \quad (1.3)$$

and is therefore equivalent to the force acting per unit mass, expressed in gals. Anomalous bodies are generally measured in milligals (10^3 mgal = 1 gal) or in microgals (10^4 microgal = 1 gal).

Gravity instruments determine the vertical component of the gravitational attraction. The size of a buried sphere can be expressed as

$$g_{z(\max)} = \frac{\gamma \sigma V}{d^2} \quad (\text{radial distance}) \quad (1.4)$$

where g_z is the vertical component of the anomaly, σ the density contrast between the sphere and its surroundings and V its volume, and d the depth of the sphere below the plane of measurement.

Most features of archaeological importance hardly affect the gravitational field. Anomalies will be in the order of less than 10 microgals for buried stone constructions to 100 microgals for large chamber tombs.

In gravity surveying various factors influence the readings and have to be corrected for. The most relevant in archaeological surveying are:

- (1) variation of gravity with height, where for instance a 4 cm height change corresponds to 10 microgals for an average density contrast σ between soil and surface rock; (*combined free air + Bouguer correction*)
- (2) time variations in the gravity field which necessitate the use of a base station;
- (3) microtopographical changes in the form of minor surface variations.

Differences between theoretical and observed gravity due to lateral variations of density beneath the earth's surface are known as the Bouguer anomaly.

Taking readings is a slow and time consuming process. Keeping the height of the instrument constant above the ground is often difficult especially in loosely textured soils. Mechanical and temperature disturbances must also be avoided. The required accuracy demands a high density in measurement points. Readings have to be taken with extreme accuracy which only heightens the already vast expense of current instrumentation.

On the whole this method has so far proved unsuccessful in archaeological applications.

1.6. Ground Penetrating Radar

Radar has shown to be a promising technique for the detection of underground discontinuities in mainly dry, desert-like environments (Vickers and Dolphin, 1975). Its operation relies on the observation that a radar pulse transmitted into the soil will on striking a feature, return echoes to the radar receiver. Interpreting the echo is rather complicated as any information concerning subsurface material will depend on the delay or range to the echo, phase and amplitude relationships, two-dimensional shape or pattern of the echo, the specular reflection of the object and the characteristic frequency of the received pulse as well as its attenuation through the medium (Bevan and Kenyon, 1975). It is

also often difficult to differentiate between the various effects. Depth penetration will vary from medium to medium and is inversely proportional to the attenuation of the radar wave within the medium. The following figure provides an indication of this for a number of materials (Fig. 1.8).

In essence the lower the microwave losses the better, with extremely dry and non-conductive soils exhibiting a high dielectric constant between a feature and the surrounding medium, providing best results.

Surveying consists of pulling a cart, on which a small radar system is mounted, across the ground. So far tests have been confined to a radar system with a peak power of 35 W and a peak frequency of circa 100 MHz. The block diagram is shown in Fig. 1.9. Echo signals in the form of a radar profile are recorded on a chart recorder using electro-sensitive paper. In many ways radar profiling is analogous to seismic reflection profiling. It should not be applied to complex sites as the response form would become too difficult to interpret. Also, the current system cannot resolve features which are within 1 m of the surface. The limiting factor is the length of the pulse envelope, which in turn relates to the design of the antenna. (Dolphin et al, 1978).

Finally, the smoother the ground the better.

So far the results have been very promising and this technique would clearly be ^{especially} of use in dry, arid environments.

1.7. Seismic and Sonic Methods

The most relevant techniques are either based on refraction or reflection seismology. In the former use is made of the fact that any wave which encounters an interface between media of varying velocities is partly refracted as well as reflected. The velocity of the medium refers to the speed at which seismic waves travel through that medium. The various ray paths are outlined in Fig. 1.10.

In the figure S denotes the shotpoint, G the position of the

geophones, h the depth to the interface, V_1 and V_2 define the velocities of the mediums, and ρ their density. Ray 1 is the surface or direct wave; Ray 2 results in a reflected wave which returns to the surface and a refracted wave which travels virtually parallel to the interface boundary; Ray 3 meets the interface and is completely refracted parallel to the boundary as its angle of incidence (i_c) is too great for it to be reflected upwards. The relationship $2h \tan i_c$ denotes the minimum distance from S required to record the arrival time of one of the rays.

The basic premise is that, if a homogeneous elastic medium is suddenly stressed, several kinds of elastic waves are propagated within that medium (Fig. 1.11). Most important are:

- (1) longitudinal, compressional or P (primary) waves which move as spherical fronts. Their velocity is given by:

$$V_p = \sqrt{\left(\frac{k + (4/3)n}{\rho}\right)} \quad (1.5)$$

where k is the bulk modulus, n the shear modulus or modulus of rigidity (both k and n apply to the elasticity of a medium), and ρ is the density of the medium.

- (2) the slower S (secondary) waves which travel normal (tangential) to the pulse front. Their velocity is related to the density and elastic constant of the medium as

$$V_s = \sqrt{(n/\rho)}$$

- (3) in conjunction with the abovementioned body waves, an even slower surface wave, known as the Rayleigh wave, occurs in a homogeneous ground. A combination of vertical and horizontal ground motions travel along the surface according to a distinct phase relationship (Fig. 1.11).

Reflection and refraction are expressed according to familiar

concepts in optics. Therefore $i_1 = i_1'$ in the figure and

$$\sin i_1 / V_1 = \sin i_2 / V_2 \quad (\text{Snell's Law})$$

This provides the refractive index of the interfaces.

Basic survey procedure consists of a shotpoint and a series of geophones arranged at fixed distances from it, usually in the form of a traverse. Impact sources can either consist of a hammer which is stuck on a steel plate positioned on the ground, a weight dropped from a height, or an explosive charge buried at a suitable depth. Upon impact the resultant head waves are recorded as first arrivals on the seismogram, and plotted in the form of a time-distance graph. This is then used to calculate the depth to the interface from which they arrived. In the simple case shown in Fig. 1.12, both direct wave (S to $G_0 - G_1 - G_2$) and refracted wave (S to $AB_1 G_1$, $AB_2 G_2$, $AB_3 G_3$) are plotted on a graph against shotpoint-detector distances (SG_0 , SG_1 , SG_2 etc.). From the graph, the depth h to the interface can be calculated as follows:

$$h = \frac{1}{2} \sqrt{\frac{V_1 - V_0}{V_1 + V_0}} x_c \quad (1.6)$$

where V_0 and V_1 define the velocities of the mediums, and x_c gives the distance to the point where direct and refracted waves arrive at the same time: on the graph this will be the point at which the two straight lines intersect. The refraction method primarily provides information as concerns the depth and type of material, and its relative thickness.

Unfortunately the resolution of refraction seismology is rarely adequate enough for archaeological purposes. It has been successfully applied in the location of tomb chambers (Masca, 1969) and a Roman wall (Chapellier, 1974) and attempts have been made to produce a computerised system (Ozawa and Matsuda, 1979). In practice, though, it still very much remains a suitable system for depth estimates of geological

structures (Carson, 1962), as the amplitude of the refractions coming from small features is not large enough. This is further compounded by the severe overload to the amplifiers caused by the direct wave, from which they cannot recover in time to pick up very shallow reflections.

In reflection seismology the waves essentially travel downwards until they are reflected back by structures of which the acoustic impedance suddenly changes. The geophone arrangement is very similar to refraction seismology except that the maximum shot-detector distance is kept within or smaller than the depth of the nearest interface of interest. This restricts the signal to reflected rays. A typical shot-point-geophone arrangement is shown in Fig. 1.13. It enables continuous coverage on land. Geophones are situated on either side of B and after firing those between A and B are moved to the other side of C for the second shot to take place at C.

Although both reflection and refraction techniques are in many ways similar, there are some important differences:

- (1) refraction work involves long shot-to-geophone distances and requires a large energy input into the ground. The converse applies to reflection work.
- (2) the longer distances covered by the rays in refraction work results in mainly low frequency data as most of the high frequencies will have been absorbed by the medium. Reflection data tend to exhibit a higher frequency content.
- (3) refraction work also involves more time in shooting as larger distances are involved. However, mapping an area is generally more complicated with the reflection method, owing to the close spacing of the reflection lines.
- (4) reflection work is not so suited for shallow prospecting as the amplifiers suffer more from overload, caused by the direct wave reaching the geophones, than occurs in refraction work.

Reflection seismology has only occasionally been used on

archaeological sites (Masca,1969; Masca,1971) with minor success (Burian, Hrdlicka and Tickva, 1968; Hrdlicka and Lukasova, 1969).

The main advantages of both reflection and refraction seismology lie in their relatively unambiguous information which is readily interpreted. In areas where resistivity surveying is difficult owing to the dryness of the soil or where the results from magnetic surveying suffer severely from spurious, seismic refraction or reflection may provide valuable information. They may also be of use when the sought-after features are very deeply buried.

A number of sonic methods have at times given useful results. Acoustic techniques have aided the detection of cavities (Masca,1965). One development is the sonic spectroscope, it has so far been successfully applied in locating wall cavities, and is based on the observation that knocking a hollow wall produces a tone lower in frequency, of greater intensity and which lasts longer. This is put into practice by emitting sound waves, varying in frequency between 100 and 1200 Hz and from 200 to 2,400 Hz, against a wall. The induced wall vibrations are displayed on a monitor screen in the form of a vibration spectrum (accelerations as a function of frequencies) and recorded as well as photographed. This process is repeated at various positions along the entire wall. Cavities will assume specific resonance frequencies which tend to be higher than those produced by the wall, and therefore appear as anomalies in the vibration spectrum. The process can be repeated a second time by transmitting the recorded wall vibrations. Any wall oscillations will then be magnified enabling anomalies to be identified previously overlooked (Carabelli, 1966). This process has been applied to ground prospecting with varied success (Linnington, 1970a). The main problem is the greater elastic wave attenuation in the earth. Multiple retransmissions of the vibration signal partly overcomes this, although significantly adding to the measurement time.

Once a subterranean cavity has been detected, a number of devices are available which allow further investigation. One group of instruments uses levers which are pressed against the wall of a borehole, fissure or crack as the cavity meter travels down it. The results are in the form of a graph based on the extension of the levers against depth.

Another group, the acoustic or ultrasonic cavity meters send out waves which reflect against the wall. When received these enable the correlation ^{of} wave velocity versus distance. Light can be used in a similar approach although this does necessitate a completely dark environment (Hrdlicka, 1969).

Periscopes have been successfully applied to Etruscan tombs (Linington, 1971a).

Ultrasonic measurements, as used for determining the strength of concrete blocks, can aid the evaluation of information from other seismic sources. In practice the travel time of an ultrasonic wave is determined for differing distances of the receiving probe from the transmitter source (Hrdlicka and Lukasova, 1969).

1.8. Bosing

This forms a simple variant of the seismic methods. The technique relies on the thump pitch and timbre change of the sound of a heavy object when dropped on the ground. Success ultimately seems to depend on the experience of the operator and local soil conditions. In practice a thin and hard packed topsoil and a homogeneous subsoil, such as chalk, provides best results.

1.9. Augering and Probing

Augering (or coring) can form a valuable asset to a near-surface survey. Probing, using a thin steel rod, can be used as an aid in finding solid anomalies and feeling textural changes. Of the two,

augering is generally more of use. It enables anomalies to be checked during a survey and provides information on soil conditions. The method consists of driving a hollow rod into the ground either by hand or mechanically with the aid of a motor-driven rotary drill. Tube diameters range from 1 - 8 cm. Cores are taken right down to bedrock or an appropriate depth for the location of archaeological features. Soil textures and colours and any fragments within the soil are recorded, as well as any compression or lengthening of the core caused by the method of extraction. The results provide an indication of soil stratification and form a valuable means of determining the existence and extent of habitation when fitted into the grid structure of a site. In certain cases coring should be avoided, for instance, in the detection of chamber tombs or where damage to archaeological features would be inevitable.

The combination of a coring or a contour survey can sometimes be useful as the latter can help to establish any redistribution of archaeological remains e.g. effects of water erosion on a hilly site.

Coring results can be plotted in various ways e.g. closed dots denote positive results, open dots are negative results (Linington, 1974)

1.10. Infrared Photography

Infrared photographs can locate different sources of heat radiation on special infrared sensitive film. Sometimes archaeological features can be detected if their heat radiation contrasts with that of the surrounding medium. For best results, conditions should be dry and the sought-after features situated near the surface. The process can be refined by taking a series of photographs of the same site using infrared film sensitive to different wavelength radiations.

Further analysis of the negatives or transparencies with a micro-densitometer, enables quantitative measurement of transmitted and absorbed light which can indicate man-made features (Masca, 1973).

Experiments with infra-red photography have so far been inconclusive

in this country (Clark, 1969 and personal communication, 1977).

1.11. Radioactive Methods

Clays and most soils contain very small quantities of radioactive elements, mainly uranium, thorium and potassium. The level of radioactivity tends to vary from soil to soil with clays exhibiting higher values than sand. During the process of radioactive decay the nucleus of an atom breaks down resulting in the emission of α , β ^{particles} and γ -rays. The latter are highly penetrating and their energy is less readily absorbed by moisture than occurs with alpha and beta particles.

Soils generally contain a greater concentration of radioactive elements than the underlying strata. Detection is based on the assumption that man-made features would produce local anomalies influencing the local level of radioactivity. Unfortunately depth penetration is minimal, normally in the order of 30 cm or less.

One method, relying on neutron scattering, provided uninspiring results. The instrument used fast neutrons from an americium-beryllium source transmitted into the earth from a probe. Travelling through the ground, the neutrons are scattered and slowed down when they collide against light atoms such as hydrogen. The detector responds to the slow neutrons. In effect this technique relies on soil moisture content (hydrogen atoms) therefore resembling resistivity surveying in its sphere of detection. However, reasonable results could not be obtained as the neutron penetration was limited to circa 10 cm, hardly making this technique an asset to geophysical surveying (Alldred and Shepherd, 1963).

Another trial experiment used cosmic rays in the detection of a possible second burial chamber in the Pyramid of Chephren. Again, results were inconclusive (Alvarez et al, 1970).

1.12. Additional Techniques

Various other techniques have been tried out, with varying success; differences in reflection by archaeological features in optical polarisation (Garlick, Steigman and Lamb, 1974); selecting tone values in aerial photographs, a technique which has proved to be useful for shallow underwater features (Alvisi, 1974); by detecting the local secondary fields caused by the magnetizations and eddy currents induced in the ground by a primary field signal coming from broadcasting stations (frequencies of 180 kHz and 164 kHz), long linear features parallel to the primary field provide best results (Tabbagh, 1972); and thermal prospection (Fourteau and Tabbagh, 1979).

1.13. Divining

As a last resort, divining (or dowsing) may be worth consideration. With this technique, detection relies on the force a feature exerts on suitable divining rods, held in the operator's hands. Its efficacy is much in dispute and the method appears to fail under scientific conditions (Aitken, 1959).

METHOD	SURVEY PROCEDURE	MEASURED QUANTITY	FINAL RESULT	MAIN APPLICATIONS
Magnetic	use of magnetometers, gradiometers of varying kinds. Survey according to individual traverses or grids. Measurement of soil magnetic properties	variation in Earth's magnetic field strength	magnetic profiles; contour maps; dot density maps	detection of archaeological features with the emphasis on soil features and traces of occupation: burnt clay (kilns, hearths), iron, pits
Electrical and electro-magnetic	ground resistivity surveys; induced polarization surveys; electromagnetic surveys. Use of individual traverses or grids; in resistivity also profiling technique to establish layers	potential drop between electrodes. Natural and induced electromagnetic fields. Induced over-voltages: a) membrane or electrolytic polarization b) electrode or over-voltage	resistivity profiles; contour maps (iso-resistance curves); dot density maps; depths to rock layers of contrasting resistivity	location of walls and earth-works; determination of depth and consistency of shallow sediments (on shore pipeline surveys and site investigation)
Seismic and sonic	reflection and refraction surveys using different energy sources	time for waves to travel from one source to another after reflection or refraction by subsurface formations	depths to reflecting and refracting formation - time sections + depth sections; speed of waves; contour maps	superficial deposit surveys; location of cavities in walls; detection of tomb chambers
Gravity	use of gravity meters either for individual traverses or in grid pattern	variation in the strength of the Earth's field	Bouguer Anomaly and residual gravity maps + profiles; depths to rocks of contrasting density	location of subterranean cavities; regional and detailed geological studies

Fig. 1.1. Principal geophysical techniques in shallow exploration (after Dunning, 1970, with additions).

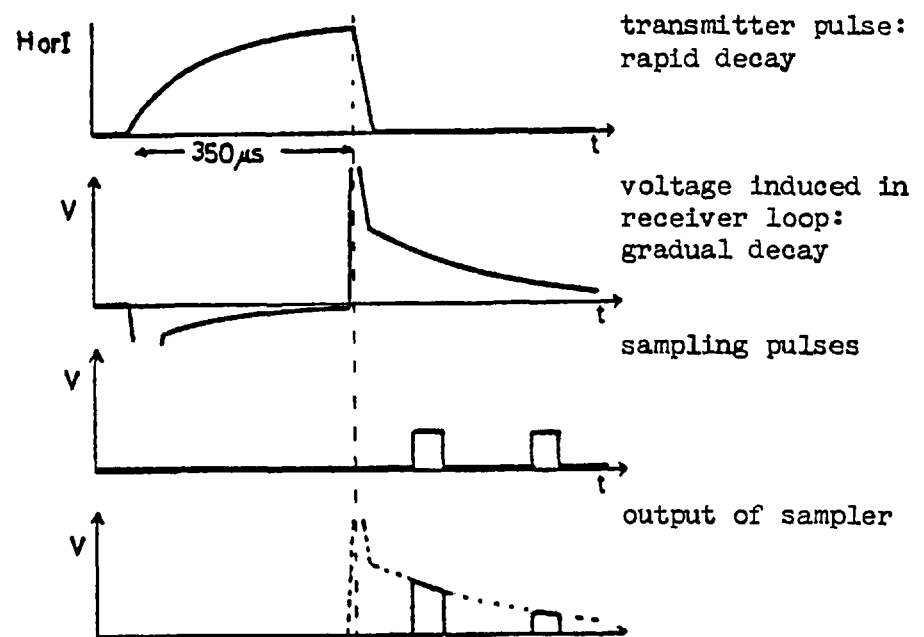


Fig. 1.2 Pulse induction meter signal characteristics

Detection depth for the full-scale P.I.M.			
Coil System		Max. topsoil thickness d_m , cm	
T_x side	R_x side	$x_{pit} = x_{topsoil}$	$x_{pit} = 2x_{topsoil}$
0.5 m	0.2 m	30	38
1.0 m	0.4 m	47	58
2.0 m	0.8 m	65	85

For a pit of 1m diameter and 65 cm depth.

Fig. 1.3 Detection depth of the Pulse Induction Meter

Detection depth using a proton magnetometer		
Pit depth dia = 1m	Max. topsoil thickness d_m	
	$x_t = x_{pit} = 50 \cdot 10^{-6}$ emu/cc	$x_t = x_{pit} = 500 \cdot 10^{-6}$
0.3 m	0.2 m	0.7 m
1.0 m	0.4 m	1.1 m

Fig. 1.4 Detection depth using a proton magnetometer

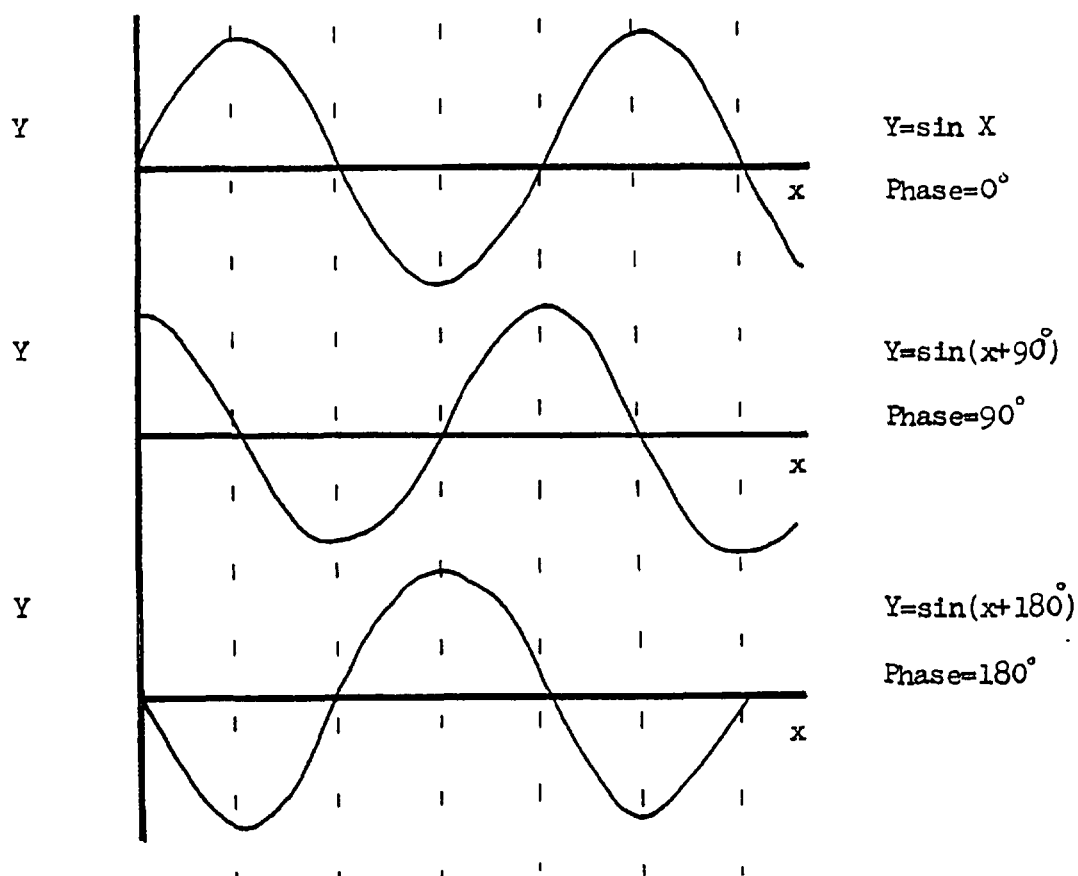


Fig. 1.5 Phase angle relationships

Detection depth for the full scale S.C.M.		
Pit radius depth = 65 cm	Max. topsoil thickness d_m , cm	
	Conducting pit	magnetic pit
28 cm	14	43
45 cm	29	59

Fig. 1.6 Detection depth for the Soil Conductivity Meter

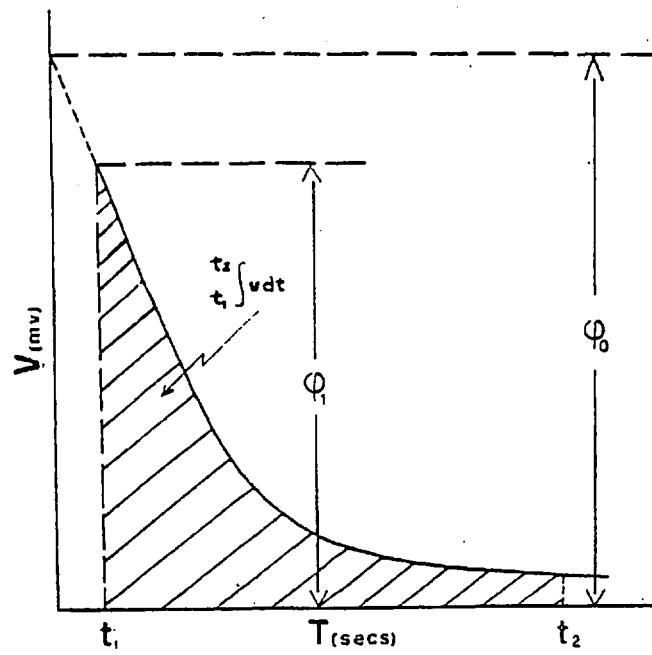


Fig. 1.7 Variation of induced polarization with time following the termination of the energising current at time $T = 0$ secs.

Material	$\sigma, \text{ohm}^{-1} \text{m}^{-1}$	ϵ_r	μ_r	$\alpha, \text{db} \cdot \text{m}^{-1}$	β, m^{-1}	γ, ohm^{-1}	η, ohm	Z, ohm
Air	0	1	1	0	30	377	0	7.1
Pure water	10^{-3}	81	1	0.18	3.3	42 ± 10.046	$2.1(10^{-2})$	19
Sea water	4.0	81	1	330	1.5	10 ± 19.4	78	42
Sandy soil, dry	$1.4(10^{-4})$	2.6	1	0.14	19	240 ± 11.2	$1.7(10^{-2})$	3.3
Sandy soil, wet	$6.9(10^{-3})$	23	1	2.3	6.0	75 ± 11.9	0.28	10
Loamy soil, dry	$1.1(10^{-4})$	2.5	1	0.12	19	240 ± 10.95	$1.5(10^{-2})$	3.3
Loamy soil, wet	$2.1(10^{-2})$	19	1	7.9	6.9	85 ± 18.5	0.91	9.2
Clayey soil, dry	$2.7(10^{-4})$	2.4	1	0.28	19	240 ± 12.4	$1.2(10^{-2})$	3.2
Clayey soil, wet	$5.0(10^{-2})$	15	1	20	7.4	87 ± 124	2.3	8.6
Iron	10^6	1	10^4	$1.7(10^7)$	-	$2.0(1 \pm 1)$	$2.0(10^4)$	$2.0(10^5)$
Copper	$5.8(10^7)$	1	1	$1.3(10^6)$	-	$0.0053(1 \pm 1)$	$1.5(10^3)$	$1.5(10^3)$
Basalt, wet	10^{-2}	8	1	5.6	11	130 ± 114	0.65	6.0
Granite, wet	10^{-3}	7	1	0.62	11	140 ± 11.8	$7.2(10^{-2})$	5.5
Shale, wet	10^{-1}	7	1	45	8.3	70 ± 148	5.2	7.6
Sandstone, wet	$4(10^{-2})$	6	1	24	11	110 ± 152	2.7	5.8
Limestone, wet	$2.5(10^{-2})$	8	1	14	11	120 ± 134	1.6	5.9

σ = conductivity
 ϵ_r = relative permittivity = $\frac{\epsilon}{8.85(10^{-12})}$; μ_r = relative permeability = $\frac{\mu}{4\pi(10^{-7})}$
 $\gamma = \alpha + j\beta = \sqrt{j\omega(\sigma + j\omega\epsilon)}$ = propagation constant, where ω = angular frequency = $2\pi(10^8) \text{ s}^{-1}$
 $\alpha = 20 \log_{10} e$ = attenuation
 $\beta = \frac{\omega}{v}$ = phase velocity
 $\eta = \sqrt{\frac{j\omega\mu}{\sigma + j\omega\epsilon}}$ = characteristic impedance

Fig. 1.8 Electromagnetic parameters for some materials at a frequency of 100MHz; data from Morey(1974), Keller(1966) and von Hippel(1954)

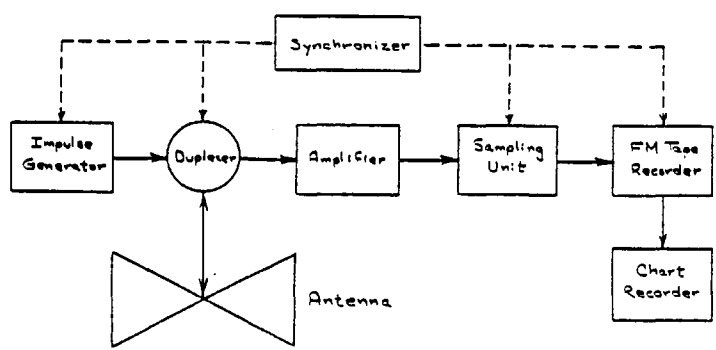


Fig. 1.9 A block diagram of the radar system

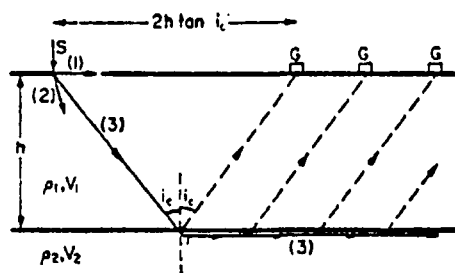


Fig. 1.10 Critically refracted ray path(full line) and a set of rays of the 'head wave' pulse(broken lines)
(After Griffiths and King, 1975)

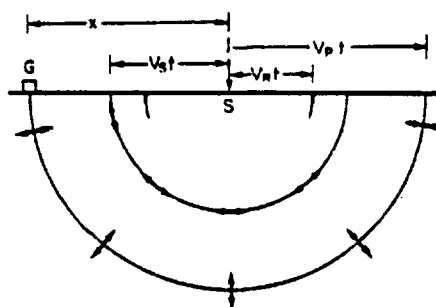


Fig. 1.11a Pulse fronts of the P, S and R wave types at a time t msec after their initiation at the point S
(After Griffiths and King, 1975)

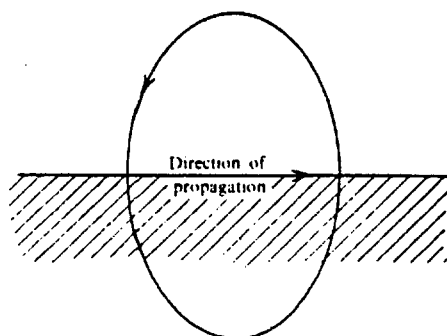


Fig. 1.11b Motion during passage of a Rayleigh wave
(After Telford et al., 1978)

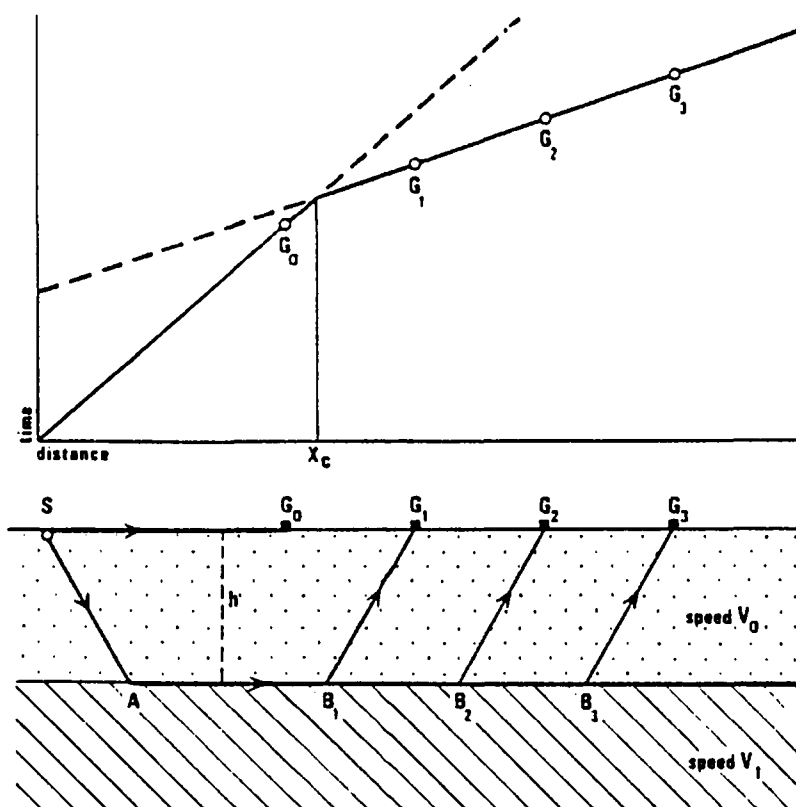


Fig. 1.12 Ray paths of refracted seismic waves arriving first at geophones and, above, time-distance plot of direct and refracted waves

(After Dunning, 1970)

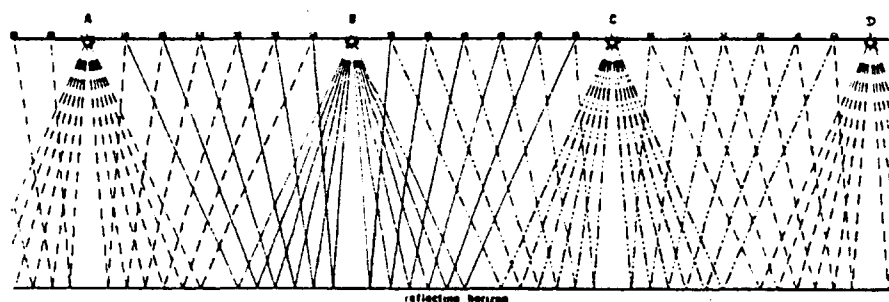


Fig. 1.13 'split-spread' shotpoint-geophone arrangement used in continuous-coverage reflection shooting

(After Dunning, 1970)

CHAPTER 2

MAGNETIC SURVEYING

Introduction

A measured magnetic field is a summation of effects from various depths: earth's magnetic field, broad crustal features, local geology and archaeological features. Any magnetic map will therefore be complex in nature and exhibit large variations. The dipole magnetic field is characterised by differences in magnitude and variations in direction. Measurement relies on detecting a contrast in magnetization between a feature and its surroundings. This magnetization will be the result of a feature's remanent (permanent) magnetization and its induction in the earth's magnetic field. Induced intensity relies mainly on the nature of the magnetizing field and the magnetic susceptibility whereas the remanent magnetization generally depends on the geological history.

Discussed are the various types of magnetization with reference to the geological context and, inherently related, the magnetic susceptibility of a number of materials. Since Le Borgne's first experiments (Le Borgne, 1955a), the various mechanisms which can lead to enhanced susceptibility of soils are better understood as well as their great importance to the detection of near surface and archaeological features.

2.1. Principles of Magnetostatics

2.1.1. Geomagnetism

Primary to magnetostatic potential is the dipole field which can be given by the scalar potential function (Telford et al, 1978):

$$F(r) = -\nabla A(r) \quad (2.1)$$

where F is the force in dynes and r a unit vector; the minus sign denotes

the attraction of the force. All units are cgs electromagnetic units.

This is based on the existence of a geomagnetic field which can be seen as the field of a dipole situated at the centre of the earth. The dipole exhibits a magnetic moment which points towards the geographical south. Magnetic poles always exist in pairs - known as dipoles - and their magnetic moment is defined as:

$$M = m \ell \mathbf{r}_1 = M \mathbf{r}_1 \quad (2.2)$$

where M is a vector pointing towards the unit vector $\mathbf{r}_1$ which extends from the negative pole $-m$ separated from the positive pole $+m$ by a distance ℓ .

A magnetic field existing at a point in space exhibits a magnetic field strength H , seen as the force exerted on a unit pole:

$$H = F / m' = (m/\mu r^2) \mathbf{r}_1 \quad (2.3)$$

where m' represents the fictitious pole at a point in space (or the measuring instrument); μ is the permeability of the surrounding medium, typically 1 in a vacuum and practically 1 in air; $\mathbf{r}_1$ is a unit vector; in electromagnetic units H is measured in oersteds (dynes/unit pole).

On being placed in an external magnetic field, a magnetic body will become magnetized by induction. This process involves the alignment of dipoles within the material to the direction of the external field. The intensity of magnetization will be proportional to the strength of this field and is known as the magnetic moment per unit volume:

$$I = M / v = J \mathbf{r}_1 \quad (2.4)$$

In turn the magnetic susceptibility determines the amount of magnetization a body can acquire, that is:

$$k = J / H \quad \text{or} \quad I = kH \quad (2.5)$$

where k is the volume susceptibility and depends on the amount of magnetic material in a given body. With rocks, for instance, the susceptibility

changes with the amount, form and composition of these magnetic minerals.

A group of magnetic dipoles, whether placed at random, although to a certain extent aligned through induction in the earth's field, or exhibiting a specific alignment (residual magnetism), provide a magnetic anomaly with a vector dipole moment per unit volume. This quantity is known as $M(r)$. The dipole nature of the magnetic field makes the calculation of anomaly strength a difficult task involving a large number of assumptions concerning the direction of magnetization, as well as any misorientation of the magnetic moment owing to residual effects. Furthermore, one has to have some knowledge as to the geometrical shape of the anomalous body. In practice calculations of the magnetic field of a geological structure are approximations, which are compared with surface observations. A satisfactory fit between the two is then obtained by adjusting the depth and dimensions of the structure. Usually spheres, ellipsoids, infinitely long cylinders or combinations of these are used in the modelling process. Needless to say, geological structures rarely meet these shapes. The techniques involved and some of the problems are briefly outlined in section 2.2.10.

As has been pointed out, the geomagnetic field comprises a number of different fields:

(1) Main Field - this can be divided into the dipolar field and the field caused by regional anomalies. The magnetic flux density vector consists of various elements (Fig.1.1). These are the magnitude of the main field (F), the inclination from the horizontal (I), and its declination (D), the angle between magnetic north and true (geographical) north.

The field further consists of the vertical Z (or V) component, and the horizontal H component with its positive components X and Y (X points to the north and Y to the east). Z is considered positive if it points downwards, as generally in the northern hemisphere, and negative if it points upwards as common in the southern hemisphere.

The earth's magnetic field at any point on the surface is therefore defined by the values of F, I and D. Both intensity (F) and inclination (I) depend strongly on the latitude.

The inclination (I) is given by $\tan^{-1} Z/H$ and forms an important factor in anomaly interpretation. Magnetic north and south poles are those points where $I = \pm 90^\circ$ as distinct from the geomagnetic poles. The magnetic equator is the imaginary line on the earth's surface that indicates the points at which $I = 0$.

All these statements are related to each other as follows:

$$F^2 = H^2 + Z^2 = X^2 + Y^2 + Z^2 \quad (2.6)$$

where F is the magnitude of the geomagnetic field. It is quoted in *nano-Tesla* (gammas (γ)) and typically 48,000 γ in Britain. The main field is not permanent and has shown extensive variations (termed secular variations) utilised in the techniques of palaeomagnetic dating.

(2) External Magnetic Field - this is probably caused by electric currents in the ionized layers which form part of the outer atmosphere and consists of a number of elements:

- a) 11-year cycle which depends on sunspot activity and of little significance in geophysical prospection.
- b) Lunar diurnal variations, cyclical in nature and with minor effect: variation of approximately 2 γ lasting up to 25 hours.
- c) Solar diurnal variations which occur daily over a 24-hour period and are of important concern. They are generally predictable and may exhibit changes of up to 100 γ or more. In mid-northern and mid-southern latitudes the diurnal variation decreases to a low at mid-day and then increases to a high in late afternoon, altogether a daily change of some 20 γ .
- d) Magnetic storms occurring as often as a couple of times a month and lasting from one to several days. They may produce

disturbances of up to several hundred gammas, or more as in the polar regions.

- e) Micropulsations of short-term nature (e.g. 10 minutes), random in behaviour and small in amplitude. These can occur at any time of the day or night exhibiting changes of approximately $0.1 - 30\gamma$, lasting from 0.01 seconds up to several tens of minutes.

(3) Anomalous Fields - this forms the main interest in prospecting. Variations in the main field (total magnetic intensity) are caused by differences in the magnetic mineral content of rocks and soils, iron objects or archaeological features.

2.1.2. Rock, Soil and Mineral Magnetism

These form the main cause of magnetic anomalies. The various magnetic minerals will react differently to an applied field (e.g. earth's magnetic field).

All magnetic materials can be grouped according to their magnetic properties:

- a) Diamagnetic - dependent on an applied field but independent of temperature; a substance with no paired electrons will develop a magnetization in opposition to the applied field.

On removal of the field, this magnetization disappears. The induced magnetic moment is proportional to an applied field over a wide range, the net effect of which is a small negative susceptibility.

Graphite, quartz and salt are some of the most diamagnetic materials, although geologically negligible.

- b) Paramagnetic - on application of a magnetic field, a substance with unpaired electrons will follow the prevailing line of magnetization. On removal of the field, thermal fluctuations leave a randomized magnetization.

Induced magnetic moment is proportional to an applied field over a wide range, the main characteristic of which is a small positive susceptibility.

- c) Ferromagnetic - an applied field induces a strong magnetic moment in certain substances such as cobalt, iron and nickel. Unpaired electrons magnetically coupled with neighbouring atoms exhibit a strong magnetization without an applied field. An external field has no effect on the direction of magnetic alignment and in effect increases it (Fig. 2.2a).

On heating above the Curie temperature (T_c) a ferromagnetic substance loses its ferromagnetism and retains a paramagnetic moment.

Its main characteristic is a large susceptibility. Iron, nickel and cobalt are important ferromagnetics.

- d) Ferrimagnetic - certain substances have their magnetic dipoles aligned in opposite directions, with one direction dominating the other and exhibiting ferromagnetic behaviour but to a weaker extent (Fig. 2.2b).

Amongst these substances, the ferrites form the most important elements in soil magnetization.

The net magnetization is weaker than that of the ferromagnetics.

- e) Antiferromagnetic - in these substances the number of magnetic dipoles oppositely aligned are equal, thereby cancelling their magnetic moments (Fig. 2.2c). Very often, though, the neutralizing of magnetic moments is not perfect. This results in a small magnetization referred to as parasitic ferromagnetism. Lattice defects are probably responsible.

Haematite is a common antiferromagnetic mineral.

2.1.3. Domains

Within a substance the way in which the dipoles align themselves is governed by 'easy' directions of minimum energy. This process and the resulting conflict caused by the magnetostatic forces acting on the magnetocrystalline structure, creates magnetic domains within each particle. These are oriented along the 'easy' directions and separated from each other by so-called Bloch walls, narrow zones where the individual dipoles gradually reverse their magnetic alignment (Fig. 2.3a). The conflict between the magnetostatic and magnetocrystalline forces is resolved as the system tries to minimise the free energy within it.

When no external magnetic field is present, the domains form closed loops within the particles. This reduces the magnetic energy. On application of an external field, this state of near equilibrium is brought about by a new process of alignment of the domain patterns and by causing some domains to increase in size. (Fig. 2.3b).

In some fine-grained materials, the particles may be so small that only single-domain grains are available. These particles exhibit a higher magnetic susceptibility than multidomain grains: often characterised as 'hard' magnetization. Most important in soil magnetization are particles with a grain size of around 30 nanometer radius (nm). The various magnetic properties of diamagnetic and paramagnetic minerals

remain unaltered when related to grain size and dilution. This contrasts with ferrimagnetic materials where a complex relationship exists between the two abovementioned factors.

2.1.4. Magnetic Susceptibility

Rock and soil susceptibility varies according to the amount, composition and form of the magnetic minerals they contain. Attempts at relating the susceptibility to the ferrimagnetic mineral content of rocks have established a statistically significant correlation between the two (Fig. 2.4).

On application of a magnetic field (H) to an unmagnetized ferromagnetic sample, its susceptibility (X) is given by the initial increase in magnetization (M or B):

$$X = M/H \quad (2.7)$$

As the field is gradually increased, the intensity of magnetization reaches saturation (M_{SAT}) in a magnetic field (H_{SAT}).

When the intensity of magnetization reaches zero, the reversed field equals the coercivity of the material (H_{CR}) in strength. The relationship between B and H results in the characteristic hysteresis loop (Fig. 2.5).

Every magnetic mineral will have a typical magnetization curve with diverse values for H_{SAT} and k (or X). Usually the field H is equivalent to the earth's field when determining the magnetic susceptibility of a material.

Susceptibility values for rocks and soils vary widely. In rocks, basic igneous rocks exhibit the highest values with sedimentary rocks giving lower ones. Within a given rock type, the susceptibility distribution is generally similar according to a log-normal form: logarithms of the values indicate a Gaussian (symmetrical) distribution.

The average value $\bar{M}$ and the standard deviation are calculated on the logarithms according to

$$\bar{M} = \log^{-1} \frac{\sum_1^N \log x}{N} \quad s = \log^{-1} \left\{ \frac{\sum_1^N (\log \bar{M} - \log x)^2}{N - 1} \right\}^{\frac{1}{2}} \quad (2.8)$$

where N represents the number of specimens, each with a susceptibility value x .

2.1.5. Residual Magnetism

This will depend upon the magnetic history of the rock or soil and often contributes to the permanent magnetization. It is known as natural remanent magnetization (NRM) and can be divided into several types:

- a) Detrital magnetization (DRM): the magnetic particles present in sediments occurring in calm water, align themselves to the prevailing magnetic field. Rotation of the particles reduces the inclination; however, the azimuth will be preserved.

Archaeomagnetic data are provided by the DRM of lake sediments and glacial varves. At the same time the DRM of deep-sea sediments provides valuable information on geomagnetic reversals.

- b) Chemical remanent magnetization (CRM): prolonged water immersion, prolonged weathering as well as the inclusion of organic material in a sample can lead to the acquisition of chemical remanence. This is caused by the formation of a magnetic mineral within a sample due to chemical change. The remanent magnetization aligns itself to the prevailing magnetic field and is of high stability.

- c) Thermoremanent magnetization (TRM): very fine ferromagnetic particles, which are smaller than the domain size, exhibit an extremely short decay time in their magnetization. Therefore they do not hold any remanence and change rapidly in magnetic field direction according to any change in the applied field. Larger particles can hold their remanence longer, exhibiting a higher remanence time. This is where TRM comes into play.

Upon cooling from above its Curie temperature, certain particles reach their blocking temperature at which the prevalent direction of magnetization is blocked indefinitely. This magnetization represents the field direction at the time of cooling (i.e. earth's magnetic field) and its relaxation time can be comparable to the geological time scale. Magnetization thus acquired is known as TRM. In rocks most of it is obtained within approximately 50°C of the Curie temperature - e.g. between 400 - 600°C for the ferromagnetic constituents. The magnetic susceptibility (X) reaches its peak at the Curie temperature and then gradually falls off (Fig. 2.6).

Both relaxation and remanence depend on particle volume and temperature giving rise to Thellier's law of partial TRM (Fig. 2.7). This represents an idealized curve for baked clay. Magnetite (multi-domain) and haematite (single domain), two important constituents of clay, have a Curie point of respectively 565°C and 675°C. As the blocking temperature (T_B) depends on grain size and the material, a whole series of blocking temperatures exist. The curves give the decrease in magnetization during cooling and the gradual demagnetization (upon cooling) of a sample when occurring in a zero magnetic field.

Baked clays are successfully used in archaeomagnetism as well as providing strong magnetic anomalies in the form of kilns and baked clay tablets.

- d) Viscous remanent magnetization (VRM): in an applied field and below Curie point, some substances build up a time-dependent remanence related to the amount of thermal agitation. This is especially pertinent to single domain grains as the magnetocrystalline structure cannot reach a state of magnetic equilibrium by enlarging the domains. They can only reduce the magnetostatic force by reversing their direction of magnetization. A single domain grain will therefore build up magnetic energy to enable subsequent reversal.

Monodomain material with a grain size of 20nm - 40nm tends to be most susceptible to viscosity effects. This especially applies to maghaemite. Paramagnetic materials are however not viscous.

Certain deep-seated igneous rocks acquire a high temperature viscous remanence at temperatures 100 - 200°C below the Curie point. The same applies to deeply buried metamorphic rocks when exposed to prolonged regional heating effects (also partially CRM).

Viscosity effects are particularly important when predictions are made concerning theoretical values for archaeological anomalies in modelling their expected response. Viscosity is also virtually independent of field strength but related to the concentration of iron oxides and their distribution within a substance. The increase with time of the magnetic moment of a sample is given by:

$$M_t = M_0 (1 + V_c \log t/t_0) \quad (2.9)$$

where M_t is the magnetic moment at time t , M_0 is the magnetic moment at a defined time t_0 , and V_c is the viscosity constant at t_0 . Its effects tend to be more pronounced with low iron oxide concentrations highly distributed in a non-magnetic matrix for example. This does not however hold true at very low iron oxide levels.

In the absence of an applied field, the domain wall gradually collapses and the net magnetic moment will decrease.

Overall the temperature and strength of the magnetocrystalline and magnetostatic forces of the material determine the extent of the decay or the acquisition of VRM.

- e) Isothermal remanent magnetization (IRM) and an-hysteritic remanent magnetization (ARM): the former occurs when a sample is exposed to high magnetic fields which break down the coercive force of some magnetic domains. On removal of the external field, the sample retains its IRM. ARM is associated with strong alternating fields in conjunction with weak steady ones and can be produced by lightning or during sample demagnetization (earth's magnetic field not properly cancelled).

2.1.6. Parent Material

Rocks and soils contain magnetic minerals, the most important of which are the iron-titanium oxides generally found in sediments as detrital particles and in igneous rocks.

a) Iron-titanium oxides in igneous and metamorphic rocks

Iron-titanium oxides are generally found in igneous and metamorphic rocks and their detritus. Of these, magnetite - which consists mainly of

iron, oxygen and titanium - is the most common, representing up to 5% of a rock. Magnetite in itself is a loose petrological term. In the diagram (Fig. 2.8) the dotted lines give the average chemical composition of the Fe - Ti oxides in the majority of igneous rocks. The arrows denote the direction of increased oxidation with constant Fe:Ti ratio, whereas the solid lines provide the more common compositions such as ulvospinel (or ulvite, Fe_2TiO_4) and true magnetite (Fe_3O_4) for basic igneous rocks. These form the titanomagnetite series, which is rich in iron and magnesium. Ulvite is an antiferromagnetic mineral and true magnetite a ferrimagnetic mineral.

A second series is formed by the ilmeno-haematites, which are characterised by the ready availability of oxygen within the rock. Its main constituents are ilmenite (FeTiO_3) and haematite ($\alpha\text{Fe}_2\text{O}_3$) and their intermediate compositions. Both minerals are basically antiferromagnetic. Haematite also has a small amount of ferromagnetism of questionable origin. It is a very important magnetic mineral and can originate by the oxidation of the titanomagnetites or the exsolution of the ilmeno-haematites. It can also originate from the decomposition of other minerals, a process associated with weathering. Very high oxidation rates cause haematite to break down into goethite ($\gamma\text{FeO.OH}$) and iron hydroxides known as limonite. Haematite is especially important in palaeomagnetic studies.

Inbetween the two series, as the rock becomes more acidic owing to a higher silica content, the increased oxygen levels enable a high oxidation rate. Magnetite (Fe_3O_4) will then oxidise to maghemite ($\gamma\text{Fe}_2\text{O}_3$) and through exsolution into magnetite with ilmenite.

The next important group of magnetic minerals is that of the iron sulphides. These are commonly associated with sedimentary rocks as well as igneous and metamorphic rocks.

b) Iron-sulphides in sedimentary rocks

Sedimentary rocks generally consist of the detrital particles and biochemical deposits of other rocks which have been compacted and are mostly held together with a calcareous or siliceous cement. The weathered products contain, amongst others, silicates and the hydroxides of iron-titanium oxides. All of the diagenetic processes favour the formation of haematite. It is therefore the most important magnetic mineral present and often acquires a chemical remanence. The iron oxide pyrrhotite is also an important though less common magnetic mineral. It varies in composition between troilite (FeS) and pyrite (FeS_2) and exhibits differing magnetic properties.

Ferrimagnetic and antiferromagnetic properties of rocks are normally classed as ferromagnetic. This distinguishes their adherence to their strong spontaneous magnetism and field alignment even after the removal of the external magnetic field.

Other prevalent iron-bearing magnetic minerals tend to be paramagnetic. The magnetism of some clays and micas can be caused by the inclusion of haematite or magnetite. ^{Other} Rust-coloured iron oxide particles, however, are of no influence and exhibit only a very small magnetism.

2.1.7. The Measurement of Magnetic Susceptibility

On placement of a magnetizable substance in an applied field of intensity H , the intensity of magnetization which the body acquires is denoted by J (J). The ratio of these two is the magnetic susceptibility per unit volume given by K . Magnetic permeability, or μ , relates to the magnetic susceptibility as:

$$K = \mu - 1, \text{ MKS units, or} \quad (2.10)$$

$$K = (\mu - 1) / 4\pi, \text{ for the commonly used CGS units.} \quad (2.11)$$

A varied number of techniques exist for the measurement of K, the simplest of which are described below. Essentially, the available methods can be divided into three groups:

- (1) An applied field, of which the strength has been determined, is used to magnetise a substance. A balance is then used to ascertain the attraction of the magnetized sample in a field gradient. Soil samples are generally inhomogeneous and also large. Therefore this technique is less suited for such samples as it can generally only accommodate small samples. It also required large fields to enable accurate measurements. Soils, however, often exhibit interesting properties at low fields.
- (2) Electrical methods which rely on the alternating field produced when a magnetized sample is moved in a coil system. Alternately, one can apply an electrical field to a sample which is then suddenly switched off. This causes the decay of the magnetic moment in the sample. A ballistic galvanometer integrates the induced current in a coil system as the magnetic moment decays. Apart from only working with strong samples, this technique is susceptible to strong sample viscosity effects which make readings difficult and unreliable.
- (3) Static low field techniques using bridge balance systems (Scollar, 1968a) or a translation magnetometer as suggested by Thellier (Scollar & Graham, 1972/3). The inductance bridge method employs a modified Owen or Maxwell a.c. bridge which is balanced resistively. Calibration can either be done for a given range providing instant susceptibility read-out or by comparison with a standard sample. The inductance method is generally applied to archaeological soil samples and a brief description follows:

A sample is placed in one of two large identical coils which form the opposite arms of a Maxwell bridge. The other two are stable resistors. The induced magnetic moment in the sample unbalances the bridge and the corresponding signal is amplified before being passed on to a phase detector and integrator. The output is then shown on a zero-centred meter. One then restores the balance of the bridge by means of a variable resistor and capacitor. The final resistance (in essence impedance for a.c.) value will then indicate the susceptibility. The bridge uses a.c. current. Therefore a sample only has a magnetic field applied for a very brief time before field reversal. As the inducted magnetic moment in the sample will be too short in duration to accurately give the same value under normal field conditions (i.e. earth's magnetic field) the measured value has to be multiplied by a constant. This is further described under section 2.2.8.

Other corrections may also have to be made:

- (a) Sample diameter: if not kept constant, the measured value must be multiplied by the square of the ratio of standard sample diameter to actual sample diameter, e.g.:

$$X = R \left(\frac{50}{\text{sample diameter, mm}} \right)^2 \quad (2.12)$$

where 50 mm is the standard diameter value and R the measured value; X is the true susceptibility.

When going by sample weight, the following simple calculation has to be applied:

$$\frac{R \times 50}{M} = X \times 10^{-6} \text{ emu.gm} \quad (2.13)$$

where R is the obtained susceptibility reading and 50 denotes

the calibration point for the meter (50 g calibration sample).
M is the sample weight in grams. This takes care of air gaps within the sample.

- (b) Viscosity effects: the measured magnetic moment of a fine-grained ferrimagnetic material when highly diluted in a diamagnetic substance and placed in a weak magnetic field, will gradually increase with time. Soils often contain ferrimagnetic material whose susceptibility is dependent on the time taken to measure it. Paramagnetic salts however do not exhibit this time dependence.

By using an a.c. bridge such problems are partially resolved. A frequency of 1175 H allows the peak field to be reached in 213 microseconds, which still leaves one in a quandary as to the effective applied field time. This makes any estimate of viscosity effects difficult.

Static low field techniques have been successfully applied to archaeological soil samples and enable an accuracy of $\pm 2 \times 10^{-6}$ emu per gram for a 100 g sample. The latter is especially useful for susceptibility measurements of weakly magnetic soils.

2.1.8. The Measurement of Remanent Magnetism

Measuring chemical, depositional, isothermal, natural thermo-remanent and viscous magnetisation poses its own problems. One method is to use an astatic magnetometer - two tiny magnets of equal moment suspended from a torsion fibre and with poles opposing each other mounted in a horizontal plane - with samples placed in differing orientations providing various angular deflections. The magnetic field gradient

caused by the sample is measured (Fig. 2.9a).

Another technique involves the moving sample or ballistic magnetometer in which the sample is moved axially between the centres of two coils. These are connected in series opposition and placed in a constant and uniform magnetic field. On moving the sample, a change induced in the coils is measured by the ballistic galvanometer providing the magnetic moment (Fig. 2.9b).

Another alternative is given by the spinner magnetometer. The specimen is spun near a coil. It induces an alternating voltage, the phase and intensity of which are compared to a reference signal and a fiducial mark on the rotating head which provides a fixed phase (Fig. 2.9c).

2.1.9. Instruments for Magnetic Field Surveys

These are described in great detail elsewhere in the literature (Telford et al, 1978, pp. 123-139). Therefore a brief summary, with special relevance to the instruments used in near surface and archaeological surveys, will suffice.

In essence these are the main forms: absolute, differential and gradiometer. This refers to the way in which the signal is measured by the instrument:

- a) Absolute: use of single sensor which measures the absolute value of the total magnetic field.
- b) Differential: use of two detectors with one detector measuring the magnetic field at a fixed point while the other detector is moved around from station to station. The signal from one detector is automatically subtracted from the other, thereby avoiding the effects of diurnal variation.
- c) Gradiometer: use of two sensors mounted above each other on a vertically held staff. In a magnetic field the sum of the signals from both the sensors will be identical if the field equally affects

both sensors. If this is not the case, as with local anomalies, then the signals will be out-of-phase as each sensor will indicate a difference in signal appropriate to the local magnetic field. In effect, the vertical gradient of the total field is measured.

Proton Magnetometer (Nuclear precession magnetometer)

This relies on the free precession of protons in a magnetic field and measures the total ambient field of the earth. Water or kerosene contains a large number of protons which have a high magnetogyric ratio as based on the principles of nuclear magnetic resonance. When contained within a detector bottle around which a coil has been wound, they will align themselves parallel to the magnetic field of a current passed through the coil. On removal of this field, the protons precess round in the direction of the prevalent earth's field. The frequency of precession, the Larmor frequency, is given by:

$$\frac{\mu}{2\pi p} F \quad (2.14)$$

where μ denotes the magnetic moment and p the angular momentum of the intrinsic spin. F is the prevalent magnetic field. Both μ and p are constants, therefore the Larmor frequency only depends on F .

The signal derived from the proton precession is amplified and passed on to a frequency measurement circuit e.g. phase-lock system. This must measure the frequency with great accuracy i.e. for a measurement sensitivity of 1 γ and an ambient field of 50.000 γ , the measured frequency will be 2000 Hz $\pm$ 0.04 Hz.

A number of liquids such as methanol, ethyl alcohol etc. are also suitable, although they exhibit differing relaxation times. That is the decay of the proton signal owing to its gradual alignment with the earth's field and the interference caused by the magnetic fields of neighbouring protons. The relaxation time also determines the length of the

polarizing field through the detector coil. By shortening the polarization period one can speed up the measurements, although at the same time reducing the length of time for signal measurement and therefore the accuracy.

Signal decay is also affected by the measured gradient, with strong gradients causing a rapid decay of signal.

Differential Proton Magnetometer

Basically one sensor is used as a reference source at a fixed location while the other one takes the measurements. The set-up can be a dual instrument in which the results from the reference source are automatically subtracted from the readings.

This avoids some of the problems encountered with the proton magnetometer such as the effects of diurnal variation and interference from d.c. railway lines if the latter occurs at great distance relative to the detector separation.

Proton Gradiometer

This system incorporates two detectors mounted at a fixed distance - approximately 1 m - on a vertically held staff (Aitken, 1960). It measures the vertical gradient of the geomagnetic field. In essence it is a differential magnetometer with a fixed spacing between sensors such that their position of measurement, Δr , is small compared to the distance, r , of the source whose gradient is to be measured. The gradient can be defined as

$$\frac{\Delta T}{\Delta r} \sim \lim_{\Delta r \rightarrow 0} \frac{T_r - T_{r + \Delta r}}{\Delta r} = \frac{dT}{dr}$$

where $\Delta T = T_r - T_{r + \Delta r}$ is the total field difference between the two sensor positions, Δr relates the distance between them, and dT/dr is the

derivative (or gradient) of T in the direction of r , while $\Delta r \rightarrow 0$ states that Δr must be small compared to the distance r .

Therefore the measured gradient is either expressed in gammas per metre in the direction of r , or as the vertical gradient dT/dz in the direction of z . As the gradiometer anomaly from a dipole varies as $1/z^4$ that is the difference in intensity between the two nearby sensors is very large for local anomalies with respect to the difference in intensity for distant sources, it effectively acts as a filter by removing the regional gradient.

The advantages of the gradiometer arrangement are:

- 1) better definition of local shallow anomalies;
- 2) increased resolution of complex features;
- 3) use of vector properties in order to determine anomaly depth and location;
- 4) insensitivity to diurnal variation.

A gradiometer using the beat frequency system (different field intensities $\rightarrow$ difference in frequency between two sensors) was developed for archaeological work. However, it is extremely tedious and frustrating to use. Further drawbacks are its low sensitivity ($>5\gamma$), and the severe interference caused by a.c. power lines and car ignition systems (Tite, 1961).

In most archaeological survey work the uppermost detector is approximately 1.5 m from the ground with the lower one kept at 30 cm. The detector height varies with expected anomaly size, with the distance between the two detectors preferably equal to the supposed depth or size of the anomaly, depending on ones preference. Any increase in detector height, however, displaces the actual anomaly position further to the south (in mid-northern and southern latitudes) (Whitwell and Wood, 1969). The latter relates to the angle of dip (I) where a decrease in I results

in a decrease in the strength of the normal anomaly (main signature of the total magnetic field intensity) with its maximum displaced to the south. On approaching the geomagnetic equator ($I = 0^\circ$) the reverse anomaly (decrease in total field intensity) becomes predominant. The southward shift specifically applies to a north-south traverse across an anomaly (see section 2.3.3).

Fluxgate Gradiometer

The actual fluxgate detector consists of a high permeability core around which a primary and a secondary coil are wound. Two cores are generally used and these are mounted parallel with their primary windings in series opposition and with the secondary windings connected to a differential amplifier. The high permeability of the core allows it to be easily saturated in weak magnetic fields. A low frequency ~~regulated~~ current is applied to the primary windings which saturates them in opposite polarity. In the absence of an external d.c. magnetic field the outputs of the two secondary coils will be zero. As soon as the coils are magnetized by an external field parallel to the cores, this arrangement is upset, and the resultant differential voltage between the two secondary windings is amplified. In archaeological prospection use is made of a gradiometer configuration with the two fluxgate sensors mounted at a set distance on a vertically held staff (Allred and Aitken, 1966; Philpot, 1972). Problems with the staff rigidity limits the distance between the two sensors to approximately 1 m. Any increase of the sensor separation would aid the instruments' sensitivity which is practically limited to $\pm 3 \gamma$.

The fluxgate offers a continuous signal enabling rapid site scanning and coverage. It measures the relative field: usually the vertical component. Anomalies affect the sensors in the same way as with the proton gradiometer: the lower sensor responds more strongly to local

magnetic anomalies than the top one. Similarly, the vertical gradient of the anomaly will not be fully represented by the instruments' indicated field strength as the top sensor is also slightly affected. Wider geological changes will affect both sensors equally and will therefore be of minor influence.

Its further advantages are that it can be operated in areas of strong gradients (unlike the proton magnetometer) and is less susceptible to overall surface noise. However, it does enhance shallow noise sources. When carrying the instrument it is important to hold it as near vertical as possible. Any tilt introduces an error signal: a tilt of up to 10% influences the measured gradient in a disturbed field by 2%.

Atomic Absorption Magnetometers

These are based on 'optical pumping' and the Zeeman effect. The complex theory of operation has been explained in great detail elsewhere (e.g. Bloom, 1962). Therefore only a brief outline will be given. The energy levels of electrons are split into sublevels or Zeeman states when subjected to an external magnetic field such as that of the earth. By irradiating a gas with a suitable light beam, atoms in a lower Zeeman sublevel will absorb energy and rise to Zeeman sublevels of a higher energy. This process is known as optical pumping. Elements found suitable for the purpose of atomic transitions are caesium, rubidium, helium and sodium.

In practice a beam of light inclined at 45° to the earth's field direction, excites the atom in a vapour cell and then focusses on a photocell. The inclination of the beam causes the electrons to align themselves with the direction of the light beam. This is done by electron precession, similar to the process described for the proton magnetometer, and results in a variation of the beam light intensity modulated at the precession frequency. This is received by the photocell. After

amplification, the signal is fed back to a coil wound round the vapour cell, resulting in a self-oscillator system. The frequency is determined by comparison with a crystal-controlled reference oscillator (Fig. 2.10).

As with the proton magnetometer, the magnetogyric ratio ($\mu/p + g$) and the field intensity (F) determine the frequency at which the atoms precess about their axes. Magnetometers using this process are known according to the gas of which the energy transition level is determined.

Rubidium Magnetometer

Magnetometers of this type have fallen into disgrace in archaeological prospection. The instrument suffers severely from orientation errors, which limits its sensitivity. This in theory approaches 0.01γ (Ralph, 1964; Breiner, 1965). However, in practice it works out at approximately 0.1γ ($10^{-6} O_e$) when used in its absolute mode. Other problems include the instruments' sensitivity to external fields such as alternating current electromagnetic interference. Also, when used in its absolute mode, the determination of anomaly polarity and magnitude becomes difficult. This is in part caused by changes in the operating condition, e.g. temperature drift, further limiting its accuracy. In differential mode, one can achieve a higher sensitivity but large separations between the detectors tend to adversely affect the stability of the readings (Ralph, Morrison and O'Brien, 1968).

The instruments' advantages lie in its instantaneous read-out and immunity to gradients. Its high sensitivity makes it useful for surveys on weakly magnetic soils. It has also been successfully used in underwater archaeology (Langan, 1966).

Caesium Magnetometer

This instrument very much suffers from the same weaknesses as its counterpart, the rubidium magnetometer, although in many ways to a lesser

extent, such as the orientation of the light beam to the earth's field direction. Therefore sensor angle must be kept within 5° of optimum.

This has made it the preferred instrument for near-surface work, owing to its greater stability.

The main problem remains the prohibitive cost of the instrument.

This applies to any of the optically-pumped varieties.

Caesium gradiometer

Initially developed by MIT this is now in common use in applied geophysics.

The sensor arrangement is essentially similar to that employed for the proton gradiometer. Unfortunately its prohibitive cost has prevented its application in near surface work.

Other magnetometers such as squid magnetometers, have so far not been used in archaeology. The electron spin magnetometer, however, has (Boyer, 1970). This instrument offers low power consumption, stable operating conditions and less sensitivity to detector orientation (Collin et al, 1973).

2.1.10. Survey Procedures

The survey technique will primarily be determined by the nature of the area under survey and the data requirements.

Archaeological prospection has developed specific techniques which are discussed.

Detector height above the ground will be based on the suggested size of the sought-after buried features, the geological and overall noise level. If placed too low, plough marks and other surface irregularities will unduly affect the readings. Alternatively, too great a sensor height above the ground impairs the instrument's resolution towards any small anomalies. However, it does prevent oversaturation of the magnetic signal in the presence of very high magnetic gradients (e.g.

sizeable anomalies, ferrous metals etc.) as the sensor is moved to a lower gradient. Normally the sensor height varies between 20 - 100 cm with 30 cm representing a typical value. The amplitude of the signal varies as $\sin^2\theta$ with the angle between the direction of the applied field to the sensor and the direction of the earth's magnetic field. Therefore to obtain maximum response, the sensor must be orientated in an east-west direction making a right angle between the sensor applied field and the direction of the geomagnetic field.

The distance between subsequent measuring points is another important factor. As a guideline, this distance should exceed the sensor height by a factor of 2. A typical measurement distance is 1 m.

Surveys are generally based on grids, usually 30 x 30 m, although the site and instrument used will cause this to vary. A smaller grid size in the order of 15 x 15 m is advisable when using an absolute magnetometer. This will lessen the effects of diurnal variation. Traverse spacing is generally also 1 meter.

Prior to commencing a survey, a single traverse line can aid in setting up the instrument and in finding a suitable area on which to lay out a grid. When undertaking traversing, it is better to have quite long ones as the readings are not indicative of the exact position of an anomaly.

In areas of weak magnetic contrast, the use of an arbitrary zero can sometimes be useful. One takes a corner of the site as the zero level and any readings will be relative to this taking on either positive or negative values (Linington, 1970b).

The problem of changing earth gradients e.g. in the vicinity of d.c. railways can be reduced by moving the reference bottle used for diurnal linkage after every surveyed grid.

When using a single magnetometer one will have to correct the readings for diurnal variation. One way of doing this is by regularly taking readings at a base station, at least every 30 minutes. The

magnetic gradient at the base station should not vary significantly and the sensor orientation should be kept identical, preferably pointing east-west (mid northern and southern latitudes). The results from the reference station are expressed as variations from the common mean.

To avoid having to constantly walk back to often distant reference points, one can walk back to the beginning of each traverse and repeat the first reading. When no diurnal linkage is available between grids, these can be linked up by taking the individual mean for each grid and by adding or subtracting the difference of the mean from the individual data items. This could, however, give rise to false straight-line anomalies where the various grids are joined together (Wilcock, 1969). It is sensible to make preliminary evaluations and draw up maps based on the obtained results whilst surveying a given area. This will enable one to rectify or widen the scope of the survey and ascertain the overall performance. With large-scale surveys, this becomes especially relevant.

It is also very important not to rely too much on archaeological notions or preconceived ideas. However, any relevant information should be noted. Close cooperation between the archaeologist and geophysicist is pertinent.

2.1.11. Magnetic Scanning and Automatic Plotting

Magnetic scanning has proved to be a valuable asset of the fluxgate gradiometer. With this instrument one can successfully scan large areas and with great speed and ease of operation. This has been especially useful in rescue archaeology and in surveying large areas prior to the construction of motorways and pipelines. The method of operation is to carry the fluxgate across an area in a traverse-like pattern. Any anomalies - as based on the instrument's response - are marked and checked with an auger. Any interesting anomalies are drawn in on a map.

Attempts have been made to develop an automatic plotting system based on hyperbolic phase navigation. The system, as developed by Plessey for the Department of the Environment, uses two fixed transmitters and two receivers, one of which is stationary while the other is carried around with the fluxgate gradiometer. A phase comparator enables a resolution of $1/3$ cm and automatically triggers a data logger at 1 m intervals. The basic system offers single-axis location but a future dual-axis system should present a two-dimensional plot on a chart recorder. Instrument signals are represented as arcs of radius proportional to signal strength and accurately located.

Unfortunately the system completely failed in practice, one of the problems being the lack in power of the transmitter system. Also the theoretical resolution turned out to be a different matter under field conditions. However, the Department of the Environment independently developed a successful system of automatic recording (Clark and Haddon-Reece, 1972). Surveys are made on 30 x 30 m grids and the results are automatically recorded on an x-y plotter in the form of pseudo-perspective plots enabling instantaneous interpretation. Consecutive with the survey, the instrument readings (fluxgate magnetometer) are also recorded on a field data logger in digital format on magnetic tape. These pulses are then transferred to paper tape using a translator, enabling further processing by computer.

The above method allows a 30 x 30 m grid to be surveyed in 30 minutes.

2.1.12. Interpretation

Fundamental is the ambiguity of the potential field in interpretation. Anomalies are extremely varied in shape, often asymmetrical and generally consist of the magnetic effects of a number of sources. Their complexity relates to the overall results of the

independent behaviour of magnetic dipoles which are expressed by a number of functions. On the basis of these and certain assumptions concerning the anomaly shape, depth and local geology one can make a qualitative interpretation regarding most anomalies.

Quantitative interpretation applies more to airborne surveys and tends to be more complex.

The following represents a basic and simplified discussion of general magnetic dipole behaviour.

Essentially an anomaly is a local intrusion in the earth's magnetic field resulting in a local change in magnetization or magnetization contrast. The observed magnetic response is a combination of induced and remanent magnetizations usually exhibiting different directions and intensities. To simplify matters, interpretation is based on induced magnetization owing to the variability of remanent magnetization and an absence of its measured properties.

Asymmetry

This is typically a result of the differing directions of the magnetic field lines of an anomalous source and the nature of the local geomagnetic field. The latter, if measured by absolute methods, will represent that component of an anomaly which lies in the direction of the earth's field.

An anomaly can be seen as consisting of a combination of magnetic dipoles (monopoles), lines of dipoles and monopoles and blocks of such arrangements. Therefore one requires a proper understanding of the dipole or monopole field.

Anomaly response

Anomaly variation with depth significantly influences its signature: the deeper it is placed the broader the overall response (longer wave-

length).

Furthermore, anomaly signature will be influenced by the shape and form of an anomaly, its direction in the earth's field, the amount and direction of permanent magnetization, the amount of induced magnetization and the susceptibility contrast between the source and its surroundings.

To facilitate interpretation procedures use is made of much simplified geological models which exhibit a uniform magnetization e.g. intrusive, fault, vertical dike, dipping dike etc.

Dipoles and monopoles

The geometry and intensity characteristics of dipoles and monopoles form an important aspect in understanding magnetic anomaly response. Magnetic monopoles, although basically non-existent, are relevant in terms of their lines of flux in geological configurations and the distance to the source: if far apart the poles of a dipole are considered as a monopole; it appears as such to a magnetometer. The nature of a dipole magnetic field such as the earth is well known. Its intensity, T , can be expressed as:

$$T = \frac{2}{3} \frac{M}{r^3} \quad \text{along the axis} \quad (2.15)$$

$$T = \frac{M}{r^3} \quad \text{along a line at right angles to the dipole} \quad (2.16)$$

For a monopole the expression becomes

$$T = \frac{M}{2r} \quad \text{in any direction} \quad (2.17)$$

where M is the magnetic moment and r the distance to the pole.

On the basis of the above description and knowing the measured response of an absolute magnetometer one can determine the normalised (dimensionless) anomaly signature for any dipole orientation. The dip of

the earth's field (I), the configuration of field lines superimposed upon the earth's field (measured anomaly vectors), dipole and monopole fall-off factor (i.e. $1/r^3$ and $1/r^2$ respectively) and a dipole-factor-of-two form the relevant contributions. The last factor relates specifically to dipoles (non-radial symmetry) and states that at a given distance the intensity varies by a factor 2 as a function of the angle between the radial line to the dipole and its axis.

One can estimate the maximum amplitude of an anomaly by using the following simplified expression

$$T = \frac{M}{r^n} \quad (2.18)$$

where T is the anomaly intensity (in gauss), M the magnetic moment, r the distance (or depth) to the source (in cm's) and n the fall-off rate ($n = 3$ for a dipole and $n = 2$ for a monopole). Any such estimate requires the depth susceptibility, and shape to be assumed or estimated.

To determine the dipole and monopole response in vertical and horizontal fields one take into account the magnitude and direction components of the dipole field as given by the radial T_r and tangential component T_θ using the following expression:

$$T_r = \frac{2 M \cos\theta}{r^3} \quad (2.19)$$

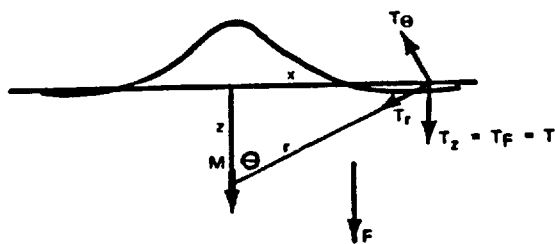
$$T_\theta = \frac{M \sin\theta}{r^3} \quad (2.20)$$

Where the dip of the earth's field is vertical or nearly vertical ($70^\circ - 90^\circ$), an absolute magnetometer measures the component t_z of an induced dipole, where

$$T_z = T_r \cos\theta + T_\theta \sin\theta \quad (2.21)$$

$$= \frac{2 M \cos^2 \theta - M \sin^2 \theta}{r^3}$$

$$= \frac{M (2 z^2 - x^2)}{(x^2 + z^2)^{5/2}}$$

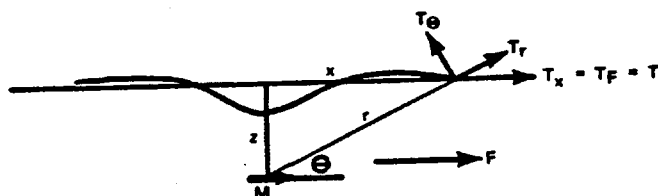


For a horizontal (e.g. equator) induced anomaly, the measured components would be

$$T_x = T_r \cos \theta + T_\theta \sin \theta \quad (2.22)$$

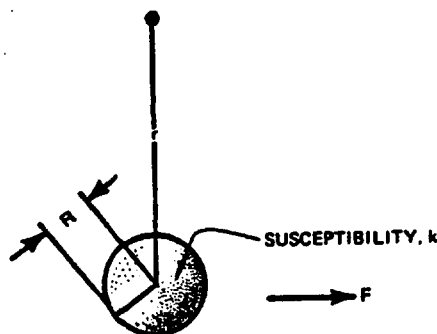
$$= \frac{2 M \cos^2 \theta - M \sin^2 \theta}{r^3}$$

$$= \frac{M (2 x^2 - z^2)}{(x^2 + z^2)^{5/2}}$$



Similar expressions apply to a monopole anomaly. Given the magnetization and a generalised form for a source the maximum amplitude can be determined with a different set of equations, for instance:

anomaly of a sphere in a horizontal field



$$T = \frac{k F \left(\frac{4}{3} \pi R^3 \right)}{r^3} \quad (2.23)$$

where k is the susceptibility (per unit volume), R the radius of the source, and F the ambient inducing field (earth's field). The units between brackets express the volume of the object under scrutiny and therefore change when relating to other features e.g. a narrow vertical dike

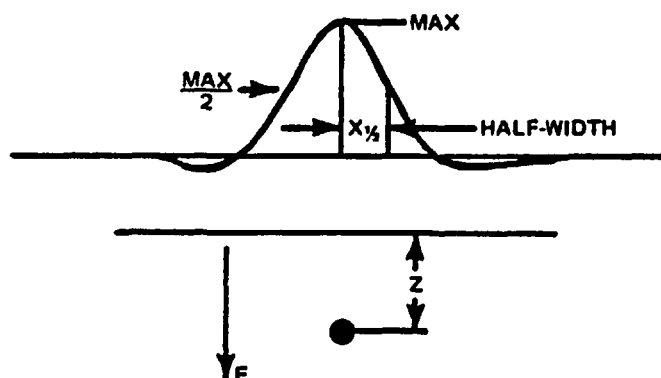
$$T = \frac{k F t}{r} \quad (2.24)$$

where t is the width of the dike.

General anomaly characteristics

In practical surveying some basic guidelines are useful. These only represent approximations:

- (1) anomaly width is generally 1 - 3 times the depth - this provides a useful estimate of depth to source;
- (2) for simple-shaped forms - spheres (dipoles), vertical cylinder (monopoles) - in mid-northern and southern latitudes one can apply a half-width rule:



half-width rule, vertical
field:

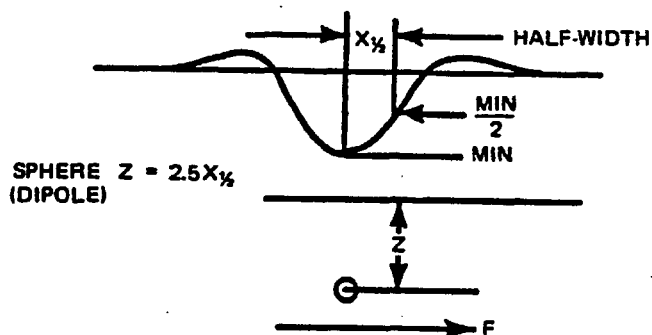
sphere (dipole) $z = 2 x_{1/2}$

vertical cylinder $z = 1.3 x_{1/2}$
(monopole)

edge of narrow dike $z = x_{1/2}$
(line of monopoles)

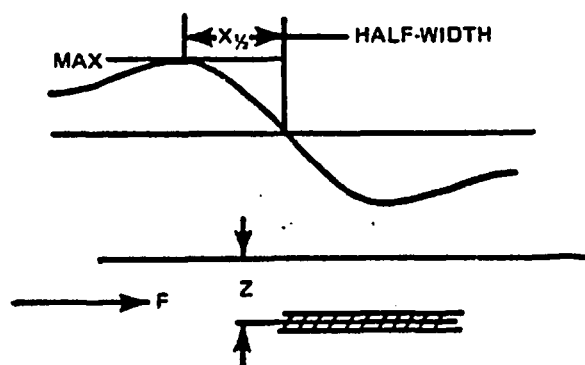
horizontal cylinder $z = 2 x_{1/2}$
(line of dipoles)

where the half-width is the point where the anomaly amplitude is exactly half its maximum value. A similar method can be applied to a horizontal (equatorial) field:



E-W cylinder $z = 2 x_{\frac{1}{2}}$

(line of dipoles)



N-S cylinder $z = 1.3 x_{\frac{1}{2}}$

(monopole)

edge of sheet $z = x_{\frac{1}{2}}$

(line of monopoles)

The above discussion forms a much simplified digest of the magnetic behaviour of simple shapes. Any of the standard texts will afford a more detailed exposition (e.g. Telford et al, 1978, pp. 147-192).

Modelling techniques provide another means of interpretation. A model is set up and compared with a calculated anomaly response. By constantly altering the model one reaches a satisfactory fit to the observed data. Interactive computing techniques have greatly speeded up this operation.

A close analogy with modelling techniques can be found in data filtering, where assumptions are for instance made concerning the wave vector distribution of a given set of data which in turn result in the selection of shapes and depths in the wave vector space through the filtering process (see chapter 4).

Anomaly modelling can be performed according to a large variety of techniques some of which have been described in the section on theoretical anomalies.

In archaeological geophysics the emphasis is often on inferring the width of a feature as based on the $1/2$ width rule, provided that the width is greater than the depth.

2.2. Review of Previous Work

2.2.1. Magnetic Susceptibility of Soils

Soil magnetic susceptibility is an important aspect in near surface and archaeological surveying. Le Borgne (1955b, 1960a, 1960b) was the first to make a serious study of soil magnetism and he found that topsoil tends to be more magnetic than the underlying soil strata. Scoller (1965) noted, however, that certain soils with a high particle mobility such as the brown earth Dudat type B exhibited a high susceptibility layer in the type B horizon, underneath the type A horizon. By definition a completely developed soil profile is divided into specific zones: the A (eluvial) zone (weathered material from which substances have been washed out), the B (illuvial) zone (into which leached material has been deposited) and C which is the unchanged bedrock.

These zones can be subdivided into profiles which exhibit intermediate properties. Conversely, some soils will not have all three main zones e.g. a newly formed soil may be described as an (A)C soil where A denotes the humus layer overlying unchanged bedrock.

As indicated, the soil susceptibility is to a certain extent dependent upon the parent material and the soil magnetic mineral content. The amount, form and composition of the mainly ferrimagnetic minerals primarily determine the susceptibility characteristics. Soils derived from volcanic or other igneous rocks would be expected to exhibit a higher susceptibility than soils weathered from sandstone, limestone or shale. The strongest magnetic mineral in soils is magnetite (Fe_3O_4). However, maghaemite, known as $\gamma\text{Fe}_2\text{O}_3$, and also very magnetic, forms the most important magnetic mineral in the majority of ^{archaeological} soils. Conversely, haematite represents the most frequently encountered iron oxide ($\alpha\text{Fe}_2\text{O}_3$). Limestone and chalk contain very few magnetic minerals - mainly FeO or Fe_2O_3 - whereas most other rocks contain from 1 - 10% by weight, with the exception of alkaline rocks which have very small amounts. In

archaeological prospecting, iron in non-silicate form, is of most interest. Ferric hydroxide gel, haematite ($\alpha\text{Fe}_2\text{O}_3$), goethite (FeO.OH) are the forms in which iron is generally encountered in temperate wet zones (Devonian and Triassic period). Titanomagnetites appear to be of less influence in North European sedimentary soils than previously assumed.

Soil susceptibility varies widely. Its main constituent iron is readily affected by processes of oxidation and reduction. Iron oxidizes to the ferric state (by hydrolysis) followed by precipitation as a ferric hydroxide in an oxygen-rich environment or it can remain ferrous as occurs when there is a lack of oxygen (e.g. waterlogged soils). The acidity of the soil-water and therefore the soil as well as the overlying humus type, determine the movement of iron and calciumⁱⁿ soils, and therefore forms one of the main factors influencing the processes of oxidation and reduction. Therefore the type of soil can either enhance the susceptibility or decrease it; podsolisation and gleying belonging to the latter, whereas brown earth soils with a free drainage and high volcanic content belong to the former. Soils on alkaline rocks, with no discernible B layer, tend to have a high susceptibility contrasting with the low susceptibility values for the C horizon. Chalk soils will exhibit a low overall magnetic susceptibility.

An indication of the variety in susceptibility can be obtained from the table in Fig. 2.11.

In general topsoil gives the highest susceptibility values. The difference in magnetic susceptibility between the uppermost soil horizon and the lower layers led to the definition of the susceptibility contrast as representing the difference in susceptibility between the various sampled layers. These variations in susceptibility form the main basis for the detection of archaeological features. The contrast between topsoil and subsoil typically lies between 5×10^{-6} to 1000×10^{-6}

emu/gm for topsoils and from 2×10^{-6} to 20×10^{-6} emu/gm for subsoils. Exceptions are notably soils formed from certain igneous rocks and soils with a high vertical particle mobility. Of additional importance is the presence of remanent magnetization in certain soils especially the viscous component in older soil horizons. Its effects are discussed at a later stage.

Research in soil magnetism led to the development of an enhancement model in which certain mechanisms were found to be responsible for an increase in soil magnetic susceptibility.

2.2.2. Mechanisms Influencing Susceptibility

A number of theories were brought forward by Le Borgne (1955, 1960a, 1960b) to explain the susceptibility mechanism. He discovered that enhanced susceptibility can be caused by the in situ change of the weakly ferrimagnetic haematite ($\alpha\text{Fe}_2\text{O}_3$) and the antiferromagnetic (with a small amount of parasitic ferromagnetism) goethite ($\alpha\text{FeO.OH}$) to maghaemite ($\gamma\text{Fe}_2\text{O}_3$), a stronger ferrimagnetic mineral. Two enhancement processes were identified:

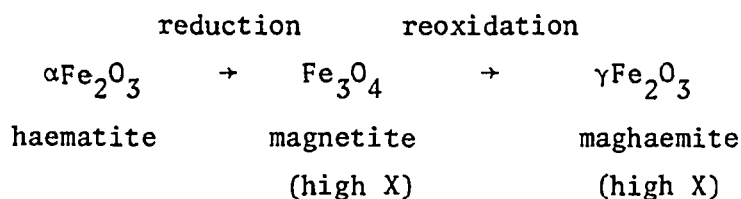
- (1) fermentation process: organic decay through bacterial action precipitated by anaerobic condition (wet periods) with reoxidation occurring during aerobic (dry) periods (mechanism of less influence in arid regions?).

The haematite-maghaemite transformation has not been adequately explained yet. Also certain soils far from human activity tend to exhibit susceptibility enhancement e.g. terra rossa soils in Italy (Linnington and Tate, 1974).

- (2) action of fire: the more probable and adequately documented mechanism (Tite and Mullins, 1971; Tite, 1972; Mullins, 1974; Graham and Scollar, 1976). Haematite is heated in the proximity of

organic material providing reducing circumstances which cause the formation of magnetite (Fe_3O_4). On cooling, air enters the system resulting in reoxidation to maghaemite ($\gamma\text{Fe}_2\text{O}_3$).

Essentially both mechanisms involve the reduction of haematite to the strongly ferrimagnetic oxide magnetite and in turn this leads through reoxidation to maghaemite:



Although adequately documented, this process is not completely understood.

Le Borgne (1955b) constructed fires and after their extinction determined that the first centimeter of the surface material had significantly risen in susceptibility value by a factor of 2 - 10 or more regardless of the nature of the parent rock (in the experiments: granulite, granite, gneissic granite, schist and loess).

Identical results were obtained from samples gathered after a harvest fire and also a forest fire. Subsequently various tests were performed under laboratory controlled conditions. The nitrogen-air heating cycle gave the highest enhanced susceptibility values with the magnetic properties affected by temperatures greater than 250°C with the highest susceptibility values occurring at just above 600°C (Le Borgne, 1960a, 1960b). Tite and Mullins (1971) repeated the heating experiments using hydrogen (providing a reducing atmosphere) as well as nitrogen (idem) in the heating process and confirmed Le Borgne's earlier experiments. They introduced the concept of fractional conversion. This relates the susceptibility value (X_0) of an unheated soil to the value obtained after heating in nitrogen-then-air (reducing-then-oxidizing

atmosphere) - X_N - as the ratio X_O/X_N . This fractional conversion of iron-oxides in a soil to a strongly ferrimagnetic form during the heating process, provides an idea of the maximum susceptibility obtainable on an archaeological site.

Therefore the closer the value X_O approximates the value X_N , the greater the extent of human occupation on that site. A maximum possible conversion indicates a 100% transformation of $\alpha\text{Fe}_2\text{O}_3$ to $\gamma\text{Fe}_2\text{O}_3$. By performing this process under laboratory conditions, standard maximum conversion values for soils are obtained.

The above is based on the assumption that a large number of fires on a site - as may be associated with extensive human occupation - will lead to a higher soil susceptibility. However, as the fractional conversion also relies on the amount of iron-oxide in the soil, a small level of occupation would be expected to have a greater effect on soils rich in iron-oxides as opposed to those with only a minor iron-oxide concentration.

It also assumes that any enhancement in magnetic susceptibility caused by the fermentation process is negligible.

Using fractional conversion, Tite and Mullins suggested that sites on soils with a high iron-oxide concentration available for conversion, such as soils derived from Jurassic strata, should provide good magnetic prospecting results. They determined that the mean value of X_O/X_H approximated 6% for normal topsoils whereas archaeological site samples gave values of up to 60%.

Tite (1972) went further and looked at the iron-oxide concentrations of a large number of samples. He used the values of magnetic susceptibility after heating (at 500°C) in hydrogen (X_H) as a measure of this concentration owing to the correlation between the values of X_H and the percentage weight of ferric oxide (estimated by using a colorimetric

method). He suggested that 1% of strongly ferrimagnetic iron-oxide produces $X = 400 \times 10^{-6}$ emu/gm.

Furthermore, X-ray diffraction measurements indicated that the weakly magnetic iron-oxide particles changed to magnetite and metallic iron after heating in hydrogen. Causing slight confusion, Tite now used the ratio X_o/X_H as the amount of fractional conversion of iron-oxide which was taking place in situ on a site. X_H provides the susceptibility value should all the available iron-oxides have been converted to maghaemite. He found that soils from the Lower and Middle Jurassic strata gave the highest iron-oxide concentration underlining data previously obtained by Scollar (1966). These were closely followed by soils from the Lower Greensand, Carboniferous and Devonian (all sedimentary).

Conversely, chalk gave the lowest values, though in itself varying considerably (Fig. 2.12).

Igneous rocks gave unstable results, possibly owing to the inclusion of non-magnetic silicates which are not readily converted. This could also perhaps account for the low X_H values from peaty moorland soils.

Mullins (1974) used hydrogen, and a lower temperature during the heating cycle. This was because it gave a closer correlation with the iron-oxide concentration, and more consistent if somewhat lower susceptibility results. He obtained lower enhanced susceptibility values, possibly caused by the formation of metallic iron, and found that the single domain grains of generally paramagnetic nature, were responsible for the magnetic soil properties as well as being directly related to the magnetic viscosity. Furthermore, he established that susceptibility and viscosity depend on the size and shape of maghaemite grains: single domain, multidomain or superparamagnetic. The ratio of viscosity to susceptibility (η/X) is independent of concentration. Its value provides an idea as to the size and shape of the maghaemite grains.

Graham and Scollar (1976) also concentrated on the heating cycle.

Their results indicated a higher magnetic viscosity and susceptibility with the nitrogen-and-air method as opposed to the lower values obtained by Mullins with the hydrogen cycle. They suggested that this was caused by the difference in end product provided by either heating process:

- (1) nitrogen + air cycle → maghaemite - superparamagnetic and single domain indicating higher susceptibility and viscosity values;
- (2) Hydrogen cycle → grains of metallic iron (confirmed by experiment) - multidomain.

They perfected the nitrogen-and-air method and advised against the hydrogen cycle as it often gave inconsistent viscosity results (viscosity depends on grain size!) and was incompatible with the nitrogen-air-method (maghaemite - single domain and therefore more consistent viscosity values). Susceptibility values obtained with the nitrogen-air cycle were one to three times those produced by the hydrogen cycle. Therefore the latter cycle will underestimate the potential susceptibility of many soils. Using the nitrogen-air method they established fractional conversion figures ranging from 1 - 24% in non-igneous soils with 5% representing a typical value. Their sampling area was confined to Western Europe with a particular emphasis on sites with a low Le Borgne contrast.

Only the beginning and end products can be measured in the nitrogen-air cycle. The maximum obtainable susceptibility in the enhancement mechanism is closely related to the iron content in the sample. Graham and Scollar (1976) established an almost linear relationship for samples with a small iron concentration of up to 2.5% by weight of iron. In turn this relationship was found to hinge on the 20 - 40 nM range in grain size.

Some soils, such as marine clays, which return low susceptibility values after heating, indicate however that the grain size distribution is not the only answer to a high conversion factor. Graham and Scollar

suggest that possibly a large amount of iron is not converted into magnetic form by the heating process owing to the structure of the material. This remains only a guess. The fermentation mechanism in which the decay of organic matter in anaerobic conditions (wet periods) leads to a reduction in soil iron-oxides, subsequently followed by reoxidation in aerobic conditions (dry periods), remains as yet impossible to prove under laboratory-controlled conditions. Attempts made by Le Borgne (1955a) and Tite and Mullins (1971) were unsuccessful. Mullins (1974) suggests that the gradual build-up of ferrimagnetic iron-oxide caused by alternating wet and dry periods would only contribute significantly to the enhancement mechanism in highly organic soils.

He found that samples of soils from non-archaeological sites and those from burial sites (little human activity!) exhibited low values of percentage conversion, typically from 0 - 10%, after heating in hydrogen (X_H). However, archaeological soil samples gave high percentage conversion values, generally above 10%. His results are shown in Fig. 2.13.

A large amount of human, animal and vegetable waste matter incorporated within the topsoil after the initial occupation would have to account for the increased enhancement. Previous work (Tite and Mullins, 1971) indicated that archaeological pits and refuse dumps gave higher susceptibility values than the surrounding topsoil (see Fig. 2.11 in section 2.2.1). This tends to point favourably towards a fermentation mechanism leading to enhanced susceptibility. Mullins finds it difficult to conceive such a high proportion of organic matter readily mixed with the soil on archaeological sites. He suggests that the fermentation mechanism, if significant, would occur in soils where the dry and wet periods alternate rapidly: of shorter period than occurring in gley soils (dilution and subsequent removal of iron-oxides) and not so rapidly as with podsoils (iron rapidly moved downwards). Brownearth soils fulfil these conditions. Graham and Scollar (1976) heated soil initially

containing little organic matter but subsequently enriched with flour (organic). The results are shown for a sample of loess soil heated to 550°C (Fig. 2.14). At first there is a very rapid increase in susceptibility until approximately 2% flour content is reached. The straight line in the figure indicates that the susceptibility remains constant after this. Sufficient flour enables the reduction cycle to be consistent. Therefore a small amount of flour was added to the samples prior to heating (calculation of X_o / X_N) in order to emulate field conditions.

