ARCHAEOLOGICAL DETECTION BY RESISTIVITY

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IN MEMORIAM

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ABSTRACT

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ARCHAEOLOGICAL DETECTION BY RESISTIVITY

by Anthony John Clark

A brief history is given of the development of resistivity detection in archaeology, followed by an outline of basic principles and theory, and of the evolution of the Martin-Clark resistivity meters, including circuit diagrams.

The chief outstanding problems are identified as choice of the most suitable probe configurations, climatic water balance effects, and speed of working.

For studying the configuration problem, the design of a rapidly operating automatic electrolytic tank system is detailed, together with a set of simulated archaeological features. Ten configurations are examined, of which the Twin Electrode, Double Dipole and Square Array are found most effective, with the addition of Wenner for selected purposes. The Triple Electrode also appears promising.

For the climate study, fixed traverse lines were established across three silted up ditches of known profile and widely varied size on Upper Chalk in southern England, and measured monthly for 19 months. The pattern of resistivity response with water balance differed greatly according to ditch size. The data, and results obtained by others for Triassic sandstone, London Clay and limestone are collated, and guidelines for interpretation and the choice of optimum survey times, probe configurations and spacings established. Some analysis of the related phenomenon of crop mark production is appended.

In combination, the tank and climate studies show that the resistivity anomalies caused by many archaeological features approximate to a horizontal high resistivity lamina.

Examples of surveys using the optimum configurations are given, the results being compared with those of magnetic surveys where possible; methods of plotting and processing the data are also compared. Some high performance survey systems incorporating results from this research are described.

ACKNOWLEDGMENTS

This work, whatever its own frailties, is founded upon the twin rocks of Richard Atkinson's original developments and encouragement, and the circuit designs of John Martin, the success of which owes not a little to a stark Scottish austerity. John Musty had the vision to realise that archaeological geophysics should be supported officially, and to ensure that it became part of the work of the Ancient Monuments Laboratory of the Ministry of Public Building and Works, later the Department of the Environment; he also ensured the support of the Department for this research. Professor Barry Cunliffe came to the writer's rescue in an academic wilderness, and David Peacock has been his patient and helpful supervisor for many years. The dedicated members of the Ancient Monuments Laboratory Geophysics Section, in particular David Haddon-Reece, Alister Bartlett and Andrew David, have contributed much to the development of the subject, not least by the enormous amount of survey data that they have steadfastly collected over the years. Chapter 7 owes much to their work. Una Clark and the other members of my family have given uncomplaining support on many a survey expedition, and while the house crumbled about them from neglect.

For rainfall records, I am indebted to the West Surrey Water Board (now part of the Thames Water Authority) and their staff at the Ladymead Pumping Station, Guildford, and to the Chief Meteorological Officer, RAF Upavon, and in particular Mr Brian Palk. The Meteorological Office supplied potential evapotranspiration data and information about its use. I am grateful to the owners of the Durrington Walls site for permission to work there, and to Surrey County Council Highways and Bridges Department for permission to work on the Hog's Back barrow.

NOTE ON NOMENCLATURE

In keeping with standard practice, capitals are used for the initial letters of the proper names of geological deposits, but not when discussing them simply as materials.

The names of electrode configurations are normally spelt out when first mentioned in a chapter or section, and subsequently are shortened, especially in discussion involving frequent repetition. The chosen style is always to dignify them with capital initials, partly as an aid to reference.

The terms 'electrode' and 'probe' are used interchangeably: generally, 'electrode' is used when the emphasis is upon the electrical function, 'probe' when it is upon use in the field. The same applies to 'configuration' and 'array' respectively.

Inconsistencies there must be: for these the reader's indulgence is requested.

1. INTRODUCTION

1.1. DEVELOPMENT OF ARCHAEOLOGICAL RESISTIVITY DETECTION

At the end of the Second World War, British archaeology faced two disparate but related challenges: the superabundant harvest of aerial discovery; and the rapid destruction of the riches thus revealed - by reconstruction, quickening development, and increasingly mechanised cultivation. Many sites recorded by air photography in large fields, or when the photographs were oblique, were difficult to locate precisely. The adaptation of techniques of geophysics to this problem was first demonstrated in 1946 by R. J. C. Atkinson, who used soil resistivity prospecting in preparation for his rescue excavations ahead of gravel extraction at Dorchester on Thames. His resistivity plan of the whole of a completely buried henge monument was deeply impressive to the writer, encamped with the RAF nearby and fortunate to be present at the birth of this powerful application of technology to the revelation of the buried past. Using the Megger Earth Tester, a substantial instrument with a hand-cranked generator, Atkinson worked out the basic modifications necessary to adapt this geophysical technique to archaeological needs, notably the five-probe 'leapfrog' method of working, and its associated switching (Atkinson, 1953; 1963).

Ten years later, F. K. Annable and the writer were confronted by a similar problem: tracing the extent of the defences of the the Roman town of Mildenhall-Cunetio, Wiltshire, which were partly visible as crop marks on oblique air photographs taken by J. K. S. St Joseph. By this time the transistor had been invented, enabling electronic apparatus to be dramatically reduced in size and power consumption, and increased in reliability, and a small transistorised alternating current Wheatstone bridge, designed by J. Martin in the instrumentation laboratory of the Distillers Company, was tried at Cunetio. The foundation of the fourth-century town wall was readily detected with this instrument (Clark, 1957), but, as the measurement was made with only two probes, the variability of contact resistance between probes and soil tended to mask the relatively minor effect of buried remains. Specially designed probes, with a crank which acted as a depth stop and also enabled them to be pushed in with the foot, mitigated but did not cure the contact problem, and a new circuit with the conventional geophysical four-probe arrangement for overcoming contact resistance was designed: the circuit, like its predecessor, was of the manually balanced null type with audio detection, operating at about 1000 Hz, and this prototype (now in the Science Museum) was the first instrument to incorporate the Martin-Clark rotary turret switch which greatly simplifies the wiring of the 5-probe leapfrog system, as well as automatically keeping the leads disentangled. With this instrument, the whole 1 km circuit of the walls of Cunetio was traced, two bastions located (see below), and the west gate of the town discovered (Annable, 1958). The further development of the Martin-Clark instruments will be described in Chapter 3.

From the late 1950's, there was a slow expansion of resistivity prospecting in archaeology. Various instruments were used, notably the Gossen Geohm in Germany (Scollar, 1959), and in Britain the Nash and Thompson Tellohm, and continued effective use of the Megger and its more refined successor by Atkinson and others. All these instruments were more substantial than the Martin-Clark and, for the leapfrog method of probe movement, required the addition of a specially made up switching system using wafer components. A significant innovation was the multiprobe system for area surveys developed by the Test Branch of the Ministry of Works: a complete row of probes at suitable spacing is set out across the area to be surveyed, and by means of a switching system they are connected to the instrument (a Tellohm) in successive groups of four, a line of readings thus being obtainable as fast as the instrument can be read and the readings recorded. Once used, the probes are moved on to similar positions on the next traverse line, a process much more economical in movement for the probe handler than the five-probe leapfrog system. An electronic form of the multiprobe system, with a constant current resistivity meter and automatic data logging, is being developed by the Ancient Monuments Laboratory at the time of writing (Haddon-Reece, forthcoming). Internal switching enables each traverse to be repeated rapidly with different configurations and spacings, thus increasing the information obtainable from a survey.

Instruments working on the constant current principle, a new generation of resistivity meters, began to appear in the late 1960's. Notable among these is the Bradphys, developed by the School of Archaeological Sciences, University of Bradford, specially designed for archaeological detection with the Twin Electrode configuration (Aspinall and Lynam, 1970). The Martin-Clark version (Chapter 3) has so far been used only experimentally in the field.

There now exist high frequency electromagnetic instruments that measure ground resistivity without contact, notably the Geonics EM31. This is, by archaeological standards, unwieldy and expensive and. having been developed for shallow geological work, seems to be able to detect only the most substantial archaeological features. A more compact version, the EM38, has recently appeared and may prove more suitable for archaeology; but the greater operational speed of such instruments compared with conventional resistivity measurement is likely to be offset by price - and their overall archaeological effectiveness has yet to be tested. If they do prove successful, they will be more suitable for large-scale operators. There should always be a place for the probe-operated instrument that is compact, simple and cheap, especially among those groups for whom money is harder to find than enthusiastic manpower. Also, as this thesis will show, great subtleties of detection can be achieved by adjustment of probe spacing and configuration, which may be difficult, or impossible, to match with electromagnetic instruments.

1.2. RESISTIVITY COMPARED WITH OTHER DETECTION METHODS

1.2.1. MAGNETIC DETECTION. After its introduction in 1958, magnetic detection rapidly developed and has become dominant in archaeology - at least among operators with fairly substantial funding - mainly because of its speed and its powerful attribute of selectivity of human occupation and activity (Clark, 1975). However, its effectiveness is greatest for fired structures, especially of clay, and the larger topsoil-filled excavations penetrating bedrock - providing there is a reasonable magnetic contrast between topsoil and bedrock, and the features are not too broad and shallow. Resistivity has always remained most generally effective for the definition of buildings and other stone-based structures, and, as a result of the work described here, it is now finding renewed use for subtle surveys on chalkland sites, where magnetic response can be inadequate because of the lack of magnetic contrast and the shallow and insubstantial nature of some of the features (see Chapter 7).

Electromagnetic instruments of the types that depend upon the magnetic properties of the soil (e.g. the soil susceptibility meter and the pulsed induction meter) suffer from problems of shallow penetration, but their most promising function, in identifying topsoils modified by human occupation, has hardly begun to be exploited (Tite, 1972; Clark, 1979), and is very different from the feature locating function of resistivity meters and magnetometers.

Some examples of the relative effectiveness of resistivity and magnetic surveys will be discussed in Chapter 7.

1.2.2. OTHER DETECTION METHODS. Aspinall and Lynam (1970) have demonstrated the effectiveness of induced polarisation as an archaeological detection technique, using an instrument also capable of measuring resistivity. Although apparently able to surpass resistivity in the definition of some types of feature, IP has, however, been litle used, probably for two main reasons: it requires specially constructed non-polarising electrodes

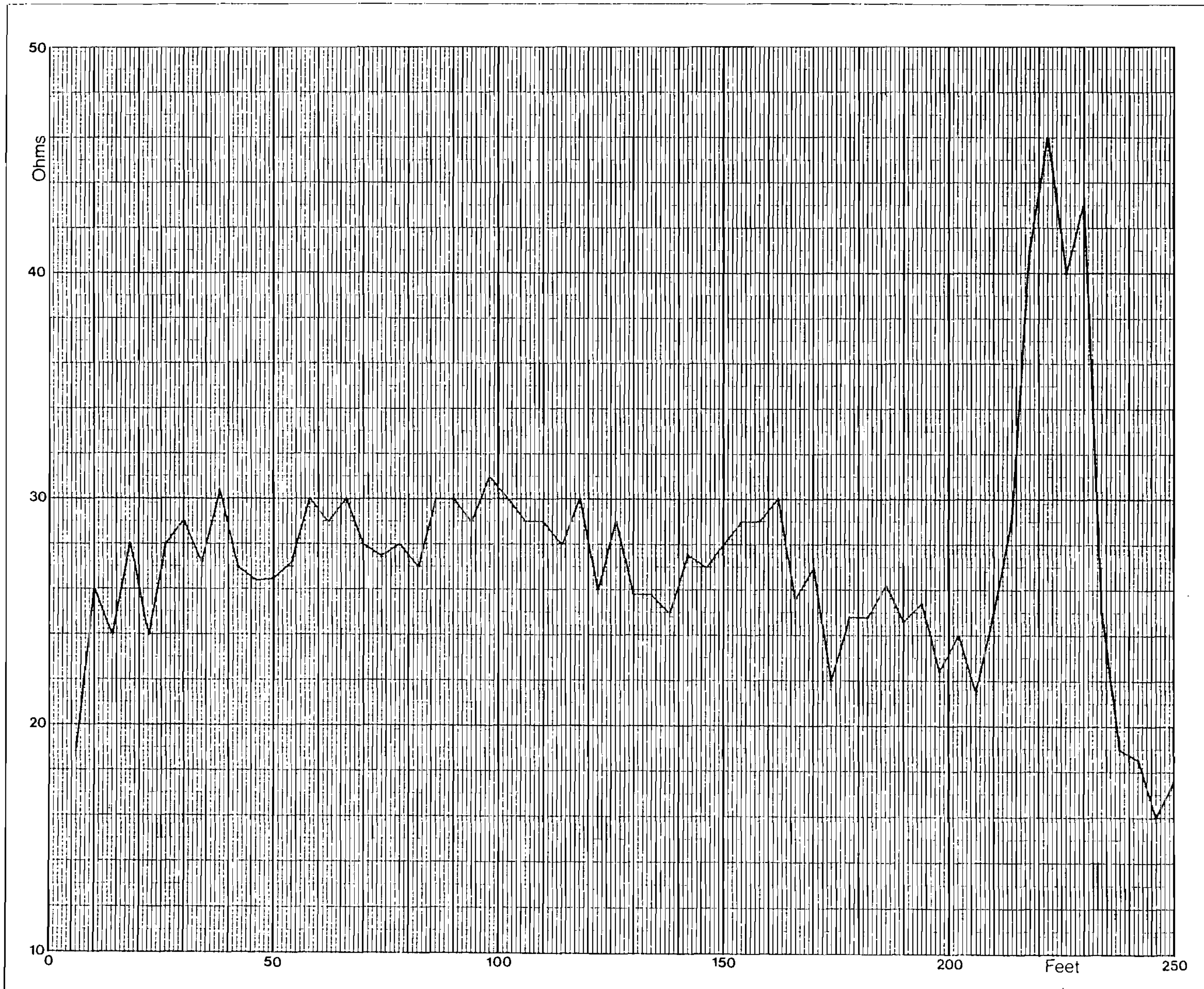


FIG. 1.1. Cathedral Close, Winchester: resistivity traverse showing Roman street (right). 4 ft Wenner

which cannot be made to combine the robustness and convenience of simple probes; and, as a finite time is required for the IP effect to build up, instantaneous measurements are not possible, and the speed of operation is thus limited.