From the above one can perhaps conclude that only a small amount of organic material affects the susceptibility mechanism to a minor extent.

Recent work by the Massachusetts Institute of Technology has come up with an interesting alternative enhancement mechanism. Certain bacteria scrounge iron from the water in which they live and synthesise it into magnetite. These bacteria have so far been found living in mud in the northern hemisphere. The row of magnetite particles within the creature act as a magnet. It would be interesting to see if these bacteria are found in organic waste matter on archaeological sites (Frankel, 1979, pers. comm.).

The abovementioned mechanisms which influence the magnetic susceptibility of soil, take place over a relatively short time span when compared to the various forms of residual magnetization such as viscosity and chemical remanence. These will affect the overall susceptibility of a given soil in much the same light as the parent material from which a soil has been derived. The effects of temperature on viscosity and the acquisition of thermoremanence (kiln sites) provide an additional means to the detection of archaeological features. Viscosity is of importance with the Pulse Induction Meter as discussed in chapter 1.

2.2.3. Identification and Measurement of Soil Iron Oxides

To enable a proper understanding of any enhancement mechanism it is important to determine the materials present before and after conversion.

The measurement of soil iron oxides has given a number of problems. Le Borgne (1955a) used differential thermal analysis and managed to identify maghaemite as the final product (on the basis of an exothermic peak at 700°C). Mullins (1974) used a colorimetric technique which does not give very convincing results, possibly leading to underestimation when compared to complexometric titration, as used by Graham and Scollar (1976) who obtained an estimated accuracy of 0.1% Fe for per cent weight. X-ray diffraction has come up with severe limitations owing to the poor crystal structure of the soil iron oxides and the very small grain size (100 - 300 Å) making any differentiation between magnetite and maghaemite difficult.

Longworth and Tite (1977) used ^{57}Fe Mössbauer spectroscopy in order to obtain more reliable results as to the exact nature of the relevant iron oxides. They tested soil samples from England and Italy, previously examined in other susceptibility studies (Tite and Mullins, 1971; Tite, 1972; Tite and Lirington, 1975). Only five samples were measured from the following geological strata: clay (Jurassic), marl (Eocene), sand (post-glacial). Their results were consistent with susceptibility measurements and underlined that Le Borgne's theories adequately documented the enhancement mechanism. They verified the formation of high susceptibility maghaemite ($\gamma\text{Fe}_2\text{O}_3$) after heating in nitrogen-air. The low susceptibility component in agricultural topsoil prior to heating was found to be goethite ($\alpha\text{FeO.OH}$).

Formation of maghaemite instead of magnetite indicates that the final stage in the conversion process occurs under oxidizing conditions.

2.2.4. Detection of Shallow Features

The detection of archaeological features generally relies on the existence of a contrast in magnetization between the sought-after feature and its surroundings. This contrast can be caused by any number of factors.

The unique refractory properties of clay have led to its extensive use in the construction of kilns. On cooling from firing it acquires thermoremanent magnetization. Kiln structures therefore provide strong magnetic anomalies. Domestic hearths, furnaces and any fired clay objects belong to this category. Kiln sites were the first to be successfully prospected (Aitken et al, 1958). Clay contains haematite and magnetite, both strong ferrimagnetics. Their magnetic domains readily align themselves to the prevailing magnetic field when clay is heated above its Curie temperature.

Another relevant factor in the detection of shallow features is soil viscosity. This primarily refers to the use of the pulse induction measuring system described in chapter 1. Its main importance here is that it affects the measurement of magnetic susceptibility as the acquisition and decay of viscosity are time dependent ($\log t$). This should be taken into account when determining the model response of a feature. In such cases viscosity can appreciably alter a feature's size and shape generally causing them to be underestimated. The most important are the enhancement mechanisms previously mentioned. During the heating process of soil material, the first underlying centimeter acquires enhanced susceptibility. Subsequent ploughing, erosion and other types of earth movement mix this enhanced layer with the upper soil horizon to a depth of circa 30 cm. Although so far unsubstantiated, magnetic enhancement may also occur through organic decay i.e. alternating periods of wetness and dryness.

The enhancement process, however, may be decelerated by the effects

of weathering which can break down the finer ferromagnetic particles. Some of the problems related to the soil environment and parent material are outlined in section 2.2.8.

Archaeological features are usually found at shallow depths. Their inclusion in a soil material may result in a magnetically detectable anomaly. The magnetic contrast will also depend on the amount of surface material present in the fill of a feature. This especially applies to subsurface ditches. Graham and Scollar (1976) defined the dilution factor as the percentage of surface material introduced in the fill, where surface material represents the first 30 - 50 cm of biologically active material known as the A horizon in pedology. The dilution factor of a ditch or pit is especially relevant in modelling studies. Therefore a ditch dug into a low susceptibility B horizon and filled with a high susceptibility A horizon should provide a good anomaly owing to the low dilution factor and high contrast.

Clearly a large number of variables will influence the success or failure of a magnetic survey. The detectability of roads strongly depends on their construction material. For instance, Roman roads can be constructed from weakly magnetic cobbles (glacial erratics) and iron slag (high TRM), which in a low susceptibility background would provide a positive anomaly.

Walled structures tend to be problematic. They often suffer from severe erosion usually caused either by ploughing or stone robbing. Also their construction material is rarely magnetic, except in the case of fired mud-brick. Large non-magnetic walls tend to show up best and then generally when the surrounding soil has a high susceptibility. The resultant magnetic low should not be confused with the magnetic low sometimes associated with a ditch structure (Linington, 1966c). Wattle and daub structures, however, are often readily detectable as they are made of clay which may have acquired TRM, if burnt.

Caves have sometimes been successfully located. This generally

applies to large caves surrounded by magnetic material. They will therefore show up as a magnetic low anomaly. Tombs very much come under the same heading. When constructed in sedimentary rock they only tend to give very small (magnetic low) anomalies. In most cases they remain undetectable.

In certain instances anomalies may cancel each other out. This applies, for instance, to a heap of pottery sherds. Their randomly oriented TRM results in a relatively weak anomaly. Naturally this would not be relevant to induced magnetisation.

The cancelling out of anomalies may also be brought about by the use of certain filtering techniques (aliasing), described elsewhere (Chapter 4).

2.2.5. Enhanced Susceptibility of Soils

The importance of soil iron oxides has been pointed out. In general iron forms only a few per cent (by weight) of the topsoil with the exception of soils derived from iron-bearing geological strata. Very little is known about the exact nature of soil iron oxides and hydrated oxides and most of the studies have been confined to temperate-climate soils. Magnetically one can distinguish two main types (Mullins, 1974):

- a) Soils derived from igneous rocks: the sand, silt and coarse clay soil fraction contains most of the iron in unchanged form. This exhibits a high overall susceptibility (as well as TRM of underlying rocks) and is hardly affected by the enhancement mechanism.
- b) soils derived from sedimentary rocks; these are of paramount importance in Great Britain.

The iron content of the sedimentary sands (e.g. lower Greensand) is generally non-ferromagnetic and through weathering most of it is converted into a number of different iron oxides with the remainder unaltered in chemical composition. The same applies to the sedimentary soils where iron occurs in the silt, sand or coarse clay fraction, and breaks down into iron carbonates, iron silicates and goethite. Clay minerals such as montmorillonite and biolite contain non-ferromagnetic iron.

All the above forms of iron are not readily influenced by the enhancement mechanism.

The crystalline oxides such as haematite ($\alpha\text{Fe}_2\text{O}_3$), goethite ($\alpha\text{Fe}_2\text{O}_3 \cdot \text{H}_2\text{O}$) and limonite ($\text{FeO}(\text{OH}) \cdot n\text{H}_2\text{O}$), as well as the crystalline iron oxides and hydrated oxides are affected by the enhancement mechanism to a varying extent. These oxides are all non-ferromagnetic and are part of the clay fraction of a soil. The same applies to iron in the form of an iron oxide gel. This gel coats soil particles giving them their varied colours. Also relevant is the mobility of the soil iron content. Unfortunately little is known. The important iron oxides haematite, limonite and goethite are not readily dissolved and tend to stay in place.

The maximum susceptibility a soil can obtain, through the heating mechanism, depends to a large extent on its iron content. Therefore the success or failure of a survey can be closely related to these two factors. The results of work done by Tite (1972) and Mullins (1974) has already been discussed.

Graham and Scollar (1976) undertook a similar approach to a large number of archaeological soil samples from Western Europe (mainly from north German and Dutch sites). Their sampling showed a bias in favour of samples of low magnetic susceptibility. The results for the fractional conversion using nitrogen and air, are shown in Fig. 2.15 and refer to the topsoil. Values range from 6% to 89%, with the average lying below 10%. The higher figures (< 30%) relate to soils derived from igneous strata. Recent volcanic activity, and probably not fractional conversion as applied here, account for the high values obtained for volcanic sites. The authors suggest that the values in the mid-teen range are for the most part caused by intense human occupation.

Similarly the results can be related to the soil iron content. The following diagram (Fig. 2.16) shows that the susceptibility (after heating) is proportional to the iron content (scatter is less than $\pm 20\%$).

The iron content of the samples was obtained using complexometric titration. Therefore one can probably dispense with the complex heating method by directly measuring the iron content of a soil, with low values of iron concentration giving the best correlation.

Clearly sites with a high iron concentration should overall provide good surveying conditions: sites on sedimentary deposits followed closely by limestone formations give good results whereas sites on chalk can be unpromising.

Practice has underlined the above as well as highlighting some of the additional problems:

Topsoil thickness tends to be more uniform than previously thought (Graham and Scollar, 1976). However, this need not always be the case. For instance, undulations in the underlying clay of a site may cause positive anomalies to cancel out negative ones.

Areas with strong rock erosion e.g. Mediterranean, often suffer from phenomena such as solution holes, periglacial cracks and pockets of boulder clay. These may be wrongly interpreted as man-made anomalies (Linington and Tite, 1974).

On hilly sites, topsoil tends to converge (owing to erosion) along the junction between a slope and a plateau resulting in either a positive or a negative anomaly often mistakenly seen as either a wall or a ditch (Linington, 1973a).

Sites on igneous geology lead to a variety of problems. The magnetic iron silicates are not readily converted into haematite when heated according to the enhancement model. Also the slight TRM of the strongly ferrimagnetic soil iron oxides has a masking effect on any underlying anomalies. A measured signal will be readily saturated by the high signal and unable to differentiate small variations. This especially applies to total field measurement systems. Only large negative anomalies may then be detectable.

One such area, which has given unpromising results, is the Tertiary basalt of the Antrim plateau.

Successful results have, however, been obtained in such areas by using a fluxgate gradiometer. Ditches cut into subsoil with a detrital remanent magnetization were located owing to the random alignment of the ditch fill (Haddon-Reece, 1973). Therefore areas with a smooth and highly remanent magnetic background, e.g. lava flows, should also provide useful results.

Agriculture aids the breakdown of soil silicates increasing the influence of the heating mechanism. Sites on agricultural soils are more readily detected than those for instance on non-agricultural peaty moorland soils developed from granite (Tite, 1972).

2.2.6. Soil Noise and Minimum Detectability

One can distinguish between two main classes of noise depending on whether or not its magnetic values can be correlated from point to point in space (Scollar, 1970). The following uncorrelated (randomly oriented) noise sources apply to magnetic surveying:

- (a) those of instrumental origin;
 - (b) rapid external electrical/magnetic disturbances e.g. earth current transients, engine noise (vicinity of roads), power line noise;
 - (c) surface scatter of small iron objects;
 - (d) the position of the magnetometer detector relative to the grid and in turn the accuracy of the grid position to that of the anomaly.
- This especially applies to strong magnetic anomalies where a small lateral variation from the exact position significantly affects the reading but is equally relevant to small anomalies.

In relation to lateral variations in detector position, its height will also influence the measurement. The amplitude of a linear

anomaly e.g. wall, falls off as the square of the distance (anomaly to detector). For small anomalies (point sources e.g. pits) the amplitude falls off as the cube of the distance.

Naturally, surface susceptibility variations will play an important role in the sum total of any measured signal. Therefore an optimum detector height exists at which these effects are minimum, yet retaining adequate signal for the detection of the smallest sought-after anomalies.

Correlated noise sources affect adjacent measurement points (i.e. predictable variation). One can use the autocorrelation function of a set of data as a measure of their repetitiveness. Another way in distinguishing signal from noise is by looking at the noise spectra of a set of data and then separating the two by the use of appropriate filter techniques (see chapter 4). A large number of correlated noise sources exist which influence a magnetic survey:

- (a) long-term drift in instruments e.g. thermal drift;
- (b) natural irregularities in the superficial susceptibility distribution.

Generally ploughing helps to even these out. Local variations seldom exceed more than 10% of the mean value (Graham and Scollar, 1976). A notable exception is soil noise in volcanic areas.

- (c) irregularities in subsurface and topsoil e.g. variations in the thickness of the plough layer; gulleys in the subsoil subsequently filled in; effects caused by erosion (soil movement).
- (d) man-made sources e.g. old field boundaries and established plough patterns; buried pipes or cables. If their pattern coincides with the frequency of the filter technique used for the interpretation, aliasing may be the result.

Scollar (1970) went into the effects of partly correlated noise sources on the data using computer modelling techniques and Fourier

transforms. The noise spectra were subsequently displayed in three-dimensional pseudo-perspective plots and combined with signal spectra from a number of archaeological sites with known features (Fig. 2.17). The less correlated noise in a spectrum, the more uniform a spectrum will be over the entire plane. Correlated noise, commonly associated with medium to low wave vector components, would appear as high amplitudes in the centre of the wave plane, as more than one measurement is affected. In uncorrelated noise all spectral components will have nearly equal amplitudes. One can then apply various filters and examine their effects on the combined signal and noise spectra. Clearly the detectability of shallow features does not only rely on instrument sensitivity. One can identify the following parameters:

- (1) shape of the measured signal
- (2) signal strength
- (3) context of the measured signal (noise in its environment)
- (4) the geometry of a feature (angle of dip etc.)
- (5) the geometry of the noise sources (hopefully different from that of the feature).

An appropriate interpretation (e.g. filtering) and presentation (e.g. dot density) method can significantly increase the signal to noise ratio of surveying data. The relevant techniques are explained in chapter 4.

2.2.7. Typical Anomaly Values and Related Instrument Sensitivity

As can be expected, enormous variations exist in anomaly amplitude. Some typical results: ditches tend to vary from 2 - 30 γ , pits from 5 - 50 γ , pottery and tile kilns and other anomalies with a high thermo-remanent magnetization, range from 100 - 500 γ or more. In general, high instrument sensitivity should aid anomaly detection. An instrument with a sensitivity of 1 γ should detect an object next to the

sensor of 2×10^{-5} cgs units. For an instrument of 0.25 γ sensitivity this would be 5×10^{-6} cgs units. Anomaly and related signal strength fall off as the inverse of the cube of the distance (d^{-3}).

Practical instrument sensitivity relies on a number of parameters, as discussed under section 2.2.6. To these one can add that the resolution of a magnetometer will be increased when using it in its differential mode thus providing constant diurnal linkage.

2.2.8. Vertical and Horizontal Variation of Susceptibility and Viscosity

Variation of susceptibility with depth. This is to a large extent dependent on geological and pedological factors as indicated by the following examples (Graham and Scollar, 1976):

- a) braunerde or parabraunerde soils - A horizon with a reduced susceptibility, B horizon exhibits an increased susceptibility due to the high lateral particle mobility, probably of fine maghaemite grains of the critical 20 - 40 nM radius; low Le Borgne contrast. Anomalies will have low values.
- b) rendzinas on chalk - increased soil development; features themselves can be shallower as it is difficult to dig into the subsoil; large Le Borgne contrast ^{possible} Overall high anomaly values.
- c) waterlogged soils - reversal of Le Borgne contrast; gleying and subsequent low susceptibility values. One can expect low anomaly values. Soil colour changes (blue to rust coloured) may be caused by the change from ferric to ferrous hydroxide.

Clearly a varied number of factors are of importance: drainage and associated particle mobility, depth of water table (oxidation-reduction conditions), fill factor, Le Borgne contrast and the amount of iron available for conversion and last but not least the stratigraphy.

No real attempts have been made to correlate the vertical variation in susceptibility with stratigraphic observations. Graham and Scollar

(1976) observed the variation in susceptibility with depth of a number of buried ditches. These were compared with viscosity measurements. Their results indicated some correspondence between the two and, in most cases, a fall-off with increasing depth. In determining the horizontal variation in soil viscosity they found that values tend to centre around 3.5 and 5.5% viscosity coefficient. Both carbonates and igneous rocks were outside this region emphasizing the effect of the critical grain size (20 - 40 nM). Viscosity for values for samples with susceptibilities below 50 units were not obtained owing to result inaccuracies.

The viscosity coefficient was based on the relationship:

- (1) to determine an approximate measure of viscosity

$$V_c = 1 - k (X_{ac}/100)$$

with the parameters derived from:

- (2) to determine the effective measurement time of susceptibility in a constant field:

$$\frac{X_{ac}}{X_{100}} = 1 + V_c (\log (t/100) / 100) \quad (2.25)$$

$$\text{and} \quad k = \log (t/100) / 100 \quad (2.26)$$

where $k = .045$ as determined by a straight line fit to the author's data

V_c = viscosity constant at t_o (defined time = 100 sec.)

X_{ac} = a.c. susceptibility value

X_{100} = constant field susceptibility at 100 sec.

t = effective a.c. measurement time.

They suggest that for soils with X_{100} between 50 - 500 a viscosity constant (V_c) of 4.5% may be assumed. Igneous soils with a high

susceptibility tend to be in the 1 - 2% range whereas low susceptibility carbonate rocks centre around 6%.

Soils with X_{100} smaller than 10 will not exhibit any viscosity.

Similarly, Graham and Scollar (1976) made a study of the variation in horizontal magnetic susceptibility. They found that it was generally uniform for low susceptibility soils. Therefore surface sampling of the topsoil on weakly magnetic sites in order to ascertain the existence of anomalies as previously suggested by Scollar (1965) would be inadvisable. Correlation between the two can, however, be expected on soils with a high fractional conversion based on extended human occupation and a high level of iron oxides available for conversion. Under such conditions surface noise may become predominant. Graham and Scollar suggest that sites with a normalised Le Borgne contrast (ratio of Le Borgne contrast to the topsoil susceptibility) less than .5 are probably outside the limits of detectability.

2.2.9. Measurement of Soil Magnetic Susceptibility

In general the magnetic properties of soils are difficult to measure. A large number of options are available some of which have been discussed in sections 2.1.8. and 2.1.9.

Soil susceptibility measurements form an essential part of magnetic survey work. They can help to ascertain the validity of conducting a survey in a given area: the greater the Le Borgne contrast the better the conditions. Soil susceptibility measurements also enable one to establish a number of survey parameters e.g. detector height, grid spacing, expected Le Borgne contrast, and guide towards methods of data evaluation.

Soil samples can either be taken at regular intervals based on a grid pattern, over possible or existing anomalies or along excavated areas. One can also rely on in situ measurement. In practice an in situ

coil is plugged into the susceptibility meter (e.g. Bison Model 3200) and placed on a reasonably flat surface for measurement. The sample material must have a horizontal dimension equal to at least 2 - 3 times the coil diameter, and a sample thickness equal to at least 1 coil diameter. A weathered or irregular surface as well as insufficient volume of material will impede the result accuracy. The obtained susceptibility reading will refer to a volume of material beneath the in situ coil which in diameter will approximate that of the coil and in depth approximate one half the coil diameter. Two corrections are necessary:

- a) multiplication by calibration factor relevant to the appropriate measuring instrument;
- b) if the in situ coil does not come into contact with the sample then the measured value will have to be multiplied by a correction factor based on the average spacing between the sample and the bottom surface of the in situ coil.

Usually topsoil samples are sieved using a 2 mm sieve thereby removing any coarse material and pebbles. Subsoil samples, however, are usually not sieved owing to their coarseness. Typically 150g of material is then inserted into a previously calibrated susceptibility meter and a note made of the indicated value. Some five readings should be taken and their mean used as the final value. One can also measure 150g of unsieved samples to enable a comparison ^{to be made} between the two.

A more comprehensive sample treatment is provided by Mullins (1974, pp. 14-17) and Graham and Scollar (1976, pp. 41-45).

An a.c. bridge (Scollar, 1968a) is commonly used, making it possible to measure a wide range of susceptibilities (X_{ac}). Measurement values should be multiplied by 2 to provide a better symmetry with actual field conditions. This applies to inductance measurements made at a frequency of 1555 Hz.

The correction factor is especially relevant when making

theoretical anomaly calculations. At the above frequency the magnetic moment induced in a sample varies sinusoidally. This makes it difficult to determine the value t in the equation

$$M_t = M_0 (1 + V_c \log t/t_0)$$

where M_t is the magnetic moment at experimental time t , M_0 the magnetic moment at time t_0 , and V_c the viscosity constant at time t_0 .

The value has been set at 10^{-4} seconds through calibration (Graham, 1977).

D.C. susceptibility measurement techniques provide values more relevant to the actual anomalies in situ (induced magnetization) but tend to be inconvenient for measurement purposes.

When calculating theoretical anomaly values and superimposing these results on those obtained in the field, a further discrepancy occurs owing to the fact that one takes volume susceptibility into account (susceptibility per unit volume) and this changes with dried samples. Therefore samples may be measured according to a constant (dried) weight. However, 10 - 20% in weight can be lost, generally occurring exponentially. Weight measurements are used in the susceptibility calculation: the accuracy of the measured balance should be within 0.1 g. One then corrects for soil density to enable volume susceptibility calculations.

Bulk density values range from 1.1 - 1.6 for soils, 2.6 - 2.7 for soil minerals, with 1.6 as an average for sandy soils and 1.1 as an average for aggregated loams and clays.

Graham and Scollar (1976) take a mean value of $1.4 \pm .1$ for volumetrically correct plastic sleeved samples. The resultant susceptibility values obtained from a sampled grid can be filtered using, for instance, a 2.5 symmetrical filter (Scollar, 1966).

2.2.10. Theoretical Anomalies

The basic causes of archaeological and near surface anomalies are generally well known (TRM, VRM, susceptibility differences). Anomaly calculations, however, are complex in nature. This especially applies to archaeological features as their form and shape is rarely consistent.

Prior knowledge of the magnetic effects of different anomalies - using simplified anomalies or model studies - greatly aids interpretation as well as providing guidelines towards survey logistics. Sites which especially benefit from model studies are complex sites such as settlement areas comprising a large number of structures, often in the vicinity of each other causing considerable signal overlap. Models also enable us to ascertain whether the observed fluctuations on site concur with theoretically derived results (is a feature detectable or not?).

The following discussion applies to magnetic as well as resistivity results although the parameters differ and tend to be more complex in magnetics.

Prior to commencing a survey it is important to formulate a set of objectives which also take the site conditions into account. Preliminary coring or trial excavation forms an important source of information. Relevant factors are for instance: nature of the subsurface and topsoil, depth of the sought-after anomalies, their possible dimensions and separation from each other. All these details enable the expected response to be calculated as near^{ly} as possible. A large variety of methods are available according to which the anomaly shape can be calculated:

- (1) use of simple geometrical forms (dipoles or monopoles) to represent the shape of the anomaly. The main problem revolves around the difficulty in accurately portraying the shape of archaeological anomalies. Results therefore tend to be tenuous. Also, any observed

anomaly results from the vector addition of the geomagnetic field and the disturbing field of the feature. Exact calculation is difficult with the simplest form being a sphere of uniformly magnetised material, the field of which approximates that of a dipole located at its centre.

- (2) use of graphs based on general assumptions (e.g. Peters, 1949). These are generally limited in scope as they only account for limited features.
- (3) Model experiments and field tests. Anomalies produced by models have often been of value. These can either be laboratory scale models (Aitken and Alldred, 1964, 1966) or computer models based on polygons or other figures. The same applies to field tests on archaeological features. However, one feature rarely approximates another making it difficult to find suitable features.

One can add a number of further complications to those already mentioned. Any calculated anomaly response depends on a number of variables:

- a) angle of dip (I) at the point concerned;
- b) feature orientation;
- c) nature of the related deposit, its contents, subsoil changes, depth of topsoil, etc.;
- d) measurement method used: measurement spacing - too large a spacing decreases image resolution and distorts anomaly shape. At a typical spacing of 1 m, an error of 10 cm in measurement position can clearly cause anomaly distortion.

All these various factors necessitate the calculation of a large number of possible cases. More than one feature will complicate matters. Similarly, the nature of archaeological deposits is rarely consistent: use of different material in construction as well as the effects of destruction and robbery. Therefore a wall may well represent a series of

irregular bodies. Initially a pit may be seen as approximating a sphere cylinder, cone or inverted cone. Any inconsistencies in its fill, however, may render such approximation useless.

The use of simple geometrical forms will often suffice as the number of variables make any complicated approach seem dubious. In essence, one uses spheres, groups of spheres and horizontal cylinders. In representing features of roughly spherical form, the magnetic dipole forms an adequate approximation. A dipole weaker than the earth's magnetic field and lying with its field parallel to it allows the following calculation for an anomaly with a similar direction of magnetization. The anomaly height above the dipole equals the sum of the depth of burial plus the elevation of the measuring instrument. Total magnetic intensity is given by

$$f = \frac{M}{d^3} \cdot \frac{3 \sin^2 I - 1 - 6x \sin I \cos I + x^2(2-3 \sin^2 I) - y^2}{(1 + x^2 + y^2)^{5/2}} \quad (2.27)$$

where M represents the dipole magnetic moment, I the angle of dip, d the depth of the dipole below the plane, x and y the distance from the point based on an origin in the plane directly above the dipole and measured in north-south and east-west direction in units of d (xd and yd). The above equation applies to the total magnetic intensity at any point in the required plane (Lirington, 1964). Maximum anomaly amplitude relates directly to d according to an inverse cube relationship for spherical anomalies. Line sources follow an inverse square rule. Expressing the dipole anomaly, using the radial distance r from the source of magnetic moment M, gives

$$f = \frac{M}{r^3} \cdot \frac{3 \sin^2 I - 1 - 6x \sin I \cos I + x^2(2-3 \sin^2 I) - y^2}{1 + x^2 + y^2} \quad (2.28)$$

In its simplest form this can approach the following relationship when

expressed in terms of distance factor x and depth d :

$$f = \frac{M}{r^3} \cdot \frac{1}{(1 + x^2)^{3/2}} \quad (2.29)$$

Based on the above, a series of north-south and east-west anomaly responses are given for a number of angles of dip (D) (Fig. 2.18a).

The graphs in Fig. 2.18b represent the simple inverse cube relationship for a spherical anomaly (graph A) and the inverse square rule for a line source (graph B). P is the point or line source at depth d and y the anomaly variation for a line passing above it. x is measured in units of d . $I = 50^\circ$. A decrease in the angle of dip results in a southward shift of the anomaly. Both anomalies are quite similar. This approximation would apply to $I \geq 50^\circ$.

Based on the above, one can formulate certain basic rules for a localised feature of either spherical nature or point source:

- (1) anomaly size varies with depth according to inverse cube relationship.
- (2) anomaly width varies with depth where the width is taken at the point where the anomaly amplitude is half the maximum value (dashed line in Fig. 2.18b). For a localised feature this will be approximately 1.5 times its depth.
- (3) anomaly overlap: this will depend on anomaly size, separation and depth. The results for a series of cases using simplified anomalies are shown in Fig. 2.19.

Column A shows the effects for two identical features at equal depths whereas in column B the depth has been varied. In column C one can see the results for a number of equally spaced anomalies. Feature separation is indicated relating to depth as the ratio between the two expressed in the vertical left-hand column, e.g. $1/2$ indicates that separation of features is equal to half their depth.

As can be seen from column A, a discernible anomaly separation

occurs when separation equals $1\frac{1}{2}$ times the depth. For features at varying depth, the situation deteriorates.

- (4) anomalies caused by other shapes: these can be approximated as the sum of several localised features. An inverse square relationship will apply to a linear feature e.g. anomaly width should be 2 times the source depth.

A number of aspects such as asymmetrical effects and reverse anomalies have not been discussed. The above only serves as a simplification of complex field conditions, and is only applicable to areas where the angle of dip is greater than 50° .

For more complex problems a feature can be approximated by a series of elements represented by for instance point sources of which the various anomalies are summed algebraically as opposed to being added up vectorically. Archaeological anomalies are generally small when compared with the earth's magnetic field therefore algebraic addition is quite adequate as only the components that lie parallel to the earth's field are used. Using an inverse cube anomaly simplifies the calculations. When applying this method to a symmetrical rectangular feature only part of the anomaly need be calculated (both feature and anomaly are symmetrical in form). Results from theoretical studies - based on this method - of rectangular or square features have assisted in forecasting the complexity in anomaly response (Linington, 1966a):

- (1) the central minimum can become very weak and disappear completely;
- (2) difficult to distinguish individual walling except where the spacing is large and the wall itself massive or shallow in depth.

Therefore discovering the plan of a structure will only be possible under fairly ideal circumstances. Mostly magnetic results will be confused compounded by orientation problems e.g. overestimation of the size of a structure caused by the southward shift of an anomaly.

The simplified theoretical anomaly for a double square with cross sections is shown in Fig. 2.20. The depth of the feature is double the width of the individual walls.

Clearly any interpretation runs into difficulties. The outer square cannot be clearly discerned and the maxima at each cross-point of walls may be wrongly interpreted as separate anomalies.

While enabling the effects of complex features to be better understood certain problems still remain: that of representing a linear feature as a series of point sources and the asymmetrical nature of the actual magnetic variations. The latter effect will become more marked with a decrease in angle of dip (D). Also, various parts of a feature can be oriented differently to magnetic north resulting in completely contrasting anomaly responses. Therefore a rectangular wall could indicate a much stronger anomaly for the east-west oriented walls as opposed to the north-south ones. This applies to mid-northern and southern latitudes. Instead of the time consuming effort of summing the effects of different dipole sources used to approximate a given feature, one can use combinations of the simple inverse cube anomalies (Linington, 1966b). This was found to give very good approximations to the overall form of a dipole anomaly (op. cit.).

The advantage of the above system hinges on its simplicity and its avoidance of considering the orientation and distribution of features relative to magnetic north, as is common with the normal dipole anomaly.

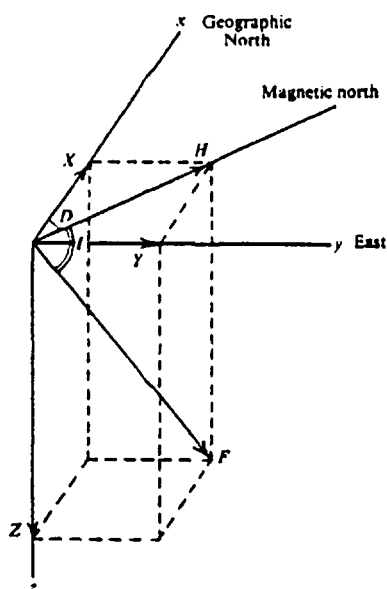


Fig. 2.1 Elements of the earth's magnetic field
(After Telford et al., 1973)

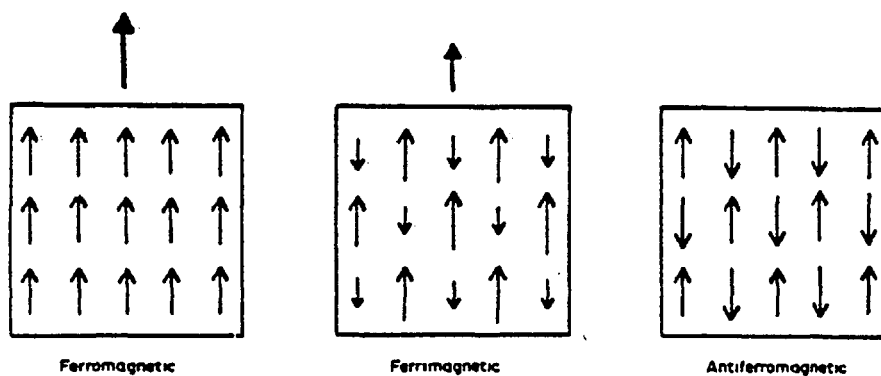


Fig. 2.2 Ferromagnetism, ferrimagnetism and antiferromagnetism. In small volumes of ferromagnetic substances, all magnetic dipoles are parallel and there is a correspondingly large magnetisation. In ferrimagnetic substances, the magnetic dipoles are antiparallel, but one lattice dominates the other so that it has a low magnetisation. In antiferromagnetic materials, both antiparallel lattices are equal and the substance has no external magnetic field.

(After Tarling, 1971)

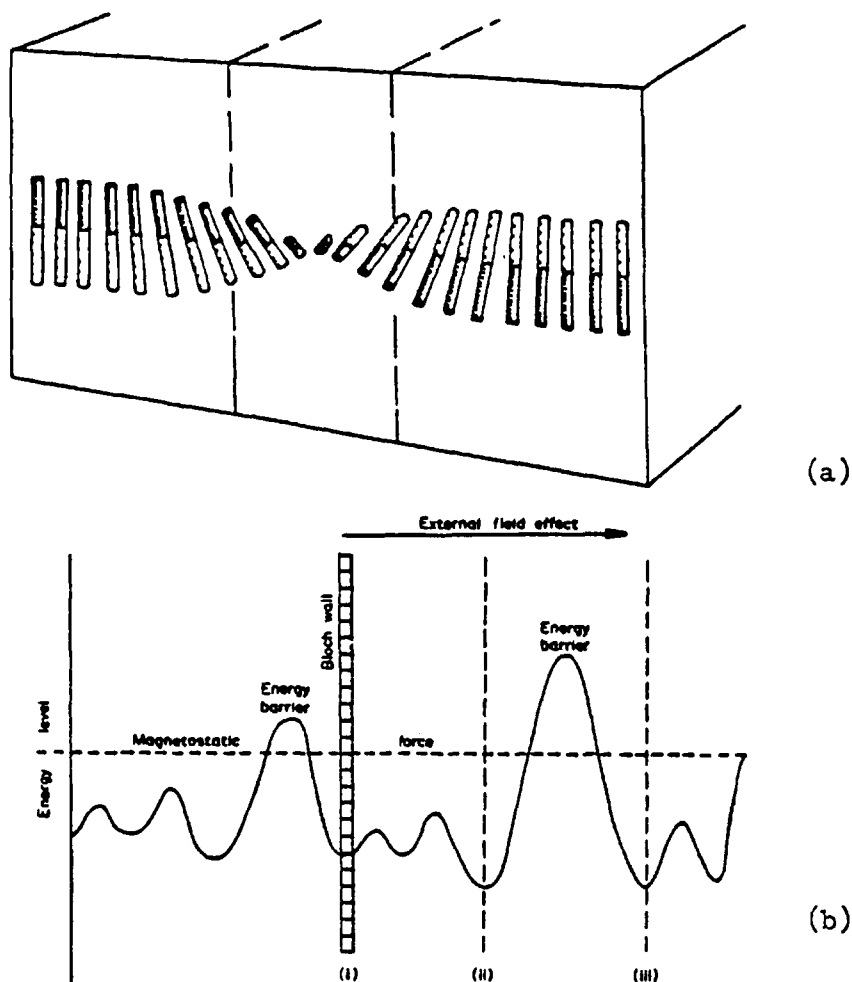


Fig. 2.3a The Bloch wall - (a) individual magnetic dipoles cant over from their direction in one domain to another.
 (b) on application of an external field, Bloch wall 'unrolls' from (i) to (iii) crossing energy barriers.
 (After Tarling, 1971)

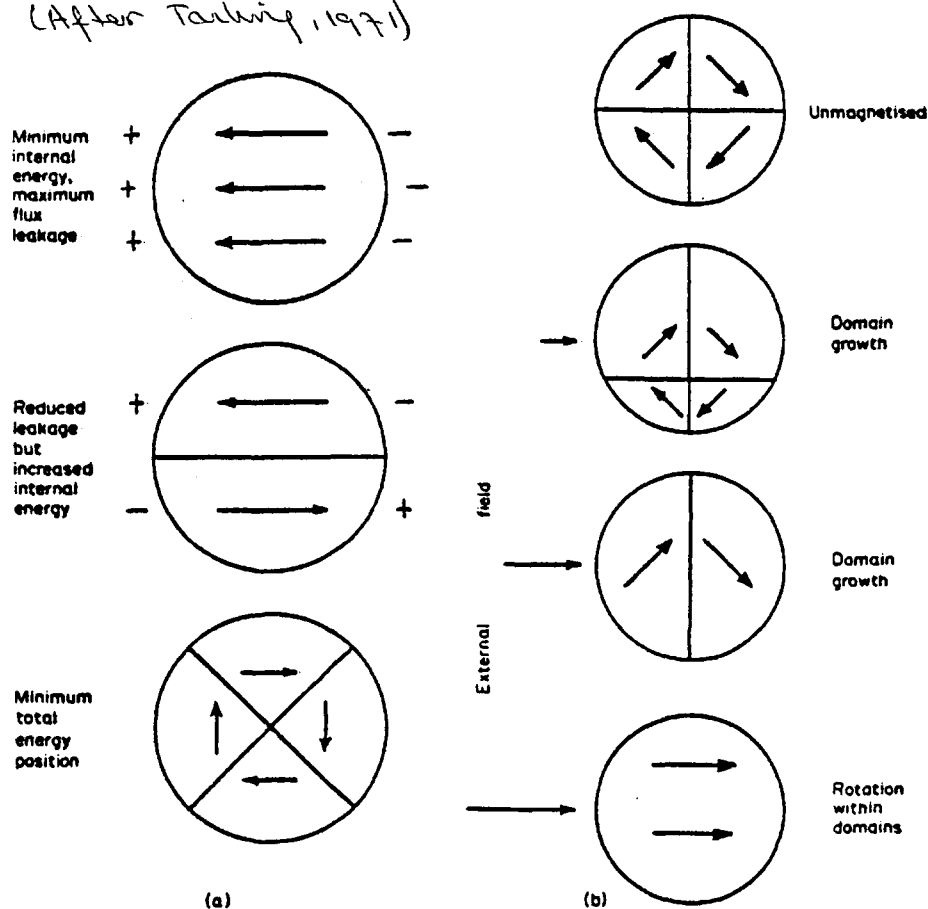


Fig. 2.3b Domain patterns
 (After Tarling, 1971)

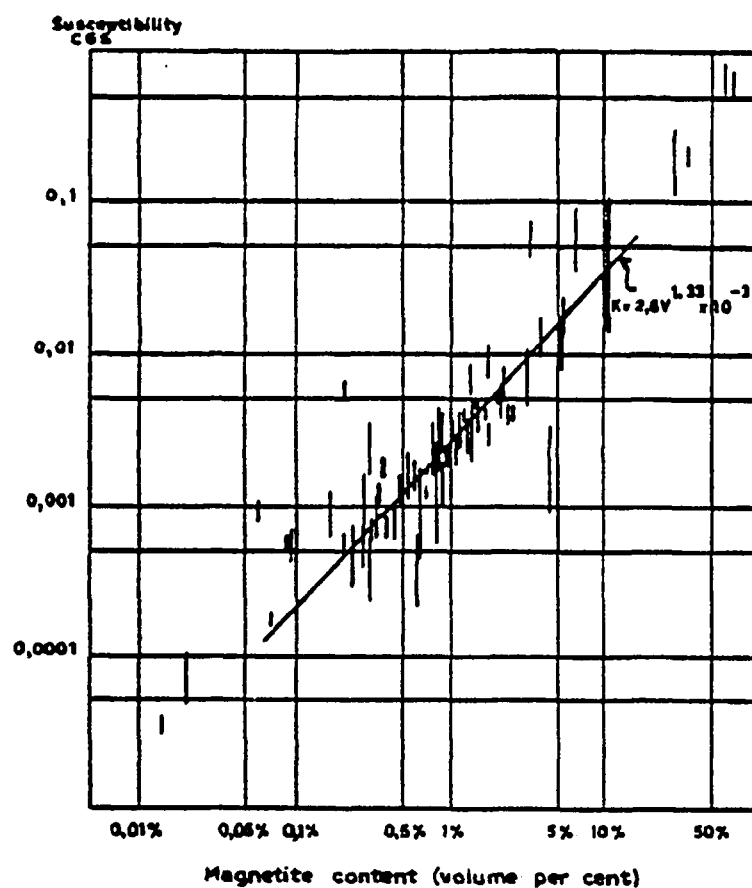


Fig. 2.4 Variation of susceptibility with magnetite content.
After Balsley and Buddington (Economic Geology, Nov. 1958)

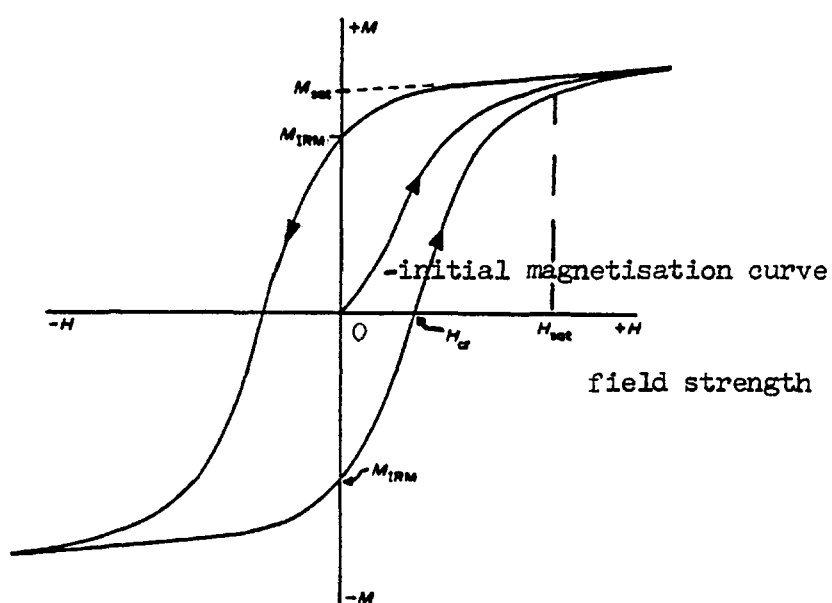


Fig. 2.5 The hysteresis loop

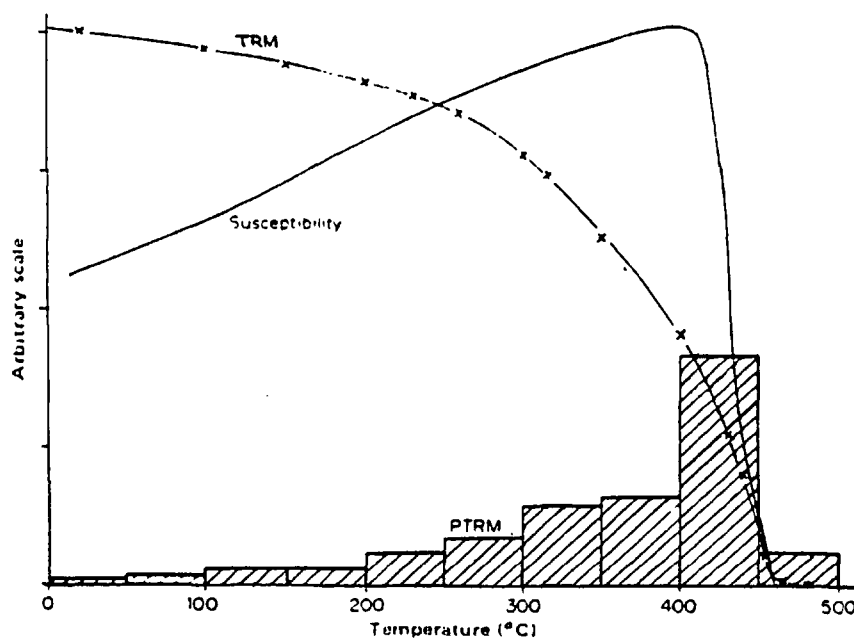


Fig. 2.6 The acquisition of thermal remanence
(After Tauxy, 1971)

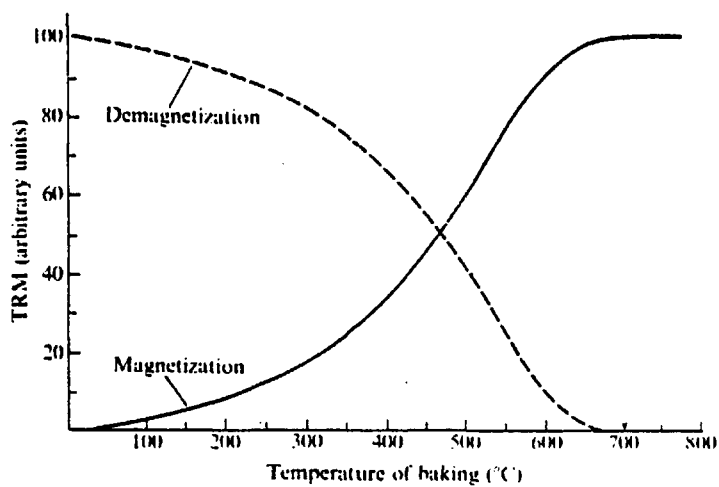


Fig. 2.7 The acquisition of TRM
(After Aitken, 1974)

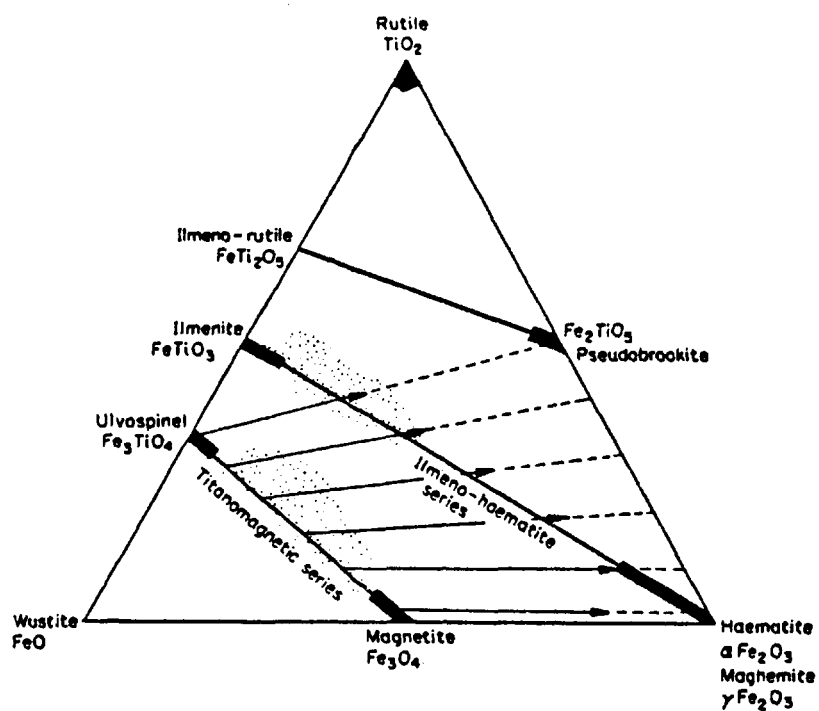


Fig. 2.8 Ternary diagram of the composition of the common iron-titanium oxides

(After Tarkenton, 1971)

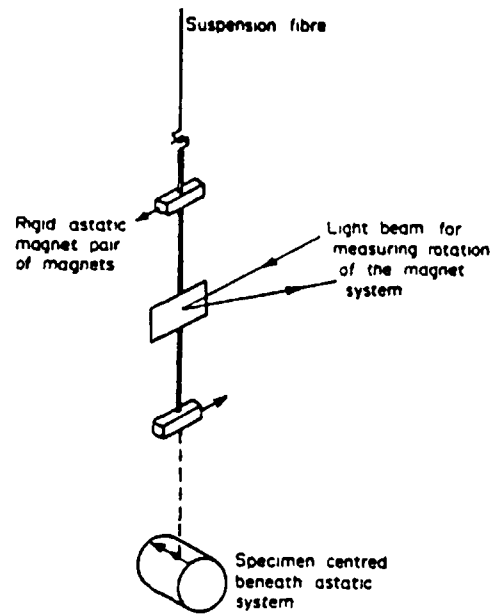


Fig. 2.9a An astatic magnetometer
(After Tarkington, 1971)

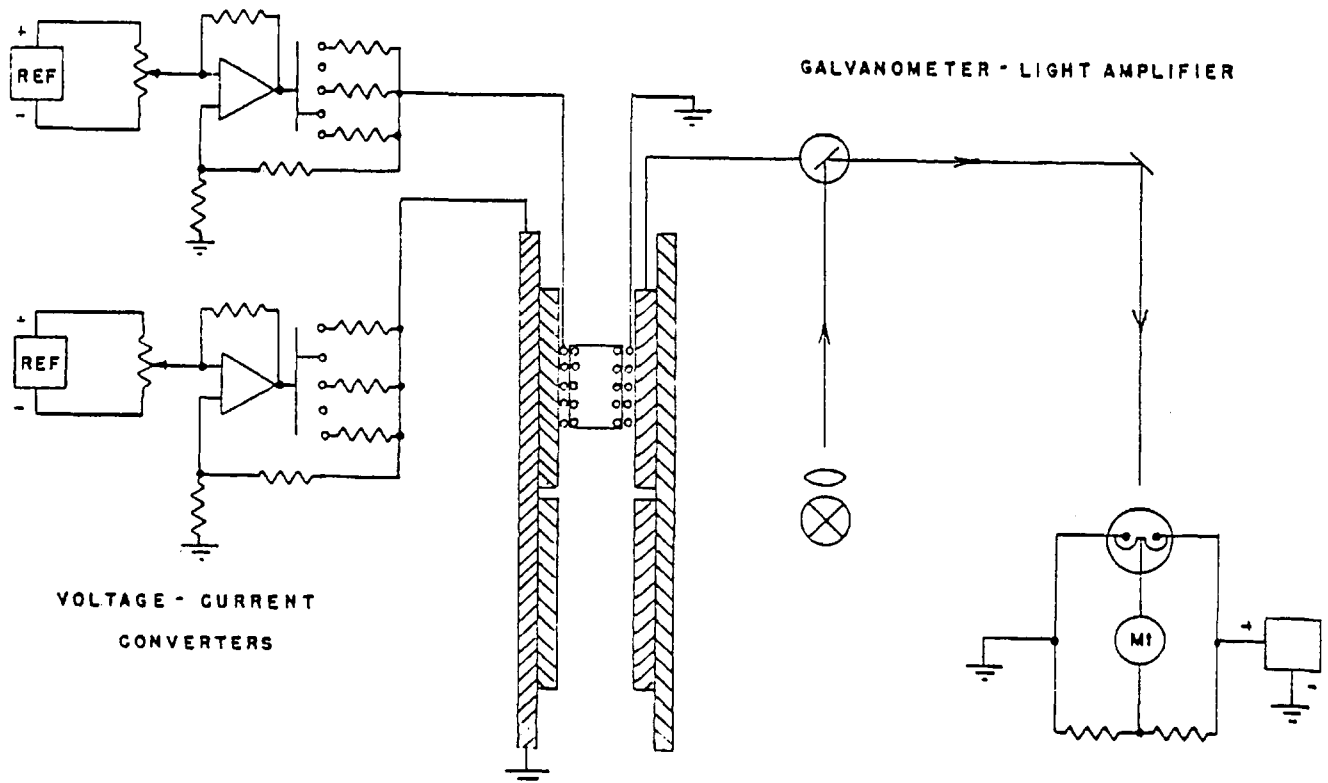


Fig. 2.9b Moving sample magnetometer - block diagram, electronics
(After Scollar and Graham, 1973)

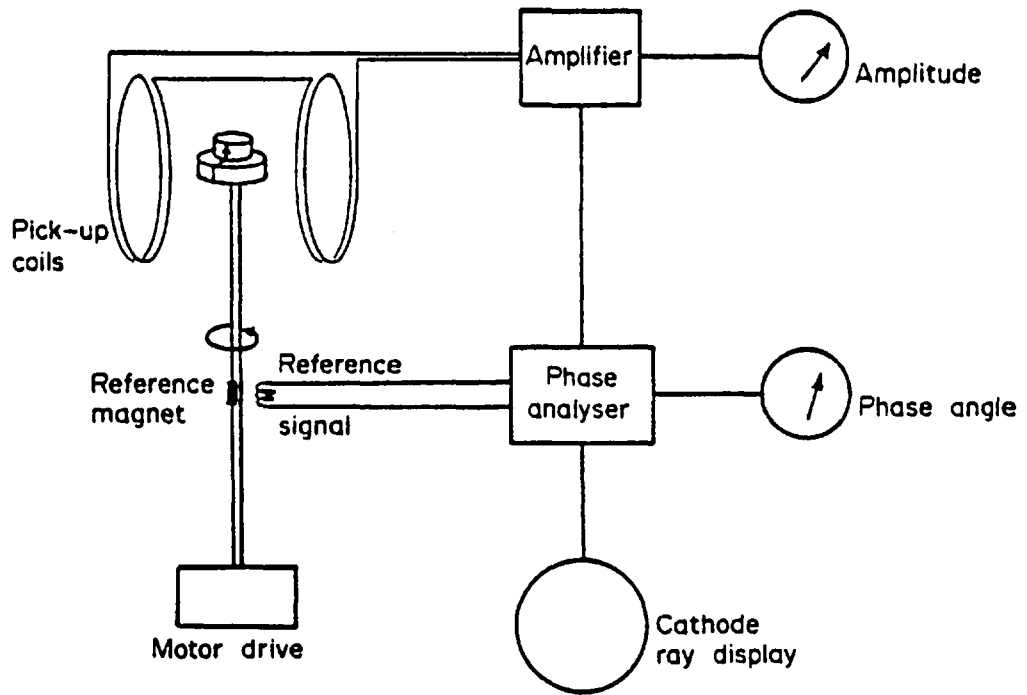


Fig. 2.9c A spinner magnetometer
(After Tankin, 1971)

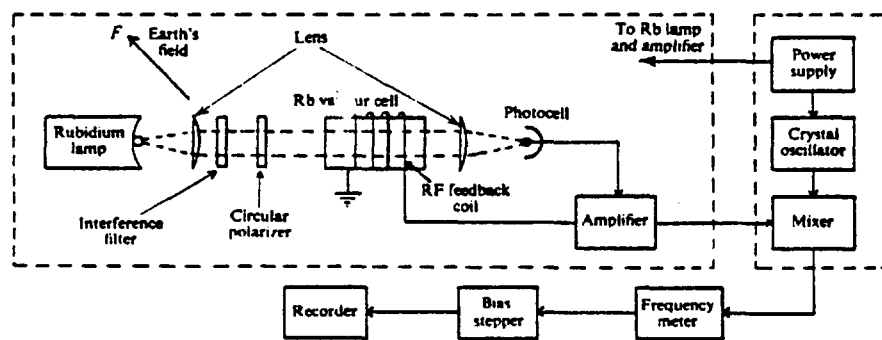


Fig. 2.10 Rubidium vapour magnetometer (schematic)
(After Telford et al., 1978)

Fig. 2.11 Enhancement of the magnetic susceptibility of soils

Archaeological results

Site code	Site	Archaeological data	Subsoil geology	Susceptibility (emu/gm $\times 10^6$)			
				Subsoil	Topsoil	Pits	Ditches
AR	Ardleigh, Essex	Iron Age farm	Gravel: glacial	6	18	—	7
BA	Baldock, Herts.	Iron Age-Roman settlement	Chalk: Cretaceous	20	60-110	150-170	90
BF	Burton Fleming, Yorks.	Iron Age cemetery	Chalk: Cretaceous	2	45-70	—	35-75
CA	Castor, Northants.	Roman industrial settlement	Sand, clay: Upper Lias-Jurassic	—	160-210	250	330
CC	S. Cadbury, Somerset	Iron Age-Saxon hill-fort	Limestone: Inferior Oolite-Jurassic	3	290	290-720	—
CH	Colchester, Essex	Iron Age-Roman settlement	Sand, gravel: post glacial	2	30-60	20-200	—
DC	Dane's Camp, Worcs.	Iron Age hill-fort	Limestone: Inferior Oolite-Jurassic	—	400	270-560	—
IDR	Dragonby, Lincs.	Iron Age-Roman settlement	Sand: post glacial	6	190-450	930	100-400
MH	Much Hadham, Herts.	Roman kiln site	Sand, gravel, clay: glacial	5	10-200	130-190	—
MT	Mucking, Essex	Bronze Age-Saxon settlement and cemetery	Gravel, clay: post glacial	5	30-50	60-80	40-95
NE	N. Elmham, Norfolk	Saxon-post medieval settlement	Sand, gravel, clay: glacial	15	40-60	50-170	30-45
ST	St. Albans, Herts.	Iron Age-Roman settlement and cemetery	Sand, gravel: post glacial	7	25-65	18-100	—
TH	Thetford, Norfolk	Saxon town	Sand, gravel: post glacial	4	100-410	250-510	52
WY	Wytham, Essex	Saxon town	Sand, gravel: glacial	—	110	—	10-20

Table Geological results

Geological period	Code	Geological strata	Principal rock types	No. of soil samples	$\chi_H (\times 10^{-6} \text{ emu/g})$
Drift (recent)	A	East Anglia	Alluvium, river gravels, glacial deposits	14	240-640
	B	Central England		9	820-1380
Cretaceous	h_3	Chalk	Chalk	16	100-630
	h_{3-4}	Upper Greensand, Gault	Sandstones, clays,	4	205-460
	h_2	Lower Greensand	Sandstones	4	1840-4400
	h_1	Weald Clay	Clays	3	790-1520
	h	Hastings Beds	Sandstones	3	350-440
Jurassic—upper	g_{12}	Kimmeridge Clay	Clays	2	580-680
	g_{11}	Corallian	Limestones, clays	4	190-820
	g_{10}	Oxford Clay	Clays	2	180-560
	g_9	Cornbrash	Limestones	3	700-1660
	g_{6-8}	Great Oolite Series	Limestones, clays	6	670-1390
	g_5	Inferior Oolite Series	Limestones, sandstones	12	970-7700
	g_{3-4}	Upper Lias	Limestones, clays	4	500-2030
	g_2	Middle Lias		4	550-6000
	g_1	Lower Lias		5	450-1950
Triassic	f_6	Keuper Marl	Marls	1	180
Permian	e_3	Lower Marl	Marls	1	830
	e_2	Lower Sandstone	Sandstones	3	500-740
Carboniferous	d_3	Productive Coal Measures	Shales, sandstones	2	800-970
	d_4	Culm Measures		3	950-1630
	d_{1-3}	Carboniferous Limestone	Limestones	2	320-640
Devonian	c_3	Upper Devonian	Slates, limestones, sandstones	3	1070-1420
	c_2	Middle Devonian		2	960-1100
	c_1	Lower Devonian		2	570-1210
Igneous	$G(m)$	Granite—moorland	—	4	10-29
	$G(a)$	Granite—agricultural	—	4	240-550
	D	Diabase	—	1	1140
	F_5	Pillow Lava	—	1	1770

Fig. 2.12a Influence of geology on the magnetic susceptibility of soils

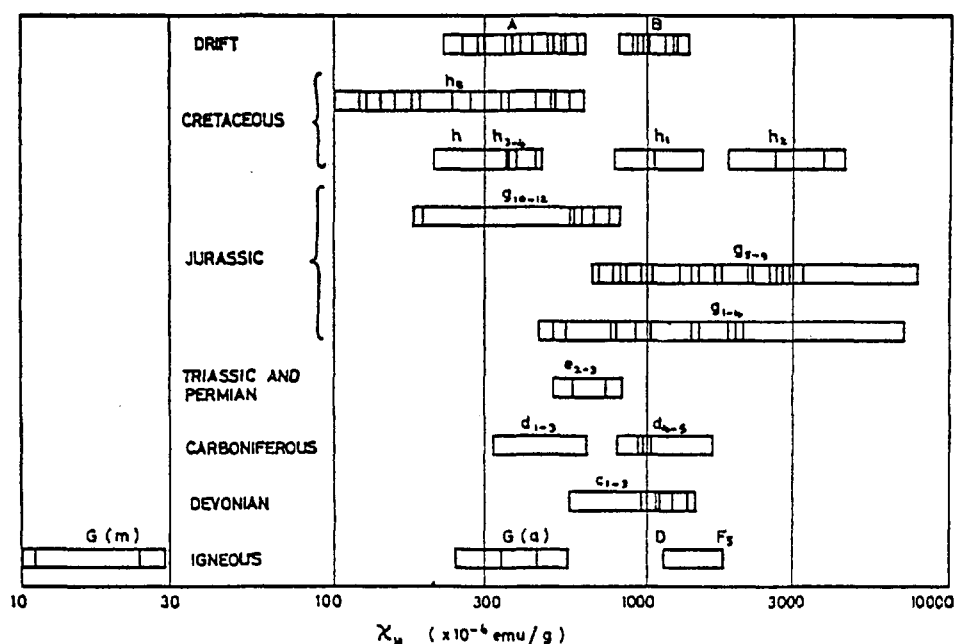
Fig. 2.12b Magnetic susceptibility (χ_H) after heating in hydrogen for soils derived from different geological strata. Each vertical 'line' represents one soil sample.

Fig. 2.13a Values of soil susceptibility: X_0 and X_H

TABLE

Sample	Soil Type	Parent material	Underlying Geology	Drainage	Susceptibility e.m.u./g10 ⁻⁶	
					X_0	X_H
A ₁	Gley soil with clay substrata	Chalky Boulder Clay	Boulder Clay	Poor	37	635
A ₂	Gley soil 30cm beneath A ₁	"	"	"	36	549
C ₁	Brown calcerous soil with gleying	"	"	Imperfect	19	-
D ₁	Rendzina	Loamy chalk over chalk	Middle Chalk	Free	37	495
E ₂	Browneath	Chalky, sandy & loamy drifts	"	"	25	514
E ₄	" 20cm beneath E ₂	"	"	"	16	629
E ₅	"	" " "	"	"	24	566
F ₁	"	" " "	Lower Chalk	"	42	511
G ₁	Peaty & humose gley soil	Reworked Gault Clay	Gault Clay	{ Drained Fen }	31	456
G ₂	" 20cm beneath G ₁	" " "	"	{ Imperfect-poor }	11	443
H ₁	Baisin peat	Peat	Peat (formed on Kimmeridge Clay)	Drained Fen, Free	139	603
J ₁	Gleyed browneath	Drift with Lower Greensand loams	Lower Greensand	Imperfect	79	2660
J ₂	" "	" " "	"	Imperfect	24	4410
K ₁	Peaty & humose gley soil	Reworked Ampthill Clay	Ampthill Clay	Drained fen, imperfect-poor	72	620
L ₁	Brown calcerous soil	Brashy limestone	Upware Limestone	Free	50	823
L ₂	" 20cm beneath L ₁	" "	"	"	51	746
M ₁	Baisin peat	Peat	Peat (formed on Gault Clay)	Drained Fen, free	130	-
N ₁	Peaty & humus gley soil	Reworked Kimmeridge Clay	Kimmeridge Clay	" imperfect-poor	14	676
P ₁	Browneath	Ferruginous (Lower Green sand) coarse loam	Lower Greensand	Free	38	3850
Q ₁	Gleyed Browneath	Gravelly loams	2nd terrace river gravel	Free-imperfect	32	544

TABLE

Site location	Label	Type	Average value of topsoil, pit or ditch X_H , emu/g. 10^{-6}	Topsoil*(2) Texture	Soil parent material	Subsoil X_H , emu/g. 10^{-6}
Ardleigh, Essex	AR	Iron Age farm	280	Loam	Gravel:glacial	100
Baldock, Herts	BA	Iron Age - Roman settlement	450	Sandy loam	Chalk:Cretaceous	128
Burton Fleming, Yorks	BF	Iron Age cemetery	730	Sandy loam	Chalk:Cretaceous	76
S. Cadbury, Somerset	cc	Iron Age - Saxon hill-fort	1200	Loam	Limestone:Inferior Oolite-Jurassic	1075
Castor, Northants	CA	Roman industrial settlement	1150	Sandy loam	Sand,clay:Upper Lias-Jurassic	-
Colchester, Essex	CH	Iron Age - Roman settlement	350	-	Sand,gravel:post glacial	-
Dane's Camp, Worcs	DC	Iron Age hill-fort	1700	Silt loam	Limestone:Inferior Oolite-Jurassic	-
Dragonby, Lincs	DR	Iron Age - Roman settlement	450	Loamy sand	Prodingham ironstone Iron pan (red sand) Yellow sand White sand	7610 502 380 95
Madmarston, Oxon	MM	Iron Age hill-fort	3000	-	Clay:Upper Lias - Jurassic	-
Much Hadham, Herts	MH	Roman kiln site	300	Silt loam	Sand,gravel,clay:glacial	1010
Mucking Thurrock, Ex.	MT	Bronze Age - Saxon settlement & cemetery	540	-	Gravel,clay:post glacial	855
North Elmham, Norfolk	NE	Saxon - post mediaeval settlement	500	Sandy loam	Sand,gravel,clay:glacial	1145
Owlesbury, Hampshire	OW	Iron Age - Roman settlement	300	-	Chalk:Cretaceous	-
St. Albans, Herts	VR	Iron Age - Roman settlement & cemetery	440	Sandy loam	Sand,gravel:post glacial	875
Thetford, Norfolk	TH	Saxon town	(1)	Sand	Chalky boulder clay	200
Winchester, Hampshire	WI	Saxon - mediaeval town	150	-	Chalk:Cretaceous	-
Witham, Essex	WY	Saxon town	430	-	Sand,gravel:glacial	-

Notes: (1) This value is unreliable because of the effect of iron smelting.

(2) This is obtained from the mechanical analysis described in section 4.1.1. using the American textural designation system (Comber p.39, 1960). However, this is somewhat unreliable as explained in section 4.3.4.

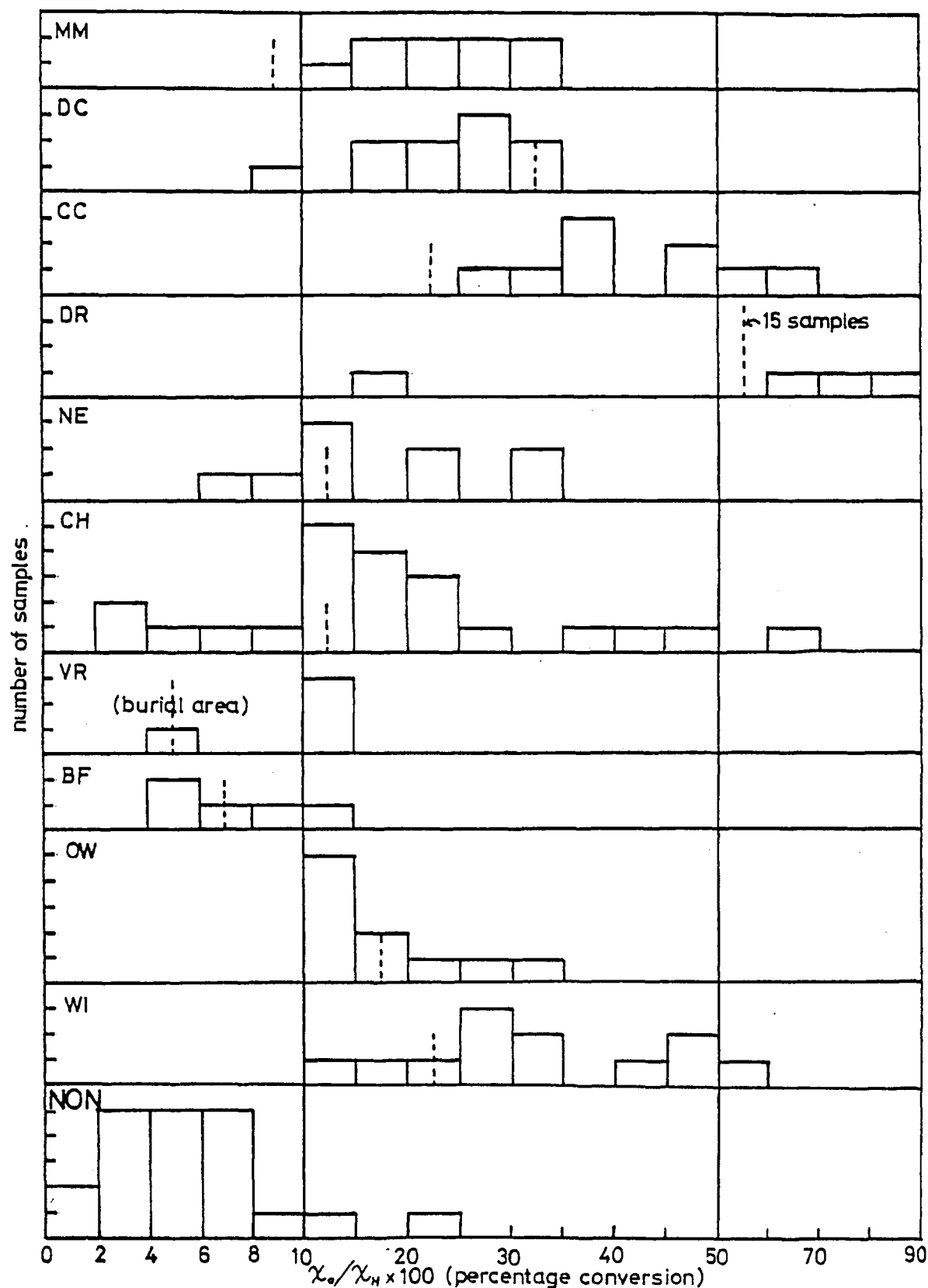


Fig. 2.13c Percentage conversions ($\frac{X_o}{X_H} \times 100$) for soil samples from archaeological and non-archaeological sites (for relevant sample codes, see fig 2.13a and fig 2.13b)

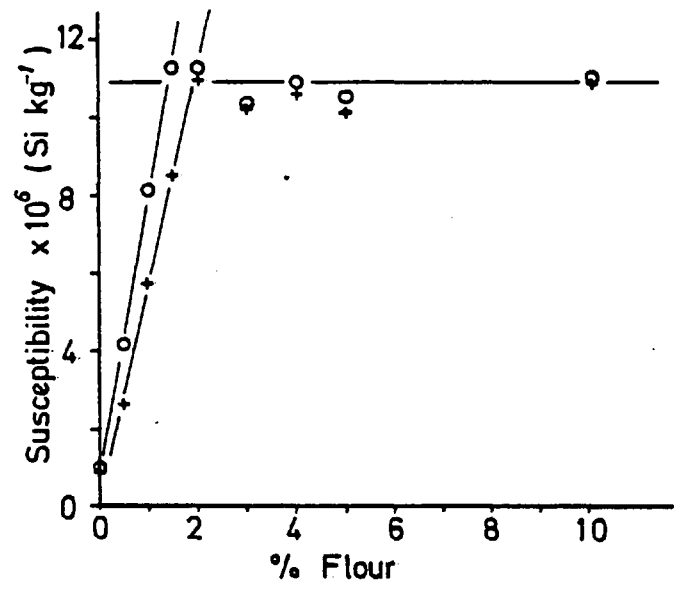


Fig. 2.14 Susceptibility of loess samples after heating to 550°C with various amounts of flour

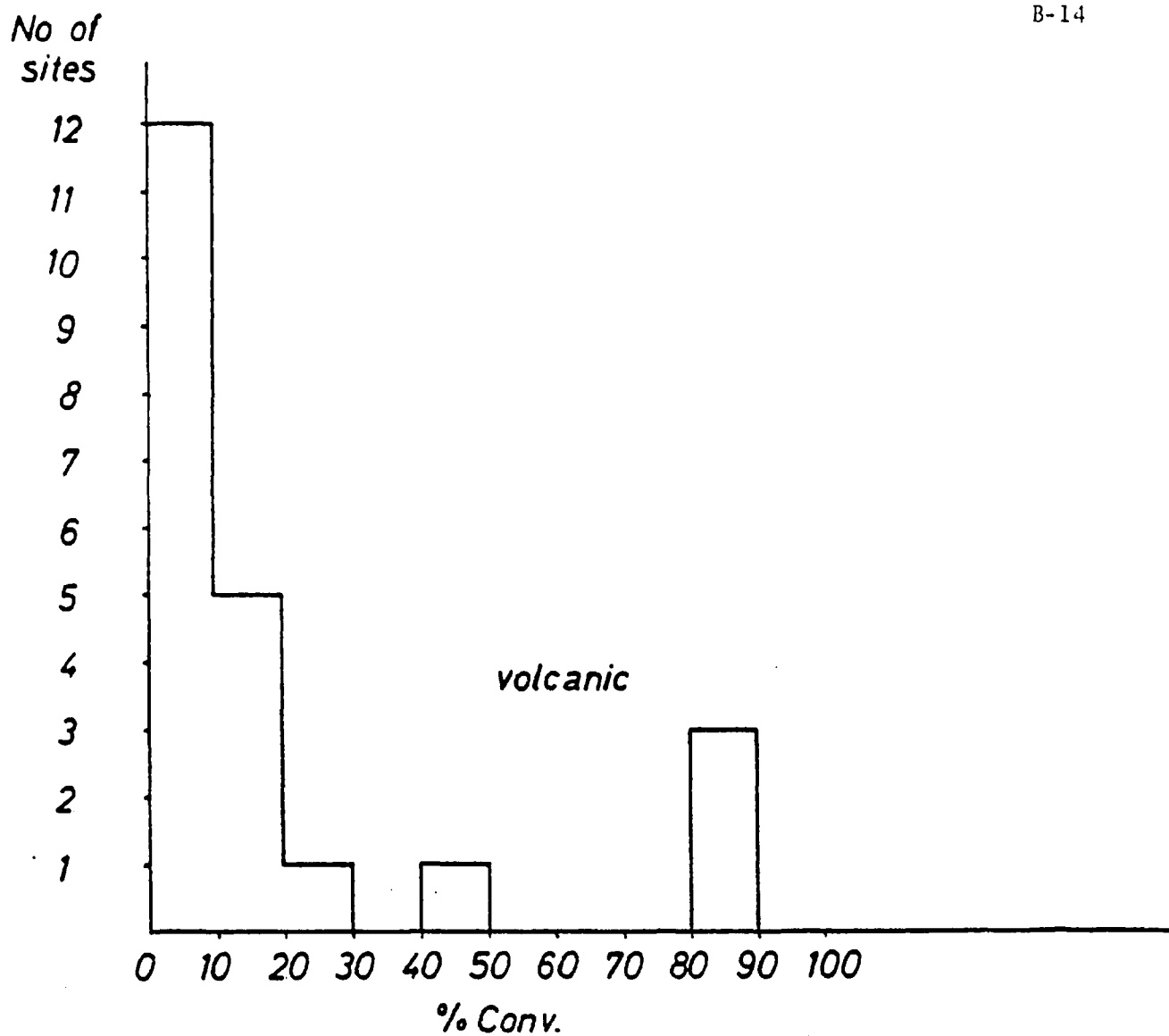


Fig. 2.15 Histogram of the fractional conversion ($\frac{X_o}{X_N}$) of topsoil samples

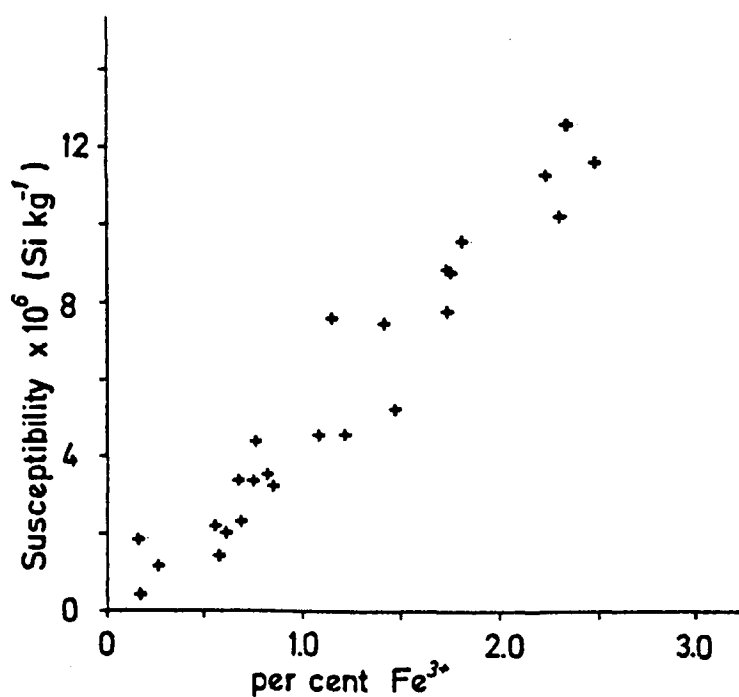


Fig. 2.16 The variation of soil susceptibility after heating, with the iron content determined chemically

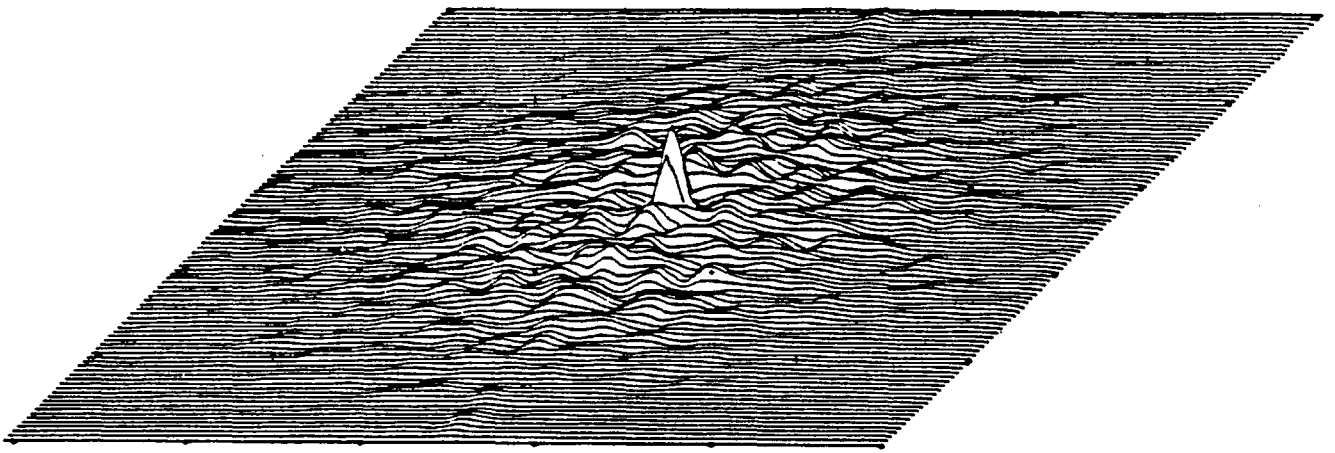


Fig. 2.17 Fourier spectrum of partly correlated noise
(After Graham and Scott, 1976)

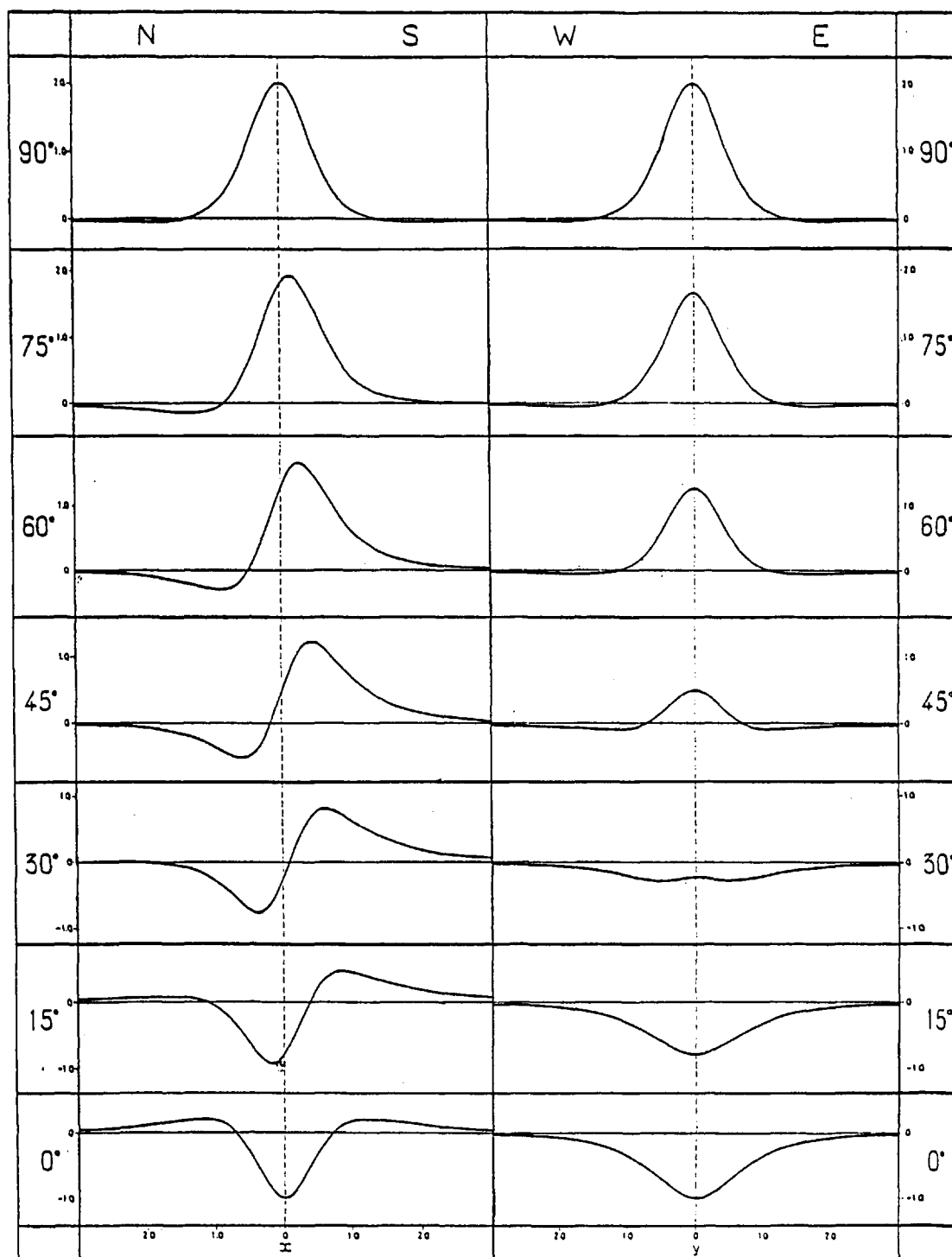


Fig. 2.18a Angles of D - anomalies produced by a magnetic dipole lying in the same direction as the earth's field
(After Livingston, 1964)

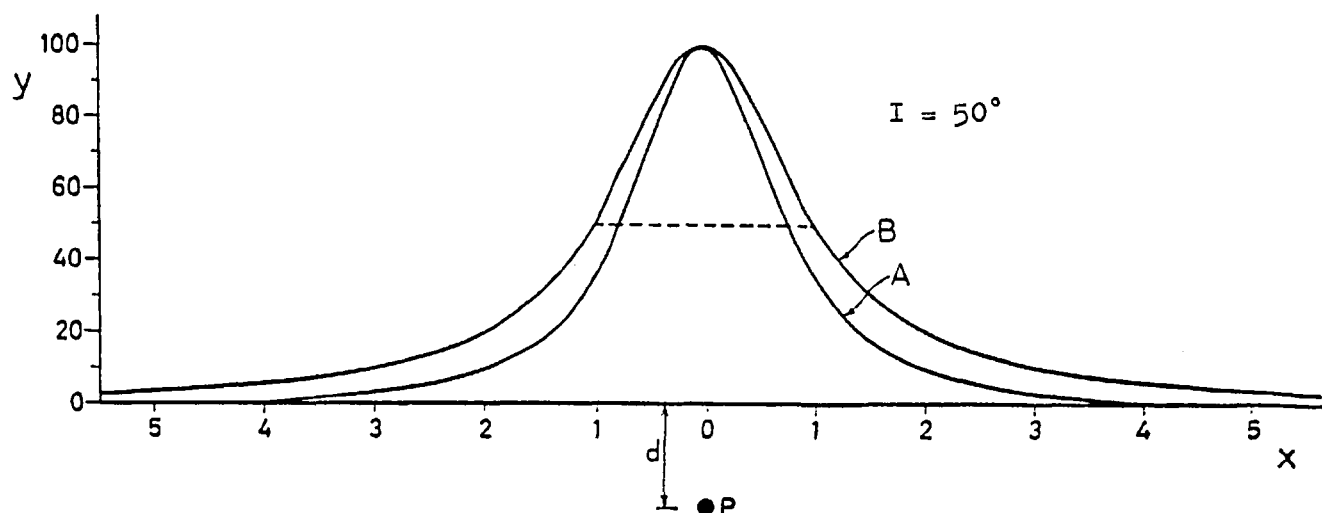


Fig. 2.18b Basic anomalies for an inverse cube rule (graph A) and an inverse square rule (graph B)

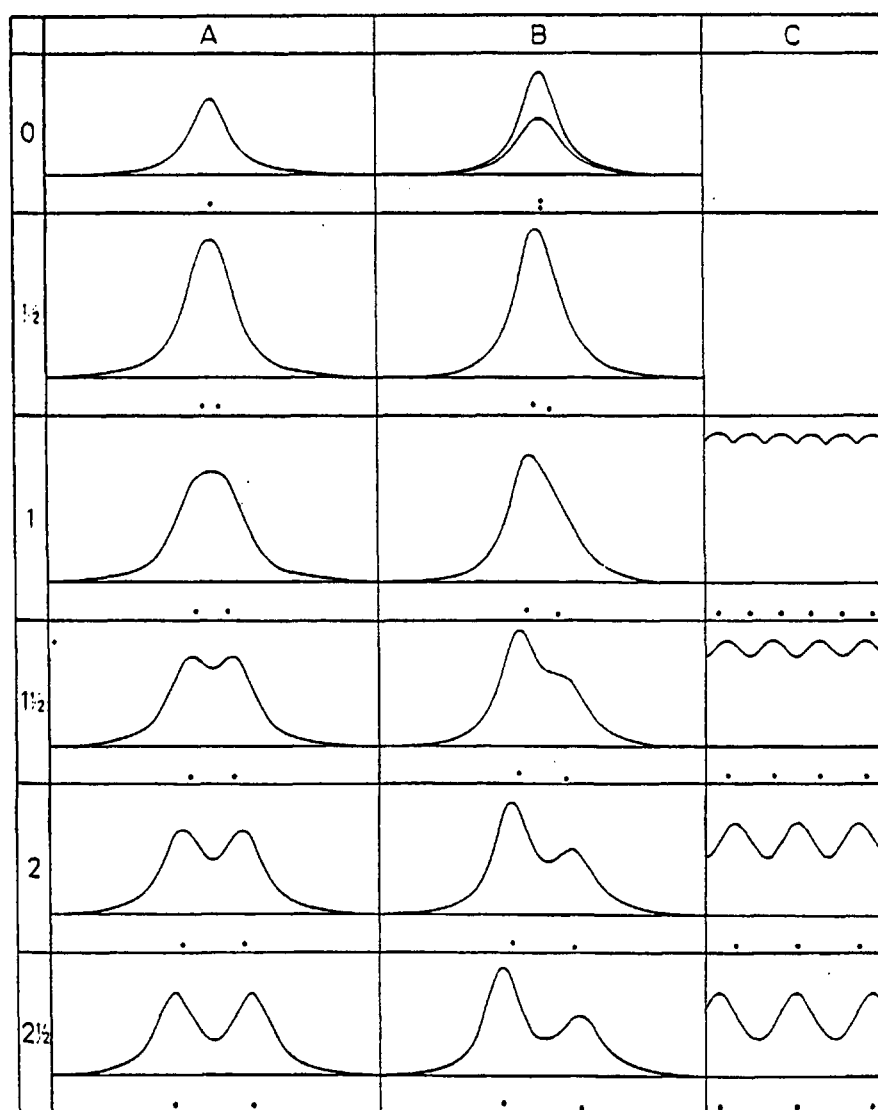


Fig. 2.19 The effect on anomaly shape of different separations between features as deduced using simplified theoretical anomalies
(After Livingston, 1964)

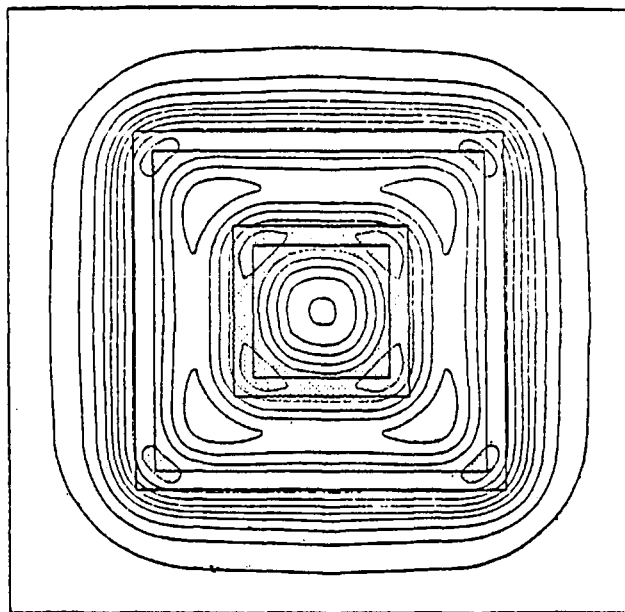


Fig. 2.20a Simplified theoretical anomaly for a double square feature
(After Livingston, 1966a)

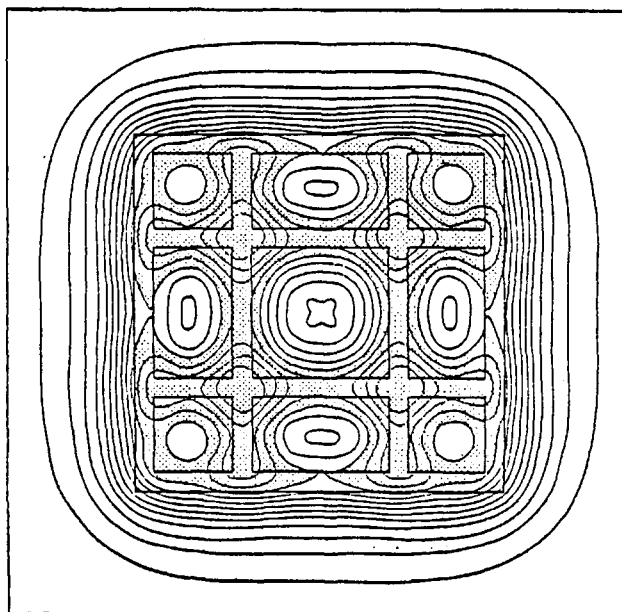


Fig. 2.20b Simplified theoretical anomaly for a double square feature (as above), with the addition of extra 'walls'
(After Livingston, 1966a)

CHAPTER 3

RESISTIVITY SURVEYING

Introduction

Resistivity measurement relates to the ability of certain materials to conduct an electrical current on application of a voltage. In turn conduction relies on electronic or ionic processes. There are three main types of solid conductors: metals such as gold, copper etc.; electron semiconductors, for instance most sulfide ore minerals; and solid electrolytes, e.g. silicate rock minerals.

Rocks contain minerals and owing to their porosity, a certain amount of water, usually in a salt solution. It is through this that most of the current passes. Only when either completely frozen or when the rock itself contains highly conductive minerals, will current go through ^{the rock matrix} ~~solid rock~~. This also applies to very deep rocks whose pore structure is closed by the overlying material. Measurements are made of the conducting properties of a given medium and the results are based on the resistance offered to the applied current.

In practice an artificial source of current is driven through the ground using electrodes. These are placed in the ground according to a specific configuration of usually four electrodes. Current introduced through one pair sets up a potential difference in the earth which is measured with the second electrode pair. The relevant current is also noted unless done by the instrument. These measurements enable the effective or apparent resistivity of the underlying ground to be determined.

The advantages of resistivity chiefly lie in the use of a controlled source. Its principal drawbacks are its high noise level and the cumbersome method of measurement.

The following presents a brief survey of the principles with particular emphasis on facts relevant to the use of resistivity in near-surface surveying.

3.1. Principles

3.1.1. Current Flow in Homogeneous Media

Conductivity expresses a material's ability to conduct an applied voltage whereas resistivity refers to the resistance of the material to the electrical current. Ohm's law defines these parameters as:

$$\frac{\Delta V}{I} = R \quad (3.1)$$

where ΔV is the potential difference between two surfaces of constant potential, I the current in a conducting body and R a constant which defines the resistance between the surfaces.

The conversion between the mks unit ohm-meter and cgs unit ohm-centimeter is readily obtained:

$$1 \text{ ohm} - \text{m} = 100 \text{ ohm} - \text{cm} \text{ and } 1 \text{ ohm} - \text{cm} = 0.01 \text{ ohm} - \text{m}.$$

Ohm's law applies to direct current sources and also to low frequency a.c. if the displacement currents are negligible.

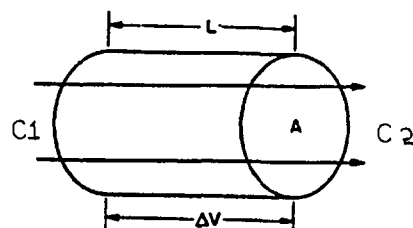
To enable quantitative interpretation, the ground is seen as consisting of various layers of differing resistivity. The boundaries between these layers are known as plane interfaces.

Current passing with its flow lines parallel over a cross-sectional area A of a cylinder encounters a resistance ρ defined by:

$$I \propto V$$

$$R \propto L \quad \rho = \frac{RA}{L} \quad (3.2)$$

$$R \propto 1/A$$



where L is the distance between the equipotential surfaces C_1 and C_2 , I the current flow, A the area, V the potential difference and R the effective resistance between the equipotential surfaces.

Normally electric current lines pass at right angles to a surface.

The total current over the area A is determined by:

$$I = \frac{\Delta V}{R} = \Delta V \cdot \frac{A}{\rho L} \quad (3.3)$$

and the 'current density' j as

$$j = \frac{I}{A} = \frac{\Delta V}{\rho L} \quad (3.4)$$

If the current density varies through the conductor, the relationship becomes:

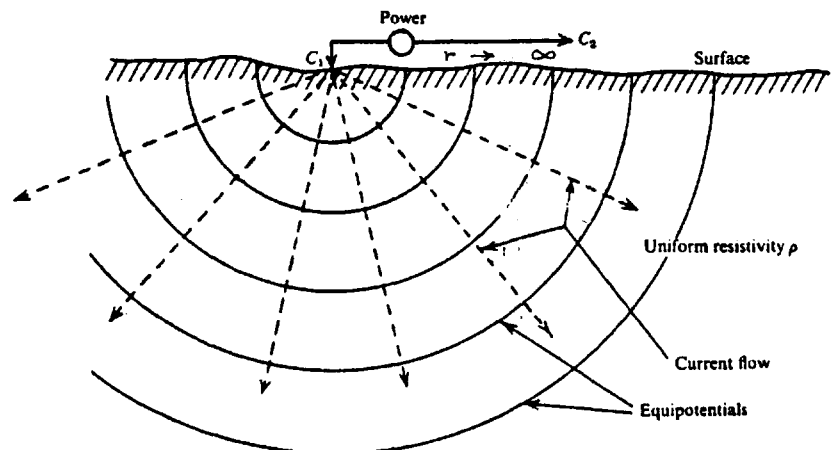
$$j = - \frac{1}{\rho} \cdot \frac{dV}{dL} \quad (3.5)$$

where $\frac{dV}{dL}$ describes the argument as relating to an element of the conductor which may have curved equipotential surfaces. The negative sign indicates that the increase in potential is in the opposite direction from the current flow.

Development of the theory leads us on to the potential gradient measured at a point, distance r from the surface source (point source of current). As the applied current will be known, the resistivity is readily found

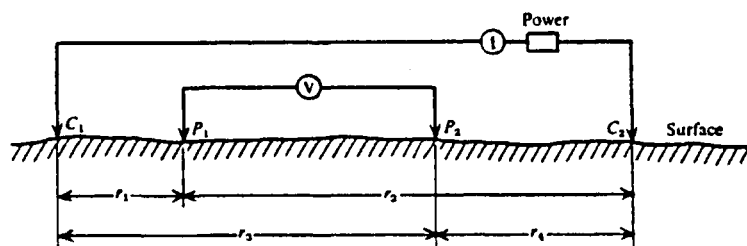
$$V = \frac{I\rho}{2\pi r} \quad (3.6)$$

$$\text{or } \rho = 2\pi rV/I$$



where r is the distance from the first electrode.

The above applies to one current electrode at the surface. A finite distance between two current electrodes causes a distortion of equipotentials and current flow lines as one current electrode affects the other (Fig. 3.1). This becomes important for the four-electrode spread generally used in field work.



Two current and two potential electrodes on the surface of homogeneous isotropic ground of resistivity ρ .

The difference in potential between P_1 and P_2 will be

$$\Delta V = \frac{I\rho}{2\pi} \left(\frac{1}{r_1} - \frac{1}{r_2} \right) - \left(\frac{1}{r_3} - \frac{1}{r_4} \right) \quad (3.7)$$

The quantitative distribution of current in depth is closely related to the electrode separation. An increase in separation will increase the depth of investigation. The variation in current density in a vertical plane midway between the current probes ($C_1 - C_2$) can be plotted as a function of the ratio of depth to electrode separation, for a fixed probe separation (Fig. 3.2). This applies to the current flow in a homogeneous ground. The plot clearly indicates that the probe separation is of decisive influence on the variation in current density with depth. In layered ground, the resistivities of the various layers assumes importance. Layered earth problems do generally not apply to archaeological surveying where anomalies are seen as local resistivity contrasts within the first few meters of the underlying soil. It is

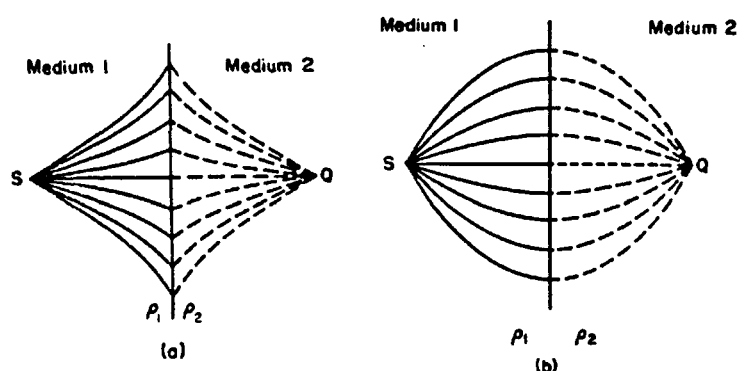
therefore important to ensure the maximum possible variation in potential gradient at the surface. This is achieved by focussing a maximum density in current at the depth of the interface. The relationship between electrode separation and the current density at a given depth in homogeneous ground is shown in Fig. 3.3. Maximum current density occurs at a current electrode separation of $1.4 h$. This provides a useful guideline in most situations, but does not apply to large resistivity contrasts in the soil.

3.1.2. Current Flow in Inhomogeneous Media

A homogeneous ground occurs very rarely and is of no real significance in near-surface surveying where the object primarily is to detect buried masses and structures. The interpretation in such cases is difficult and even the simplest of buried bodies, the sphere, requires complex mathematics.

A body positioned close to the earth's surface causes interaction between the body and its electrical image, the latter in analogy with geometrical optics. Similar^{ly} to ray intensity, current density decreases with the inverse square of distance from a point source.

With two media of differing resistivity separated by a plane interface both current flow and potential become distorted:



*The effect of a boundary on the distribution of lines of current flow
(a) where $\rho_2 > \rho_1$, (b) where $\rho_1 > \rho_2$.*

The above situation becomes more complicated if the current source and potential point are located on the surface, as they are in reality. One then has to deal with an infinite number of images as there are three media and two interfaces owing to the ground surface. The effect of a boundary is to 'reflect' a certain amount of the source depending on the source strength S and the reflection coefficient k . The value of k is a constant and lies between ± 1 and depends on the resistivities of the media, with each successive medium reducing the potential at P .

The disturbing effects of a buried sphere are discussed in section 3.2.4.

3.1.3. Apparent Resistivity

On rearrangement, the equation for the four-electrode array (eq. 3.7) becomes

$$\rho = \frac{2 \pi \Delta V}{I} p \quad (3.8)$$

where p refers to the electrode geometry.

The measured resistivity values remain constant in a homogeneous isotropic earth. This however rarely occurs especially when the ground is traversed using a fixed electrode spacing or when measurements are made by varying the probe spacing. Therefore its magnitude will depend on soil inhomogeneities and the probe configuration used. The measured resistivity is referred to as the apparent resistivity ρ_a . In homogeneous soils this will represent the true resistivity. The influence of geology on electrical resistivity is next discussed.

3.1.4. Electrical Resistivity Related to Geology

Electricity is conducted through the ground by means of electronic (ohmic) or ionic (molecules with an excess or deficiency of electrons) processes. The form of the current flow within the earth as well as the

potential distribution will be altered by any variation in subsurface conductivity. Electrical conduction through most rocks is basically electrolytic. The mineral content of a rock is sometimes also of influence. Enough magnetite or specular haematite for continuous conduction paths, for instance, can significantly increase the conductivity resulting in a decrease in the bulk resistivity of a rock. Other examples of conducting minerals frequently encountered are graphite, carbon and pyrite. These are especially relevant to slates. The distribution pattern of the mineral in a rock also affects its bulk resistivity.

Most near-surface rocks are water-bearing resulting in electrolytic conduction. This in turn depends on the amount of water, its salinity and distribution. Rock porosity forms an important factor, and has been classed as follows:

- a) intergranular porosity e.g. consolidated sedimentary rocks, volcanic ash beds - the porosity consists of spaces left between the grains after the rock compacted;
- b) joint porosity e.g. igneous rocks - the porosity occurs in the joints inbetween the rock material;
- c) irregular porosity e.g. limestones and some volcanics - the porosity is in the form of irregular solution holes in the rock material (limestones) or as gas bubbles (volcanic rocks).

Any one rock can exhibit varying stages of porosity: sedimentary sandstones and shales mainly consist of intergranular porosity (5 - 60%) and some joint porosity. The resistivity of porous water-bearing rocks (free of clay minerals) varies approximately as the inverse square of its porosity. This observation leads to Archie's law:

$$\rho = a \rho_w \phi^{-m} \quad (3.9)$$

where ρ is the bulk resistivity of the rock, ρ_w the resistivity of the water in the pores, ϕ the porosity expressed as a fraction per unit rock

volume, and m and n parameters of which the values are made to fit the equation to a set of measurements. The value of n will approximate 2.0 if more than 30% pore space is filled by water. M relies on the degree of cementation or the geologic age of the rock (as they both often correlate well).

Archie's law has been developed for a number of rock formations. In practice it is difficult to determine, as it relies on vague relationships such as the choice of value for ρ_w which is difficult to measure.

The following factors concerning the circulation of water in the zone of aeration above the water table are of direct relevance to near-surface resistivity:

- a) penetration of rain water from the surface into the underlying soil or rock;
- b) lateral movement of this water through an aerated or semi-dry zone towards the water table;
- c) upward movement of this water during dry periods either directly or through plant transpiration.

A soil will hold a certain amount of water dependent on the drainage and the rate of evaporation. Soil grain size is an important factor, where soils with a fine pore structure tend to hold on to the available water through capillary action and larger grained soils loose water through gravitational force. Grain size is generally more relevant than the distance to the water table with fine-grained soils containing more water than coarse-grained ones.

Another important factor is the interaction between water and solid minerals. A large amount of water generally leads to low conductivity values. This is because there is a gradual leaching of the exchange ions from the clay minerals in a soil, which reduces the conductivity of the

electrolyte. Conversely, a large amount of water evaporation without subsequent replenishment, a process generally associated with arid regions, causes an upward movement of water from the permanent water table. This process leads to an increase in the salinity of near-surface water augmenting the effective electrical conductivity. In certain cases this has brought about the formation of caliche zones (areas of mineral deposit).

Therefore soils in arid areas are generally more conductive than those in humid climates.

An increase in salinity affects finer-grained soils to a greater extent than it does coarse-grained ones.

From the above it will be realized that the resistivities of formations and soils vary widely. Unfortunately there is no overall correlation between lithology and resistivity. Some generalization, however, does apply. The following is in order of decreasing resistivity: crystalline rocks, limestone, gravel, sand and clay, are some examples. (Fig. 3.4).

3.1.5. A.C. and D.C. Measurement Methods

In near-surface geophysics almost all surveying is done with an alternating current. This avoids electrochemical e.m.f.'s between the metal electrodes and the ground as well as the effects of natural earth currents. Both effects are unidirectional. In ^{groundwater} geophysics use is generally made of high power d.c. equipment.

The frequency of the alternating current must be carefully chosen: frequencies below 1 Hz are influenced by induced (electrolytic) polarization whereas those above circa 60 Hz run into problems with ground inductance (inductive coupling between adjacent current and potential leads) and leakage currents. These problems become especially apparent when the ground is wet, leading to erratic readings.

In low resistivity areas one also gets skin effects with a.c.

To avoid the above problems when using the d.c. method, the polarity of the direct current must be periodically reversed. Furthermore, porous pots (non-polarizing) are used for the electrodes and a note is made of the self-potential effect (electrochemical mechanism that leads to a natural current and ionic flow in the earth) before each reading. This is subsequently subtracted from every reading. This process has been automated in some systems.

Basically the measured resistivity will show no difference when using a direct current method or a high frequency alternating current. This applies to conductors and semiconductors but not to solid electrolytes (e.g. most rock-forming minerals) where resistivity, to a certain extent, does depend on the frequency. This is in turn related to the temperature: the resistivity is nearly inversely proportional to the frequency at low temperatures with higher temperatures providing lower but more constant values.

In practice a.c. measurements are generally lower than the true d.c. values.

3.1.6. Dielectric Constant, Polarization Effects and Magnetic Permeability

When using a d.c. current non-polarizing probes are used. This is because the measured resistance between the probes would otherwise gradually increase with time on application of a current.

With the a.c. measurement technique probe polarization is only of marginal influence. This effect relates to dielectric conduction which takes place in poor conductors or insulators, when the external field changes with time. A varying electric field causes a slight displacement of the atomic electrons relative to their nuclei, resulting in the separation of positive and negative charges. This mechanism is known as

the dielectric polarization of a material and the significant parameter is the dielectric constant, k . When a steady current moving through an electrolytic conductor containing a mineral substance, is suddenly switched off, ion build-up occurs between the mineral interface of the electrolyte. This prevents the immediate decay of the current and therefore creates an opposing potential. The magnitude of this potential depends on the mobility, amount and concentration of dissociation of the ions, the latter referring to the dielectric constant.

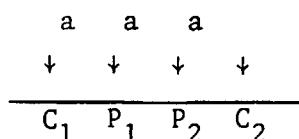
Displacement currents can be largely avoided by using a low enough frequency.

Alternating fields are further affected by the magnetic permeability of the material through which they pass. This only becomes significant when substances contain a large amount of ferromagnetic minerals.

3.1.7. Electrode Configurations

A large number of probe configurations have been developed. The following have been applied to near-surface prospecting:

- (a) Wenner configuration (or Wenner α): this employs combined current and potential electrode pairs equidistant from each other along a straight line. Interchanging the current and potential probes does not affect the apparent resistivity readings by virtue of Helmholtz's reciprocity theorem in the theory of electrical currents. This applies to any configuration.



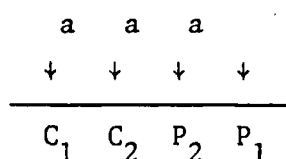
a = electrode separation

$$\text{where } R_o \text{ (measured resistance)} = \frac{\rho_a}{2\pi a} \quad \begin{array}{l} \text{(geometric factor} \\ \text{of the array)} \end{array} \quad (3.10)$$

$$\text{and } \rho_a \text{ (apparent resistivity)} = 2\pi a \Delta V / I \quad (3.11)$$

In electrical depth sounding the probes are gradually expanded about a fixed centre at set increments of the spacing a . When traversing the spacing remains constant and all four probes are moved along a line. The apparent resistivity refers to a point at the centre of the array.

- (b) Dipole dipole configuration (Double dipole, Eltram or Wenner β): this array is very similar to the Wenner array except that the current probes are at one end of the array and the potential pair at the other end.



where $R_o = \frac{\rho a}{6\pi a}$ (3.12)

and $\rho_a = 6\pi a \Delta V / I$ (3.13)

In depth sounding and lateral exploration the same procedure as used for the Wenner array applies.

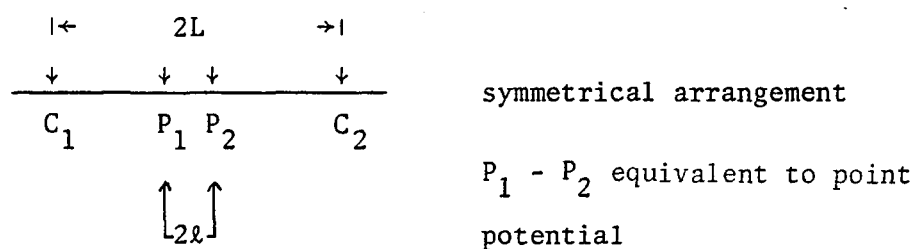
Both Wenner and Dipole dipole configuration will provide virtually similar results when traversing across a broad feature. In general the Wenner results will be more pronounced owing to its greater sensitivity which is achieved by the use of adjacent current-potential electrodes. A traverse across a narrow feature, identical in width to the probe spacing, will result in a characteristic double peak with the Wenner configuration and a single intermediate peak for the Dipole dipole array. Across high resistance anomalies the double peaking will be in the form of an M, with the inverse

(a W) occurring for low resistance anomalies (Fig. 3.5). The double peaking effect complicates the interpretation. This especially applies to complex sites. Furthermore, the width of both peaks does not generally correspond to that of the feature: it is usually broader than the feature itself. Wenner also has problems in differentiating features $1\frac{1}{2}$ times the probe spacing. Double peaking is caused by each current-potential pair 'seeing' the same anomaly. With the Dipole dipole array the feature is located with the central $C_2 - P_2$ pair, with the outer $C_1 - P_1$ pair slightly strengthening the response.

Therefore it is useful to take readings with both Wenner and Dipole dipole when traversing. Any Wenner response can then be substantiated and simplified by the Dipole dipole results. Both configurations have been successfully applied to a large number of archaeological sites.

The depth response of the Wenner configuration is approximately equal to the electrode spacing a and with the Dipole dipole array this will be rather less than the electrode spacing.

- (c) Schlumberger configuration: this is identical in layout to the Wenner array, except that the current electrodes are spaced much further apart than the potential pair.



where $\rho_a = \frac{\pi L^2}{2\ell} \left(\frac{\Delta V}{I} \right)$ (3.14)

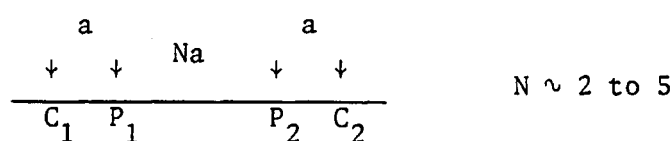
The distance of the inner potential pair to that of the outer current pair is generally kept at a ratio of 1:10 or more e.g. 1 m for the inner pair and 10 m for the outer pair, in near-surface field work.

The above formula applies to this ratio. At best the spacing of the inner potential pair ($P_1 - P_2$) should, as near as possible, be adjusted to the scale of the sought-after features. Apparent resistivity values apply to the midpoint of the array.

As one can imagine, moving the entire array along a line of lateral exploration at a fixed spacing may cause severe inconvenience and make for difficult logistics. It is therefore rarely used in archaeological surveying. The array tends to broaden out features though less so as with the Palmer configuration.

In depth probing the inner pair is kept fixed while the outer pair is expanded symmetrically with respect to the centre of the array. It is often used for such work as shallow resistivity variations remain constant (fixed potential pair) and only two probes have to be moved (outer current pair). At large separations of the outer pair during depth sounding, the distance of the inner pair may have to be increased to enable a measurable potential to be obtained.

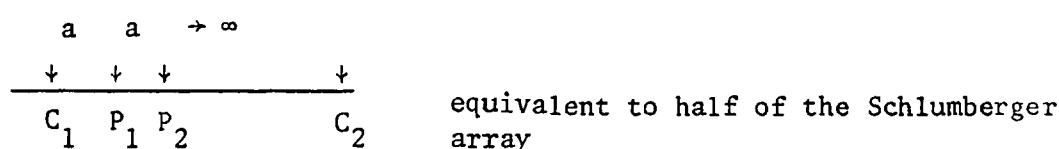
- (d) Palmer configuration: again very similar to the Wenner arrangement except that the individual distance between the two current-potential electrodes ($C_1 - P_1$ and $C_2 - P_2$) is much smaller than that between both pairs.



This array has hardly been used in near-surface applications. It is

very sensitive and gives rise to double peaking as with the Wenner array, yet further distorts an anomaly by considerably broadening it. Best results are obtained by traversing parallel to known linear features (Clark, 1975)

- (e) Three-probe (pole-dipole) configuration: three probes are situated near each other at a fixed distance (in some cases it is varied) while the fourth electrode is placed at a great distance.

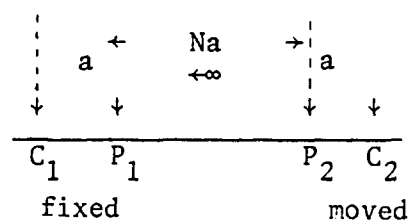


where $R_o \approx \frac{\rho a}{4\pi a}$ (3.15)

and $\rho_a = 4\pi a \frac{\Delta V}{I}$ (3.16)

The electrode C_2 need not be in line with the other electrodes, but must be situated at least three times the distance of the nearest probe spacing. This is to ensure that it has as little influence as possible on the remaining probes.

- (f) Twin-electrode configuration: this uses a fixed current-potential pair while the other c - p pair are moved across the site in a line.



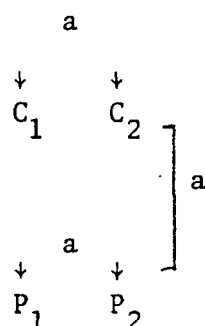
where $R_o \approx \frac{\rho a}{\pi a}$ (3.16)

Anomalies show up as single symmetrical peaks independent of probe

orientation. This enables great ease of use: fewer response ambiguities and only two probes have to be moved. The current penetration will increase with greater electrode pair separation causing a higher background level. A non-homogeneous geology will then increasingly affect the results producing small amplitude/long wavelength variations as distinct from man-made anomalies (high frequency). As the responses from archaeological features will be superimposed on the geological signal, the two can easily be separated.

If $a = 1$ and $N = 30$ then changing N by a factor of 10 to 300 will affect the measured resistance in a homogeneous isotropic earth by not more than 3%. When using a minimum separation of 60 times, this will be reduced to 1.3%. Under such conditions the measured resistance will also be insensitive to electrode alignment. Therefore N must be kept greater than 30 (Aspinall and Lynam, 1970).

- (g) Square array configuration: this system was devised by Clark (1968) and used for a short time in the field. Four electrodes form the legs of a table on which the resistivity meter rests. The probe spacing is therefore fixed at a value of circa 0.75 m.



The effects of double peaking are smoothed by averaging two orthogonally orientated readings taken at each point by changing the

probe configuration through a right angle by means of a switch.

Reduced probe separation and a corresponding lack in depth penetration as well as the difficulty in inserting the table legs into any compacted soil, limit the usefulness of this method.

3.1.8. Instrumentation

Use is generally made of instruments specifically developed for near-surface surveying: the Martin-Clark resistivity meter and the Aspinall-Pickard direct reading earth resistance meter, for instance.

Naturally, any equipment suitable for resistivity field work can be applied. The following represents a brief discussion of some of the available instrumentation.

One of the first instruments used for archaeological field trials was the Meggar Earth Tester (Atkinson, 1952, 1953). Voltage is generated by means of a hand cranked d.c. generator. Early versions had an applied voltage on open circuit of about 200 V at 40 Hz. The resistance is read directly on an ohm-meter. Later versions (Geophysical Meggar) work at a lower frequency which varies between 10 - 20 Hz depending on the rotation speed of the handle and an output voltage of 100 V. A schematic diagram of the instrument is given in Fig. 3.6. The scale factor was inadequate on earlier versions of the Meggar: it did not work at very high or very low resistivity ranges. The instrument also suffered from probe contact resistance. This was overcome in the Geophysical Meggar as it uses a null balance technique. Later versions of this instrument are battery operated.

Another useful instrument is the Tellohm Soil Resistance Meter. A potentiometer measures the potential difference across the inner probes while an a.c. voltage is generated by a reversing relay and supplied to the two outer electrodes (Fig. 3.7). As can be seen from the diagram, the potentiometer is part of the current electrode circuit. Therefore

any variation in the supply voltage will have the same effect on the potentiometer and the current electrodes. The transformer (T) enables any voltage which develops across the potentiometer to be compared with the inner probe voltage. One then adjusts the potentiometer, which is calibrated in ohms, until the balance point (zero deflection) is reached. The great advantage of the null balance technique is that the resistance between the probes and the ground does not affect the total measured resistance. No current is taken through the inner potential probes for the detection circuitry.

The instrument uses an a.c. voltage of approximately 150 V r.m.s. at 110 Hz. Its range varies from 0.3 Ω to 10.000 Ω full scale with an accuracy of $\pm 1\%$ at full scale.

Perhaps the most used resistivity meter is the Martin-Clark. A transistorised oscillator provides the outer-probe current and the rectified output of an amplified current is fed to a sensitive meter which uses the null balance technique. Early versions were run from a 4.5 V battery and used a frequency of 400 Hz which could cause phase shifts of up to 5° between the transformer and the detected voltage, because of earth capacitance effects. Later models (mark 4) operate at a voltage between 9 - 12 V and a frequency of 67 Hz and also incorporate a switch allowing a choice between Double Dipole or Wenner. Speed of operation is greatly enhanced by the use of a rotary turret switch and five probes. The fifth probe is made spare after each reading by advancing the turret switch and then brought to the head of the line by an assistant while a reading is taken with the remaining four probes. These are cranked enabling them to be easily inserted by foot. Furthermore, the instrument is very compact and light and relatively inexpensive.

Another instrument specifically developed for archaeological purposes is the Bradphys (Aspinall and Picard, 1971). Current supply

comes from a 200 V square-wave generator operating at a frequency of 128 Hz. Its main characteristic is an input stage with a high input impedance of 100 M Ω connected to the potential probes, and a stabilised alternating current source (CC probes) held constant irrespective of load resistance variations (Fig. 3.8). The system therefore avoids the necessity of null-balancing and provides virtually instantaneous readout. This becomes especially advantageous when the probe-contact resistance is high causing a sluggish meter response with null-balance instruments.

Other instruments include the Gossen Geohm (Schwarz, 1967a) and the ABEM Terrameter (Griffiths and King, 1975) but these are rarely used in near-surface surveying. Braissant and Chapellier (1971) mention the use of a d.c. system in which polarization effects are subtracted by means of a storage system.

3.1.9. Survey Procedure

Basic field application is the same as described for magnetic surveying. Probes are inserted into the ground along a traverse according to the relevant probe configuration and with a typical probe spacing of 1 m. The latter should be kept as accurate as possible: although lateral displacements hardly affect the results, linear ones do. Depth penetration closely relates to the probe spacing: any increase leads to greater depth penetration and decreases the resolution. The resultant value will therefore be a compromise.

Surveys are generally made according to a grid system. Using a traverse and probe spacing of 1 m a typical 30 m grid can be surveyed in approximately 3 hours. When searching large areas, traverse lines of 15 m length and 5 m apart can be effectively applied looking for buildings and other large anomalies. An individual ditch can readily be outlined by traverses across the ditch at regular intervals.

Results can either be plotted as graphs of resistance against the

traverse distance or in the case of grid surveys in the form of iso-resistive contours. Subsequent filtering and the use of the dot density technique can often greatly enhance the results.

3.2. Review of Previous Work

3.2.1. Soil Conductivity

Many of the pertinent processes have already been discussed. In effect very little research has been done into shallow soil conductivity. One therefore relies, to a large extent, on generalizations.

Naturally, soil moisture content is of prime importance. Conductivity is further helped by the available salts and, preferably, ferromagnetic minerals (e.g. magnetite). Another relevant factor is the acidity of a soil: a more acid soil will marginally increase the resistivity whereas a basic soil will lead to a decrease.

One of the first studies into the effects of precipitation and sun exposure on the first few meters of a soil was undertaken by Al Chalabi and Rees (1962). They carried out Wenner measurements across large buried defence ditches associated with a Roman fortress. The ditches had been cut in soft Triassic sandstone and later backfilled with sand, turf and clay. During a year-long study it was found that they stood up most clearly as anomalies after a hot dry period. Correlating the resistivity measurements with weather statistics it was shown that best results could be obtained from June to September, with July being the favourite. Further work along these lines was done by Hesse (1966). His experiments concentrated on recording the variation of apparent resistivity over a number of fixed squares in France. He established a generally predominant daily variation in resistivity, ranging from a high in the early morning to a low in the early afternoon. This variation could in turn be superimposed on a slower cycle extending over several days to a season. Differences in surface resistivity also tended to be far more prominent

over a small area than a larger one.

The season and the variation in temperature were found to be most important. During day periods, soil moisture content played a very important role, although its effects were slow. During rainfall, however, resistivity readings became erratic. This was caused by the gradual seepage of moisture to lower soil layers.

Temperature effects were found to be long term in nature: a drop in in surface temperature had a gradual effect on the resistivity readings. No correlation was found between resistivity and daily variations in surface temperature.

Tests conducted for a year and a half over a known anomaly, established the following phases:

- (1) humid phase: small daily variations in resistivity occur over the anomaly with a gradual long-term smoothing effect on prominent peaks;
- (2) frost phase: with light frost only a marginal increase in resistivity values takes place. Heavy frost, however, results in the complete disappearance of the anomaly among random fluctuations;
- (3) dry phase: a rise occurs in general soil resistivity with a concomitant increase in anomaly values.

One can conclude that near-surface prospecting can be undertaken during wet conditions though a greater measurement accuracy will then be called for.

During dry periods any anomalous values should be verified and generally good results can be achieved. Measurements should be avoided during periods of frost. Furthermore, when surveying large areas, it may be useful to obtain reference values from a control station. These can subsequently be correlated with the area results. Clark (1975) published a further study on the influence of seasonal variations on near-surface features. He focussed on the chalklands and repeated his measurements during 1½ years on three ditches ranging in size from 2.5 m wide and

1.1 m deep, to 17.7 m wide and 6.0 m deep. The ditches were located in chalk bedrock and their fill mainly consisted of natural silt and an upper layer of plough soil. Most of the measurements were based on the Wenner configuration ($a = 1$ m and 1.5 m) though Dipole dipole readings were also taken over a 5-month period using an identical probe spacing.

The results corroborated with the rainfall are shown in Fig. 3.9. As can be seen, measurements vary according to ditch size:

- (1) large ditch (17.7 m wide, 6.0 m deep) - it appears as a negative anomaly with especially good results during the winter period and first half of the year when there is an increase in rainfall;
- (2) medium ditch (6.3 m wide, 2.1 m deep) - the results are confusing though overall it appears as a negative anomaly with best results during wet periods;
- (3) small ditch (2.5 m wide, 1.1 m deep) - it disappears during the winter period, subsequently reappearing as a clear positive anomaly during the second half of the year when there is a decrease in soil moisture content.

The above can be explained in view of the greater porosity of the ditch fill, compared to the underlying bedrock. With the large ditch, the moisture content remains more stable with evapotranspiration losses during dry periods. Any loss in soil moisture is balanced by water obtained through capillary action.

With the small ditch any water drains rapidly, and the instrument detects the high resistivity of the coarse primary silt. During a rainy period this quickly saturates, swamping any results.

The medium-sized ditch behaved in an intermediate manner.

Clearly soil texture, moisture content and related evapotranspiration as well as drainage are the most important factors influencing the results.

All three ditches show up during the second part of the year.

During a rainy period results may be achieved if the soil of small ditches remains relatively dry (rapid drainage) compared to the surrounding soil. A large ditch will then show up if the ditch fill saturates more rapidly than the surrounding (chalk) bedrock.

Overall best results were obtained with the Dipole dipole configuration using a probe spacing of 1 m.

Similar tests were conducted on masonry (on a limestone bedrock) and in most cases this gave clear results regardless of the time of year, with dry periods providing the best resolution (Hesse, 1966). This has been corroborated by Clark (1975).

No tests have so far been done on pits, though their behaviour may be assumed to be analogous to small ditch sections.

3.2.2. Problems Associated with Lateral Exploration

Probe separation and resolution are important parameters on which a compromise has to be made. When for instance traversing across high resistivity anomalies placed next to each other, a large probe spacing may result in both features being fused together, as the average gradient will be measured. Conversely, too small a spacing will impair the resolution of any features larger than the probe spacing (Fig. 3.10). Also, when the potential electrodes are placed too near each other, it will become difficult to accurately measure the potential difference.

Angle of strike is also of importance, though in practice often difficult to predetermine. A traverse running perpendicular to a feature will provide ease of operation but also leads to anomaly distortion with some configurations giving more distortion than others. Other problems are often brought about by the site geology. Examples are natural chalk outcrops in an otherwise homogeneous soil or undulations in the bedrock (solution holes). These effects can be decreased by varying the probe spacing or by applying one of the

filtering techniques described in chapter 4.

Many of the limitations come under the heading 'noise'. Some examples are: a rocky topsoil (often associated with limestone), cultivation ridges, old field boundaries (unless sought after), uneven soil moisture content, and temperature effects. Concerning the latter, a 1°C increase in temperature can result in a 2% drop in resistance. This applies to temperate climates (Hesse, 1966). The problems associated with dry arid regions are discussed in chapter 6. In Europe similar conditions may prevail, for instance on dry hilly slopes or sandy soils. Watering the individual probes or the entire area under survey helps, although the measured resistivity values then depend on the degree of watering and the soil drainage. In dry conditions special probes may have to be used. Another method is to lengthen the probes to enable penetration of moist underlying layers (Linington, 1967a). However, very shallow features would then be undetectable.

Sources of noise related to the measurement technique are probe contact resistance, inductive effects between the probes, external electromagnetic currents and fields associated with high-tension lines or electric railways. Most of these problems lead to erratic readings.

Errors may also be caused by fine probe insertion. If the depth (h) of the inserted probe is kept within $1/5$ of the probe spacing, the effect on the inner probe resistance should be negligible for constant values of h . Aitken (1974) found that the inner probe resistance decreases by 10% when the depth (h) of the inserted probe (8 mm diameter) is increased from 5 cm to 15 cm for a probe separation of 1 m. The percentage drops to 2% for a probe separation of 2 m. Similarly, errors may be introduced by inaccurate probe separation. Increasing the overall probe separation decreases any such errors: at $a = 2$ m a positive error of 3 cm the inner probe separation causes the inner probe resistance to be 4% too high whereas a positive error of 3 cm the outer probe separation

will change that figure to 3% too low. However, these values deteriorate to 8% and 5.5% respectively for a probe separation of 1 m. The probe distance must be kept to within ± 1 cm to keep the error on the inner probe resistance within 14%.

It is often worthwhile to use more than one probe configuration when surveying a site. This is very much simplified with the Martin-Clark resistivity meter which enables both Wenner and Dipole dipole to be used at the change of a switch.

Similarly, varying the probe spacing can provide useful results. For instance, by taking measurements at $a = 1$ m and $a = 2$ m with the Wenner method, estimates can be made concerning the depth of any features as the response will be decreased by half at the increased spacing (Linington, 1967, 1968), *only in a uniform medium.*

3.2.3. Electrode Configuration Performance Evaluation

Tests conducted by Clark (1972) using the Wenner, Dipole dipole, Palmer and Square array established that the Dipole dipole and Square array gave the best results in detecting buried ditches. This applied to electrolytic tank work as well as field trials.

Overall the response of the various probe configurations to a feature ranges in order of magnitude from Schlumberger, Wenner, 3-probe, Palmer to 2-probe with the latter system exhibiting a 35% reduction in resolution when compared to the Wenner method, e.g. a buried conducting sphere equal in diameter to the probe spacing and placed near the earth's surface will only give a 15% variation above the background reading as opposed to 50% for the Wenner method (Aspinall and Lynam, 1970).

The above presents a generalised evaluation of electrode arrays. A detailed assessment of the sensitivity and resolution of the various probe configurations is clearly of value in determining the correct choice of array for a given site. Certain probe configurations will provide

greater sensitivity at depth, whereas others are better at resolving at closely spaced and shallow features.

Electrolytic tank experiments (see section 3.2.5) provide a valuable means of assessing the performance of an array. A way of determining the *sensitivity* of a probe configuration is by gradually increasing the depth (S) of a sphere situated underneath the centre of a given array, while the probe spacing (a) is kept constant (Lynam, 1970). The response magnitude of the ratio ρ_a/ρ_1 (ρ_1 = resistivity of the medium) can then be used as an indicator of array sensitivity. One must take into account that the maximum response generally occurs beneath the centre of a probe configuration, the 2-electrode method forming the exception, where this takes place beneath the current electrode in near-surface applications. The obtained curves will, however, apply to a homogeneous isotropic medium, a rather impractical situation. A better assessment of the practical situation can be obtained by observing the sensitivity of a series of arrays to inhomogeneities within the background medium. Some arrays are more sensitive to this noise than others, which would make it difficult for them to distinguish a feature. Taking the above into account, Lynam (1970) constructed a table providing a sensitivity index for the various configurations. This was based on the introduction of an additional 'noise' sphere touching the surface, and in size one third of the radius of the main sphere. The total relative electrode separation is given by the parameter P .

The results give the ratio of the response from the main sphere to that of the noise sphere, effectively providing an indication of noise on the measurements.

<u>Configuration</u>	<u>Sensitivity Index</u>
3-electrode	5.5
Wenner	4.5
2-electrode	3.0
Schlumberger	0.75

where $S_m = 1.5$ (main sphere)

$S_a = 1.0$ ('noise' sphere)

and $P = 1.0, 2.0, 2.0, 3.0$ for the 2-electrode, Wenner, 3-electrode and Schlumberger arrays respectively.

In the above table, a high value indicates a high susceptibility to noise. Clearly the Schlumberger response can be expected to be the least affected by noise with the 3-electrode system giving the worst results.

Similarly, one can construct a table indicating the susceptibility of the various arrays to deep-lying geological variations. These are represented in the form of a large sphere in diameter 20 times that of the main sphere and lying at greater relative depth.

Again, the values have been defined as the ratio of the main sphere to that of the additional ('geological') sphere (Lynam, 1970):

<u>Configuration</u>	<u>Geological Index</u>
Schlumberger	1.7×10^4
Wenner	0.2×10^4
3-electrode	0.13×10^4
2-eletrode	0.02×10^4

where $S_m = 1.5$ (main sphere)

$S_a = 3.0$ ('geological' sphere)

and the values of P are the same as before.

The Schlumberger method is clearly the least susceptible to geological variations whereas the 2-electrode configuration comes last.

As the above values are small, the effects of geological changes need not seriously impair the response profiles of any of the arrays mentioned. Furthermore, geological structures would appear as low frequency variations underlying the high frequency variations of (smaller) near-surface variations. The *resolution* of an array also plays an important role. To identify this, one can ascertain the maximum width of the response profiles, of the various probe configurations, due to a buried sphere. The end points of the profile width are determined when

$$\rho_a/\rho_1 = 0.$$

The response profiles of two spheres situated at the same depth will fuse if the above ratio does not approach unity. Taking into account that the maximum profile widths for a given configuration remain virtually constant at any relative depth of a sphere, one can calculate a resolution index and compare this with the response profile width of an indicator array.

The results below are therefore based on the ratio:width for the 2-electrode array to width for the array under consideration (Lynam, 1970):

<u>Configuration</u>	<u>Resolution Index</u>
2-electrode	1.0
Schlumberger	0.95
3-electrode	0.84
Wenner	0.67
Palmer	0.40

where $P = 2.0$.

From these results it can be seen that the 2-electrode array will resolve anomalies better than the other configurations, with the Palmer array coming last.

In practice the resolution index values would be less as the total relative electrode separation would probably be larger than 2.0, leading to increased maximum profile widths.

3.2.4. Field Application

The first application of resistivity in archaeological prospecting dates back to 1946. Since then a large number of surveys have been carried out with this technique, enabling a reasonable amount of practical experience to have been gained. As a method it has proved most successful in the detection of buildings e.g. the geophysical programme at Prague Castle (Burian et al, 1968) and the survey at

Barnsley Park (Rees and Wright, 1969). In Fig. 3.11 the results are shown for a survey of a Roman villa.

Resistivity surveys of ditches have not always proved to be very reliable. Some of the relevant factors have been previously outlined (see section 3.2.1). Good results have been obtained for underground cavities and tombs (Samson, 1979; Carabelli, 1967) e.g. the survey of the Etruscan necropolis of Tarquinia (Carabelli and Brancaloni, 1968). Attempts have been made to speed up the measurement process but these have so far proved either unsuccessful or have remained in the prototype stage. A noteworthy example is the use of a framework somewhat resembling a manual lawn-mower. One electrode pair is attached to the spiked wheels while the other pair remains stationary at a fixed distance (2-probe configuration). This device is pushed along and the continuous output is fed to a trace recorder. Unfortunately adequate probe contact proved to be the main stumbling block. A more encouraging development is the multiprobe system. The first attempt (Peschel, 1967) used 11 electrodes positioned along a traverse. Five different readings could be obtained by the turn of a multi-switch, with the results plotted as comparative graphs of resistivity versus varying spacings. This enabled the depth of a feature to be determined. The basic instrument was mechanical which did not make for good reliability.

Currently development favours a 24-probe system which uses the Wenner, Dipole dipole, 2 and 3 electrode system. These probes are inserted into the ground along a traverse and activated by means of an electronic switching system. The continuous output is plotted on a chart recorder and logged on a data logger (A.M. Laboratories).

Such a system would allow great speed of operation combined with maximum information retrieval.

3.2.5. Model Studies

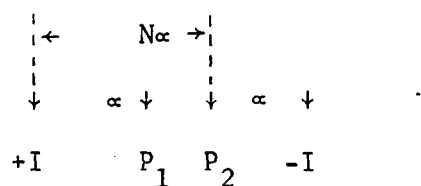
A fair number of model studies have been carried out for large-scale geophysical applications (e.g. Kiyono, 1950; Van Nostrand and Cook, 1966). However, only one detailed study by Lynam (1970) on buried near-surface features has been published. He closely looked at the disturbing effects of a sphere on a number of electrode configurations and derived a general expression for the potential difference between the measured electrodes. This applies to any linear configuration:

$$V_{P_1} = \frac{\rho_1 I}{2\pi} \left[\frac{1}{\alpha} - \frac{1}{\alpha + \alpha (N - 1)} \right] \quad (3.17)$$

$$V_{P_2} = \frac{\rho_1 I}{2\pi} \left[\frac{1}{N\alpha} - \frac{1}{\alpha} \right] \quad (3.18)$$

$$V_{P_2} - V_{P_1} = \frac{\rho_1 I}{2\pi} \left[\frac{N - 1}{N} \right] \quad (3.19)$$

where $N\alpha$ takes any positive value and depends on the probe configuration, α is the probe separation, V_{P_1} the potential at P_1 , V_{P_2} the potential at P_2 , and ρ_1 the electrical resistance of the medium.



general linear configuration

The values of N depend on the probe configuration.

<u>Configuration</u>	<u>N</u>
2-electrode	100
Palmer	5.0
Schlumberger	1.2
Wenner	2.0
3-electrode	2.0

An important parameter is the geometric factor (G.F or k) which is defined by the factors which depend on the electrode geometry. Therefore every electrode configuration has its own geometric factor. When multiplied by the measured resistance it provides the equivalent resistivity value for a uniform medium.

The following general expression enables the calculation of the response profiles of a buried sphere when traversed by the 2-probe configuration:

$$\rho_{\alpha} = \rho_1 \left[1 + \frac{\rho_2 - \rho_1}{\rho_1 + 2\rho_2} \right] + P(k) \quad (3.20)$$

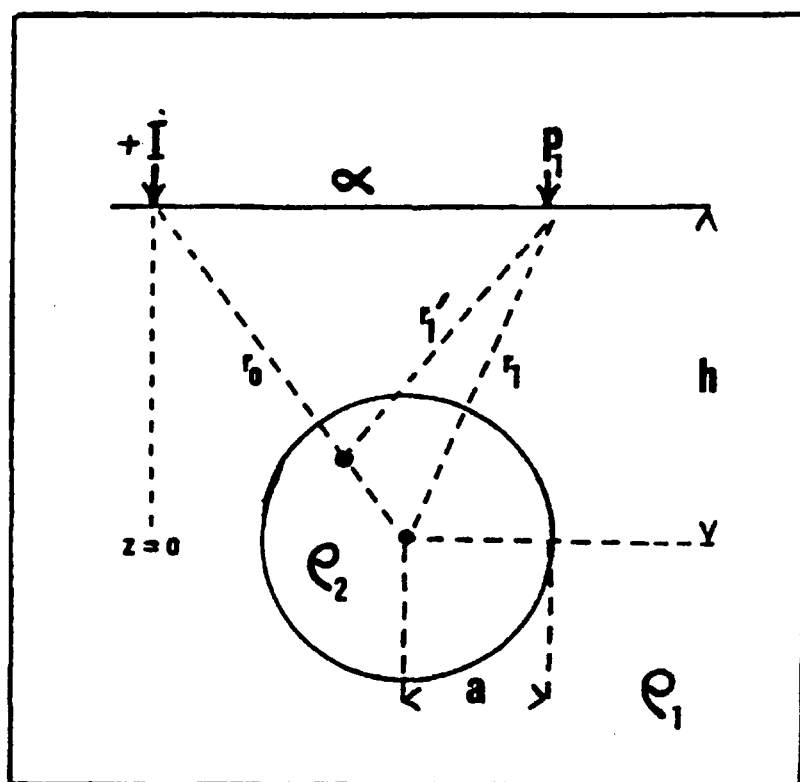
where ρ_{α} is the apparent resistivity, ρ_2 the resistance of a sphere introduced to a medium of resistivity ρ_1 , k the geometric factor and P the relative electrode separation.

The above equation applies to any sphere position within the plane containing the electrodes.

The geometric factor (k) is a function of the ratios:

$$P = \frac{a}{a} \quad S = \frac{h}{a} \quad L = \frac{z}{a} \quad (3.21)$$

where P is the relative electrode separation, S the relative depth of the sphere, and L the relative horizontal position of the sphere. As an example, the geometrical arrangement for an anomalous sphere in the vicinity of a 2-probe⁶ configuration is shown below:



Geometrical arrangement for an
anomalous sphere in the neighbourhood
of a two-electrode configuration.

The response profile calculations have been done as follows: parameters P , S and the radius of the sphere are kept constant, k is then calculated for a number of values of L . Subsequently either the values of S are altered or those of P . The relevant profiles are shown for a sphere passing under the configuration at issue (Fig. 3.12). The relative depth (S) of the sphere has been varied between 1.2 and 2.6 of which the value 2.0 corresponds to the sphere's diameter. P has been kept constant at 2.0 with the electrode separation (α), therefore equal to twice the radius of the sphere.

A highly resistive sphere would give a virtually similar, though reverse, response with a decrease in overall magnitude. The response forms for a conducting sphere placed very near the surface exhibit two separate minima with a maximum point lying exactly inbetween. This point corresponds to the apparent resistivity when the sphere lies precisely inbetween the two probes. The nearer the sphere is positioned towards the surface, the greater this maximum will be, possibly overshadowing the minimum peaks. This may lead to confusion as to the real identity of the anomaly (positive instead of negative). It is known as pseudo-focussing and is a property of the applied configuration. Furthermore, the observed minima will not coincide with the electrode position but exhibit a gradual shift with decreasing depth of the sphere. If the depth (S) is increased, the overall response forms become flatter and wider with a gradual increase in the magnitude of the minima, until they

correspond exactly with the position of the electrodes. The maximum associated with the pseudo focussing effect will then disappear. When the relative depth of the sphere corresponds to the relative electrode separation, the response will become smooth losing any peaks.

For different values of the relative electrode separation (P) the following changes occur in the response profiles (Fig. 3.13) of a conducting sphere:

- (1) increase in P - the overall amplitude of the response forms decreases; the two minima and the intermediate maximum become more prominent (greater pseudo focussing);
- (2) decrease in P - the overall amplitude of the response forms increases with more pronounced curves; the two minima and the intermediate maximum disappear quicker as the depth of the sphere is increased. An optimum value of P exists at which a conducting sphere will provide a single minimum point concurring with the centre of the 2-probe array. The relevant value of P can be used to determine the size and depth of the sphere.

The response forms of the Wenner configuration may be similarly analysed using the following equation which takes the background voltage into account:

$$\frac{(V_T)_\Omega}{(V_O)_\Omega} = \frac{\rho_a}{\rho_1} = 1 \pm \left(\frac{N}{N-1} \right) \left[\frac{\rho_2 - \rho_1}{\rho_1 - 2\rho_2} \right] P \left[(k) - (k)_1 + (k)_3 - (k)_2 \right] \quad (3.22)$$

where V_T is the total voltage and V_O the observed voltage (background potential difference) and $\rho_2 - \rho_1 / \rho_1 + 2\rho_2$ provides the resistivity contrast term. For a sphere directly underneath the centre of the array:

$$(k)_2 = (k)_1 \quad \text{and} \quad (k) = (k)_3$$

The above equation equally applies to other symmetrical electrode

configurations with the relevant geometry factor equated to the parameters P , S and L .

Fig. 3.14 relates the response forms for a sphere of very high resistivity when traversed by the Wenner configuration. Relative sphere depth (S) has been varied from 1.2 to 2.6 and the sphere radius is equal to half the electrode separation. One can clearly see two minima with a substantial maximum point halfway inbetween and two other smaller maximum points on the outer limits of the profile. This characteristic profile comes across most clearly the closer the sphere lies to the surface. Pseudo-focussing occurs with values of S below 1.2. On increasing the relative sphere depth, the two minima gradually become smaller until they finally disappear and the overall response forms become smoother.

As can be seen, the maximum response profile occurs when the sphere is located underneath the centre of the configuration.

When varying the relative electrode spacing (P) the results are very similar to those obtained with the 2-probe method. The results for an insulating sphere (Fig. 3.15) indicate that:

- (1) increase in P - the overall amplitude of the response forms decreases; the three maxima and the two minima become more prominent (greater pseudo focussing);
- (2) decrease in P - the overall amplitude of the response forms increases with fewer peaks; the three maxima and the two minima disappear quicker as the depth of the sphere is increased and the pseudo-focussing effect goes.

The response profiles for the Schlumberger configuration indicate a higher resolution with a corresponding increase in anomaly amplitude when compared to the Wenner profiles. They also exhibit less pseudo-focussing as well as a more pronounced central peak inbetween the two side peaks (Fig. 3.16).

On a comparative basis, the Schlumberger configuration has a low background resistance combined with a high anomaly resolution. The Wenner configuration comes next with a slightly higher background resistance reading and decreased resolution, with the 2-probe method coming last. Based on the above, the Wenner response profiles are generally more complicated as any peaks tend towards similarity causing greater confusion and making anomaly interpretation more difficult.

Taking the process of theoretical response profiles a step further, one can attempt to establish a number of master curves which enable one to determine the depth, radius and resistivity contrast of a buried sphere. Lynam (1970) provided a number of 'constant magnitude' curves of S against P for the Wenner, Schlumberger and 2-probe configuration and superimposed these: Wenner - Schlumberger and Schlumberger - 2-probe. The intersection points on the curves then provide values of P and S for a buried sphere. This necessitates passing over a feature twice using two different probe configurations. Lynam indicates that this method breaks down for small values of P and S and that the method only works when the resistive contrast of the sphere is known. As the theory only applies to either very resistive or conducting spherical anomalies, a large number of problems remain. The response from bodies of arbitrary shape is one of these. A number of techniques are available for bodies of regular shape. The use of image theory employing the Newtonian potential principle is one of them. It is especially effective in determining the profiles of structures which extend downwards from the surface at an angle of 90° . This solution therefore applies to dykes and faults but becomes very complex for buried structures.

The mathematical process becomes quite daunting for completely arbitrarily shaped bodies and only has limited success (Keller and Frischknecht, 1977). Such techniques generally rely on joining up a number of spheres or triangles to represent the required shape (as in

magnetic modelling). Any calculations have to take a whole series of factors into account e.g. response from each sphere, cylinder or triangle, their interaction and optimum radius or dimensions, to minimize computation. This represents the so-called building block concept. One can for instance use a series of elementary spheres to form the required shape and add the response from each sphere algebraically. Any solution will be approximate owing to interaction effects. When comparing the response forms of buried spheres to those obtained for buried cylinders, using the building block concept in the latter case, one comes across quite a close approximation e.g. insulating sphere (Wenner at $P = 2.0$) (Fig. 3.17a) and insulating cylinder (Wenner at $P = 2.0$) (Fig. 3.17b). The latter exhibits greater maximum response regardless of depth of the cylinder and overall the response forms differ slightly.

Lynam undertook a number of model experiments in the laboratory using a polythene tank filled with brine and compared the experimental profiles with the theoretical response forms. Experiments were limited to the Wenner and 2-probe configuration. In practice anomaly specimens were moved underneath stationary stainless steel (non-polarizable) electrodes positioned in a background medium of brine. The electrical conductivity of this medium can be suitably altered by the addition of sodium chloride. An instrument operating frequency of 135 H prevented polarization effects which generally occur at a lower frequency. A factor of importance in determining the magnitude of near-surface anomalies is the depth of the electrodes underneath the brine surface. In small-scale experiments the potential gradient may more closely resemble the equipotential lines of a driven stake as opposed to that generated by a point source. This applies to electrode depths smaller than 4 - 6 times the stake penetration of the surface (Van Nostrand and Cook, 1966). Exact equivalence between field and model response profiles can be sought by taking the percentage or fractional change from the

background resistivity for different electrode penetrations and matching this with the theoretical requirements. The observed fractional change will then be the same regardless of scaling factor. In the absence of a sphere the medium has a background or normal resistance ρ_1 . Variations from this can be expressed as ρ_α/ρ_1 . Lynam normalised the experimental profiles and superimposed these on the theoretical response forms. This process was only applied to either very conducting or highly insulating specimens: spheres, cylindrical bodies and vertical rectangular structures. Overall most of the results gave a positive correlation within the experimental error flags with only minor discrepancies e.g. insulating sphere at small relative depth ($S = 1.2$) (Fig. 3.18).

Identical profile comparisons between theory and experiment for increased sphere depth (S) using the Wenner array came up with similarly successful results indicating the usefulness and reasonable accuracy of theory in predicting the essential characteristics of an anomalous body. In general, experimental errors tend to be most prominent for features placed very close to the surface. Theory usually underestimates the actual response in these cases ($S < 1.2$) and is caused by boundary interaction effects between the anomalous body and its boundary image. Lynam verified that the limit of S (SLIM) was an inverse function of the relative electrode separation P e.g. when $P = 1.0 \rightarrow \text{SLIM} = 1.6$, whereas for $P = 3.0 \rightarrow \text{SLIM} \pm 1.1$ for a conducting sphere. This deviation from theory tends to be greater for conductors than it is for insulators over a wide range of relative electrode separations.

A similar comparison was undertaken for the Schlumberger and 2-probe configurations. The results for the 2-probe method concurred with theory for the insulating sphere. However, a conducting sphere introduced a certain amount of error with the experimental response being smaller than theory suggests. A value of $\text{SLIM} = 1.2$ applies for conducting spheres. No such value was given for an insulating body.

For the Schlumberger method a value of $\text{SLIM} \approx 1.35$ applied to a

conductor and $SLIM \approx 1.3$ to an insulator.

It was found that experiment significantly deviated from theory for values below $SLIM$ for conducting bodies, whereas greater conveyance was shown between the two for insulators (below $SLIM$).

The above applies to pure insulators or conductors but can be similarly used for any contrast situation as the latter only tends to affect the response magnitude (Van Nostrand and Cook, 1966). In such cases the response form of an insulator tends to be greater than that for a conductor (Lynam, 1970).

Lynam also obtained profiles from cylinders and other structures. Cylinders usually gave far more pronounced profiles than spheres, when using the Wenner configuration. (Fig. 3.19).

In the experimental response profiles one can clearly distinguish a high central maximum with two smaller maxima on either side. Increasing the cylinder depth tends to even out the side peaks with the central one still remaining prominent although diminishing in amplitude. The experimental results for an insulating cylinder are in many ways similar. However, the minima on either side of the central maximum peak are more pronounced and will, at small values of S , cause pseudo-focussing (Fig. 3.20). These experimental response profiles were found to be in good agreement (though differing considerably in response magnitude owing to assumptions concerning the contrast term) with the theoretical response forms based on the spherical building block concept, except for small values of S (for conductor or insulator). The discrepancy was probably due to interaction effects. As with spherical bodies, better comparison between theoretical and experimental response forms occurs with larger values of P , with a corresponding decrease in values of $SLIM$. Furthermore, conductors show a greater correlation than insulators.

The experimental response profiles for rectangular structures are also shown (Fig. 3.21). Sharp central peaks with smaller side lobes and

two distinct minima are the main characteristics. This applies to an insulating vertical body when traversed at 90° with the Wenner configuration. The width of the structure equals half the electrode separation P . On increasing the depth of the feature, the pseudo-focussing effects gradually disappear greatly simplifying the overall response form. Taking a minimum contrast of 10% with the background level as the limit of detectability, the feature would become undetectable if the depth to the top of the structure were to exceed $2/3$ of the value of P . For a horizontal perfectly insulating plate the limit of detectability is reached when the depth to the surface of the structure equals the electrode separation, as the response amplitude falls off less quickly. In form the profiles are quite similar to those for insulating vertical bodies.

Lynam worked out the limit of detectability for spherical bodies based on a minimum background contrast level of 10%. The table below gives these values of SLIM for a number of probe configurations.

<u>Array type</u>	<u>Conductor (SLIM)*</u>	<u>Insulator (SLIM)*</u>
Schlumberger	2.5	2.0
Wenner	2.05	1.65
3-probe (asymmetrical)	2.0	1.6
2-probe	1.7	1.5

* very good conductor/insulator.

The Schlumberger configuration enables spheres to be detected at greater depth, followed by the other configurations with the smallest relative depth reached by the 2-probe method.

Clearly a large number of problems have to be negotiated when interpreting the response forms of buried features. Fortunately the

exact dimensions of a feature rarely have to be calculated. It is usually only of importance to establish their existence and location. The results from model studies provide us with useful guidelines which enable the correct probe configuration and probe spacing to be determined for optimum results. A clear idea of the various characteristic response profiles aids the final interpretation as well as determining suitable filter parameters for computer enhancement techniques.

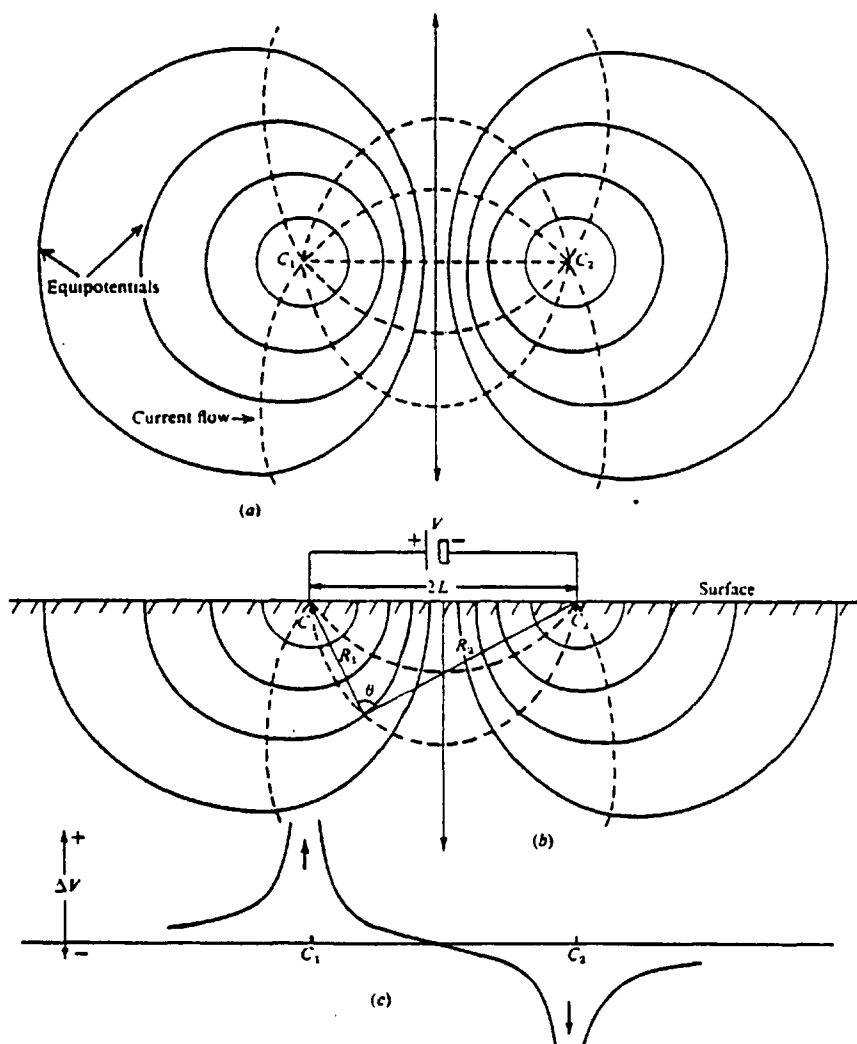


Fig. 3.1 Distortion of equipotentials and current flow-lines for two point sources of current(after Dobrin,1960).
 (a) plan view
 (b) vertical section
 (c) plot of potential variation at the surface along a straight line passing through the point sources
 (After Telford et al., 1978)

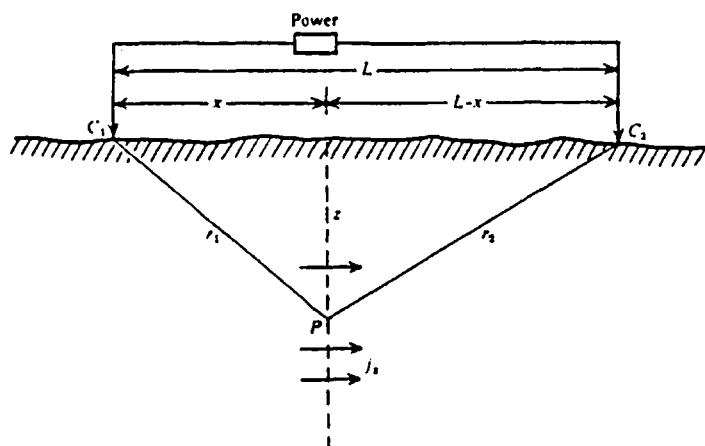


Fig. 3.2a Determining the current density in uniform ground below two surface electrodes
(After Telford et al., 1978)

$$j_z = \frac{I}{2\pi} \frac{L}{(z^2 + L^2/4)^{3/2}}$$

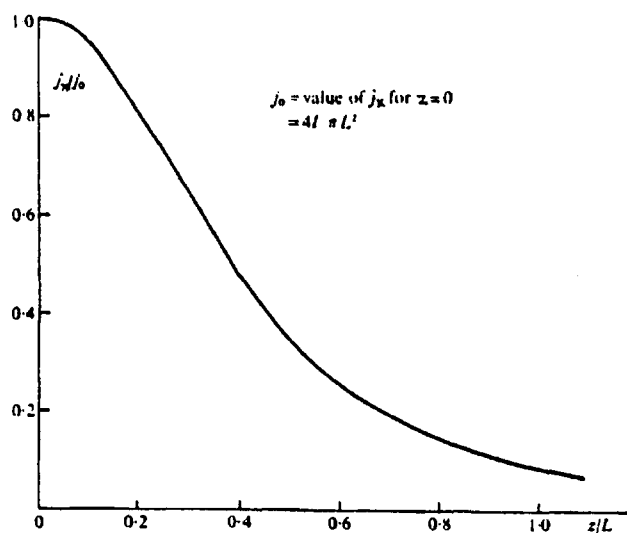


Fig. 3.2b Current density versus depth, fixed electrode spacing
(After Telford et al., 1978)

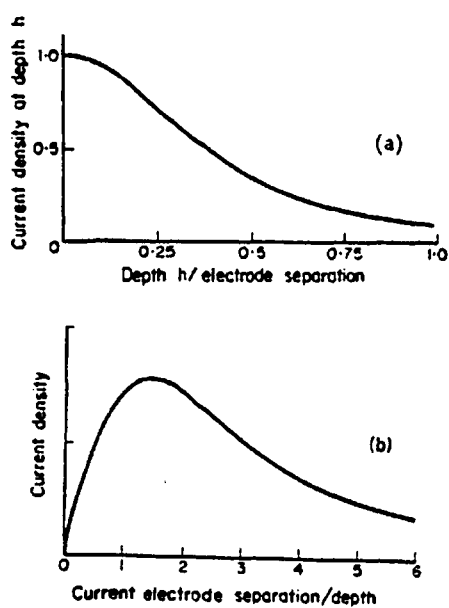


Fig. 3.3 Current density at depth as a function of probe separation
 (a) the variation of current density (expressed as a fraction of its value at the surface) with depth in a plane mid-way between the current electrodes
 (b) current density at unit depth as a function of current electrode spacing

(After Griffiths and Uny, 1975)

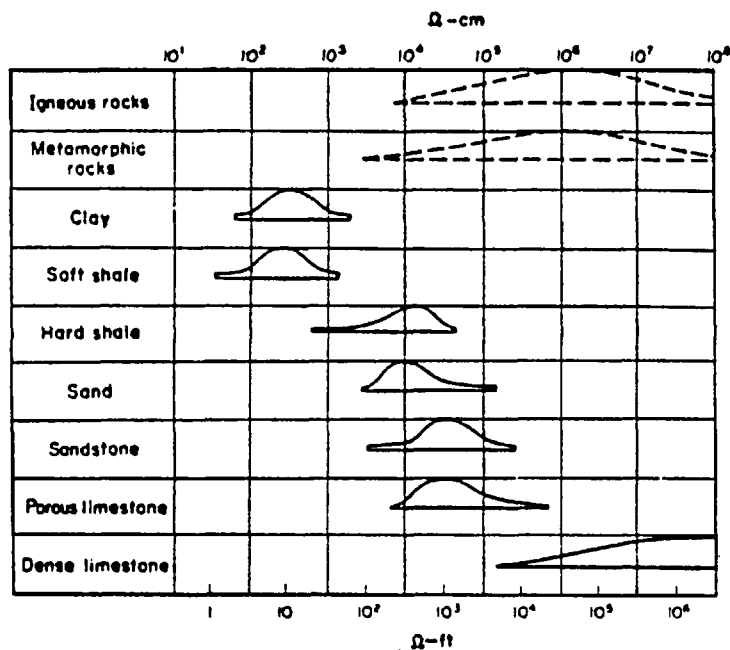


Fig. 3.4 The electrical resistivities of rocks (data from Jones and Skibitzke, 1956, with additions)

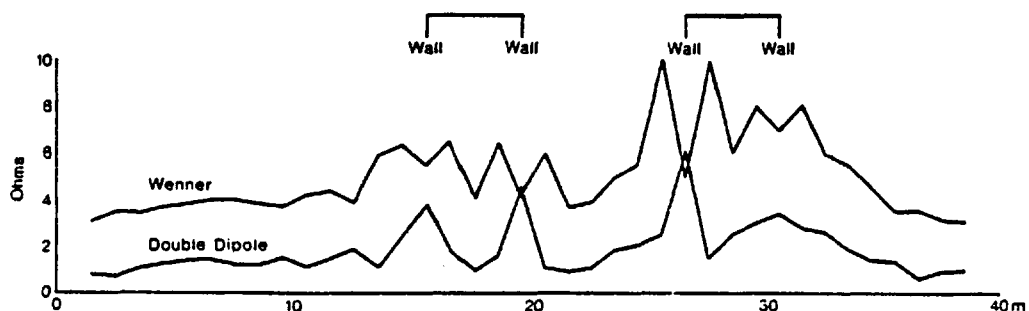


Fig. 3.5 Resistivity measurements along a line across two Roman buildings combining Wenner and Dipole Dipole arrays at a probe spacing of 1m

(After Clark, 1975)

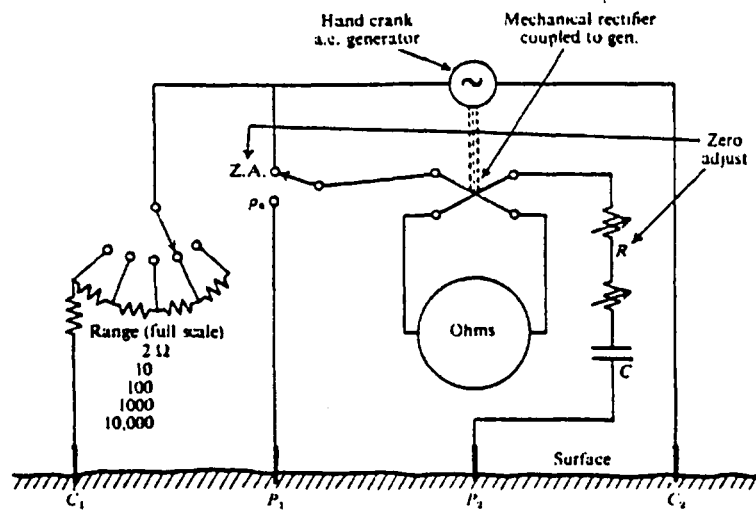


Fig. 3.6 Geophysical Meggar
(After Telford et al., 1978)

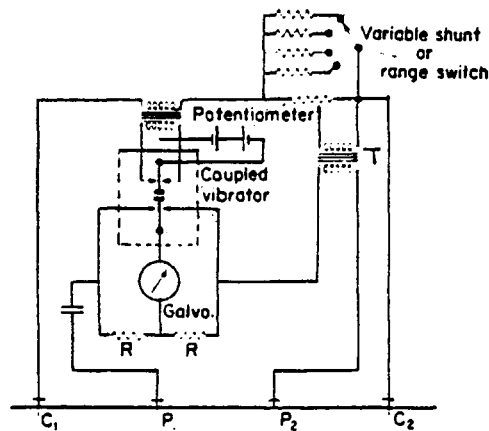


Fig. 3.7 Simplified diagram for the Tellohm Resistance Meter
(After Griffiths and King, 1975)

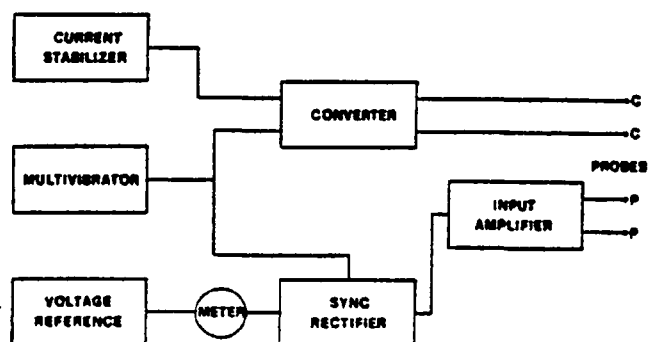


Fig. 3.8a Block diagram of the Bradphys resistance meter
(After Aspinall and Pickard, 1971)

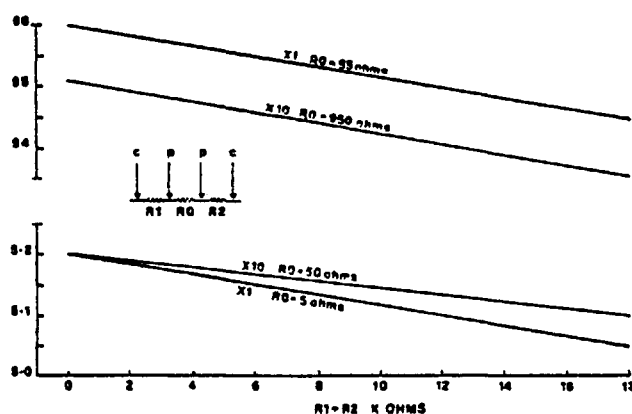


Fig. 3.8b Variation of measured resistance with current probe contact resistance (Bradphys)
(After Aspinall and Pickard, 1971)

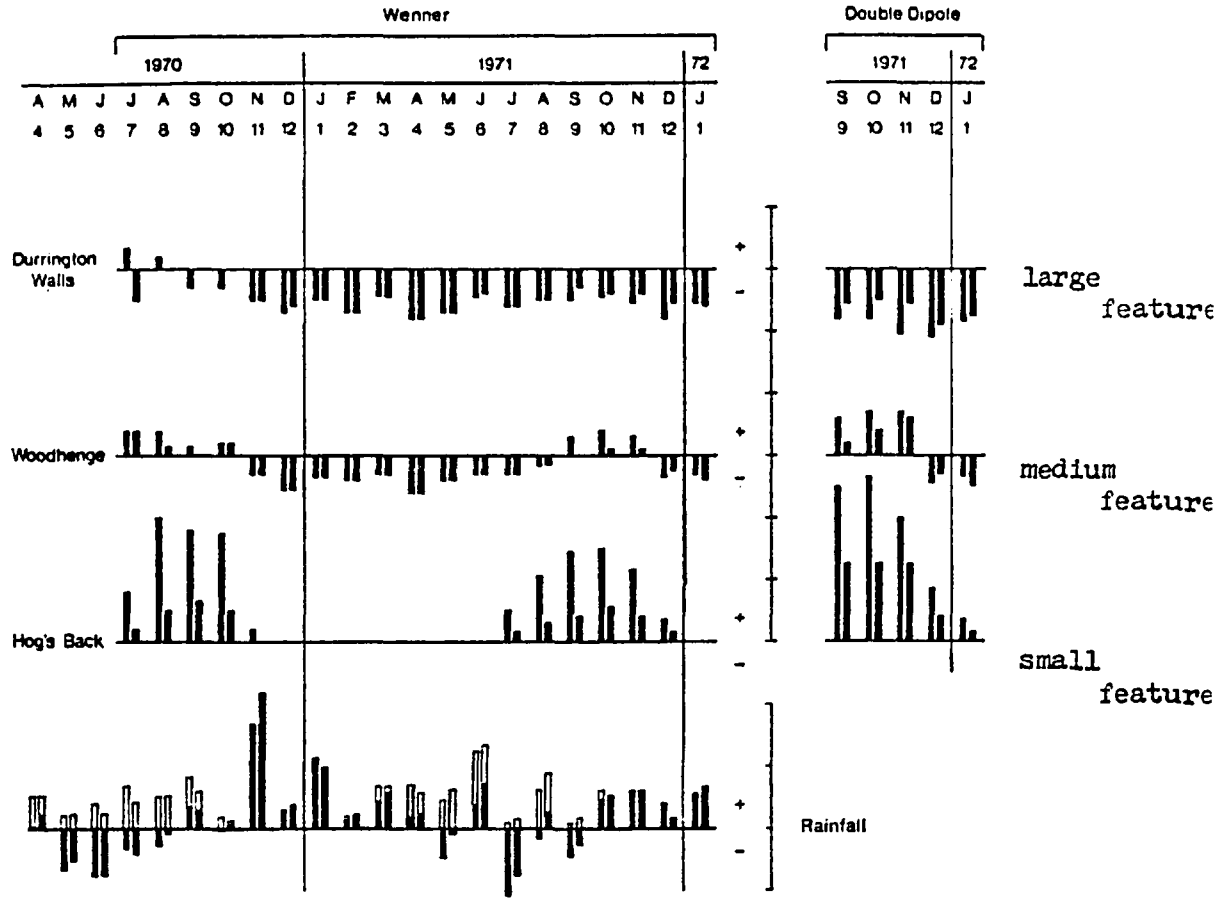


Fig. 3.9 The effect of rainfall on shallow resistivity features
(After Clark, 1975)

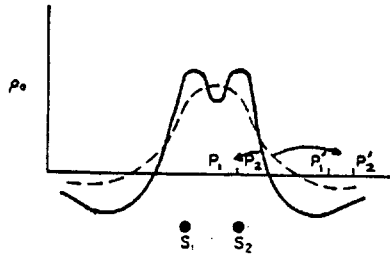


Fig. 3.10 The effect of increasing electrode separation on the resistivity anomaly due to small bodies S_1 and S_2 .
— anomaly obtained with a small separation P_1, P_2
-- anomaly obtained with a large separation P'_1, P'_2

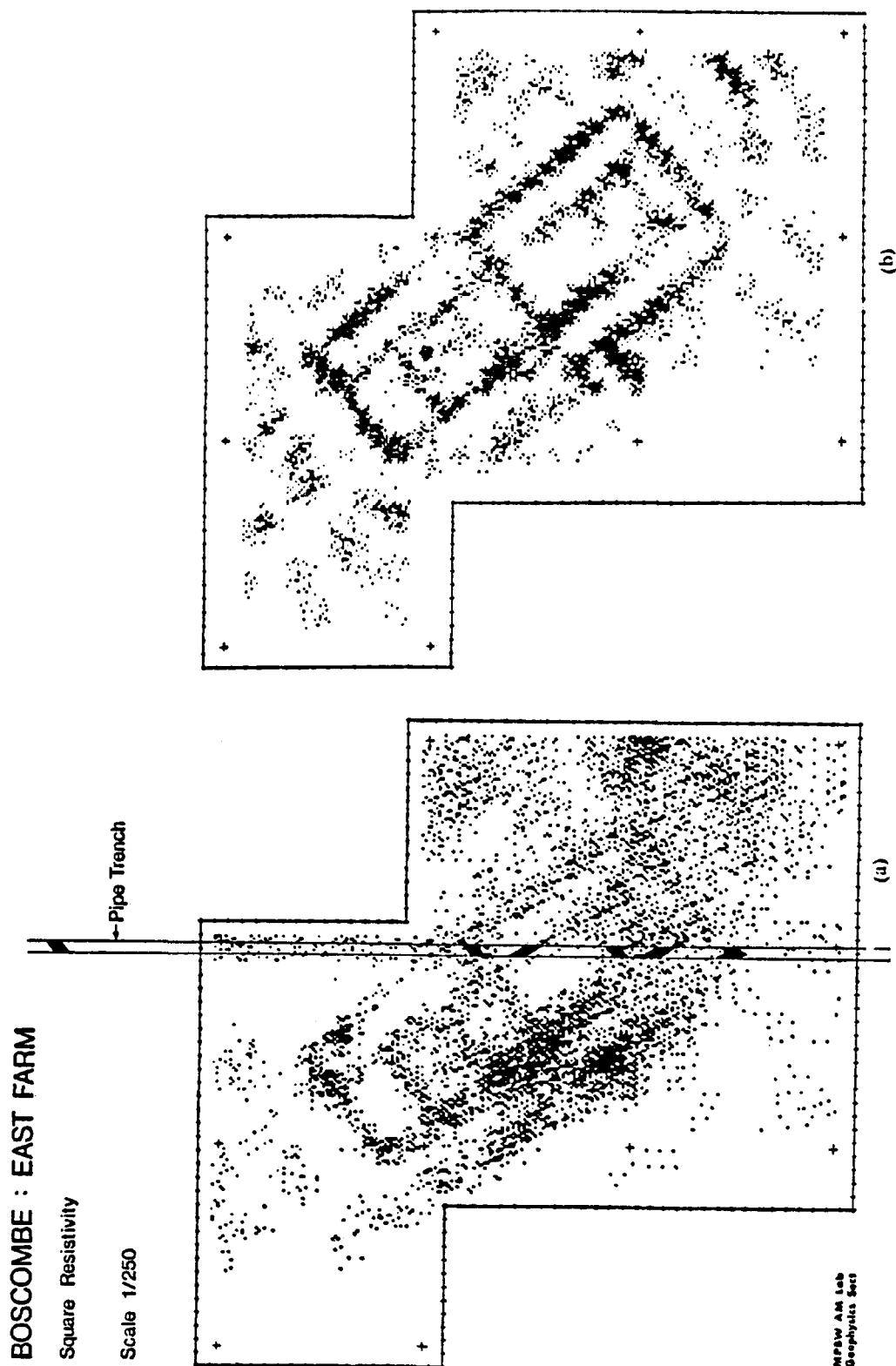


Fig. 3.11 Computer plotted resistivity survey of a Roman villa .
 (a) before filtering
 (b) after filtering
 Marginal ticks at 1m interval
 (After Bantlett, 1979)

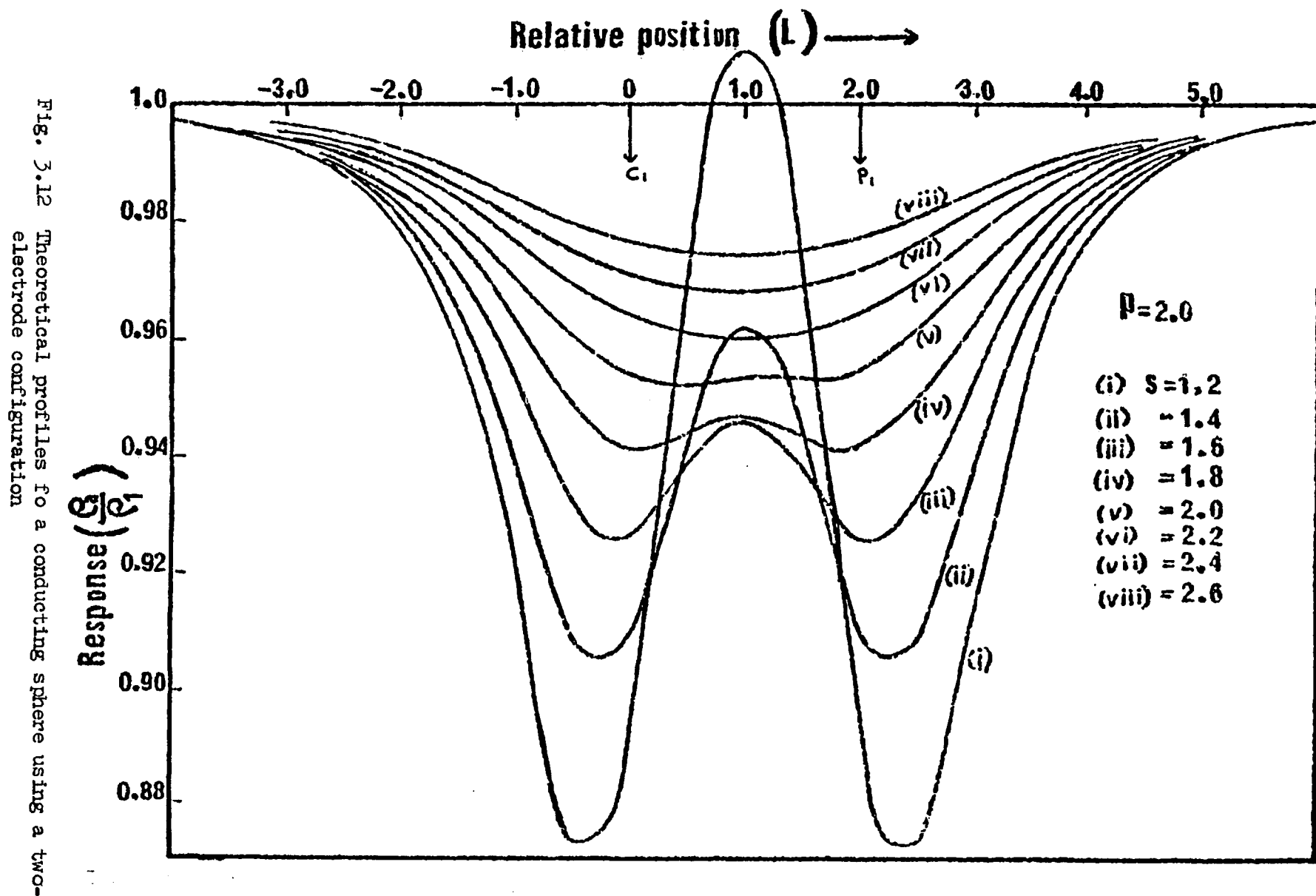


Fig. 3.12 Theoretical profiles for a conducting sphere using a two-electrode configuration

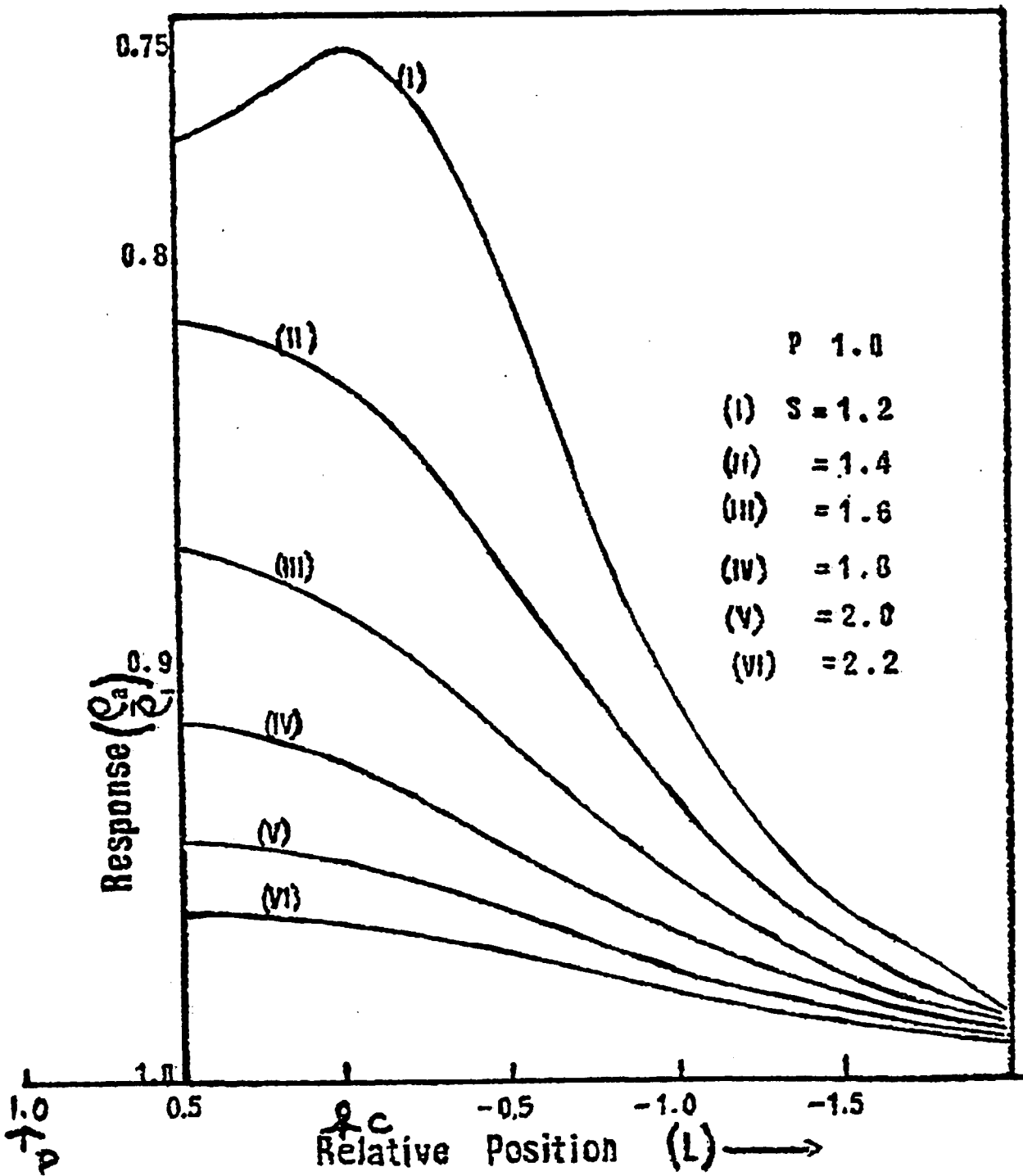


Fig. 3.13a Theoretical two-electrode semi-profiles for a conducting sphere ($P = 1.0$)

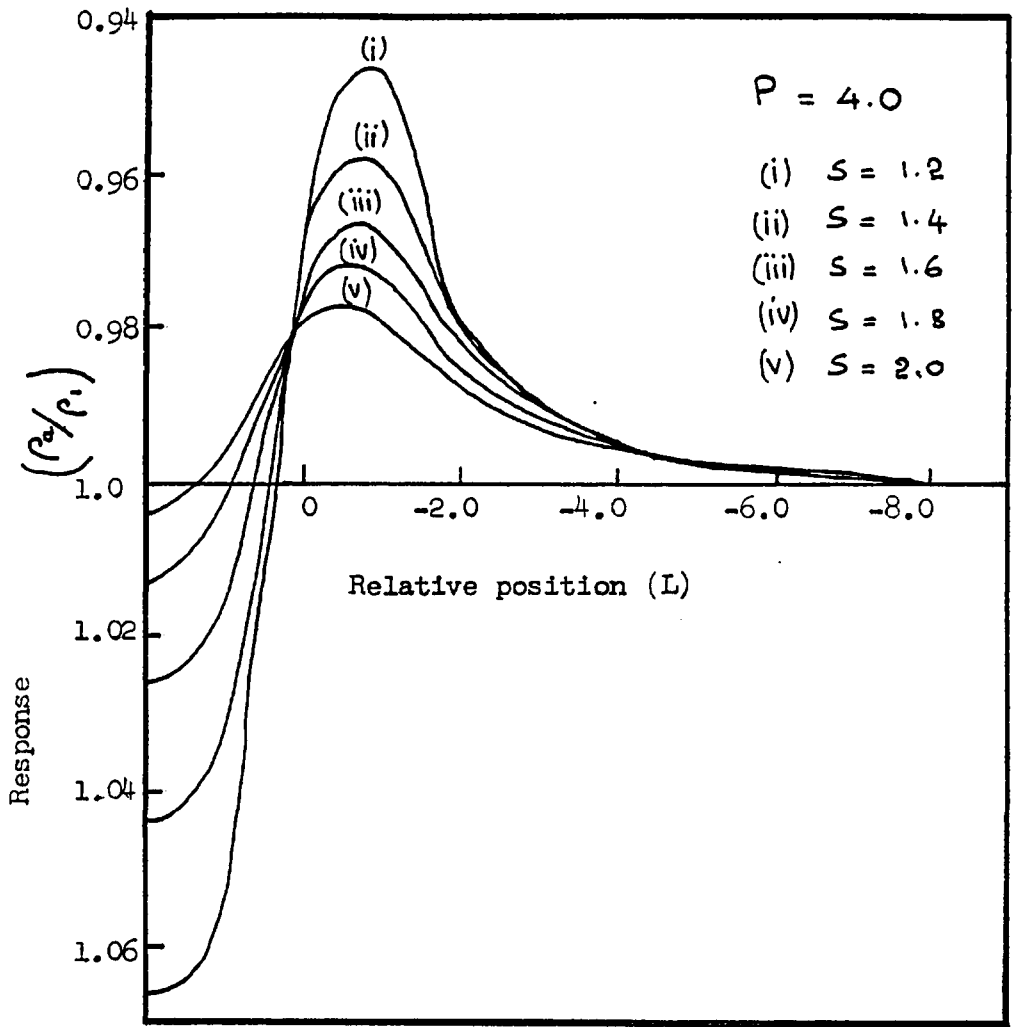
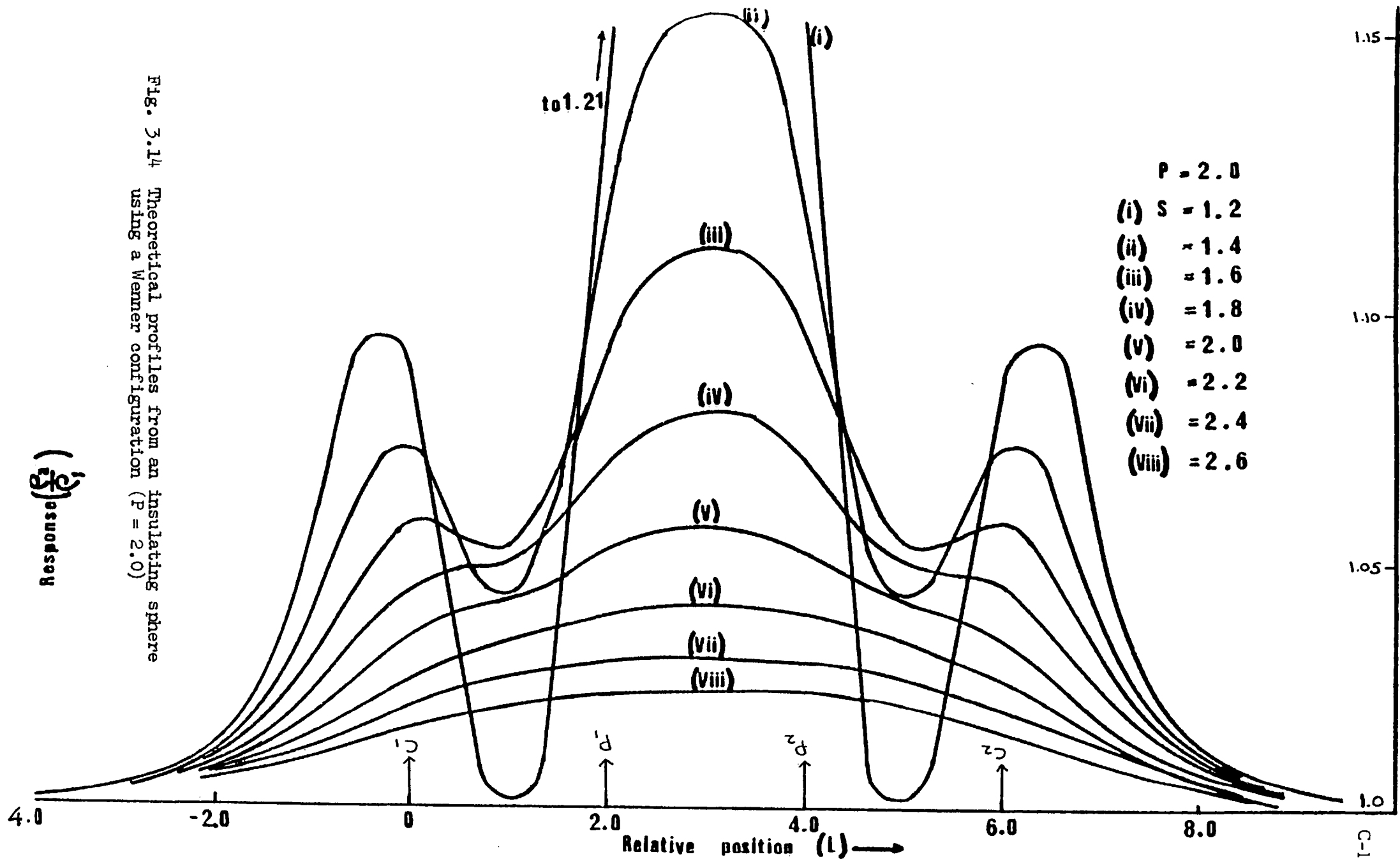


Fig. 3.13b Theoretical semi-profiles for a conducting sphere using a two-electrode array ($P = 4.0$)

$\left(\frac{r_1}{r_2}\right)_{\text{response}}$

Fig. 3.14 Theoretical profiles from an insulating sphere using a Wenner configuration ($P = 2.0$)