Seismic refraction and reflection, and ground penetrating radar, have been attempted, with some indication of success, but their effectiveness to date have fallen far short of the well established techniques of resistivity and magnetic detection.

1.3. EARLY SURVEYS WITH MARTIN-CLARK METERS

For all the earliest work, the Wenner configuration (CPPC) was used exclusively. A 4 ft (1.22 m) probe spacing was found to be a very generally useful compromise: in many surveys, both wider and narrower spacings gave diminished response, and the narrower were often accompanied by an unacceptable increase in 'noise'. Linear traverses predominated over area surveys, mainly because of limitations of time and manpower in those pre-professional days.

A dramatic early demonstration of the effectiveness of linear surveys was the location of the bastions of Cunetio (Clark, 1964; 1969), achieved with three traverses: two across the town wall located its position; then, using these findings, a third was laid out parallel to the outer face of the wall so as to cross the bastions, which were clearly detected. Before the resistivity survey, a trial trench, laid out on the basis of the air photograph alone, missed the wall by a substantial margin.

The Wenner configuration at 4 ft, with some detailed work at 3 ft and 2 ft spacing, was used on the lawns of Dartington Hall to provide information for the history of the house (Emery, 1970). The bedrock of tilted shale strata gave an irregular resistivity background, but it was possible to distinguish the regular patterns of foundations cutting across this; the drying effect of tree roots also had to be allowed for. Survey of the central courtyard showed that remains were probably absent there; but a survey over the remains of the south courtyard provided information that supplemented and clarified the results of a previous excavation.

The excavations in Winchester provided some of the greatest tests for resistivity detection, with results ranging from failure to striking success (Biddle, 1965; 1966). Gardens in the Cathedral Close provide a substantial amount of open space, subject to little subsequent development, in the south-east quadrant of the Roman town. Long traverses in these gardens revealed the hitherto unknown most southerly east-west street, and confirmed and accurately located another at right angles to it. These streets were not excavated, but the clarity of the response to them is demonstrated by the graph (Fig. 1.1) of one of the traverses; and both streets were exactly 400 Roman feet from the next parallel streets, centre to centre.

An area survey on the Cathedral Green revealed clearly those parts of the Old Minster that had not been too heavily robbed, and also gave some indication of the plan of the robber trenches that represented much of the building, even though these were normally covered by at least 4 ft (1.22 m) of overburden which included graves. All these surveys were done with the 4 ft Wenner configuration: an attempt to plan another building on the Green with the 2.5 ft (0.76 m) Square Array was not very effective, and this apparatus produced inadequate and misleading pictures of the ditch of the Iron Age defences at Oram's Arbour (Chalk bedrock). This work showed that it is important to use a fairly wide probe separation in urban conditions to overcome the depth and complexity of the overburden to be expected, and for substantial features such as the Iron Age ditch to avoid distracting, relatively superficial, effects. The Oram's Arbour work could have been more effective if the results of the present research had been available. A particularly clear response on one of the Oram's Arbour traverses proved on excavation to be a medieval chalk pit, which would have been apparent if an area survey had been made.

1.4. SCOPE OF THIS THESIS

This thesis summarises the contribution of the writer to archaeological resistivity prospecting, and attempts to erect signposts for its practice and interpretation. Some problems raised are not fully resolved, nor could be in the time available to one fully-employed person. It is hoped that others will be stimulated to follow them up.

In Chapter 2, the theory of soil resistivity measurement is briefly summarised. Chapter 3 summarises the development of the Martin-Clark resistivity meters. Chapter 4 identifies the two most important sources of uncertainty in resistivity detection: the choice of the most suitable probe configurations, and climatic effects, especially water balance. It argues in favour of the use of a rapidly operating electrolytic tank for studying the configuration problem, and the importance of studying climatic effects on sites that lie on Chalk bedrock. It also considers the problem of increasing the speed of resistivity surveying. Chapter 5 describes the design of a novel electrolytic tank fulfilling the above requirement of speed, and the results of its use. Chapter 6 describes a series of long-term experiments on Chalk sites, relating resistivity response to ditches of various sizes to variation in water input to the soil; it also summarises work on three other bedrock types. Chapter 7 gives a series of 'case histories', demonstrating the application of the probe configurations found most effective in Chapter 5, in some cases comparing the effectiveness of resistivity with magnetic detection. Developments in survey methods incorporating the results of the work are also briefly summarised. Chapter 8 sums up the results and indicates further work that would be desirable.

2. FUNDAMENTALS OF RESISTIVITY DETECTION

2.1. RESISTIVITY OF ROCKS AND SOILS

Electrical conduction by rocks and soils is almost entirely due to electrolysis of water contained within their interstices, made conductive by salts dissolved from them. Measurements are made in terms of resistivity in ohms, the unit of specific resistance or resistivity being the ohm-metre (Ωm). The water capacity and retentivity of geological materials differs enormously, so that there can be great contrasts in resistivity between them; also the resistivity of a particular material can vary substantially with wetness. For example, a non-porous rock like granite has a resistivity range of 10^7 to 10^9 ohm-metres; dry sandstone 5×10^7 to 10^9; dry limestone 700, wet limestone 400; dry garden soil 16.7, wet garden soil 0.6; dry clay 14.5, wet clay 0.16 (Eve and Keys, 1954). Thus it is easy to comprehend that buried archaeological features comprising stone structures buried in soil, or soil-filled excavations cut into a bedrock such as limestone, sandstone or gravel are detectable with suitable resistivity measuring apparatus.

2.2. METHOD OF MEASUREMENT

To make a measurement, the electrodes of a soil resistivity meter need only make contact with the surface of the soil: the power of the method lies in the fact that, as the ground is effectively a semi-infinite medium, the current is not constrained as in a wire and spreads out to substantial depths. As already mentioned in Section 1, a four-terminal measurement is necessary to prevent readings being dominated by relatively large and unpredictable contact resistance. The power source of the instrument is put across two electrodes called the current electrodes (C_1 and C_2), thus setting up a subsurface field of potential gradient which is sampled without drawing current by a second pair of electrodes called the potential, voltage, or sometimes the detector electrodes (P_1 and P_2). Using the basic concept of Ohm's Law, the instrument circuit is arranged to give a resistance value in terms of the ratio of the current (I) to the potential (V):

$$R = \frac{V}{I} \qquad (2.1)$$

R is proportional to ρ, the mean resistivity of the ground to a certain depth, the factor of proportionality and the depth depending on the electrode arrangement (also known as the configuration or array). Typically, the depth approximates to 1.5 times the electrode spacing.

As (2.1) depends only upon potential measurement without drawing current, and upon the current actually flowing in the ground, it is independent of the resistance of contact of any of the probes, and it can be readily visualised that in poor contact conditions I will be low and V proportionately so, without affecting their ratio.

There are two other problems for which a soil resistivity meter must be compensated. Polarisation occurs if measurement is made using direct current, the positive ions of the aqueous electrolyte accumulating around the negative electrode and the negative ions around the positive electrode, forming barriers to current flow manifesting themselves as rapidly increasing resistance readings. Earth currents are another source of interference encountered: small DC currents of natural origin and alternating currents from the public supply.

The use of alternating or commutated DC current overcomes polarisation and DC earth currents, and a detection circuit phase-locked to the instrument supply frequency will filter out AC interference. These problems will be discussed in greater detail in Section 3.

In geological work, resistivity is perhaps most used for depth studies, exploiting the increasing depth of detection as electrode spacing is expanded about a fixed station. In archaeology the prime need is for surveys at fixed probe separation, buried features being revealed as anomalous values in lines or areas of such readings.

2.3. THEORY

The following analyses (Aitken, 1961, 1974; Aspinall & Lynam, 1970) establish the essential equations of earth resistivity measurement.

2.3.1. SINGLE PROBE. Consider a single electrode probe making point contact with the surface of ground of uniform resistivity. A current maintained by a battery with a remote earth-return flows from the probe in straight radial lines and the equipotentials are hemispherical surfaces so that at a radius r the current crossing unit area of such a surface is given by j, where

$$j = \frac{r}{2\pi r^2} \tag{2.2}$$

Since j is related to the electric field E at any point by the relation

$$j = \frac{E}{\rho} \tag{2.3}$$

it follows that

$$E = \frac{\rho I}{2\pi r^2} \tag{2.4}$$

where ρ is the resistivity. By integration, the potential at any radius r is given by

$$V = \frac{\rho I}{2\pi r} \tag{2.5}$$

This is the fundamental equation of earth resistivity measurement.

2.3.2. GENERAL FOUR-PROBE ARRAY. In equation (2.5), substituting R, the measured resistance, for V/I gives

$$R = \frac{\rho}{2\pi r} \tag{2.6}$$

In the general four-electrode array depicted in Fig. 2.1, substitute for r in terms of a and b in equation (2.6) to obtain the net potential difference between P_1 and P_2 due to the sources $+C_1$ and $-C_2$:

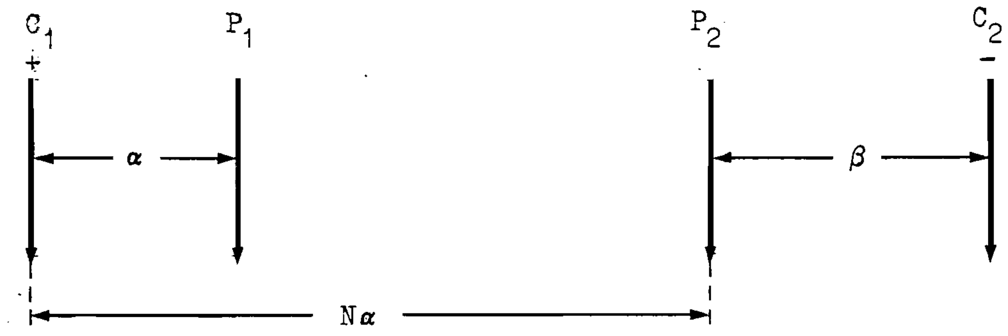


FIG. 2.1

$$R = \frac{\rho}{2\pi}\left[\frac{1}{\alpha} - \frac{1}{N\alpha} + \frac{1}{\beta} - \frac{1}{N\alpha-\alpha+\beta}\right] \qquad (2.7)$$

If we make the condition $\beta = \alpha$, then (2.7) becomes

$$R = \frac{\rho}{2\pi}\left[\frac{2}{\alpha} - \frac{2}{N\alpha}\right] \qquad (2.8)$$

Rearranging gives

$$R = \frac{\rho}{\pi\alpha}\left[\frac{N-1}{N}\right] \qquad (2.9)$$

Or

$$\rho = \left[\frac{N}{N-1}\right]\pi\alpha R \qquad (2.10)$$

These enable us to obtain expressions for ρ in terms of R, α and β for the various configurations of probes (Fig. 5.7). The simplification when $\beta = \alpha$, evident from equations (2.9) and (2.10), is relevant to the configurations found most successful in this thesis. For instance, for the Wenner array, $\rho = 2\pi\alpha R$; Double Dipole, $\rho = 6\pi\alpha R$; Square, $\rho = \frac{2}{2-\sqrt{2}}\pi\alpha R$; Twin (assuming both pairs of probes are in uniform ground of the same resistivity), $\rho = \pi\alpha R$. The strength of this configuration lies in the fact that, as N becomes increasingly large, the ratio of N to N-1 tends to 1, so that the background reading level changes little as N is varied; thus it does not change more than 3% when the separation is increased from 30α to 300α, and a minimum separation of 60α will reduce this factor to a mere 1.3%.