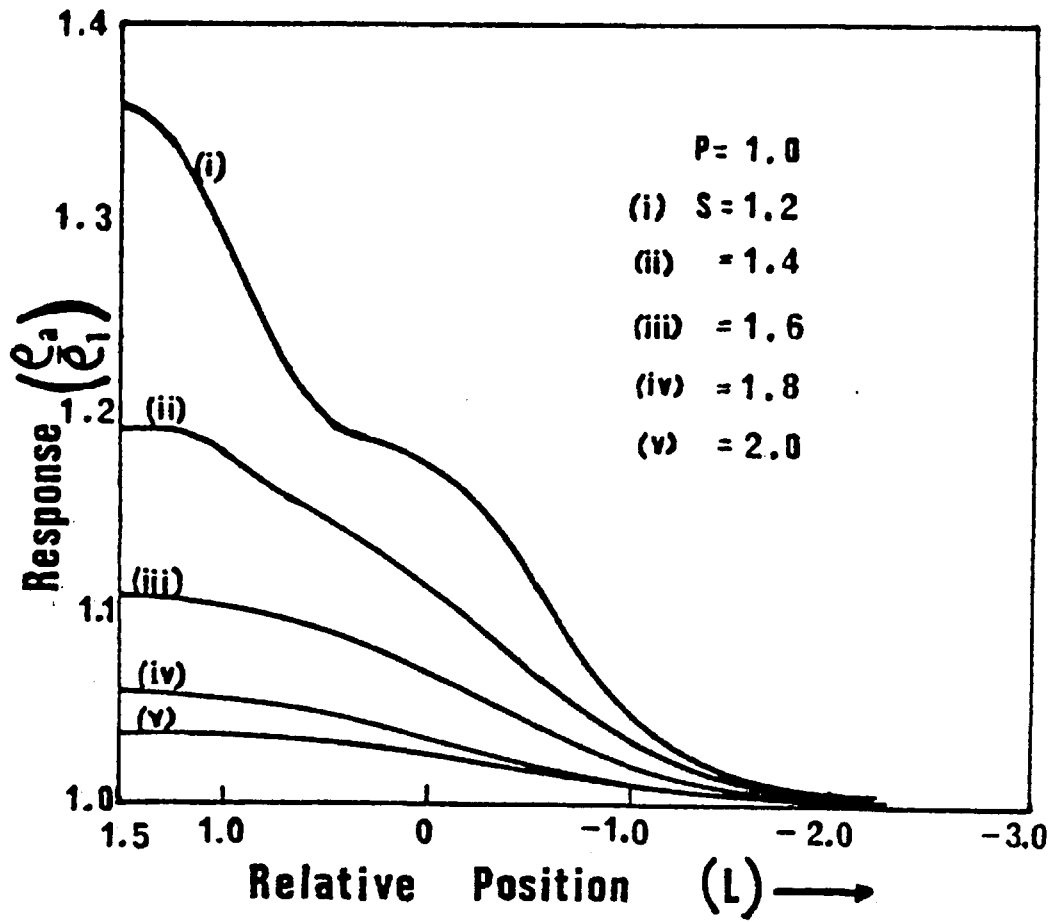


Fig. 3.15a Theoretical longitudinal semi-profiles from an insulating sphere when traversed by a Wenner array ($P = 1.0$)

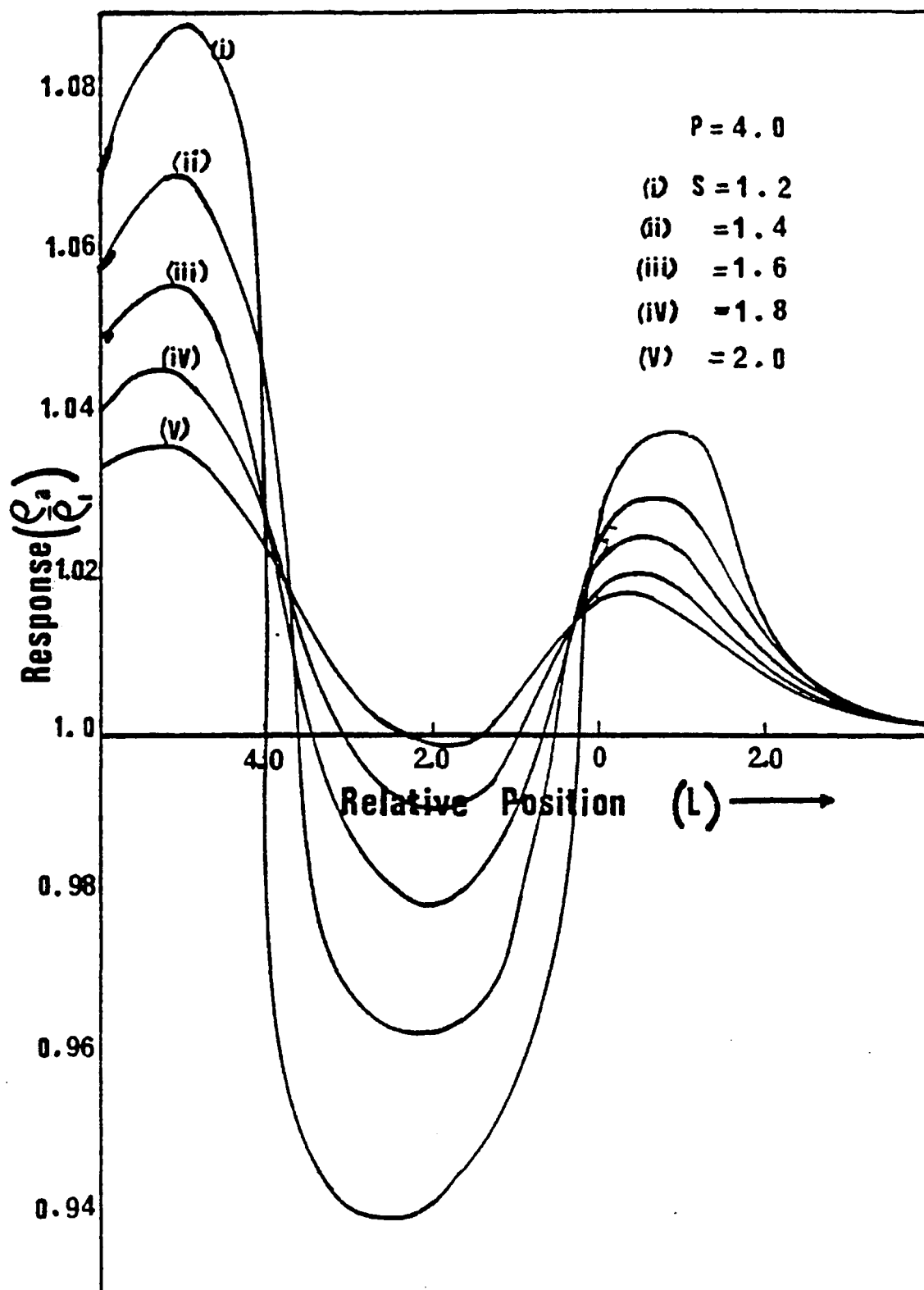
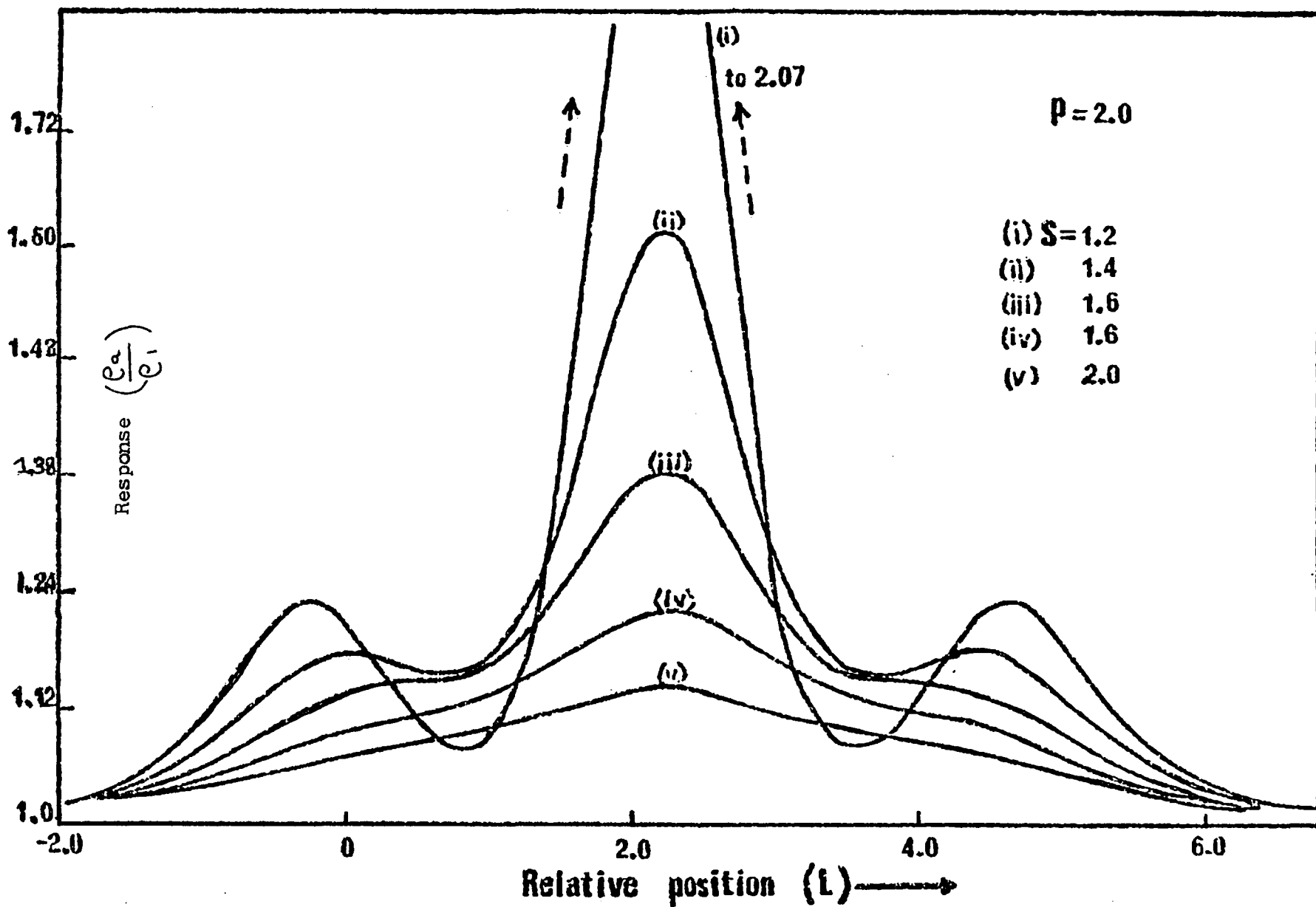
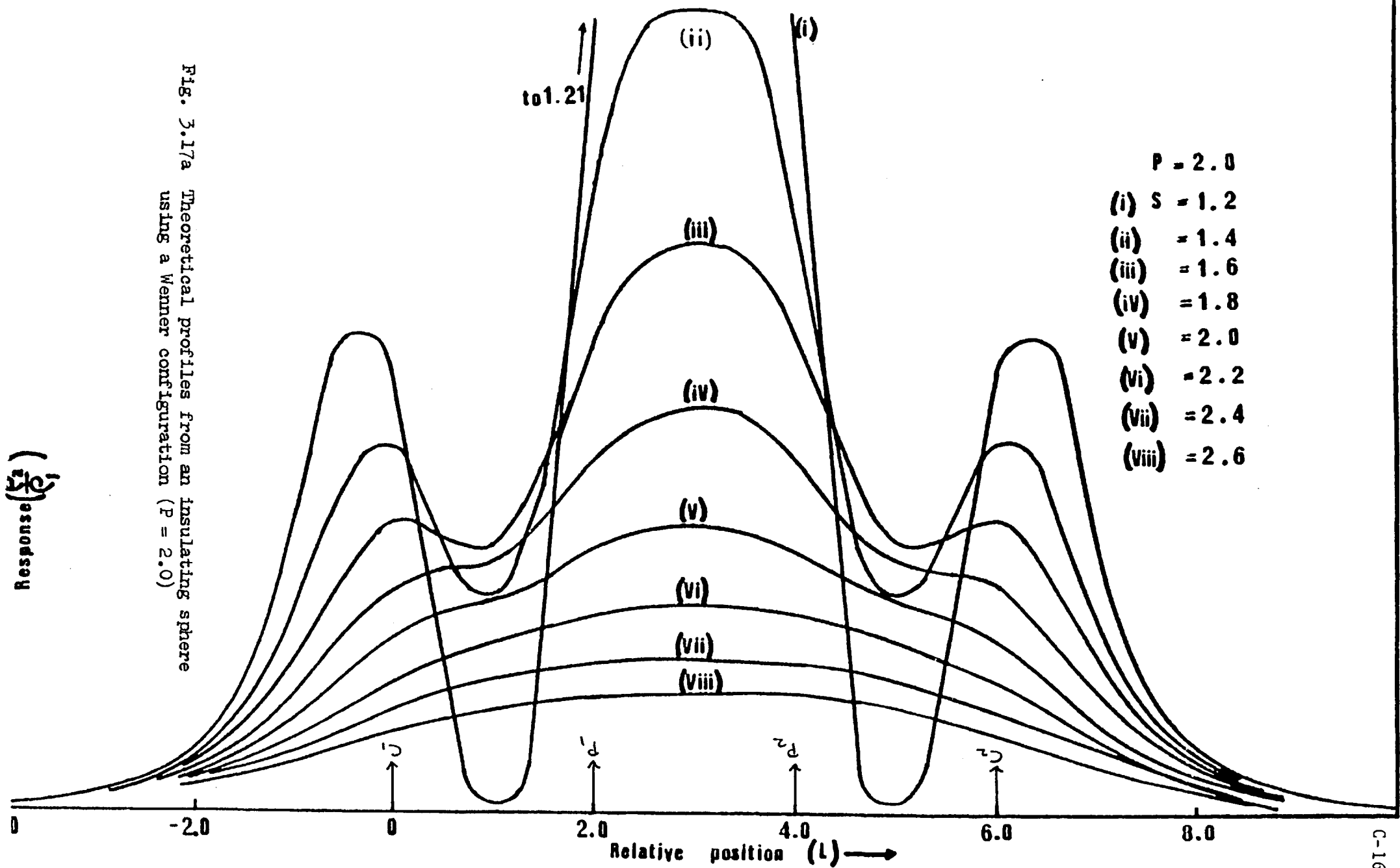


Fig. 3.15b Theoretical response semi-profiles for an insulating sphere using a Wenner array ($P = 4.0$)

Fig. 3.16 Theoretical response profiles for an insulating sphere using a Schlumberger configuration ($P = 2.0$)





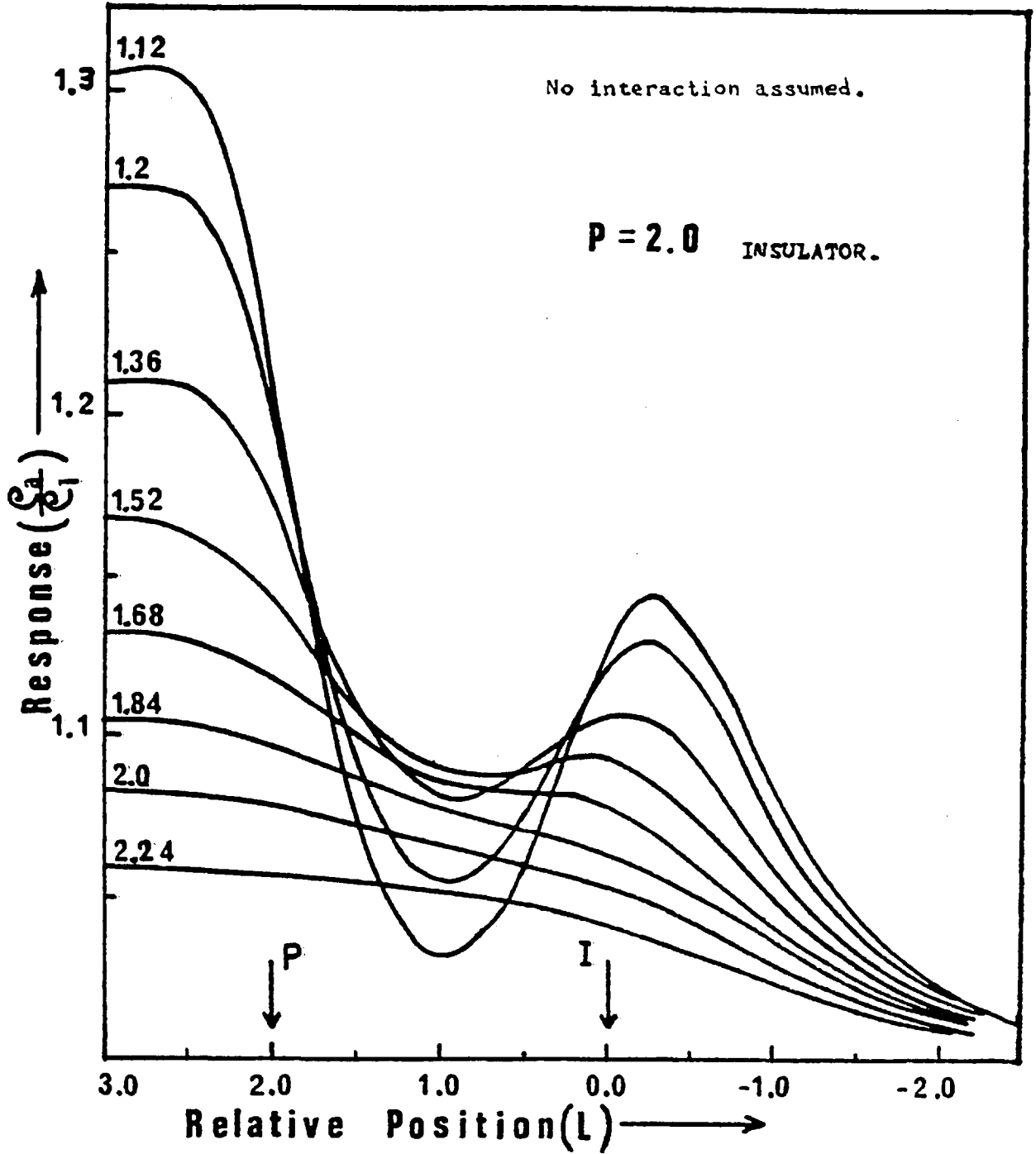


Fig. 3.17b Longitudinal profiles employing a Wenner configuration over a horizontal cylinder which lies at different relative depths beneath the surface ($P = 2.0$)

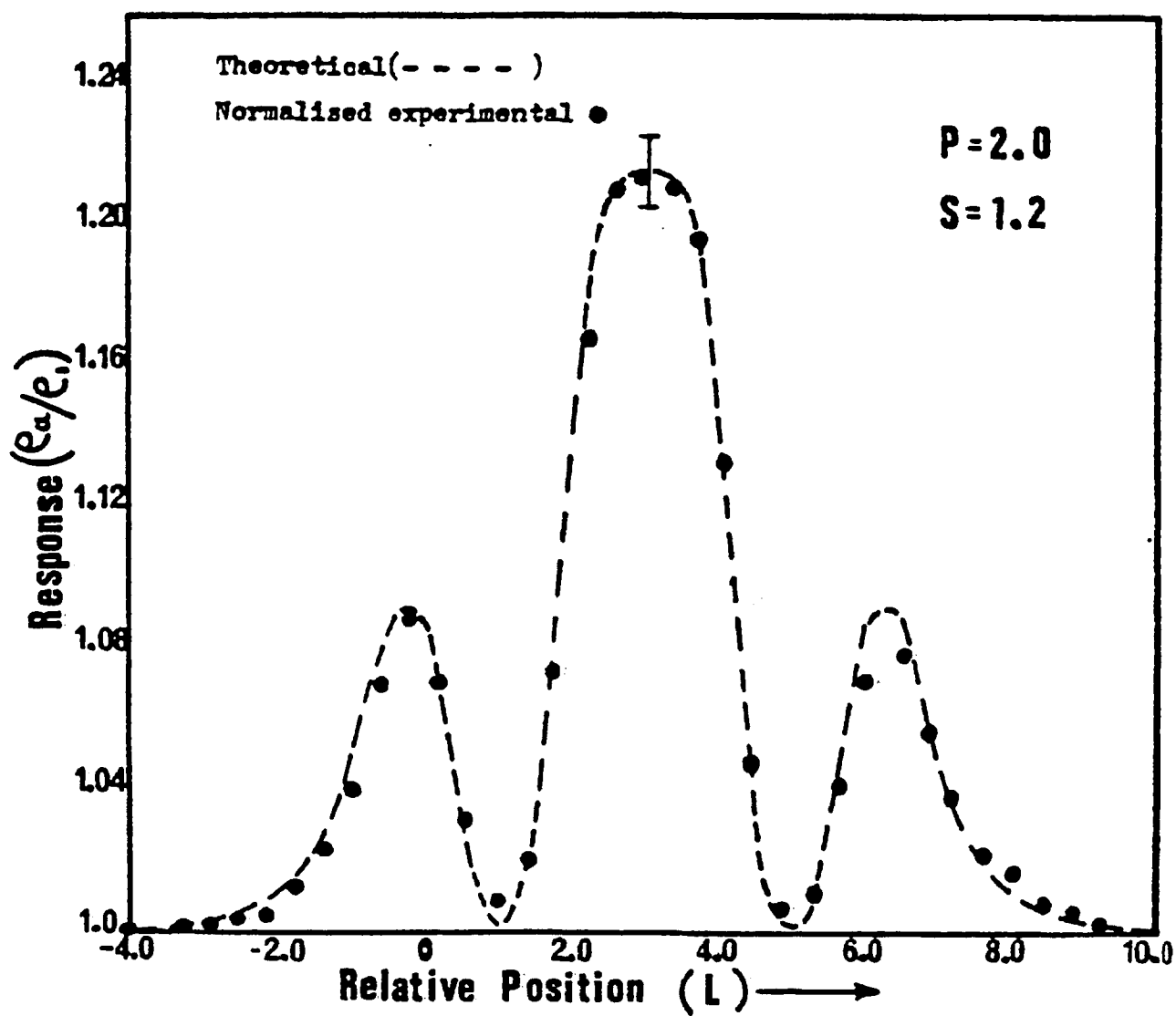


Fig. 3.18a Comparison between theory and experiment for the resistance effect of an insulating sphere using a Wenner array ($P = 2.0$)

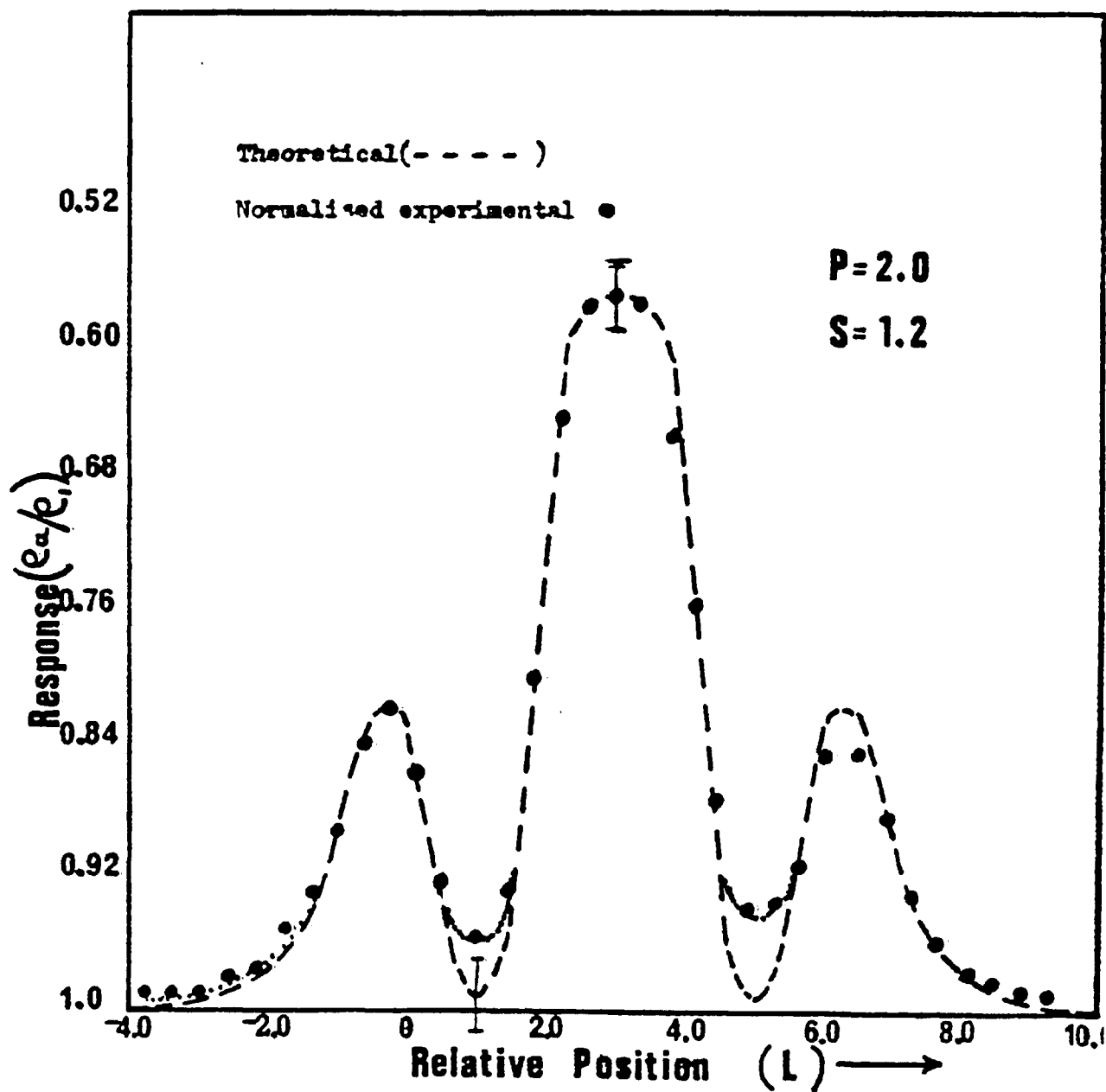


Fig. 3.18b Comparison between the theory and experiment for the resistance effect of a conducting sphere using a Wenner array ($P = 2.0$)

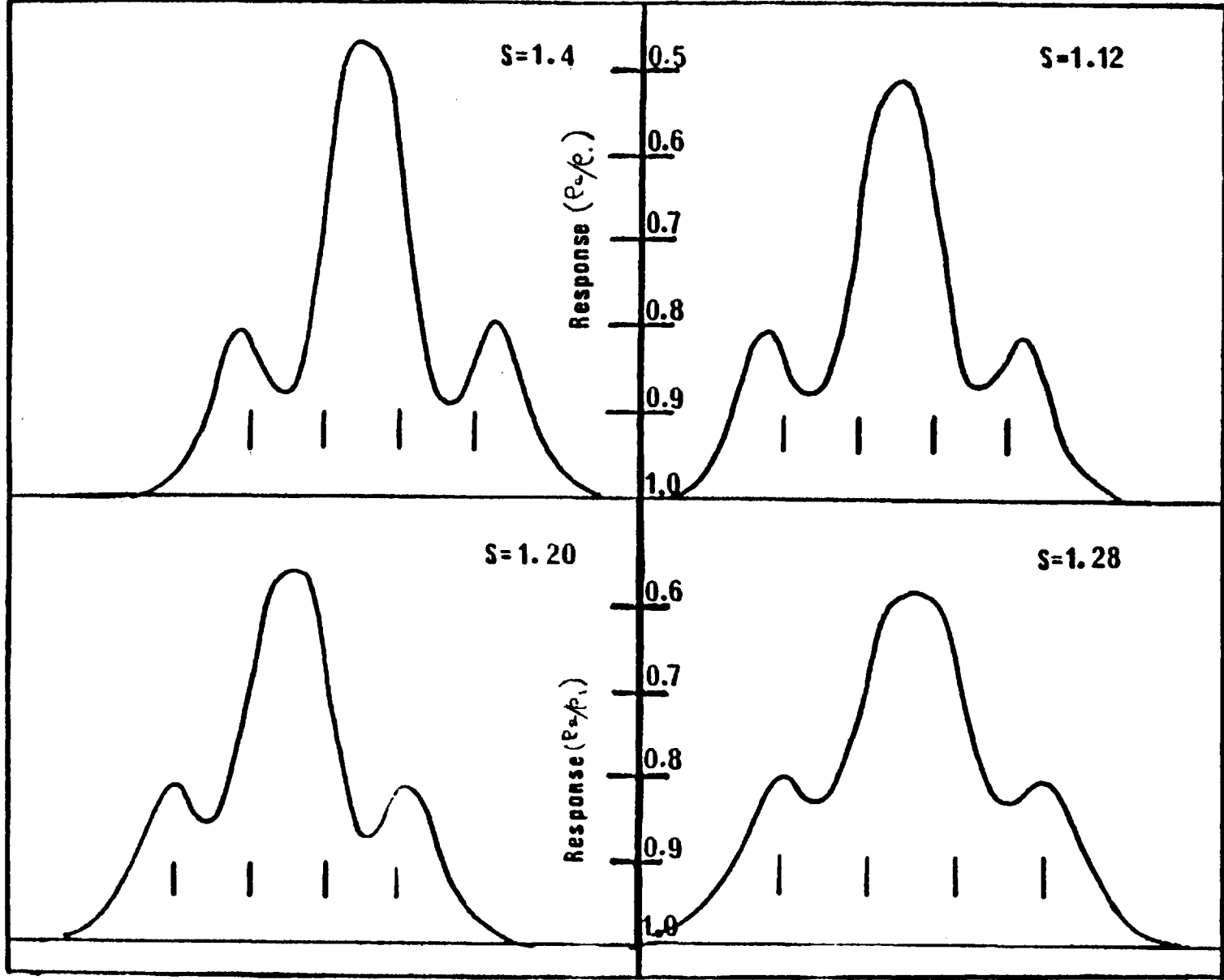


Fig. 3.19 Experimental response forms over a conducting cylinder using a Wenner array of separation $P = 2.0$

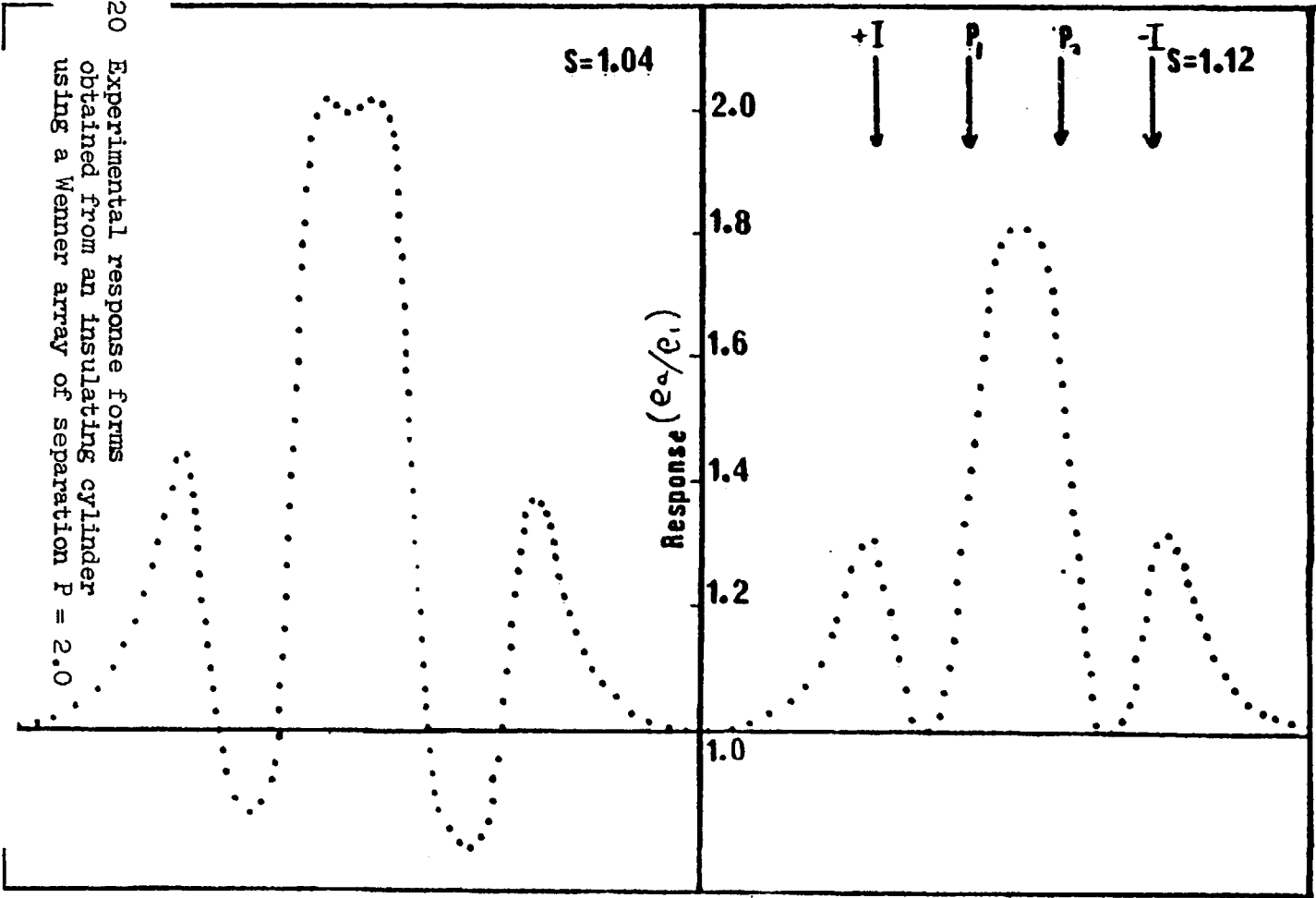
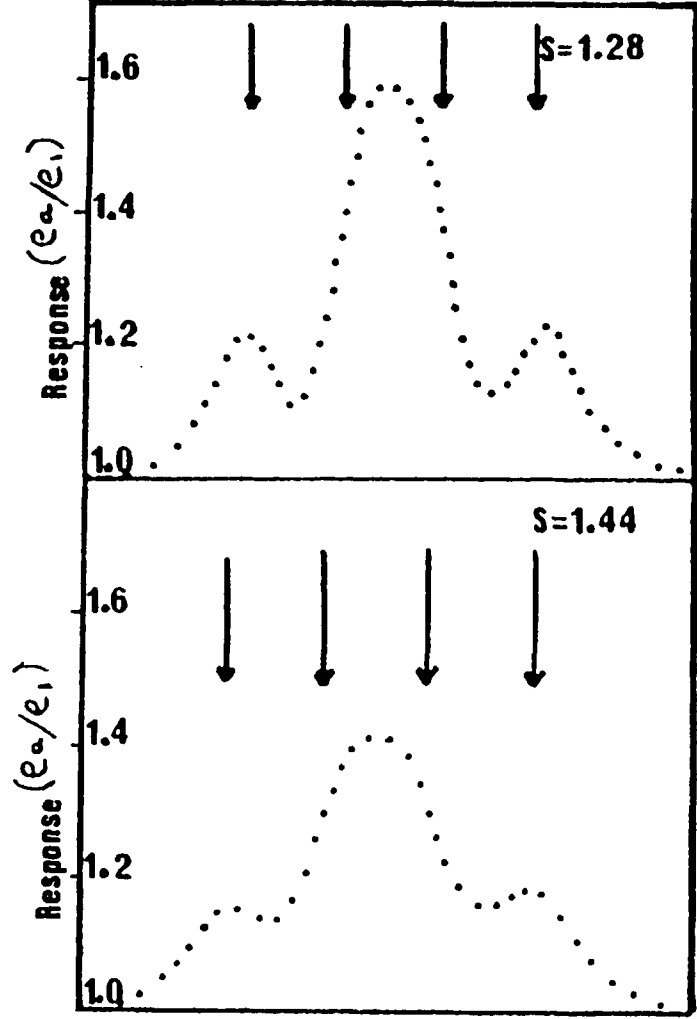


Fig. 3.20 Experimental response forms obtained from an insulating cylinder using a Wenner array of separation $P = 2.0$

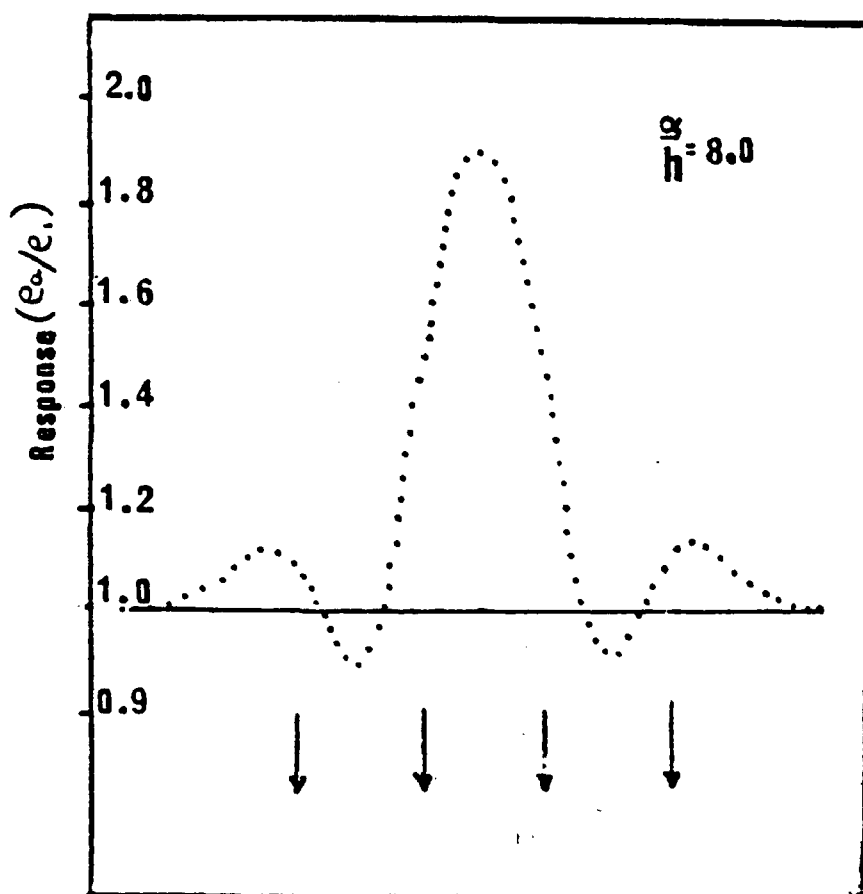
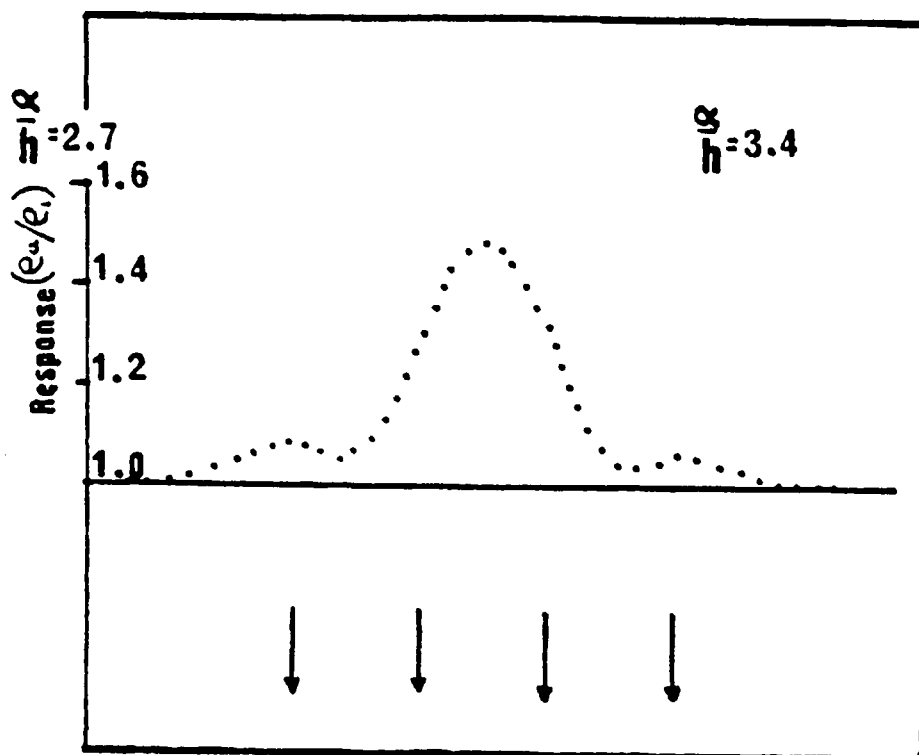


Fig. 3.21 Experimental response forms obtained with an insulating vertical plate of thickness 2.4cm using a Wenner array of separation 4.8cm

CHAPTER 4

RESULT INTERPRETATION AND PRESENTATION

Introduction

Adequate enhancement and presentation of the results can significantly increase the signal to noise ratio of geophysical data. Use of the dot density display technique already enables one to discern blurred images at very poor signal to noise ratios. Matched filtering will greatly improve on this especially if the shape and orientation of the filter are appropriately chosen and a large number of data points are correlated with each other. This specifically applies to spatial analysis, which is commonly used. Using such techniques^{in magnetics}, linear and curved features with an amplitude of 0.5γ can be detected with an instrument sensitivity of $\pm 1 \gamma$. Increasing the latter to $\pm 0.1 \gamma$ will enable the detection of anomalies of 0.05γ in low-noise environments. However, the situation deteriorates for small isolated features such as pits, of which the anomaly shape is easily lost among random noise (Graham and Scollar, 1976).

The choice of methods relating to the mathematical treatment of results is enormous and has produced a prodigious body of literature. Therefore a broad spectrum will be presented of the available techniques with specific reference to near-surface applications and with a bias towards simplicity.

Data presentation also forms an essential part of the process and the various options are discussed.

Prior to any treatment of the results, one must have a clear idea of the limitations involved. Most of these have been pointed out in the chapters dealing with the various surveying techniques. A similar

appreciation of the inherent strengths and weaknesses involved in existing methods of data treatment is also pertinent. However, the old maxim still applies: "Garbage in - garbage out" (GIGO)!

4.1. Interpretation

4.1.1. Near Surface Prospecting Results

Almost invariably one will be dealing with thousands of data values. Most survey work involves grids in varying sizes and a small distance between measurements, to enable a reasonable anomaly resolution. As a general guideline, the maximum anomaly resolution will be obtained if the measurement spacing equals half the width of the smallest detectable feature. Therefore some 100,000 values could be involved when surveying a hectare grid with a measurement spacing of 0.5 meters.

Furthermore, any anomalies tend to be complex in nature and will often be degraded in appearance or partly destroyed owing to erosion, robbing and other disturbances. The observed anomaly of a linear feature may well finally represent a series of irregular lines or ovals. This effect will be enhanced if differences in direction occur of the feature to the regular plough pattern. Anomaly distortion can also be brought about by changes in the physical properties of the deposits, irregular topsoil depths and geological variations. The anomaly will also be altered by errors associated with the method of measurement: magnetometer counting errors, errors in the detector height and position etc. This will be aggravated by orientation errors.

These problems are compounded when surveying complex sites such as settlement areas: features of differing sizes and at varying depths, stronger anomalies masking weaker ones and the effects of closely spaced features. A preference exists for simple systems of data analysis. The large number of data items often require a significant amount of computer

time in turn generally restricted by limited budgets. Therefore the beneficial effects of complex mathematical data treatment must be considerable to allow justification.

The required information is basically two-dimensional in nature: anomalies of varying size and shape situated near the surface as archaeology is rarely deeper than the immediate subsoil. Difficulties exist in quantitative three-dimensional results. Therefore most techniques centre around image processing and the enhancement of the signal to noise ratio as well as the reconstruction of indistinct features.

4.1.2. Image Analysis and Enhancement

In image analysis one extracts regional, local and micro-anomalies from data through a process of separation. Spatial frequency components are disseminated by filtering either directly using Fourier transforms or indirectly by convolution (Gonzalez and Wintz, 1977).

Fourier methods

With the Fourier method complicated functions are separated into a series of elementary linear functions representing the actual data. In essence one first obtains the frequency spectrum and then multiplies its components. One way of doing this is by using sines, cosines and other periodic functions, and by progressively increasing their frequencies. These in effect provide the closest correlation to a least squares function. The more elements one uses, the greater the approximation to the desired function. In a one-dimensional plane these elements are known as wave numbers. This technique is described as Fourier synthesis.

By reversing the process, that is defining the elements which are used to make up a given feature, one uses Fourier analysis.

One prime advantage of sines and cosines is their orthogonality,

which leads to the use of related vector properties. The Fourier transform separates the input data or function into distinct periodic functions using the following equation:

$$F(u) = \int_{-\infty}^{\infty} f(x) \exp(-j 2\pi ux) dx \quad (4.1)$$

with the inverse transform given by

$$f(x) = \int_{-\infty}^{\infty} F(u) \exp(+j 2\pi ux) du \quad (4.2)$$

where $f(x)$ represents an arbitrary one-dimensional function and $F(u)$ the Fourier transform. The frequency content of $f(x)$ can be expanded into real and imaginary parts:

$$F(u) = \int_{-\infty}^{\infty} f(x) \cos 2\pi ux dx - j \int_{-\infty}^{\infty} f(x) \sin 2\pi ux dx \quad (4.3)$$

For a function of two variables the filter wave number behaviour relates to the following equations:

$$F(u,v) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} f(x,y) \exp^{-2\pi j (ux + vy)} dx dy \quad (4.4)$$

direct transform

and

$$f(x,y) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} F(u,v) \exp^{+2\pi j (ux + vy)} du dv \quad (4.5)$$

indirect transform

where $(F(u,v))$ belongs to the wavenumber/frequency domain and $f(x,y)$

belongs to the space/dime domain, u and v are wavenumbers or frequencies.

The function $F(u,v)$, when written as

$$F(u,v) = A(u,v)e^{j\phi(u,v)} \quad (4.6)$$

relates to $|A(u,v)|$ in the amplitude spectrum and $\phi(u,v)$ in the phase spectrum.

In near-surface surveying, use is generally made of discrete sampled data. Therefore modification of the Fourier transform equation provides us with

$$F(u,v) = \frac{1}{M,N} \sum_{x=0}^{M-1} \sum_{y=0}^{N-1} f(x,y) \exp(-j2\pi(\frac{ux}{M} + \frac{vy}{N})) \quad (4.7)$$

This exemplifies the practical two-dimensional case in discrete sampled data where

$$u = 0, 1 \dots M - 1 \quad \text{and} \quad v = 0, 1 \dots N - 1.$$

A convenient way of displaying the results is by drawing a pseudo-perspective plot in which the magnitude (= amplitude) of the equivalent vectors, disregarding their direction, is displayed. The vector sum of $f(x)$ provides the modulus or length. In two-dimensional wave vector plots, the lowest vectors are placed in the centre of the plot, with the highest vectors along the plane edges. The central value will represent the sum of all the data values. In the event of a normalized transform, it indicates the average of the data (Fig. 4.1). It is important to remember that the transform is rotated 90° relative to the original data. As long as the original as well as the feature are not rotated, the characteristic transform of each anomaly shape will not alter.

The method of data sampling restricts the available transform methods: the use of data sampled at regular intervals (in grid form) means that the edge of the frequency plane occurs where the wavelength equals the sampling interval. This will be the highest wave number that can mirror the sampling interval, and is known as the Nyquist number. Therefore the Fourier transform cannot contain wavenumbers higher than

the Nyquist limit which means that any detail within the data will be restricted to twice the sampling interval.

Aliasing will occur when wave vector components lie above the Nyquist limit and are therefore folded back within the spectral range causing spurious peaks, which result in false anomalies. Certain filtering techniques are susceptible to this.

4.1.3. Frequency Domain Filtering

Two-dimensional data involve two sampling intervals, one in either direction:

measurement interval
 • → •
 ↓
 • grid traverse line

If equal distances are used, the sampling interval will be identical and have the same Nyquist limits. However, if this is not the case any features within the data will become direction dependent.

The analysis of spatial data using combinations of orthogonal functions has been outlined. Fourier synthesis uses the inverse Fourier transform to determine the sine and cosine coefficients which make up the data. This move back to the real data can take place at any time provided linear transformation has been applied.

Having transformed a data set, one can filter it by modifying components of the frequency spectrum. Some of the simplest operations on spatial data involving replacement of a central value by a new data value is described further on. Each of the peripheral points in such cases can be weighted with a set constant. This is known as convolution.

A similar process exists with Fourier analysis. Prior to the inverse transform, all transformed data are each multiplied according to a predetermined function providing a form of spatial filtering. This

function is referred to as the transfer function of the relevant filter. The use of fast Fourier transforms (Scollar, 1970) enables data to be rapidly filtered according to any transfer function, at the same time generally avoiding some of the problems of weighted coefficients in convolution methods e.g. the susceptibility to individual data items and the dependency on direction.

Such simple bandpass filters do, however, enable hand calculation as a means of preliminary data evaluation. Weighting data alters the wave vector (or frequency) response of those data items whether using convolution or by establishing appropriate filter transfer functions. In a frequency domain filter the latter can take on any value between 0 and 1. A weighted group of multipliers using the value 1 will pass all the data items, whereas any smaller value will attenuate them, prior to the inverse transform being taken, which in turn provides a filtered data set.

When dealing with Fourier transforms, the real part is formed by the cosine waves and the imaginary part by the sine waves. Both are used when calculating the real transfer function, and each coefficient has a relevant amplitude (vector magnitude) and phase (arctangent). It is important that these factors exhibit no shift in phase or position which would adversely affect the linearity of the data set. This problem tends to occur when filtering in the space domain, especially when only a small number of elements are involved. Phase shift can be virtually eliminated in wave vector domain filtering. However, deliberate phase shifts are sometimes advantageous e.g. in correcting data exhibiting linear displacement.

A large number of filters are available, each with a characteristic impulse response and transfer function (Fig. 4.2). They all fall into three basic categories:

- (1) high pass (or residual) filter - in which 'high' refers to the frequency (wavenumber) passed. The filter emphasizes short wavelengths and eliminates wavelengths longer than the cut-off wavelength (Fig. 4.2).
- (2) low pass (or regional) filter - the filter emphasizes long wavelengths and eliminates wavelengths shorter than the cut-off wavelength (Fig. 4.3).
- (3) band pass filter - the filter passes all wavelengths within the defined band (Fig. 4.4).

An important function of a filter is its step response, that is, the effect of a sudden rise or dip in the data. The more precise^{ly} the coefficients in a Fourier transform follow the data, the less the over- or undershoot (also known as ringing) will be. However, ringing can be used to one's advantage when one, for instance, focusses on edge effects (feature outline) in the data. Here the use of the second derivative in convolution has provided useful results. Ringing caused by a poor response to iron spikes, surface irregularities etc. can lead to false anomaly interpretation. One way to minimize ringing is to allow for a smooth transition from 1 to 0 in the transfer function as given by an apodizing (characteristic curve) function: if the transition follows a Gaussian (bell shaped) function, then no ringing will occur at all when applying a low pass filter.

The cut-off characteristic of the apodizing function will determine the sharpness of the filter, with a rapid cut-off providing a sharp filter and vice versa. Various other useful apodizing functions are available (Scollar, 1970).

Ideally the rise and fall-off of a filter applied to either low or high wave numbers should be controlled according to the filter requirements and with a minimum argument adjustment and a proper impulse response.

All the above filters are centro-symmetrical, that is, they have no particular orientation. In near-surface geophysics one often invariably has to discriminate between linear features running in various directions. Therefore directional filters are necessary which can be rotated, thereby enhancing information from specific directions at the same time suppressing background disturbances. One way to obtain a directional filter is by constructing the expected response from a theoretical linear anomaly, e.g. ditch, and by taking the Fourier transform of this. In essence this method can be equated to cross-correlation, though involving a very much faster calculation process than the latter. Unfortunately, one rarely has any precise details on the sought-after anomalies in situ. Scollar (1970, p. 20) describes a method using the complex conjugate of the Fourier transform of a given feature as opposed to the modulus so far referred to.

When devising the optimum matched filter by using the power spectrum of the signal as a reference source to which one applies a filter to assess its performance, a symmetric transform function applies, e.g. real input data $\rightarrow$ real filtered output.

This method does necessitate devising a whole series of different filters for various power spectra, with each spectrum presupposing knowledge of the expected output from an anomaly. Any such filter standardisation will greatly aid the efficiency of the operation. Although Fourier transforms may discriminate between the individual wavelengths (or numbers) the various anomalies contained within the data consist of a large spectrum of wavelengths often overlapping each other (spectrum across spectrum). Phase relationships will have changed (different anomaly location) when using the amplitude spectrum within the Fourier transform or amplitudes are lost when using the phase spectrum.

Also changing from space domain to wave number domain makes any comparison between processed data and additional information such as site

maps impossible.

One can readily change from one mode to the other: the inverse transform of a frequency domain transfer function leads to a set of coefficients equivalent to a convolution filter with appropriate impulse response characteristics. However, some of the problems so far outlined should be taken into effect.

To enable comparison between transfer functions in the wave vector domain and convolutions in the space domain one applies a function containing all the frequencies as data in the form of a single impulse in the centre of a plot. This function is known as the Dirac delta function and it provides the impulse response of a transfer function:

$$f(x,y) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} f(p,q) \delta(x - p, y - q) dp dq \quad (4.8)$$

for a continuous f .

In practice the Fourier transform of the Dirac delta function is taken and multiplied by the transfer function of the filter after which follows the inverse transform.

Most of the information on archaeological features in frequency domain filtering is concentrated in the low and medium wave vector, with isolated anomalies forming the only exception. Therefore any filter should preferably concentrate on these areas. Interference from either correlated or uncorrelated noise will also be suppressed owing to the different geometric signal properties of a feature, in turn associated with the source geometry.

4.1.4. Spatial Filtering

With convolution in the space domain (Zurflueh, 1967) the emphasis will be on high pass filters which emphasize narrow linear features such as ditches or walls as well as isolated anomalies. In

magnetic surveying noise will mainly consist of correlated sources whereas in resistivity the main sources of interference will consist of geological and background changes.

In wavelength filters the phase will be retained, although spectral overlap, as evidenced by the use of Fourier transforms, still remains.

Simple anomaly definition can be based on the measurement of the distance from peak to trough, effectively half the anomaly wavelength. Anomaly overlap can then be attenuated by the use of sharp filters with a steep wavelength cut-off, the latter referring to the point where the filter attains 50% of the maximum response. This relies on the assumption that small anomalies have low amplitudes and wide anomalies large amplitudes, enabling the cut-off to be tailored to the required anomaly size. Depth effects are, however, not taken into account, that is, anomalies at differing depths which alter the anomaly spectra and require specific filters (Bhattacharyya, 1966).

Any subsequent filters will be based on the above assumptions concerning the Fourier spectra of anomalies, and the basic set-up is very similar to that mentioned under frequency domain filtering: regional, residual and band-pass filters with appropriate wave number responses (e.g. steep cut-off similar to a step function). By keeping the filter symmetrical around the central value, any phase (location) shift will be eliminated.

When applying wavelength filters to square grids, the filter step response can be equated to the grid distance and its effect will then be directly dependent on it. Therefore filter cut-off described in grid units ascertains which wavelengths are passed and which are cut-off. A suitable choice of grid distance will then allow any desired wavelength to be filtered.

Computer filter design can be simplified by inverting the sign of the coefficients and adding a positive central spike value. Its magnitude

will be equal to the sum of the remaining coefficients. This effectively results in a high pass filter when applied to low pass filtered results by means of convolution and negates the process of subtracting low pass values from the original data.

In practice, wavelength filters, although representing a reliable and compatible picture with other (e.g. geological) maps, will result in the loss of a strip of data equal to half the width of the filter array. This can be overcome by extrapolation. Furthermore, gridded data form a prerequisite for wavelength filters.

The process of multiplying by a normalized coefficient array has lead to a number of greatly simplified approximations, conveniently termed ring residual filters. The basics are discussed below, and form the basis of the technique used by the author.

4.1.5. Simple Filtering Techniques

A large number of simple methods of data treatment are available (Linington, 1969, 1970c). One can identify two groups:

- (1) process of averaging - this essentially removes small random irregularities;
- (2) comparison or subtraction procedure - this enhances the interpretation of results by reducing unwanted effects. It must, however, be exercised with care as it may create unwanted anomalies or lead to result misinterpretation.

Some basic averaging methods are:

- a) simple running average

$$\frac{A + B + C}{3} = B' \quad \frac{B + C + D}{3} = C' \quad \text{etc.} \quad (4.9)$$

where A, B, C, D ... etc. represent the measurement points;

b) three-point weighted running average

$$\frac{A * 1 + B * 2 + C * 1}{4} = B' \quad \text{etc.} \quad (4.10)$$

c) five-point weighted running average

$$\frac{A + 2B + 4C + 2D + E}{10} = C' \quad \text{etc.} \quad (4.11)$$

d) symmetrical average

$$\bar{X} = \frac{X + \Sigma x}{n + 1} \quad (4.12)$$

or

$$\bar{X} = \frac{2X + \Sigma x}{n + 2} \quad (4.13)$$

for a symmetrical data outlay

$$\begin{array}{c} \cdot \\ \cdot * \cdot \\ \cdot \end{array}$$

where X is the central value and Σx is the sum of the surrounding values. Normally $n = 4$ but less if blank values occur.

The simple symmetrical arrangement above can be expanded

(Linington, 1970c):

<u>Radius A</u>	<u>Radius B</u>	<u>Filter no.</u>
<pre> + . + </pre>	<pre> + + . + + </pre>	(1)
<pre> + . + </pre>	<pre> + + . + + </pre>	(2)
<pre> + + . + + </pre>	<pre> + + + + . + + + + </pre>	(3)
<pre> + . + </pre>	<pre> + + . + + </pre>	(4)
<pre> + . + </pre>	<pre> + + . + + </pre>	(5)
<pre> + . + + . + </pre>	<pre> + . + + . + + . + </pre>	(6)
<pre> + + + + . + + + + </pre>	<pre> + . + + . + + . + + . + + . + </pre>	(7)
<pre> + + + + + + . + + + + + + </pre>		(8)

where $\cdot$ is the central value and $+$ represents the surrounding measurement points.

For instance, one can replace the central value by the average of a group of four values situated symmetrically around it and including the central value (example 4, radius B). This will basically reduce soil noise and slightly enhance weak anomalies. However, the end result will not be a true representation of the actual anomaly with probably only parts of it shown. This effect specially applies to linear features and in such cases care should be exercised not to confuse these with areas of general change.

Prior to using more complicated filtering systems, one can apply filters based on the comparison of symmetrical values (Linington, 1970c). This involves observing how often a central value is higher or lower than the surrounding ones, with the result replacing the respective central reading. On the basis of this comparison, a map is drawn up using symbols: each group of symbols represents the number of times the central value differs from the neighbouring ones, e.g.

$$x = 0 \quad x = 2 \quad 0 = 4 \quad + = 6$$

The symmetrical system of comparison does not operate well in revealing weak anomalies. Anomaly maxima tend to show up most clearly when traversed at right angles to their location. This especially applies to linear features. Only occasionally will one be working under these optimum conditions.

Furthermore, the grid measurement points need not coincide with the exact position of the anomaly. The symmetrical comparison method is therefore overall of limited use. It also overemphasizes minor fluctuations leading to confusion in the interpretation. At best it can be used on survey data from sites exhibiting low noise and which are relatively uncomplicated in nature. Filters with a wider context are also inadvisable as these will place less emphasis on minor fluctuations.

To allow for differences in anomaly direction, one can rotate the

filter using different filter directions, e.g. B5 instead of B4. The results of both filters can then be compared by superimposition.

Finally, one should not base estimates of anomaly width, length and strength on the filtered results as these will have been ignored.

The limitations of the comparative symmetrical filtering system leads to slightly more evolved systems.

One such method involves taking the sum of the differences between the central value and the surrounding ones. This value is then divided by the number of values used and replaces the central value. Any configuration can be used. This process also tends to be very susceptible to the orientation of the filter relative to the anomaly. It is therefore sensible to use all four filter directions. The emphasis in the final result will not be so much on random fluctuations but will also take intermediate values into account: weak anomalies will show up better. Again, anomaly dimensions should not be derived from the filtered results as these on the whole will have been reduced to single lines.

The results of tests on theoretical features are shown in Fig. 4.5. The actual features are shown in the centre of each set of six elements, the top one representing an undisturbed feature whereas the bottom feature has been damaged. On either side the results are given with those on the left providing the unfiltered symbol diagrams whilst those on the right have been filtered using a simple filter. Theoretical anomaly calculations are based on an angle of dip of 60° and magnetic north as shown in the figure. Therefore all results have undergone a slight northward shift.

In part A, the intersections and east-west parts of the feature provide the strongest response with the north-south sections coming through less marked and disappearing completely in the damaged sections. The filter consisted of a star shape (filter 3B) as has been applied in all cases. In part B, the left-hand column indicates the results for an

inverted feature, with the right-hand column referring to the normal anomaly. One can clearly see the distortion of the actual anomaly leading to a false interpretation.

In part C, filtering has been applied to values greater than 100 units with the right-hand diagrams referring to the left to the inverted version. A slight, though dubious, improvement can be seen.

Part B gives the results when only values above 250 units are considered. The filtered results for the normal case (on the right-hand side) indicate good agreement with the actual feature, with the inverted anomaly (on the left-hand side) not showing much improvement. Choosing suitable limits for the symbols can therefore give problems, this especially applies to inverted anomalies. The situation will be compounded when inverted anomalies are found together with normal features (magnetic susceptibility will be greater and smaller than the general background) (Linington, 1971b).

4.1.6. Haar and Walsh Transforms

With the advent of the fast Fourier transform, filtering directly in the frequency domain became feasible instead of having to generate an array of convolution coefficients. As an alternative, emphasis has shifted to similar techniques such as Haar and Walsh transforms (Gubbins et al, 1971) which use up less computing time.

Walsh functions are either symmetric, allowing an identical procedure to be used for the transform as well as the inverse transform, or antisymmetric with values of ± 1 .

The Haar function can either be ± 1 or 0 and is non-symmetric. Haar transform times are linearly proportional to the number of data whereas those of the Walsh transform require $N \log^2 N$ additions or subtractions with the final normalization only necessitating multiplications. The basic Walsh transform requires additions or subtractions comparing favourably

with the complex multiplications and additions of the Fourier transform. When using Haar and Walsh transforms for filtering, overshoot and ringing as evidenced with Fourier transforms (which therefore use tapered transfer functions leading to a gradual cut-off thus impairing transient response) are very much attenuated and no filter tapering is necessary. However, these transforms do not follow a given shape as well as Fourier transforms do and they also suffer from aliasing (as with discrete Fourier, the information content of the data lies for wavelengths in the range: $\frac{1}{2}$ total length of data set $\rightarrow 2 \times$ sampling interval or Nyquist wavelength).

As with Fourier transforms, the data must also be despiked before applying Walsh transforms and this is also advisable with Haar transforms.

When using Walsh and Haar transforms for the filtering of two-dimensional data a number of problems arise. Irregular pass bands along the sides and along the diagonal make Haar transform filter marginally direction sensitive. In some cases this can be used to attenuate noise aligned in a given direction.

Unfortunately the practical results of Haar and Walsh transforms on two-dimensional simulated data have been disappointing (Fig. 4.6).

Any features are made difficult to interpret as the filtered information comes across in 'blocks'. This would make especially linear anomalies difficult to distinguish apart from the spurious anomalies already introduced by the filtering process.

4.1.7. Edge Effects and Despiking

Almost any system of data treatment will reduce the final number of data points eg. in conventional convolution data of width $M' - 1$ or $N' - 1$ points is lost where the data array is $A(k, \ell)$, $k = (0, M - 1)$ and $\ell = (0, N - 1)$ and the array of weighting coefficients will be $B(m, n)$ with $m = (0, M - 1)$ and $n = (0, N - 1)$.

One way to avoid edge effect problems is through filtering by means of multiplication in the wave vector domain as the coefficient set used in the convolution exactly matches the original data set.

Another method relies on placing zeroes around the data prior to convolution, although a preference exists (Black and Scollar, 1969) for repeating the actual line of data as this will have identical noise characteristics to the data itself.

Extrapolation as well as polynomial surface fitting form other suitable remedies.

Wave vector domain filtering tends to be sensitive to regional trends, which introduce spuriae. Therefore these will have to be removed prior to filtering. The same applies to boundaries of different sets of data or grids when these are joined together. Both problems can be tackled by fitting a plane to the data using a least squares technique and then subtracting it. The resultant values will have zero mean and zero regional/boundary trend.

Grid matching can also be simply done by multiplying the readings by the ratio of the mean values calculated for each grid. Similarly, one can add the difference in mean values to each grid.

When two grids do not exactly fit onto each other one can extrapolate by using the line average or by triple exponential smoothing and then apply either of the techniques described above.

Incomplete blocks of data may present a problem. This especially applies to frequency domain filtering. Missing readings can be filled in by interpolation. The length and width of a data array can also be suitably tailored to fit the processing requirements of the applied filtering technique using this method.

Spikes in the readings caused by scattered pieces of iron often need to be excluded. Despiking can be effectively done by looking at the histogram of the statistical distribution of the data and by cutting off

values which lie significantly outside it. The resultant gaps can then be filled in by interpolation, least squares etc.

4.1.8. Related Filtering Techniques

Some of the methods which have remained unmentioned are the use of the second derivative and polynomial surface fitting. Compared to wavelength filtering, the second derivative (Darby and Davies, 1967) will be quite similar for an appropriate wavelength when observing the frequency response. Wavelength filters, however, allow better anomaly differentiation owing to their sharper step response whereas a derivative filter may well contain long wavelengths superimposed on short ones as the cut-off will not be strong enough. This may lead to masking. However, wavelength filters suffer from ringing which may cause pseudo anomalies.

With polynomial surface filtering the coefficients tend to be overly susceptible to high amplitude features and these may subsequently swamp any low amplitude anomalies. Furthermore, any polynomial surface fit, although reliable in the centre, gradually decreases in consistency towards the edges. This will be especially evident when fitting adjacent grids with polynomials causing incompatibility between the two. Polynomial surfaces also often suffer from pseudo-anomalies, this becoming all the more apparent with data of high dynamic range. They also require a large amount of computer storage as well as complicated computer programmes. However, they can be applied to irregularly spaced data. It is a technique often used on contour maps for differentiating between the various anomalies. With downward and upward continuation the focus tends to be on short wavelength anomalies.

Optical filtering suffers from a limited dynamic range and difficulties in the presentation of a suitable variable density (Scollar, 1970).

4.2. Presentation

4.2.1. Result Presentation

Adequate result presentation forms an essential part of any survey and enhances the interpretation. A large number of methods can be applied:

- (1) contouring - this is best used for large variations in the readings and features of longer wavelength. It is inadvisable for very weak anomalies.
- (2) symbol and symbol density diagrams - in which symbols are used to represent given values of anomaly strength. It is important to make a sensible choice of symbols. In practice areas of, for instance, high field strength or high resistivity should preferably show up as darkened areas with an appropriate symbol choice to achieve a proper gradation between low and high values.

Best results will be obtained if the method is used for wide or very distinct anomalies which are preferably of virtually the same order and reasonably well separated. If using too many symbols to characterise a wide variety of differing features, the resultant symbol diagram will only confuse.

- (3) graph representation - usually the anomaly strength will be recorded on the vertical scale with the measurement spacing placed on the horizontal scale. Graphical traces enable anomaly interpretation based on gradient and profile as well as magnitude and extent (Fig. 4.7).
- (4) perspective or isometric drawings - a useful technique offering a three-dimensional view of survey data. At best the results should not be too diverse in character otherwise a confused picture will be the result. Computer graphics techniques are generally employed for the automatic reduction of field data with the results displayed on a visual display unit or with the aid of a high-speed line

printer. Three-dimensional pseudo-perspective plots are also very suitable for displaying the modulus of the discrete Fourier transform of data (Fig. 4.8).

- (5) dot density diagrams - in these measured values are represented by a cluster of dots in density proportional to the value. In practice the dots should not be geometrically arranged over a given area but randomly orientated over that area, otherwise false anomalies may be produced as well as the final result being irritating to the eye.

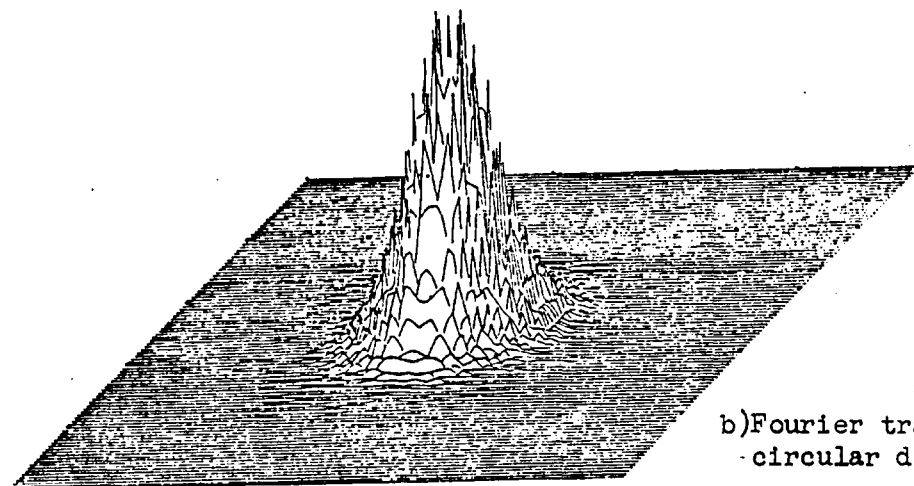
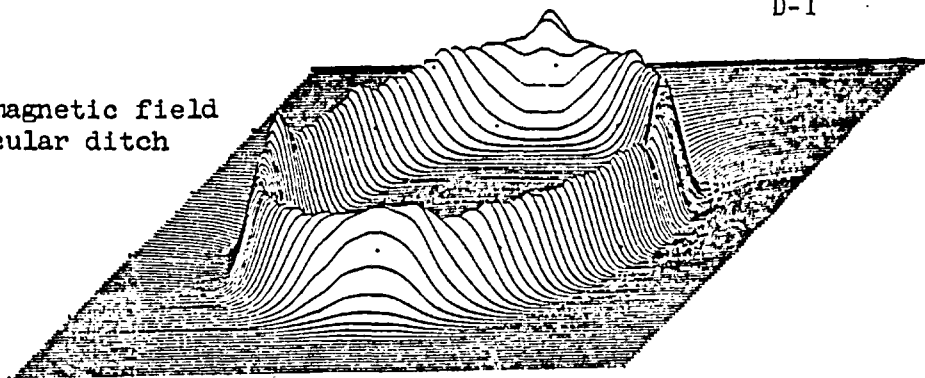
A dot density display will enable very weak linear features to be picked out as well as strong ones, with small isolated anomalies being difficult to distinguish. The interpretation will be based on the magnitude and extent of features presented as a mixture of half-tones: higher readings providing greater density than low ones.

It provides one of the most useful methods available for data representation and has been widely applied for the display of near-surface data (Scollar and Krückeberg, 1966).

Its implementation is discussed in the following chapter.

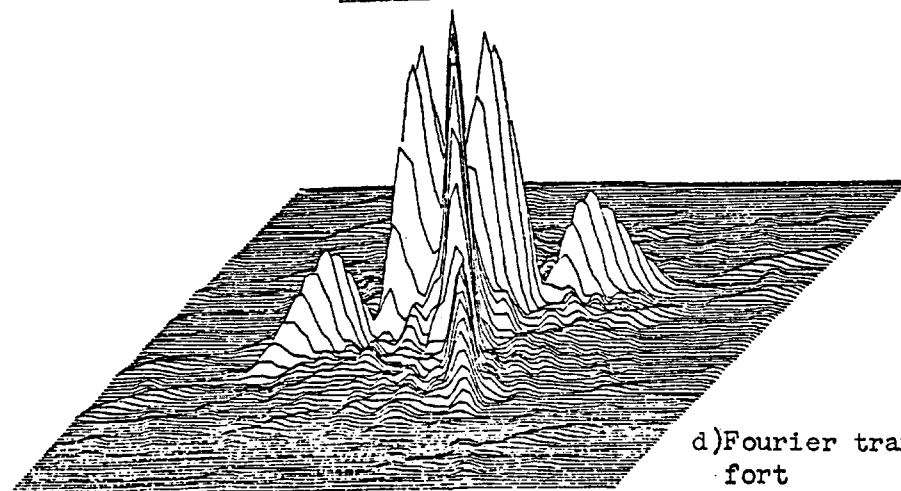
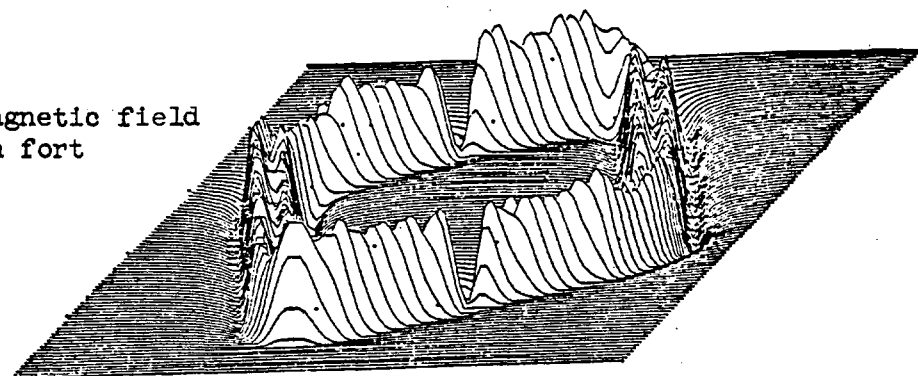
- (6) colour raster plots - the data set is seen as a spatially ordered matrix of measurements recorded over each point of a site. This matrix is the raster of xy matrices. These are converted to colour representations based on the data value corresponding to each matrix and results in a spatially ordered colour digital image of a given site.

a) theoretical magnetic field
due to a circular ditch



b) Fourier transform of the
circular ditch

c) theoretical magnetic field
due to a Roman fort



d) Fourier transform of the Roman
fort

Fig. 4.1 Two-dimensional wave vector plots
(After Scollar, 1970)

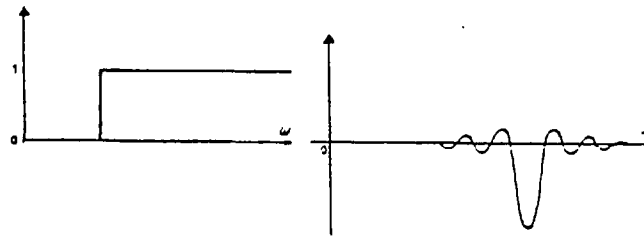


Fig. 4.2 High-pass filter, impulse response

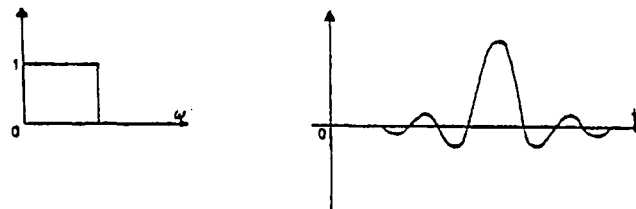


Fig. 4.3 Low-pass filter, impulse response

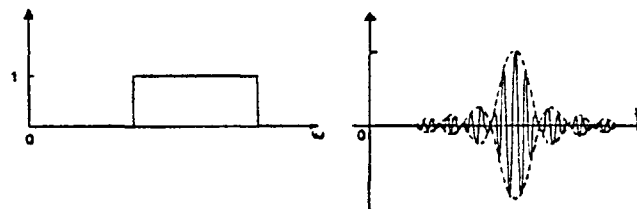
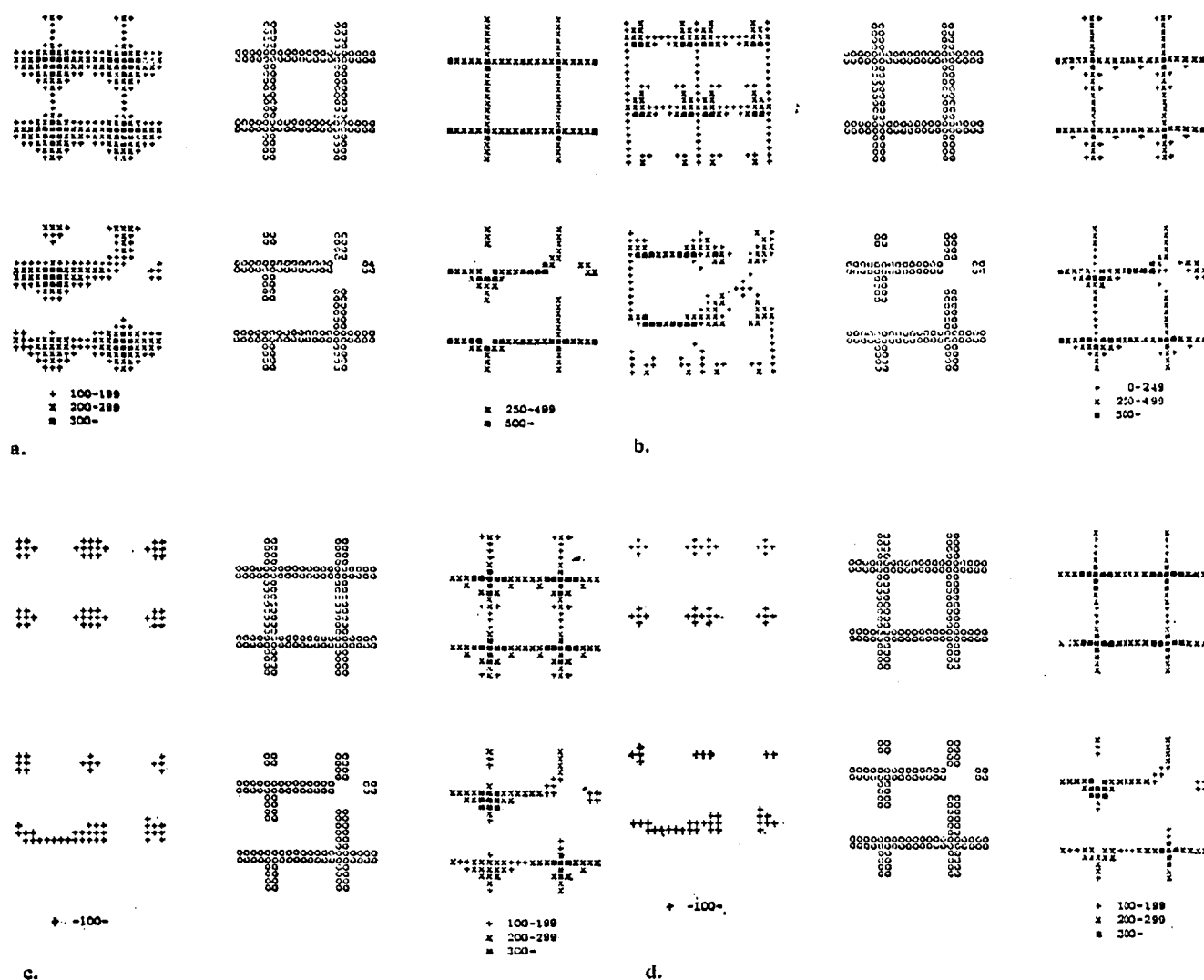


Fig. 4.4 Band-pass filter, impulse response

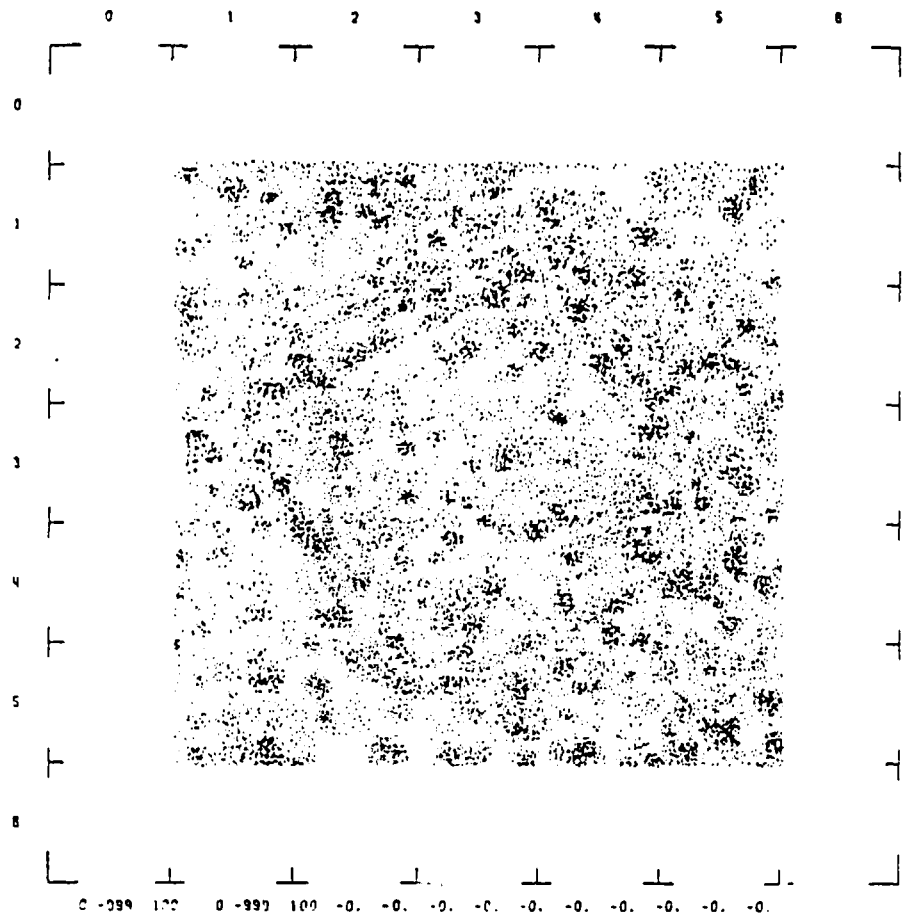


Tests on two theoretical studies of various methods of non-symmetrical filtering. The two features are shown in the central column of each part. Part a. gives the original results, on the left, and the simple filtered results on the right.

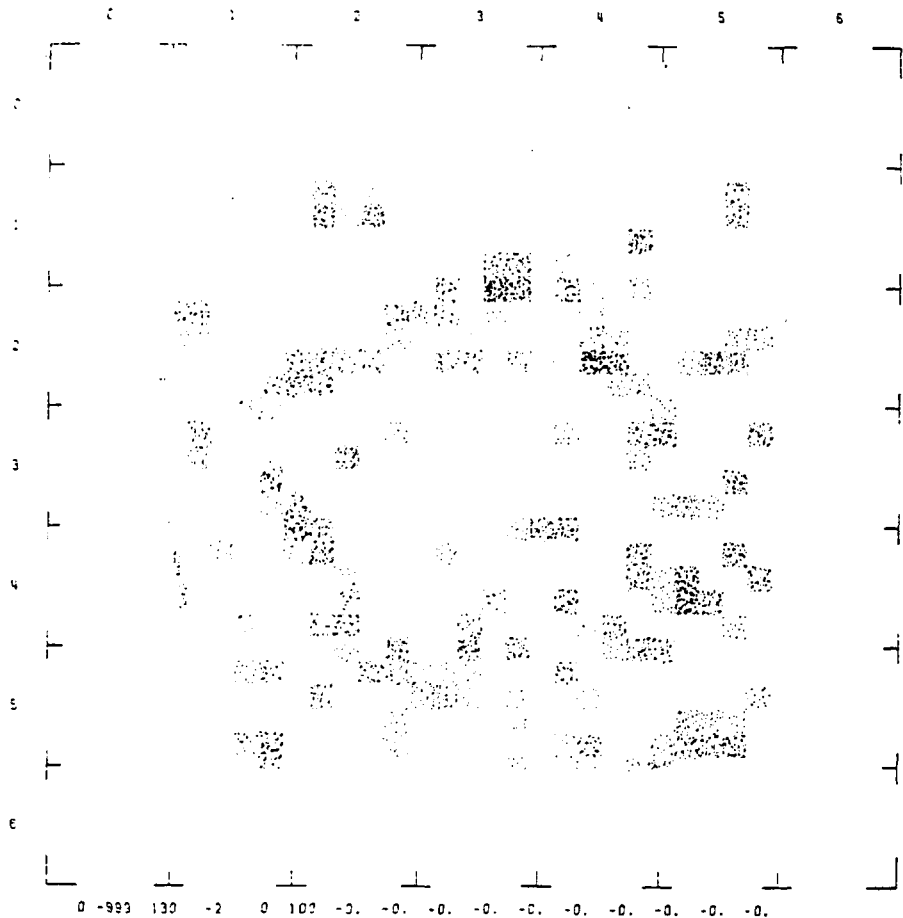
Part b. shows how false results can be obtained if the wrong part of the anomalies is considered (on the left)

whilst parts c. and d. show how a modified procedure reduces this risk whilst still giving good results in the normal case.

Fig. 4.5 The effect of non-symmetrical filtering on square linear features
(After Livingston, 1971)

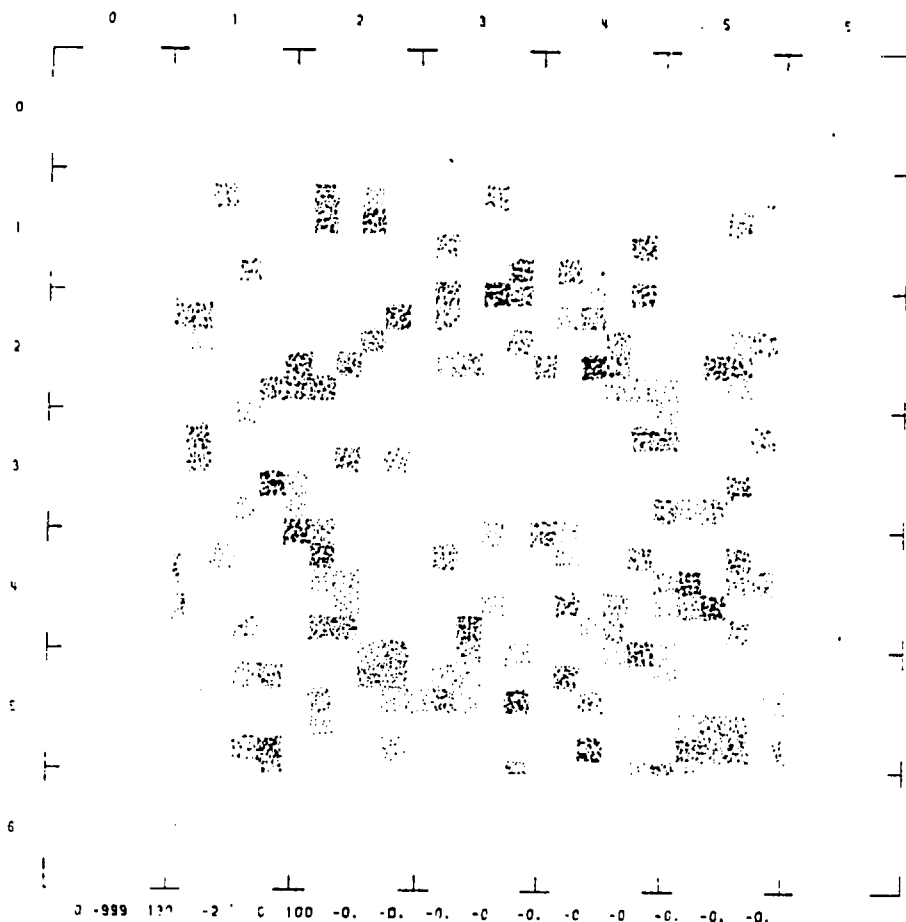


a) simulated magnetic anomaly due to a Roman fort in soil with a signal to noise ratio of 1:10, dot density plot, no filtering

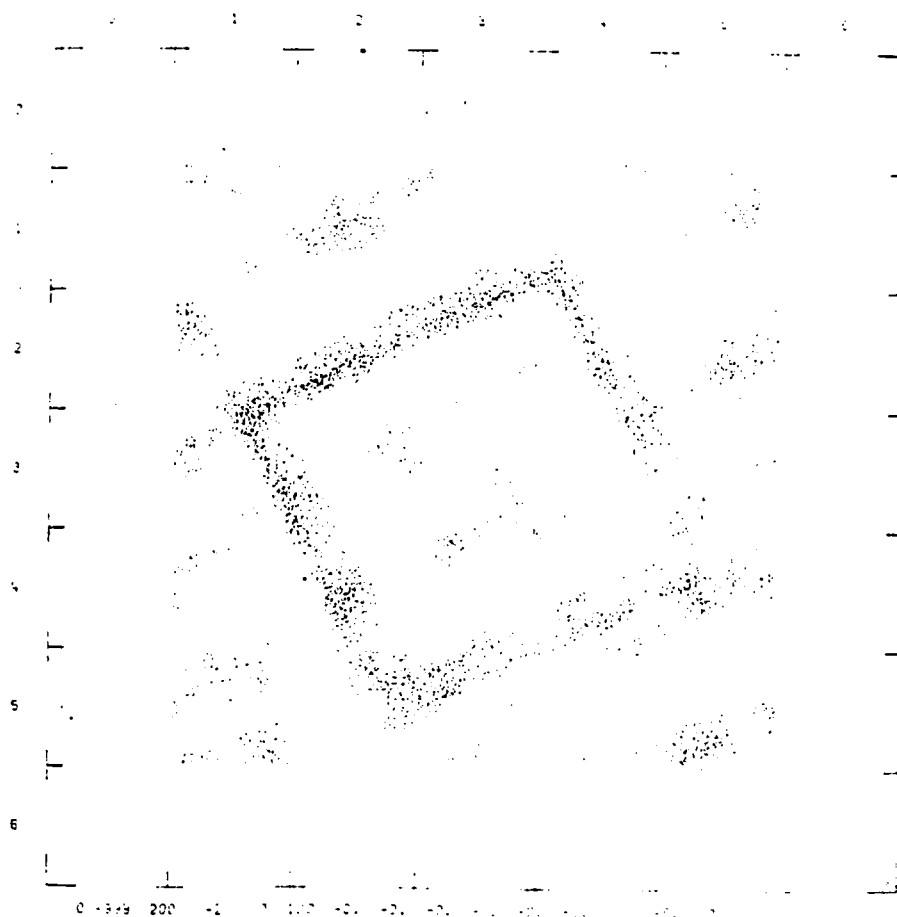


b) the data of (a) passed through a low pass filter, sequences 0-32 Walsh transform

Fig. 4.6 The effect of Haar and Walsh transforms on 2-dimensional data



c) the data of (a) passed through a low pass filter, order 32, Haar transform



d) the data of (a) passed through an optimum matched (modulus) filter, Fourier transform

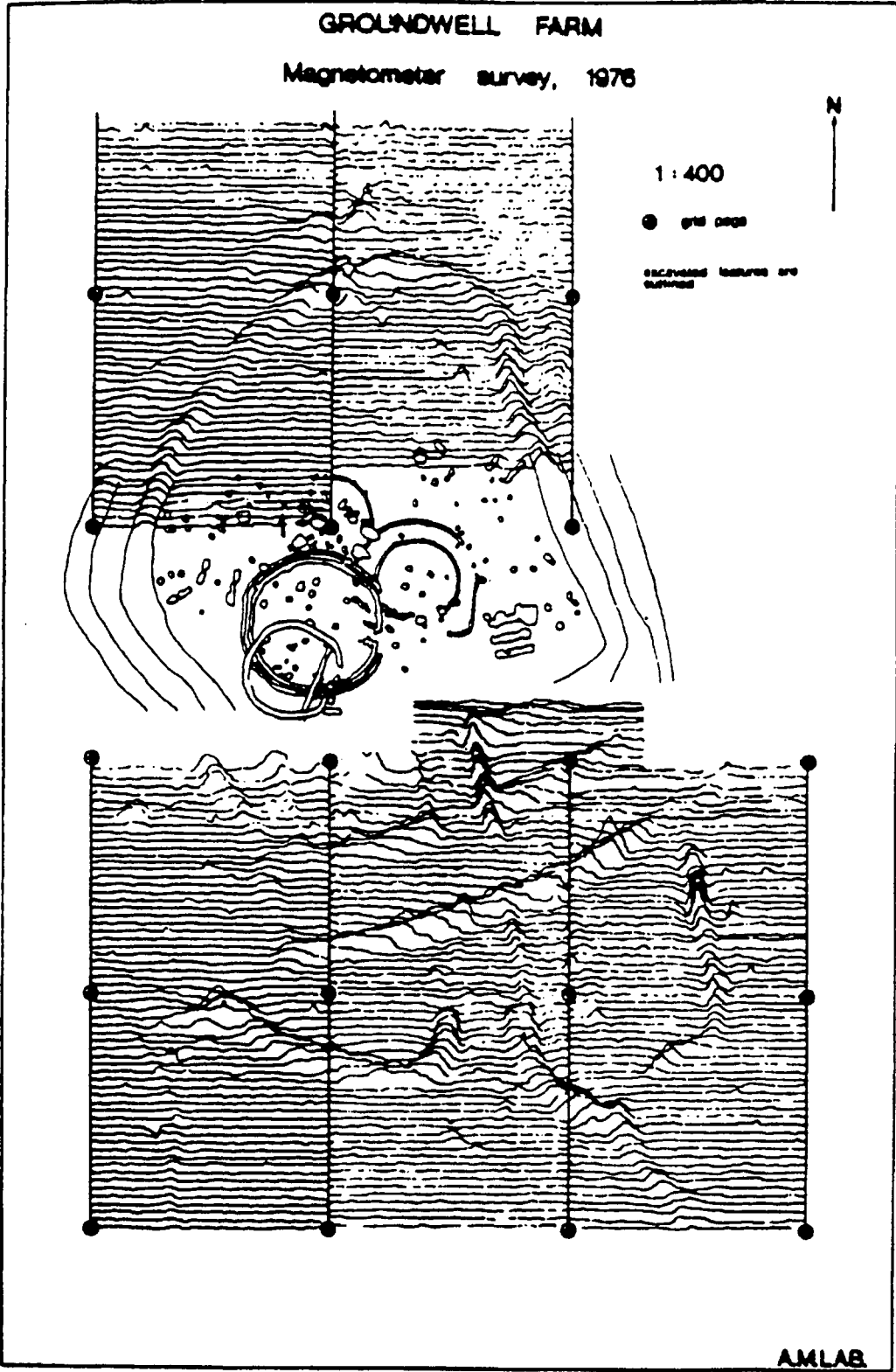


Fig. 4.7 Magnetometer survey plot of Iron Age enclosure with plan of excavated homes at Groundwell Farm, Swindon
(After Bartlett, 1979)

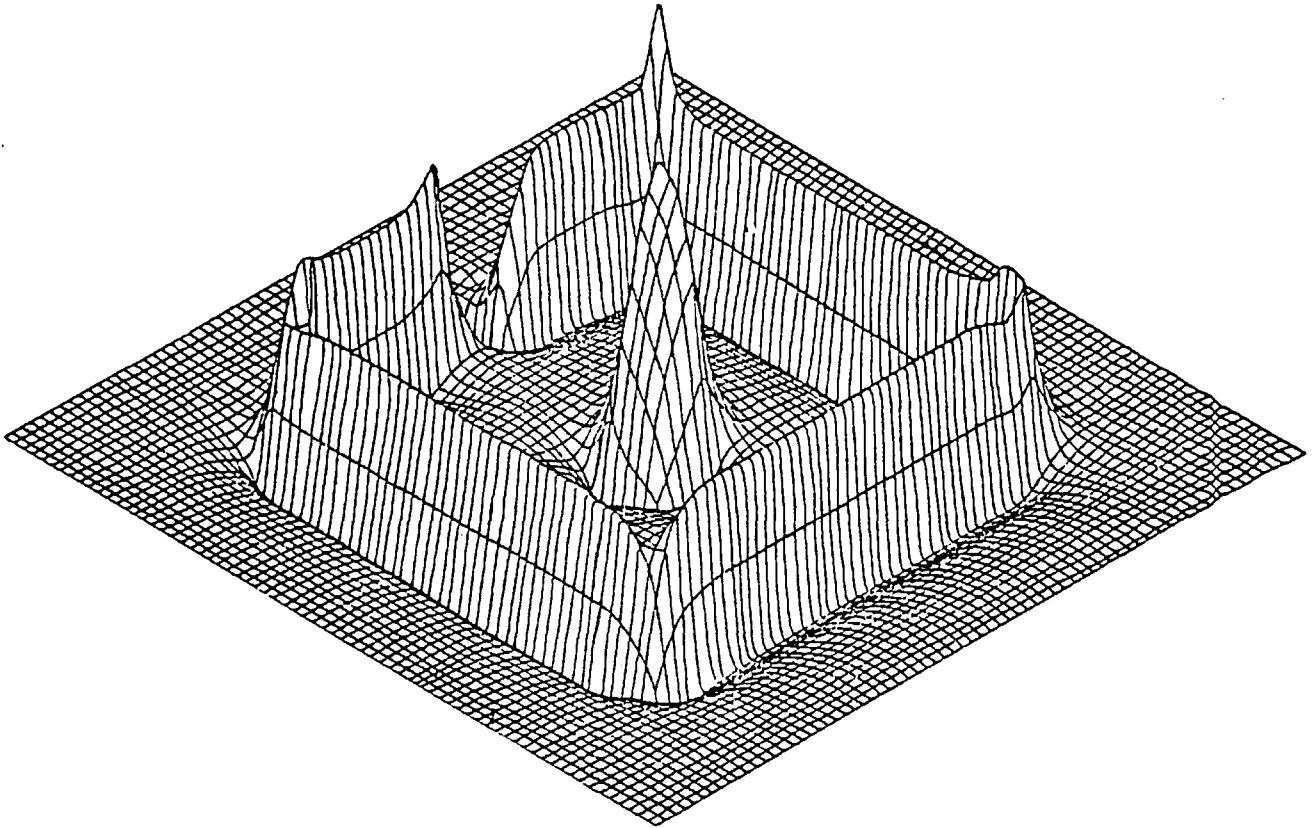


Fig. 4.8 Perspective drawing of Roman encampment
(After Livingston, 1969)

CHAPTER 5

COMPUTER IMPLEMENTATION

Introduction

The first computer programmes, specifically adapted for the analysis and display of geophysical data from archaeological sites, were introduced by Scollar (1966, 1968b, 1968c) and Linington (1968b, 1969). Since their publication very little has subsequently appeared in the literature although specific systems have been developed at Bradford University and the Geophysics Section of the Department of the Environment (Bartlett, 1979). The system described below was based on the extensive computing facilities at Imperial College. Its main aim was simplicity in operation coupled with great flexibility. Facilities to extract spacial features have been kept to a minimum with priority on the methods of display.

The Imperial College computer system has access to a very large number of programme libraries such as NAG (Numerical Algorithms Group) or CERN (Conseil Européen pour la Recherche Nucléaire). Usage has been restricted to a number of NAG routines and these are discussed where relevant.

5.1. Input of Data

Data are put onto permanent file through a time-sharing terminal using the TEXT facility. This enables the entry of data, text or programme statements without line numbers. The system recognises this as text and therefore does not process it. On exit from the TEXT mode, the command PACK results in the information being seen as one logical record. Data can be subsequently added onto a file by obtaining the relevant file and going into TEXT mode. This will automatically add the

new data to the end of the accessed file.

Readings are held in sequential binary units with the file name generated by the user. The data can either be real (floating point) or integer. When using gridded data it is important that these conform to a uniform rectangular field. If the data lines are irregular, dummy values should be added to present a complete matrix.

5.2. Data Treatment Using Specific Programmes

A number of simple programmes were developed to enable basic data correction and filtering. The following programme enables data arrays to be corrected for diurnal variation. The various parameters are entered in response to keyboard e.g. screen prompts. A complete description follows.

5.2.1. Programme Diurnal (FORTRAN IV)

1. Purpose

Programme diurnal corrects data arrays for diurnal variation and is designed for repeat readings rather than the results from a recording magnetometer base station. It assumes a linear relationship between the two reference values. These refer respectively to the reading taken at a base station prior to a survey and upon its termination. The programme therefore only applies to a period of gradual increase or decrease in the diurnal variation. One should note that this sequence need not apply e.g. a survey during the late morning and early afternoon (decrease in magnetic field strength followed by an increase). In such cases correction can be undertaken in separate phases.

2. Description

Having entered the two-dimensional data file ("filename") requiring correction as well as the relevant file dimensions, the appropriate base

station values are also keyed in. These are subtracted from each other and the scale determined by dividing the resultant value by the total number of data. A counter is then activated which is multiplied by the scale. The result is either subtracted from the accessed data value as in the case of a decrease in total field intensity or the converse when there is an increase in total field intensity. Thus

$$y = r_2 - r_1$$

$$s = y/a_k$$

if $r_2 - r_1 = > 0$ then

$$a_i = a_i - (i \times s)$$

if $r_2 - r_1 = < 0$ then

$$a_i = a_i + (i \times s)$$

where r_2 and r_1 are the base station values, s is the scale, and $a = [a_i] \quad i = 1, \dots, k$.

3. Parameters

A - two-dimensional real array (free format) of maximum
 DIMENSION 32 x 32. The values given by the subscripts should
 be altered accordingly if files exceeding the storage
 requirement are used.
 Input file.

- RNEW - two-dimensional real array (free format) of maximum DIMENSION 32 x 32. If the input file exceeds the storage requirement, the subscripts should be changed accordingly. Output file.
- FNCODE - Integer array of length 4. This contains the permanent file command GET with the relevant input TAPE. The accessed file is entered and stored under FNCODE.
- FICODE - Integer array of length 5. This contains the permanent file command SAVE with the relevant output TAPE. The corrected file is given a new file name which is stored under FICODE and saved as a permanent file. Character length must not exceed seven characters.
- MSG - Integer array of length 4. Any error messages will be contained within this array and can be looked up in Appendix B of the NOS Reference Manual.
- ICODE - INTEGER
This receives any permanent file error codes, a complete list of which is given in Appendix B of the NOS Reference Manual.
- MAXR - INTEGER
This defines the maximum number of rows of the accessed file. Programme aborts if the entered value falls outside the file length. However, blocks of files may be entered and processed.
- MAXC - INTEGER
This defines the maximum number of columns of the accessed file. Programme aborts if the entered value falls outside the file length. However, blocks of files may be entered and processed.

REF1 - REAL

The first reference value is entered and stored under REF1.

REF2 - REAL

The second reference value is entered and stored under REF2.

4. Example

→ printout - programme
 - data
 - results.

(see Appendix).

A number of filtering routines were subsequently developed to enable numerical filtering of two-dimensional data files. Simple filter options can be obtained by taking the mean of a specified configuration of data values around a central data point. A high-pass filter will be formed by subtracting the mean from the central value or alternatively on adding it to this value, the filter becomes low-pass. This filter action approximates the process of multiplying by a normalized coefficient array. The resultant precise cut-off frequency may cause ringing, which one should take into account.

These filters are known as ring residual filters. In near surface archaeological applications, high-pass filters are commonly used to distinguish linear features from general regional trends. Low-pass filtering is generally unnecessary owing to the coarse sampling interval of the survey compared to the size of the anomalies. In magnetics the emphasis will especially concern the attenuation of correlated noise whereas in resistivity the background variations need to be suppressed. The following programme was based on these specifications.

5.2.2. Programme Filter (FORTRAN IV)

1. Purpose

Programme filter represents a numerical filtering programme providing a number of filter options at either radius 1 or 2 (where applicable) and with an optional centre weighting factor (greater than 1). Any two-dimensional data file can be entered using quotation marks ("filename"). The filtered data values are assigned a new file name and saved as a permanent file.

2. Description

The numerical filters are in the form of ring residual filters (spatial filters) with the following options:

a) 4 element ring residual filter

radius 1

•	x	•	1	2	3
x	θ	x	4	5	6
•	x	•	7	8	9

radius 2

•	•	x	•	•
•	•	•	•	•
x	•	θ	•	x
•	•	•	•	•
•	•	x	•	•

x = filter values

θ = central filtered value

• = unfiltered values

High pass:

$$A_5 = \text{IWT} * R_5 - \frac{R_2 + R_4 + R_6 + R_8}{4}$$

Low pass:

$$A_5 = \text{IWT} * R_5 + \frac{R_2 + R_4 + R_6 + R_8}{4}$$

IWT = centre weighting

The same principles apply to all other filters e.g. if the filter consists of 6 elements then 6 values are used and divided by 6. Examples are restricted to high-pass filters.

b) 4 element square residual filter

radius 1

x	•	x	1	2	3
•	θ	•	4	5	6
x	•	x	7	8	9

radius 2

x	•	•	•	x
•	•	•	•	•
•	•	θ	•	•
•	•	•	•	•
x	•	•	•	x

High pass:

$$A_5 = \text{IWT} * R_5 - \frac{R_1 + R_3 + R_7 + R_9}{4}$$

c) 8 element star residual filter

radius 2

•	•	x	•	•	1	2	3	4	5
•	•	x	•	•	6	7	8	9	10
x	x	θ	x	x	11	12	13	14	15
•	•	x	•	•	16	17	18	19	20
•	•	x	•	•	21	22	23	24	25

High pass:

$$A_{13} = \text{IWT} * R_{13} - \frac{R_3 + R_8 + R_{11} + R_{12} + R_{14} + R_{15} + R_{18} + R_{23}}{8}$$

d) 6 element square residual filter

radius 1

x	x	x	1	2	3
•	θ	•	4	5	6
x	x	x	7	8	9

radius 2

x	•	x	•	x
•	•	•	•	•
•	•	θ	•	•
•	•	•	•	•
x	•	x	•	x

High pass:

$$A_5 = \text{IWT} * R_5 - \frac{R_1 + R_2 + R_3 + R_7 + R_8 + R_9}{6}$$

e) 8 element square residual filter

radius 1

x	x	x	1	2	3
x	θ	x	4	5	6
x	x	x	7	8	9

radius 2

x	•	x	•	x
•	•	•	•	•
x	•	θ	•	x
•	•	•	•	•
x	•	x	•	x

High pass:

$$A_5 = \text{IWT} * R_5 - \frac{R_1 + R_2 + R_3 + R_4 + R_6 + R_7 + R_8 + R_9}{8}$$

f) 8 element ring residual filter

radius 2

•	•	x	•	•	1	2	3	4	5
•	x	•	x	•	6	7	8	9	10
x	•	0	•	x	11	12	13	14	15
•	x	•	x	•	16	17	18	19	20
•	•	x	•	•	21	22	23	24	25

High pass:

$$A_{13} = \text{IWT} * R_{13} - \frac{R_3 + R_7 + R_9 + R_{11} + R_{15} + R_{17} + R_{19} + R_{23}}{8}$$

The convolution process will result in blank areas towards the edge of the data array. These are subsequently filled in with zeros. The use of corresponding values from the unfiltered array was discarded as this led to a spurious high anomalous zone at the edges. Therefore the filter response will be least defined at the data boundaries, with a corresponding loss in accuracy.

Each filter has been defined within an elaborate subroutine. This was done to enable the subsequent incorporation of separate filter routines in future programmes, with the more extended options provided by this programme available when required.

3. Parameters

Main routine:

- A - two-dimensional real array (the format) of maximum DIMENSION 32 x 32. The values given by the subscripts should be altered accordingly if files exceeding the storage requirement are used.
Input file.
- Z - two-dimensional real array of DIMENSION 32 x 32. The values given by the subscripts should be altered accordingly if files exceeding the storage requirement are used.
Array of filtered values.
Output file.

- NFILT - INTEGER
Filter number. This refers to the relevant filter option.
User selected.
- IWT - INTEGER
Filter weighting factor ≥ 1 . User selected.
- NRAD - INTEGER
Filter radius 1 or 2. User selected.
- MAXR - INTEGER
This defines the maximum number of rows of the accessed file.
Programme aborts if the entered value falls outside the file
length. However, blocks of files may be entered and processed.
- MAXC - INTEGER
This defines the maximum number of columns of the accessed
file. Programme aborts if the entered value falls outside the
file length.
- NPASS - INTEGER
This determines the filter response where:
 1 - high pass filter
 2 - low pass filter.
- FNCODE - Integer array of length 4. This contains the permanent file
command GET with the relevant input TAPE. The accessed file
is entered and stored under FNCODE.
- FICODE - Integer array of length 5. This contains the permanent file
command SAVE with the relevant output TAPE. The filtered file
is given a new file name which is stored under FICODE and
saved as a permanent file. Character length must not exceed
seven characters.
- MSG - Integer array of length 4. Any error messages will be
contained within this array and can be looked up in Appendix
B of the NOS Reference Manual.
- ICODE - INTEGER
This receives any permanent file error codes a complete list
of which is given in Appendix B of the NOS Reference Manual.

SUBROUTINE FILTER 1 - FILTER 6 (A, Z)

A - see above

Z - see above

4. Example

→ printout - programme

- data

- results (based on experimental data containing number of features and using dot density).

(see Appendix)

5.3. Dot Density Routine

In essence a data value is represented by a number of dots proportional to the strength of the reading. The dots are randomly orientated within a display cell producing a half-tone effect. Of importance are the number of dots used as well as their size. Too large a number of dots would increase the plotting time disproportionately whereas too few would make it difficult to saturate the plot. Resolution can be improved by interpolation but this would lead to a significant increase in plotting time.

The technique was first developed in 1966 (Scollar and Krückeberg, 1966). It enables weak linear features to be easily recognised by using the inherent spatial correlation within the data. The main problem therefore centres around small isolated anomalies which are difficult to discern against the general background. By using interactive display techniques the various parameters can be optimally defined by the user.

5.3.1. PROGRAMME DOT2 (FORTRAN IV)

1. Purpose

The main aim of the programme was to provide a comprehensive data processing and display system using basic convolution filters and a dot density display linked to a statistical plotting range. This is based on the assumption that the data values will roughly conform to a normal distribution with 95% of the readings lying within the mean ($\bar{x}$) and ± 2 standard deviations (σ) with a corresponding value of 99% within $\bar{x}$ and $\pm 3\sigma$. Anomalies will lead to skewness in the distribution, with distinct anomalies resulting in a bimodal distribution. When they lie within the mode of the distribution they may be separated through filtering depending on their inherent properties.

A histogram of the data enables an appropriate plotting range to be defined. One can also observe the effects of filtering.

All plotting is done on a visual display unit with a hard copy facility. Windowing, in which the plot fills up the entire screen, is not used. Instead, the scale has been set at 1:200 enabling a maximum plot size of 30 x 30 metres. Grids smaller than 15 x 15 metres are automatically plotted at the larger scale of 1:100. Unfortunately grids which exceed a dimension of 30 x 30 m cannot be accommodated as they fall outside the available field length of 67.000.

2. Description

Use is made of the SIMPLE (SIMulated PLottEr) package. This is a library of Fortran-callable subroutines available within the Imperial College Graphics Communication System (GCS). It enables interactive displays on terminals such as the Tektronix graphics terminals which are connected on-line to the computer system providing a direct display interface. There is, however, no facility for picture storage and any picture reconstruction must therefore be done according to user instructions. CALL START (I) performs the initialisation for SIMPLE and defines the plotting bounds, where I is the size of the plotting area. This is normalised into the physical screen size (circa 10 x 8 inches). Any information which falls outside it is automatically cut off at the boundary.

Input is entered in response to keyboard/screen requests with the data stored in two-dimensional format as a permanent file. Characters must be entered inbetween quotation marks ("...") with the CAPS/LOCK key depressed.

The appropriate file is entered with its physical dimensions (number of rows, columns).

One then has to select a filter control option, with the following filter options:

a) 4 element ring residual filter, radius 1 or 2

radius 1

•	x	•	1	2	3
x	θ	x	4	5	6
•	x	•	7	8	9

radius 2

•	•	x	•	•
•	•	•	•	•
x	•	θ	•	x
•	•	•	•	•
•	•	x	•	•

x = filter values

θ = centre filtered value

• = unfiltered values

High pass:

$$A_5 = IWT * R_5 - \frac{R_2 + R_4 + R_6 + R_8}{4}$$

Low pass:

$$A_5 = IWT * R_5 + \frac{R_2 + R_4 + R_6 + R_8}{4}$$

IWT = centre weighting, where IWT = 1 → no weighting; IWT > 1 → weighting factor.

b) 4 element square residual filter, radius 1 or 2

radius 1

x	•	x	1	2	3
•	θ	•	4	5	6
x	•	x	7	8	9

radius 2

x	•	•	•	x
•	•	•	•	•
•	•	θ	•	•
•	•	•	•	•
x	•	•	•	x

High pass:

$$A_5 = \text{IWT} * R_5 - \frac{R_1 + R_3 + R_7 + R_9}{4}$$

c) 8 element star residual filter, radius 2

radius 2

•	•	x	•	•	1	2	3	4	5
•	•	x	•	•	6	7	8	9	10
x	x	0	x	x	11	12	13	14	15
•	•	x	•	•	16	17	18	19	20
•	•	x	•	•	21	22	23	24	25

High pass:

$$A_{13} = \text{IWT} * R_{13} - \frac{R_3 + R_8 + R_{11} + R_{12} + R_{14} + R_{15} + R_{18} + R_{23}}{8}$$

On entering the appropriate filter option, radius and weighting factor, a choice has to be made between high-pass or low-pass filtering. The blank areas around the filtered array are filled in with zeros. Any negative values are altered in sign through the addition of a constant.

All the filtered/unfiltered values are subsequently added up and their mean and standard deviation determined. A histogram subroutine then constructs a frequency distribution according to routine calculated class boundary values. Twenty-five classes are used.

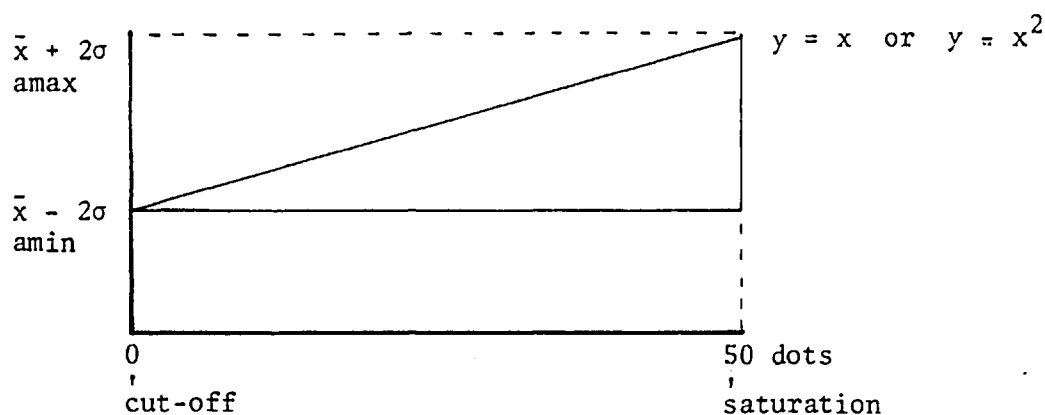
Plot annotation is provided with a plot heading of the accessed file and information concerning the data. A control option provides the choice of reprocessing the accessed file, entering a new data file or to continue processing the available data.

Plotting can either be done according to a metric or imperial scale. Basic scale is 1:100 for grids smaller than 15 x 15 m, and 1:200 for

larger grids.

The cut-off and saturation levels determine the plotting levels within the statistical distribution: $\bar{x} - 2\sigma$ to $\bar{x} + 2\sigma$. These are suggested values. A larger deviation (σ) can be used and if this falls outside the distribution the programme automatically refers to either tail end of the distribution ($x_{\min} - x_{\max}$).

The dot density process can vary according to a linear or logarithmic slope:



where $\text{range} = a_{\max} - a_{\min}$

and $\text{scale} = \frac{\text{range}}{\text{max no. of dots}}$

such that $\frac{r_1 - a_{\min}}{\text{scale}} = \text{no. of dots}$

r_1 = reading

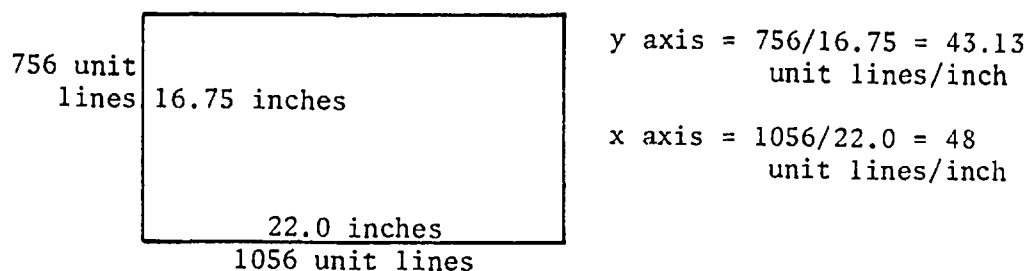
The maximum number dots depends on the plotting scale:

a) metric - 1:100 $\rightarrow$ 50 dots; 1:200 $\rightarrow$ 25 dots

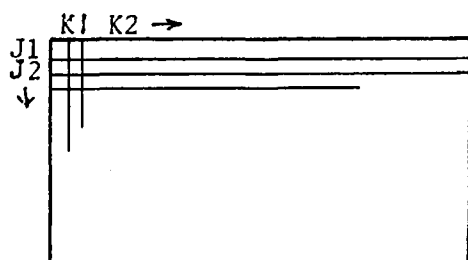
b) imperial - 40 dots

For the plotting process the maximum field of the main boundaries of the x-y coordinates is taken as 15" x 15". This conforms to a grid of 30 x 30 metres at a scale of 1:200.

Page space on the VDU has the following dimensions:



The subject space for a grid will have the following matrix field:



where the matrix reference coordinates are determined by the accessed row and column number.

Each dot is randomly orientated within the matrix using a random number generator to supply the x and y coordinates. In effect the dots are small diamonds.

As soon as each plot is finished and annotated, a number of control options are available:

- (1) reprocessing of the accessed file;
- (2) access new data file;
- (3) magnification of screen pictures;
- (4) hard copy;
- (5) termination of programme.

Option 3 (MAGNIFY) enables screen pictures to be blown up or reduced in size with the point of interest selected by the Tektronix cross-hair cursors. A picture will not immediately be regenerated at the new size as the routine only sets static display conditions. Therefore the plotting parameters will have to be reset.

3. Parameters

Main routine

- A - Two-dimensional real array (free format) of maximum DIMENSION 32 x 32
Input file.
- AFLT - Two-dimensional real array (free format) of maximum
DIMENSION 32 x 32.
Array of filtered values.
- ADOT - Two-dimensional real array (free format) of maximum
DIMENSION 32 x 32.
Plotting array containing the number of dots for each
display cell.
- XPAGE - Real array of DIMENSION 32. This contains the plotting
coordinates of the x-axis.
- YPAGE - Real array of DIMENSION 32. This contains the plotting
coordinates of the y-axis.
- MAXR - INTEGER
This defines the maximum number of rows of the accessed file.
Programme aborts if the entered value falls outside the file
length. However, blocks of files may be entered and
processed.
- MAXC - INTEGER
This defines the maximum number of columns of the accessed
array. Programme aborts if the entered value falls outside
the file length. However, blocks of files may be entered and
processed.

- NFILT - INTEGER
- Filter number. This refers to the relevant filter option.
User selected.
- NRAD - INTEGER
- Filter radius 1 or 2. User selected.
- IWT - INTEGER
- Filter weighting factor ≥ 1 . User selected.
- NPASS - INTEGER
- This determines the filter response where:
- 1 - high pass filter
 - 2 - low pass filter.
- FNAME - INTEGER
- Subroutine argument which refers to the accessed file.
- FNCODE - Integer array of length 4. This contains the permanent file command GET with the relevant input TAPE. The accessed file is entered and stored under FNCODE.
- MSG - Integer array of length 4. Any error message will be contained within this array and can be looked up in Appendix B of the NOS Reference Manual.
- ICODE - INTEGER
- This receives any permanent file error codes a complete list of which is given in Appendix B of the NOS Reference Manual.
- NDOTL - INTEGER
- Maximum number of dots.

CUT - REAL

On entry, CUT specifies the cut-off level of the plot. If it falls outside the statistical distribution the programme automatically accesses XMIN for normal plots and XMAX for reverse plots.

SAT - REAL

On entry, SAT specifies the saturation level of the plot. If it falls outside the statistical distribution, the programme automatically accesses XMAX for normal plots and XMIN for reverse plots.

SUBROUTINE FILTER 1 (A, Z)

A - see above

Z - two-dimensional real or integer array (free format) of maximum DIMENSION 32 x 32. Array of filtered values.
Changes on exit to become array AFLT.

SUBROUTINE FILTER 2 (A, Z)

A - see above

Z - see above

SUBROUTINE FILTER 3 (A, Z)

A - see above

Z - see above

SUBROUTINE L HIST (FNAME, AFLT, AVE, SD, XMAX, XMIN)

FNAME - see above

AFLT - see above

AVE - REAL

The mean of the filtered or unfiltered array, depending on the chosen filtering control option.

SD - REAL

The standard deviation of the filtered or unfiltered array, depending on the chosen filtering control option.

XMAX - REAL

This is the largest value in the array x.

XMIN - REAL

This is the smallest value in the array x.

X - Real array of DIMENSION 1024. This provides the values of the variable for which the frequency distribution is required.

CINT - Real array of DIMENSION 25. The routine calculates class boundary values which are contained within CINT in ascending order.

YIFREQ - Real array of DIMENSION 25. This contains the frequencies in each class.

SUBROUTINE ANNOT (FNAME)

FNAME - see above.

4. Example

→ printout - programme

- data

- results (based on experimental array containing number of features).

(see Appendix)

5. Auxiliary Routines

This programme calls the following NAG library routines:

- a) G05CCF - this yields different subsequent sequences of random numbers based on calculations from the setting of a real-time clock.
- b) G01AEF - this constructs a frequency distribution of a variable according to routine calculated class boundary values.

5.4. Graphics Software

The Imperial College computer system has extensive facilities and a library of supporting routines for the production of graphical output.

Use was made of MATMAP. This is an interactive graphics package which enables graphical representation of matrices. It has the following options (ICCC Bulletin 6.3/8):

- a) HIDE - this provides a picture of a set of plane parallel sections through a surface from various viewpoints. Hidden lines are removed.
- b) BLOCK - this draws a picture consisting of each successive traverse running parallel to the x-axis with the removal of hidden lines. The picture may be viewed from various angles.
- c) CONTR - a contour diagram is constructed using an interpolation algorithm. The contours are regularly spaced from an initial level, usually the minimum value in the matrix plus half the interval between successive contours.
- d) MPLT - a set of traverses are drawn parallel to the x-axis with another set running parallel to the y-axis resulting in a facet plot. Hidden lines are removed.
- e) TMAP - This constructs a tonal map produced by a combination of various characters. There is a maximum of 10 shades.

Most of these routines have been applied where relevant.

A small programme was written to present a suitable data file in binary format to the package.

5.4.1. PROGRAMME HIDE (FORTRAN IV)

1. Purpose

Programme HIDE constructs a data file in binary format on TAPE60. It has the option to write a single data file or a sequence of data files onto the tape. Each file must contain an identification number which is entered in response to a keyboard e.g. screen command.

2. Description

The interactive graphics package MATMAP (ICCC Bulletin, 6.3/8) requires a data file in binary format on TAPE60. This will consist of a file identification number, the number of rows and the number of columns of the data file, followed by a real array containing the relevant data. TAPE60 will be a local file which can be subsequently saved as a permanent file.

The appropriate two-dimensional data file is entered inbetween quotation marks ("filename") in response to the keyboard request FILENAME. At the end of the programme sequence a process control option enables additional files to be processed.

MATMAP itself is controlled by a series of keyboard commands outlined in the abovementioned bulletin.

3. Parameters

XMAT - Two-dimensional real array (free format) of maximum
 DIMENSION 32 x 32. The values given by the subscripts
 should be altered accordingly if files exceeding the storage
 requirement are used.
 Input and output file.

- FNCODE - Integer array of length 4. This contains the permanent file command GET with the relevant input TAPE. The accessed file is entered and stored under FNCODE.
- MSG - Integer array of length 4. Any error messages will be contained within this array and can be looked up in Appendix B of the NOS Reference Manual.
- ICODE - INTEGER
Any permanent file errors are defined within ICODE. A complete list of error codes can be found in Appendix B of the NOS Reference Manual.
- NROW - INTEGER
Number of rows of the accessed file.
- NCOL - INTEGER
Number of columns of the accessed file.
- ID - INTEGER
File identification number. User defined.

4. Example

- printout - programme
- data
- results.

(see Appendix)

5.5. Field Calculations

A number of programmes were developed to enable basic calculations in the field using a Texas Instruments TI 58 or 59 programmable calculator. Both units are very similar, only differing by the following:

TI 58	TI 59	Available registers
up to 60	up to 100	data storage
up to 480	up to 960	programme storage
NO	YES	reads and writes magnetic cards

An outline of the various programmes is given in the appendix.

CHAPTER 6

FIELD SURVEYS

6.1. Previous Work

Very little work has been done into the effectiveness of geophysical prospection on archaeological sites in the Middle East. One of the first publications was by Hesse (1967), in which he outlined the problems in detecting walled structures covered by sand at the site of Mirgissa in the Nubian desert. He found a marked susceptibility contrast between the weakly magnetic sand and the highly magnetic coarse bricks used as construction material:

Material	Mass suscept. $\times 10^{-6}$ emu CGS
Eocene sand (3 samples)	3 - 6 - 20
coarse brick, mortar (4 samples)	295 - 254 - 240 - 100
clay and Nile sand (3 samples)	375 - 375 - 100

Very satisfactory results were obtained with a proton magnetometer.

Electrical resistivity measurements suffered severely from probe contact problems. Results were difficult to reproduce owing to electrostatic and ionic effects and the influence of wind on the conductors according to the author. He did not specify what sort of effects (effect on wires? impedance of meter?). The resistivity of dry sand was estimated between 1.000 and 100.000 Ωm . Fortunately, there was an abundant source of water in the vicinity in the form of the river Nile. To enable proper current flow, use was made of perforated tins filled with sand instead of metal stakes. These were copiously watered.

Test results were plotted for the variation of current intensity after watering for a number of different sediments and water solutions (Fig. 6.1).

These suggest that measurements can be taken quite some time after prior watering of a site. Watering increases the area of effective probe contact as well as aiding ionic conduction, although the latter only provides minimal current development as attested by the results when using a copper sulphate solution. In a later work, Hesse (1973) described the results from geophysical surveys on a number of archaeological sites in Israel. He used magnetometry for the detection of tombs cut into limestone and covered with a superficial and strongly magnetic soil. The tombs therefore gave a low magnetic response. Overall the main problem concerned natural irregularities in the underlying bedrock which produced spurious anomalies.

Resistivity was applied to the detection of habitation sites where the walls were constructed from limestone rocks. Although probe contact problems affected the readings, the large contrast in resistivity between the stone walls and the surrounding soil enabled successful results. Most of the current passed through the superficial soil layers, which limited the depth penetration to shallow features.

Overall the results pointed favourably to the use of geophysical exploration in the region. This was further emphasised by subsequent surveys of the Mount of the Temple, Jerusalem, and at Tel Aphek near Tel Aviv (Ginzburg and Levanon, 1976). Direct current resistivity was used with the aid of special leak-proof porous pots as electrodes. The thickness of the south wall of the Mount of the Temple was determined and the pre-Herodian city walls were successfully located, employing the Wenner continuous depth profiling technique. Their construction material consisted of limestone and dolomite with an alluvial cover. At Tel Aphek the buried Bronze Age city wall surrounding the site was mapped.

Geophysics has also been applied to a number of archaeological sites in Turkey. Most notable perhaps is the work undertaken by Yaramanci (1970, 1971). Unfortunately, little detail is provided of the geological

background. Measurements were primarily restricted to the continuous current resistivity technique using the Wenner configuration.. Apart from taking resistivity profiles at different probe separations and drawing the horizontal potential gradient ratio curves, the geophysical project stands out as being one of the first attempts at locating archaeological features on large artificial mounds or tells. These form a very heterogenous structure consisting of the accumulated remains of ancient settlements built up over a period of hundreds or thousands of years. Determining a clear geophysical stratigraphy of such a mound, where the cultural remains blend into each other, is virtually impossible. The electrical characteristics of archaeological field remains, eg. original soil, cultivated soil, mudbrick structures and stone structures were established at the site of Norsun Tepe, based on electrical profiles correlated with excavation results. This seems rather a dubious process when one is dealing with such a complex geophysical site as an artificial mound. Unfortunately, the author does not provide any detailed evidence. Use is made of second derivative, relaxation and frequency analysis (numerical filtration) for the data interpretation. An interesting result was the possibility of determining that the resistivity of calcareous stones, used for construction material was higher than the resistivity of natural calcareous stones forming the mound (at Marcaba). This led to the conclusion that the construction material had been imported.

In North Africa, one of the few published near surface geophysical surveys was at Carthage in Tunis (Iciek et al, 1974). Resistivity was the main technique used with additional results from a nuclear magnetometer and a gravity meter. The survey almost entirely concentrated on the detection of stone walls and with great success (Fig. 6.2).

Electrical soundings were applied to ascertain the depth of the wall foundations and the thickness of the archaeological layer. Unfortunately, this was made impossible by the very high salt-water table as the site was

situated next to the sea. The gravity meter was used to check a strong resistivity anomaly. Its results suggested an underground cistern or passage.

Overall, the survey met with success. Unfortunately, very little mention was made of the working conditions.

6.2. Field Surveys

6.2.1. Tel Lachish, Israel

1. Introduction

Tel Lachish is the second largest Tel (settlement mound) in Israel, and was one of the most important cities of the Biblical era. It is situated southwest of Jerusalem in the vicinity of Kiryat Gat. The occupation levels date back to the 4th millenium B.C. and beyond.(Site plan)

A series of geophysical surveys were undertaken at the request of Professor D. Ussishkin, who is connected to the Archaeology Department at Tel Aviv University. The Tel encompasses a large number of occupation layers. This is amongst others evidenced by the abundance of walled structures on the mound. Any geophysical stratigraphy is further complicated by the frequent destruction of the site during its past history and the evidence of robbing.

The main aim of the various surveys was the detection of stone walls making resistivity surveying the most suitable technique. A prototype Martin-Clark series 4 resistivity meter was used for the measurements. Its power supply had been increased to 12 V enabling a higher voltage output. All traverses used the Wenner and Dipole Dipole configuration with a fixed spacing between the metal probes. All values have been multiplied by 10 to increase the contrast. Owing to the extreme hardness of the soil, the probes had to be individually hammered into the ground, a tedious and time consuming business. The scarcity of water precluded any watering of the

probes to facilitate current flow.

2. Surveys

a) Area A: Triple Gate

Outline

To determine the possible use of resistivity on the Tel, a number of traverses were laid out over the unexcavated part of the Triple Gate (Diagram A1) by analogy with excavated areas possibly containing large masonry gate footings. The area was rather uneven with large surface boulders near the city wall. Differing probe spacings were tried ranging from 1 - 2 m, depending on the probable height of the terrain above the feature of interest.

Analysis

Reproduced (Diagram A2) are the results from traverse t_1 and t_2 , both clearly indicating a positive response to the buried walls. Their in situ position has been drawn in the diagram. Best results are obtained with an electrode separation of 1 m as in t_1 . The DD response provides a single intermediate peak with a smaller adjacent peak, the latter probably caused by the large width of the wall (2 m) relative to the small electrode spacing ($a = 1$ m). Notable are the very low resistivity values ranging from 5 - 16 Ω for the DD configuration and from 16 - 29 Ω for Wenner. In t_2 the response is less positive with a fall-off in contrast mainly as a result of the increased probe spacing ($a = 1.5$ m).

Positional accuracy of the peaks has also been reduced. Traverse t_3 and t_4 are shown in diagram A3. Readings were taken at $a = 1.5$ and $a = 2$ m owing to the increased depth of overburden.

The response is far from satisfactory. This may be caused by most of the current being conducted within the uppermost soil layer owing to its ^{41c} very low resistivity ^{and} (down to 1.2 Ω !).

Conclusion

The survey provided satisfactory results for the continued use of resistivity with the emphasis on small probe spacings and minimum depth of overburden.

b) Area B:

Outline

The aim of the survey was to determine the continuation of a stone wall partially visible on the surface. Its suggested position, based on archaeological deduction, has been indicated in the diagram (B1).

To test the efficacy of this deduction, a number of traverses were laid out over the area of interest. Traverses tx1 (Diagram B2) and tx2 gave a positive response in locating the buried part of the main wall (number 2 in the diagram), an adjacent wall (number 1 in the diagram) as well as a large number of additional structures (walls numbered 3 - 8).

A grid was then laid out over the suggested trajectory of the wall. The first three traverses (12 m length) were situated on uneven terrain next to a steep bank. Traverse spacing was kept at 1 m. T_4 was placed on top of the bank running parallel to t_3 at a distance of 2 m. Its length and that of subsequent traverses was extended to 16 m. A traverse separation of 1 m again applies.

Various probe spacings were used: 0.75 and 1 m in the northern part of the surveyed area (3 x 12 m) and 1 m, 1.5 m (only t_4) and 2 m in the southern much higher part of the site (6 x 16 m).

Analysis

The results using a probe spacing of $a = 0.75$ m are shown in diagram B3.

Wenner provides the best results with the relevant walls and oddly enough shown as single peaks corresponding with their suggested in situ location.

The resolution at $a = 1.5$ m and $a = 2$ m was found to be extremely

poor as evidenced by the profiles from diagram B4.

It was therefore decided to apply dot density to the far more promising results obtained with the 1 m probe spacing.

The histogram of the Wenner readings indicated an overall variation from 0 to 17 ohms. For the Dipole Dipole configuration the range was from 0 to 6.8 ohms. The plots shown are centred around the DD results as these are the least ambiguous to interpret. Only when the Wenner plot indicates a significant digression from the DD interpretation will it have been included.

Plot B1: DD results at $a = 1$ m. All the values ranging from the mean ($\bar{x}$) to the mean plus 2 standard deviations (2σ) have been plotted as a dot density in which the density of dots is logarithmically proportional to the reading. This places the emphasis on anomalies with a high resistivity, a number of which can be distinguished. Some tenuous suggestions have been outlined in red. The main wall section (wall no. 2 in diagram B2) and its counterpart (wall no. 1 in diagram B2) are features no. 1 and 2 in this plot. They are seen slightly fused at first, the probe configuration not enabling the spatial resolution of the Wenner array. The improved depth response of the DD configuration can be seen in the occurrence of feature no. 3 which is not visible in the identical Wenner plot. Entry and exit point of the main wall of interest, as proposed in diagram B1, have been marked by an asterisk.

It could be suggested that walls no. 2 and 3 interconnect with the wall section running east to west and possibly transecting the grid. This is unlikely owing to the wrong angle of strike of the incoming walls relative to the E-W wall section, as determined from diagram B1. It must also be remembered that the

southern section of the grid (6 x 16 m) lies on a raised bank approximately 1.25 to 1.5 m above the lower part of the grid (4 x 12 m). Previous results have indicated the poor resolution at depth. This suggests that the sought-after wall section (no. 2) cannot be detected and we are instead dealing with a series of structures constructed at a later date above walls no. 1, 2 and possibly 3.

Plot B2: The DD results have been filtered using a high pass square residual filter, radius 1. This will emphasize linear features narrower than the filter. Plotting parameters are identical to the previous plot. Filtering has greatly improved the clarity of the plot, with a number of wall sections clearly visible. These have been outlined. Entry and exit points of wall no. 1 and 2 as based on diagram B1 have again been indicated. Both walls can be seen entering the plot but there is no evidence to suggest their continuation. This does not, however, discount the possibility. Unfortunately, the data resolution is at its worst at the southern end of the grid making any such interpretation impossible.

Traverse t_{11} was situated at the proposed exit point outside the grid. Readings were taken using a probe spacing of 1 m and 1.5 m. The results were inconclusive.

Conclusion

The number of features appearing in the plots indicates the complexity of the survey. Part of the wall extension (Diagram B1) seems to be in evidence. Any inference as to its suggested outline towards the west would be very tenuous owing to the poor depth penetration. The main part of any evidence would also have been based on the actual corner of the wall which

should occur to the extreme south of the grid. This is exactly where the data resolution is poorest.

c) Area C:

Outline

Traverses were positioned to determine the actual location of two walls possibly forming part of a building. Their suggested outline, based on archaeological deduction, has been indicated in diagram C1.

Probe spacings of 0.75 m and 1 m were used.

Analysis

First both Wenner and Dipole Dipole readings were plotted in the form of graphs. These are shown in diagrams C2 - C5.

The fall-off in response with increased probe spacing can be clearly seen. A large number of features become apparent with the smallest probe spacing ($a = 0.75$ m) giving the best results. Traverse t_9 was repeated in order to ascertain the reliability of the readings. Both Wenner and Dipole Dipole were fairly similar with the latter providing the best correlation.

For computing convenience, the results from the individual traverses were plotted side by side. It should be emphasized that this introduces no interaction between the data from any previous traverses. Anomalies shown by this treatment were then transplanted to their correct positions on the plan (Diagram C6).

Plotted side by side using dot density gave the following results. The histogram of the Wenner readings indicated a range from 0 to 36.5 ohms at a probe spacing of $a = 0.75$ m. For the DD array the corresponding variation was between 1.5 to 16.4 ohms.

Plot 1C: DD results at $a = 0.75$ m. All the values ranging from the mean ($\bar{x}$) to $\bar{x} + 2 \sigma$ have been logarithmically plotted. Areas of medium to high density are most likely to conform to existing

wall structures.

Both Wenner and Dipole Dipole plots have been compared with the graphs of the readings (Diagrams C2 - C5) and the results have been collated in diagram C6.

The results were also plotted using a high-pass square residual filter, radius 1, in order to demonstrate the danger of applying filtering to otherwise unconnected data (not included).

Conclusion

The suggested position of possible walls in diagram C6 does not entirely conform to the archaeological deduction. Further traverses could be made based on the outline provided in the diagram, followed by trial excavation.

d) Area D: City Wall

Outline

The position of the City Wall of Tel Lachish around the actual mound is not exactly known. It was thought that resistivity could provide a means of determining its location.

A small part of the City Wall is visible - in a varying state of preservation - on the surface. Excavation has indicated that the wall consists of a combination of primarily two walls constructed at different dates (see cross section in diagram D1). The Judean City Wall was destroyed by Sennacherib and the Assyrian army in 701 B.C. On top of this rests the later Judean City Wall destroyed by Nebuchadnezzar and the Babylonian army in 528-6 B.C. These walls are, however, not necessarily superimposed along their length and may fork and run in different directions. Construction materials are stone and mudbrick.

Analysis

To determine the feasibility of using resistivity, traverse t_1 was situated next to an excavated section of the City Wall(s) (Diagram D1).

Probe spacings of 1 m and 1.25 m were used. The results have been plotted and are shown in diagram D2.

All the profiles indicate a positive response to the City Wall(s) with the smaller probe spacing ($a = 1$ m) providing the best results.

Further traverses were placed radially from the top of the mound to interact with the presumed location of the City Wall(s) (Diagram D1).

Diagram D3 gives the results.

The various profiles are rather complex and show a number of features. These can, however, not be directly associated with the City Wall(s) as the distance between the individual traverses is too great.

Conclusion

It is suggested that, bearing in mind the ambiguities arising from the existence of towers situated at intervals along the City Wall(s), increased depth of overburden, divergences of walls away from the searched area etc., a future intense survey should be done at 1 m intervals. This survey should start from a known section of the City Wall(s) and gradually follow it along.

6.2.2. Lachish Cemetery (7000), Israel

1. Introduction

The Bronze Age burial site of Lachish lies at the foot of Tel Lachish and served as a cemetery for its inhabitants. The graves are situated in an area of locene limestone overlain by a terrace of alluvial clay in which horizons of gravel and pebble occur.

It was hoped that a geophysical survey would find the approximate positions of the graves and any associated metal grave goods. A varied number of surveying techniques were applied in many ways complementing each other, enabling one to ascertain the usefulness of any one technique under the prevailing conditions. It also allowed a reasonable interpretation of the area under survey and could prevent undue reliance on any one technique alone.

Approximately one year prior to the survey, part of the cemetery was exposed by the removal of substantial amounts of topsoil. In certain areas this had been done to a depth of 1.25 m. The areas least disturbed by bulldozer activity were surveyed (see site plan).

2. Surveys

a) Resistivity surveys

Outline

The results are based on readings taken on a grid with a measurement and traverse spacing of 1 m. A Martin-Clark Series 4 resistivity meter was used. Its power supply had been increased to 12 V, enabling a higher voltage output. The metal probes had to be hammered into the ground owing to the extreme hardness of the uppermost clayey alluvium soil layer. No water was available to enable probe watering. In order to allow for variations caused by the gradual drying-out of the soil during the day, control measurements were taken for a limited period, at hourly intervals, at a base station set up in a corner of Area A. No major resistivity

fluctuations were established: <1% for Wenner, <3% for Dipole dipole. Data correction was therefore not found necessary.

Both Wenner and Dipole Dipole probe configurations were used. All values have been multiplied by 10 to increase the contrast.

Analysis

(1) Area A (20 x 27 m)

The histogram of the DD results indicated an exceedingly small contrast with values ranging from 0 to 2.4 ohms. If one may assume that the grave fill is more moisture retentive than the surrounding medium, any graves will be found at the lower end of the distribution. The low resistivity area was found to be fairly well spread out. For Wenner the range was from 1.3 to 5.1 ohms.

Plot 1A: DD readings for a probe spacing of $a = 1$ m. These have been linearly plotted within the range $\bar{x} - 2\sigma$ to $\bar{x} + 2\sigma$. The high resistivity areas are probably associated with geological variations caused by small pockets of gravel. This has been partially confirmed by a trial pit.

Plot 2A: Filtered DD readings at $a = 1$ m, using a high pass ring residual filter, radius 1 and a range from $\bar{x} - 0.75\sigma$ to $\bar{x} - 2\sigma$. The plot is a negative one with a density logarithmically proportional to the reading. Therefore the lower the value the greater the density. The filter emphasizes circular features smaller than the filter radius.

A large number of possible graves can be seen and have been outlined in red. It would appear that most graves are relatively small and shallow. Anomalies 1 to 6 were subsequently excavated and confirmed this.

A low pass ring residual filter, radius 1, was also applied. It focussed on areas of low resistivity as opposed to individual features indicating that the anomaly detail lies in the high frequency range.

(2) Area A extension (10 x 13 m)

The extension grid was placed 4 m inwards from the main grid (Area A) because of road debris and associated soil disturbance.

The DD results at $a = 1$ m gave a variation from 0 to 1.6 ohms. For Wenner the range was from 0 to 4.5 ohms.

Plot 1B: Negative logarithmic plot of the filtered DD readings using a probe spacing of $a = 1$ m and a high pass ring residual filter, radius 1. The range has been taken from $\bar{x} - 0.75 \sigma$ to $\bar{x} - 2 \sigma$. A number of low resistivity anomalies can be seen and have been outlined.

If we make the same assumptions as we did for Area A, then these anomalies are almost definitely graves with the exception of those numbered A to F. These are caused by the filter producing spuriae at the boundary interface between data and zero blank fill-in values for the slope.

Features no. 1 and 2 were excavated and found to be graves, confirming the interpretation.

(3) Area B (10 x 20 m)

This area sloped off to various directions (see site plan). Increased water run-off with concomitant lower resistivity could be expected near some of the slopes. The histogram of the DD results gave a range from 0 to 3.4 ohms for the 1 m probe spacing. For Wenner the corresponding variation was from 0 to 8.4 ohms.

Plot 1C: DD results at $a = 1 \text{ m}$, within the range $\bar{x} - 2 \sigma$ to $\bar{x} + 2 \sigma$. The density is linearly proportional to the reading. Overall the dot distribution is fairly uniform with no indication of archaeologically interesting anomalies, as substantiated by subsequent plots.

Features 1 and 2 are in effect areas of high resistivity which fall outside the plotting range. The area of zero density near the northern slope confirms the suggestion of increased water run-off leading to low resistivity values.

Conclusion

Resistivity appears to have been successful in the context of the difficult nature of the site. A large number of possible graves have been found in Area A and in the extension to Area A. Many of these have been verified by subsequent excavation suggesting that any further archaeological work should concentrate on the remaining anomalies.

b) Magnetometer surveys

Outline

Soil samples were taken and their susceptibility measured.

Sample code	50 g $\times 10^{-6}$ emu gm	100 g $\times 10^{-6}$ emu gm	Comments
S106	80	154	Mudbrick lining Grave 2 Area A
S107	76	155	Soil on surface near Grave 2 Area A
S108	62	118	Clay soil on site, Area A
S109	49	112	Soil from the bottom of Grave 2 ($\pm 1 \text{ m}$ depth)

Reading repetition: $\pm 5\%$ error.

The results indicate a sufficient difference in magnetic susceptibility between subsoil and topsoil to allow detection of anomalies using a magnetometer.

No appreciable susceptibility contrast is evident between the supposed mudbrick and the surrounding soil. It was hoped that any mudbrick on site would also be detectable, as the material itself forms one of the most important building materials in Middle Eastern archaeology.

An Elsec 592 proton magnetometer was used throughout the survey. Readings are inversely proportional to the measured field strength, and after calculation can be related in gamma:

$$\text{eg. field in } \gamma = \frac{24051}{N} \quad (\text{related to switch position})$$

where N is the value obtained with the magnetometer. Instrument sensitivity approximates 1 γ .

Measurements were taken along traverses 1 m apart and at 1 m intervals with the detector head held 30 cm above the ground.

At the end of each traverse, a control reading was taken at a base station to enable correction for diurnal variation. Areas A and B were surveyed (see site plan). Approximately 10 cm of topsoil had been removed from Area A by previous bulldozer activity.

Analysis

(1) Area A (20 x 27 m)

A certain amount of ferrous metal debris on the surface had a slight masking effect on the results. This was aggravated by two large metal stakes driven into the ground in the vicinity of the areas near the benchmark indicated as anomalies by resistivity.

The histogram gave a range from 0 to 92 γ , with most of the definition at the lower end of the distribution.

Plot 1D: Facet plot of the entire distribution. A ditch-like structure (A) with an adjacent bank (B) can be seen running through the plot.

Plot 2D: Linear plot with a range from $\bar{x} - 2\sigma$ to $\bar{x} + 2\sigma$. The linear feature from the previous plot clearly stands out. This could possibly represent a wall (mudbrick). A similarly intriguing curvilinear feature can also be seen running through the plot (ditch?). Features no. 1 and 2 are caused by metal stakes driven into the soil.

Plot 3D: Linear plot with a range from $\bar{x} - 0.25\sigma$ to $\bar{x} + 1.25\sigma$. The plot emphasizes the central linear feature and the adjacent structure as well as the curvilinear anomaly.

Plot 4D: Negative logarithmic plot of the filtered values upon application of a high pass ring residual filter, radius 1, and within the range $\bar{x} - 0.75\sigma$ to $\bar{x} - 2\sigma$. A number of small positive anomalies can be seen. Features numbered 1 to 4 correspond to the location of excavated graves, throwing some credence on the results.

(2) Area B (10 x 20 cm)

The relevant histogram gave a range from 82 to 316 γ with the upper tail end distorted by spurious high readings.

Plot 1E: Linear plot within the range $\bar{x} - 2\sigma$ to $\bar{x} + 2\sigma$. The plot appears to be fairly uniform with no indication of interesting anomalies. Additional filtering confirmed this.

Conclusion

A number of features of possible archaeological significance appear in Area A. Excavation of a small anomalous area seems advised. No clear association can be made with the results obtained with resistivity. This could possibly be caused by mudbricks on the site having a slightly higher magnetic susceptibility masking any anomalies.

Area B does not indicate any features of interest confirming the resistivity results.

c) Electromagnetic survey

Outline

The use of a metal detector seemed justified by the nature of the site. A Bronze Age cemetery could well have metal artifacts associated with the graves. Furthermore, the removal of part of the topsoil would increase the prospects of successful detection because of the shallow penetration of the instrument.

Use was made of an Arado IBA 45 impedance balance metal detector. It could in theory distinguish between ferrous and non-ferrous metals. In practice the method of differentiation proved doubtful and was therefore mainly avoided.

Only Area A was surveyed owing to premature instrument failure. The metal detector was slowly scanned across the ground in 1 m traverses and any anomalies were marked on a site plan (see diagram L1).

Analysis

(1) Area A (20 x 27 m)

The instrument response from the surveyed area was rather 'noisy', increased response sometimes corresponding to areas of visible graves (not marked on the diagram). Most of the metal appearing near the road running to the west of the site is probably road debris.

The resistivity anomalies (outlined in red), derived from plot 3A (DD results), have been superimposed on the metal detector results for comparison.

Conclusion

Three possible conclusions arise:

- 1) the graves near the benchmark have metal grave goods (as partly evidenced by excavation); overall the graves lack metal artifacts.
- 2) the possible grave sites as determined by resistivity are false (excavation has conceded otherwise).
- 3) the mudbrick in evidence on site produced an instrument response obscuring that of small metal grave goods.

d) Phosphate analysis (Schwarz method)

Outline

Human and animal detritus in the form of rubbish, dead bodies etc. ^{and persists} is gradually taken into the soil as inorganic phosphates. This can be measured by taking small samples of 50 mg of earth and testing these chemically (Schwarz, 1967; Goodyear, 1971). With this method one can sample large areas and determine zones of archaeological interest. Furthermore, anomalies can be checked and verified.

In practice, samples of earth are taken at regular intervals (minimum 5 m to circa 50 m maximum), preferably in the framework of a grid allowing the results to be accurately recorded. 50 mg of each sample is placed on a filter and first treated with two drops of ammonium molybdate with sulphuric acid (or nitric acid) and approximately half a minute later (some soils require three minutes as they react very slowly) with two equal (!) drops of ascorbic acid. The colouring of the paper provides an indication of the phosphate content: 0 result = < 0.08% P_2O_5 ; trace - blue to ~ 2 mm from sample = ~ 0.08% - 0.15%; weak - etc.

Contamination of the filter must be avoided and it is advisable to store chemicals in the shade as they are light sensitive. Results are based on comparison and samples should therefore be treated in their entirety.

Area A was divided into grids of 5 x 5 m and samples were taken from a depth of a few centimetres in each grid. Samples from suggested resistivity anomalies (see plot 3A) were also checked.

Random sampling was done of the surrounding area.

Analysis (see site plan)

Most possible grave anomalies (marked a to r on site plan) indicated a positive response. The positive results in Area B remain ambiguous (as based on evidence obtained with resistivity and magnetometry).

Conclusion

The general disturbed nature (earth removal by bulldozer) of the samples area makes any clear assumption on the basis of the results, a cautious one.

Sampling at greater depth may prove to be more worthwhile as most of the soil disturbance is on the surface.

e) Electrical trenching and magnetometer traverses

Outline

Areas of interest were searched by laying out traverses approximately 5 m apart. These are shown on the main site diagram (traverse t_1 to t_5). The results provided no positive identification of interesting anomalies, and have therefore not been included.

3. Summary

In view of the results obtained, the geophysical survey has, at least in certain areas, justified its preliminary application. Such results

should, however, be seen in the context of the limitations of the various techniques and the rather poor operating conditions. The latter may be summed up under three main headings:

- 1) Soil salinity: surprisingly enough, the resistivity readings were extremely low; overall between 0 - 50 Ω . The probable cause of this is the soil salinity. A preliminary geological and pedological study of Lachish Cemetery¹ found that the soil was comparatively saline and contained significant amounts of gypsum. Soil pH varied between 7 - 8 (alkaline side of neutrality). The graves had been cut into the alluvial terrace deposits which were overlain by a calcareous surface crust formed by upward percolation of calcium-rich waters. This explains the apparent resistivity contrast.
- 2) unevenness of terrain (especially Tel Lachish).
- 3) soil disturbance by past and present human interference.

6.2.3. Qadesh, Syrian Arab Republic

1. Introduction

The site of Tel Nebi Mend or Qadesh lies some 20 km southwest of Homs on the banks of the river Orontes and its tributary, the Mukadiyah. It was occupied from the second millenium to the present day and plays an important role in Syrian history.

The Tel measures approximately 450 x 200 m in size and is 30 m high at its northern and highest point. It commands a dominating view of the Orontes floodplains.

The general geology consists of a very thin layer (typically 20 - 100 cm in depth) of red/brown clay-like soil overlying an indurated lacustrine

¹ Bell, M., 1978, 'Second preliminary report on geological and pedological studies of a Bronze Age cemetery east of Tel Lachish, Israel'. Unpublished report.

marl of irregular surface. Regular ploughing has cut up the hardened bedrock giving the soil a stoney texture.

A number of geophysical surveys were undertaken as part of a University of London project directed by Mr P.J. Parr, during two seasons of excavation. The first season, which took place at the end of August and the beginning of September, mainly consisted of resistivity surveying as the proton magnetometer malfunctioned.

The second season, from the beginning of July to the end of August, consisted of resistivity, magnetic and VLF-EM surveys.

The results from both seasons are discussed below.

2. Resistivity surveys

a) Instrumentation

A Martin-Clark series 4 resistivity meter was used for most of the resistivity work. Its power supply had been increased to 12 V enabling a higher voltage output. Only minor use was made of a Bradphys resistivity meter. This instrument provides a 200 V a.c. output at constant current.

Both Wenner and Dipole Dipole arrays were applied with a fixed spacing between the metal probes. Owing to the extreme hardness of the soil these had to be hammered into the ground.

(1) Enclosure

Outline

The relatively flat area to the west of Tel Nebi Mend is dominated by part of a rectangular enclosure (Diagram A). Present depth of the ditch structure is approximately 5 m with an overall width of 30 cm.

On the surface one can discern the two sides of the rectangle of which the western end runs for 800 m. The southern arm peters out in the floodplain of the river Mukadiyah, to reappear on the other side where it can be traced for a short distance.

Towards the S.W. corner of the rectangle, the eastern side of the

embankment veers outwards to form a square-like enclosure. A modern track runs from the eastern corner of this and passes through the western embankment.

During the summer of 1977 a section - known as Trench VI - was dug across the ditch and both embankments. It was situated to the north of the square enclosure in the S.W. corner. The excavated section indicated that the base of the eastern embankment was originally 16 m wide and consisted of stone and clay obtained from the ditch. This had been vertically cut into the natural subsoil and was 16 m wide. Its depth could not be determined owing to the proximity of the water table to the surface, but exceeded 3 m.

The aim of the survey consisted of the following:

- 1) did the enclosure conform to the results obtained from the excavated trench?
- 2) did the enclosure continue where there was no visible evidence on the surface?
- 3) was there any connection with the river?

To obtain an idea of the resolution obtainable with resistivity, traverse t_1 was positioned running parallel to the excavated trench at a distance of 2 m. This would enable a comparison to be made between the resistivity and excavation results.

The traverse could not be positioned immediately adjacent to the excavated trench as soil disturbance caused by the excavation would make it difficult to obtain representable results. Therefore, any summary correlation need not fit exactly owing to the change in traverse position.

The first 10 m of the traverse went from the top of the eastern bank to the bottom of the ditch; from 10 m - 40 m it ran across the actual ditch and the remaining 10 m (40 m - 50 m) traversed the western bank terminating at its crest.

Where possible, all subsequent traverses were laid out in the same

pattern.

The Martin-Clark resistivity meter was mainly used. Probe spacing and station interval were kept at 1 m.

A series of probe contact resistance measurements were taken along traverse t_6 , with the following results:

- a) between 17 - 20 m along t_6 (ditch section) $\rightarrow$ P_1P_2 (Wenner) - 14 k Ω
 P_1P_2 (Dipole Dipole) - 15 k Ω
 C_1C_2 (" ") - 9 k Ω
- b) between 33 - 36 m along t_6 (edge bank 2) $\rightarrow$ P_1P_2 (Wenner) - 11 k Ω
 P_1P_2 (Dipole Dipole) - 11 k Ω
 C_1C_2 (" ") - 15 k Ω
- c) between 41 - 44 m along t_6 (bank 2) $\rightarrow$ P_1P_2 (Wenner) - 37 k Ω
 P_1P_2 (Dipole Dipole) - 10 k Ω
 C_1C_2 (" ") - 70 k Ω

Probe spacing and station interval were kept at 1 m.

Analysis

Traverse t_1 : Correlation with the soil profile obtained from the excavated trench (see diagram B1) proved to be inconclusive.

As expected, high resistivity values occurred where the bedrock came up to the surface (points A and B). During dry periods in Britain, ditch fill generally appears as an intermediate (negative) anomaly. However, under the given circumstances it can be expected to be more moisture retentive than the surrounding bedrock. One would therefore expect intermediate resistivity values, as is the case.

Unfortunately, the interface between bedrock and soil response cannot be clearly differentiated, except at point C. Most probably water run-off from the banks causes the dip (= low) in the resistivity readings.

An interesting anomaly appears at point D. This correlates with a conglomeration of soil lenses as evidenced in the soil profile. Later evidence points to the existence of a separate inner bank otherwise not visible on the surface. Readings were also taken with an electrode spacing of 2 m. Instrument resolution proved to be abysmal, and subsequent use of the more powerful Bradphys resistivity provided equally - though marginally better - disappointing results (Diagram B2). This is most probably caused by masking due to the high saline content of the soil. All current invariably passes through the uppermost soil layer.

Traverse t_2 : This was laid out parallel to t_1 at a distance of 5 m. Both Wenner and Dipole Dipole values have been smoothed (Diagrams B2 and B3) using a 3-point weighted average. Where bedrock comes right up to the surface has been shown above the relevant graphs. Often no readings could be taken under these circumstances owing to the hardness of the material.

The existence of a minor bank can clearly be seen at point 1. The sharp dip at point 2 leads to the supposition of a lower intermediate area between inner bank and outermost embankment.

The main ditch itself shows up as a negative anomaly and runs from points 3 to 4, some 22 m. This would make it slightly wider than the 16 m found at Trench VI.

Traverse t_3 : Again parallel to the previous traverses at a distance of 5 m. It gave identical results to t_2 .

Traverses t_4 , t_5 , t_6 : Each at 10 m from the previous traverse.

The inner bank becomes progressively more pronounced as especially evidenced in t_5 .

It was then decided to run a number of traverses to the south of the excavated trench to see whether an identical response to the previous traverses could be obtained.

Traverse t_{10} : This was laid out at a distance of 20 m. running parallel to t_1 . It gave no clear results.

Traverse t_{11} : Positioned at 10 m from t_{10} , it indicated both sides of the enclosure as well as the inner bank.

Traverse t_{12} : It was placed 50 m from t_{10} and on the southern corner of the enclosure running diagonally across the track (position of which indicated above the graph). One can only discern the western embankment as the traverse started at the foot of the eastern embankment.

Traverse t_{13} : Running parallel to t_{12} at 10 m distance, it does indicate the eastern embankment. This traverse also crossed the track. The high readings at point 1 correspond to this. No clear evidence, however, of an inner bank.

To determine whether the enclosure continued where there was no surface indication, two traverses t_A and t_B (see insert diagram A) were positioned outside the western arm of the enclosure and along its hypothetical axis. The distance between the traverses was approximately 100 m. Although no evidence appears of an inner bank, one can see the

edges (embankments) of what most probably is a continuation of the ditch (Diagram B2 and B3). An expanding Wenner configuration, placed in the centre of the ditch and running parallel to traverse t_1 was used to determine the depth of the ditch. Unfortunately, the available instrumentation was not powerful enough to provide useful results.

Conclusion

Overall the resistivity survey indicates that the excavation results provide a reasonable idea of the outline of the enclosure. This especially applies to its western arm. The resistivity results have also brought forward the suggestion of an inner bank, otherwise not visible on the surface. Further survey work could substantiate whether this inner bank coincides with a separate much smaller ditch between it and the outermost (western) embankment.

The evidence furthermore tentatively suggests the continuation of the western arm of the enclosure.

(2) Grid 1 (10 x 30 m)

Outline

During the excavation of Trench VI a number of Roman and/or Byzantine graves were found cut into the eastern embankments. Their size varied from a pit of 80 cm diameter to a grave 2 m wide and some 3 m deep. Surface finds of pottery scattered over a large area indicated that other graves probably existed. A grid of 10 x 30 m was laid out in an area adjacent to the embankment (see Diagram A), which slightly sloped from west to east.

Resistivity measurements were taken with an electrode spacing and traverse interval of 1 m. It was hoped that any graves dug into the hard underlying bedrock and subsequently filled with a looser-textured soil,

would show up as low-resistivity anomalies.

Analysis

The histogram indicated a range from 2.9 to 16.7 Ω for the DD results and from 10.5 to 30.8 ohms for the Wenner reading, both using a probe spacing of $a = 1$ m.

Plot A1: Unfiltered DD readings at $a = 1$ m and within the range $\bar{x} - 2.5 \sigma$ to $\bar{x} + 2.5 \sigma$. The dense area in the plot is at the top of the slope and probably indicates the thin nature of the soil cover (response to underlying bedrock). No interesting features became apparent. The three circular features at the top of the plot conform to areas of high resistivity and fall outside the plotting range.

Plot A2: Negative plot of the DD readings with a range $\bar{x} - 0.25 \sigma$ to $\bar{x} - 2 \sigma$. The curious linear and rectangular features in the plot partially coincide with the direction in which the soil has been ploughed. These features are therefore most probably caused by ploughmarks in the underlying bedrock.

Conclusion

No areas of possible archaeological interest can be outlined.

(3) Grid 2 (20 x 20 m)

Outline

An additional grid of 20 x 20 m was laid out to the east of grid 1 (see diagram A).

Electrode and traverse spacing were kept at 1 m. The survey had to be terminated after the completion of 3 traverses as a thin veneer of

topsoil (typically 10 cm) covered the ground, making it difficult to establish proper probe contact.

Analysis

No interesting anomalies appear in the graphs (Diagram C). The high resistance anomaly (denoted A) in traverse t_1 is most probably of geomorphological origin.

(4) Embankment (southside)

Outline

Traverses were laid out over the southern section of the embankment and adjoining ditch (see Diagram D1).

The aim of the survey was threefold:

- a) did the ditch connect up with the river?
- b) is there any evidence of an inner bank with a separate and much smaller ditch, as suggested for the western ditch section (Diagram B3, B4)?
- c) how reliable are the data?

Traverse t_1 was placed near the river and across the projected axis of the ditch (Diagram D1). Its length was 64 m. During the first 6 m the station interval was kept at 0.2 m. This was done in order to obtain something nearer a continuous profile. One could then concentrate on the effect of station density on the confidence limits of the data. This would give an insight into how much of the data are spurious and the result of aliasing. Where possible, the probe contact resistance was kept smaller than 1000 Ω , with the emphasis placed on the potential probe pair. Prior to measurement each probe was watered with approximately 250 cc of a salt/water solution. The conductivity of the latter was kept between 150 - 200 Ω . Probe watering was applied to all three traverses.

With t_1 (0 - 6 m) and t_3 (0 - 50 m) a station interval of 0.2 m applies (at $a = 1$ m). The remaining length of t_1 (6 - 64 m) and the entire

length of t_2 were surveyed at the usual probe spacing of 1 m.

Resistivity measurements were also taken prior to probe watering, in the case of t_1 (0 - 6 m) and t_3 (0 - 50 m). Both traverses t_2 and t_3 were placed parallel to each other at 5 m distance, across the ditch. The first 5 m of each traverse went from halfway bank 1 to the bottom of it; from 5 m - 45 m it ran across the actual ditch and the remaining 5 m (45 m - 50 m) traversed bank 2 terminating halfway up the slope.

Analysis

Measurements of probe contact resistance were taken using a Hioki AF-105 50 k Ω /V d.c. multimeter. At the beginning of the traverse (t_1) the relevant values were:

<u>before H₂O</u>	<u>after H₂O</u>	
1.4 k Ω	500 Ω	P ₁ P ₂ - Wenner
700 Ω	600 Ω	P ₁ P ₂ - Dipole Dipole
1.2 k Ω	550 Ω	C ₁ C ₂ - " "

These values improved during the survey as the first three probes were positioned in exactly the same area as the four previous probes, which will have been watered. Only the last probe (P₂ - DD) in the configuration will be positioned in a previously unwatered area. It was therefore decided to take random measurements of the probe contact resistance in order to keep a check on the overall working conditions.

In practice the soil (clay) water drainage was often high causing a gradual fall-off in the reading and making it difficult if not impossible to obtain a low probe contact resistance. Sometimes the reverse would occur with the reading exhibiting a gradual decrease indicating increased current penetration. The results from traverse t_1 , t_2 and t_3 are given in diagrams D2, D3 and D4 respectively.

In traverse t_1 the northern embankment can be seen between 0 and 8 m. There is no evidence to suggest the continuation of the southern bank.

On comparison, both watered and unwatered profiles correlate reasonably well, with probe watering leading to slightly higher Wenner readings (increased current penetration) with the reverse applying to the Dipole Dipole array.

In traverse t_2 both banks can be clearly seen but there is no indication of an inner bank as suggested for the western ditch section. The ditch itself can be followed from 6 m to approximately 34 m, making a total width of circa 28 m. Most probably the bank itself starts at 35 m as continued cultivation will have eroded the escarpment with only a slight rise in the resistivity indicating its past position.

The Wenner profile, using a station interval of 0.2 m, with superimposed the profile for the increased station interval of 1 m, is shown in diagram D4. A fair amount of noise and some aliasing appears in the signal derived by increasing the sampling interval. The decrease in sampling interval does not appear to have significantly impaired the signal (no spurious anomalies caused by aliasing), although there is some loss in high frequency content.

The effect of probe watering on the data can be seen in plot B2.

Plot B1 represents the histogram of the unwatered probes and plot B2 that of the watered probes. Both apply to traverse t_3 using the 1 m station interval.

The histogram of the results using watered probes shows an improved distribution suffering less from spurious values, with a concomitant decrease in the standard deviation.

Conclusion

It is interesting to note that the northern embankment continues to the river. This may suggest that it formed a breakwater which caught the flow of the river (northwards) and diverted part of its waters into the ditch. More information on the effect of the sampling interval on the information content of the data could be obtained by taking the respective power spectra. This would indicate how the variance or power average of

the signal is distributed over frequency. The degree of similarity between the two signals could then be determined by cross-correlation.

(5) Grid x (10 x 20 m)

Outline

A grid was placed on the supposed location of a Roman and Byzantine site situated on a hill next to the main road running to the south of the Tel (see Diagram D1). It was hoped that a clear site plan would emerge of the various wall structures, some of which were evident adjacent to the grid.

Resistivity measurements were taken using a probe spacing of 1 m and a station interval of 0.2 m. All probes were watered with circa 250 cc of a salt/water solution (150 - 200 Ω conductivity). In many instances readings suffered severely from the effects of ground inductance and leakage currents causing erratic readings. Also, the ploughed nature of the soil led to rapid water drainage and associated probe contact resistance problems.

The area itself had recently been ploughed and had a loose texture, often making it difficult to establish good probe contact. A careful check was made of the probe contact resistance.

Analysis

In practice it was found virtually impossible to obtain probe contact resistance values below 1000 Ω . At the beginning of a traverse, the effect of probe watering was marginal:

t_0 :	<u>before H₂O</u>	<u>after H₂O</u>	
	7 k Ω	6 k Ω	P ₁ P ₂ - Wenner
	12 k Ω	12 k Ω	P ₁ P ₂ - Dipole Dipole
	5.5 k Ω	5 k Ω	C ₁ C ₂ - " "

As previously explained, these values could be expected to gradually improve during the survey. The overall variation was as follows:

after H₂O

$\bar{x} = 3.6 \text{ k}\Omega$	$\sigma_{n-1} = 1.77$	$P_1 P_2$ - Wenner
$\bar{x} = 4.0 \text{ k}\Omega$	$\sigma_{n-1} = 3.83$	$P_1 P_2$ - Dipole Dipole
$\bar{x} = 3.8 \text{ k}\Omega$	$\sigma_{n-1} = 2.11$	$C_1 C_2$ - " "

Plotting has been limited to the normal probe spacing of $a = 1 \text{ m}$.

The histogram of the Wenner results gave a range from 0 to 599 ohms with most of the readings concentrated at the lower tail end of the distribution. This was also the case with the Dipole Dipole results. These varied between 0 and 415 ohms.

Plot C1: Filtered DD readings at $a = 1 \text{ m}$ using a high pass square residual filter, radius 1, and a range from $\bar{x} - 0.1 \sigma$ to $\bar{x} + 2 \sigma$. The plot is a logarithmic one showing up a large number of walled structures. These have been outlined.

Conclusion

Although successful in nature, the survey highlighted some of the problems associated with probe watering. Wetting the ground is almost definitely the cause of the inductive coupling between adjacent current and potential leads and the leakage currents. Lowering the a.c. frequency of the resistivity meter may provide a marginal improvement as these effects become especially prominent at frequencies above 60 Hz (Martin-Clark series 4 $\rightarrow$ 67 Hz).

Also, adequate probe watering becomes especially difficult with loosely textured soils

3. Magnetic susceptibility measurements

Outline

A large number of samples were collected to obtain a general idea of

the range of susceptibilities over the site. Unfortunately, no samples could be collected from any great depth as there was no coring tool available. The location of the samples can be found in diagram E1.

Each sample consisted of approximately 100 - 150 g of material. After mixing, 50 g of this was used for the magnetic susceptibility measurement. Overall the texture of the material did not warrant preliminary sieving. All samples were weighed to an accuracy of .1 g on a Sartorius 1106 weighing instrument.

A Bison 3101 supplied the susceptibility measurements. The results are shown in diagram E2. When measuring the magnetic susceptibility in the laboratory, magnetic viscosity effects are not taken into consideration. The results will therefore slightly underestimate actual field conditions.

Analysis

Readings over the sampled area indicate a reasonably wide diversity. In many cases an inverse relationship appears with samples obtained at greater depth from the same location. Normally the magnetic susceptibility falls off with depth. Only on certain soils, such as the Terra Rossa type, does this not occur (Linington, 1974b).

Sampling across the ditch gave varying results.

Conclusion

A magnometer survey should provide useful results. It would be interesting to determine the actual mechanism that causes the subsoil to have a greater susceptibility than the topsoil. One indicator here may be extensive soil erosion, leaving a soil with a truncated profile. In effect, the present-day cultivated soil then represents the lower horizons of an earlier soil.

4. Magnetic surveys

a) Instrumentation

A Barringer Research GM122 proton magnetometer (serial.6234) was used for the magnetic surveys. Measurements were taken along traverses 1 m apart and at 1 m intervals. At each measurement point, two sets of readings were taken:

- 1) sensor on surface - denoted b in the diagrams.
- 2) sensor at 1.4^m above surface - denoted t in the diagrams.

This would provide an indication of the size and depth of an anomaly as well as filtering out surface noise.

Sensor head orientation was kept constant by holding a marker line on the sensor in an E-W direction.

A control reading was taken at a base station at the end of each traverse to enable correction for diurnal variation.

Instrument sensitivity approximates 1 γ . Reading repetition was checked and found to be $\pm 1 \gamma$.

- (1) Grid 1 (20 x 20 m)

Outline

A grid was placed within the north-eastern corner of the enclosure (Diagram F1). The aim of the survey was to determine whether there were any archaeological features within the enclosure which could throw some light on its past function, as this was unknown.

Four traverses were run from three of the corners of the grid to the nearby escarpment. Traverse m_1 and m_3 were 30 m long and traverse M_2 and M_3 had a length of 20 m.

Analysis

The histogram of the results for the lower sensor gave a variation

between 44944 γ and 45106 γ . For the higher sensor the corresponding range was from 44937 γ to 45074 γ .

Plot D1: Negative linear plot of the lower sensor readings within the range $\bar{x} - 0.25 \sigma$ to $\bar{x} - 1.5 \sigma$. These have been filtered using a high pass 8 element ring residual filter, radius 1. No interesting anomalies are shown. This was further substantiated by comparing this plot with additional plots.

Conclusion

No features of possible archaeological interest can be outlined.

(2) Enclosure

Outline

A series of traverses were laid out over the entrance to the enclosure (t_1 and t_2 : 85 m), the main ditch (mta to mtn : 50 m) and its termination near the river Mukadiyah (t_x : 50 m and t_y : 90 m). The relevant traverse positions have been indicated in diagram F1.

The aim of the survey can be outlined as:

- a) was the north-western section of the ditch similar to the north-eastern part as previously determined by resistivity (Diagram B4)?
- b) was the ditch at some time connected to the river?

Traverse t_x was placed such that it would cross any former extension of bank 2 as evidenced for its counterpart across the river (section 4 : resistivity).

The main objective with t_y was to ascertain a possible correlation between anomalous high magnetic field values in the proximity of the river with past changes in its course. This was based on the observation that a river may carry a higher level of magnetite and other magnetic minerals

owing to the higher rates of erosion and concomitant heavy mineral concentration (Stanley, 1975). This would rely on the availability of iron minerals in the soil. The magnetic susceptibility measurements indicated a modest concentration,

Analysis

Both traverse t_1 and t_2 exhibited a gradual rise in total magnetic field intensity (F) but gave no indication of any interesting features. They have therefore been omitted. As one would expect, there was a fall-off in F with increased sensor height in traverse MTA (Diagram F2). This was found to be only typical of this traverse. All other traverses showed the reverse. The tapered edge of bank 1 runs from 0 to 9 m. Part of it shows up as a peak in the profile. However, this does not occur for bank 2 and with either bank in subsequent traverses, with the exception of bank 1 in traverse MTB (also tapered edge of the bank). The response forms suggest that when the topsoil cover is thin one gets low magnetic intensity values in response to the underlying bedrock as can be seen in traverse MTE (Diagram F2). No cumulation of magnetic material occurs at the foot of any of the banks as is often the case (erosion of the bank resulting in downward movement of magnetic topsoil). The explanation probably lies in the enhanced susceptibility of the subsoil as opposed to the topsoil. In this context one would expect any subsurface bank, as ascertained with resistivity, to show up in the profiles obtained with increased sensor height (1.4 m). This does not occur (contrast too small?).

From traverse MTG onwards, the profiles exhibited a gradual downward trend going from 0 to 50 m, as shown in traverse MTM (diagram F2). The sudden rise in the latter at 41 m is the result of a surface discontinuity at the top of the bank,

In traverse tx (Diagram F3), the hump in the profile at point A coincides with the extension of bank 2 suggesting its continuation.

The profile for traverse ty shows some curious features designated A to D. It is possible that A indicates the edge of the latest rivercourse with B referring to the edge of an earlier one by delimiting a zone of increased magnetic mineral content associated with rivercourse alluvium. This may - less convincingly - apply to points C and D.

Conclusion

The magnetic susceptibility samples for the north-eastern section of the ditch showed a fall-off in susceptibility with depth (Diagram E2). This has been confirmed with traverse MTA. However, the reverse occurs across the north-western section. The reason for this remains unanswered.

No evidence can be given for an inner bank or ditch. Owing to the confused nature of the soil, this should not be taken as conclusive evidence. Resistivity would appear to give more consistent results, and would therefore be more advisable for the north-western ditch section.

The suggested continuation of bank 2 towards the river should also be followed up by using resistivity.

As concerns the observations pertaining to traverse ty, appropriate soil sampling and chemical analysis may ascertain whether the ditch contains rivercourse alluvium. This would appear to enable more quantifiable results.

(3) Embankment - northside

Outline

A magnetic survey was made of the suggested continuation of the ditch at its northern end. Previous resistivity work (section 1) had positively confirmed its northern extension but had not followed this through. It was hoped a magnetic survey would indicate the exact location of the ditch as well as determining its terminus.

Traverse D1 to D4 were positioned across the projected corner of the ditch as based on a very slight change in surface contour. The continuation of the ditch was followed with traverses D5 to D8. As a precaution,

traverse D9 was laid out in an area parallel to the suggested position of the ditch in order to provide a check on the results from the other traverses (see Diagram G1).

Analysis

The results from traverse D1 to D4 confirmed the corner of the ditch. Diagram G2 gives the profiles for D1 and D3 with the edges of the ditch denoted by points A and B. This would give it a width of approximately 22 m confirming the results obtained with resistivity. A similar response applies to traverses D2, D4, D5 and D6. The latter profile is shown in diagram G3, with points C and D corresponding to the edges of the ditch. No indication of its continuation could be established from the response profiles from traverse D7 (Diagram G3) and D8. These were virtually identical to the results for D9.

Conclusion

The projected extension of the ditch has been successfully followed and found to terminate next to two artificial mounds situated to the north of the Tel.

(4) Grid A (15 x 15 m)

Outline

Grid A (15 x 15 m) was positioned on top of the artificial mound to the north of Tel Nebi Nend (Diagram G1). Very little is known about this mound and its archaeology. A large surface scatter of pottery, stone and basalt (magnetic!) attested to previous human settlement, and resulted in a high surface noise level. The lower sensor height was therefore changed to 21 cm above the ground. This gave a repeatability of 5 γ. Readings were also continued with the sensor height of 1.4 m above the ground surface.

Analysis

For the lower sensor position the histogram gave a range from 44980 γ to 45224 γ and for the higher position this was from 45068 γ to 45205 γ with a significant decrease in the standard deviation.

Plot E1: Logarithmic plot of the filtered results of the lower sensor position at $a = 1$ m, using a high pass square residual filter, radius 1. The range is from $\bar{x}$ to $\bar{x} + 2\sigma$ placing emphasis on the top end of the distribution. A series of walled structures can be seen. These have been outlined. The results were confirmed by the other plots.

Conclusion

A number of walled structures were detected, possibly made from basalt (increased magnetic response). It could be that the mound is part of the Roman Tel facing it and forms some sort of fortress connected with the ditch which terminates here (see previous section). This will have to be verified by excavation.

5. VLF EM

a) Technique

Use is made of VLF military transmitting stations situated around the world and operating in the frequency range 15 - 25 kHz. Their vertical antennae create horizontal magnetic fields running at a right angle to the direction of the station. When this primary field encounters a conducting body, it will induce a secondary vertical field within that body. Signals in the vertical and horizontal directions are compared and form the basis of measurement. As the primary field is virtually horizontal, the secondary field strength can be approximated and the difference in phase between both fields determined.

On penetrating a conducting ground, the wavelength of the primary field shortens. This will depend on the conductivity and the frequency. The resultant attenuation and consequent phase and directional distortion of the primary magnetic field can be expressed as:

$$\beta = \alpha = \left(\frac{\omega \mu \sigma}{2} \right)^{\frac{1}{2}}$$

where β = attenuation in nepers per metre

α = phase shift in radians per metre

ω = angular frequency ($2 \pi f$)

μ = magnetic permeability in henrys/m ($\mu_0 \mu_r = 4\pi \times 10^{-7}$)

σ = electrical conductivity in mhos/m

Local conductors will cause inhomogeneities in the primary field which will lead to a filtering of the total field at either side of the conductor. In practice, when entering a target, the resistive component of the material will result in a positive phase shift in the secondary field and on leaving the target there will be a negative phase shift. Also, surface features tend to exhibit positive or zero quadrature signals as opposed to the negative values obtained with deeper features. The depth to the upper edge of a target can then be equated to the horizontal distance between the maximum positive and negative readings.

The instrument itself consists of two receiving coils: one to detect the horizontal (primary) field, and the other to detect an anomalous vertical (secondary) field. Both coils are perpendicular to each other and wound on ferrite cores.

In practice, while holding the signal coil horizontally (normally vertical), the instrument is oriented along the magnetic field lines and moved about until a minimum audible signal is emitted by an inbuilt reference oscillator. This gives the direction of the primary field. With the instrument now held vertically the reference coil will be at right

angles to the transmitter station and with its axes parallel to the primary field.

The instrument is then moved back and forth in the vertical plane for minimum sound intensity from the speaker and a note made of the tilt angle measured with a built-in clinometer. A ratio of the quadrature component of the vertical secondary field to the horizontal primary field is obtained by rotating the quadrature knob on the instrument (held steady in the minimum direction) until a further signal minimum is reached. This will be the percentage of the reference signal (shifted in phase by 90°) used to compensate the voltage in the signal coil.

For the survey use was made of a Geonics EM16(R) VLF EM receiver. This is a light and portable device with negligible power consumption and enabling rapid readings to be taken. It came supplied with two transmitting station selector units:

- 1 - NAA Cutler, Maine, U.S.A., 17.8 kHz (1000 kW)
- 2 - GBR Rugby, England, 16.0 kHz (500 kW)

(1) Grid x (10 x 20 m)

Outline

This was the same grid used for the resistivity survey (see section 5: resistivity) enabling a comparison to be made of the two techniques.

GBR was found to give a stronger signal and was therefore used throughout the survey. It is important to place the measurement traverses at right angles to the sought-after feature (primary field vector across feature), within the tolerance of 45° . For Grid x the measurement angle was circa 30° .

The tolerance of the readings came to within 3 - 4% for the angle of tilt (vertical in phase signal) and within 2 - 3% on the quadrature dial.

In practice it was difficult to keep the instrument steady. This caused a variation in the angle of tilt in turn resulting in differing

quadrature readings. Field procedure was similar to resistivity in that a traverse and station interval of 1 m was applied. The results can be plotted in the form of profiles (in-phase and quadrature on the same axis) or as vectors (length of vector proportional to dip angle with its direction referring to the quadrature component).

Analysis

The histogram of the in-phase component gave a variation between 0 to 10%. For the quadrature signal the range was from -5 to +4%. The results are presented in Diagrams H1 and H2.

No inflection points (crossover profiles) can be seen which would indicate points of interest. The observed variation is most probably associated with reading error.

Conclusion

This method has proved unsuccessful. A more powerful military transmitter such as UMS (Moscow, U.S.S.R.) operating at 17.1 kHz and with a radiated power of 200 kW may provide better results owing to its more extensive coverage of the Middle East.

6.3. Discussion

Project

The project underlines the use of resistivity surveying as a successful geophysical technique in arid regions. It was found that probe watering is not a necessary prerequisite; good results can be obtained without.

A highly conductive saline alluvium leading to extremely low resistivity values (typically $\rho_{\text{Wenner}} = 4.4 \Omega\text{m}$) limited the depth penetration to circa 1 m. Increased soil salinity is a problem common to many arid regions and is particularly relevant in cultivated areas owing

to increased capillary action. The soil salinity effectively short-circuits the current and prevents any depth response.

To enable increased depth penetration, future resistivity work should concentrate on applying more current to the soil. A d.c. resistivity system with a power generator and using the Schlumberger array with a small inner probe spacing and large outer spacing, should accomplish this. Within this framework, the Gradient array should also be tried. It achieves a suitable depth response without recourse to very large potential electrode spacings and reduces current electrode effects caused by contrasts in the overburden resistivity as common with the Dipole Dipole array. With the Gradient array, the current electrodes are fixed while the potential electrodes are traversed parallel to the current line inside a rectangle within which the electric field would be uniform for a homogeneous earth. Normal interpretation methods apply although one must be careful to prevent false interpretation caused by inhomogeneities within the conductive overburden.

With magnetics the soil thickness varied considerably with lithology and geomorphology leading to spurious anomalies. More information is needed on soil profiles as well as the iron-oxide content of the soil samples. The emphasis should also be on a high resolution system of data collection preferably using a high sampling caesium magnetometer or gradient measurements.

Future Work

Future work should concentrate more on electromagnetics! The fall-off in response with depth approaches a square rather than a cube. There is also less of a problem with masking than with galvano methods. Past work in Australia (e.g. Baird et al, 1972; Preston, 1975) clearly brought out the problems associated with high conductivity surface formations which can effectively mask underlying conducting features.

This led to the development of low frequency ground e.m. methods such as ELFRAM (Extremely Low Frequency Turam system).

Worthwhile results have also been obtained with magnetometric resistivity (MMR) (Edwards and Howell, 1976; Edwards et al, 1978; Trevino and Edwards, 1979). It is based on the measurement of low level, low (100 milligamma) frequency (1 - 5 Hz) magnetic fields associated with non-inductive current flow in the ground. A coil or magnetometer measures a component of the magnetic field due to the current flow between two current electrodes. As with resistivity, a large number of probe arrays may be applied. MMR's main advantage over electrical methods lies in the mapping of regional geology beneath conductive overburden. In practice MMR is inexpensive and rapid in deployment. As a technique it has yet to be tried out in archaeological and near surface geophysics.

Instrumentation

Finally, a large amount of trouble was given by the equipment. This still appears to be one of the most prevailing events during each geophysical survey! The manufacturer of the Martin-Clark resistivity meter was advised of the poor internal contact points on the turret switch. This was subsequently modified with future models. It was also found that vibration caused by repeated hammering of the steel probes resulted in the continued shearing of the solder joints which connected the cable to the plugs. This strongly suggests that no solder joints should be used in the connecting plugs which fit into the steel probes. The resistivity probes (tempered steel) themselves suffered badly from the repeated hammering. An even more robust probe would be advisable.

Ideally, the extreme hardness of the soil necessitates a power drill to insert the electrodes into the ground. At best this should be a series of some 20 steel probes positioned along a traverse line and connected to a resistivity meter capable of handling a multiprobe array.

Apart from enabling the use of different electrode configurations this should also enable one to check the probe contact resistance and be adapted to depth investigations.