2.3.3. EFFECT OF A BURIED FEATURE. To avoid undue complexity, theoretical analysis of the anomalous resistivity effects of buried features has been mostly confined to horizontal layers of infinite extent (e.g. Uhlir, 1955, whence see Fig. 4.1) or to buried spheres. The latter is the more generally relevant to the problems encountered in archaeology: the sphere alone approximates reasonably well to many discrete features, linear features can be approximated by calculating the combined effect of a line of contiguous spheres, and it seems feasible to produce reasonable simulation of other shapes by using spherical 'building blocks'.

Various analyses of the resistivity effect of a sphere have been produced. The more exact tend to be tedious and inflexible to use (e.g. Dieter <u>et al</u>, 1969), and Lynam (1970) sought to produce an analysis that was reasonably exact yet not too computationally demanding, and the close comparison of a selection of his calculations with electrolytic tank measurements demonstrated that his approach was successful.

Following Stratton's (1941) solution of Laplace's equation for the analogous case of points external to a sphere of finite permittivity, due to the sphere alone, Lynam showed that a sphere may be approximated by a bipole system with one pole situated at the origin (the centre of the sphere), and the other at the inverse point in the sphere with respect to the current source. Fig. 2.2 shows an anomalous sphere of resistivity ρ_2 in a medium of resistivity ρ_1 beneath a two-electrode configuration consisting of a current source +I and a potential measuring point P_1 at the surface of the medium. The equivalent bipole lies on the line joining the centre of the sphere to +I, and its length is a^2/r_0.

The anomalous effect of the sphere, i.e. the change in potential at P_1 due to its presence, is given by:

$$\Delta\phi = \frac{\rho_1 I}{\pi} \cdot \frac{a}{r_0} \left[\frac{\rho_2 - \rho_1}{\rho_1 + 2\rho_2} \right] \left(\frac{1}{r_1'} - \frac{1}{r_1} \right) \qquad (2.11)$$

Although not readily apparent, it can be shown that this equation is symmetrical about the centre line between +I and P_1, so that the two probes passing in line over a sphere will produce a symmetrical response. A corollary of this is that potential and current probes in resistivity are interchangeable, which has been shown to follow from a generalised form of Helmholtz's reciprocal theorem (Searle, 1910), and has been demonstrated practically by Habberjam (1967).

It is important that the resistivity contrast term in the square brackets tends to a value of 0.5 when ρ_2 is much larger than ρ_1, and to a value of -1.0 if the reverse is the case. This means that resistivity measurement is more sensitive to a conducting than to an insulating sphere, by a factor of two in the limit.

Writing the distance parameters as a compound geometry factor (G.F.), and taking into account the effect of the distant electrode pair -I and P_2, Lynam shows that the potential difference measured in the presence of the anomalous sphere is given by

$$V_T = V_0 \left[1 + \left[\frac{\rho_2 - \rho_1}{\rho_1 + 2\rho_2} \right] P \text{ (G.F)} \right] \qquad (2.12)$$

where $P = \alpha/a$ and V_0 is the potential difference measured in the absence of the sphere. Equation (2.12) may alternatively be written as

$$V_T = \frac{\rho_a I}{\pi \alpha}$$

where

$$\rho_a = \rho_1 \left[1 + \left[\frac{\rho_2 - \rho_1}{\rho_1 + 2\rho_2} \right] P \text{ (G.F.)} \right] \qquad (2.13)$$

is the apparent resistivity measured at the surface. The contents of the outer brackets are dimensionless, and therefore equation (2.13) applies to sphere detection on any scale. Thus simulation in an electrolytic tank will depend only on the resistivities of the sphere and of the medium in which it is immersed, and on the ratio of a to α, sphere radius to probe spacing. Bearing in mind that an approximation to any feature may be built up from an assemblage of spheres, it seems reasonable to assume that this independence of scale should apply to simulated features of any shape.

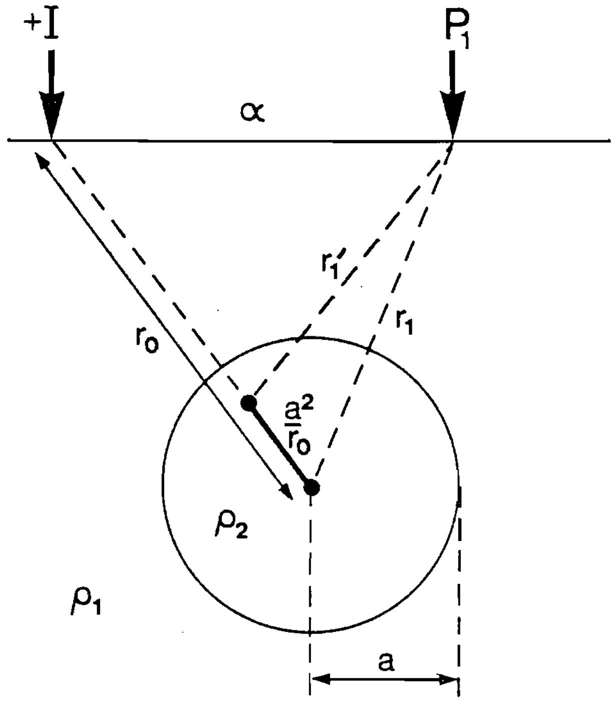


FIG. 2.2. Geometrical arrangement for an anomalous sphere in the neighbourhood of a two-electrode configuration, showing the equivalent bipole of length a^2/r_0 (adapted from Lynam, 1970)

3. THE MARTIN-CLARK RESISTIVITY METERS

3.1. BASIC PRINCIPLES

3.1.1. THE BASIC NULL BALANCE CIRCUIT. The standard Martin-Clark instruments generally available since 1960 have been of the null balance type. They have evolved through three versions, all based on an elegant principle (Aitken, 1974), of which the original Martin-Clark version is shown in Fig. 3.1. C, P, P, C represent the current and potential (voltage) contacts with the ground, arranged in the Wenner configuration. Current I from the AC source S passes through the potentiometer Pt, calibrated directly in ohms, and through the ground via C, C. P, P sample the potential gradient created in the ground by I, and the transformer T applies the voltage V thus generated between them to the high input impedance amplifier A in antiphase to the voltage across Pt. A reading is obtained by adjusting Pt to give zero output from A, as indicated by the meter M. When this balance is reached, the voltage across Pt is equal to that between P, P and, because the same current is flowing through Pt and the ground, the resistance across Pt is equal to the ground resistance.

Readings are compensated for the ground contact resistance of the probes in the following ways. If, for instance, the contact resistance of C, C is high, the current in the whole circuit is reduced, and the voltages across Pt and T proportionately so, and the point of balance on Pt is unaffected. To avoid contact resistance problems between P, P, there should be little or no current drain from them: for this reason, some other instruments have the transformer between Pt and A, and P, P feeding directly into A; however, our experience with transistorised circuits was that this arrangement produced problems of balance in some way related to the asymmetry of the circuit. Placing T across P, P caused no significant inaccuracies up to substantial contact resistances (see below), the impedance at the balance point being very high.

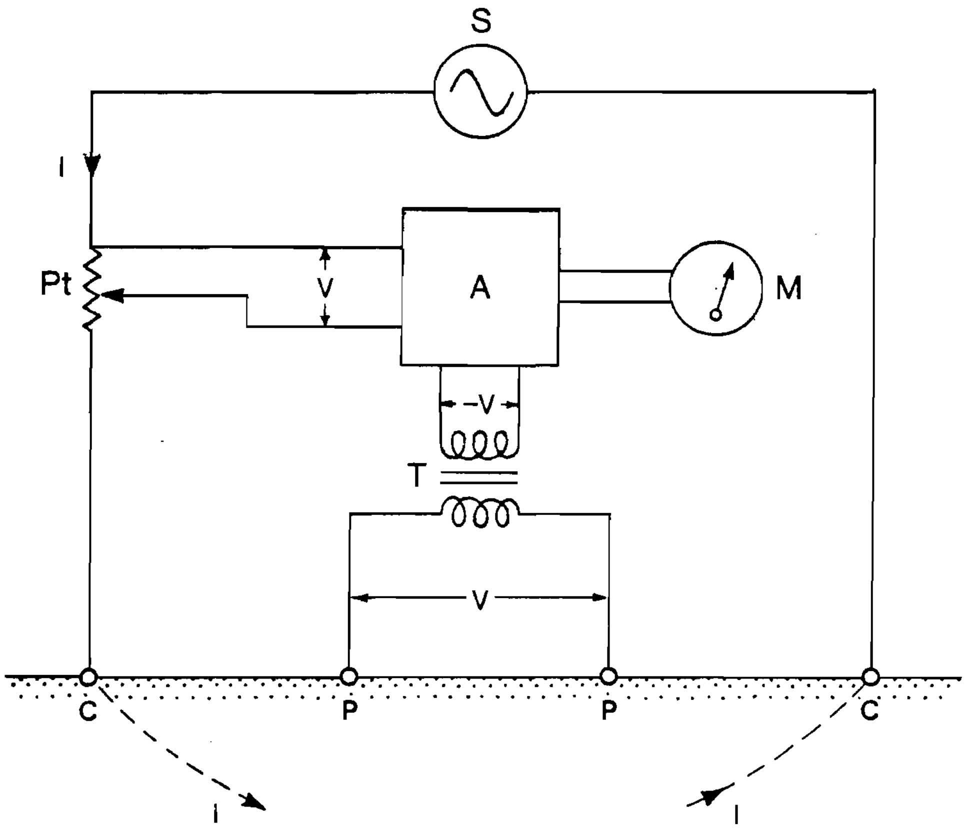


FIG. 3.1. The basic arrangement of the null balance circuits

3.1.2. DESIGN FOR FIELD OPERATION. Four major versions of the Martin-Clark meter have been produced, and each is briefly described in 3.2 below. The main design criteria, with the needs of archaeology and archaeologists very much in mind, have been comprehensiveness of equipment, simplicity in operation, low power consumption, reasonable price and compactness; the last also greatly facilitating transportation: the instrument, with leads and probes, is readily transportable by post or in a medium-sized bag. All instruments (except Type 4 at present) can be held in one hand, so that the operator can follow the probe movement and leads can be kept short.

All instruments have been designed to be powered by the Ever Ready type 1289 (or equivalent) 4.5 V dry battery with long flat brass terminals. Compared with others, this battery has a relatively large capacity in relation to its price, has a convenient flat shape, and is readily available.

In geology and civil engineering, resistivity is most frequently used for depth studies, exploiting the increasing depth of penetration as electrode spacing is expanded about a fixed station, for lines of readings at substantial electrode spacings, or for investigating localised earthing problems. These either do not need, or are not easily adapted to, the high-speed traversing necessary in archaeological applications, where the most important requirement is for large numbers of contiguous readings at a fixed small probe separation, buried features being revealed as anomalies in lines or areas of such readings. To facilitate this type of survey when using configurations such as Wenner, with four equally-spaced moving probes, Atkinson devised the 'leapfrog' mode of operation with five probes, so that one probe could be moved in readiness for the next reading while a reading was being taken with the others, and a special switch to change over the functions of the five probes simultaneously, enabling both probe handler and instrument operator to work continuously at high speed. For this switch, Atkinson made use of available wafer switch components (Atkinson, 1963). The Martin-Clark version is a special construction which greatly simplifies wiring and has other advantages.