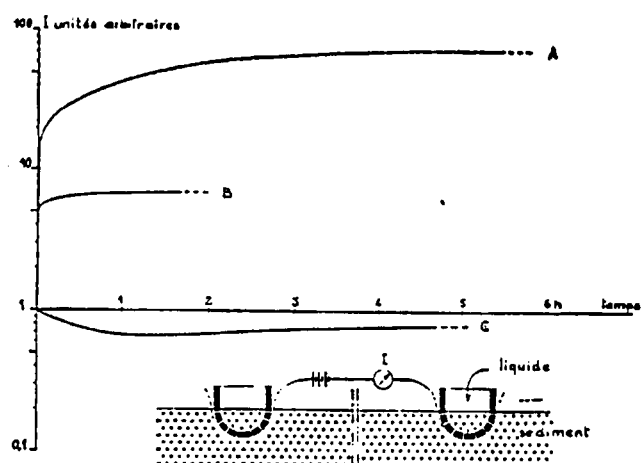


Fig. 6.1 Variation of current intensity in different sediments after watering

A - natural water in dry sand

B - copper sulphate solution in dry sand

C - natural water in saturated clay

Probes consist of perforated plastic hemispheres

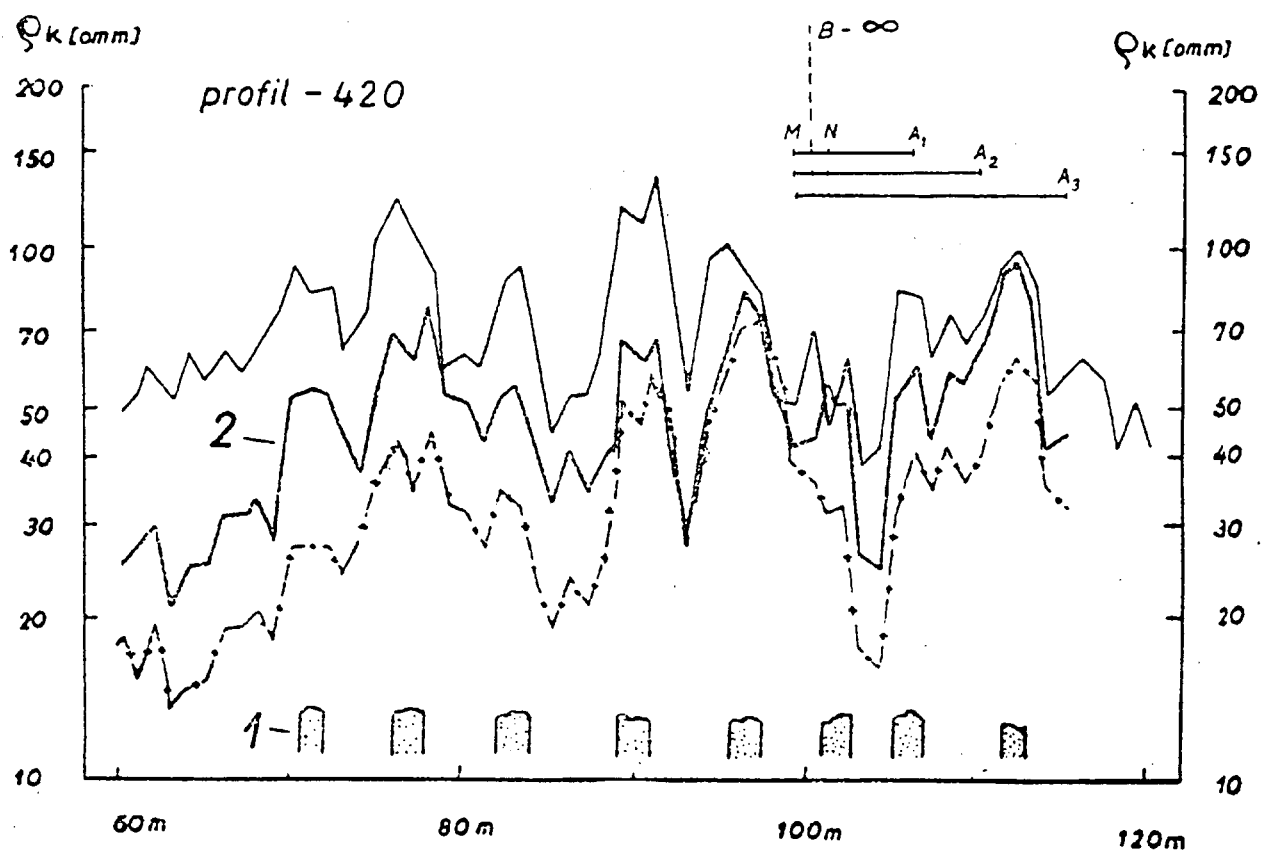
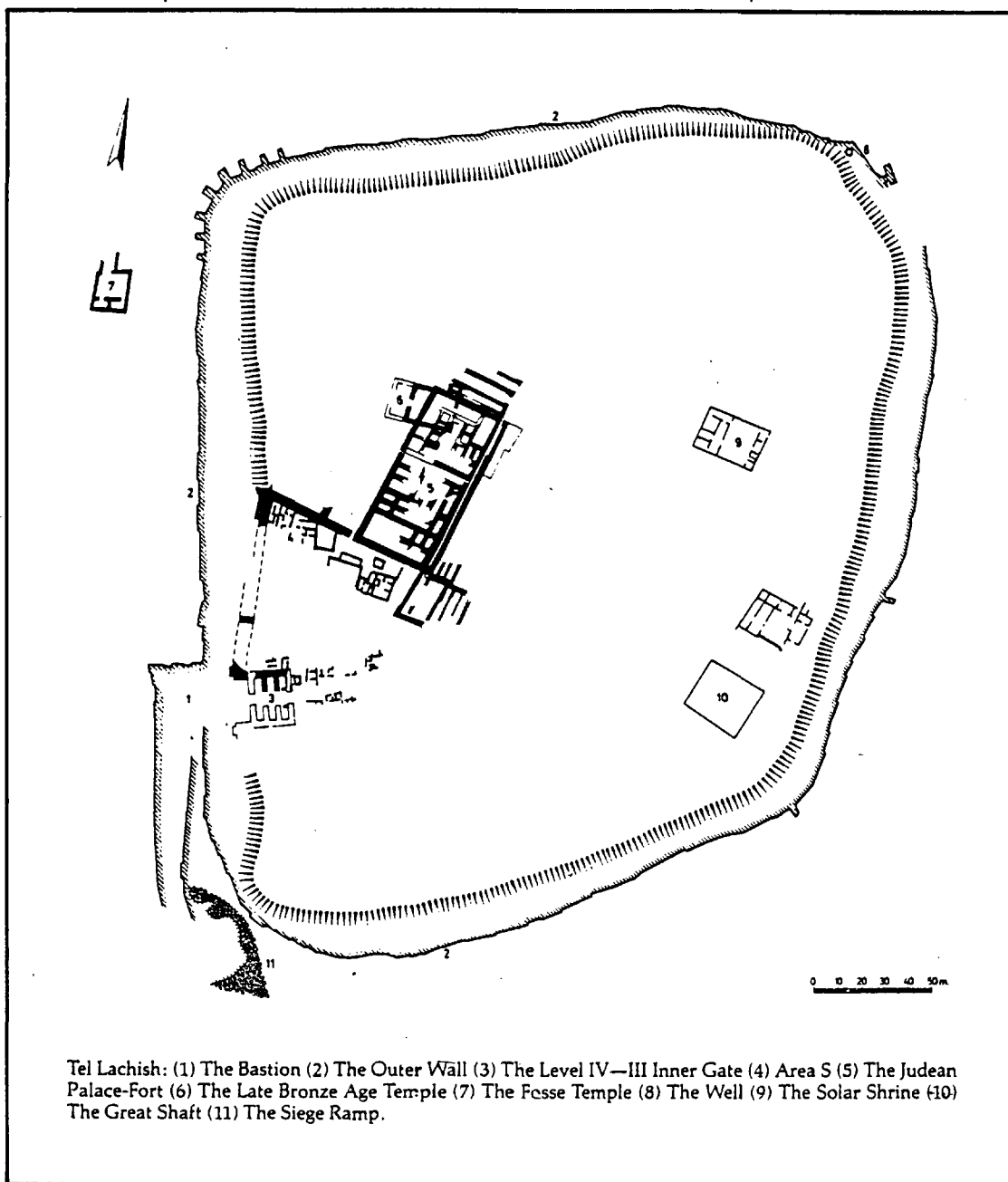


Fig. 6.2 Resistivity profiles across a Roman hippodrome
a) in situ walls
b) relevant profiles

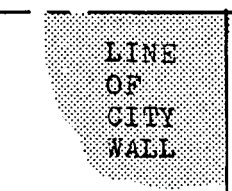
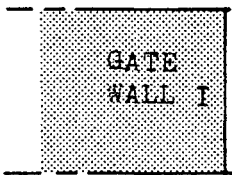
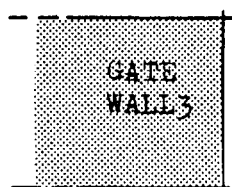
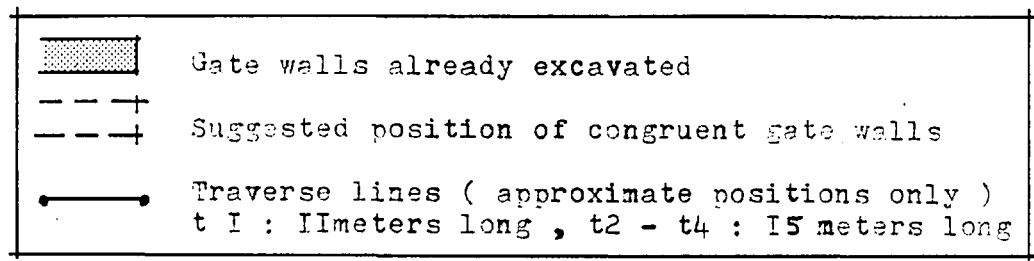
TEL LACHISH SITE PLAN



TEL LACHISH
RESISTIVITY SURVEY
AREA A
TRIPLE GATE

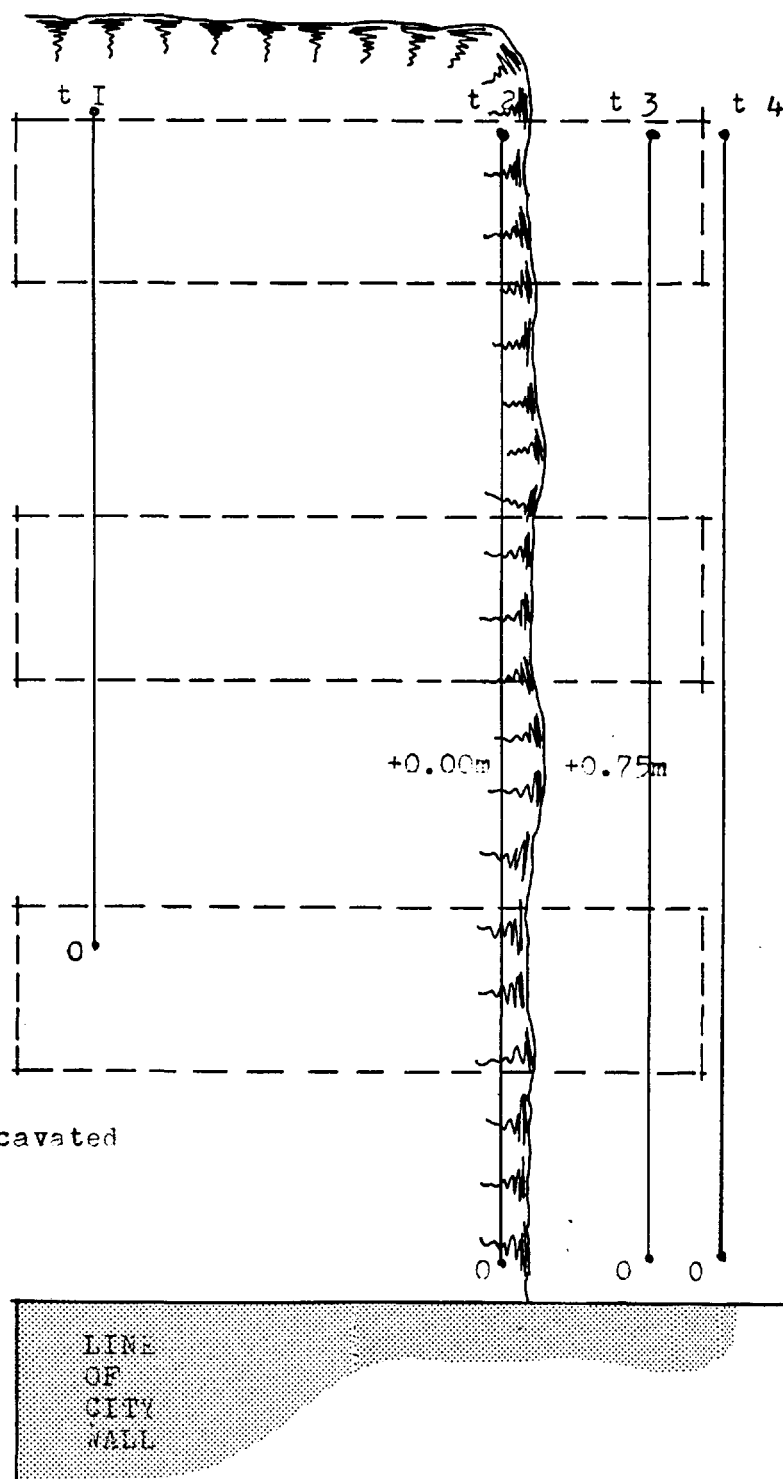
← Z →

SCALE 1 : 100

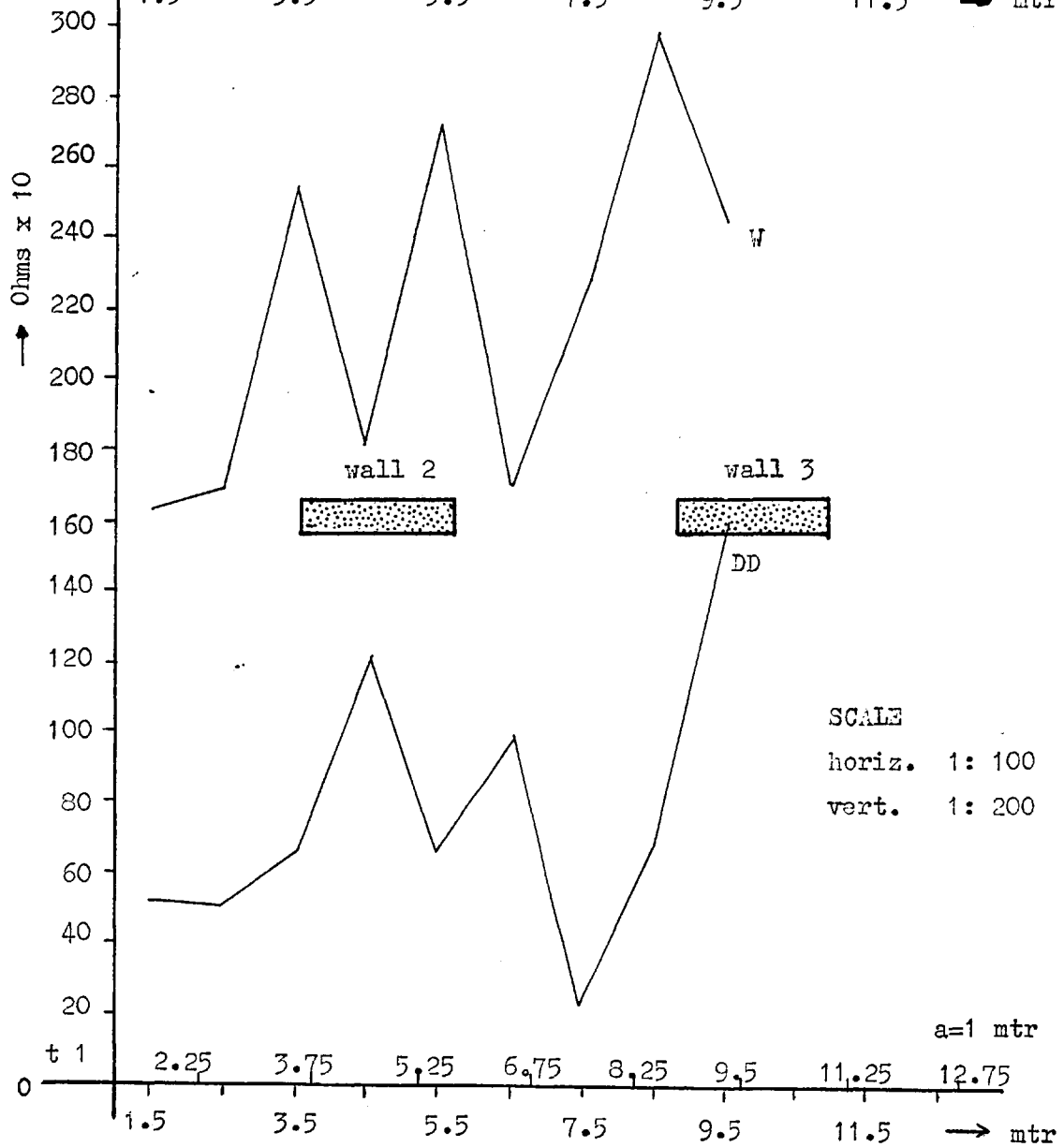
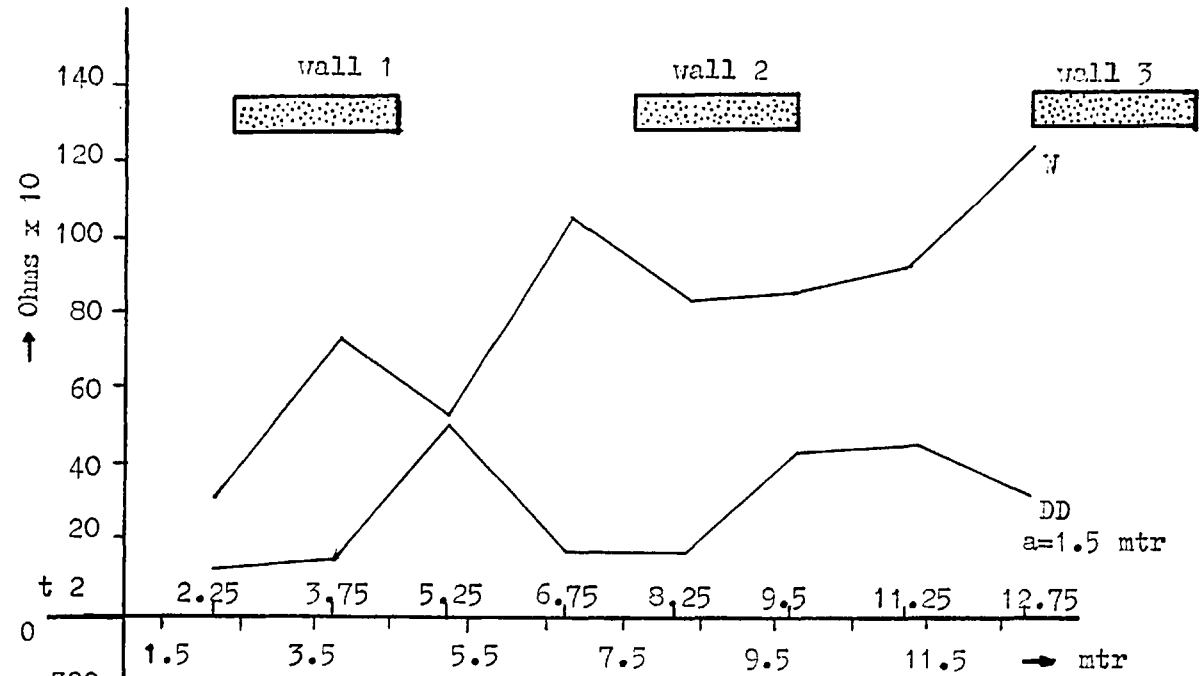


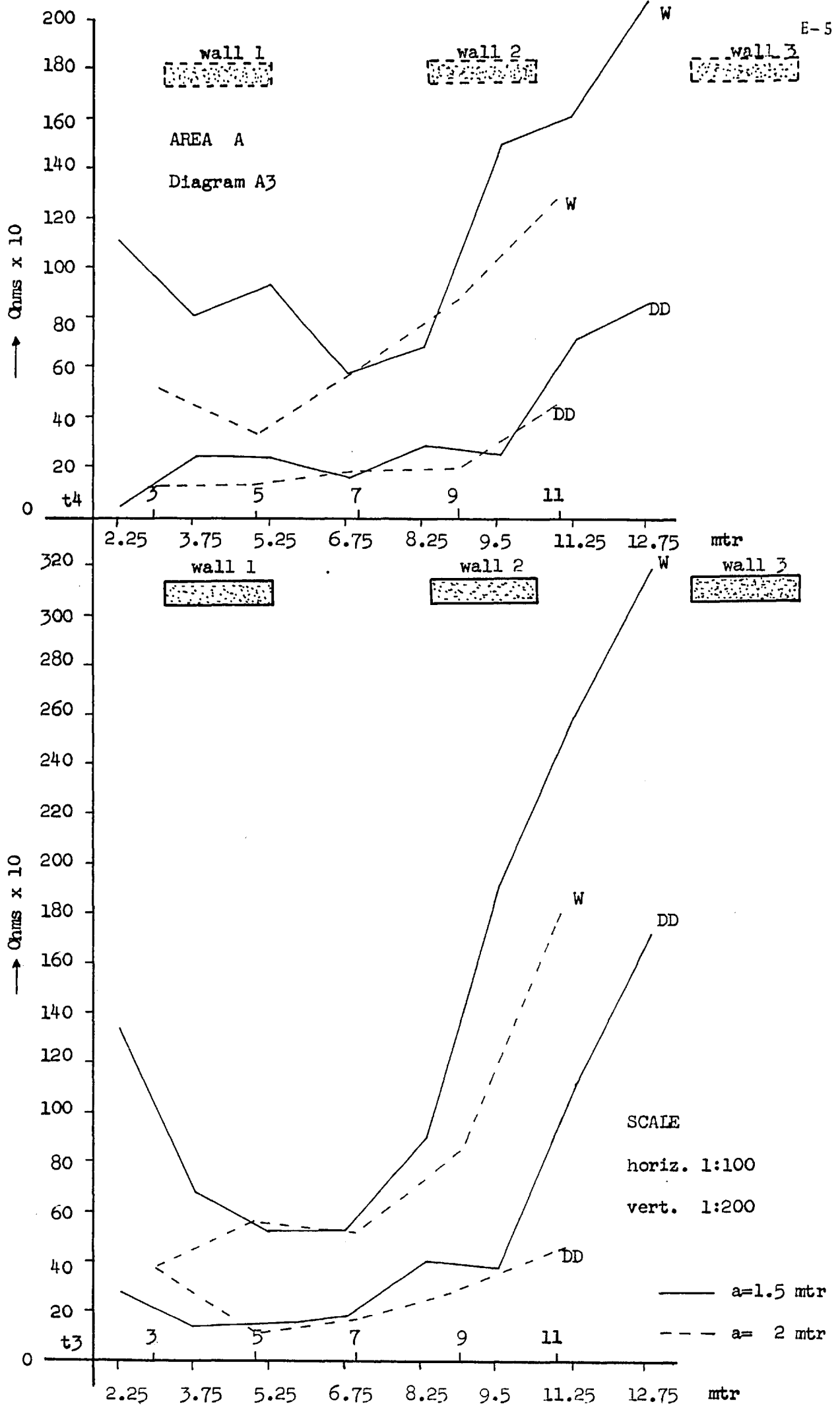
Excavated Area

Unexcavated Area



TEL LACHISH
RESISTIVITY SURVEY
AREA A
TRIPLE GATE

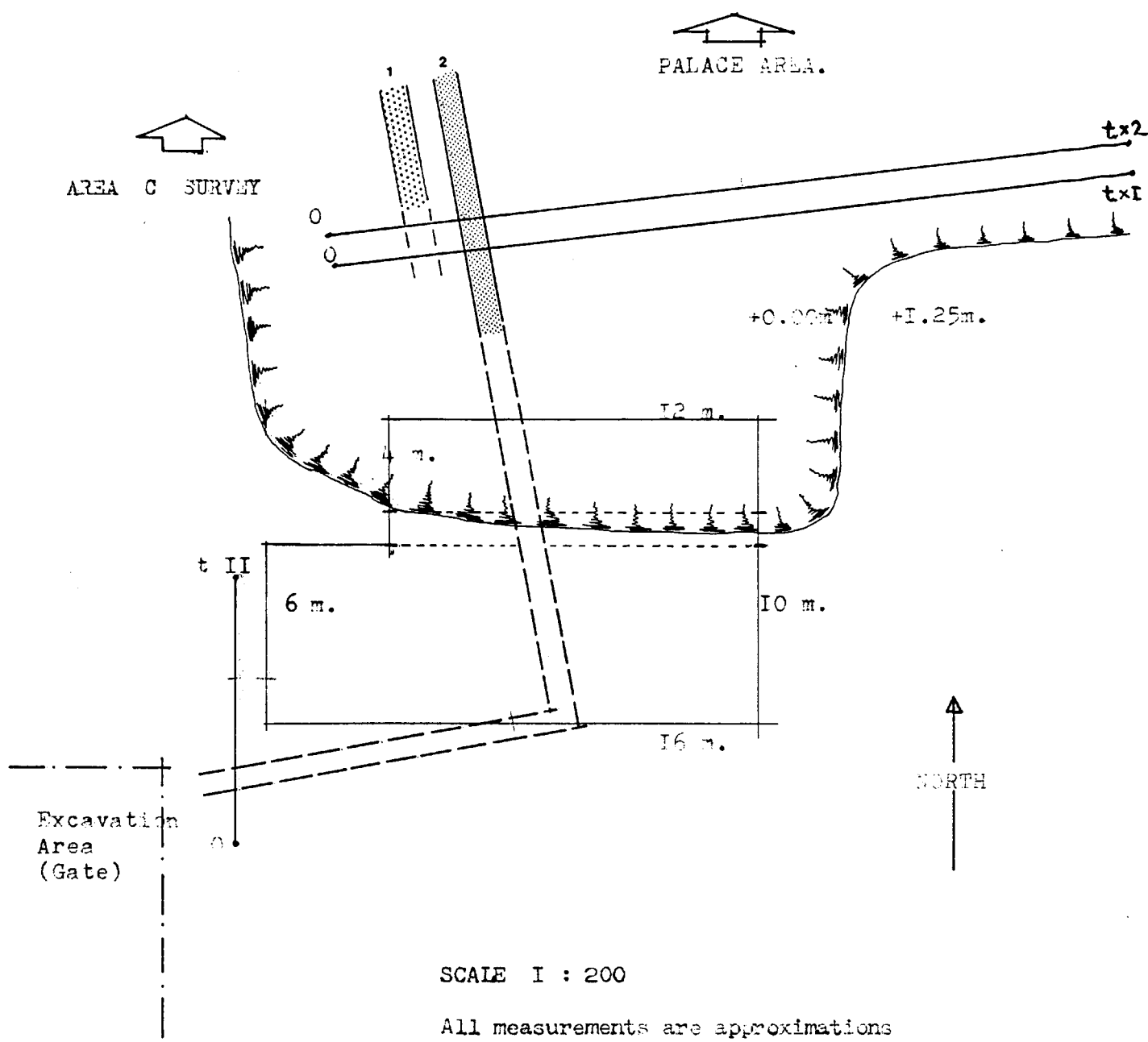
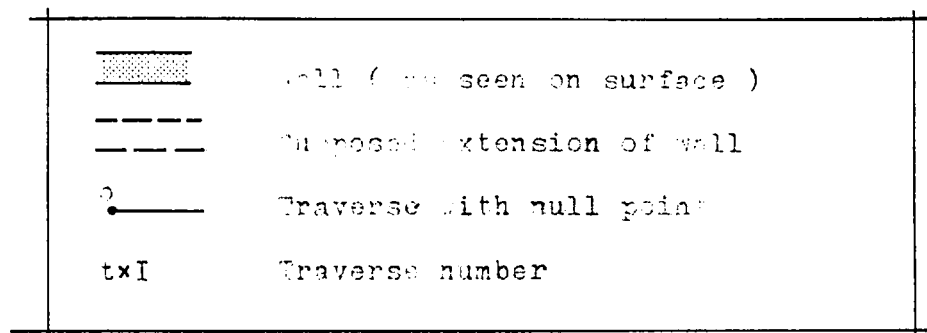




TEL LACHISH
RESISTIVITY SURVEY
AREA B

Diagram B1

E-6

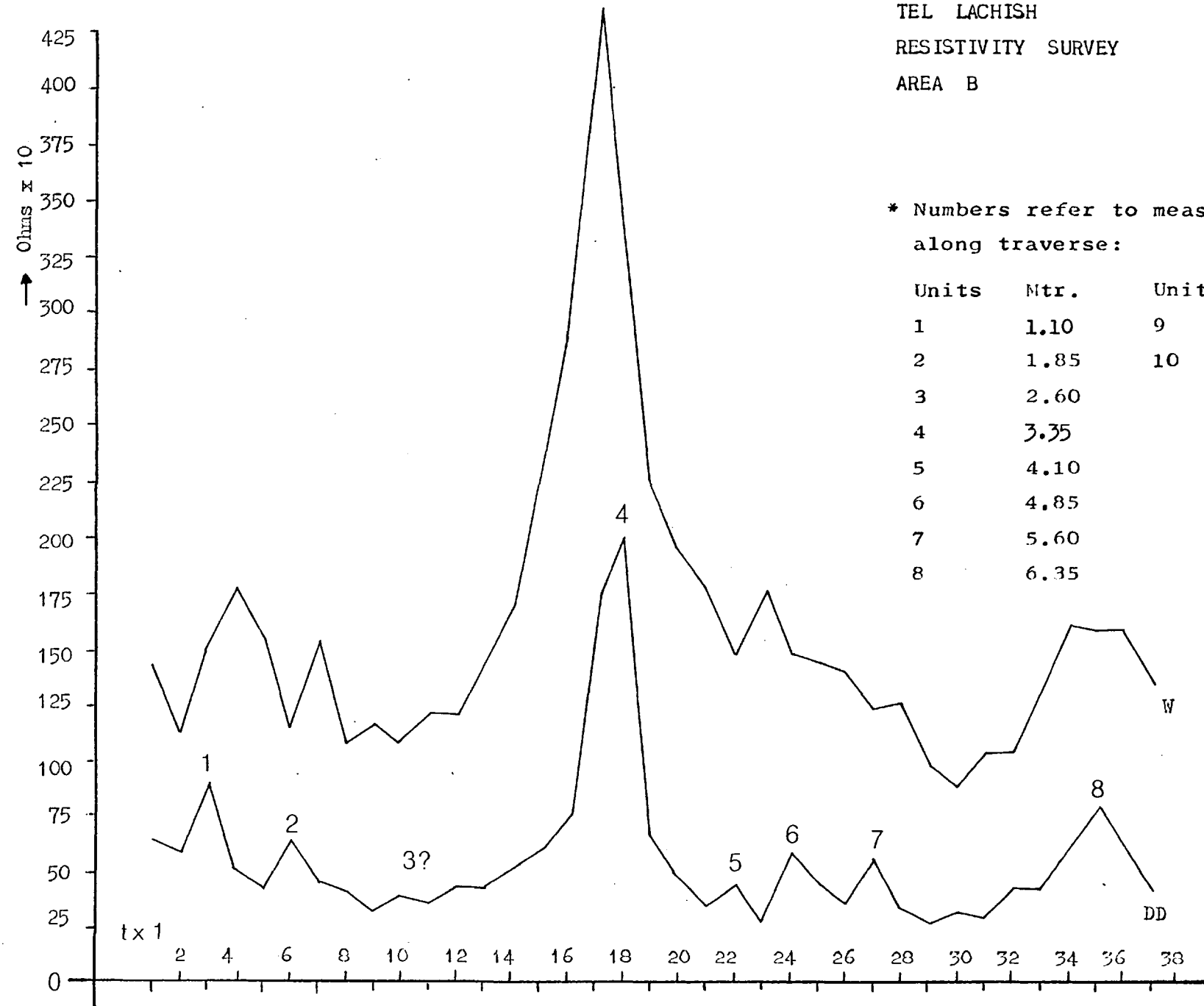


TEL LACHISH
RESISTIVITY SURVEY
AREA B

Diagram B2

* Numbers refer to measurement positions
along traverse:

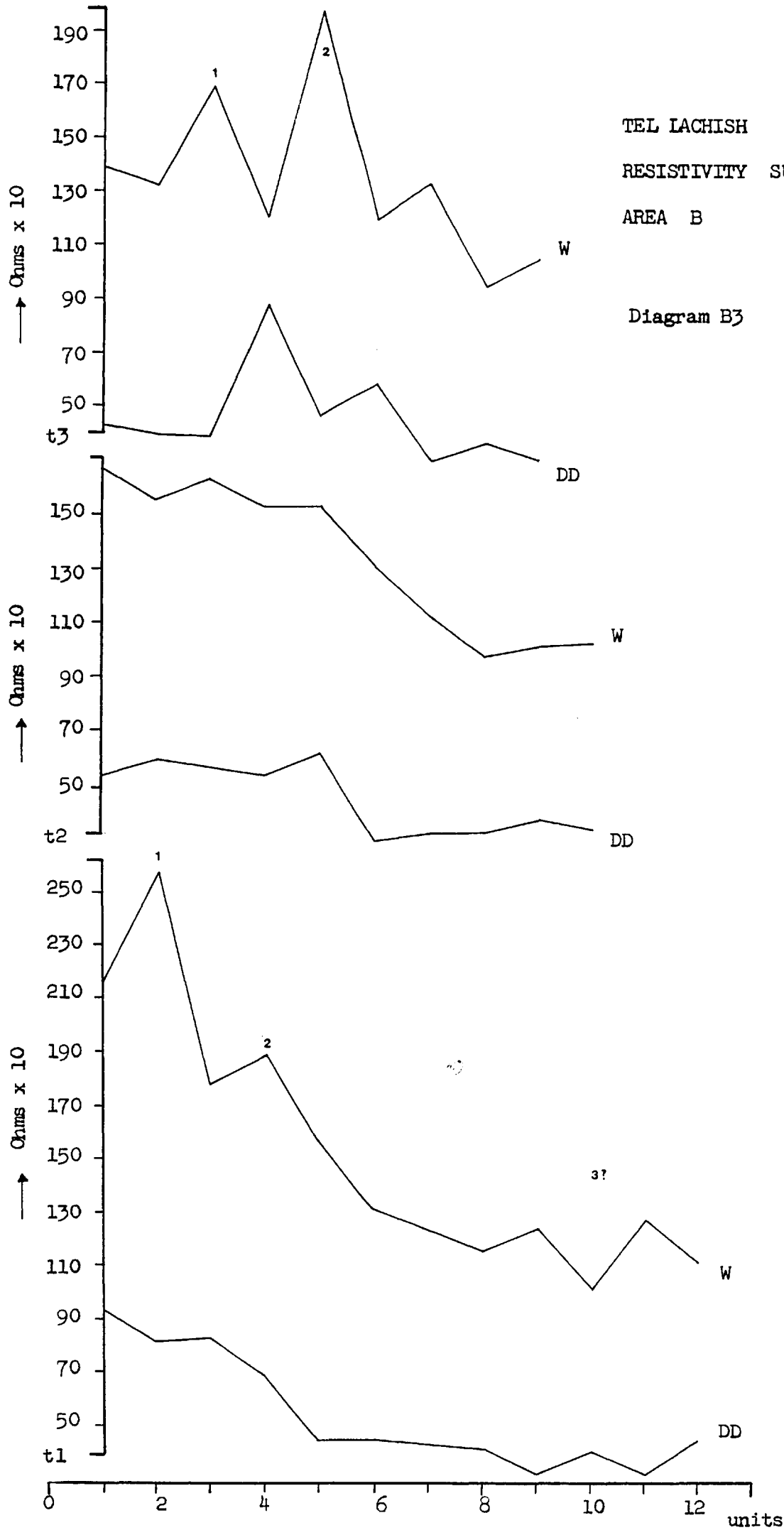
Units	Mtr.	Units	Mtr.
1	1.10	9	7.10
2	1.85	10	7.10 + 0.75 etc
3	2.60		
4	3.35		
5	4.10		
6	4.85		
7	5.60		
8	6.35		



$a=0.75$ mtr
units *

TEL LACHISH
RESISTIVITY SURVEY
AREA B

Diagram B3

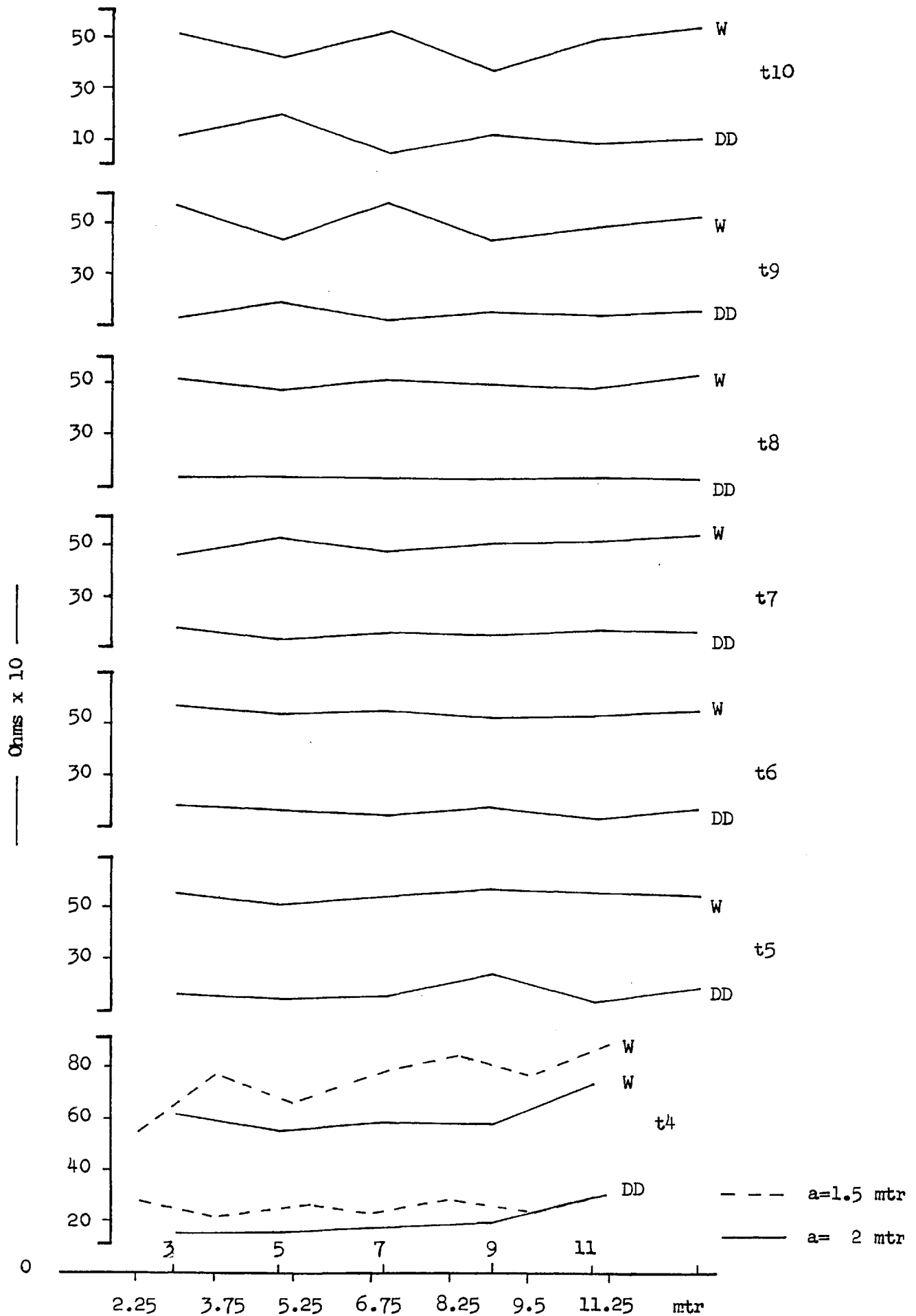


a=0.75 mtr

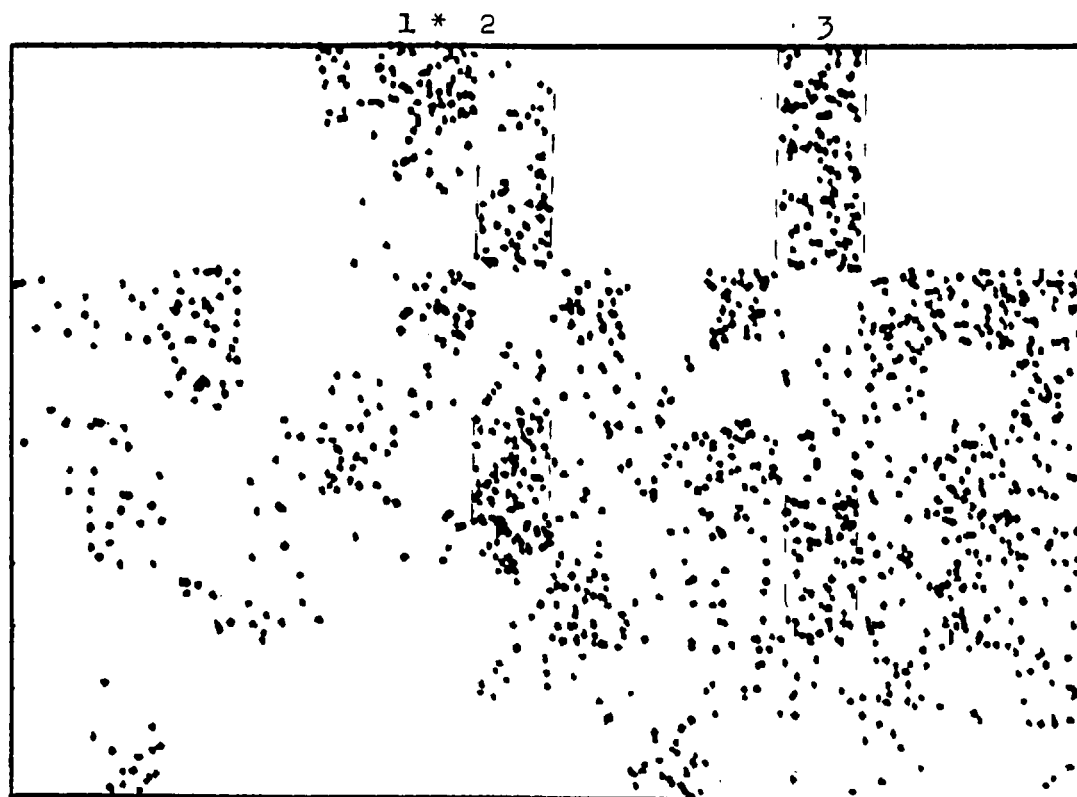
RESISTIVITY SURVEY

Diagram B4

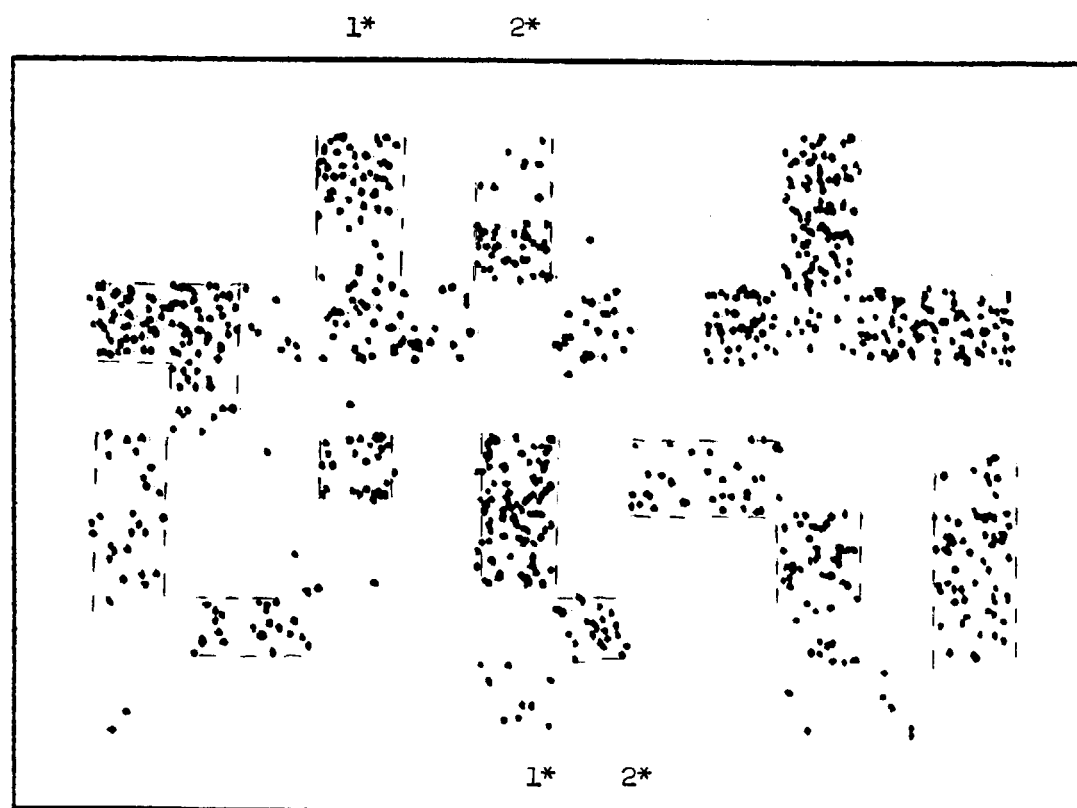
AREA B



TEL LACHISH



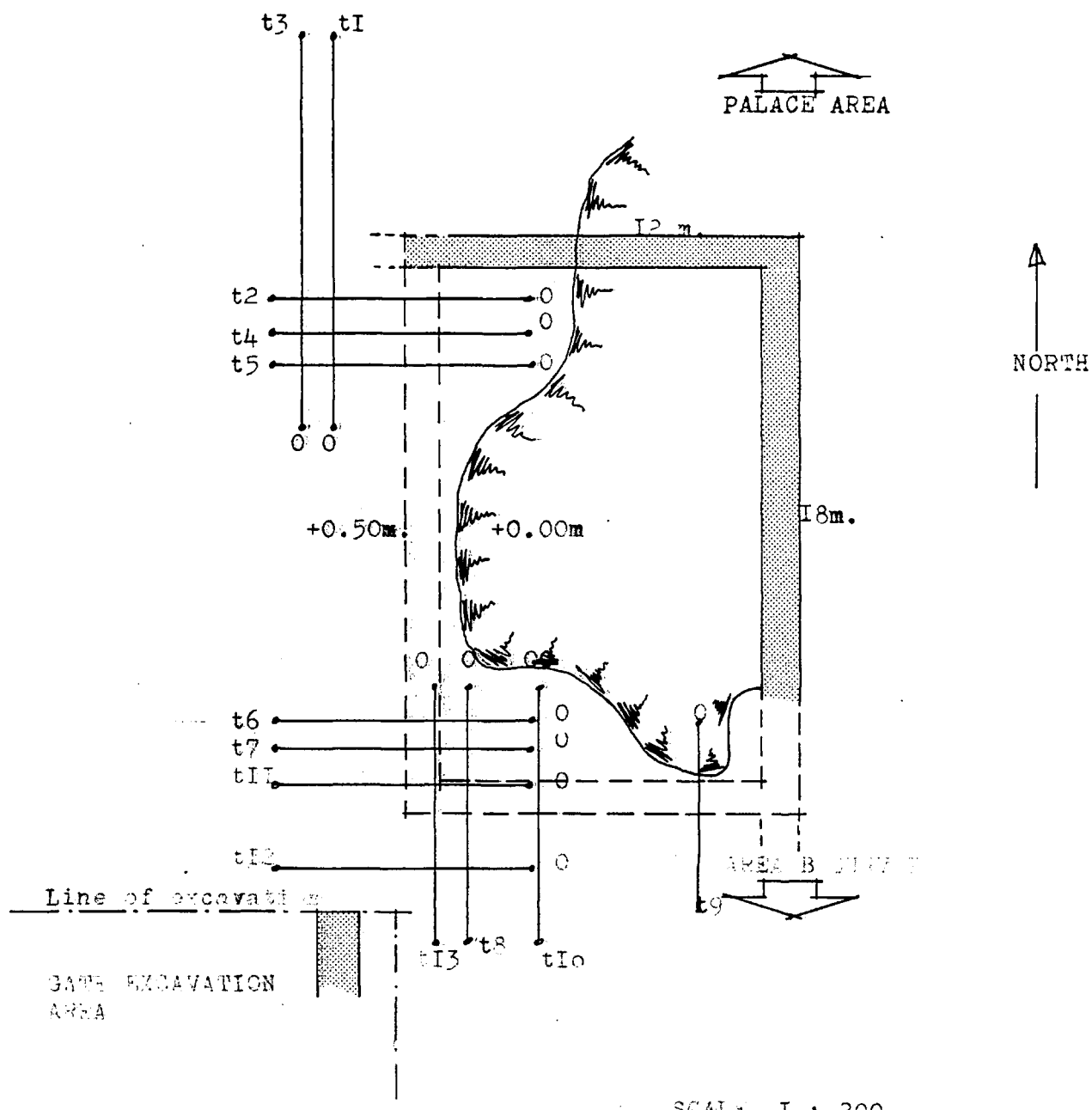
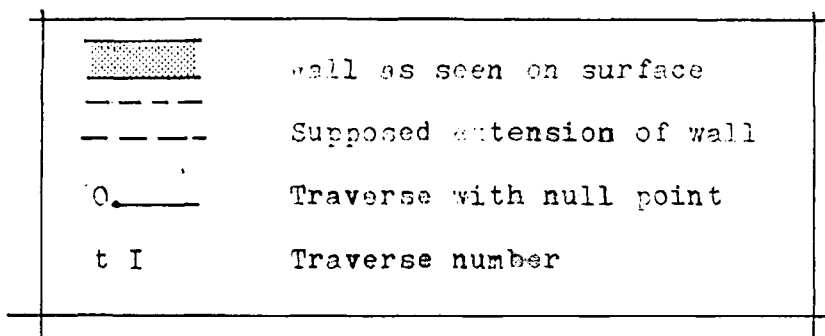
Plot B1 Dipole Dipole results Area B
 Unfiltered data
 Range: $\bar{x}$ to $\bar{x} + 2\sigma$
 Log plot
 Scale 1 : 200



Plot B2 Dipole Dipole results Area B
 High-pass 4 element square residual filter, radius 1
 Range: $\bar{x}$ to $\bar{x} + 2\sigma$
 Log plot

Diagram C1

TEL LACHISH
RESISTIVITY SURVEY
AREA C



TEL LACHISH

RESISTIVITY SURVEY

AREA C

Diagram C2

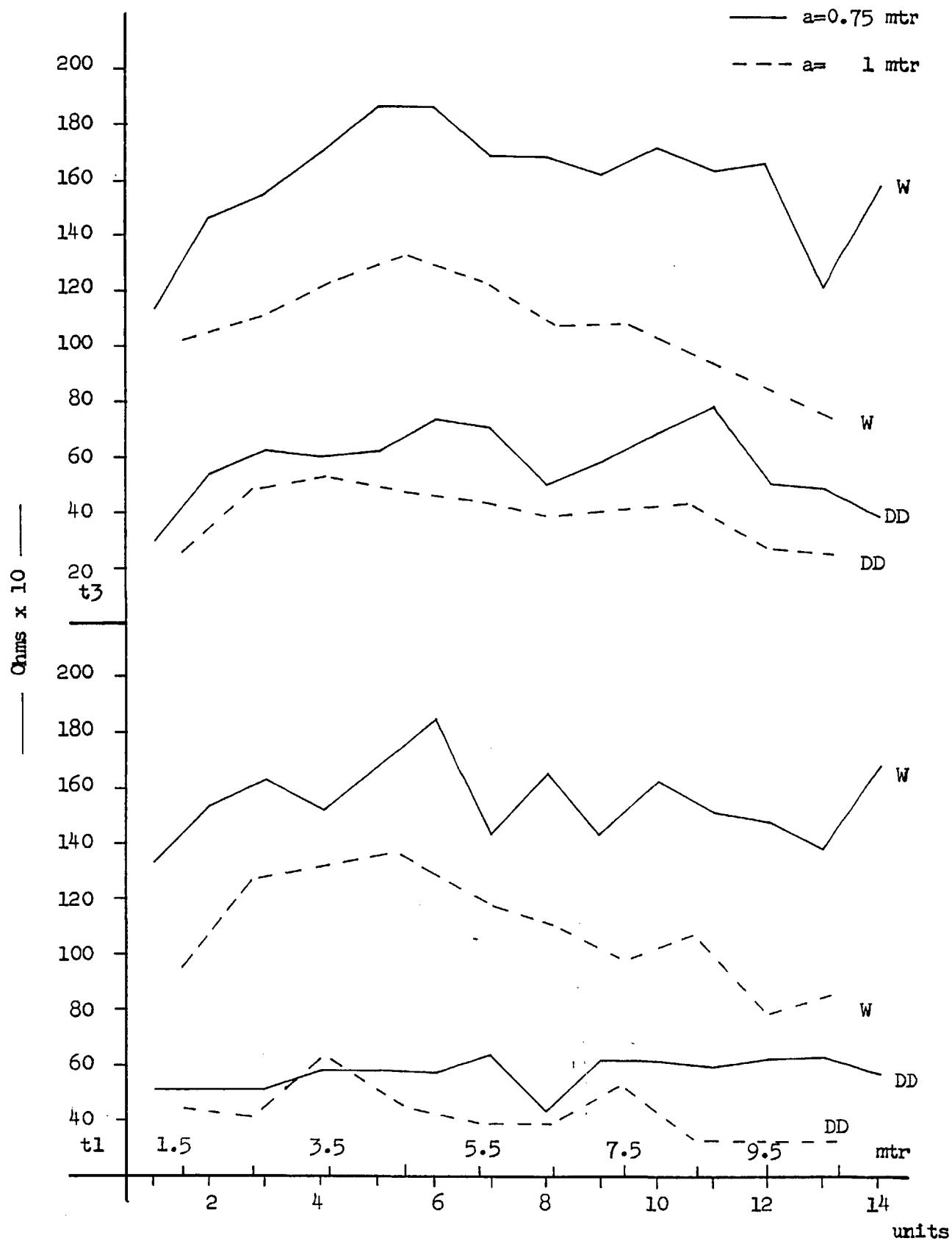
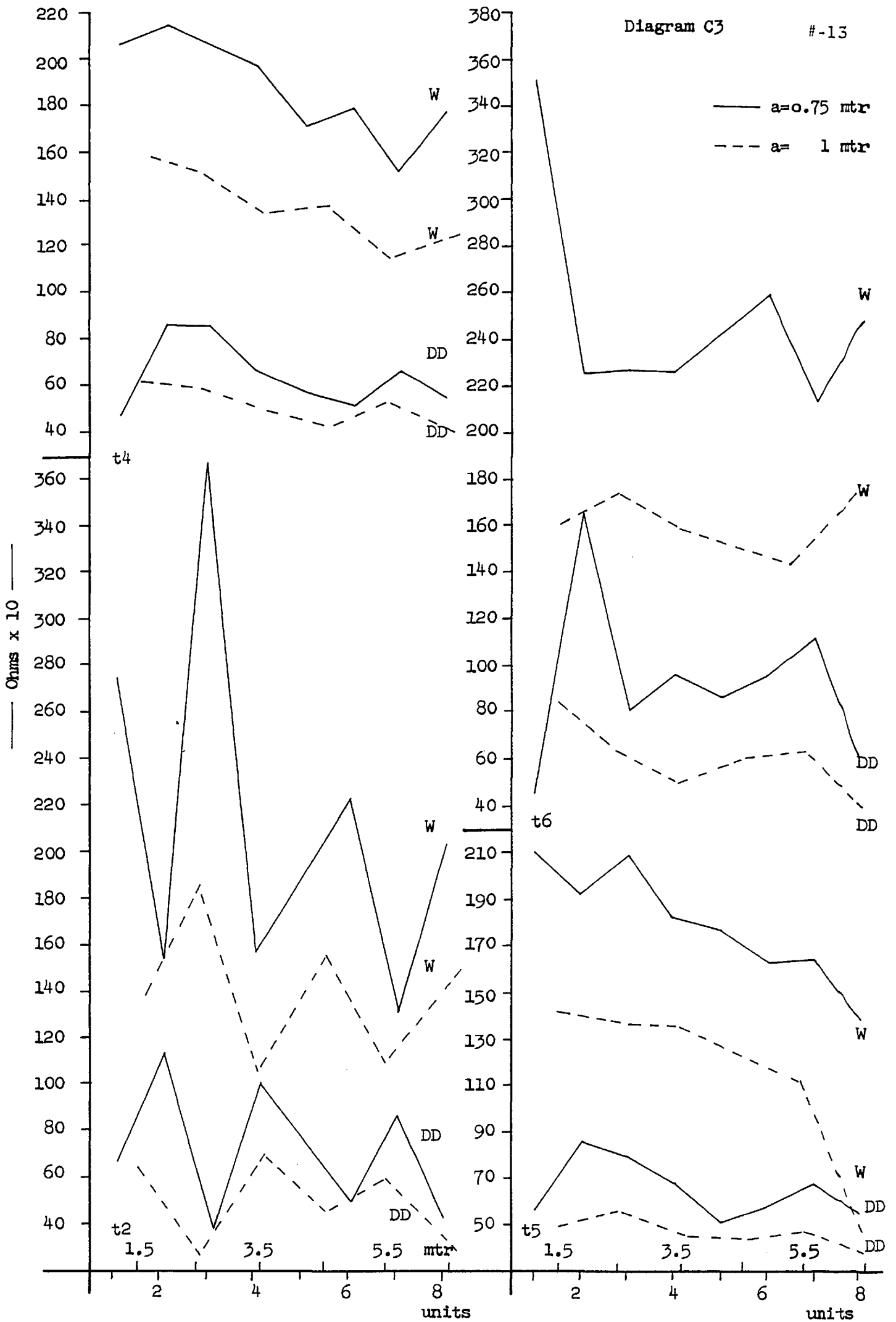


Diagram C3

#-13



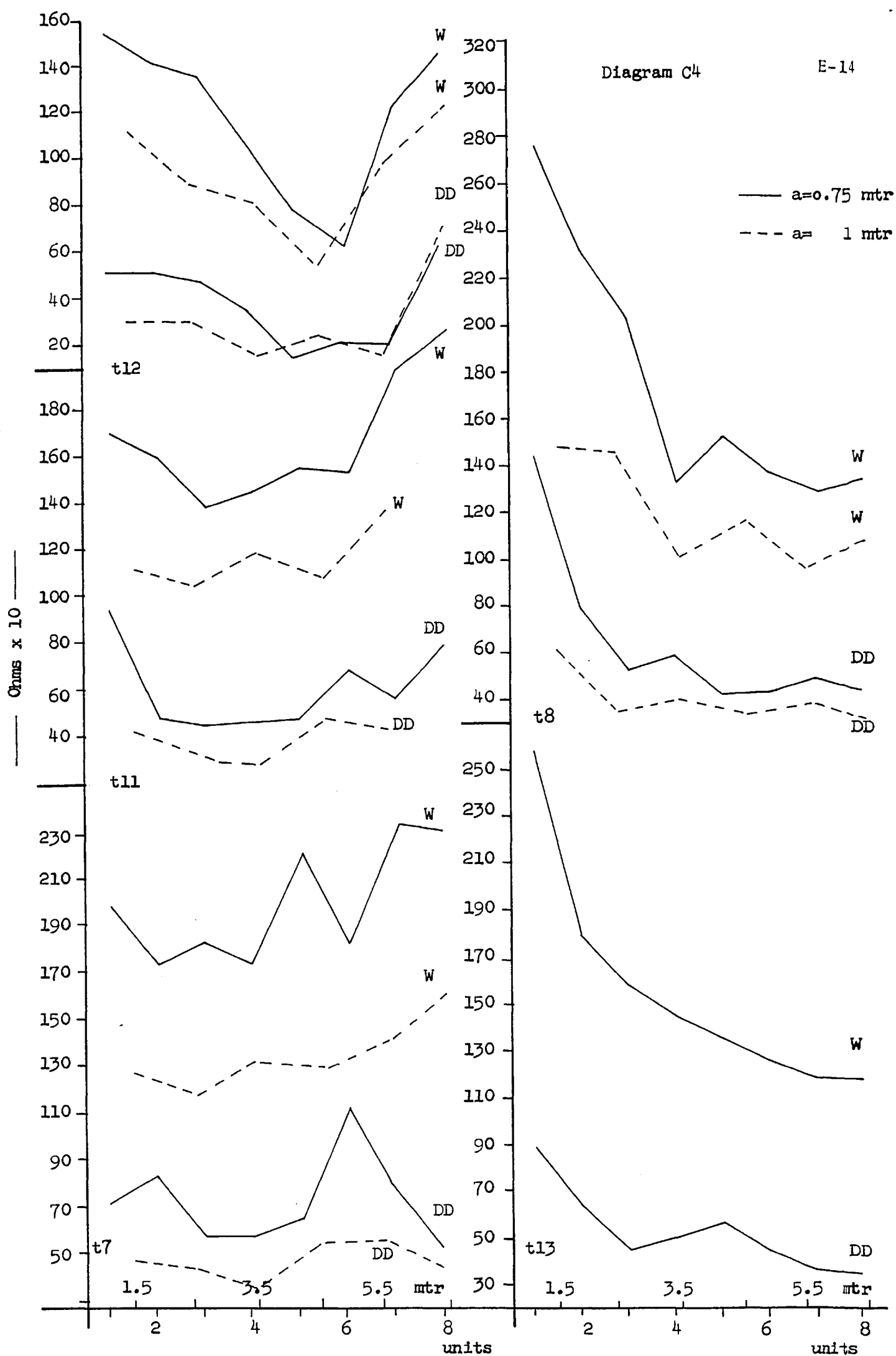
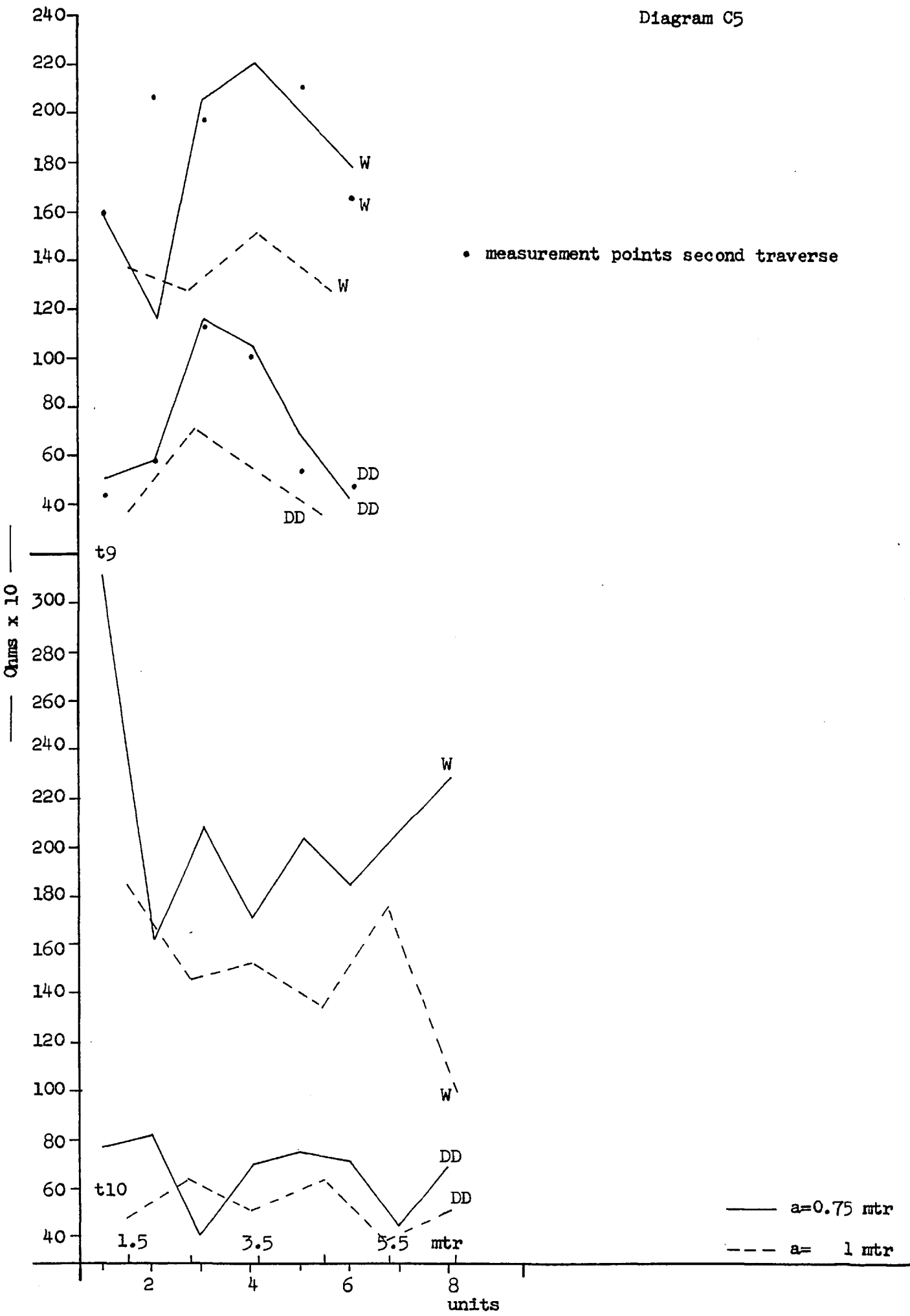


Diagram C5

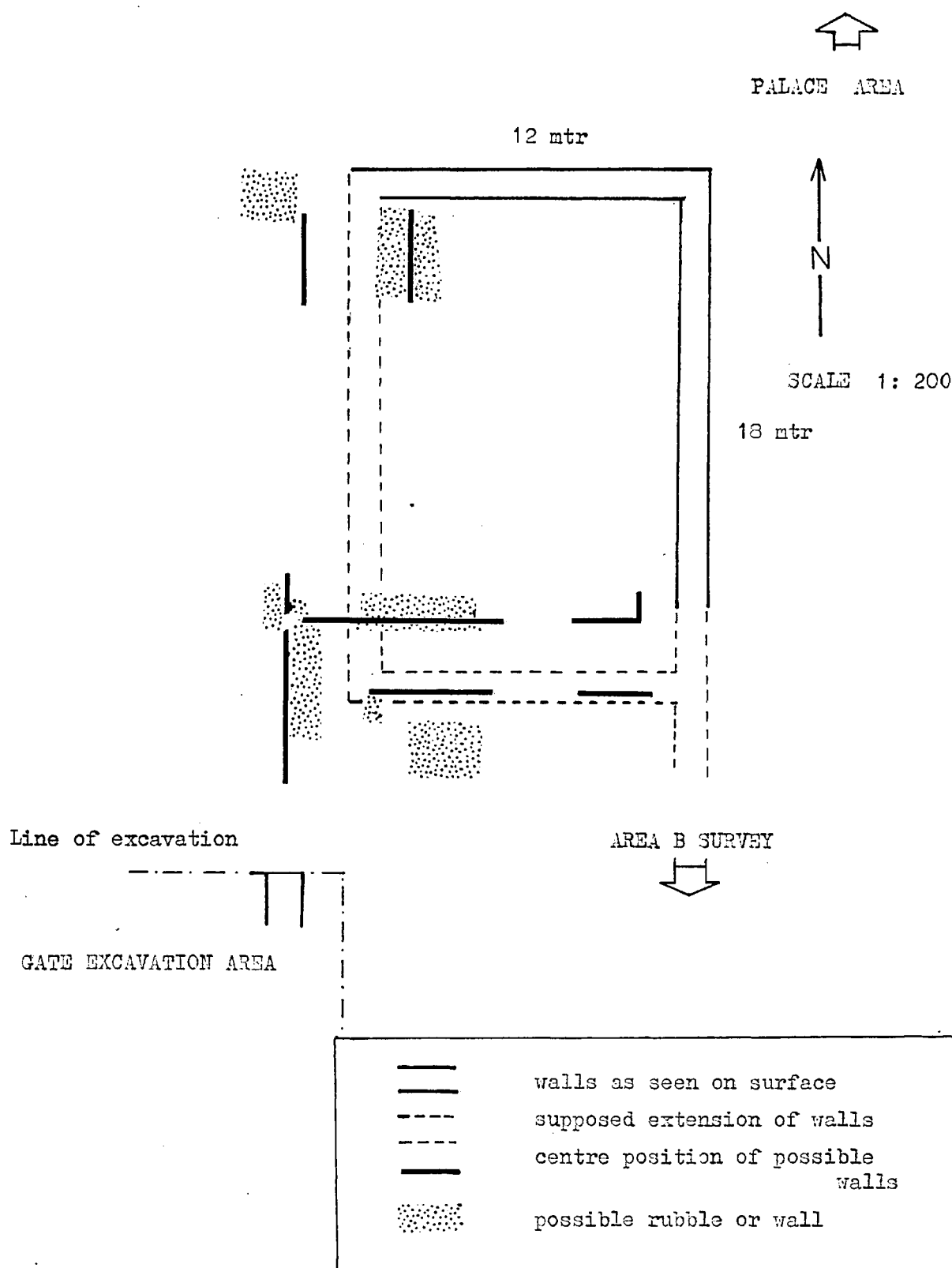


TEL LACHISH
RESISTIVITY SURVEY

Diagram C6

AREA C

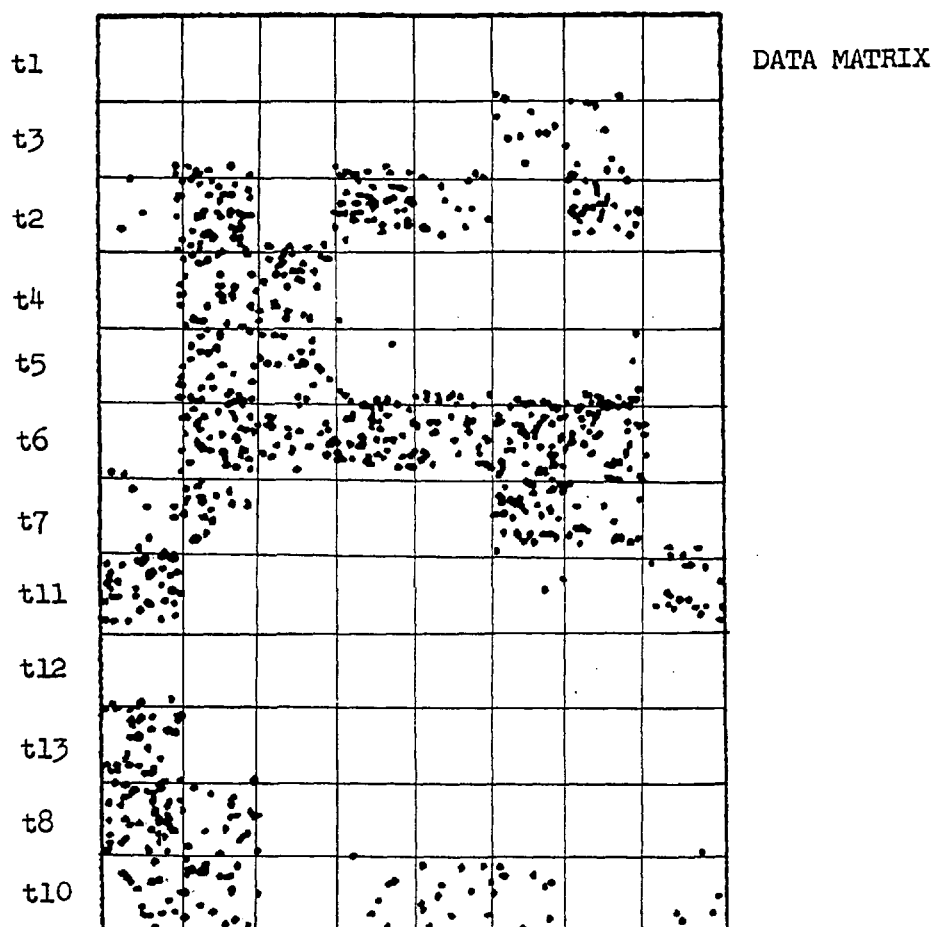
SUGGESTED POSITION OF ANOMALIES



All measurements are approximations

TEL LACHISH

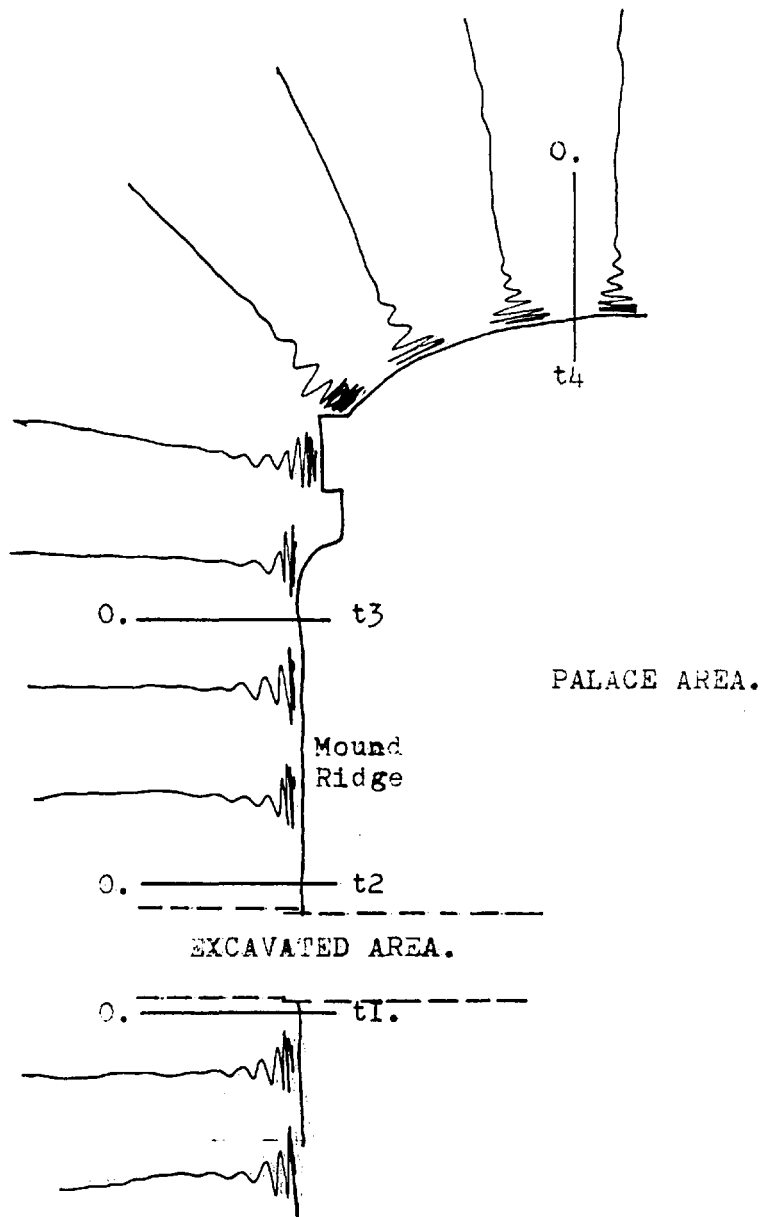
Traverse numbers



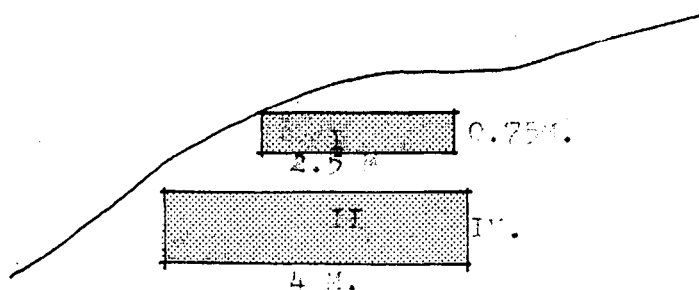
Plot 1C Dipole Dipole results Area C
Unfiltered data
Range: $\bar{x}$ to $\bar{x} + 2\sigma$
Log plot
Scale 1 : 200

Diagram D1

TEL LACHISH
RESISTIVITY SURVEY
AREA L
CITY WALL



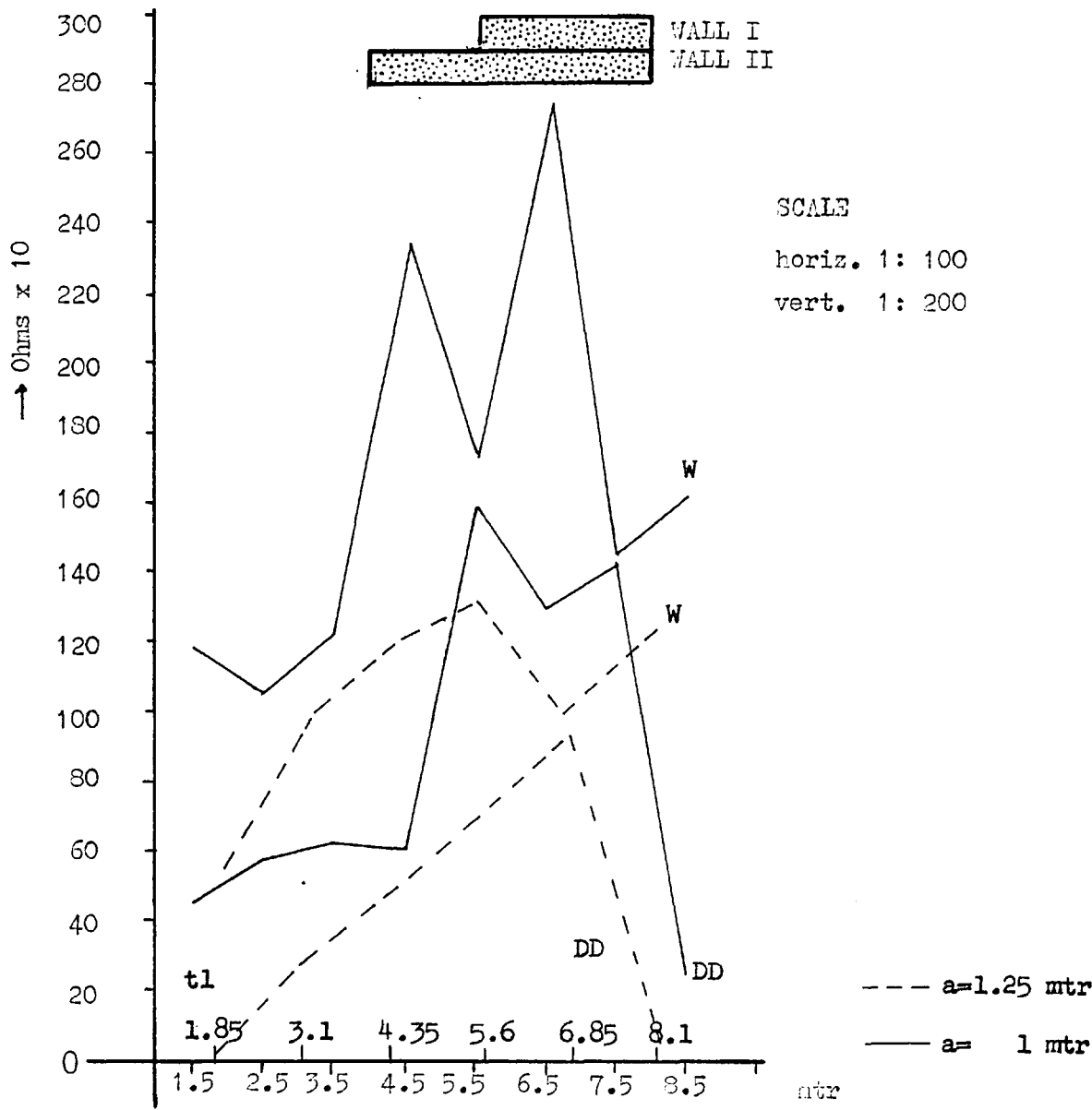
THIS DRAWING IS NOT
TO SCALE AND ONLY
SHOWS APPROXIMATE
POSITIONS OF TRAVERSES.
t1-t4 10 Meters long

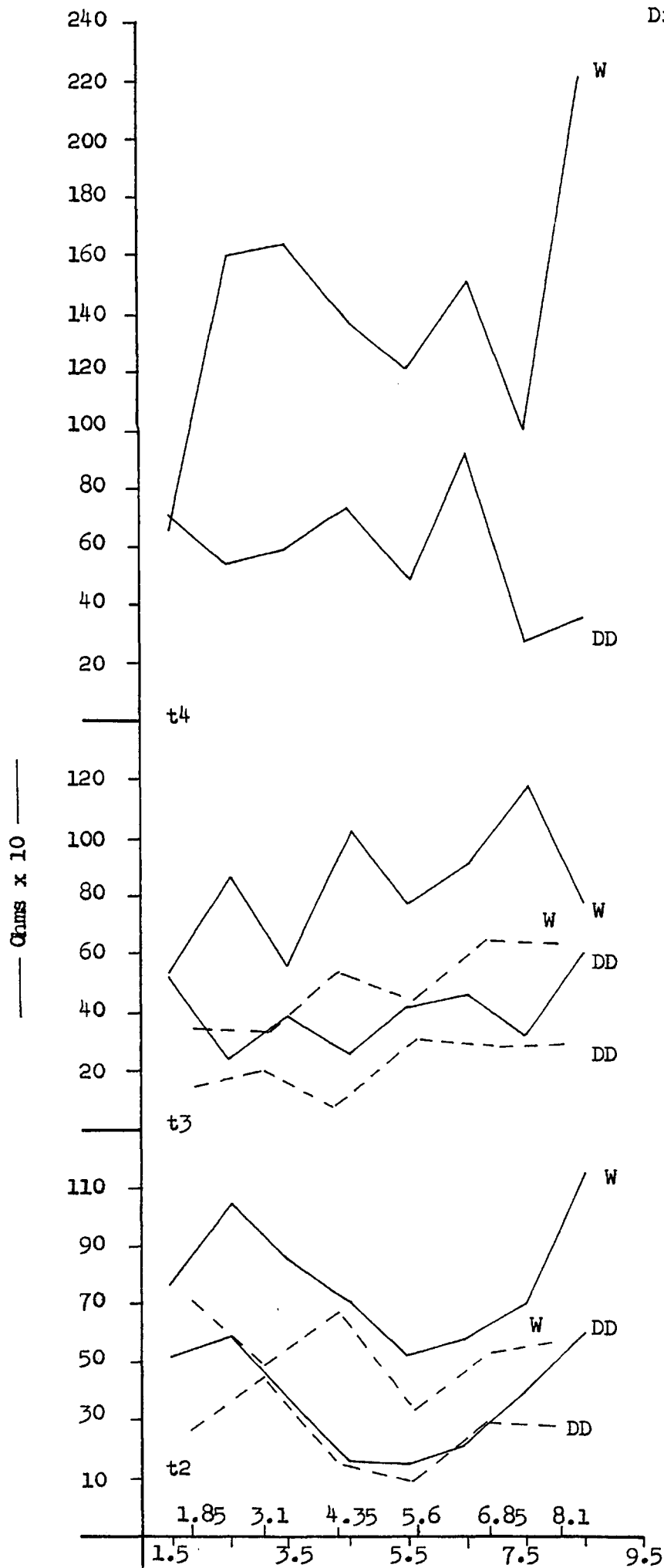


CROSS SECTION THROUGH
CITY WALL VIEWED FROM
EXCAVATION AREA.
SCALE 1 : 100.
I : UPPER CITY WALL
II : LOWER CITY WALL.

Diagram D2

TEL LACHISH
RESISTIVITY SURVEY
AREA D
CITY WALL

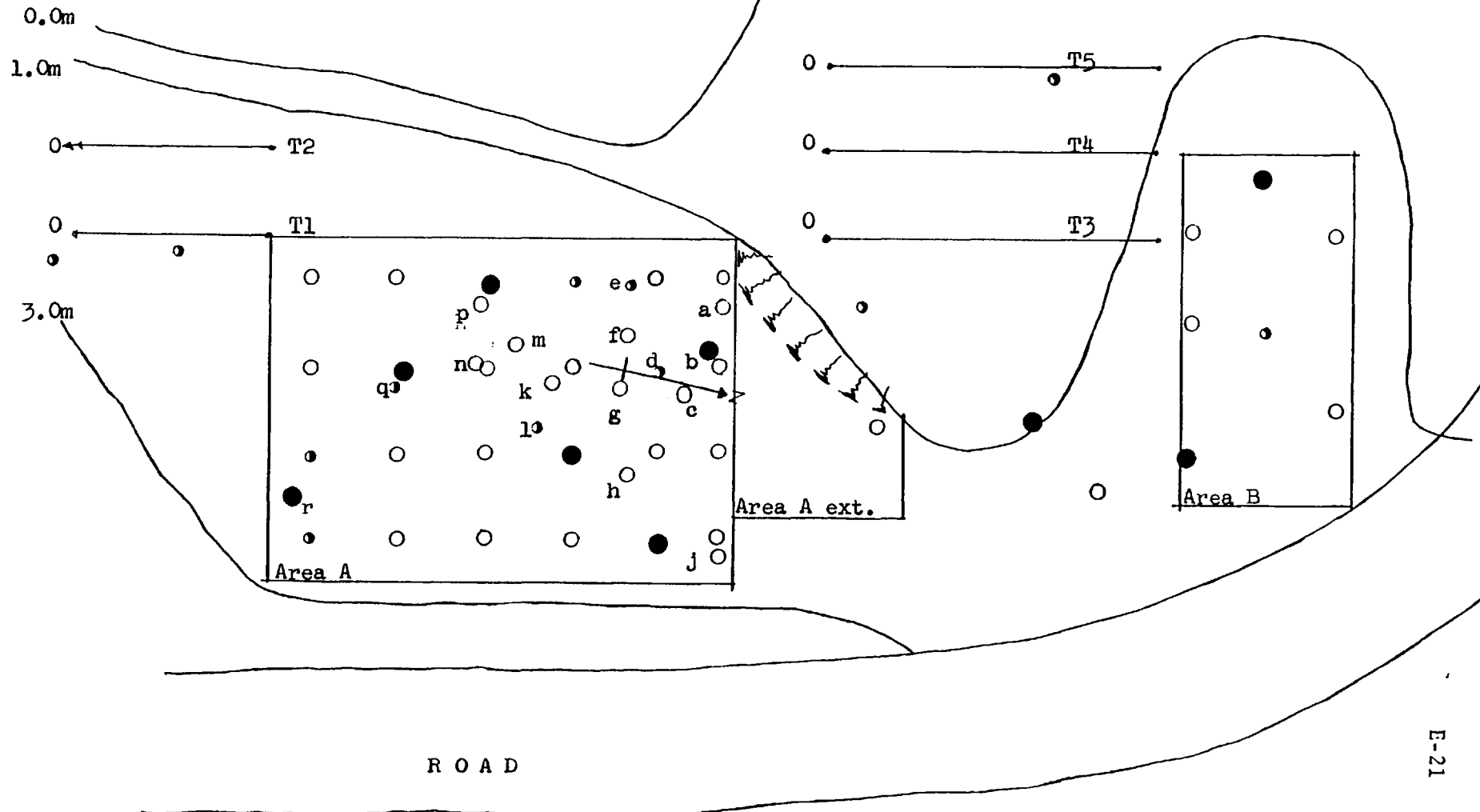
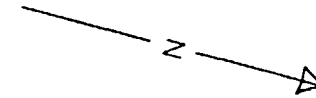
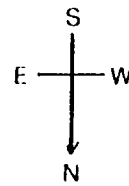




LACHISH CEMETERY 7000 SITE PLAN

PHOSPHATE ANALYSIS

●	strong
○	medium
◦	weak

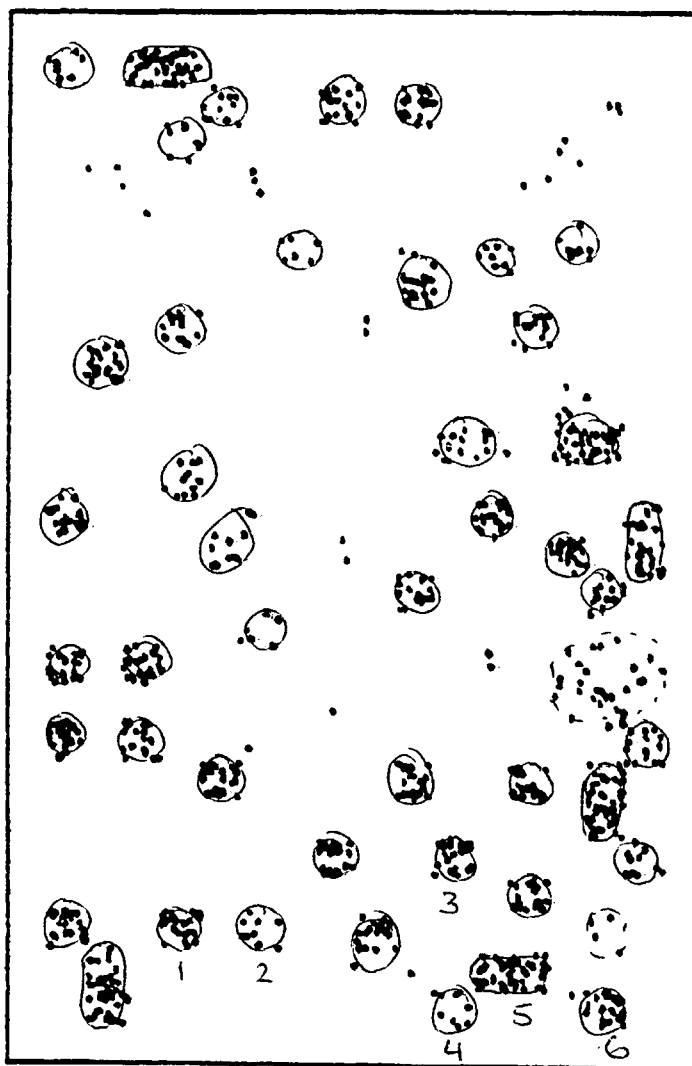


LACHISH CEMETERY



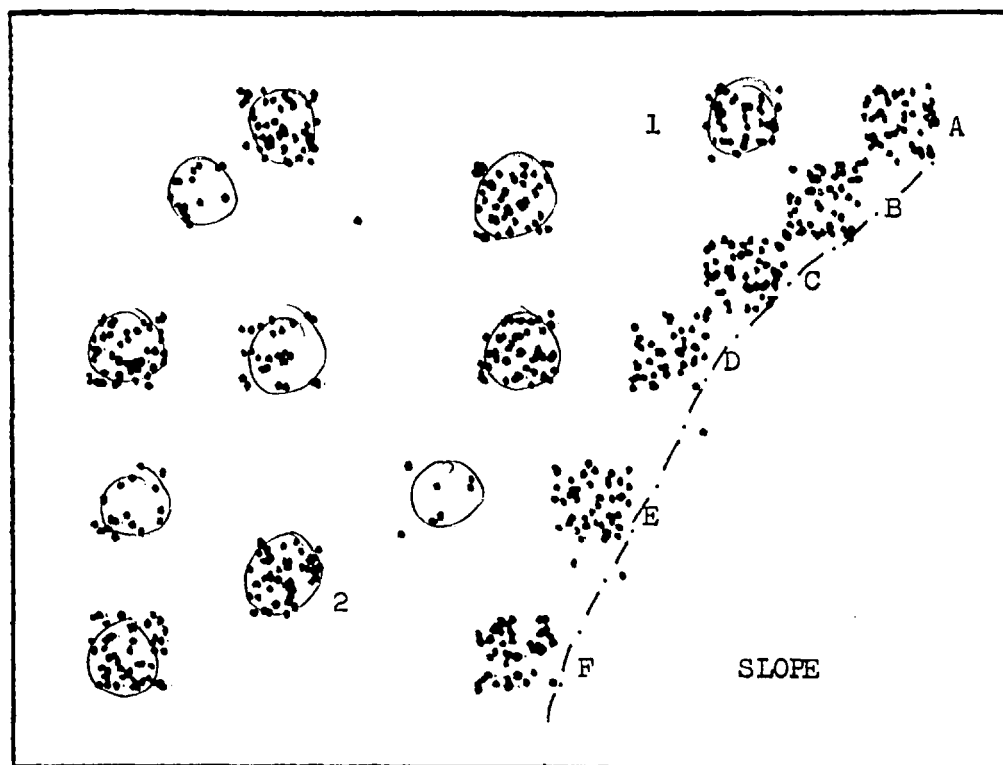
Plot 1A Dipole Dipole results Area A
Unfiltered data
Range: $\bar{x} - 2\sigma$ to $\bar{x} + 2\sigma$
Lin plot
Scale 1 : 200

LACHISH CEMETERY

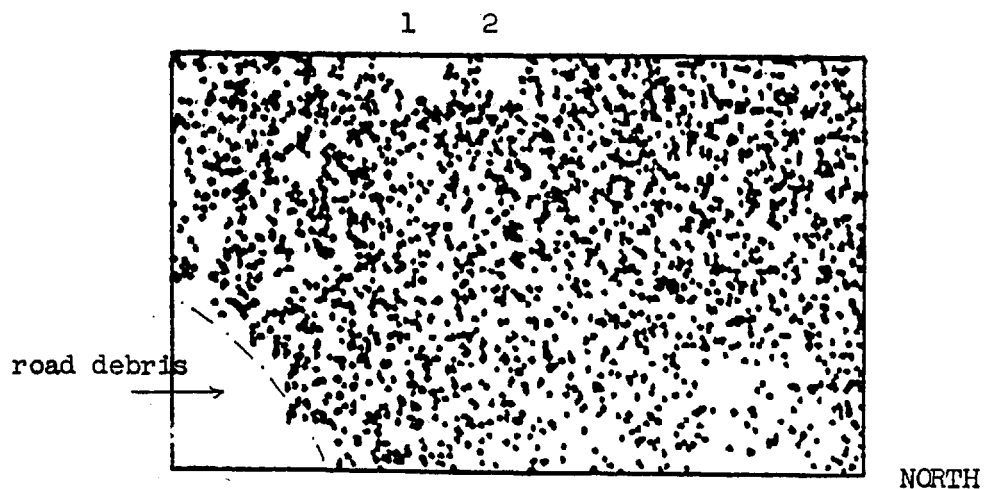


Plot 2A Dipole Dipole results Area A
High-pass 4 element ring residual filter, radius 1
Range: $\bar{x} - 0.75\sigma$ to $\bar{x} - 2\sigma$
Log plot

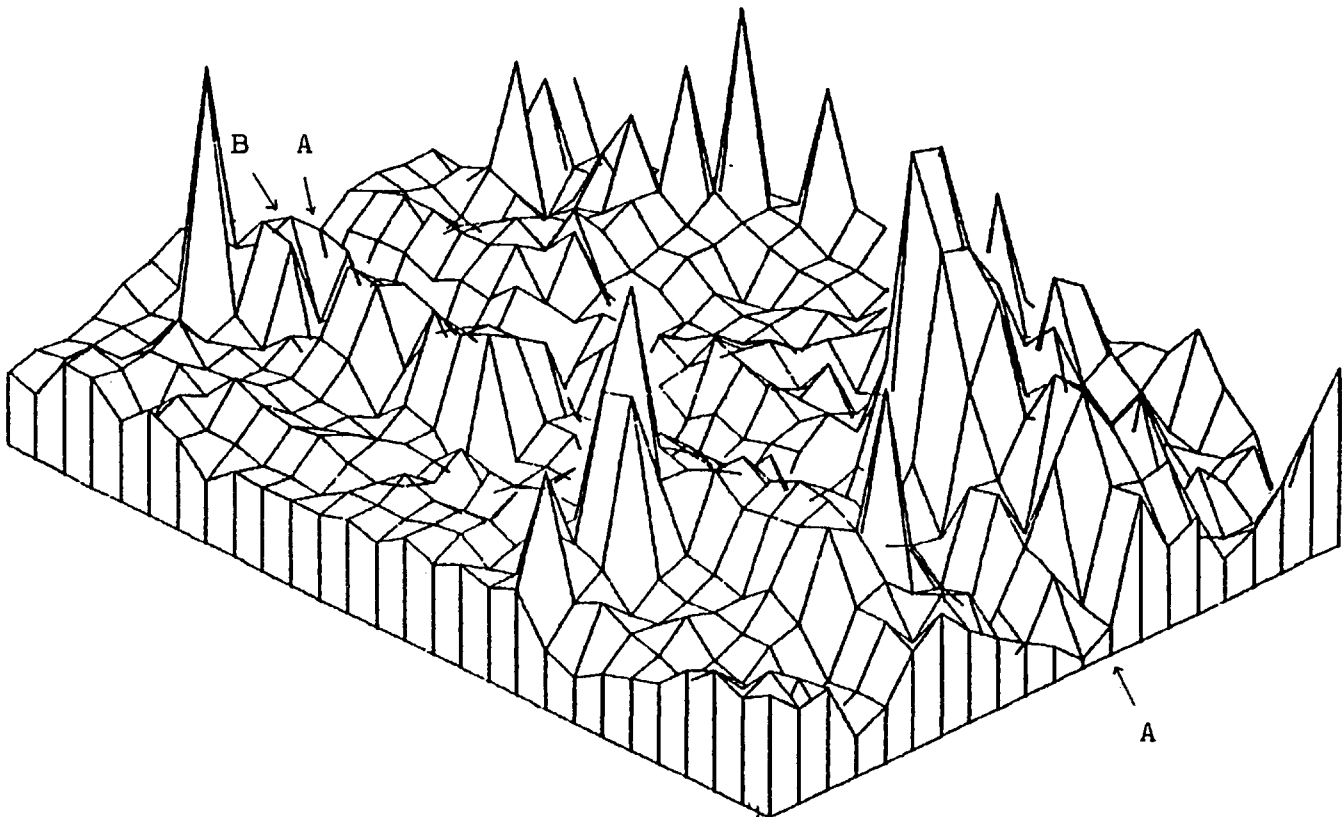
LACHISH CEMETERY



Plot 1B Dipole Dipole results Area A extension
 High-pass 4 element ring residual filter, radius 1
 Range: $\bar{x} - 0.75\sigma$ to $\bar{x} - 2\sigma$
 Log plot



Plot 1C Dipole Dipole results Area B
 Unfiltered data
 Range: $\bar{x} - 2\sigma$ to $\bar{x} + 2\sigma$
 Lin plot



Plot 1D Facet plot of the entire distribution
Magnetometer results Area A

LACHISH CEMETERY



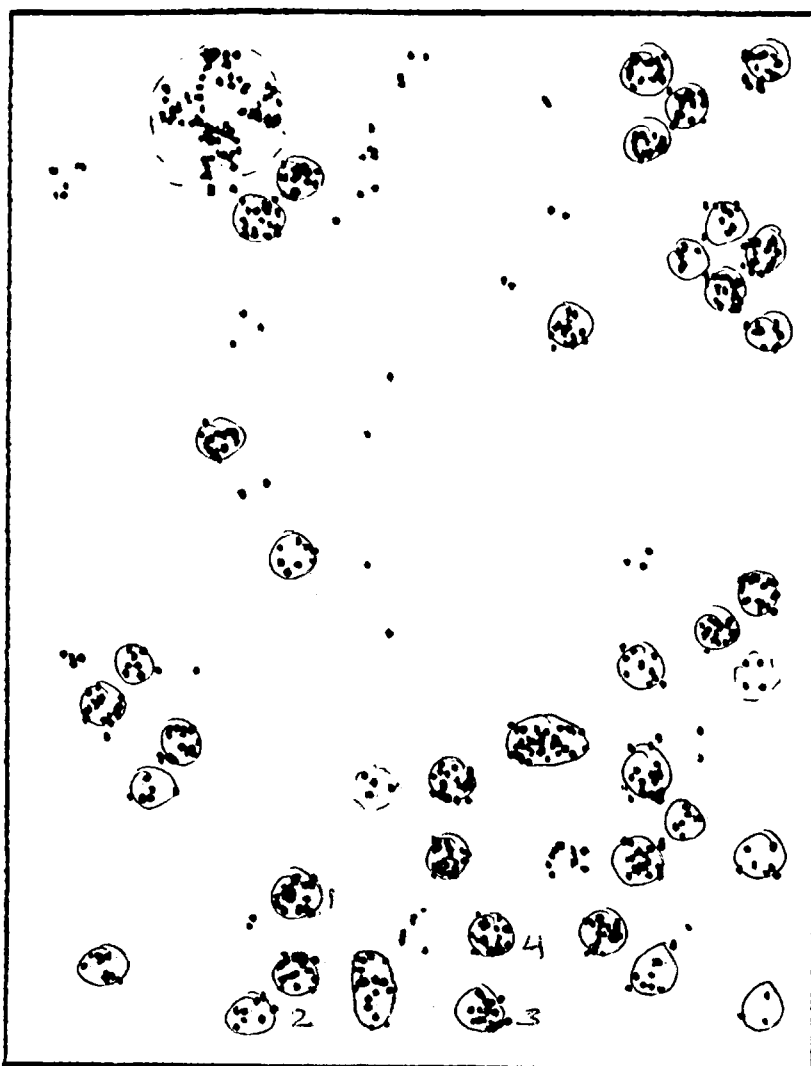
Plot 3D Magnetometer results Area A
Unfiltered data
Range: $\bar{x} - 0.25\sigma$ to $\bar{x} + 1.25\sigma$
Lin plot

LACHISH CEMETERY



Plot 2D Magnetometer results Area A
Unfiltered data
Range: $\bar{x} - 2\sigma$ to $\bar{x} + 2\sigma$
Lin plot
Scale 1 : 200

LACHISH CEMETERY



Plot 4D Magnetometer results Area A
 High-pass 4 element ring residual filter, radius 1
 Range: $\bar{x} - 0.75\sigma$ to $\bar{x} - 2\sigma$

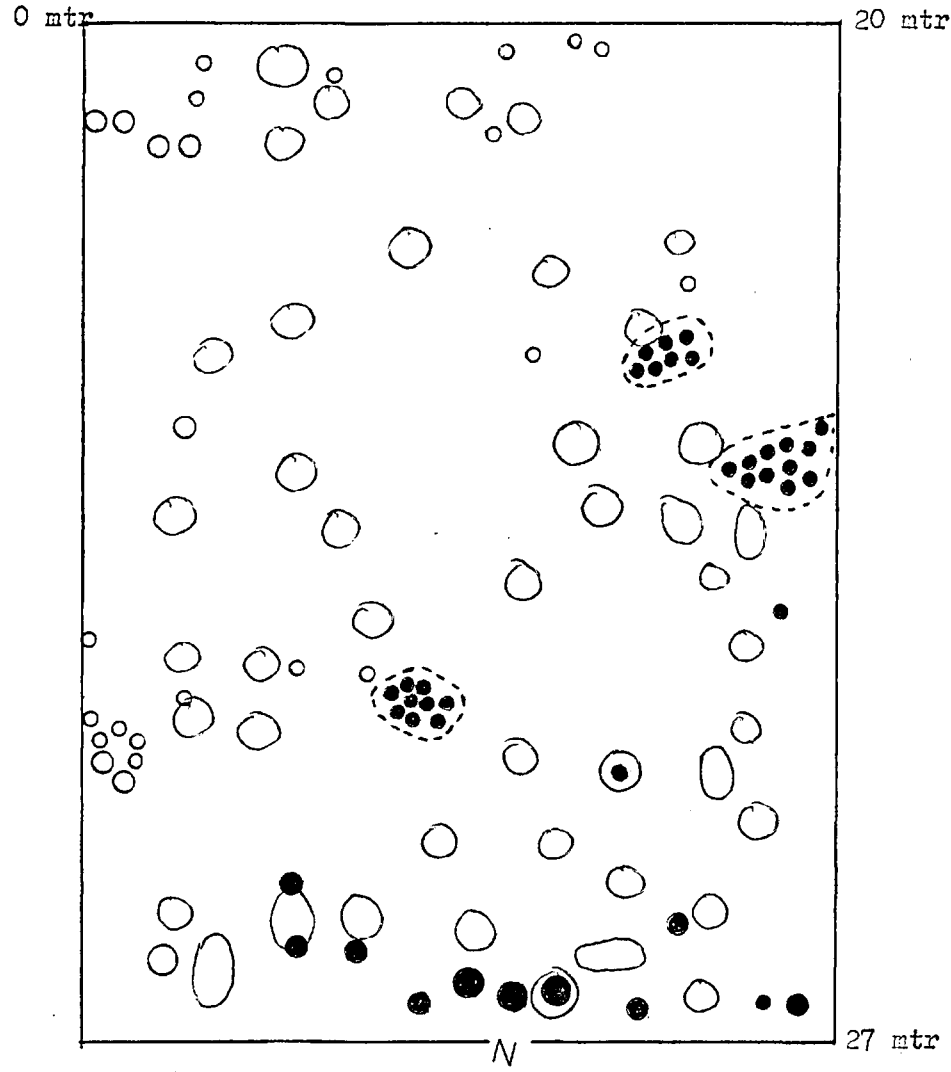


Plot 1E Magnetometer results Area B
 Unfiltered data
 Range: $\bar{x} - 2\sigma$ to $\bar{x} + 2\sigma$
 Lin plot

LACHISH CEMETERY 7000
ELECTROMAGNETIC SURVEY
AREA A

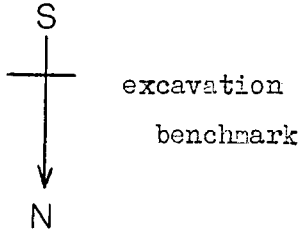
Diagram L1

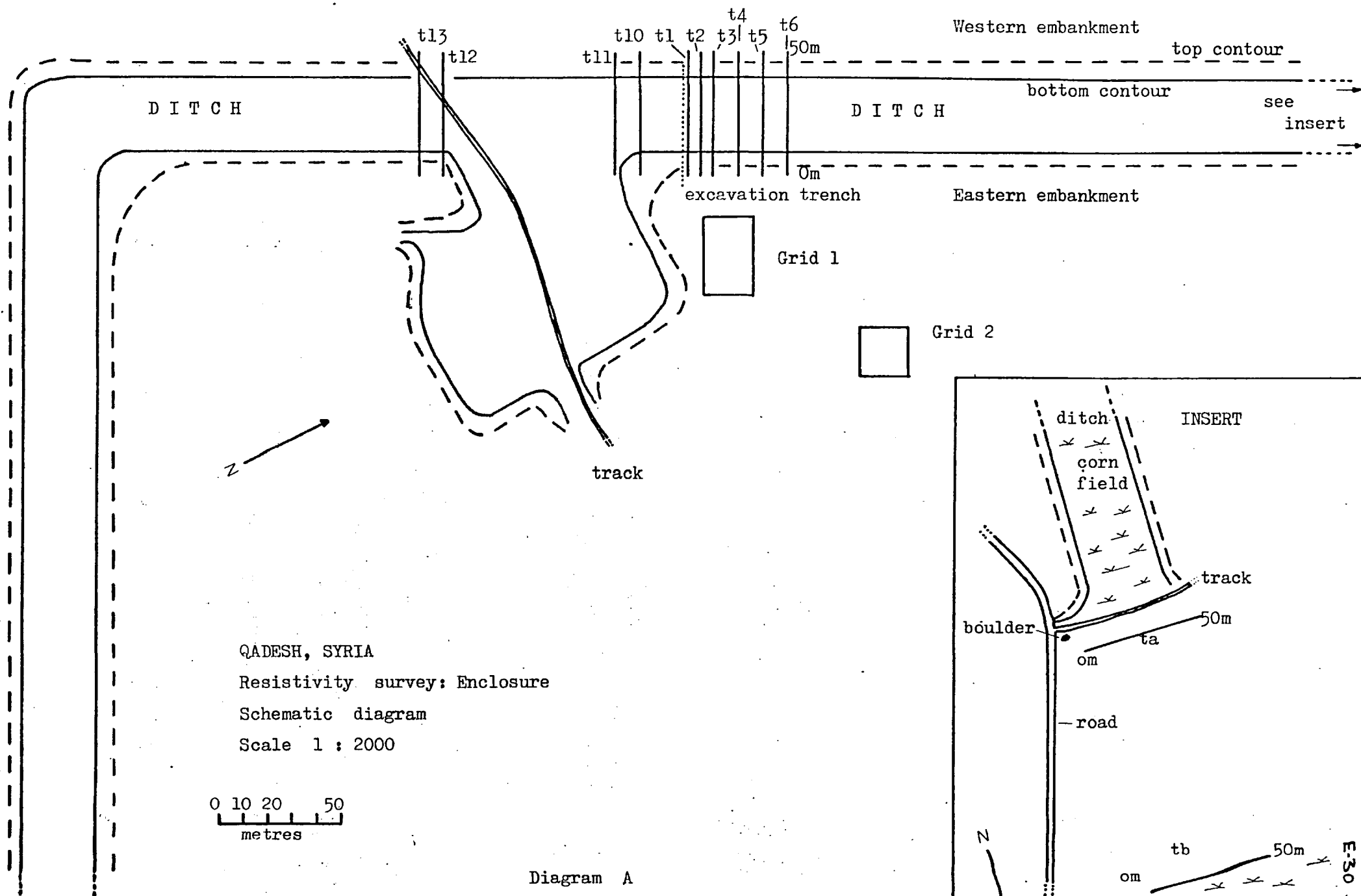
SCALE 1: 200

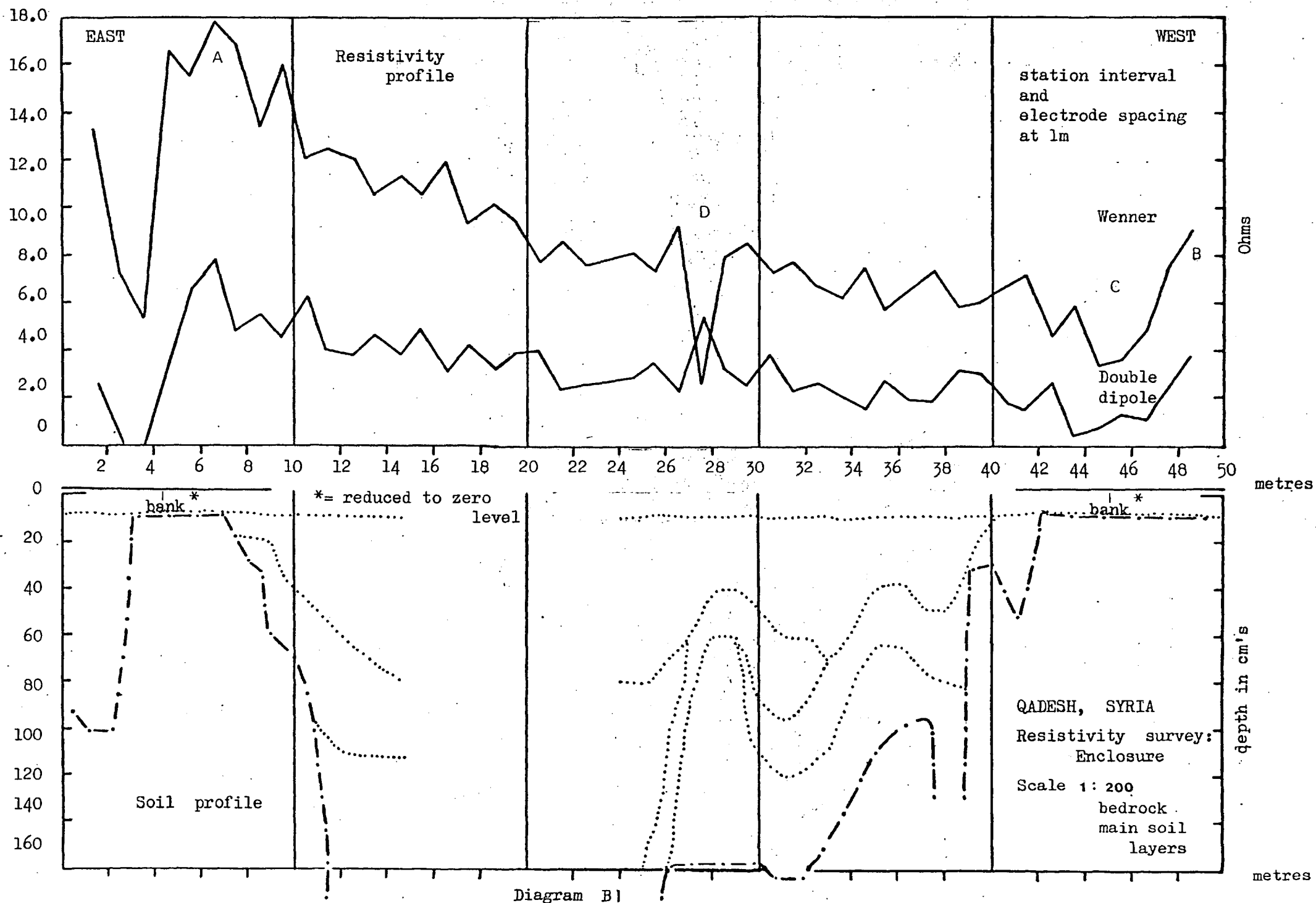


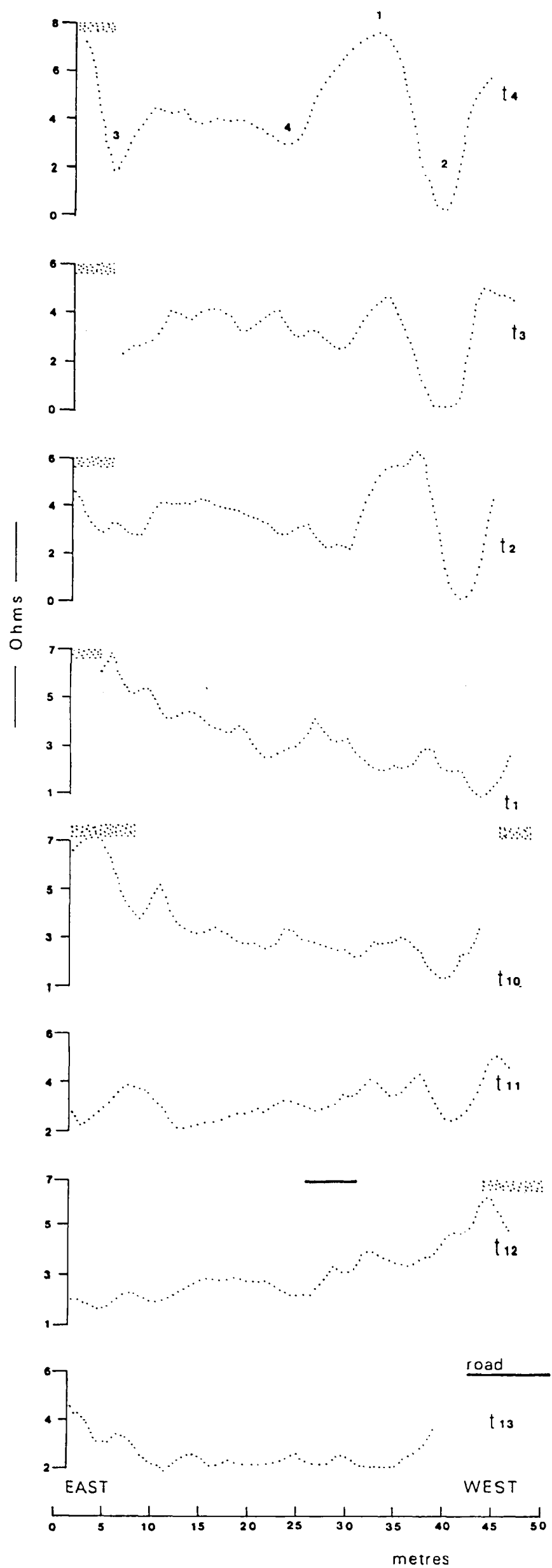
Instrument response:

ferrous	non-ferrous
○ high	● high
○ medium	● medium
○ weak	● weak
 soil response (stony areas)	









Qadesh, Syria

Resistivity survey: Enclosure -DD-

Scale: horiz. 1:500; vert. 1:200 1:400

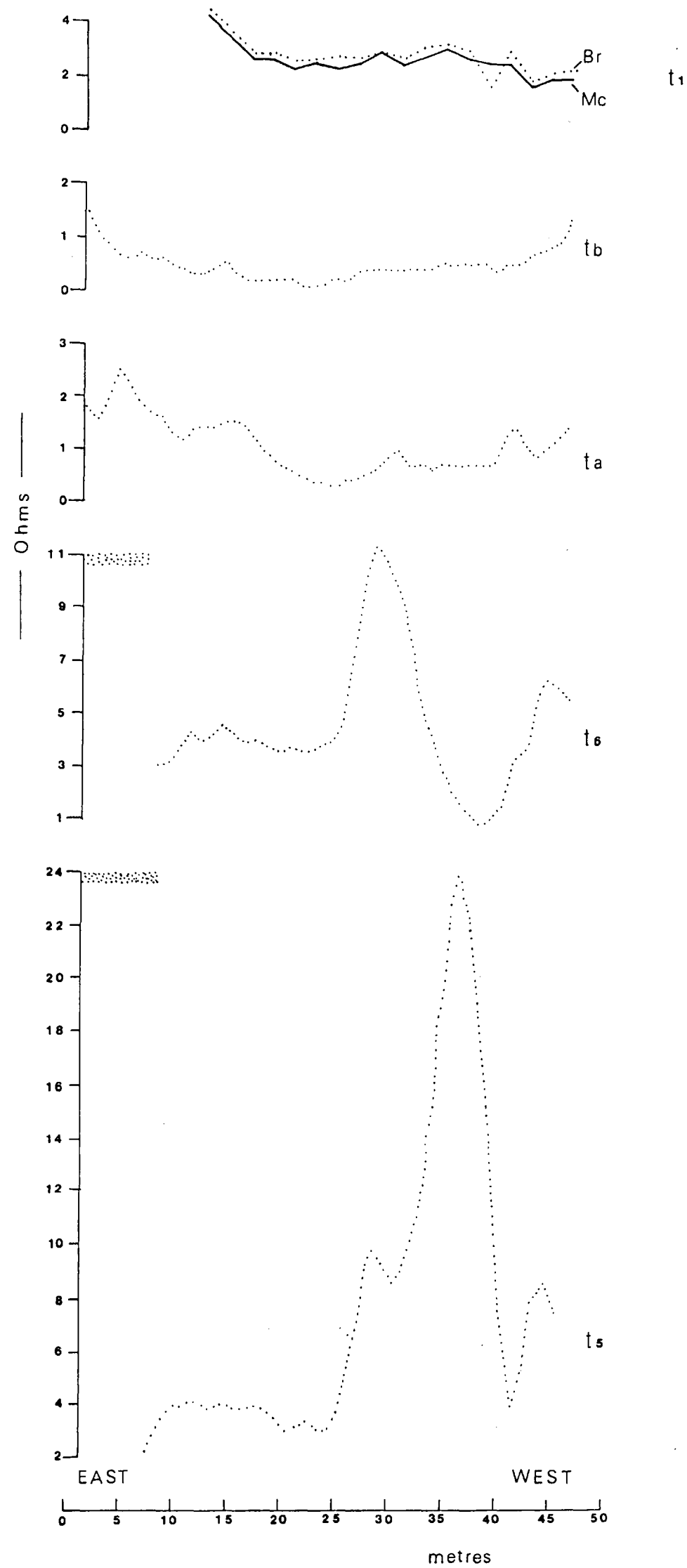
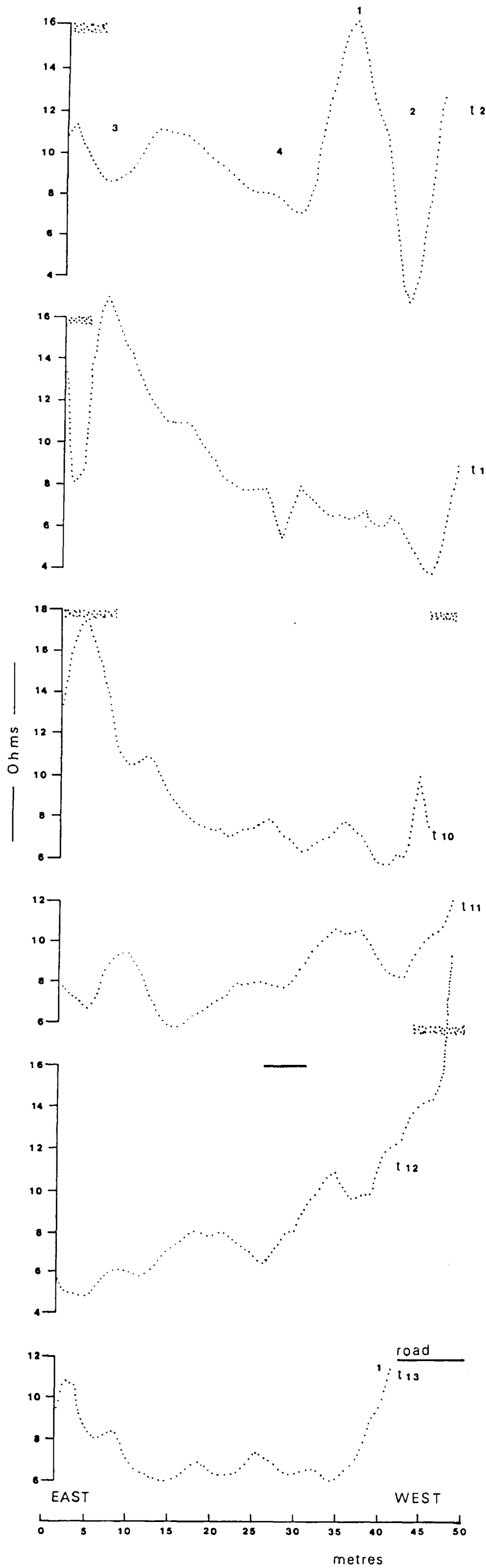


Diagram B2



Qadesh, Syria

Resistivity survey: Enclosure -W-

Scale: horiz. 1:500; vert. 1:200; 1:400

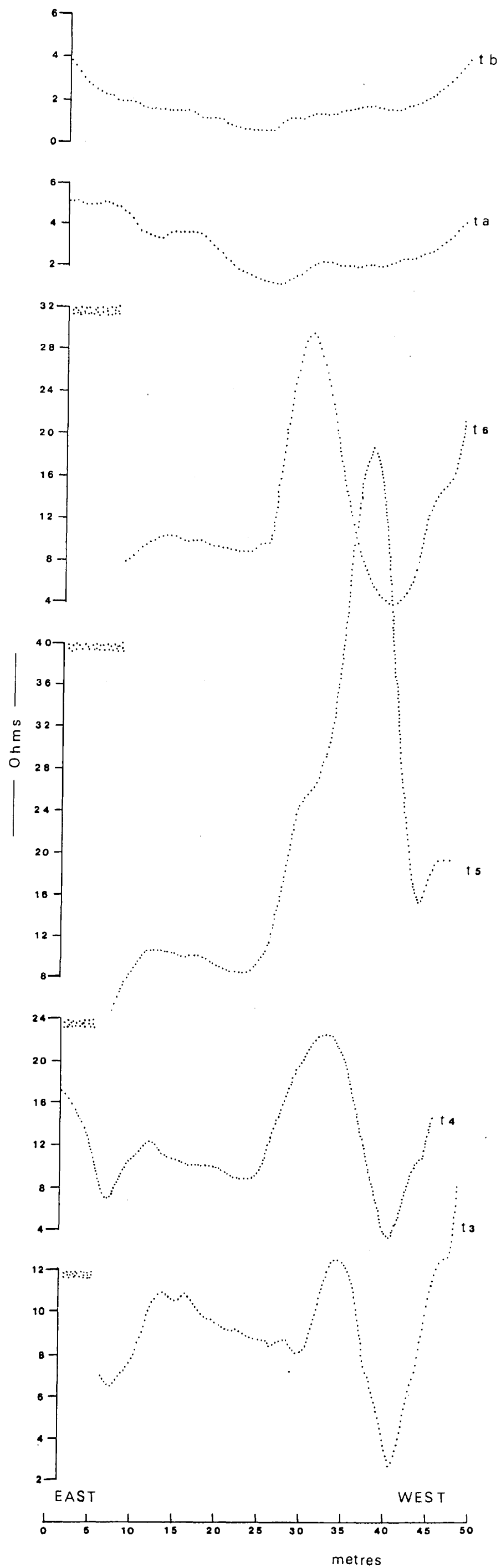
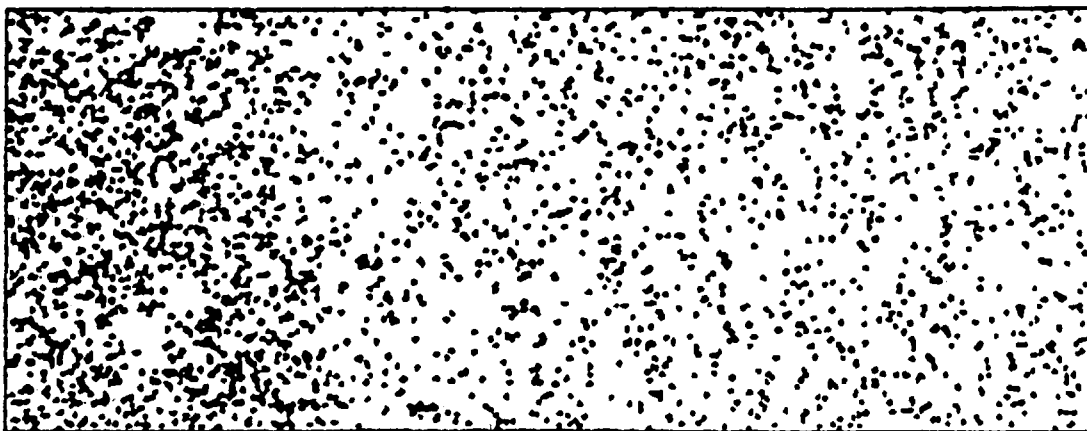


Diagram B3



Plot A1 Dipole Dipole results Grid 1
Unfiltered data
Range: $\bar{x} - 2.5\sigma$ to $\bar{x} + 2.5\sigma$
Lin plot
Scale 1 : 200



Plot A2 Dipole Dipole results Grid 1
Unfiltered data
Range: $\bar{x} - 0.25\sigma$ to $\bar{x} - 2\sigma$
Log plot

QADESH, SYRIA

E-35

Resistivity survey: Grid 2

Scale: horizontal 1:100

vertical 1:200

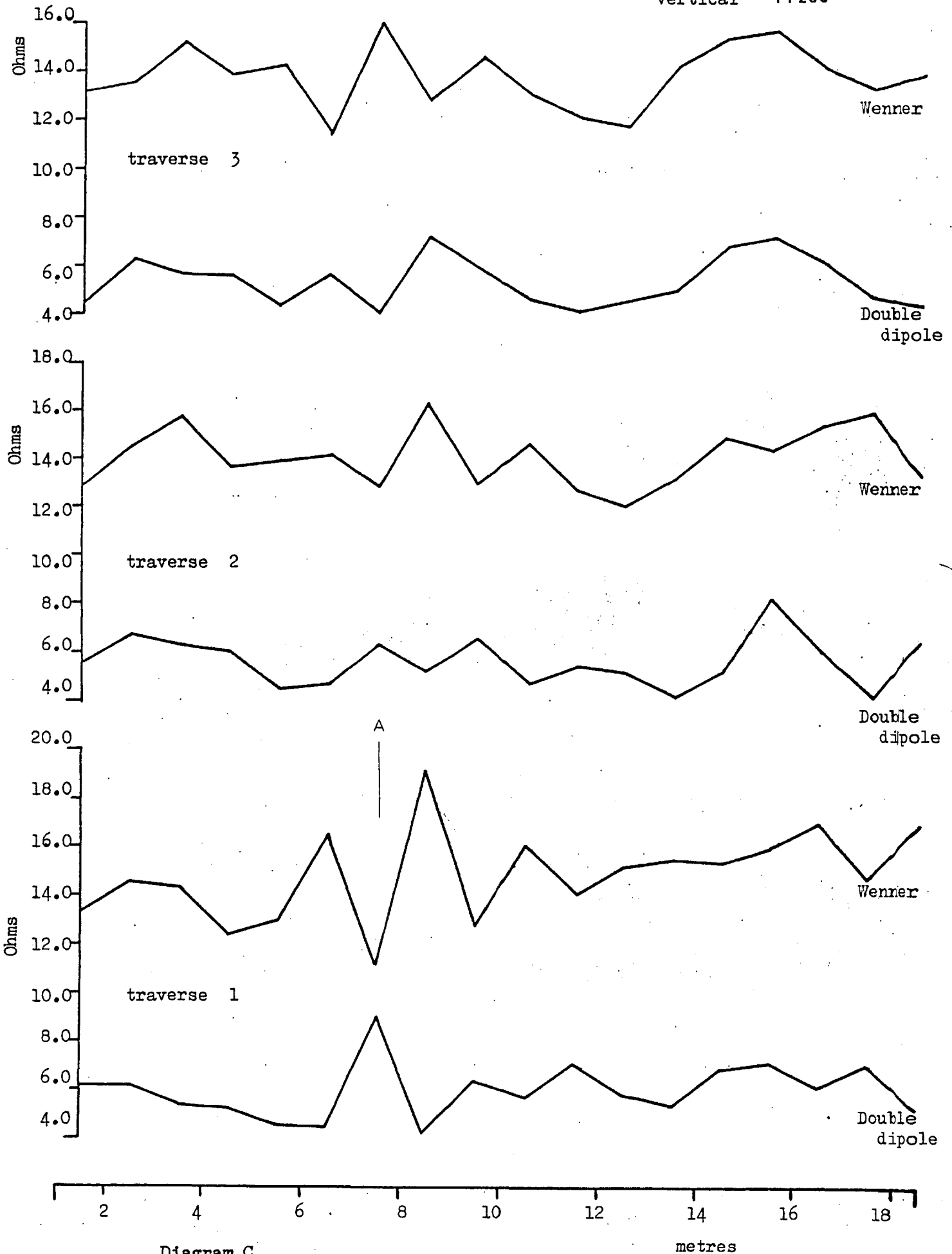


Diagram D1

QADESH, SYRIA

Resistivity survey: Enclosure

Schematic diagram

Scale 1 : 2000

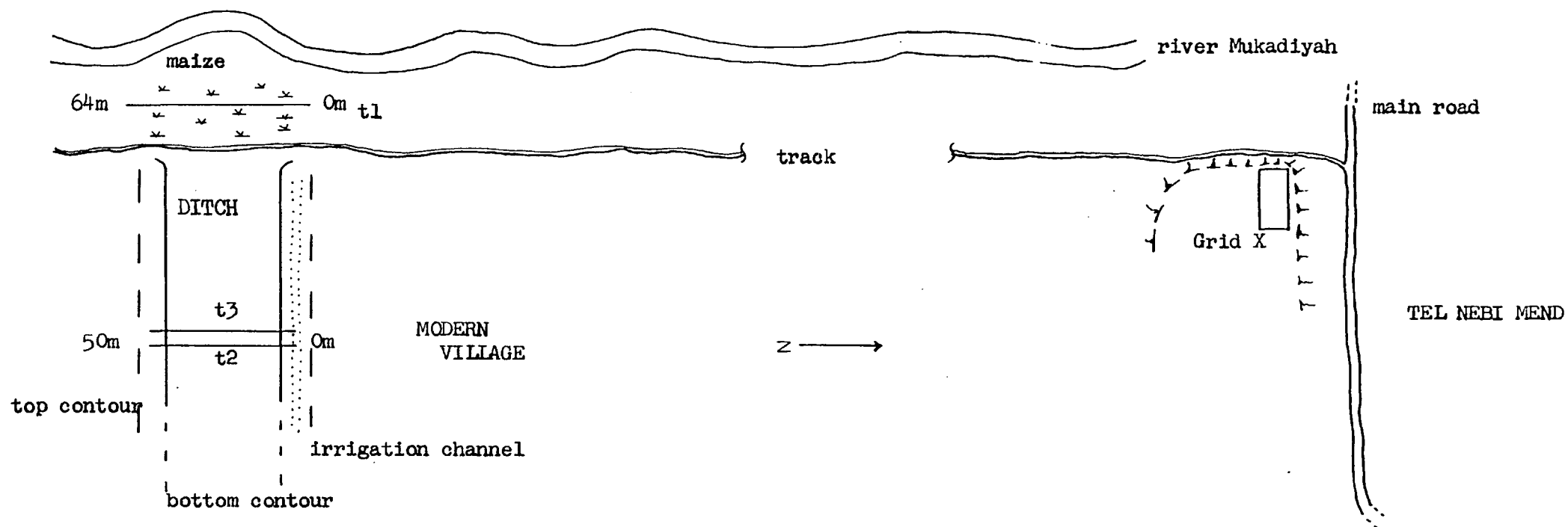
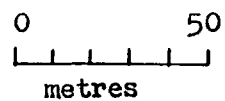
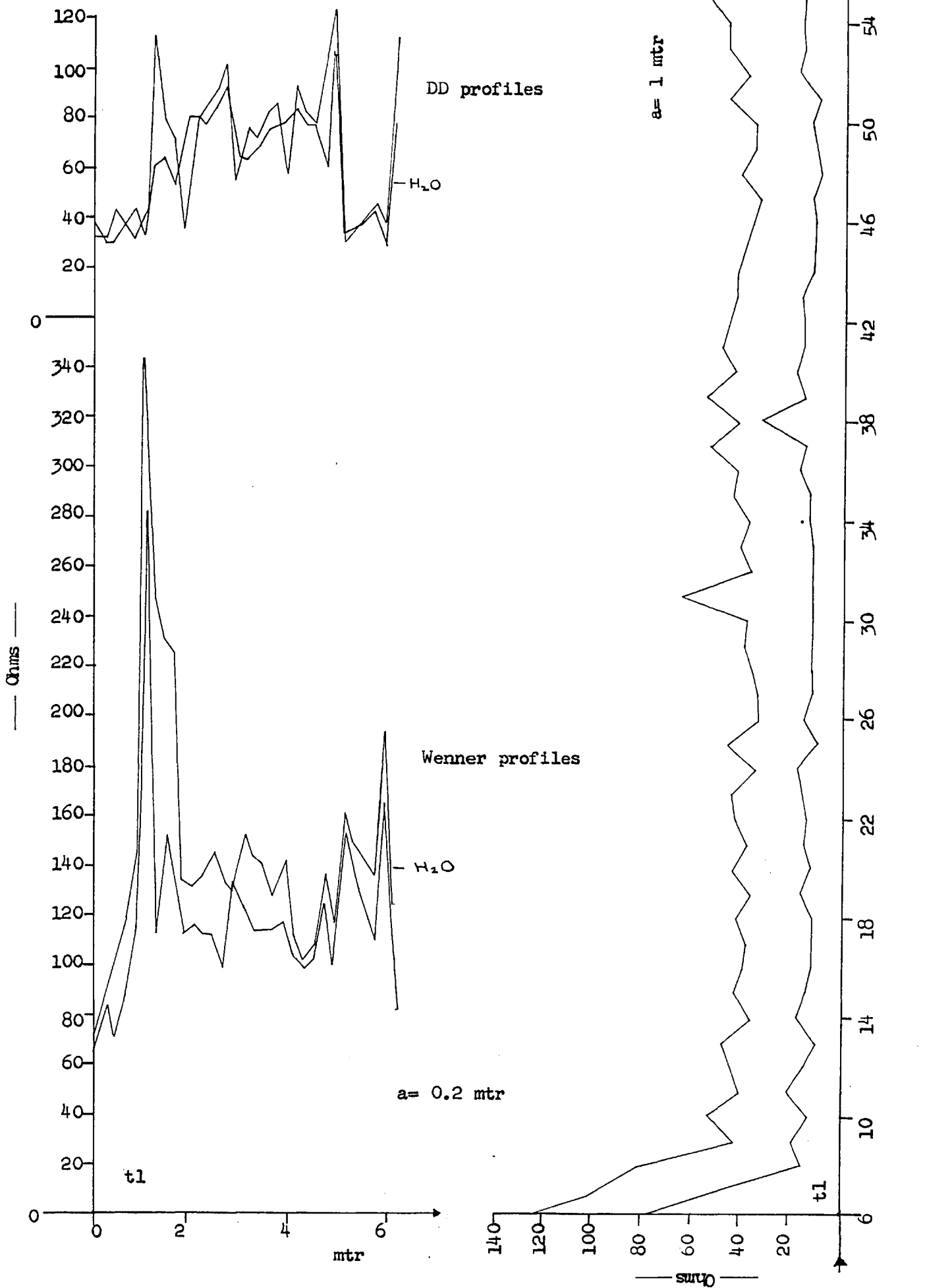


Diagram D2



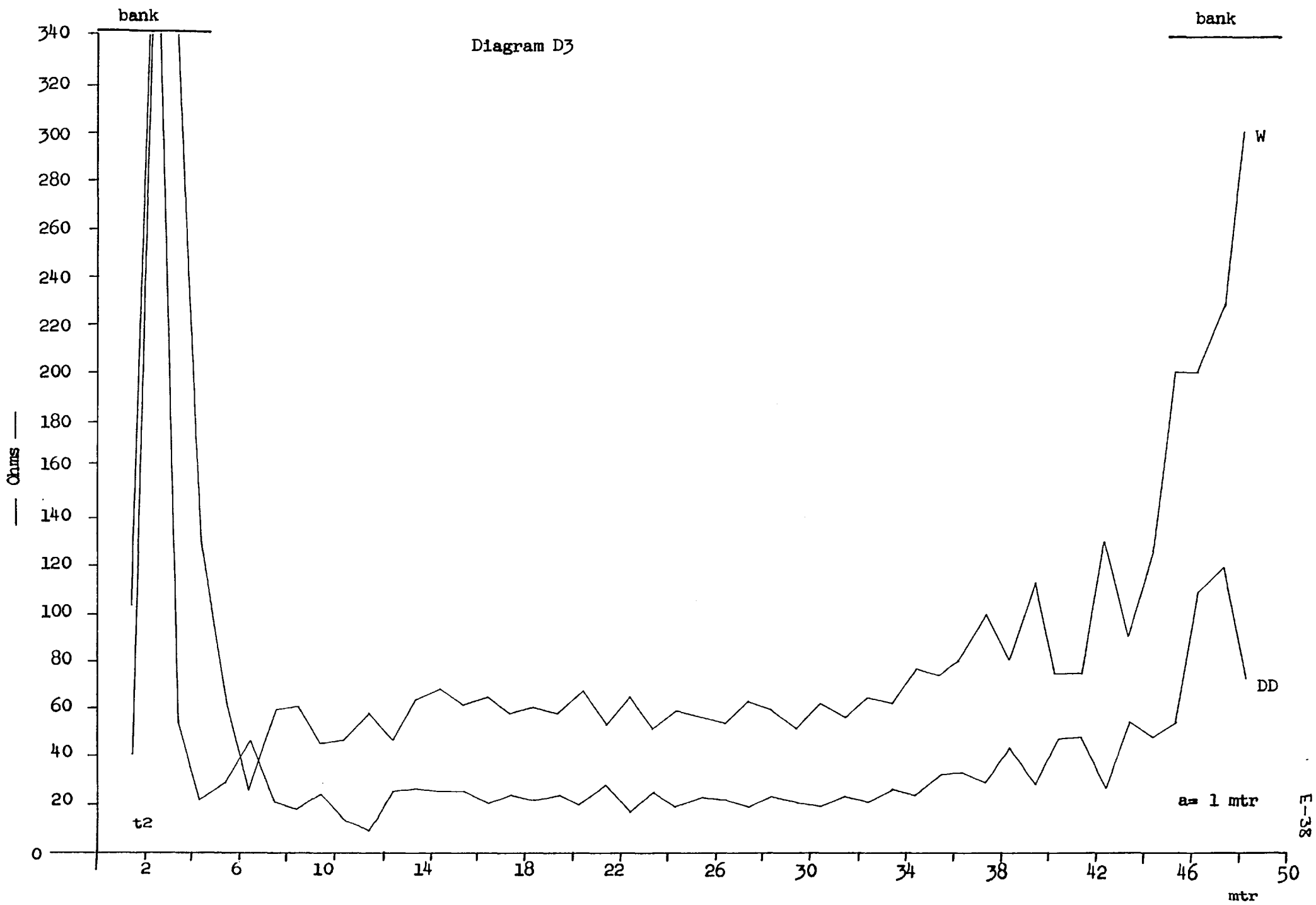
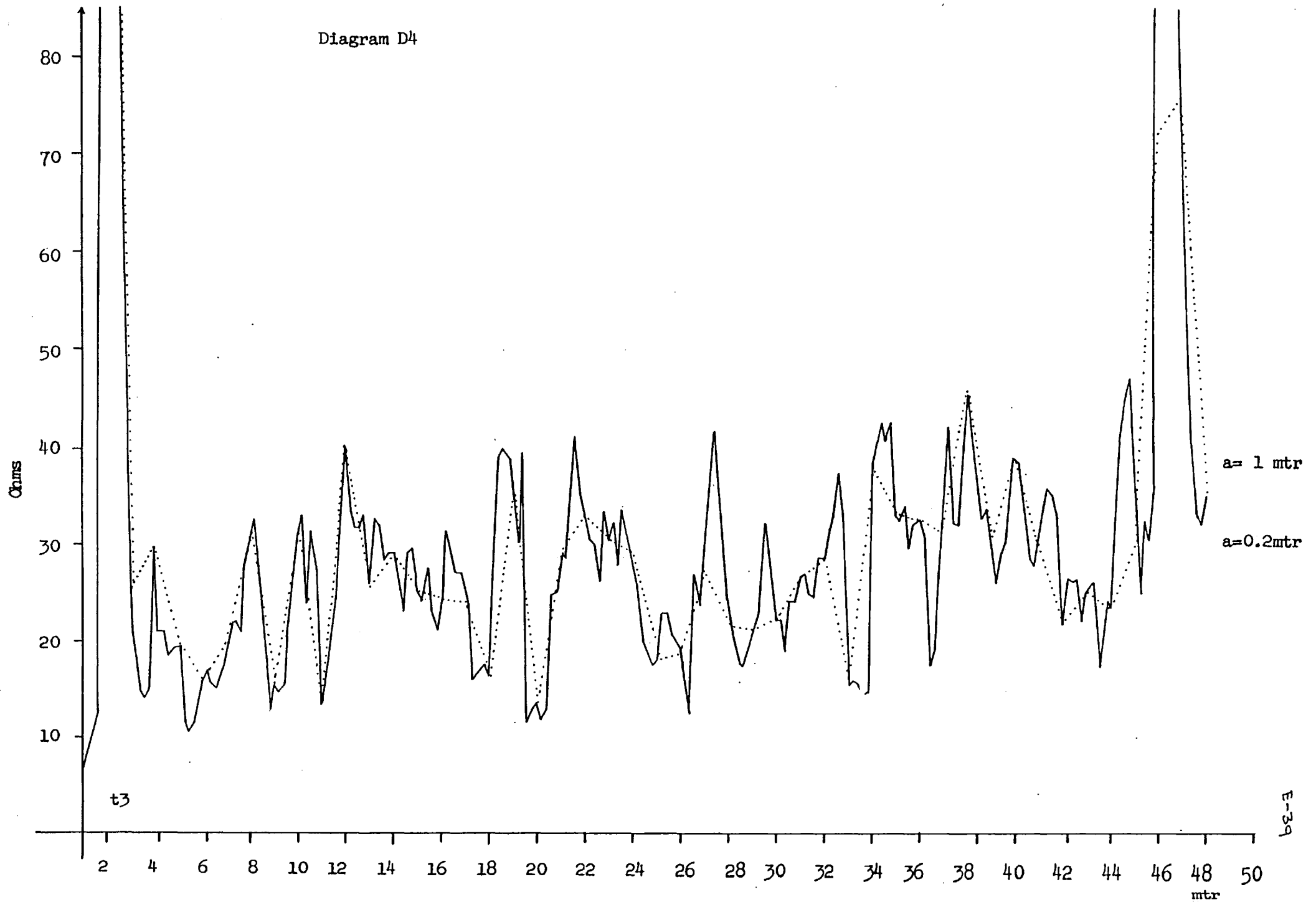


Diagram D4

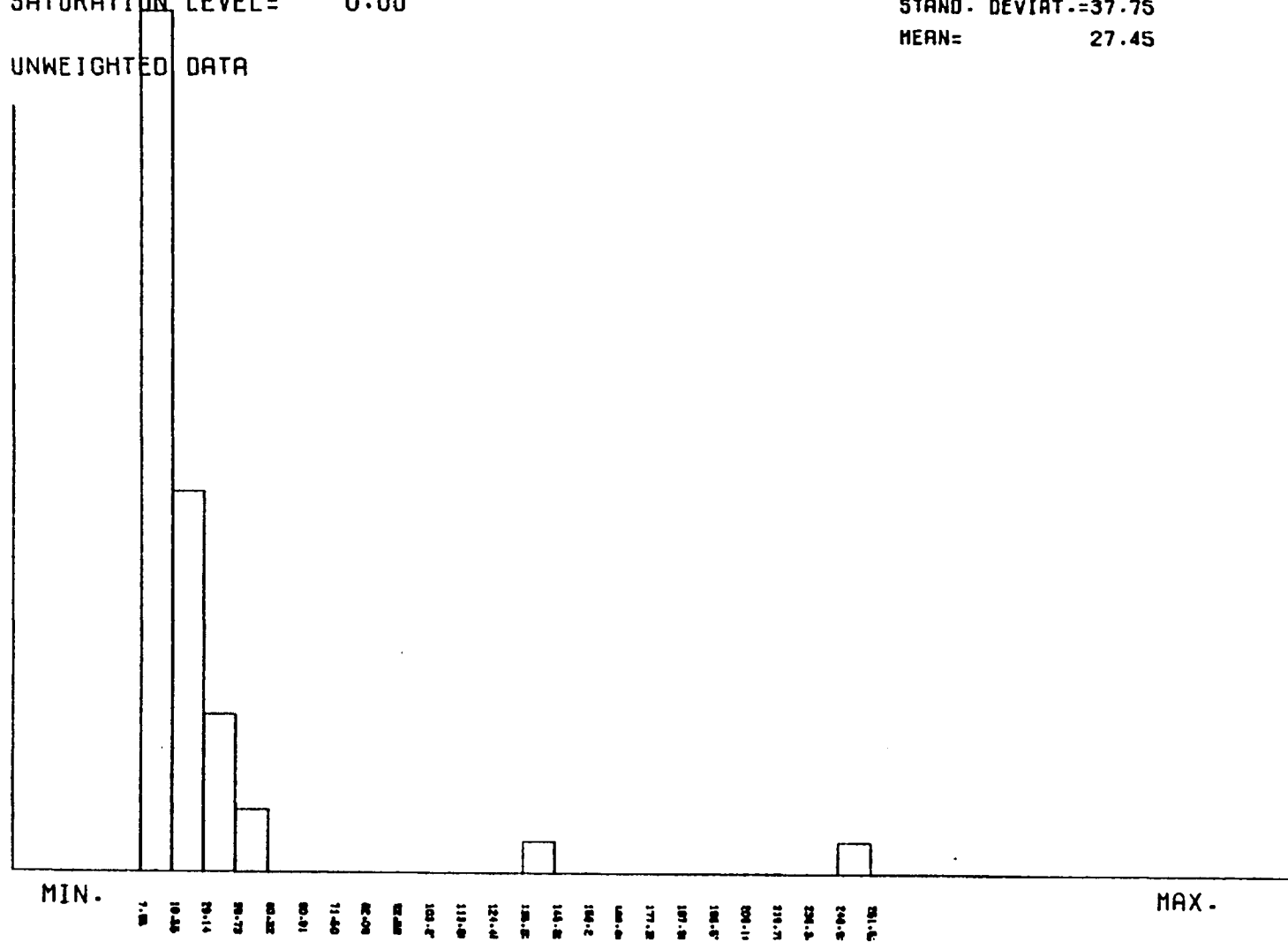


DOT DENSITY PLOT OF ET3W1
 UNFILTERED DATA
 CUT-OFF LEVEL= 0.00
 SATURATION LEVEL= 0.00

MAXIMUM= 251.40
 MINIMUM= 8.08
 NO. OF CASES= 48.00
 STAND. DEVIAT.=37.75
 MEAN= 27.45

UNWEIGHTED DATA

FREQUENCY



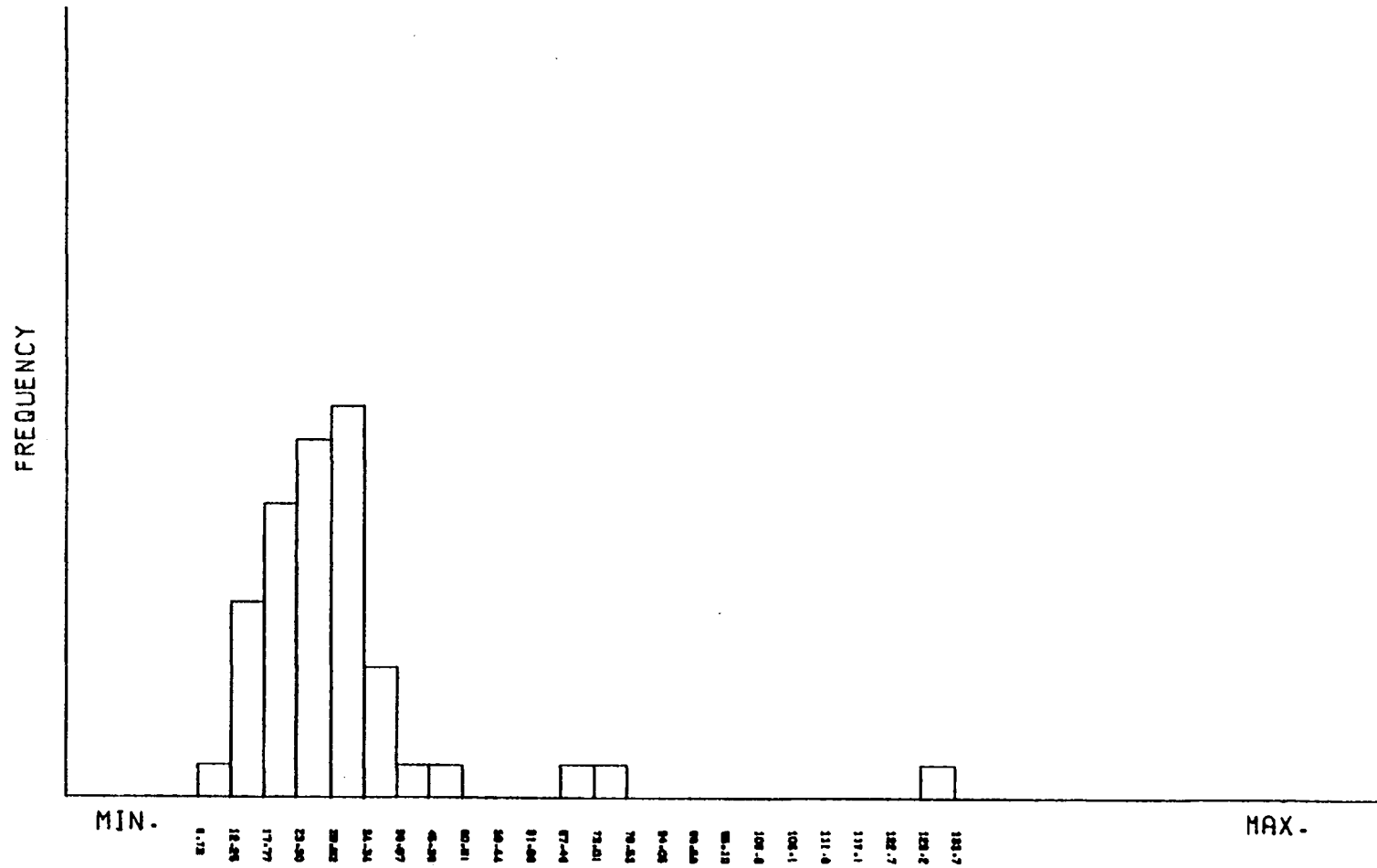
Plot B1 Histogram of the Wenner results (no probe watering)

QADESH

DOT DENSITY PLOT OF ET3HWI
 UNFILTERED DATA
 CUT-OFF LEVEL= 0.00
 SATURATION LEVEL= 0.00

MAXIMUM= 133.70
 MINIMUM= 6.79
 NO. OF CASES= 48.00
 STAND. DEVIAT.= 19.43
 MEAN= 30.39

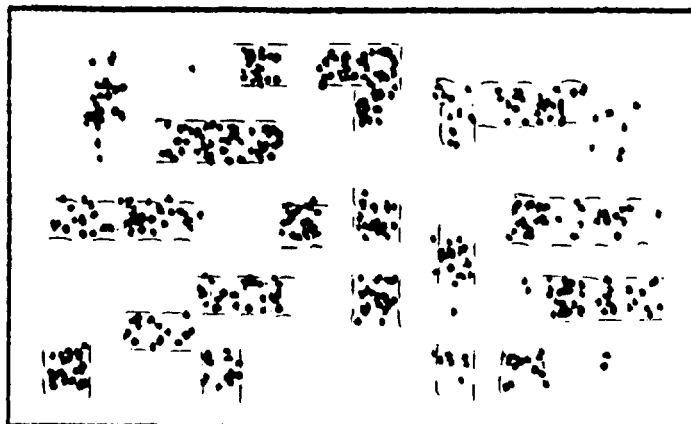
UNWEIGHTED DATA



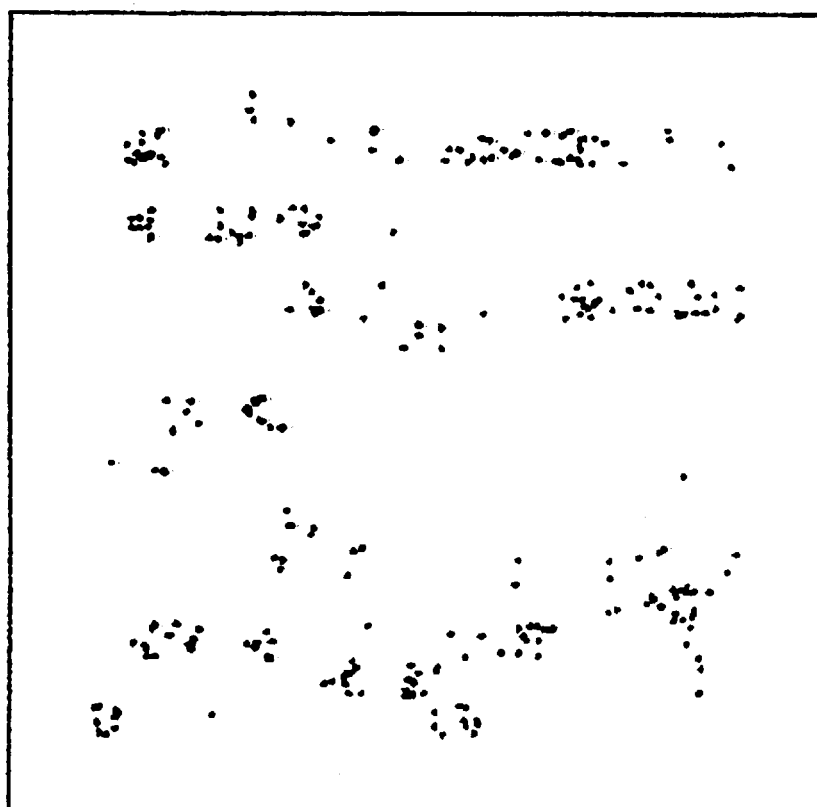
Plot B2 Histogram of the Wenier results (probe watering)

QADESH

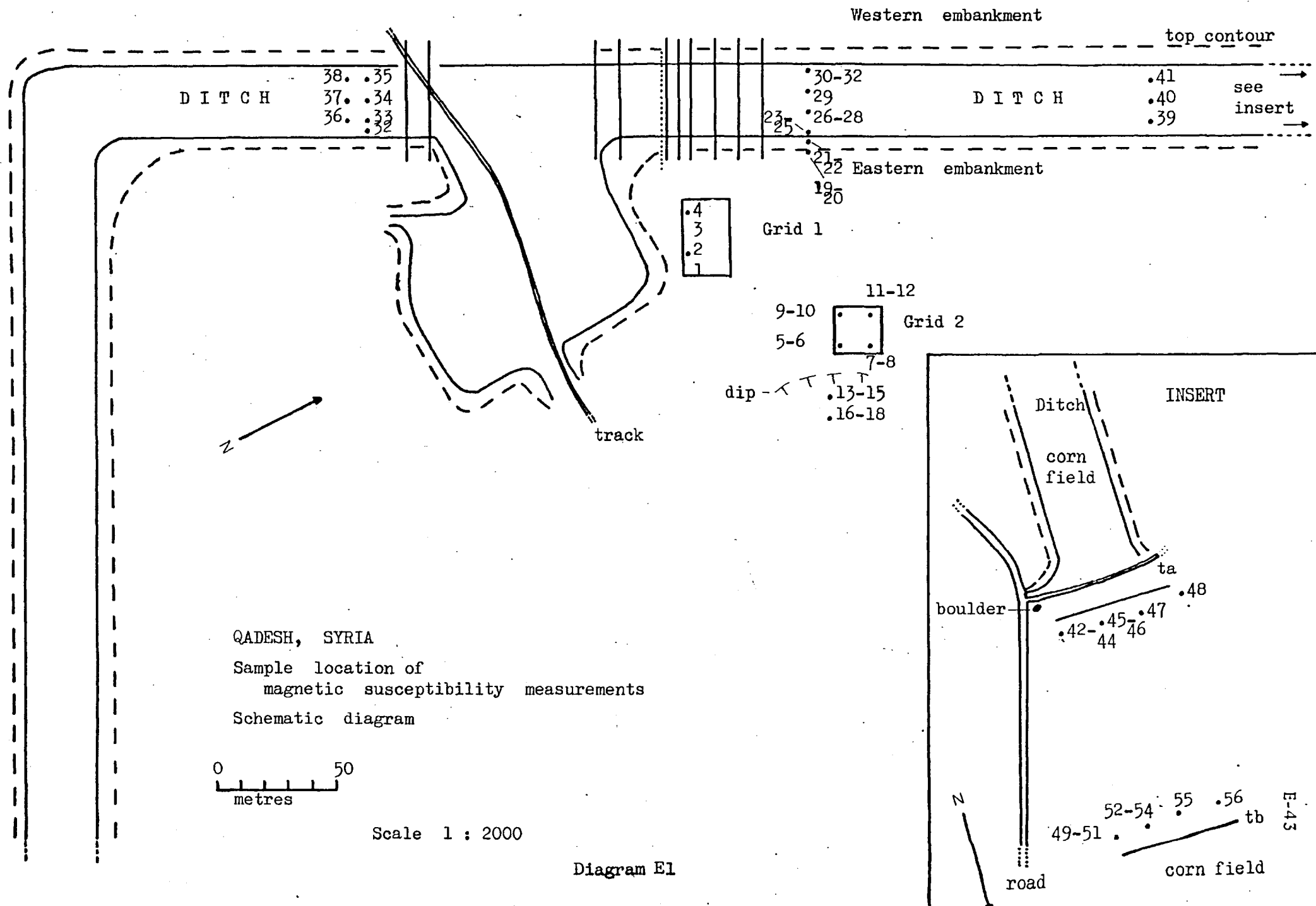
QADESH



Plot C1 Dipole Dipole results Grid X
 High-pass 4 element square residual filter, radius 1
 Range: $\bar{x} - 0.1\sigma$ to $\bar{x} + 2\sigma$
 Log plot
 Scale 1 : 200



Plot D1 Magnetometer results Grid 1
 High-pass 8 element ring residual filter, radius 1
 Range: $\bar{x} - 0.25\sigma$ to $\bar{x} - 1.5\sigma$
 Lin plot
 Scale 1 : 200



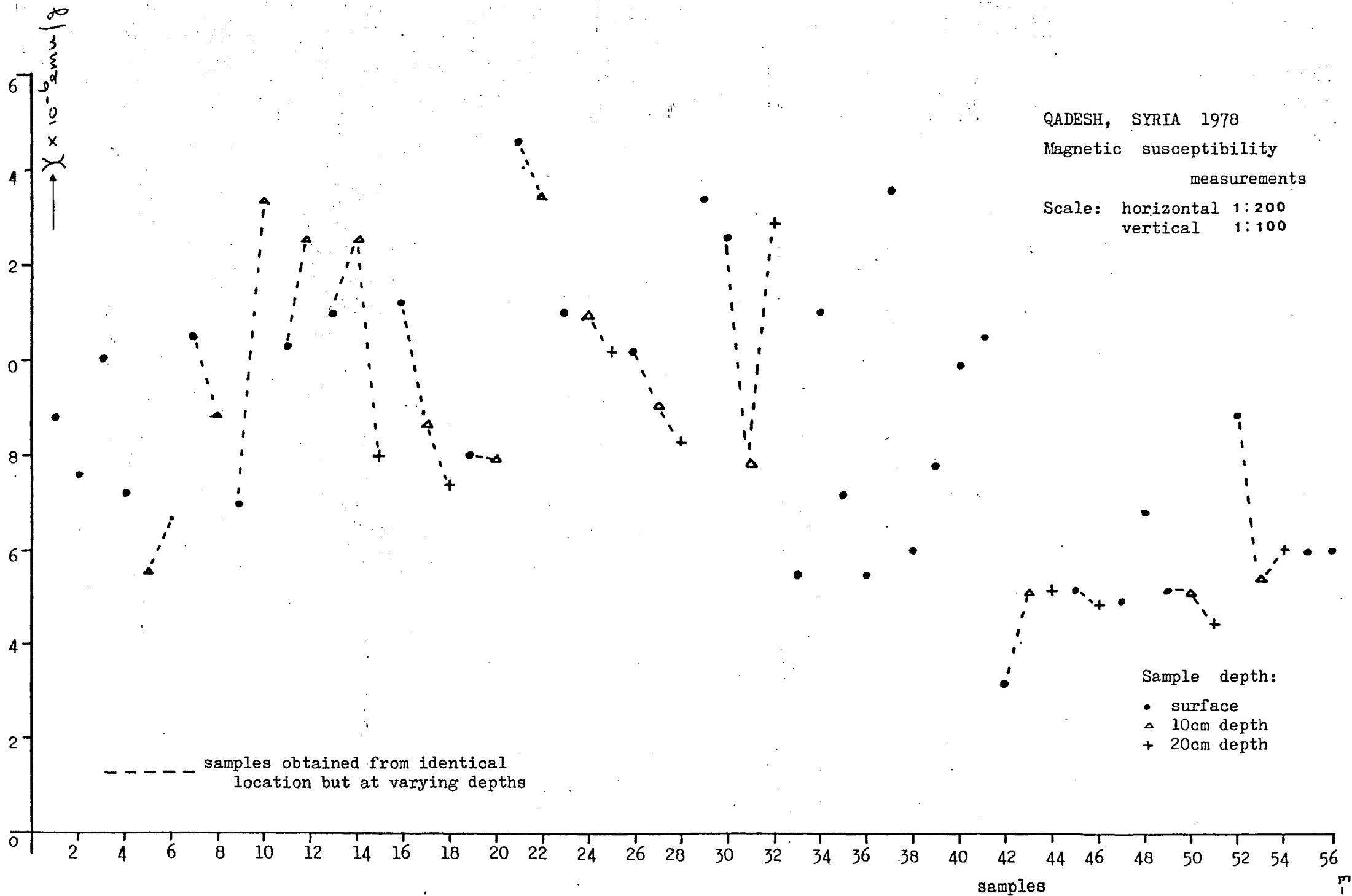


Diagram E2

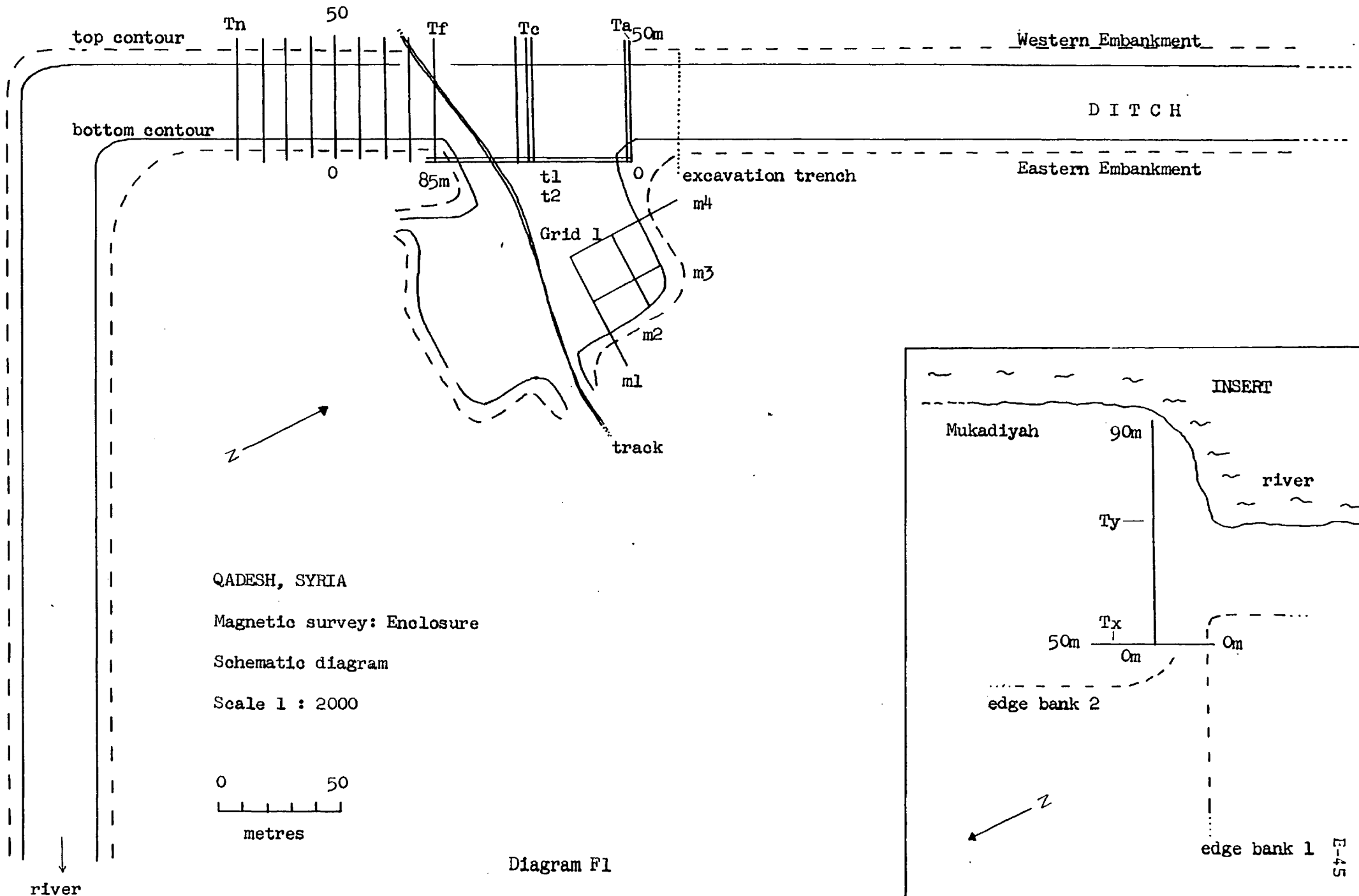


Diagram F2

** surface irregularities t-top sensor position
— bank b-bottom sensor posit.

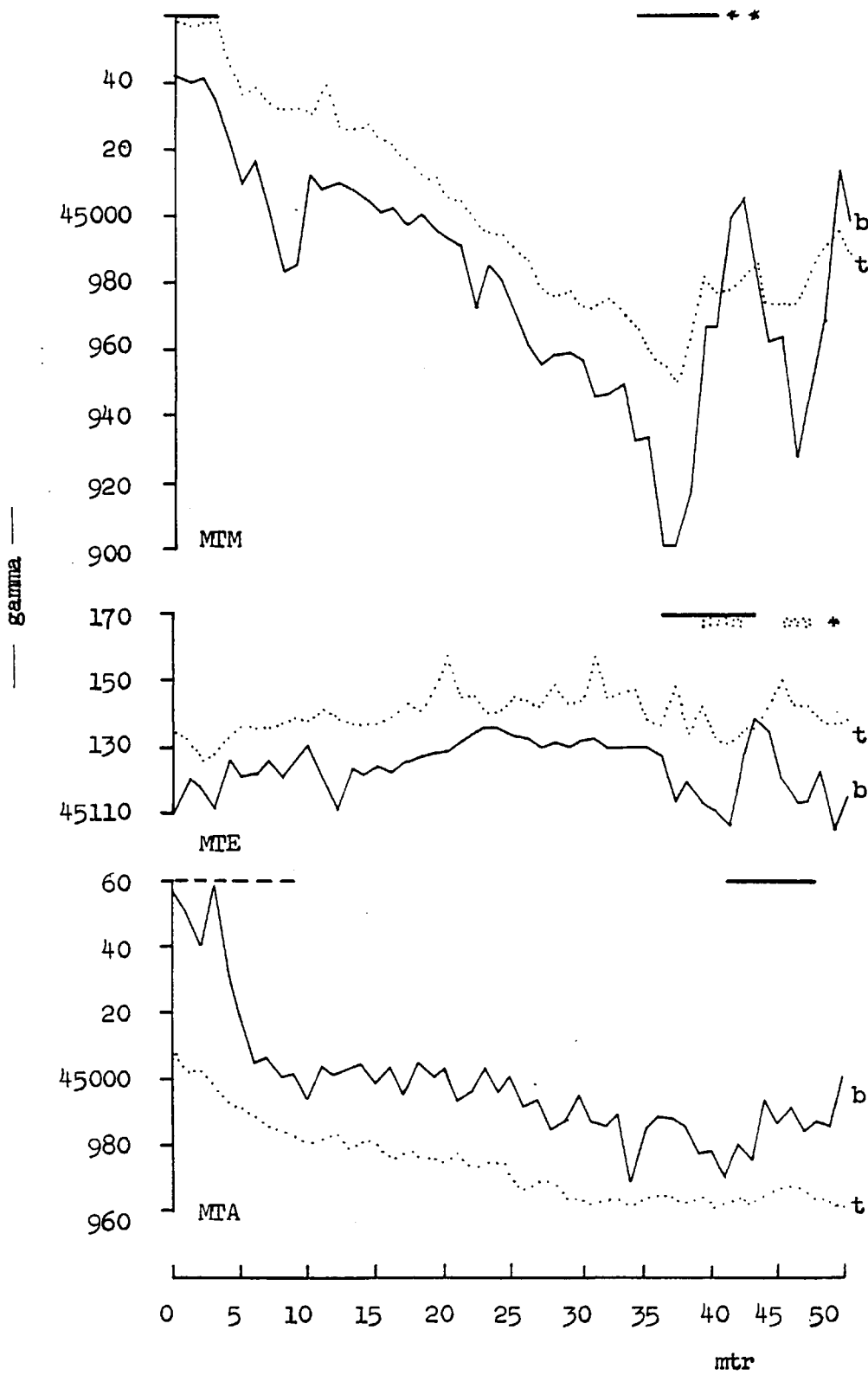
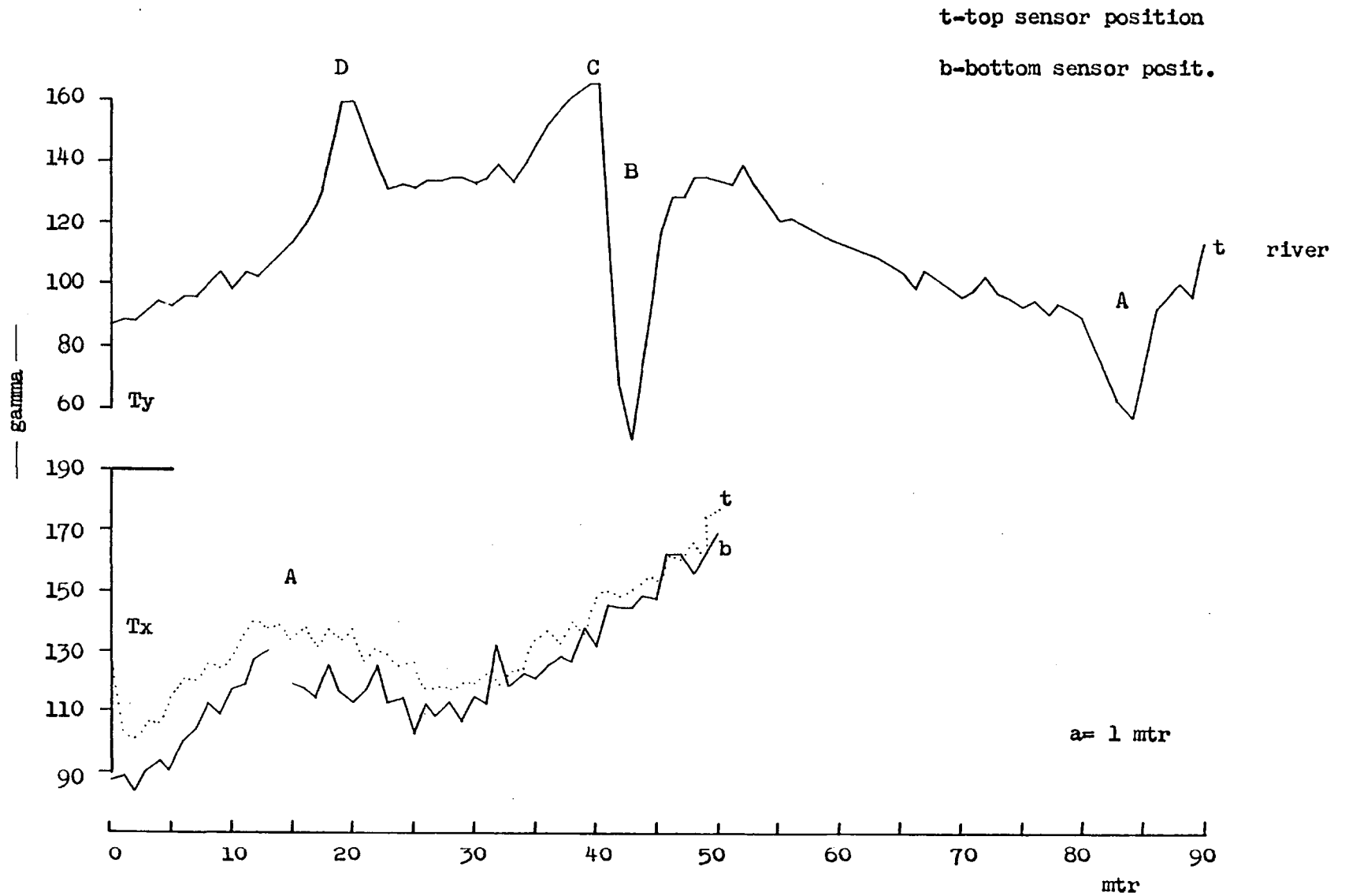
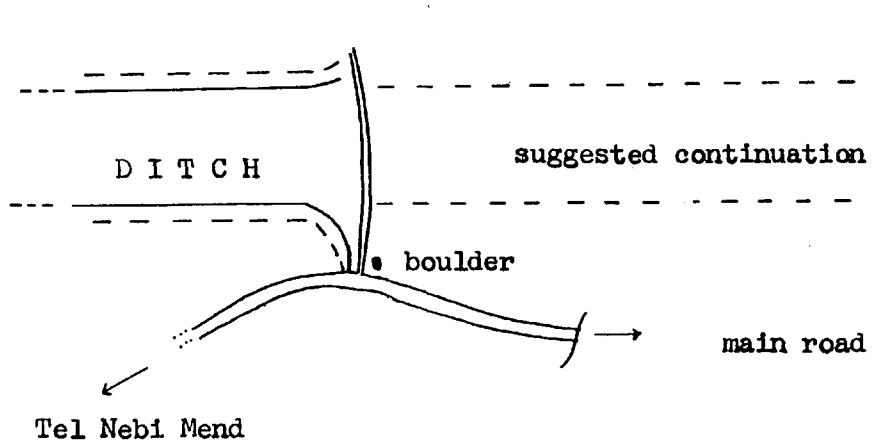


Diagram F3





QADESH, SYRIA

Magnetic surveys: Embankment (north-side)

Grid A

Schematic diagram

Scale 1 : 2000

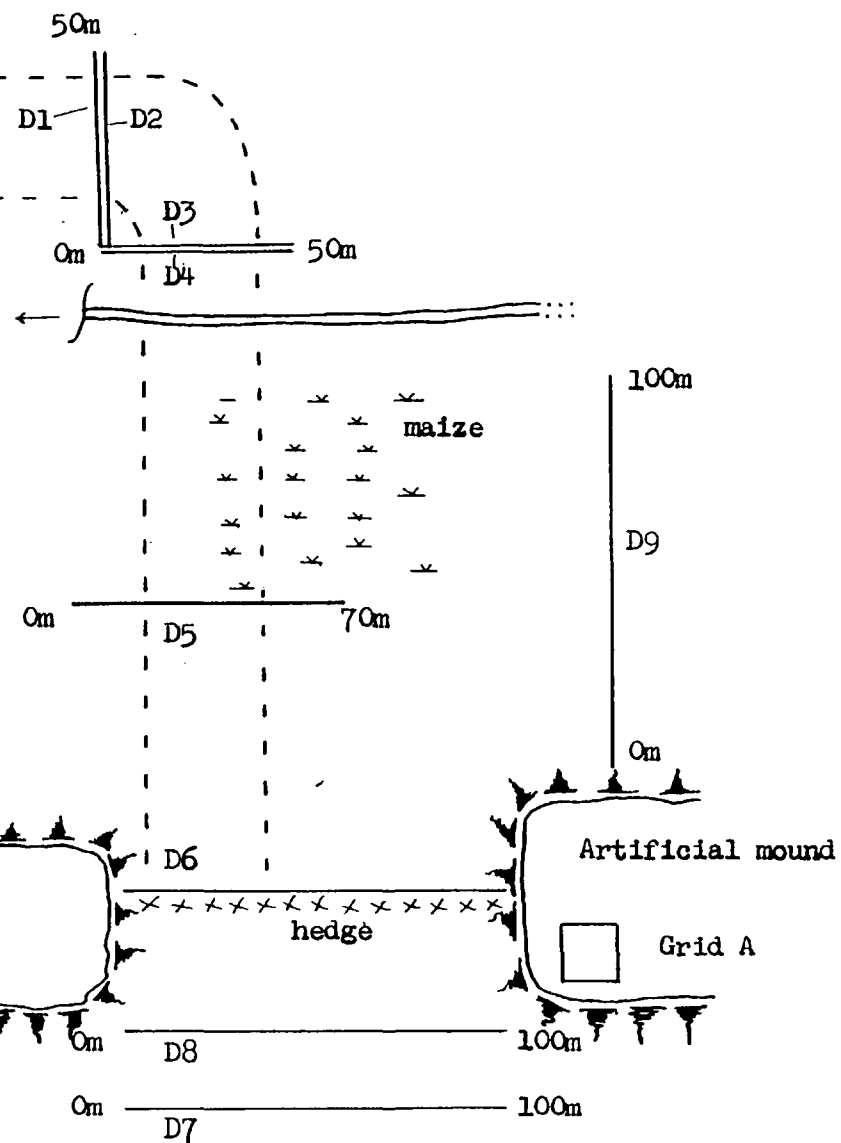
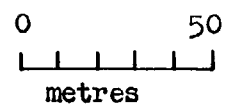


Diagram G1

Diagram G2

t-top sensor position

b-bottom sensor posit.