The switch (Fig. 3.2) has an external rotating turret to which the leads are attached. Five equally-spaced connections pass through the turret, terminating inside the instrument with contacts in the form of 2 BA round screw heads. A detente mechanism, which allows the switch to be rotated in steps of one-fifth of a turn, ensures that one of these is always uppermost and spare, while the lower four engage with fixed leaf-spring contacts connected to the instrument circuitry. In operation, a reading is taken using the probes 1, 2, 3 and 4. The switch is then rotated to activate probes 2, 3, 4 and 5; probe 1, which has become spare, is moved to position 6 in readiness for the third reading. The reading obtained is assumed to apply to the mid-point of the array of four active probes. Apart from its simple wiring, this form of switch has the advantages that it is rotated in the direction of travel, which is readily comprehensible to the operator; and the tendency of probe movement to twist the leads is counteracted. Also initial setting up in the field is facilitated because the connections to the probes are in the same order as the four live connections to the switch turret as viewed by the operator from above.

Although simple, the probe design has been an important factor in the success of the instrument. It evolved from the offset two-point probe that it was necessary to use with the experimental two-terminal instrument (Chapter 1). Before its advent, probes were usually spikes pushed in by hand with considerable exertion, or knocked in with a hammer, which made progress both physically and temporally agonising. The standard probe, shown in the inset in Fig. 3.2, is of 3/8 inch (1 cm) diameter mild steel rod bent to provide a handle and an offset for insertion by foot pressure.

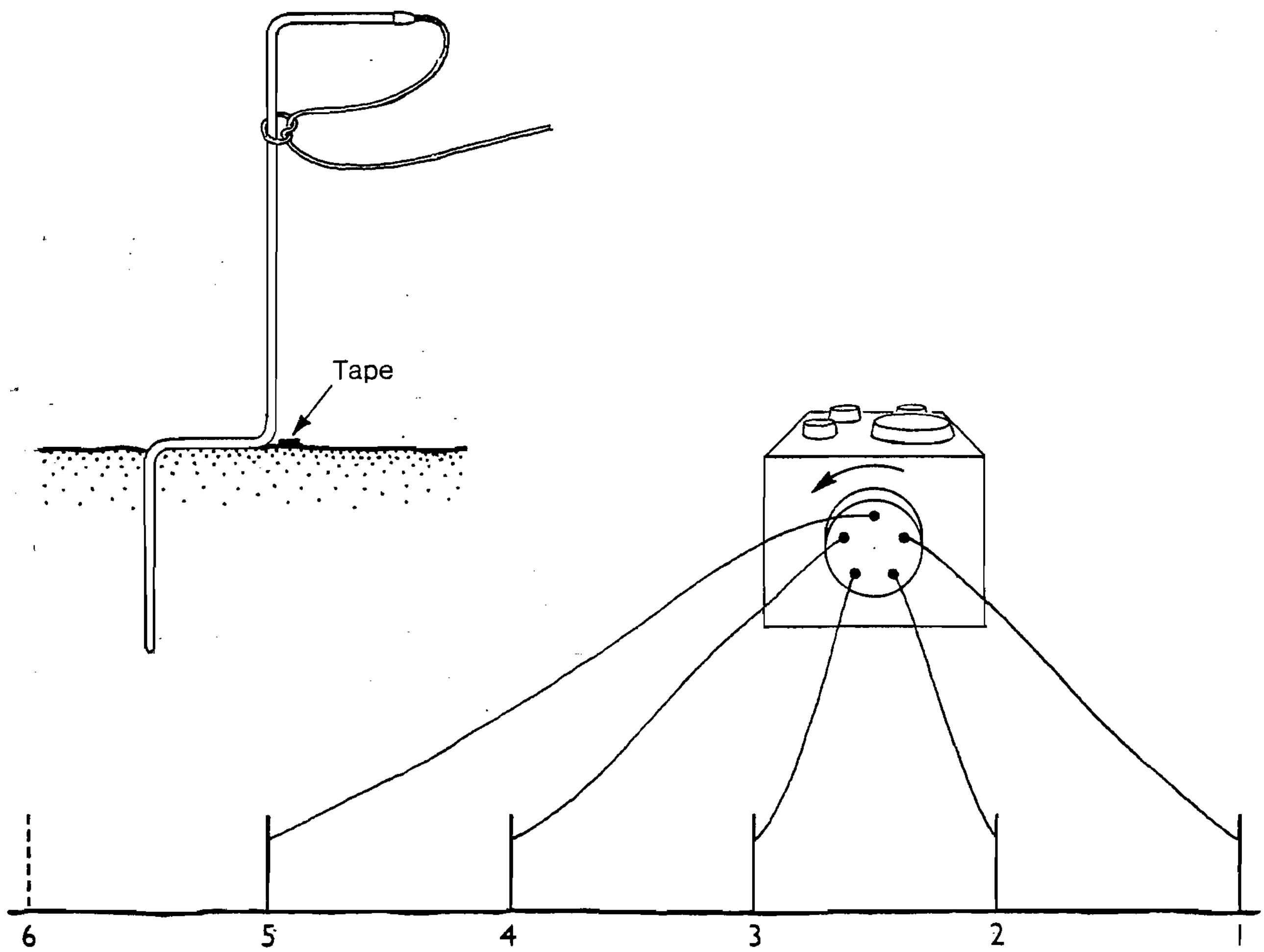
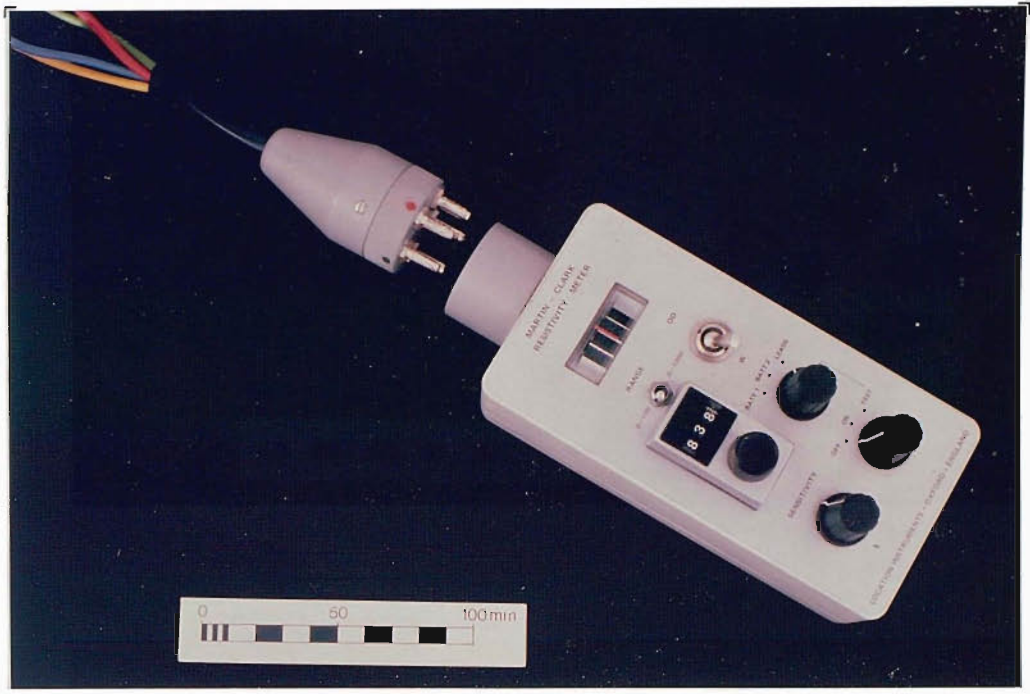


FIG. 3.2. Use of the rotary changeover switch and (inset) of the standard probe

The length of the spike below the offset is 7 inches (18 cm) which gives a good compromise between ease and firmness of insertion and adequate contact area for most soils. The height of the handle is 14 inches (35.5 cm), a compromise between convenience in use and in transport. The length of the handle and the offset are both 4 inches (10 cm), which gives an adequate grip for the hand, and enables the foot to give a firm downward thrust on the spike without slipping off in wet conditions, or tending to bend the probe as it would if the offset were wider. The handle points away from the offset so that it is clear of the leg on insertion.

When measurements are made along a tape, as they normally are, the probe is best placed with offset and handle at right angles to the tape and just clear of it, as Fig. 3.2 shows. This avoids interfering with the straightness of the tape, especially if it is stretched along the top of long grass, and ensures that any conduction between the offset and the ground does not affect the effective probe spacing. A right-handed probe handler walks to the left of the probe as illustrated, and the instrument operator is to the right, movement being into the paper. Leads were originally connected to the probes by heavy crocodile clips, but the more recent are connected by banana plugs pushed into a hole at the end of the handle, any strain on the plug being relieved by tying the lead to the stem of the probe. The leads are colour coded to aid correct connection.

A survey with a Type 1 instrument in 1963 is shown in Fig. 3.3b. Besides the people moving probes and operating the instrument, a third, in the foreground, is recording the readings. This is a labour-intensive way of doing a resistivity survey, and recent instruments can be screwed to a small board so that the operator may record on paper also attached to the board. Also, the leapfrog principle means that the probe separation is tied to the reading interval, although requirements of depth penetration and intensity of survey often make it desirable that these should be different. Solutions to this problem are linked with the efficacy of



a

b

FIG. 3.3. (a) Martin-Clark resistivity meter Type 3 with plug-in leads for 'leapfrog' surveys. (b) A survey with a Type 1 instrument, using the leapfrog method

different probe configurations, and are discussed at length in later chapters.

3.2. DETAILS OF THE INSTRUMENTS

3.2.1. TYPE 1. The circuit of the first version of this instrument is shown in Fig. 3.4. Transistor Q1 and transformer T1, and associated components, form the oscillator power supply generating a sinusoidal waveform at 520 Hz, 0.2 V peak to peak. T2 is the high impedance 1:1 transformer (100 H). Q2, Q3 and Q4 amplify the signal from T2, the gain being set by the 5 K potentiometer. T3 is a small 1:1 isolating transformer feeding the amplified signal to an earphone and to the base of Q5 which acts as a rectifier and final stage of amplification for meter M1.

Because of their low power, all Martin-Clark meters have had to be carefully designed to reject ground voltages, mostly deriving from the public 50 Hz supply, especially in the vicinity of built-up areas. This circuit, the lowest-powered of all, and with a left-hand zero meter, was particularly liable to be affected in this way, resulting in beating between the instrument and interfering frequency, often combined with an overall deflection of the meter, possibly exacerbated by phase shift in high contact resistance conditions. This could be mitigated by reducing the gain, but the speed of finding the balance point, and the precision of the reading once found, were both reduced. The audio detector was therefore provided as an alternative to the meter because it enabled a null at the instrument frequency to be recognised in the presence of a parasitic frequency; but in practice this was not as satisfactory as was hoped: there was some subjectivity in finding the null, especially when there was a residual signal at balance, so that readings could vary from one operator to another. Wind and other ambient noise could also cause difficulty with the earphones then available. Discrimination against 50 Hz interference was improved in later instru-