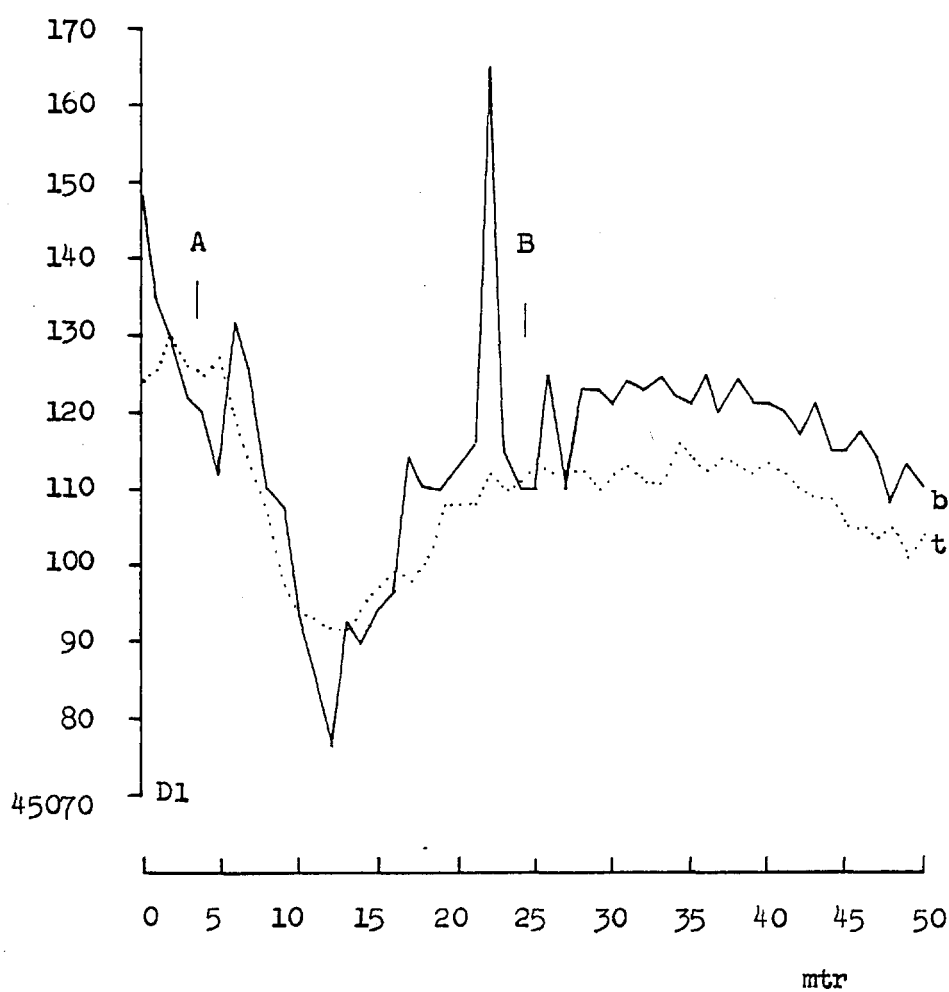
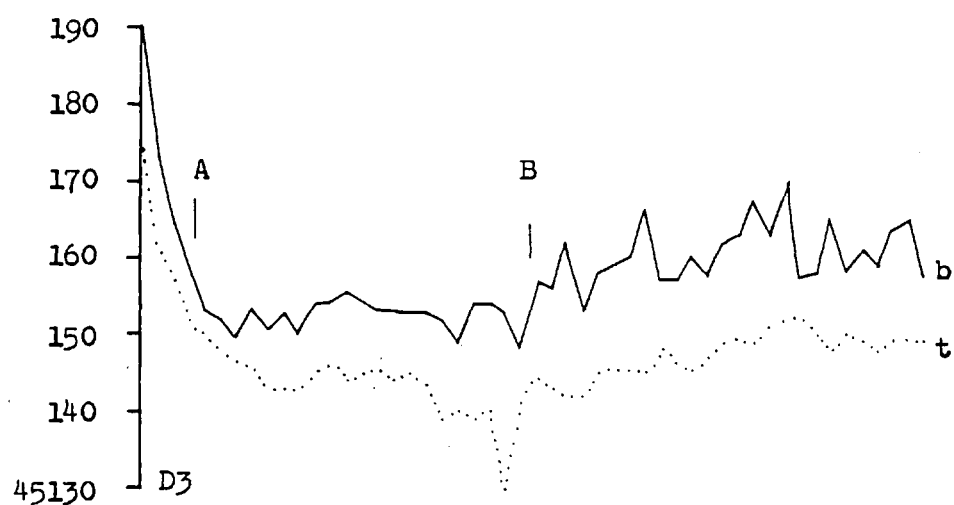
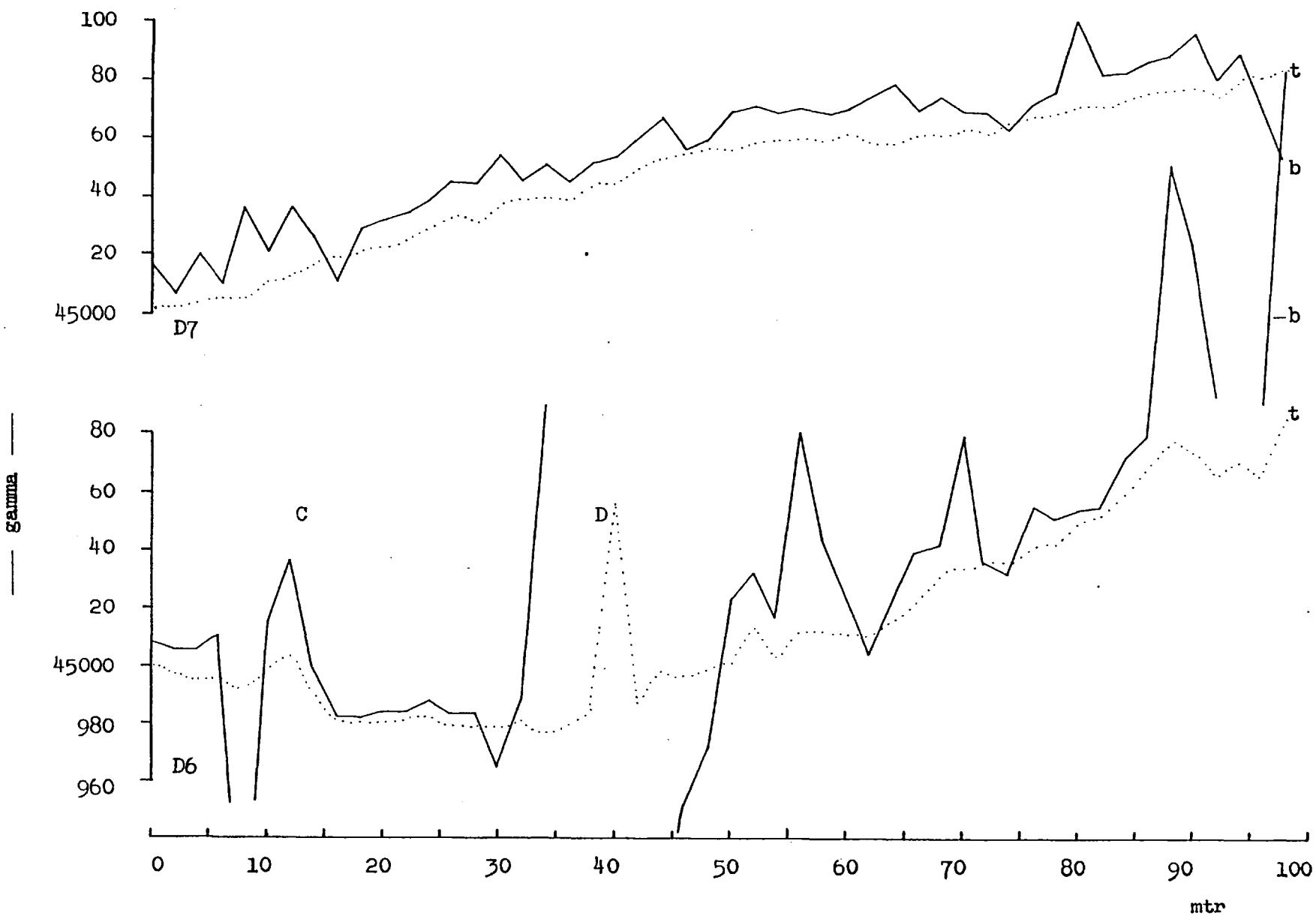


Diagram G3



QADESH



Plot E1 Magnetometer results Grid A
High-pass 4 element square residual filter, radius 1
Range: $\bar{x}$ to $\bar{x} + 2\sigma$
Log plot
Scale 1 : 200

QADESH, SYRIA VLF EM Survey Grid X

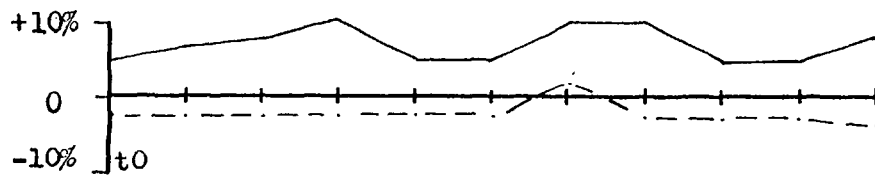
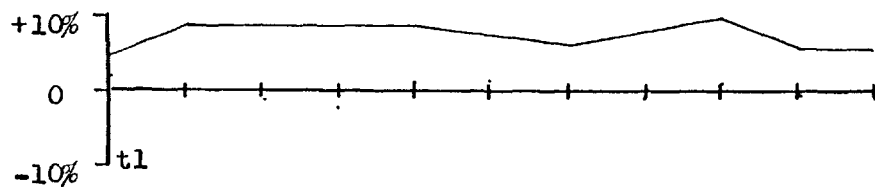
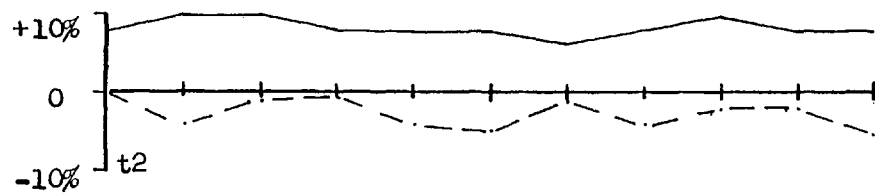
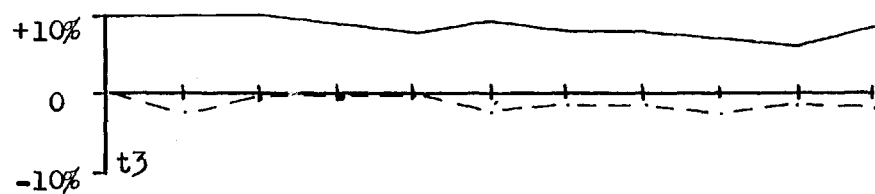
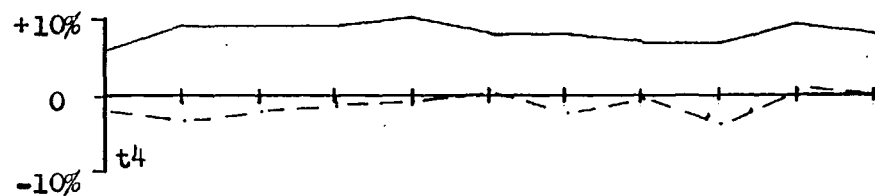
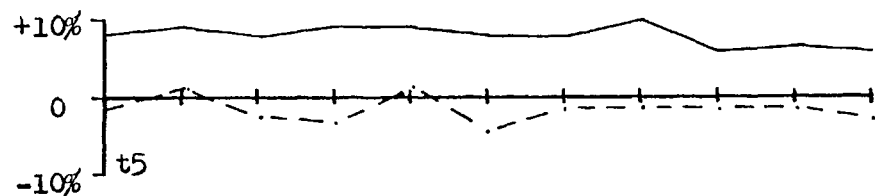
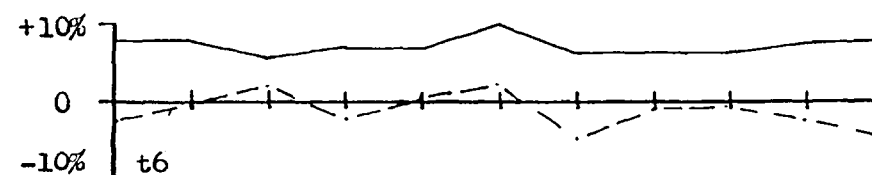
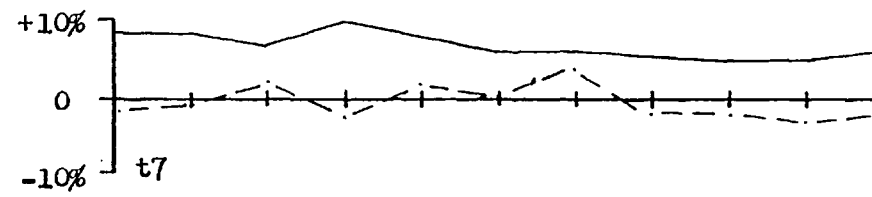
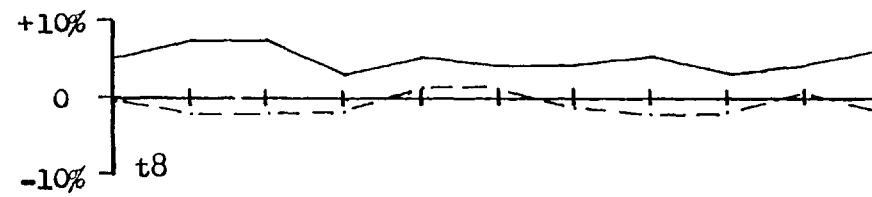
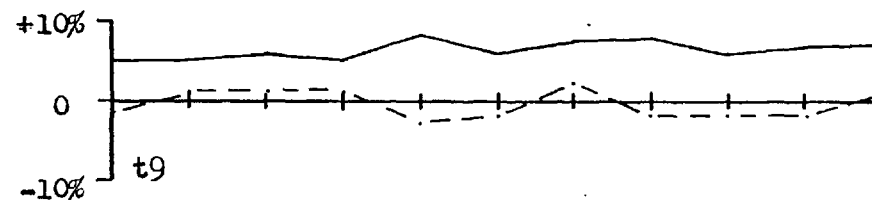
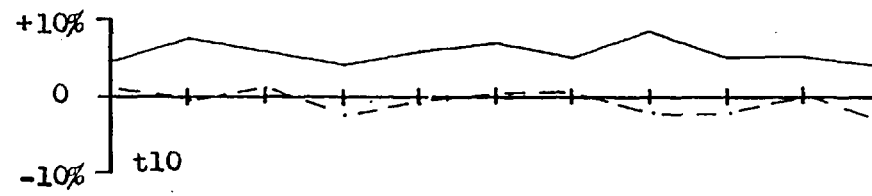
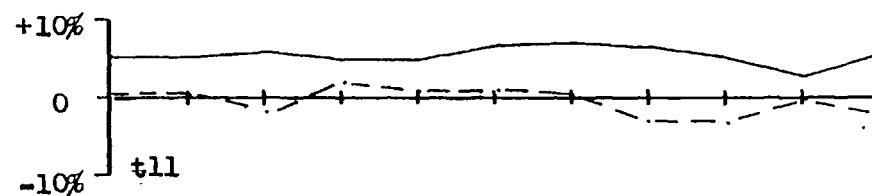


Diagram H1

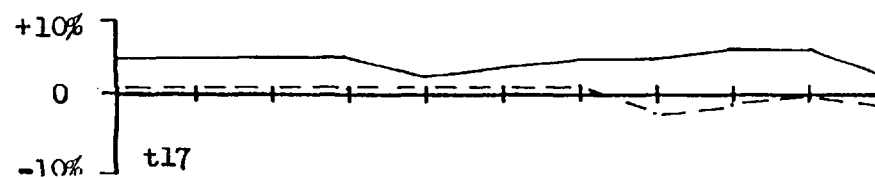
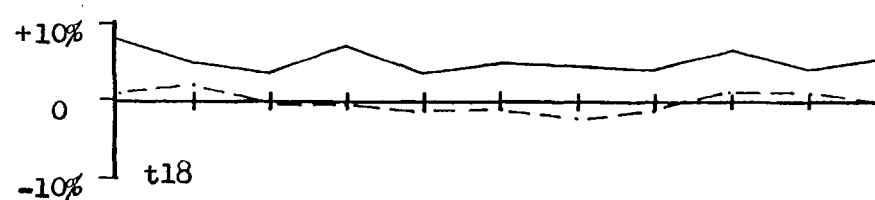
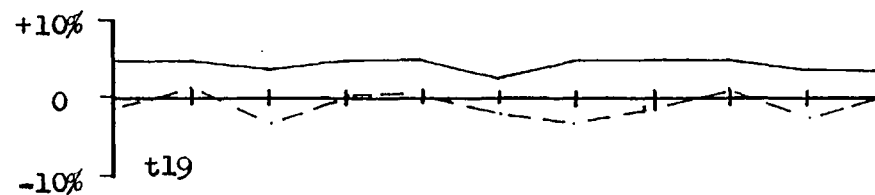
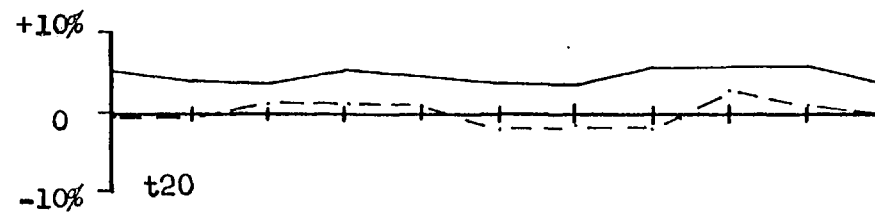
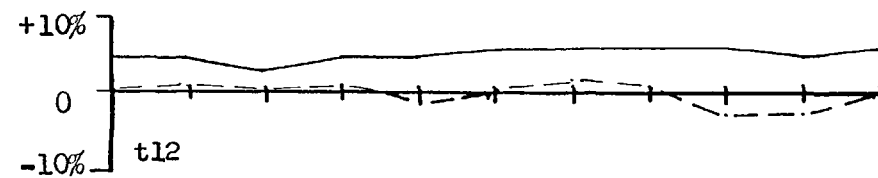
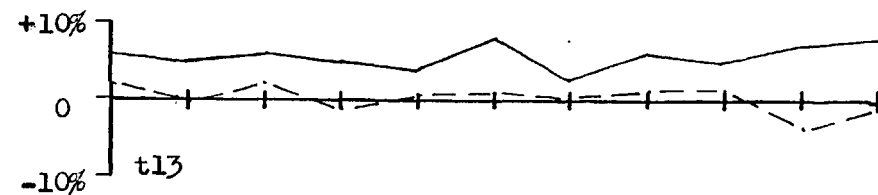
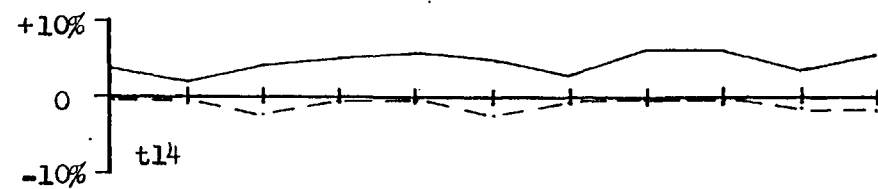
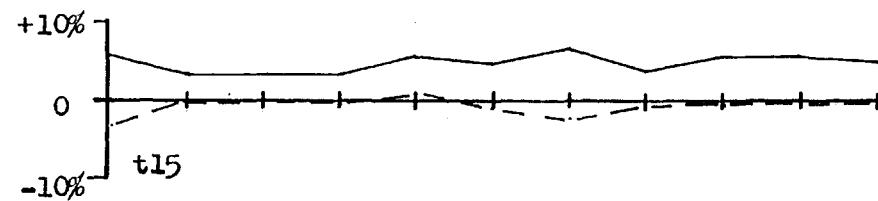
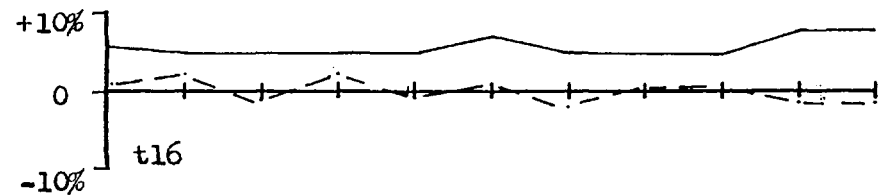


— in-phase
 --- quadrature

1 mtr E-52

QADESH, SYRIA VLF EM Survey Grid X

Diagram H2



— in-phase
--- quadrature

1 mtr
100 ft

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APPENDIX

Printout of Computer Programmes Including Example Run with
Relevant Output

PROGRAM DIURNAL (FORTRAN IV)

PROGRAM LISTING:

```
00100      PROGRAM DIURNAL(TAPE7,TAPE21,INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OU
00110C  CORRECTS DATA ARRAYS FOR DIURNAL VARIATION
00120      DIMENSION A(32,32),RNEW(32,32)
00130      INTEGER FNCODE(4),FICODE(5),MSG(4),ICODE
00140C
00150C  INPUT FILE REQUESTED AND PARAMETERS SPECIFIED
00160 100  CONTINUE
00170      WRITE(6,21)
00180 21  FORMAT(8HFILENAME)
00190      READ(5,*)FNCODE(2)
00200      FNCODE(1)=10HGET(TAPE7=
00210      FNCODE(3)=10H)
00220      FNCODE(4)=0
00230      WRITE(6,99)FNCODE
00240 99  FORMAT(1X,4020)
00250      CALL PFREQ(FNCODE(1),MSG,ICODE)
00260      REWIND 7
00270      WRITE(6,22)
00280 22  FORMAT(14HNUMBER OF ROWS)
00290      READ(5,*)MAXR
00300      WRITE(6,24)
00310 24  FORMAT(17HNUMBER OF COLUMNS)
00320      READ(5,*)MAXC
00330      RD=MAXR*MAXC
00340C
00350C  DATA READ IN
00360      DO 1 J=1,MAXR
00370      READ(7,*)(A(J,K),K=1,MAXC)
00380 1  CONTINUE
00390C
00400C  SCALE DETERMINED
00410 200  CONTINUE
00420      COUNT=1.0
00430      WRITE(6,26)
00440 26  FORMAT(16HFIRST REF. VALUE)
00450      READ(5,*)REF1
00460      WRITE(6,28)
00470 28  FORMAT(17HSECOND REF. VALUE)
00480      READ(5,*)REF2
00490      TOTD=REF2-REF1
00500      SCALE=TOTD/RD
00510      IF(REF2-REF1)10,11,12
00520C
00530C  NEG. DIURNAL VARIATION
00540 10  CONTINUE
00550      DO 2 J=1,MAXR
00560      DO 3 K=1,MAXC
00570      RNEW(J,K)=A(J,K)-(COUNT*SCALE)
00580      COUNT=COUNT+1
00590 3  CONTINUE
00600 2  CONTINUE
00610      GO TO 20
00620C
00630C  POS. DIURNAL VARIATION CORRECTION
00640 12  CONTINUE
00650      DO 4 J=1,MAXR
00660      DO 5 K=1,MAXC
00670      RNEW(J,K)=A(J,K)+(COUNT*SCALE)
00680      COUNT=COUNT+1
00690 5  CONTINUE
```

```

00000 0  CONTINUE
00700 4  CONTINUE
00710C
00720C  CORRECTED VALUES WRITTEN OUT ON TTY
00730 20  CONTINUE
00740      DO 6 J=1,MAXR
00750      WRITE(6,*)(RNEW(J,K),K=1,MAXC)
00760      WRITE(21,*)(RNEW(J,K),K=1,MAXC)
00770 6  CONTINUE
00780      REWIND 21
00790C
00800C  CHOOSE OPTIONS FOR FURTHER PROCESSING
00810      WRITE(6,42)
00820 42  FORMAT(25HOLD,NEW,SAVE,END: 1,2,3,4)
00830      READ(5,*)IOPT
00840      IF(IOPT.EQ.1)GO TO 200
00850      IF(IOPT.EQ.2)GO TO 100
00860      IF(IOPT.EQ.3)GO TO 300
00870      IF(IOPT.EQ.4)GO TO 400
00880C
00890C  CORRECTED ARRAY ASSIGNED FILE NAME
00900 300  CONTINUE
00910      WRITE(6,32)
00920 32  FORMAT(16HASSIGN FILE NAME)
00930      READ(5,*)FICODE(3)
00940      FICODE(1)=10HSAVE(TAPE2
00950      FICODE(2)=10H1=
00960      FICODE(4)=10H)
00970      FICODE(5)=0
00980      WRITE(6,101)FICODE
00990 101  FORMAT(1X,4020)
01000      CALL PFREQ(FICODE(1),MSG,ICODE)
01010      WRITE(6,34)
01020 34  FORMAT(14HFILE NOW SAVED)
01030      GO TO 400
01040C
01050C  REF2-REF1=0 NO CORRECTION REQUIRED
01060 11  CONTINUE
01070      WRITE(6,30)
01080 30  FORMAT(22HNO CORRECTION REQUIRED)
01090 400  CONTINUE
01100      STOP
01110      END
/

```


EXAMPLE PROGRAM RUN:

PROGRAM DIURNAL

FILENAME

? "tested"

07052451240120054254240523240704555555552555555555555555555500000000000000

NUMBER OF ROWS

7 10

NUMBER OF COLUMNS

? 20

FIRST REF. VALUE

? 20

SECOND REF. VALUE

? 25

20.0250	19.0500	22.0750	18.1000	20.1250
21.1500	20.1750	19.2000	21.2250	24.2500
30.2750	36.3000	34.3250	24.3500	20.3750
19.4000	18.4250	20.4500	18.4750	16.5000
22.5250	21.5500	24.5750	21.6000	26.6250
24.6500	21.6750	22.7000	24.7250	26.7500
40.7750	37.8000	34.8250	28.8500	26.8750
24.9000	22.9250	24.9500	23.9750	26.0000
35.0250	33.0500	37.0750	41.1000	37.1250
37.1500	39.1750	41.2000	42.2250	41.2500
41.2750	37.3000	39.3250	40.3500	37.3750
41.4000	37.4250	36.4500	39.4750	41.5000
29.5250	21.5500	26.5750	27.6000	21.6250
22.6500	23.6750	26.7000	27.7250	29.7500
27.7750	28.8000	29.8250	30.8500	21.8750
20.9000	23.9250	25.9500	27.9750	27.0000
22.0250	21.0500	21.0750	24.1000	25.1250
26.1500	27.1750	27.2000	25.2250	21.2500
22.2750	23.3000	24.3250	24.3500	27.3750
20.4000	19.4250	20.4500	22.4750	24.5000
22.5250	23.5500	24.5750	26.6000	20.6250
21.6500	22.6750	18.7000	22.7250	23.7500
24.7750	20.8000	22.8250	23.8500	22.8750
12.9000	11.9250	17.9500	22.9750	24.0000
20.0250	19.0500	20.0750	18.1000	21.1250
23.1500	18.1750	15.2000	23.2250	22.2500
21.2750	20.3000	19.3250	19.3500	19.3750
11.4000	11.4250	15.4500	18.4750	23.5000
11.5250	10.5500	9.57500	11.6000	13.6250
15.6500	11.6750	10.7000	9.72500	9.75000
15.7750	15.8000	17.8250	19.8500	23.8750
19.9000	18.9250	20.9500	21.9750	24.0000
10.0250	10.0500	11.0750	12.1000	13.1250
14.1500	14.1750	13.2000	13.2250	10.2500
16.2750	13.3000	18.3250	20.3500	24.3750
25.4000	24.4250	23.4500	22.4750	24.5000
14.5250	16.5500	16.5750	20.6000	20.6250
18.6500	18.6750	20.7000	25.7250	16.7500
10.7750	10.8000	16.8250	18.8500	20.8750
24.9000	24.9250	25.9500	24.9750	25.0000

OLD,NEW,SAVE,END: 1,2,3,4

1

RUN COMPLETE

PROGRAM FILTER (FORTRANIV)

PROGRAM LISTING:

```

      PROGRAM FILTER(INPUT,OUTPUT,TAPES=INPUT,TAPE7,TAPE21,
+      TAPE6=OUTPUT)
C  NUMERICAL FILTER PROGRAM PROVIDING A NUMBER OF FILTER OPTIONS
C  AT RADIUS 1 OR 2(WHERE AVAILABLE)AND OPTIONAL CENTRE
C  WEIGHTING FACTOR(GREATER THAN 1)
C
C
C  TAPE7=EXTERNAL DATA FILE
C  MNF5
      COMMON IWT,NRAD,MAXR,MAXC,NPASS
      REAL A(32,32),Z(32,32)
      INTEGER FNCODE(4),FICODE(5),MSG(4),ICODE
C
C  EXTERNAL FILE REFERENCED AND PARAMETERS ENTERED
100 CONTINUE
      WRITE(6,10)
10  FORMAT(8HFILENAME)
      READ(5,*)FNCODE(2)
      FNCODE(1)=10HGET(TAPE7=
      FNCODE(3)=10H)
      FNCODE(4)=0
      CALL PFREQ(FNCODE(1),MSG,ICODE)
      WRITE(6,12)
12  FORMAT(14HNUMBER OF ROWS)
      READ(5,*)MAXR
      WRITE(6,14)
14  FORMAT(17HNUMBER OF COLUMNS)
      READ(5,*)MAXC
C
C  DATA READ IN
      DO 15 J=1,MAXR
        READ(7,*)(A(J,K),K=1,MAXC)
15  CONTINUE
C
C  ACCESSED FILE WRITTEN ON TTY
      DO 16 J=1,MAXR
        WRITE(6,*)(A(J,K),K=1,MAXC)
16  CONTINUE
C
C  INFORM USER OF CONTROL OPTIONS
      WRITE(6,17)
17  FORMAT(* FILTER OPTIONS ARE:*,//,
+      * 1: 4 ELEMENT RING RESIDUAL FILTER, RADIUS 1 OR 2
+*,//,
+      * 2: 4 ELEMENT SQUARE RESIDUAL FILTER, RAD
+IUS 1 OR 2*,//,
+      * 3: 8 ELEMENT STAR RESIDUAL FILTE
+R, RADIUS 2*,//,
+      * 4: 6 ELEMENT SQUARE RESI
+DUAL FILTER, RADIUS 1 OR 2*,//,
+      * 5: 8 ELEMENT SQU
+ARE RESIDUAL FILTER, RADIUS 1 OR 2*,//,
+      * 6: 8 ELE
+MENT RING RESIDUAL FILTER, RADIUS 2*)
C
C  FILTER PARAMETERS DETERMINED
200 CONTINUE
      WRITE(6,18)
18  FORMAT(40HENTER FILTER NO.,RADIUS,WEIGHTING FACTOR)
      READ(5,*)NFILT,NRAD,IWT
      IF(NFILT.GT.6.OR.NRAD.GT.2)GO TO 200
C
C  HIGH PASS OR LOW PASS FILTER OPTION

```

```

        WRITE(6,19)
19  FORMAT(43HFILTER RESPONSE:1(HIGH PASS) OR 2(LOW PASS))
        READ(5,*)NPASS
C
        IF(NFILT.EQ.1)CALL FILTER1(A,Z)
        IF(NFILT.EQ.2)CALL FILTER2(A,Z)
        IF(NFILT.EQ.3)CALL FILTER3(A,Z)
        IF(NFILT.EQ.4)CALL FILTER4(A,Z)
        IF(NFILT.EQ.5)CALL FILTER5(A,Z)
        IF(NFILT.EQ.6)CALL FILTER6(A,Z)
C
C  BLANK AREAS AROUND FILTERED VALUES FILLED IN
C  WITH ZERO'S AND NEGATIVE VALUES ARE MADE ZERO
        IF(NRAD.EQ.1)INT=0
        IF(NRAD.EQ.2)INT=1
        DO 1 J=1,MAXR
        DO 2 K=1,MAXC
        IF(J.EQ.1.OR.J.EQ.NRAD.OR.J.EQ.MAXR-INT.OR.J.EQ.MAXR)Z(J,K)=0.
        IF(K.EQ.1.OR.K.EQ.NRAD.OR.K.EQ.MAXC-INT.OR.K.EQ.MAXC)Z(J,K)=0.
        2 CONTINUE
        1 CONTINUE
C
C  FILTERED VALUES WRITTEN ON TTY AND TAPE 21
        DO 50 J=1,MAXR
        WRITE(6,*)(Z(J,K),K=1,MAXC)
        WRITE(21,*)(Z(J,K),K=1,MAXC)
        50 CONTINUE
        REWIND 21
C
C  CHOOSE OPTIONS FOR FURTHER PROCESSING
250 CONTINUE
        WRITE(6,20)
        20  FORMAT(16HOLD,NEW,SAVE,END)
        READ(5,*)IOPT
        IF(IOPT.EQ.3HOLD)GO TO 200
        IF(IOPT.EQ.3HNEW)GO TO 100
        IF(IOPT.EQ.4HSAVE)GO TO 300
        IF(IOPT.EQ.3HEND)GO TO 400
C
C  FILTERED VALUES SAVED UNDER NEW FILENAME
300 CONTINUE
        WRITE(6,22)
        22  FORMAT(16HASSIGN FILE NAME)
        READ(5,*)FICODE(3)
        FICODE(1)=10HSAVE(TAPE2)
        FICODE(2)=10H1=
        FICODE(4)=10H)
        FICODE(5)=0
        CALL PFREQ(FICODE(1),MSG,ICODE)
        WRITE(6,24)
        24  FORMAT(14HFILE NOW SAVED)
C
C  PROCESS CONTROL OPTION
        WRITE(6,26)
        26  FORMAT(32HPROCESS OPTION:1(RETURN), 2(END))
        READ(5,*)IOPT1
        IF(IOPT1.EQ.1)GO TO 250
400 CONTINUE
        STOP
        END
C
C
C
        SUBROUTINE FILTER1(A,Z)
C  4 ELEMENT RING RESIDUAL FILTER
C  RADIUS 1 OR 2
        COMMON IWT,NRAD,MAXR,MAXC,NPASS

```

```

      REAL A(32,32),Z(32,32)
      IF(IWT.LE.0)IWT=1

```

6

```

C      WRITE(6,110)
110  FORMAT(38H4 ELEMENT RING RESIDUAL FILTER RESULTS)
      IF(NRAD.EQ.1)WRITE(6,112)
      IF(NRAD.EQ.2)WRITE(6,114)
112  FORMAT(8HRADIUS 1)
114  FORMAT(8HRADIUS 2)
      IF(NRAD.NE.1)GO TO 111

```

```

C
C  RADIUS 1
      J=1
      K=2
      L=2
      M=2
      JSET=1
      KSET=1
      JKSET=2
      MSET=0
      MJSET=1
      GO TO 102

```

```

C
C  RADIUS 2
111 CONTINUE
      J=1
      K=3
      L=3
      M=3
      JSET=2
      KSET=2
      JKSET=4
      MSET=1
      MJSET=3

```

```

C
C  FILTERING ROUTINE
102 CONTINUE
      VAL=0.0
      VAL=VAL+A(J,K)
      J=J+JSET
      K=K-KSET
      VAL=VAL+A(J,K)
      K=K+JKSET
      VAL=VAL+A(J,K)
      J=J+JSET
      K=K-JSET
      VAL=VAL+A(J,K)
      J=J-JSET
      AVAL=A(J,K)*IWT
      IF(NPASS.EQ.1)Z(L,M)=AVAL-(VAL/4)
      IF(NPASS.EQ.2)Z(L,M)=AVAL+(VAL/4)
      M=M+1
      J=J-JSET
      K=K+1
      IF(K.NE.MAXC-MSET)GO TO 102
      J=J+1
      IF(J.EQ.MAXR-MJSET)GO TO 202
      K=(K+JKSET)-MAXC
      M=(M+JKSET)-MAXC
      GO TO 102

```

```

C
202 CONTINUE
      RETURN
      END

```

```

C
C
C

```

```

L
      SUBROUTINE FILTER2(A,Z)
C 4 ELEMENT SQUARE RESIDUAL FILTER
C RADIUS 1 OR 2
      COMMON IWT,NRAD,MAXR,MAXC,NPASS
      REAL A(32,32),Z(32,32)
      IF(IWT.LE.0)IWT=1
C
      WRITE(6,210)
210  FORMAT(40H4 ELEMENT SQUARE RESIDUAL FILTER RESULTS)
      IF(NRAD.EQ.1)WRITE(6,212)
      IF(NRAD.EQ.2)WRITE(6,214)
212  FORMAT(8HRADIUS 1)
214  FORMAT(8HRADIUS 2)
      IF(NRAD.NE.1)GO TO 222
C
C RADIUS 1
      J=1
      K=1
      L=2
      M=2
      KSET=2
      JSET=1
      MSET=1
      MJSET=2
      MKSET=2
      KJSET=0
      GO TO 302
C
C RADIUS 2
222 CONTINUE
      J=1
      K=1
      L=3
      M=3
      KSET=4
      JSET=2
      MSET=3
      MJSET=4
      MKSET=4
      KJSET=1
C
C FILTERING ROUTINE
302 CONTINUE
      VAL=0.0
      VAL=VAL+A(J,K)
      K=K+KSET
      VAL=VAL+A(J,K)
      J=J+KSET
      K=K-KSET
      VAL=VAL+A(J,K)
      K=K+KSET
      VAL=VAL+A(J,K)
      J=J-JSET
      K=K-JSET
      AVAL=A(J,K)*IWT
      IF(NPASS.EQ.1)Z(L,M)=AVAL-(VAL/4)
      IF(NPASS.EQ.2)Z(L,M)=AVAL+(VAL/4)
      M=M+1
      J=J-JSET
      K=K-KJSET
      IF(K.NE.MAXC-MSET)GO TO 302
      J=J+1
      IF(J.EQ.MAXR-MSET)GO TO 402
      K=(K+MJSET)-MAXC
      M=(M+MKSET)-MAXC
      L=L+1

```

GO TO 302

8

C

402 CONTINUE
RETURN
END

C

C

C

SUBROUTINE FILTER3(A,Z)

C 8 ELEMENT STAR RESIDUAL FILTER

C RADIUS 2

COMMON IWT,NRAD,MAXR,MAXC,NPASS

REAL A(32,32),Z(32,32)

IF(NRAD.NE.2)NRAD=2

C

WRITE(6,310)

310 FORMAT(38H8 ELEMENT STAR RESIDUAL FILTER RESULTS)

WRITE(6,312)

312 FORMAT(8HRADIUS 2)

C

C RADIUS 2

J=1

K=3

L=3

M=3

C

C FILTERING ROUTINE

1000 CONTINUE

VAL=0.0

VAL=VAL+A(J,K)

J=J+1

VAL=VAL+A(J,K)

J=J+1

K=K-2

VAL=VAL+A(J,K)

K=K+1

VAL=VAL+A(J,K)

K=K+2

VAL=VAL+A(J,K)

K=K+1

VAL=VAL+A(J,K)

J=J+1

K=K-2

VAL=VAL+A(J,K)

J=J+1

VAL=VAL+A(J,K)

J=J-2

AVAL=A(J,K)*IWT

IF(NPASS.EQ.1)Z(L,M)=AVAL-(VAL/8)

IF(NPASS.EQ.2)Z(L,M)=AVAL+(VAL/8)

M=M+1

J=J-2

K=K+1

IF(K.NE.MAXC-1)GO TO 1000

J=J+1

IF(J.EQ.MAXR-3)GO TO 2000

K=(K+4)-MAXC

M=(M+4)-MAXC

L=L+1

GO TO 1000

C

2000 CONTINUE
RETURN
END

C

C

C

SUBROUTINE FILTER4(A,Z)

```

C 6 ELEMENT SQUARE RESIDUAL FILTER
C RADIUS 1 OR 2
      COMMON IWT,NRAD,MAXR,MAXC,NPASS
      REAL A(32,32),Z(32,32)
      IF(IWT.LE.0)IWT=1
C
      WRITE(6,320)
320  FORMAT(40H6 ELEMENT SQUARE RESIDUAL FILTER RESULTS)
      IF(NRAD.EQ.1)WRITE(6,322)
      IF(NRAD.EQ.2)WRITE(6,324)
322  FORMAT(8HRADIUS 1)
324  FORMAT(8HRADIUS 2)
      IF(NRAD.NE.1)GO TO 333
C
C RADIUS 1
      J=1
      K=1
      L=2
      M=2
      KSET=1
      JSET=2
      KJSET=0
      MSET=1
      MJSET=2
      MKSET=2
      GO TO 1010
C
C RADIUS 2
333 CONTINUE
      J=1
      K=1
      L=3
      M=3
      KSET=2
      JSET=4
      KJSET=1
      MSET=3
      MJSET=4
      MKSET=4
C
C FILTERING ROUTINE
1010 CONTINUE
      VAL=0.0
      VAL=VAL+A(J,K)
      K=K+KSET
      VAL=VAL+A(J,K)
      K=K+KSET
      VAL=VAL+A(J,K)
      J=J+JSET
      K=K-JSET
      VAL=VAL+A(J,K)
      K=K+KSET
      VAL=VAL+A(J,K)
      K=K+KSET
      VAL=VAL+A(J,K)
      J=J-KSET
      K=K-KSET
      AVAL=A(J,K)*IWT
      IF(NPASS.EQ.1)Z(L,M)=AVAL-(VAL/6)
      IF(NPASS.EQ.2)Z(L,M)=AVAL+(VAL/6)
      M=M+1
      J=J-KSET
      K=K-KJSET
      IF(K.NE.MAXC-MSET)GO TO 1010
      J=J+1
      IF(J.EQ.MAXR-MSET)GO TO 2008

```

```

      K=(K+MJSET)-MAXC
      M=(M+MKSET)-MAXC
      L=L+1
      GO TO 1010
C
2008 CONTINUE
      RETURN
      END
C
C
C
      SUBROUTINE FILTER5(A,Z)
C 8 ELEMENT SQUARE RESIDUAL FILTER
C RADIUS 1 OR 2
      COMMON IWT,NRAD,MAXR,MAXC,NPASS
      REAL A(32,32),Z(32,32)
      IF(IWT.LE.0)IWT=1
C
      WRITE(6,410)
410  FORMAT(40H8 ELEMENT SQUARE RESIDUAL FILTER RESULTS)
      IF(NRAD.EQ.1)WRITE(6,412)
      IF(NRAD.EQ.2)WRITE(6,414)
412  FORMAT(8HRADIUS 1)
414  FORMAT(8HRADIUS 2)
      IF(NRAD.NE.1)GO TO 444
C
C RADIUS 1
      J=1
      K=1
      L=2
      M=2
      KSET=1
      JSET=2
      KJSET=0
      MSET=1
      MJSET=2
      MKSET=2
      GO TO 1004
C
C RADIUS 2
444 CONTINUE
      J=1
      K=1
      L=3
      M=3
      KSET=2
      JSET=4
      KJSET=1
      MSET=3
      MJSET=4
      MKSET=4
C
C FILTERING ROUTINE
1004 CONTINUE
      VAL=0.0
      VAL=VAL+A(J,K)
      K=K+KSET
      VAL=VAL+A(J,K)
      K=K+KSET
      VAL=VAL+A(J,K)
      J=J+KSET
      VAL=VAL+A(J,K)
      K=K+JSET
      VAL=VAL+A(J,K)
      J=J+KSET
      K=K-JSET

```



```

        VAL=VAL+A(J,K)
        K=K+KSET
        VAL=VAL+A(J,K)
        K=K+KSET
        VAL=VAL+A(J,K)
        J=J-KSET
        K=K-KSET
        AVAL=A(J,K)*IWT
        IF(NPASS.EQ.1)Z(L,M)=AVAL-(VAL/8)
        IF(NPASS.EQ.2)Z(L,M)=AVAL+(VAL/8)
        M=M+1
        J=J-KSET
        K=K-KJSET
        IF(K.NE.MAXC-MSET)GO TO 1004
        J=J+1
        IF(J.EQ.MAXR-MSET)GO TO 2004
        K=(K+MJSET)-MAXC
        M=(M+MKSET)-MAXC
        L=L+1
        GO TO 1004
2004 CONTINUE
        RETURN
        END
C
C
C
        SUBROUTINE FILTER6(A,Z)
C  8 ELEMENT RING RESIDUAL FILTER
C  RADIUS 2
        COMMON IWT,NRAD,MAXR,MAXC,NPASS
        REAL A(32,32),Z(32,32)
        IF(IWT.LE.0)IWT=1
        IF(NRAD.NE.2)NRAD=2
C
        WRITE(6,510)
510  FORMAT(38H8 ELEMENT RING RESIDUAL FILTER RESULTS)
        WRITE(6,512)
512  FORMAT(8HRADIUS 2)
C
C  RADIUS 2
        J=1
        K=3
        L=3
        M=3
C
C  FILTERING ROUTINE
1006 CONTINUE
        VAL=0.0
        VAL=VAL+A(J,K)
        J=J+1
        K=K-1
        VAL=VAL+A(J,K)
        K=K+2
        VAL=VAL+A(J,K)
        J=J+1
        K=K-3
        VAL=VAL+A(J,K)
        K=K+4
        VAL=VAL+A(J,K)
        J=J+1
        K=K-3
        VAL=VAL+A(J,K)
        K=K+2
        VAL=VAL+A(J,K)
        J=J+1
        K=K-1

```

```

VAL=VAL+A(J,K)
J=J-2
AVAL=A(J,K)*IWT
IF(NPASS.EQ.1)Z(L,M)=AVAL-(VAL/8)
IF(NPASS.EQ.2)Z(L,M)=AVAL+(VAL/8)
M=M+1
J=J-2
K=K+1
IF(K.NE.MAXC-1)GO TO 1006
J=J+1
IF(J.EQ.MAXR-3)GO TO 2006
K=(K+4)-MAXC
M=(M+4)-MAXC
L=L+1
GO TO 1006

```

```

C
2006 CONTINUE
      RETURN
      END

```

EXAMPLE PROGRAM RUN:

```

FILENAME
? "testad"
NUMBER OF ROWS
? 10
NUMBER OF COLUMNS
? 20

```

20.0000	19.0000	22.0000	18.0000	20.0000
21.0000	20.0000	19.0000	21.0000	24.0000
30.0000	36.0000	34.0000	24.0000	20.0000
19.0000	18.0000	20.0000	18.0000	16.0000
22.0000	21.0000	24.0000	21.0000	26.0000
24.0000	21.0000	22.0000	24.0000	26.0000
40.0000	37.0000	34.0000	28.0000	26.0000
24.0000	22.0000	24.0000	23.0000	25.0000
34.0000	32.0000	36.0000	40.0000	36.0000
36.0000	38.0000	40.0000	41.0000	40.0000
40.0000	36.0000	38.0000	39.0000	36.0000
40.0000	36.0000	35.0000	38.0000	40.0000
28.0000	20.0000	25.0000	26.0000	20.0000
21.0000	22.0000	25.0000	26.0000	28.0000
26.0000	27.0000	28.0000	29.0000	20.0000
19.0000	22.0000	24.0000	26.0000	25.0000
20.0000	19.0000	19.0000	22.0000	23.0000
24.0000	25.0000	25.0000	23.0000	19.0000
20.0000	21.0000	22.0000	22.0000	25.0000
18.0000	17.0000	18.0000	20.0000	22.0000
20.0000	21.0000	22.0000	24.0000	18.0000
19.0000	20.0000	16.0000	20.0000	21.0000
22.0000	18.0000	20.0000	21.0000	20.0000
10.0000	9.00000	15.0000	20.0000	21.0000
17.0000	16.0000	17.0000	15.0000	18.0000
20.0000	15.0000	12.0000	20.0000	19.0000
18.0000	17.0000	16.0000	16.0000	16.0000
8.00000	8.00000	12.0000	15.0000	20.0000
8.00000	7.00000	6.00000	8.00000	10.0000
12.0000	8.00000	7.00000	6.00000	6.00000
12.0000	12.0000	14.0000	16.0000	20.0000
16.0000	15.0000	17.0000	18.0000	20.0000
6.00000	6.00000	7.00000	8.00000	9.00000
10.0000	10.0000	9.00000	9.00000	6.00000
12.0000	9.00000	14.0000	16.0000	20.0000
21.0000	20.0000	19.0000	18.0000	20.0000
10.0000	12.0000	12.0000	16.0000	16.0000
14.0000	14.0000	16.0000	21.0000	12.0000
6.00000	6.00000	12.0000	14.0000	16.0000
20.0000	20.0000	21.0000	20.0000	20.0000

FILTER OPTIONS ARE:

1: 4 ELEMENT RING RESIDUAL FILTER, RADIUS 1 OR 2
 2: 4 ELEMENT SQUARE RESIDUAL FILTER, RADIUS 1 OR 2
 3: 8 ELEMENT STAR RESIDUAL FILTER, RADIUS 2
 4: 6 ELEMENT SQUARE RESIDUAL FILTER, RADIUS 1 OR 2
 5: 8 ELEMENT SQUARE RESIDUAL FILTER, RADIUS 1 OR 2
 6: 8 ELEMENT RING RESIDUAL FILTER, RADIUS 2

ENTER FILTER NO.,RADIUS,WEIGHTING FACTOR

? 1,1,1

FILTER RESPONSE:1(HIGH PASS) OR 2(LOW PASS)

? 1

4 ELEMENT RING RESIDUAL FILTER RESULTS

RADIUS 1

0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	-3.25000	-1.00000	-6.00000	.750000
-2.00000	-5.00000	-4.00000	-3.50000	-6.00000
6.75000	.500000	-.250000	-2.75000	-1.00000
-2.75000	-3.50000	-1.00000	-3.25000	0
0	4.25000	5.75000	10.2500	5.50000
6.25000	8.25000	8.50000	8.50000	6.25000
4.50000	.500000	3.75000	6.25000	4.75000
11.2500	6.25000	4.50000	7.00000	0
0	-6.00000	-.250000	-.750000	-6.50000
-4.50000	-5.25000	-3.25000	-3.25000	.250000
-2.75000	-.750000	-1.00000	1.75000	-7.25000
-6.00000	-2.00000	-1.25000	-.750000	0
0	-1.00000	-3.00000	-1.00000	2.00000
2.00000	2.25000	2.75000	.500000	-4.00000
-2.00000	-.750000	-.750000	-2.25000	5.00000
.250000	.250000	-1.00000	-1.50000	0
0	1.75000	1.75000	4.75000	-3.00000
-1.50000	1.25000	-3.25000	0	1.00000
2.75000	-2.00000	.750000	1.50000	2.00000
-3.75000	-3.50000	.250000	2.25000	0
0	.500000	2.25000	-1.75000	2.25000
4.00000	0	-2.50000	5.75000	2.75000
.500000	1.00000	-.750000	-1.25000	0
-4.50000	-3.00000	-1.75000	-2.50000	0
0	-2.00000	-3.75000	-1.75000	-1.75000
0	-3.00000	-1.75000	-4.50000	-4.75000
0	-1.00000	-.500000	-.500000	3.00000
0	-.250000	1.00000	.500000	0
0	-2.00000	-1.00000	-2.00000	-2.00000
-1.25000	-.250000	-1.50000	-1.50000	-3.75000
3.75000	-2.00000	1.25000	0	1.75000
2.00000	1.25000	0	-1.25000	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0

OLD,NEW,SAVE,END

? "end"

.390 CP SECONDS EXECUTION TIME

/

DATA:

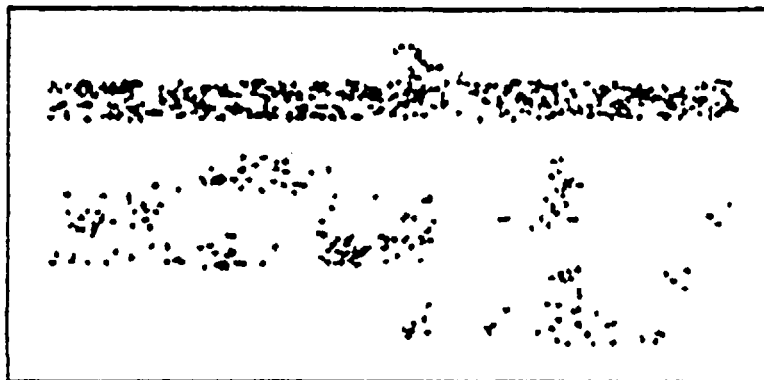
FILE TESTGD

20,19,22,18,20,21,20,19,21,24,30,36,34,24,20,19,18,20,18,16
 22,21,24,21,26,24,21,22,24,26,40,37,34,28,26,24,22,24,23,25
 34,32,36,40,36,36,38,40,41,40,40,36,38,39,36,40,36,35,38,40
 28,20,25,26,20,21,22,25,26,28,26,27,28,29,20,19,22,24,26,25
 20,19,19,22,23,24,25,25,23,19,20,21,22,22,25,18,17,18,20,22
 20,21,22,24,18,19,20,16,20,21,22,18,20,21,20,10,9,15,20,21
 17,16,17,15,18,20,15,12,20,19,18,17,16,16,16,8,8,12,15,20
 8,7,6,8,10,12,8,7,6,6,12,12,14,16,20,16,15,17,18,20
 6,6,7,8,9,10,10,9,9,6,12,9,14,16,20,21,20,19,18,20
 10,12,12,16,16,14,14,16,21,12,6,6,12,14,16,20,20,21,20,20
 /

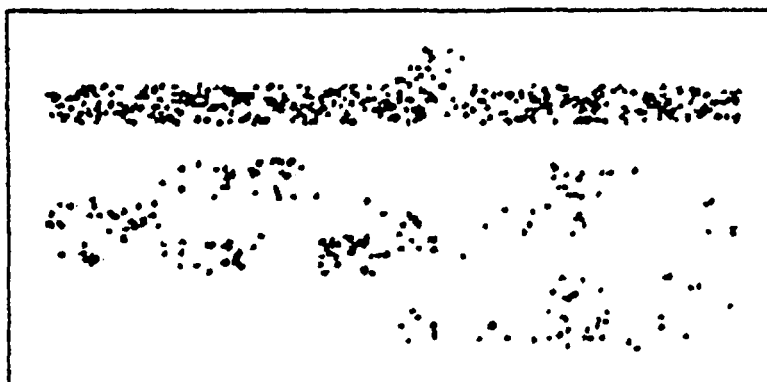
RESULTS AND COMMENTS:

Data file TESTGD was used. This has a number of features within
 the data (wall, ditch, pit), a plan of which is given in plot
 1D (see plots PROGRAM DOT2).
 Not all filters were equally successful at bringing out these
 features. Plots 1F to 3F give the results which most clearly showed
 up the walled structure, whereas plots 4F to 6F apply to the
 ditch and pit.

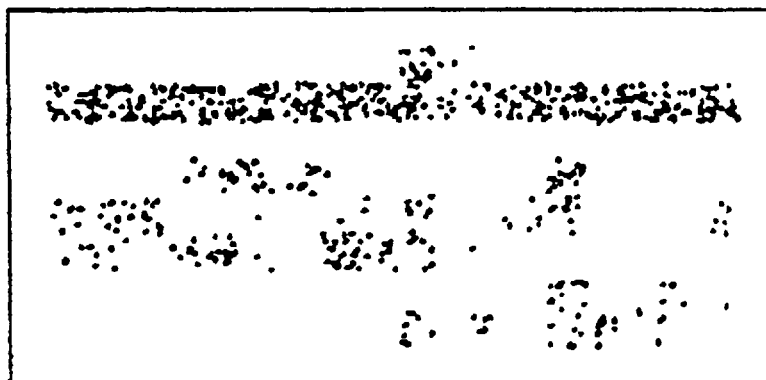
PROGRAM FILTER - WALL



Plot 1F High-pass 4 element square residual filter, radius 1
Cut-off level = 0.0
Saturation level = 2.0
Linear plot

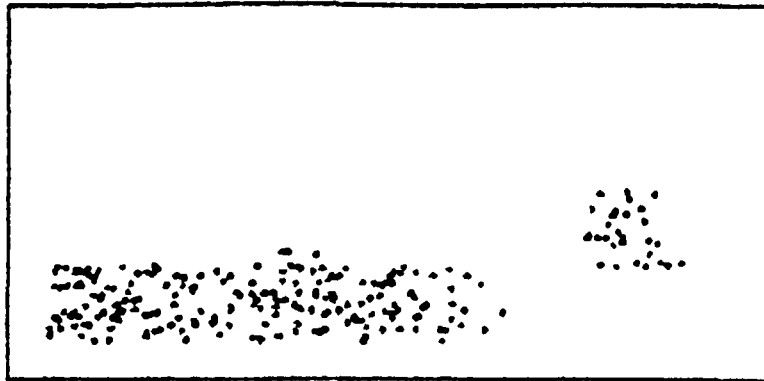


Plot 2F High-pass 6 element square residual filter, radius 1
Cut-off level = 0.0
Saturation level = 2.0
Linear plot

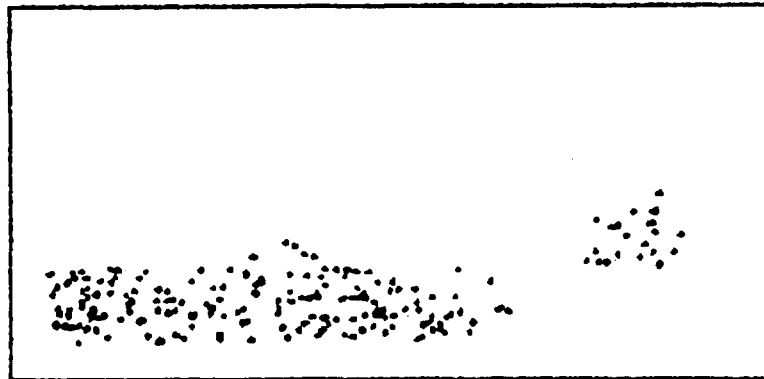


Plot 3F High-pass 8 element square residual filter, radius 1
Cut-off level = 0.0
Saturation level = 2.0
Linear plot

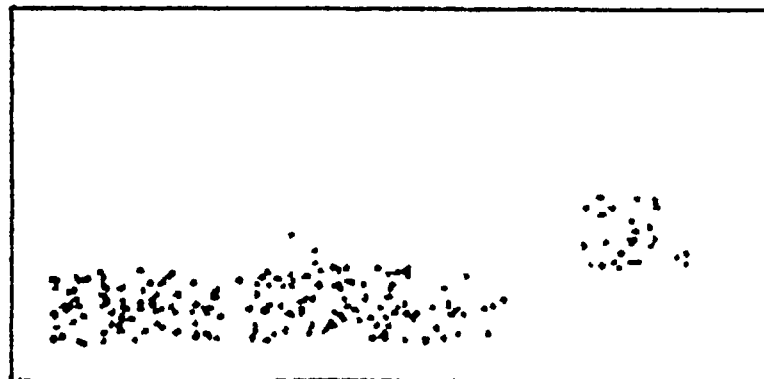
PROGRAM FILTER - DITCH + PIT



Plot 4F Low-pass 4 element ring residual filter, radius 1
 Cut-off level = 0.0
 Saturation level = -1.25
 Linear plot



Plot 5F Low-pass 4 element square residual filter, radius 1
 Cut-off level = 0.0
 Saturation level = -1.25
 Linear plot



Plot 6F Low-pass 8 element square residual filter, radius 1
 Cut-off level = 0.0
 Saturation level = -1.25
 Linear plot

PROGRAM DOT2 (FORTRAN IV)

PROGRAM LISTING:

```

      PROGRAM DOT2(INPUT=131B,OUTPUT=131B,TAPE5=INPUT,TAPE7=221B,
+          TAPE6=OUTPUT,TAPE61=1021B,TAPE66=1021B)
C  DOT DENSITY DATA HANDLING AND PLOTTING PROGRAM
C  IMAGE PROCESSING PACKAGE
C  DATA TYPE=REAL ARRAY ON EXTERNAL FILE
C  TAPE7=DATA INPUT FILE
C  TAPE 61+66=SIMPLE HANDLING TAPES
C  MNF5 UNDER SIMPLE
C  USE OF NAG7F LIBRARY FOR RANDOM NUMBER GENERATOR
C  HISTOGRAM ROUTINE USING NAG7F LIBRARY
C  PROGRAM DEVELOPED BY J T HACKMANN, GEOPHYSICS DEP., RSM
      DIMENSION A(32,32),AFLT(32,32),ADOT(32,32),XPAGE(50),
+          YPAGE(50)
      COMMON/A/MAXR,MAXC
      COMMON/B/NFILT,NRAD,IWT,NPASS
      COMMON/C/CUT,SAT,IOPT3
      DATA NFILT,NRAD,IWT,CUT,SAT,IOPT3/0,0,0,0.0,0.0,0/
      INTEGER FNAME,FNCODE(4),MSG(4),ICODE
      REAL G05CAF
C
C  CALL SIMPLE START-UP ROUTINE TO DEFINE PLOT AREA
C  22.0*16.75 INCHES
      CALL START(2)
C
C  INPUT FILE REQUESTED
100 CALL PROMPT(8HFILENAME,8)
      READ(5,*)FNCODE(2)
      FNCODE(1)=10HGET(TAPE7=
      FNCODE(3)=10H)
      FNCODE(4)=0
      CALL PFREQ(FNCODE(1),MSG,ICODE)
      REWIND 7
      FNAME=FNCODE(2)
C
C  FILE DIMENSIONS REQUESTED
      CALL PROMPT(14HNUMBER OF ROWS,14)
      READ(5,*)MAXR
      CALL PROMPT(17HNUMBER OF COLUMNS,17)
      READ(5,*)MAXC
      RD=MAXR*MAXC
C
C  FILE READ-IN AS 2-DIMENSIONAL
      DO 1 J=1,MAXR
        READ(7,*)(A(J,K),K=1,MAXC)
        DO 2 K=1,MAXC
          AFLT(J,K)=A(J,K)
        2 CONTINUE
      1 CONTINUE
C
C  DATA CONTROL OPTION
125 CALL PROMPT(39HSELECT DATA OPTION: 1(NORM.) OR 2(NEG.),39)
      READ(5,*)IOPTD
      IF(IOPTD.EQ.1)GO TO 200
      IF(IOPTD.EQ.2)GO TO 150
      IF(IOPTD.LT.1.OR.IOPTD.GT.2)GO TO 125
C
C  CONSTANT IS ADDED TO NEGATIVE VALUES TO NEGATE SIGN

```

C CONSTANT IS ADDED TO NEGATIVE VALUES TO NEGATE SIGN

18

```
150 CONTINUE
      DO 23 J=1,MAXR
      DO 24 K=1,MAXC
      AFLT(J,K)=100+(AFLT(J,K))
24    CONTINUE
23    CONTINUE
C
C SYMBOL PLOT DENOMINATORS RESET
200 CONTINUE
      NFILT=0
      NRAD=0
      IWT=0
C
C SELECT FILTERING CONTROL OPTION
      CALL PROMPT(37HSELECT FILTER OPTION: 0(NO) OR 1(YES),37)
      READ(5,*)IOPT1
C
C BRANCH ON SELECTED OPTION
      IF(IOPT1.EQ.0)GO TO 400
      IF(IOPT1.EQ.1)GO TO 300
      IF(IOPT1.LT.0.OR.IOPT1.GT.1)GO TO 200
300 CONTINUE
C
C INFORM USER OF CONTROL OPTIONS
      WRITE(6,1000)
1000 FORMAT(* FILTER OPTIONS ARE:*,//,
+          * 1: 4 ELEMENT RING RESIDUAL FILTER, RADIUS 1 OR 2
+*,//,
+          * 2: 4 ELEMENT SQUARE RESIDUAL FILTER, RAD
+IUS 1 OR 2*,//,
+          * 3: 8 ELEMENT STAR RESIDUAL FIL
+TER, RADIUS 2*,//)
C
C FILTER PARAMETERS DETERMINED
      CALL PROMPT(40HENTER FILTER NO.,RADIUS,WEIGHTING FACTOR,40)
      READ(5,*)NFILT,NRAD,IWT
C
C HIGH PASS OR LOW PASS FILTER OPTION
      CALL PROMPT(43HFILTER RESPONSE:1(HIGH PASS) OR 2(LOW PASS),43
+)
      READ(5,*)NPASS
C
C RING RESIDUAL FILTER 1
      IF(NFILT .EQ. 1)CALL FILTER1(A,AFLT)
C
C SQUARE RESIDUAL FILTER 2
      IF(NFILT .EQ. 2) CALL FILTER2(A,AFLT)
C
C 8 ELEMENT STAR RESIDUAL FILTER
      IF(NFILT .EQ. 3) CALL FILTER3(A,AFLT)
C
C BLANK AREAS AROUND FILTERED VALUES FILLED IN
C WITH ZERO'S AND A CONSTANT IS ADDED TO NEGATE SIGN
      IF(NRAD.EQ.1)INT=0
      IF(NRAD.EQ.2)INT=1
      DO 14 J=1,MAXR
      DO 15 K=1,MAXC
      IF(J.EQ.1.OR.J.EQ.NRAD.OR.J.EQ.MAXR-INT.OR.J.EQ.MAXR)AFLT(J,K
+)=0.
      IF(K.EQ.1.OR.K.EQ.NRAD.OR.K.EQ.MAXC-INT.OR.K.EQ.MAXC)AFLT(J,K
+)=0.
      AFLT(J,K)=100+(AFLT(J,K))
15    CONTINUE
14    CONTINUE
C
C FILE VALUES ADDED
400 CONTINUE
      SUM=0.0
```



```

SUM=0.0
INPUT=0
DO 3 J=1,MAXR
DO 4 K=1,MAXC
SUM=SUM+AFLT(J,K)
INPUT=INPUT+1
4 CONTINUE
3 CONTINUE
C
C AVERAGE AND SD
SUMD=0.0
AVE=SUM/RD
DO 5 J=1,MAXR
DO 6 K=1,MAXC
R=AFLT(J,K)-AVE
R=R*R
SUMD=SUMD+R
6 CONTINUE
5 CONTINUE
SUD=SUMD/RD
SD=SQRT(SUD)
C
C CLEAR DISPLAY
CALL NEWPAGE
C
C FREQUENCY HISTOGRAM
CALL LHIST(FNAME,AFLT,AVE,SD,XMAX,XMIN)
C
C RESET OR CONTINUE PROCESSING
425 CALL PROMPT(44HSELECT PROCESS OPTION:1(OLD),2(NEW),3(CONT.),
+ 44)
READ(5,*)IOPT2
IF(IOPT2.EQ.1)GO TO 200
IF(IOPT2.EQ.2)GO TO 100
IF(IOPT2.EQ.3)GO TO 450
IF(IOPT2.LT.1.OR.IOPT2.GT.3)GO TO 425
450 CONTINUE
C
C CLEAR DISPLAY AND RESET PLOT ORIGIN
CALL NEWPAGE
C
C METRIC OR IMPERIAL PLOT SCALE
CALL PROMPT(35HSET PLOT SCALE:1(METRIC) OR 2(IMP.),35)
READ(5,*)IOPT5
IF(IOPT5.EQ.1)GO TO 61
IF(IOPT5.EQ.2)GO TO 62
61 CONTINUE
NSCALE=4
IF(MAXR.LE.15.AND.MAXC.LE.15)NSCALE=2
XLEN=(MAXC*1.36)/NSCALE
YLEN=(MAXR*1.36)/NSCALE
NDOTL=25
IF(NSCALE.EQ.2)NDOTL=50
GO TO 63
62 CONTINUE
XLEN=MAXC/2
YLEN=MAXR/2
NDOTL=40
63 CONTINUE
C
C CUT-OFF AND SATURATION LEVELS
CALL PROMPT(26HCUT-OFF LEVEL:-2.0 TO +2.0,26)
READ(5,*)CUT
CALL PROMPT(29HSATURATION LEVEL:-2.0 TO +2.0,29)
READ(5,*)SAT
C
C RANGE AND SCALE

```

```

C RANGE AND SCALE
    AMAX=AVE+(SAT*SD)
    AMIN=AVE+(CUT*SD)
    IF(SAT.GT.0.0.AND.AMAX.GT.XMAX)AMAX=XMAX
    IF(CUT.LT.0.0.AND.AMIN.LT.XMIN)AMIN=XMIN
    IF(SAT.LT.0.0.AND.AMAX.LT.XMIN)AMAX=XMIN
    IF(CUT.GT.0.0.AND.AMIN.GT.XMAX)AMIN=XMAX
    RANGE=AMAX-AMIN
    SCALE=RANGE/NDOTL
C
C LINEAR OR LOG DOT FUNCTION
475 CALL PROMPT(43HSELECT PLOT CONTROL OPTION:1(LIN) OR 2(LOG),
+           43)
    READ(5,*)IOPT3
    IF(IOPT3.EQ.1)GO TO 500
    IF(IOPT3.EQ.2)GO TO 600
    IF(IOPT3.LT.1.OR.IOPT3.GT.2)GO TO 475
C
C TABLE OF LINEAR DOT NUMBERS
500 CONTINUE
    DO 7 J=1,MAXR
    DO 8 K=1,MAXC
    ADOT(J,K)=0.0
    NDOT=(AFLT(J,K)-AMIN)/SCALE
    IF(NDOT.GT.NDOTL)NDOT=0
    IF(NDOT.LE.0)NDOT=0
    ADOT(J,K)=NDOT
    8 CONTINUE
    7 CONTINUE
    GO TO 60
600 CONTINUE
C
C TABLE OF LOG DOT NUMBERS
    DO 9 J=1,MAXR
    DO 10 K=1,MAXC
    ADOT(J,K)=0.0
    DOTLG=(AFLT(J,K)-AMIN)/SCALE
    IF(DOTLG.LE.0.0)DOTLG=0.1
    NDOT=(ALOG10(DOTLG))*DOTLG
    IF(NDOT.GT.NDOTL)NDOT=NDOTL
    IF(NDOT.LE.0)NDOT=0
    ADOT(J,K)=NDOT
    10 CONTINUE
    9 CONTINUE
    60 CONTINUE
C
C ENABLE HARD COPY
    CALL SWITCH(10HHARDCPY ON)
C
C CLEAR DISPLAY AND RESET PLOT ORIGIN
    CALL NEWPAGE
C
C PLOT ANNOTATION
    CALL ANNOT(FNAME)
C
C SET-UP X-Y COORDINATES OF MAIN BOUNDARY FIELD
C MAX. FIELD 15*15 INCHES
    CALL PLOT(XLEN,0.0,2)
    CALL PLOT(XLEN,YLEN,-2)
    CALL PLOT(-XLEN,0.0,-2)
    CALL PLOT(0.0,-YLEN,-2)
    CALL PLOT(0.0,0.0,-3)
C SUBROUTINE REFERENCES G05CCF(NAG7F LIBRARY) TO DETERMINE
C PLOTTING AXIS
C FUNCTION REFERENCES G05CAF
C LOCAL SCALARS
C XPAGE AND YPAGE DIMENSIONED FOR ARRAY MAX 50x50

```

```

C  PLOTTING ROUTINE
C  COUNT=0.0
C  XCOUNT=XLEN/MAXC
C  YCOUNT=YLEN/MAXR
C  ADD=YLEN
C  CALL G05CCF
C  DO 11 J=1,MAXR
C      DO 12 K=1,MAXC
C          NVALUE=ADOT(J,K)
C          IF(NVALUE.LE.0)GO TO 70
C          DO 13 I=1,NVALUE
C              X=G05CAF(X)
C              XPAGE(I)=COUNT+((X)*XCOUNT)
C              X=G05CAF(X)
C              YPAGE(I)=ADD-((X)*YCOUNT)
C              CALL SYMBOL(XPAGE(I),YPAGE(I),0.03,5,0.0,-1)
13      CONTINUE
70      CONTINUE
C          COUNT=COUNT+XCOUNT
12      CONTINUE
C          COUNT=0.0
C          ADD=ADD-YCOUNT
11      CONTINUE
C
C  BUFFERS CLEARED
C      CALL BUFFEM
C
C  SELECT CONTROL OPTION
700  CALL PROMPT(43HSELECT CONTROL OPTION.OLD.NEW.MAG.HARD.END.,43)
C      READ(5,*)IOPT4
C
C  BRANCH ON SELECTED OPTION
C      IF(IOPT4.EQ.3HOLD)GO TO 750
C      IF(IOPT4.EQ.3HNEW)GO TO 100
C      IF(IOPT4.EQ.3HMAG)GO TO 800
C      IF(IOPT4.EQ.4HHARD)CALL HARDCPY
C      IF(IOPT4.EQ.3HEND)GO TO 900
C      STOP
C
C  MAIN ARRAY RESET TO INITIAL DATA ARRAY AND
C  SYMBOL PLOT DENOMINATORS RESET
750  CONTINUE
C      DO 18 J=1,MAXR
C      DO 19 K=1,MAXC
C          AFLT(J,K)=A(J,K)
19      CONTINUE
18      CONTINUE
C
C  CLEAR DISPLAY AND RESET PLOT ORIGIN TO CONTINUE
C      CALL NEWPAGE
C      GO TO 200
C
C  REQUEST MAGNIFICATION FACTOR
800  CALL PROMPT(19HENTER MAGNIFICATION,19)
C      READ(5,*)XMAG
C
C  CHANGE MAGNIFICATION FACTORS
C      CALL MAGNIFY(XMAG)
C      GO TO 700
900  CONTINUE
C      END
C
C
C
C      SUBROUTINE FILTER1(A,Z)
C  A ELEMENT RING RESIDUAL FILTER

```

C 4 ELEMENT RING RESIDUAL FILTER

C RADIUS 1 OR 2

22

```
DIMENSION A(32,32),Z(32,32)
COMMON/A/MAXR,MAXC
COMMON/B/NFILT,NRAD,IWT,NPASS
IF(IWT.LE.0)IWT=1
IF(NRAD.NE.1)GO TO 111
```

C

C RADIUS 1

```
J=1
K=2
L=2
M=2
JSET=1
KSET=1
JKSET=2
MSET=0
MJSET=1
GO TO 102
```

C

C RADIUS 2

```
111 CONTINUE
J=1
K=3
L=3
M=3
JSET=2
KSET=2
JKSET=4
MSET=1
MJSET=3
```

C

C FILTERING ROUTINE

```
102 CONTINUE
VAL=0.0
VAL=VAL+A(J,K)
J=J+JSET
K=K-KSET
VAL=VAL+A(J,K)
K=K+JKSET
VAL=VAL+A(J,K)
J=J+JSET
K=K-JSET
VAL=VAL+A(J,K)
J=J-JSET
AVAL=A(J,K)*IWT
IF(NPASS.EQ.1)Z(L,M)=AVAL-(VAL/4)
IF(NPASS.EQ.2)Z(L,M)=AVAL+(VAL/4)
M=M+1
J=J-JSET
K=K+1
IF(K.NE.MAXC-MSET)GO TO 102
J=J+1
IF(J.EQ.MAXR-MJSET)GO TO 202
K=(K+JKSET)-MAXC
M=(M+JKSET)-MAXC
L=L+1
GO TO 102
202 CONTINUE
RETURN
END
```

C

C

C

SUBROUTINE FILTER2(A,Z)

C 4 ELEMENT SQUARE RESIDUAL FILTER

C RADIUS 1 OR 2

```

C      RADIUS 1 OR 2
      DIMENSION A(32,32),Z(32,32)
      COMMON/A/MAXR,MAXC
      COMMON/B/NFILT,NRAD,IWT,NPASS
      IF(IWT.LE.0)IWT=1
      IF(NRAD.NE.1)GO TO 222

C
C  RADIUS 1
      J=1
      K=1
      L=2
      M=2
      KSET=2
      JSET=1
      MSET=1
      MJSET=2
      MKSET=2
      KJSET=0
      GO TO 302

C
C  RADIUS 2
222 CONTINUE
      J=1
      K=1
      L=3
      M=3
      KSET=4
      JSET=2
      MSET=3
      MJSET=4
      MKSET=4
      KJSET=1

C
C  FILTERING ROUTINE
302 CONTINUE
      VAL=0.0
      VAL=VAL+A(J,K)
      K=K+KSET
      VAL=VAL+A(J,K)
      J=J+KSET
      K=K-KSET
      VAL=VAL+A(J,K)
      K=K+KSET
      VAL=VAL+A(J,K)
      J=J-JSET
      K=K-JSET
      AVAL=A(J,K)*IWT
      IF(NPASS.EQ.1)Z(L,M)=AVAL-(VAL/4)
      IF(NPASS.EQ.2)Z(L,M)=AVAL+(VAL/4)
      M=M+1
      J=J-JSET
      K=K-KJSET
      IF(K.NE.MAXC-MSET)GO TO 302
      J=J+1
      IF(J.EQ.MAXR-MSET)GO TO 402
      K=(K+MJSET)-MAXC
      M=(M+MKSET)-MAXC
      L=L+1
      GO TO 302
402 CONTINUE
      RETURN
      END

C
C
C
      SUBROUTINE FILTER3(A,Z)
      C ELEMENTS OF A BEING FILTERED

```

C 8 ELEMENT STAR RESIDUAL FILTER

C RADIUS 2

24

```
DIMENSION A(32,32),Z(32,32)
COMMON/A/MAXR,MAXC
COMMON/B/NFILT,NRAD,IWT,NPASS
IF(NRAD.NE.2)NRAD=2
```

C

C RADIUS 2

```
J=1
K=3
L=3
M=3
```

C

C FILTERING ROUTINE

502 CONTINUE

```
VAL=0.0
VAL=VAL+A(J,K)
J=J+1
VAL=VAL+A(J,K)
J=J+1
K=K-2
VAL=VAL+A(J,K)
K=K+1
VAL=VAL+A(J,K)
K=K+2
VAL=VAL+A(J,K)
K=K+1
VAL=VAL+A(J,K)
J=J+1
K=K-2
VAL=VAL+A(J,K)
J=J+1
VAL=VAL+A(J,K)
J=J-2
AVAL=A(J,K)*IWT
IF(NPASS.EQ.1)Z(L,M)=AVAL-(VAL/8)
IF(NPASS.EQ.2)Z(L,M)=AVAL+(VAL/8)
M=M+1
J=J-2
K=K+1
IF(K.NE.MAXC-1)GO TO 502
J=J+1
IF(J.EQ.MAXR-3)GO TO 602
K=(K+4)-MAXC
M=(M+4)-MAXC
L=L+1
GO TO 502
602 CONTINUE
RETURN
END
```

C

C

C

SUBROUTINE LHIST(FNAME,AFLT,AVE,SD,XMAX,XMIN)

C HISTOGRAM SUBROUTINE USING NAG7F LIBRARY

C PROGRAM REFERENCES G01AEF ROUTINE

```
REAL AFLT(32,32),X(1024),CINT(25),XMIN,XMAX,YIFREQ(25)
INTEGER IFREQ(25),N,ICLASS,K2,IFAIL,J
INTEGER FNAME
COMMON/A/MAXR,MAXC
COMMON/B/NFILT,NRAD,IWT,NPASS
COMMON/C/CUT,SAT,IOPT3
```

C

C DATA FILE CONVERTED INTO 1-DIMENSIONAL FILE

```
L=0
DO 20 J=1,MAXR
  DO 21 K=1,MAXC
```

L=L+1
X(L)=AFLT(J,K)

25

21 CONTINUE

20 CONTINUE

```
C
C SUBROUTINE PARAMETERS SET
C NO. OF VALUES
  N=MAXR*MAXC
C
C NO. OF CLASSES
  K2=25
C
C CLASS BOUNDARY VALUES ROUTINE CALCULATED
  ICLASS=0
C
C ERROR INDICATOR
  IFAIL=0
  CALL G01AEF(N,K2,X,ICLASS,CINT,IFREQ,XMIN,XMAX,IFAIL)
  IF(IFAIL.GE.1)GO TO 80
C
C FILE HEADING AND ANNOTATION PROVIDED
  CALL ANNOT(FNAME)
C
C AXES SET-UP AND ANNOTATED
  CALL PLOT(20.,0.,2)
  CALL PLOT(0.,0.,3)
  CALL SYMBOL(0.5,-0.5,0.25,4HMIN.,0.0,4)
  CALL SYMBOL(18.0,-0.5,0.25,4HMAX.,0.0,4)
  CALL PLOT(0.,0.,3)
  CALL PLOT(0.,12.,2)
  CALL PLOT(0.,0.,3)
  CALL SYMBOL(-0.5,5.0,0.25,9HFREQUENCY,90.0,9)
  CALL PLOT(0.,0.,3)
C
C SCALE ADJUSTED ACCORDING TO GRID SIZE
  IF(N.LE.100)YSCALE=2.0
  IF(N.GT.100)YSCALE=20.0
C
C FREQUENCY HISTOGRAM PLOTTED
  CALL PLOT(2.0,0.,-2)
  K=2
  DO 22 J=1,K2-1
    CALL NUMBER(0.0,-0.5,0.1,CINT(J),270.0,2)
    CALL PLOT(0.,0.,3)
    YIFREQ(K)=IFREQ(K)/YSCALE
    CALL PLOT(0.,YIFREQ(K),-2)
    CALL PLOT(0.5,0.,-2)
    CALL PLOT(0.,-YIFREQ(K),-2)
    K=K+1
  22 CONTINUE
C
C PLOT ANNOTATION
  CASE=N
  CALL SYMBOL(0.0,15.0,0.2,8HMAXIMUM=,0.0,8)
  CALL NUMBER(3.0,15.0,0.2,XMAX,0.0,2)
  CALL SYMBOL(0.0,14.5,0.2,8HMINIMUM=,0.0,8)
  CALL NUMBER(3.0,14.5,0.2,XMIN,0.0,2)
  CALL SYMBOL(0.0,14.0,0.2,13HNO. OF CASES=,0.0,13)
  CALL NUMBER(3.0,14.0,0.2,CASE,0.0,2)
  CALL SYMBOL(0.0,13.5,0.2,15HSTAND. DEVIAT.=,0.0,15)
  CALL NUMBER(3.0,13.5,0.2,SD,0.0,2)
  CALL SYMBOL(0.0,13.0,0.2,5HMEAN=,0.0,5)
  CALL NUMBER(3.0,13.0,0.2,AVE,0.0,2)
  80 CONTINUE
C
C RESET PLOT ORIGIN
```

```

C  RESET PLOT ORIGIN
      CALL PLOT(0.0,0.0,-3)
      CALL BUFFEM
      RETURN
      END
C
C
C
C  PROVIDES PLOT HEADING OF ACCESSED FILE AND ANNOTATES IT
      SUBROUTINE ANNOT(FNAME)
      COMMON/B/NFILT,NRAD,IWT,NPASS
      COMMON/C/CUT,SAT,IOPT3
      INTEGER FNAME
C
C  ACCESSED FILE HEADING
      CALL SYMBOL(0.0,15.0,0.25,19HDOT DENSITY PLOT OF,0.0,19)
      X=6.0
      Y=15.0
      HEIGHT=0.25
      ANGLE=0.0
      FNAME=FNAME
      DO 30 I=1,10
      JT=77B.AND.FNAME
      IF(JT.NE.55B)GO TO 90
      FNAME=SHIFT(FNAME,54)
30  CONTINUE
      PRINT*,"PROCESS FAULT"
90  CONTINUE
      N=11-I
      CALL SYMBOL(X,Y,HEIGHT,FNAME,ANGLE,N)
C
C  PLOT ANNOTATION
      WT=IWT
      IF(NFILT.EQ.0)
      +      CALL SYMBOL(0.0,14.5,0.25,15HUNFILTERED DATA,0.0,15)
      IF(NFILT.EQ.1)
      +      CALL SYMBOL(0.0,14.5,0.25,20HRING RESIDUAL FILTER,0.0
      +,20)
      IF(NFILT.EQ.2)
      +      CALL SYMBOL(0.0,14.5,0.25,22HSQUARE RESIDUAL FILTER,0
      +.0,22)
      IF(NFILT.EQ.3)
      +      CALL SYMBOL(0.0,14.5,0.25,20HSTAR RESIDUAL FILTER,0.0
      +,20)
      IF(NRAD.EQ.1)CALL SYMBOL(6.0,14.5,0.25,8HRADIUS 1,0.0,8)
      IF(NRAD.EQ.2)CALL SYMBOL(6.0,14.5,0.25,8HRADIUS 2,0.0,8)
      CALL SYMBOL(0.0,14.0,0.25,14HCUT-OFF LEVEL=,0.0,14)
      CALL NUMBER(5.0,14.0,0.25,CUT,0.0,2)
      CALL SYMBOL(0.0,13.5,0.25,17HSATURATION LEVEL=,0.0,17)
      CALL NUMBER(5.25,13.5,0.25,SAT,0.0,2)
      IF(IOPT3.EQ.1)
      +      CALL SYMBOL(0.0,13.0,0.25,11HLINEAR PLOT,0.0,11)
      IF(IOPT3.EQ.2)
      +      CALL SYMBOL(0.0,13.0,0.25,16HLOGARITHMIC PLOT,0.0,16)
      IF(IWT.EQ.0)
      +      CALL SYMBOL(0.0,12.5,0.25,15HUNWEIGHTED DATA,0.0,15)
      IF(IWT.GE.1)
      +      CALL SYMBOL(0.0,12.5,0.25,17HWEIGHTING FACTOR=,0.0,17
      +)
      IF(IWT.GE.1)
      +      CALL NUMBER(5.0,12.5,0.25,WT,0.0,2)
C
C  RESET PLOT ORIGIN AND SYMBOL PLOT DENOMINATORS
      CUT=0.0
      SAT=0.0
      IOPT3=0
      CALL PLOT(0.0,0.0,-3)
      CALL BUFFEM
      RETURN
      END
/

```


PROGRAM DOT2

LOADING PROCEDURE:

```
/SETFL,67000
/SETTL,200
/-NAG7F
/X,LIBRARY(NAG7F)
/GET(DOT2)
/MNF5(I=DOT2,B,L=0)
/-SIMPLE
```

EXAMPLE PROGRAM RUN

-Characters underlined are printed by the computer-

```
FILENAME? "TESTGD"
NUMBER OF ROWS? 10
NUMBER OF COLUMNS? 20
SELECT DATA OPTION: 1(NORM.) OR 2(NEG.)? 1
SELECT FILTER OPTION: 0(NO) OR 1(YES)? 1
ENTER FILTER NO., RADIUS, WEIGHTING FACTOR FILTER OPTIONS ARE:
  1: 4 ELEMENT RING RESIDUAL FILTER, RADIUS 1 OR 2
  2: 4 ELEMENT SQUARE RESIDUAL FILTER, RADIUS 1 OR 2
  3: 8 ELEMENT STAR RESIDUAL FILTER, RADIUS 2
? 1,1,1
ENTER FILTER RESPONSE: 1(HIGH PASS) OR 2(LOW PASS)
? 1
```

VDU SCREEN PROVIDES HISTOGRAM OF FILTERED DATA

```
SELECT PROCESS OPTION: 1(OLD), 2(NEW), 3(CONT.)? 3
SET PLOT SCALE: 1(METRIC) OR 2(IMP.)? 1
CUT-OFF LEVEL: -2.0 TO +2.0? 0.0
SATURATION LEVEL: -2.0 TO +2.0? 2.0
SELECT PLOT CONTROL OPTION: 1(LIN) OR 2(LOG)? 1
```

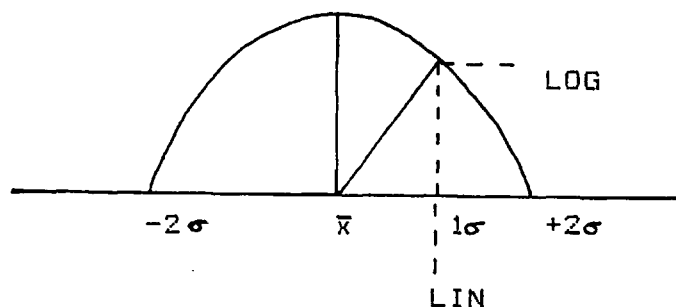
VDU SCREEN PROVIDES DOT DENSITY PLOT

```
SELECT CONTROL OPTION,OLD.NEW.MAG.HARD.END.? "END"
```

RESULTS AND COMMENTS:

Plot A gives an example of the histogram and Plot B provides a dot density image of the file TESTGD (see results PROGRAM FILTER). The plan of the features within the data can be seen in Plot 1D. By altering the cut-off and saturation levels, the various features can be made to stand out from the overall distribution. The results are shown in Plots 2D to 5D.

The LOG Plot option sharpens the image. In the survey results essential detail was often found to lie at either end of the histogram. Therefore the LOG option was constructed such that it extended the dot distribution to the tail end of the histogram and was not limited to the specified range(as applies to the LIN option):



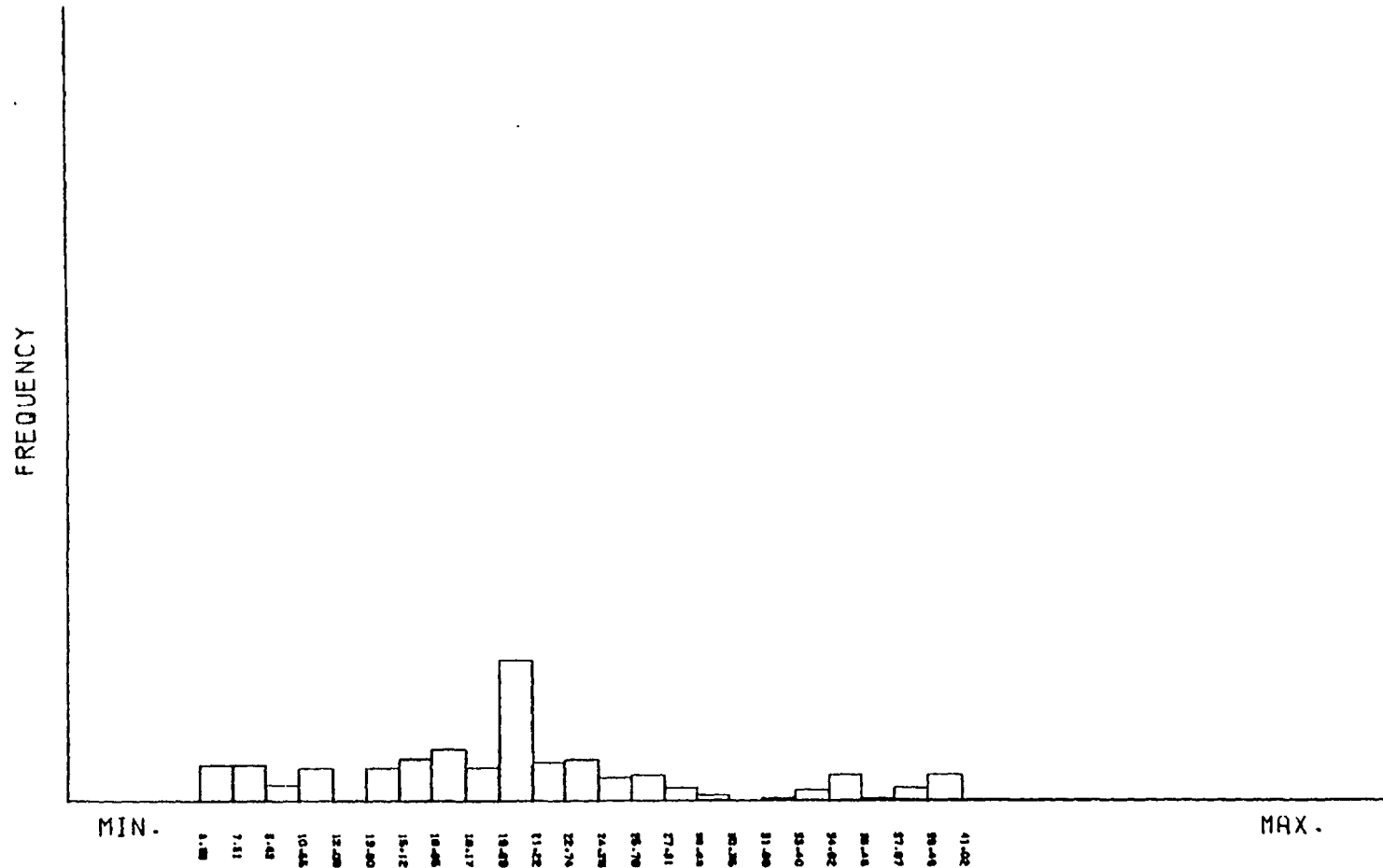
e.g. cut-off level = $\bar{x}$
 saturation level = $\bar{x} + 1\sigma$

DOT DENSITY PLOT OF TESTGD
 UNFILTERED DATA
 CUT-OFF LEVEL= 0.00
 SATURATION LEVEL= 0.00

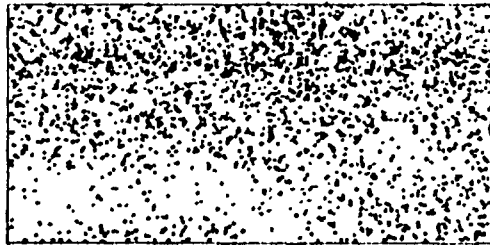
MAXIMUM= 41.00
 MINIMUM= 6.00
 NO. OF CASES= 200.00
 STAND. DEVIAT.=8.37
 MEAN= 20.46

UNWEIGHTED DATA

Plot A PROGRAM DOT2 - histogram

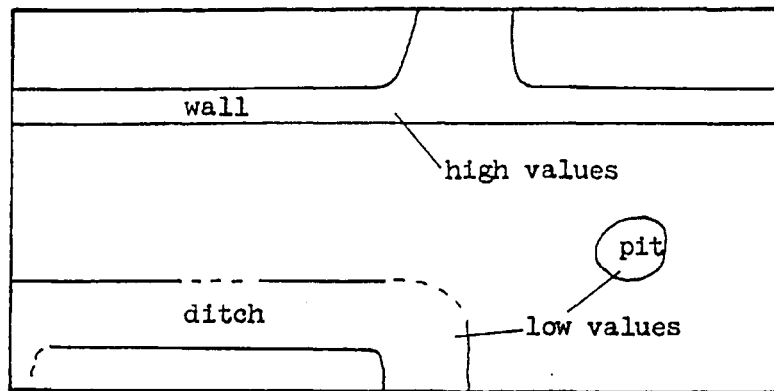


DOT DENSITY PLOT OF TESTGD
UNFILTERED DATA
CUT-OFF LEVEL= -2.00
SATURATION LEVEL= 2.00
LINEAR PLOT
UNWEIGHTED DATA



Plot B PROGRAM DOT2 - printout of the results

PROGRAM DOT2 - File TESTGD - dot density plots



Plot 1D Plan of features within data
Scale 1 : 200



Plot 2D Unfiltered data
Cut-off level = -2.0
Saturation level = 0.0
Linear plot

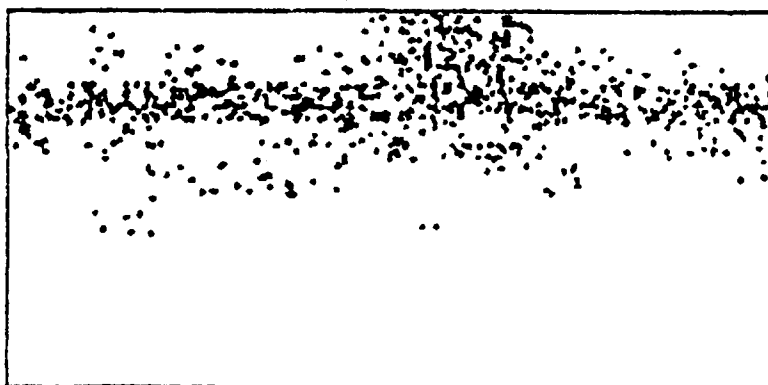


Plot 3D Unfiltered data
Cut-off level = 0.0
Saturation level = -2.0
Linear plot

PROGRAM DOT2 - File TESTGD - dot density plots



Plot 4D Unfiltered data
Cut-off level = 0.0
Saturation level = -2.0
Logarithmic plot



Plot 5D Unfiltered data
Cut-off level = 0.0
Saturation level = 2.0
Linear plot

PROGRAM HIDE (FORTRAN 1V)

PROGRAM LISTING:

```

      PROGRAM HIDE(INPUT,OUTPUT,TAPE5=INPUT,TAPE7,TAPE60,TAPE6=OUTP
+UT)
      DIMENSION XMAT(32,32)
      INTEGER FNCODE(4),MSG(4),ICODE
C   INPUT FILE REQUESTED
100 CONTINUE
      WRITE(6,10)
10   FORMAT(8HFILENAME)
      READ(5,*)FNCODE(2)
      FNCODE(1)=10HGET(TAPE7=
      FNCODE(3)=10H)
      FNCODE(4)=0
      CALL PFREQ(FNCODE(1),MSG,ICODE)
      REWIND 7
C   FILE DIMENSIONS REQUESTED
      WRITE(6,12)
12   FORMAT(14HNUMBER OF ROWS)
      READ(5,*)NROW
      WRITE(6,14)
14   FORMAT(17HNUMBER OF COLUMNS)
      READ(5,*)NCOL
C   FILE READ IN
      DO 1 I=1,NROW
        READ(7,*)(XMAT(I,J),J=1,NCOL)
1     CONTINUE
C   ENTER FILE IDENTIFICATION
      WRITE(6,16)
16   FORMAT(14HENTER FILE I.D)
      READ(5,*)ID
C   PARAMETERS WRITTEN ONTO TAPE60 FOR MATMAP
      WRITE(60)ID,NROW,NCOL,((XMAT(I,J),I=1,NROW),J=1,NCOL)
      WRITE(6,18)
18   FORMAT(18HDATA NOW ON TAPE60)
C   ENTER ADDITIONAL FILES
      WRITE(6,20)
20   FORMAT(31HANY MORE FILES: 1(YES) OR 0(NO))
      READ(5,*)IOPT1
      IF(IOPT1.GT.0)GO TO 100
      STOP
      END
/

```

EXAMPLE PROGRAM RUN:

```

FILENAME
? "TESTGD"
NUMBER OF ROWS
? 10
NUMBER OF COLUMNS
? 20
ENTER FILE I.D
? 1
DATA NOW ON TAPE60
ANY MORE FILES: 1(YES) OR 0(NO)
? 0
      .169 CP SECONDS EXECUTION TIME
/

```

PROCEDURE FILE:

A file control card must be used for TAPE60 with an LDSET card for the load sequence as the data generation program is compiled under MNF. This necessitates the following control directives contained within the procedure file PFILE of which a listing is given.

```

/-PFILE
GET,HIDE
FTN(I=HIDE,L=LIST)
FILE(TAPE60,RT=S,BT=C)
LDSET(FILES=TAPE60)
LGO.
SAVE(TAPE60=DHIDE)

```

LOADING PROCEDURE:

```

/-PFILE
/-MATMAP

```

The control of MATMAP is further outlined in the relevant ICCB Bulletin (4.22/3) e.g.

```

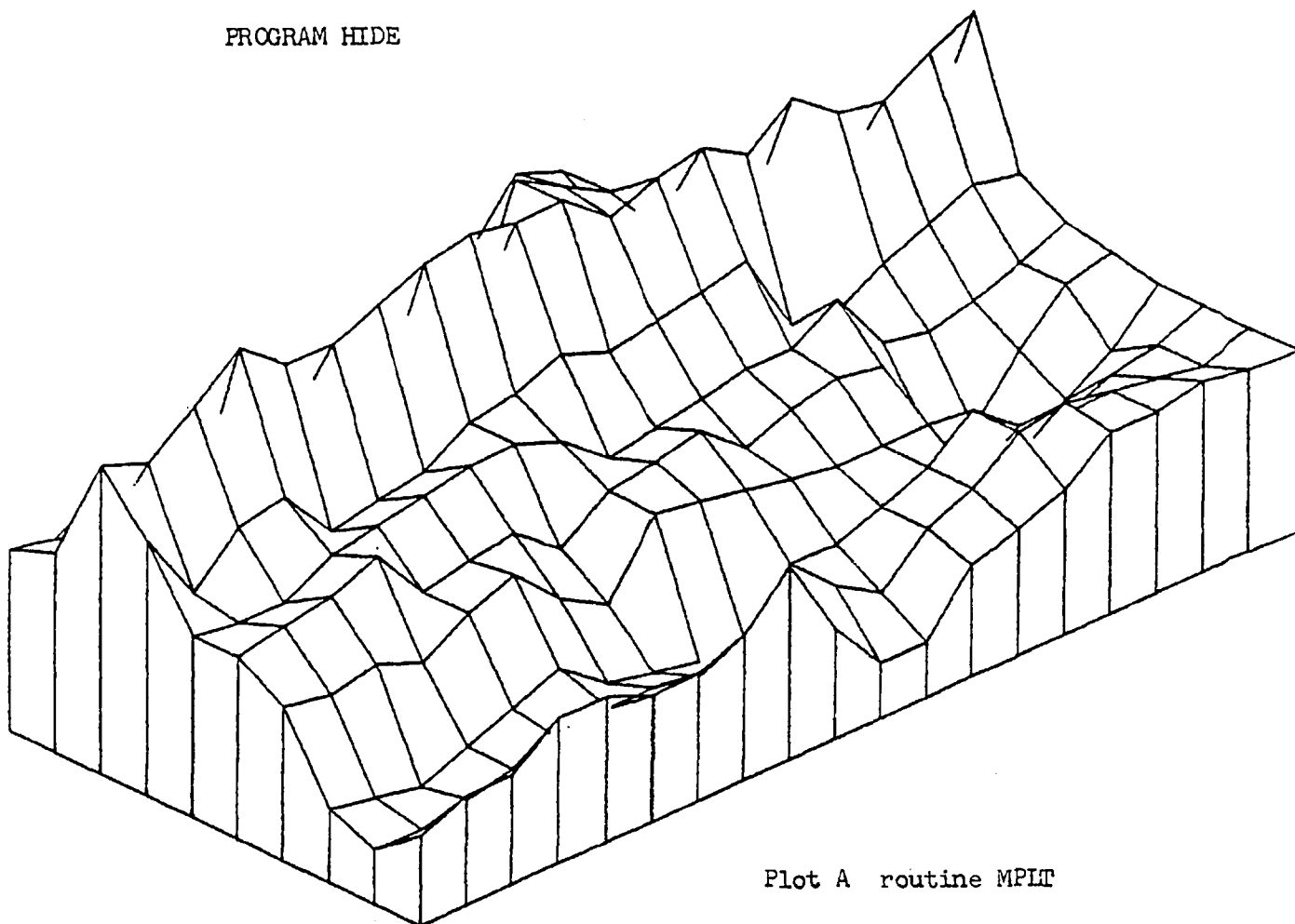
ACCEPT,HIDE
END
VIEW
ACCEPT,END      to terminate program

```

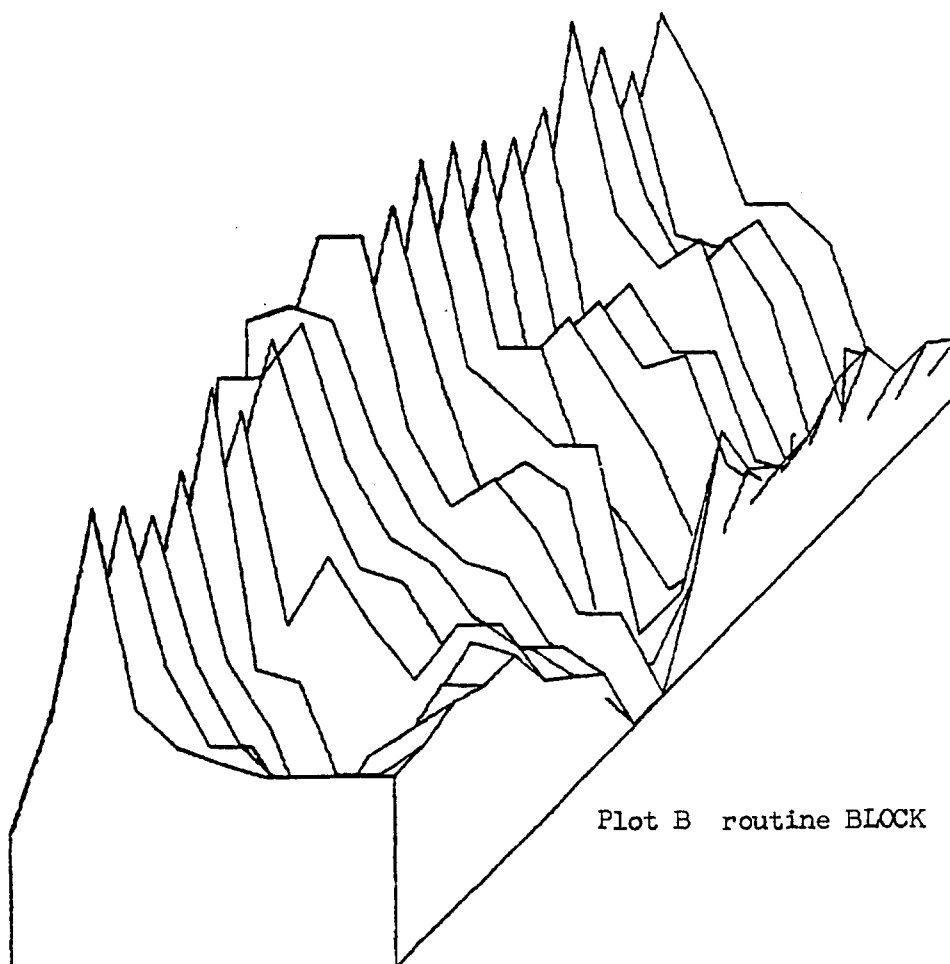
RESULTS AND COMMENTS:

Routines MPLT and BLOCK were found to give the most useful results. These are reproduced in Plots A and B using the file TESTGD (see Plots PROGRAM FILTER).

PROGRAM HIDE



Plot A routine MPLT



Plot B routine BLOCK

*PLOTTING PROGRAM (Texas Instruments)

1. Description

In essence the program forms a simple variant on the dot density program DOT2 (FORTRAN IV). One is referred to this program for additional detail of the process involved.

This routine enables a small number of data to be put into storage, the relevant mean and standard deviation to be worked out, with a choice of a number of plotting ranges within which the dot distribution will be defined. The final plotting will have to be done by hand although this could be committed to the optional print cradle.

2. Program listing

2ND IBL A

```

39 STO 7
2ND PGM 1 SBR CLR
4 2ND OP 17
R/S
→ STO 2ND IND 7
  2ND  $\Sigma$ +
  2ND OP 3 7
  R/S
  — GTO 14

```

2ND IBL B

```

2ND  $\bar{X}$ 
STO 8
INV 2ND  $\bar{X}$ 
STO 9
2ND PGM 1 SBR CLR
2 SUM 0
R/S

```

2ND IBL 2ND A'

```

0
→ STO 2ND IND 0
  2ND DISZ 0 52
  GTO 82 —————→ ②
→ R/S
  2ND IBL 2ND B'
  (RCL 9  $\div$  2)
  — GTO 43
①

```

```

      2ND IBL 2ND C'
      ① → RCL 9
          GTO 43

      2ND IBL 2ND D'
          (RCL 9 x 2)
          GTO 43

② → RCL 8
    SUM 2
    (RCL 8 - RCL 1)
    STO 1
    RCL 1
    INV SUM 02
    25 STO 3
    RCL 3
    INV 2ND PRD 02
    39 STO 7
    → (RCL 2ND IND 7 - RCL 1)
    ÷ RCL 2 =
    R/S
    2ND OP 3 7
    GTO 113

```

Amax
Amin
Range
No. of dots (set at 25)
Scale

3. Sequence

Press A to initiate program. Display will indicate the number of available program steps and the memory space: 159,39 for the TI58.

Key in first data value, then press R/S. Display will indicate 1.

Key in next value. The display shows the number of values keyed in.

With the TI58 up to 30 values can be put into storage.

For $\bar{X}$ press RCL 01; for $\bar{X}^2$ press RCL 02.

Press B. Display indicates 2. For $\bar{X}$ press RCL 08; for σ_{n-1} , press RCL 09.

Now select the saturation level:

- (1) Press 2ND A' → $\bar{X}$
- (2) Press 2ND B' → $\bar{X} + \frac{1}{2}(\sigma_{n-1})$
- (3) Press 2ND C' → $\bar{X} +$
- (4) Press 2ND D' → $\bar{X} + 2(\sigma_{n-1})$

Next select the cut-off level by depressing either (1) to (4) e.g.

(4) will give a cut-off level of $\bar{X} - 2(\sigma_{n-1})$.

Note the sign inversion.

The display will now indicate the number of dots for data value 1.
Press R/S and the number of dots will be given for data value 2 etc.
The saturation density can be varied by altering the relevant value
in store 8 (STO 8).

A number of filtering programs are available on request.