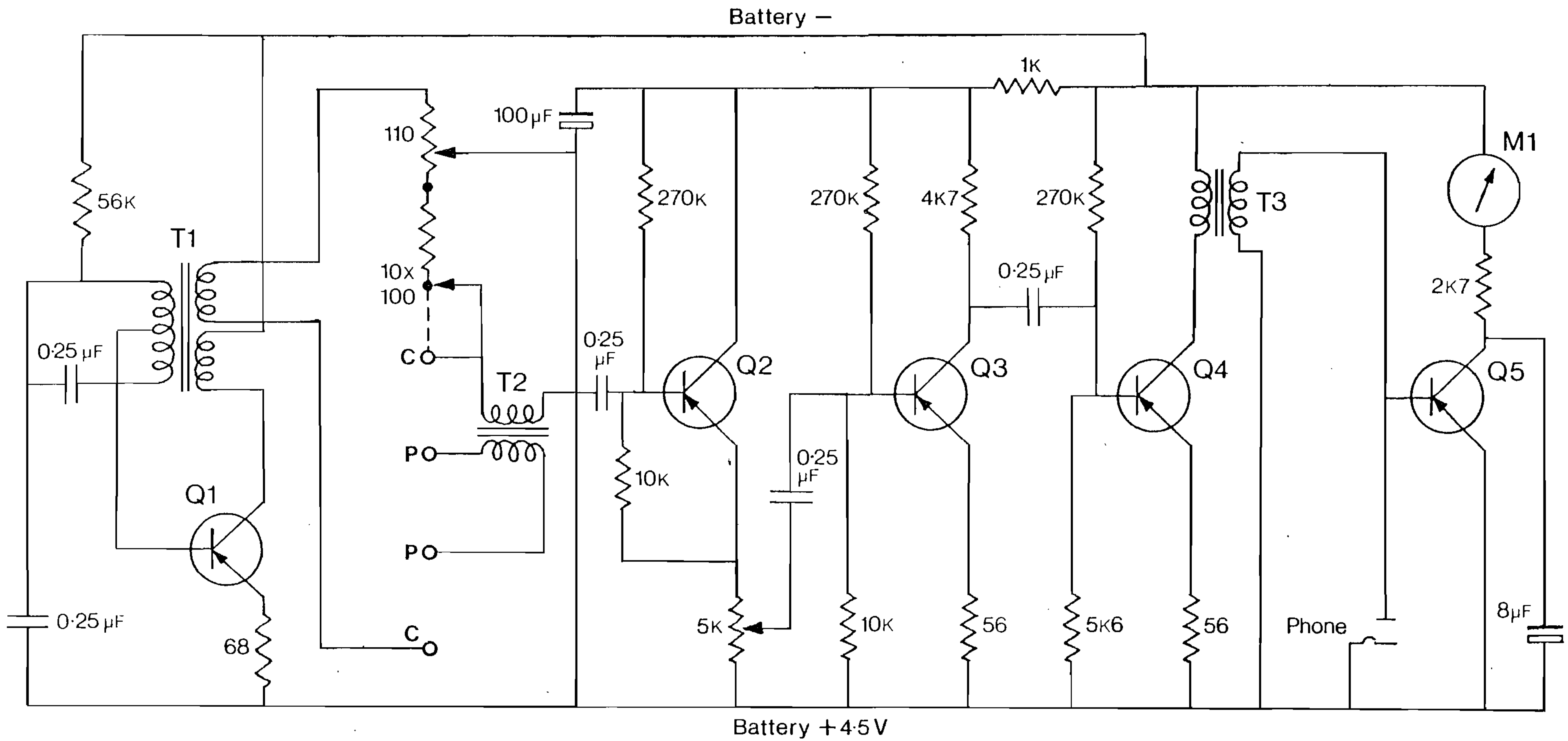


FIG. 3.4. Circuit of Martin-Clark Resistivity Meter Type 1

ments by putting a 0.1 F capacitor (not shown) across the primary of T3 to tune the detector circuit to the instrument frequency.

Originally, the ranges of the instrument were additive, in steps of 100 ohms, as shown in Fig. 3.4, so that the discrimination was the same for all ranges. The basic potentiometer was 110 ohms, giving an overlap between ranges; it was also non-linear, with the scale expanded at the lower end to improve discrimination of the lowest readings. It was found in practice, however, that the short additive steps often required too frequent range changes, especially at higher readings, because variations tend to be in proportion to the general level. Therefore a Type 1B instrument was produced with ranges of 0-10, 0-100 and 0-1,000 ohms, obtained by shunting a 1,000 ohm potentiometer.

The instrument was housed in a zinc alloy diecast box approximately 9 x 11.5 cm and 8 cm deep. The rotary changeover switch was machined from $1\frac{1}{2}$ inch diameter Perspex and was 1 inch long, the leads being soldered into 1 inch long, $\frac{1}{4}$ inch diameter brass tubes (spacers) threaded internally and screwed directly to the 2 BA screws, recessed in the Perspex, whose heads formed the contacts within the instrument. Sleeves of PVC tubing served the double purpose of waterproofing and of preventing excessive flexure leading to breakage of the leads where they entered the terminals. The connections were very close-set and difficult to dismantle, and were therefore left permanently in position, and were difficult to repair when there was any breakage at the terminals. The objective was a switch so solidly built that maintenance was hardly ever required, but it was not fully achieved.

The maximum contact resistance tolerance of this circuit is effectively 10 kilohms per probe. Although the accuracy remains high at this level, the instrument is so insensitive beyond it that discrimination is impracticably low.

3.2.2. TYPE 2. This circuit was more powerful than Type 1, and problems

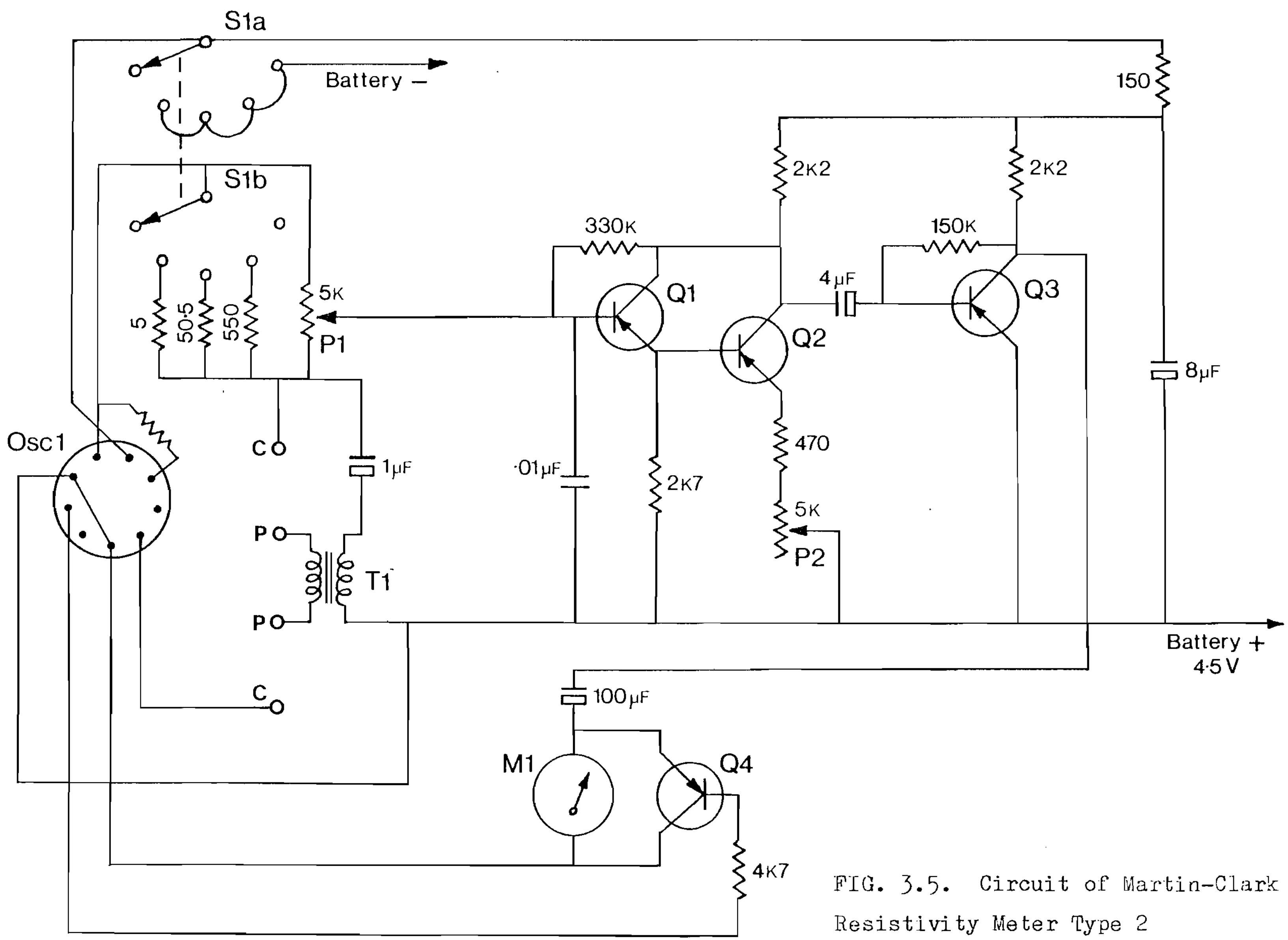


FIG. 3.5. Circuit of Martin-Clark Resistivity Meter Type 2

of interference were largely overcome by the greater power, combined with synchronous rectification with a centre-zero meter. In its original form (Fig. 3.5), use was made of an interesting forerunner of the integrated circuit, the Bailey Meters solid state oscillator, Series S011, with components 'potted' in resin in a small aluminium can. This gave a primary square-wave output of 18 V peak to peak at 405 Hz, from a 4.5 V battery, while a second output switched the transistor Q4, providing synchronous rectification for the centre-zero meter M1. Production of the S011 eventually ceased, and a special oscillator with similar characteristics (not illustrated) was designed for later instruments. The instrument was provided with ranges of 0-5, 0-50, 0-500 and 0-5,000 ohms by shunting a 5 K potentiometer as shown.

Probably because of phase shift caused by capacity effects, erroneous readings could occur when using long twin leads with this circuit, for instance with the Twin electrode configuration, although these could be avoided by using separate leads for each probe.

With contact resistance of 10 kilohms per probe, readings are depressed by 2 - 3 ohms. This means that, when using the two higher ranges, rather higher contact resistances are tolerable; but for the two lower ranges, especially the 0-5 ohms, contact resistances should be lower than 10 K.

The instrument was originally housed in a similar diecast box to Type 1, but only 5.5 cm deep. A later version made by Geoelectronics was contained in a box fabricated from rectangular section PVC tubing.

Continued attempts were made to improve the reliability and ease of servicing of the connections between the leads and the turret switch. Initially, the leads were screwed into threaded $\frac{1}{4}$ inch diameter brass spacers, the thread gripping the insulation. Pressure contact with the recessed screws of the switch was achieved in the following way. Flanged rubber sleeves behind the spacers passed through holes in a metal plate which, when screwed to the switch, compressed the flanges so that they held the spacers against the screws. The sleeves also provided protection against excessive flexure. Although this arrangement was very easily serviced, requiring no solder, it was still not sufficiently reliable. In the Geoelectronics version, the spacers were embedded in the switch (now of filled PVC) and permanently attached to the screws, while the leads terminated in banana plugs held in a PVC plate so that they could be pushed simultaneously into the spacers. Sleeves for protection from flexure were dispensed with in favour of extra-flexible leads. Previously, flat twin flex, with the two cores combined, had been used for the leads, because its flatness enabled any twisting to be easily recognised and removed. The new leads were light and vulnerable, especially at the banana plugs, whether with solder or pressure contact, but they did have the advantage of being readily detachable from the instrument.

The later instruments of this type have a switch for selecting either the Wenner or Double Dipole configurations, which is simply achieved by interchanging a potential and a current lead. The advantages of this facility, which arose from the electrolytic tank work, will be discussed in later chapters.

3.2.3. TYPE 3. This was designed to take advantage of integrated circuits and to effect all-round improvements. A high priority was to obviate the use of transformers, particularly the high-impedance 1:1 transformer which, as well as being heavy, was specially wound and therefore expensive and subject to uncertainties in delivery. Also, to overcome any capacity effects, it seemed important to design a lower frequency power oscillator than had been used hitherto.

The integrated circuits are RS Components type 741 throughout (Fig. 3.6). A1 and A2 act as buffers to ensure that the input impedance of the differential amplifier A3 is constant. The output of this is balanced by A4 by adjusting the 5 K balance potentiometer. The resultant signal is

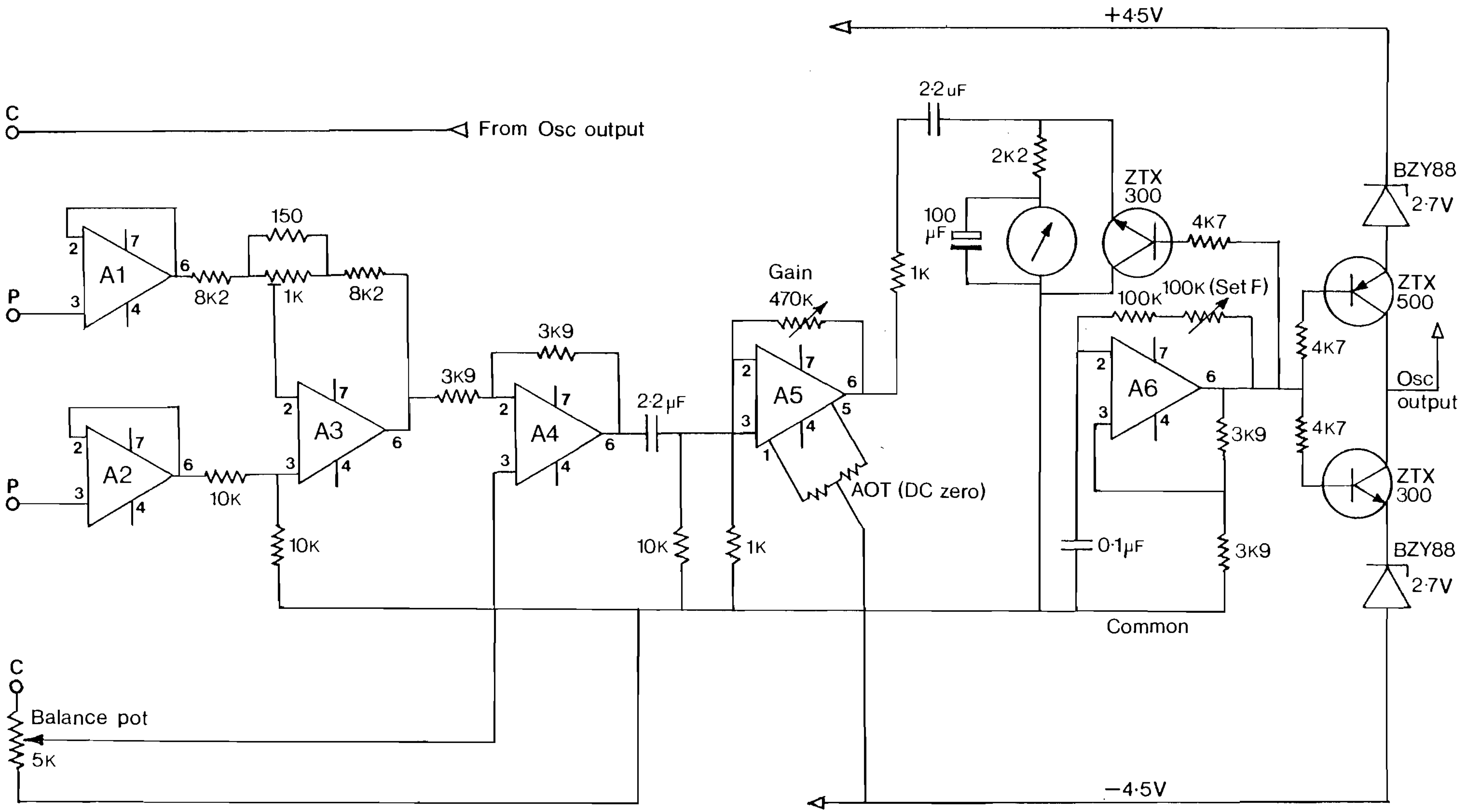


FIG. 3.6. Circuit of Martin-Clark Resistivity Meter Type 3

further amplified by A5 before passing to the centre-zero meter where it is synchronously rectified by the transistor switched by the oscillator. The square-wave oscillator is set at 67 Hz, a frequency low enough to remove capacity problems, and a minimal tendency to beat with either the 50 Hz mains used in Europe or the 60 Hz of the USA. The zener diodes BZY88 reduce the output to avoid saturation of the detector circuitry in low-resistance conditions. Two batteries are used, to provide a common rail. With 4.5 V batteries, the output of the oscillator is about 4 V peak to peak; but such is the adaptability of the circuitry that batteries up to 12 V can be used if required in dry conditions.

Because of the high input impedance of the circuit, it can tolerate high contact resistance. It is little affected by contact resistances up to at least 40 kilohms, even when there is a substantial variation from one probe to another. Even 100 K in each lead reduces a reading of 50 ohms only to 43 ohms. With 9 V batteries, the instrument has been used successfully in near-desert conditions in the Near East.

The instrument (Fig. 3.3a) is housed in a weather-sealed ABS box 16 x 8 cm and 5.5 cm deep. The readout potentiometer has ten turns and a digital dial which saves the operator having to translate an analogue indication. The greatly expanded scale provided by the multi-turn potentiometer has made it possible to have only two ranges, of 0-100 and 0-1,000 ohms, yet the 100 ohm range can discriminate to 0.2 ohm. There is a Wenner/Double Dipole switch, and comprehensive built-in test circuitry, which works as follows: When the on/off switch is set to TEST, the test selector switch above it is activated. BATT 1 and BATT 2 on this switch check the state of the batteries on the instrument meter. The LEADS test position checks the continuity of the leads and the turret switch contacts. It connects one side of one of the batteries to the top right-hand turret switch connection, and the other side of the battery to the remaining three active turret switch connections. Linking in turn the remote ends of these leads to the first gives a meter deflection similar to the battery test if the leads and terminals and turret switch contacts are in good condition. The fifth lead is tested by rotating the turret and testing again.

For the turret switch, the plug-in concept used in the last version of the Type 3 meter is retained, but the leads terminate in a housing, from which they all emerge together through a single anti-flexure sleeve, the function of which is aided by the mutual support of the bunched leads, which are of a more substantial high-flexibility type than those previously used. Within the housing, the leads are clamped to the banana plugs without solder, so that field repairs are quite easily made. This switch has worked very satisfactorily.

3.2.4. TYPE 4. The interim form of this circuit, designed for use with the electrolytic tank, is shown in Fig. 3.7. The integrated circuits are shown schematically: those actually used were the early type 72709, and required considerable ancillary circuitry which is not shown. The supply circuitry, shown to the left of C, P, P, C, and detection circuitry to the right, have separate 9-0-9 V supplies.

In early experimental measurements with the tank, using the Type 2 circuit, darkening of the electrodes suggested that there may have been some minor asymmetry in current flow, causing deposition due to polarisation. It was therefore decided that the oscillator for the constant current instrument should be designed to give as pure a sine wave as possible. This is A1 and associated components. The two 10 K resistors and two .047 μF capacitors form a Wien network. This attenuates the output by three at resonance, so that the voltage fed back is output/3. To maintain oscillation, the loop gain must not be less than unity, so the amplifier gain must be three. If the gain is higher, the output waveform squares; if it is less than three, it will not oscillate. The thermistor (Type R53) and 270 Ω fixed resistor hold the gain so that the circuit is

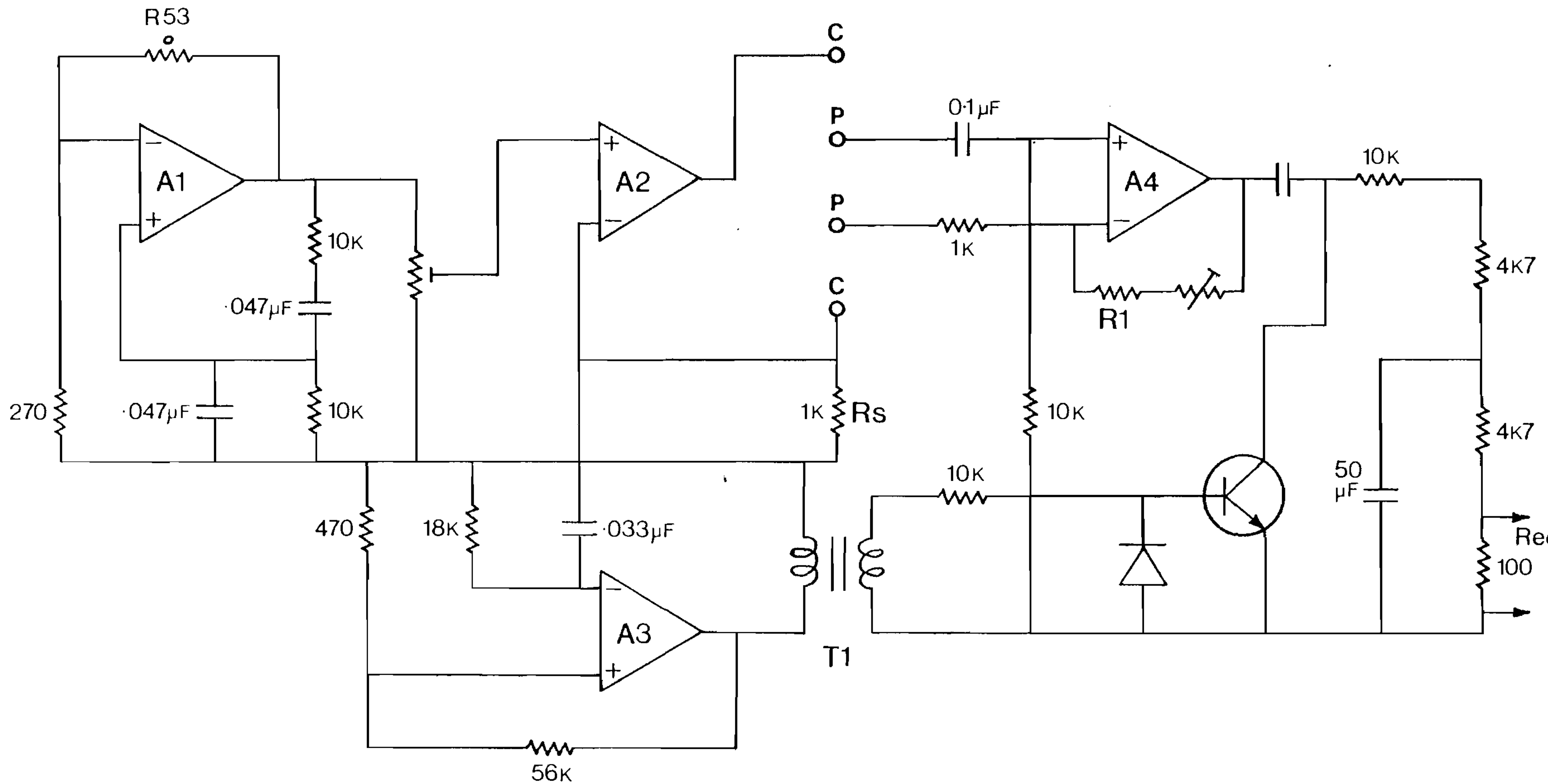


FIG. 3.7. Circuit of Martin-Clark Resistivity Meter Type 4. The power supply connections to the integrated circuits are not shown

just at oscillation and the output is a good sine wave. If the output tends to increase, the increased current fed back through the thermistor tends to heat it and its resistance drops, so reducing gain; and the opposite happens if the output goes down. The thermistor is inherently liable to be affected by changes in ambient temperature, but it is sealed in an evacuated envelope and run fairly warm to minimise the effect of these.

The constant current amplifier is formed by A2 and the associated 1 K resistor Rs. For any given input V_{in}, the amplifier will force a current through the load and Rs such that the voltage across Rs = V_{in}. If V_{in} is a constant, I_{out}.Rs is constant and, as Rs is fixed, I_{out} is constant. This applies for any value of load until the voltage available from the amplifier is insufficient to supply the current.

A3 and its associated circuitry is the switching amplifier, via the isolating transformer T1, for the phase sensitive rectifier.

With Rs = 1 K, and an output voltage swing of $\pm$ 6 V, the circuit is capable of supplying a constant current of 100 μA into an external load (mainly contact resistance between the current electrodes) of up to 59 kilohms. Although this is a very small current, the instrument has worked effectively in the field as well as the tank, the action of the phase-sensitive rectifier effectively rejecting external interference even on urban sites. The current can be increased with sacrifice of external load tolerance. The weakest aspect of the instrument for field work at present is the relatively low input impedance of A4, which causes a 1% drop in response per 1 K increase in resistance between the potential electrodes; but this can be improved by substituting a modern high-impedance integrated circuit for A4. At present A4 allows the instrument to be used up to a maximum reading of 200 ohms.

An important difference between this type of instrument and the others is that its output is not a direct readout in ohms, but a voltage proportional to the resistance. It must therefore be calibrated against a fixed resistance, and for this purpose an accurate 100 ohm resistor has been built into the instrument for checking calibration, the recorder being adjusted to give a convenient scaling for this. The instrument also has a small moving-coil meter for checking the batteries: both sets can be checked separately, either with the instrument switched off, or in the more realistic conditions when it is running.

As the instrument is designed to be used with a potentiometric recorder, the philosophy for field use of the prototype has been to assume that it will be used statically (especially with the Twin configuration) and to sacrifice easy portability in favour of a substantial long-life power supply in the form of eight 1289 batteries. It is therefore housed in a die-cast box 18.5 x 11.5 cm and 8 cm deep.

The operating frequency of the prototype circuit is 310 Hz.

4. PROBLEMS IN RESISTIVITY PROSPECTING

4.1. PROBE CONFIGURATIONS (Fig. 5.7)

The probe arrangement used by Atkinson, and by many others, has been the straightforward sequence CPPC with equal spacing due to Wenner (1916). This is normally called simply the Wenner configuration, but is sometimes distinguished as the Wenner α according to the nomenclature of Carpenter (1955). Apart from the ease with which it could be adapted to the five-probe 'leapfrog' method of working described in Chapter 3, this electrode sequence seemed initially to be the natural choice, having had a long history of successful use in larger scale geophysics - as well as being established in the scientific subconscious as the standard sequence of connections for measuring low resistivity samples in the laboratory. However, it became clear that the Wenner array was not always satisfactory for archaeological work: features almost always appeared too wide, and very many, especially those of high resistivity relative to the background, produced complex responses, most frequently in the form of double peaks. With experience in interpretation, well separated simple features can be sorted out in spite of these effects, but on a complex site interpretation can become very difficult, and a plot of the survey a poor representation of the buried structures.

An improvement was achieved at the expense of some loss of sensitivity by the use of the Schlumberger array (Dunk, 1962; Rees, 1962; Hesse, 1966a; Rees and Wright, 1969) in which the separation of the potential electrodes is reduced relative to the current electrodes. It was made convenient to use by mounting the probes on an easily carried hinged insulated framework, which was pressed with the foot for probe insertion. However, Palmer (1960) advocated the quite different approach of widening the relative separation of the potential electrodes. This gave high sensitivity, but the double peak effect was so aggravated that Palmer recommended that it should be used 'broadside on' - which assumed that one was looking for linear features and knew which way they were going, and meant that the line of electrodes had to be kept parallel to the feature as they were moved across it, a tedious and slow process, though Palmer alleviated it by linking the adjacent C and P probes in pairs with insulators.

It seemed to the writer that the deficiencies of all these arrays were probably due to the large spread of electrodes diffusing the

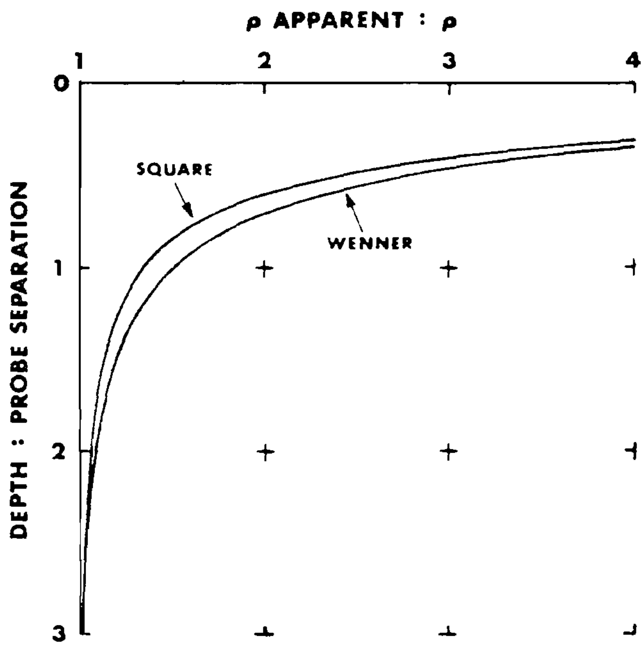


FIG. 4.1. Graph showing variation in the apparent resistivity of a layer of relatively low resistivity above a base layer infinite in resistivity and lateral extent at varying depths. Depth is shown in terms of the probe separation; measured resistivity in terms of that of the upper layer.

representation of the limits of features and distorting the picture of small ones. Uhlir (1955) advocated the use of a square arrangement of electrodes for measurements on small semiconductor samples, with the current electrode pair opposite to the potential pair. The square array seemed attractive in several ways as a field system: it could be in the form of a table supporting the instrument and recording system, so that there were no trailing leads and it could be operated by one person; and by simple switching, the functions of the electrodes could be inter-

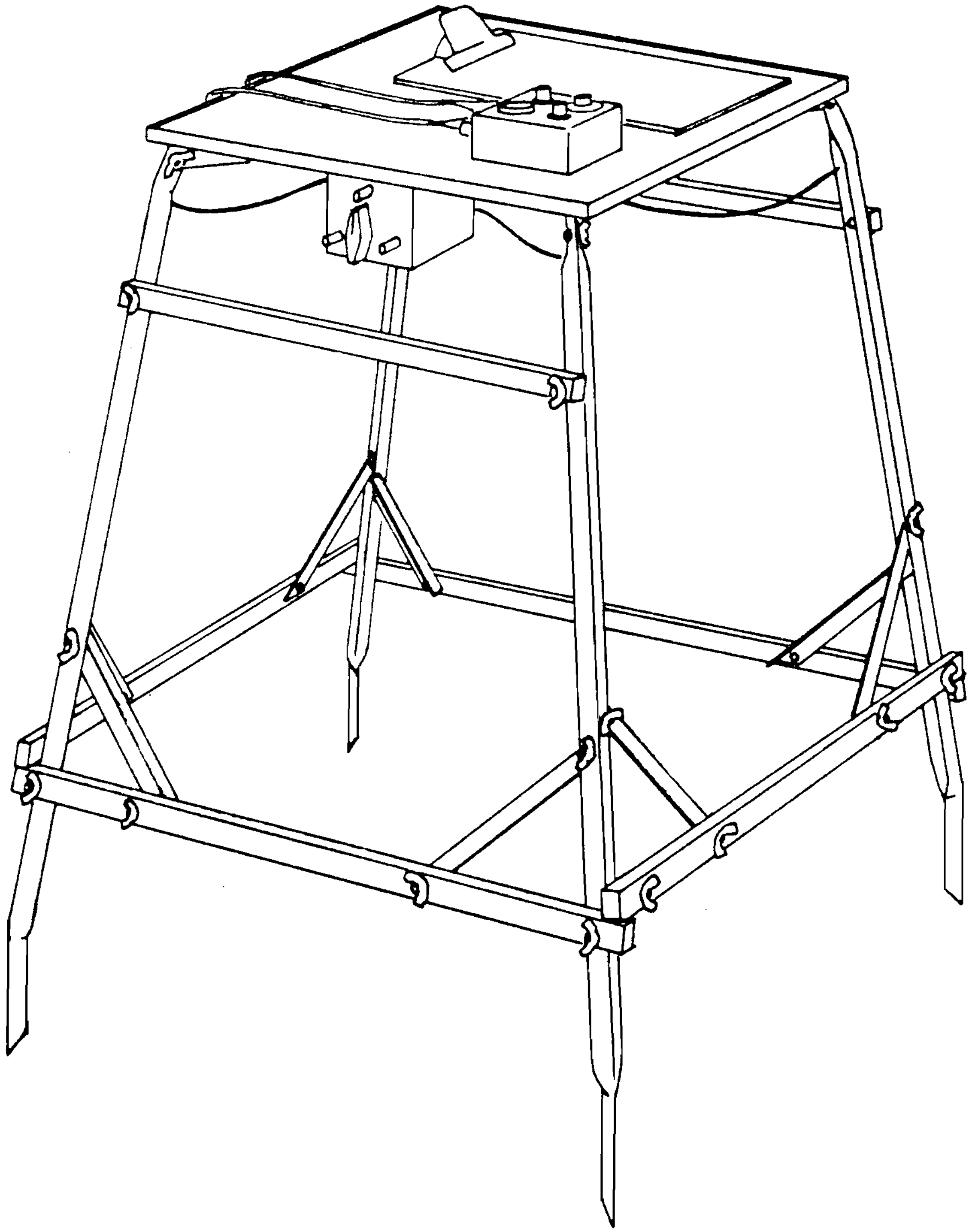


FIG. 4.2. The 2.5 ft prototype square array. The table top is 1.5 ft square and supports the resistivity meter and a clip board for recording readings. Four orthogonal electrode sequences can be chosen with the rotary switch housed under the table top on the left hand side; because this is a 12-way wafer switch, the cycle is repeated three times, the beginning of each cycle being marked by a projecting pillar which is recognised by touch without distracting visual attention from the table top. The length of the legs is 3.54 ft.

FIG. 4.3. The prototype square array in use before the changeover switch had been added

changed orthogonally so that two or even four readings could be obtained at each position and averaged to smooth out any bias or distortion that might be inherent in the measurement. The theory published by Uhlir showed that the detection depth of the square system should be closely comparable with the Wenner of the same spacing (Fig. 4.1), and that readings would be at a satisfactory level of about 0.6 times as great.

A square array apparatus was constructed (Clark, 1968) with a fixed electrode spacing of 2.5 ft (0.762 m) (Figs 4.2, 4.3). The light steel Dexion angle used for the legs was folded flat at the ends to form blade-like electrodes which, compared with normal cylindrical probes, are both easier to insert and have a larger surface area per unit cross-section, so that insertion need not be as deep. Any relative weakness of these slender electrodes was counteracted by the support of those perpendicular to them. The table top was of 12 mm plywood, and the supporting struts and handles of deal, with brackets of angle aluminium. The whole was demountable and rapidly assembled by means of captive screws and wing nuts. The total weight of the assembly with a Martin-Clark meter is 7 kg. In spite of the careful optimisation of the electrode shape, an expected cause of difficulty is that the operator is required to push four electrodes into the ground simultaneously; however, one pushes down with both arms, and foot pressure can, if necessary, be used on the framework; and, in conditions where the surface of the soil is at all damp, it is only necessary to place the assembly on the ground to obtain a reading. The speed of operation will be discussed below.

At the same time as the square array was being developed, Habberjam and Watkins (1967) were working independently on the application of the square resistivity configuration to the very different problems of large-scale geophysics.

The superior resolution of the square array compared with those described earlier was demonstrated on several sites (e.g. Figs 7.2 and

7.3). However, the design was, as an archaeological field system, empirical. Meanwhile, it was demonstrated (Carabelli, 1967; Carabelli and Brancaleoni, 1968) that an unambiguous representation of archaeological features was possible with the CCPP Double Dipole (Eltran or Wenner β) configuration, and Schwarz (1967), followed by Aspinall and Lynam (1970) produced the CP - CP Twin Electrode (Two Electrode) configuration, which not only seemed to show archaeological features as clearly as the Double Dipole but, with only two moving electrodes, could be very easy to use. Peschel (1967) showed that the Triple Electrode (Three Electrode) configuration, with three moving electrodes and one fixed current electrode (CPP - C), also produced single peaks over archaeological features, with some displacement and asymmetry that could be overcome by repeating each reading with the functions of the moving probes reversed: he also rather optimimistically claimed that depth profiles could be constructed from data obtained by combination of readings at different spacings.

By this time, a comprehensive understanding of the functioning of the rival configurations, with the objective of optimising archaeological resistivity detection, seemed an important priority. Such a study, based on the use of a novel electrolytic tank, forms one of the two main subjects of the research described here. Considerable use has been made of electrolytic tanks for simulation in earth resistivity studies (e.g. Carpenter, 1955; Habberjam, 1969); they have also been applied specifically to the problems of archaeological detection, but without producing the broad comparative study of the relative merits of electrode configurations that is the essential starting point for the further development of the subject. Probably the main reason for this is that tanks have been tedious to operate, requiring the taking of many individual readings (Hesse, 1966 a; Carabelli and Brancaleoni, 1968): time was simply against them. It therefore seemed important to the writer that a tank should be designed in which it would be possible to make numerous comparative runs, and to adjust a variety of parameters, with maximum ease and speed. The design, construction and use of such a tank is described in the next chapter. It should be added that, about the same time, a tank with some of the same advantages - motorised movement of the simulated features and continuous recording - was built in the (now) School of Archaeological Sciences, Bradford University.

A copy of the tank described here is now in use in the Department of Geophysics and Planetary Physics, University of Newcastle upon Tyne.

4.2. SPEED OF OPERATION

The slowness of resistivity measurement has always been cited as a disadvantage when it has been compared with magnetic prospecting. The speed of operation is dependent upon the type of probe configuration used (as well as the instrument and the recording method), and the favoured configuration must be one that gives a clear representation of buried remains at the greatest speed. The advances in speed brought about by the five-probe leapfrog system, and the integrated Square Array, have already been alluded to, but a full discussion is reserved for Chapter 7, after the relative merits of the various arrays as detection systems have been established.

4.3. CLIMATIC EFFECTS

As the electrical resistivity of the ground is dependent on the content of water and its distribution, it has long been realised that the measurements obtained are dependent on the weather (e.g. Atkinson, 1963). Al Chalabi and Rees conducted a year-long experiment on the buried ditches of a Roman defence system on Triassic sandstone at Wall in Staffordshire, and there they demonstrated that resistivity anomalies varied in size through the year with seasonal changes in water input (Al Chalabi and Rees, 1962; Rees, 1962). They concluded by expressing the hope that further experiments of the same sort would be undertaken on other soil types and in other climatic conditions. Similar experiments have been carried out by Hesse (1966a; 1966b) on a limestone bedrock in central

France, and by Janes (1975) on London Clay in Surrey. These are summarised, together with the writer's work, at the end of Chapter 6.

The southern English chalklands are of considerable archaeological importance, yet the writer had experienced very variable success in resistivity work upon them. They were therefore made the subject of the climatological study described in Chapter 6. The test sites also provided an opportunity to check some of the results of the electrolytic tank work at full scale.

Hesse has made a study (Hesse, 1966a; 1966b) of the effects of temperature on ground resistivity measurement. At practical probe spacings, these are insignificant compared with the water balance, except in extreme conditions of the sort discussed in 6.6.2.

4.4. OTHER PROBLEMS

The basic technical problems of the effects of length of probe insertion and errors of probe spacing have been considered by Aitken (1974). They are not a primary concern of this work, but his conclusions for the Wenner configuration may be summarised as follows. Effect of probe depth: For an increase from 5 to 15 cm, less than 2% at spacings in excess of 60 cm; probes with a depth stop will overcome even this small effect. Probe spacing errors: with 60 cm spacing, errors of 2.5 cm in placement along the line of the probes give reading errors of up to 4% with the inner probes, and 3% with the outer probes. These are either additive or subtractive, depending on the direction of the error. The effect of a particular size of error rapidly diminishes with increasing spacing, and it can be calculated, for instance, by means of equation (2.7). Errors due to lateral displacement of the electrodes from the straight line are relatively insignificant.

Some problems associated with instrument design are discussed in the next chapter.

5. RESISTIVITY CONFIGURATIONS : THE ELECTROLYTIC TANK STUDY

5.1. DESIGN OF THE TANK SYSTEM

In designing this system, the need for fine machining was largely avoided, the most sophisticated tool used being a bench drill. The basic concept is as follows. As in other tanks, end-effects from the tank walls are avoided by keeping the electrodes in a fixed position while the simulated archaeological features are moved beneath them. Readings are plotted continuously by a potentiometric recorder, the moving chart actually towing the simulated feature through the tank, so that there is an exact 1:1 relationship between feature movement and the recorded signal. An essential addition is a continuously reading resistivity meter, and the Martin-Clark Type 4 prototype was developed initially for use with the tank.

The apparatus is shown in Fig. 5.1 and in elevation and plan in Figs 5.2 and 5.3. The tank is a 'water play' tank in transparent plastic designed for school use. The main framework of the superstructure is of slotted aluminium 'Handy Angle' (a) supported on 'Lab Jacks' which enable the structure to be lowered and precisely positioned for operation, and lifted clear of the tank for adjustments to be made and so that it may be covered between experiments. The sliding and support surfaces are of 1/16 inch T-section aluminium angle (b) made for sliding window systems; the lower pair have the 'crossbar' of the T downwards, providing on the inside support and precise location for the sheet of Perspex carrying the electrodes, and on the outside a runway for the feature supports (Fig. 5.5) which are pulled by two Meccano chains (d) passing over two sets of sprocket wheels to the top of the apparatus where they lie on the upper pair of T-section slides, which have the 'crossbar' upward to provide a broad surface, and are linked to the recorder chart (h) by another piece of the T-section aluminium.

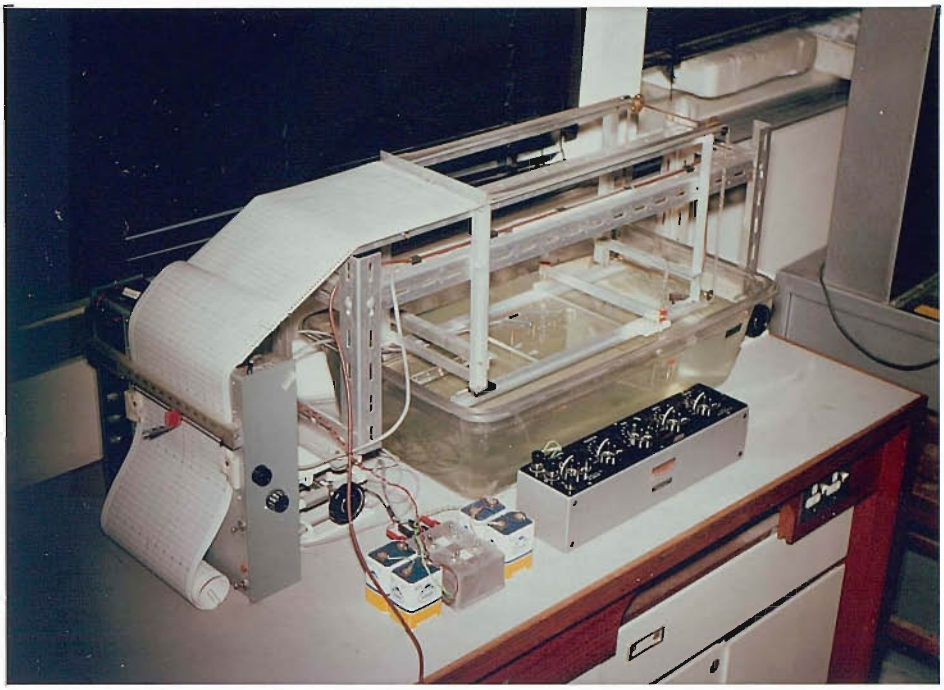


FIG. 5.1. The electrolytic tank system. In the foreground are the prototype of the Type 4 resistivity meter and a standard resistance box for calibration

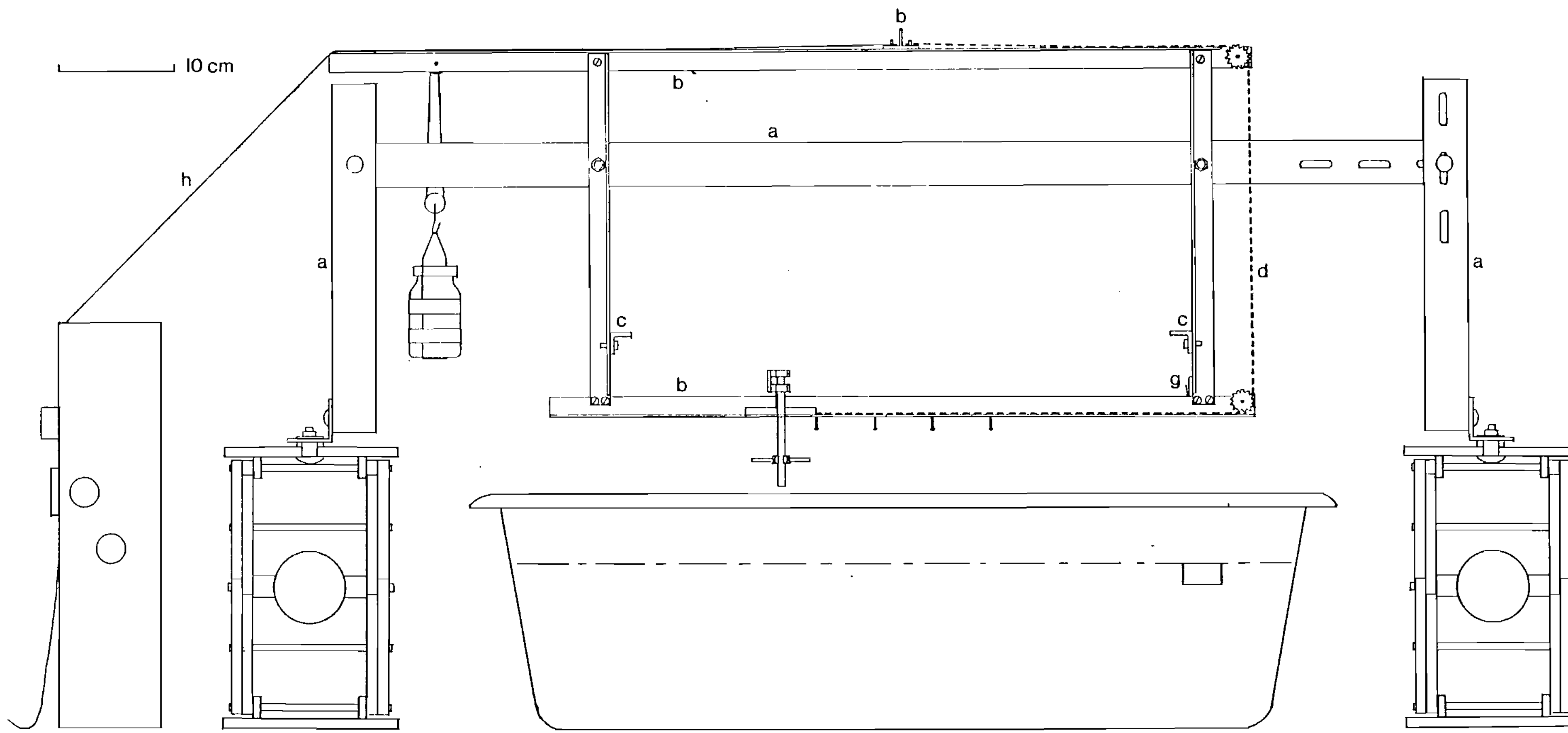


FIG. 5.2. Side elevation of electrolytic tank apparatus

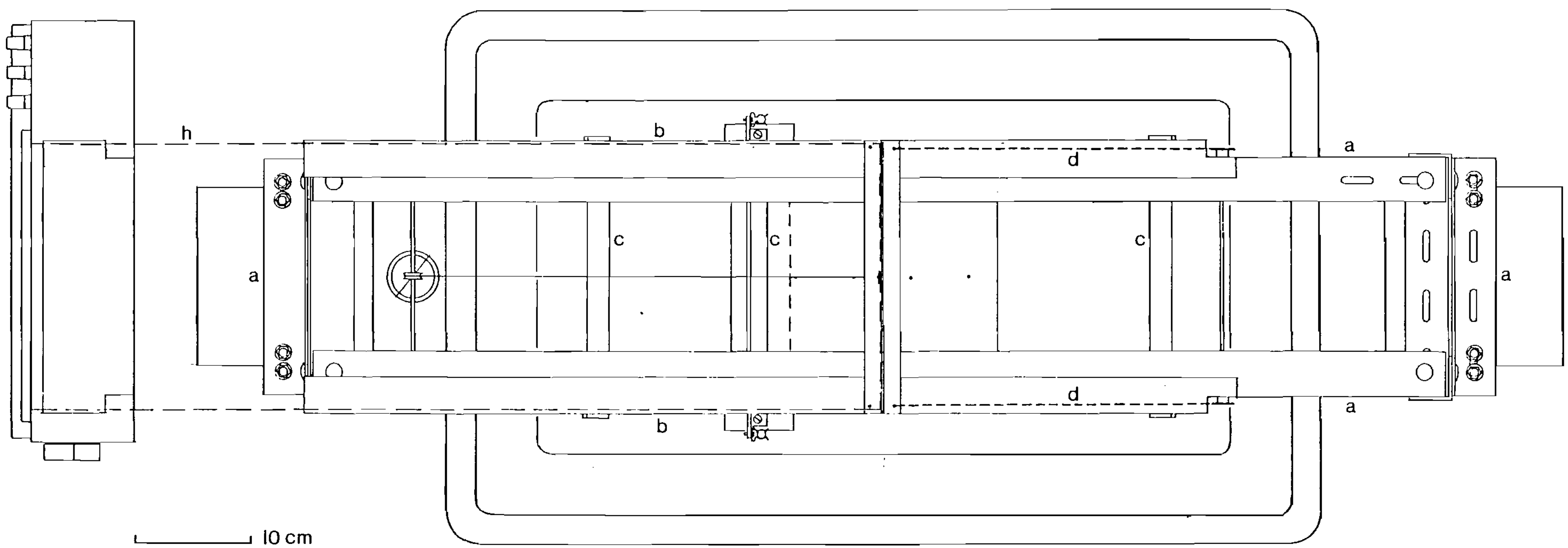


FIG. 5.3. Plan of electrolytic tank apparatus

The sub-frame supporting the T-section slides and the crossbar of the anomaly support carriage are constructed with $\frac{3}{4}$ inch x 1/8 inch thick L-section aluminium angle (c).

There follows below a more detailed description of the various parts of the apparatus.

5.1.1. THE ELECTRODE SYSTEM (Fig. 5.4). The electrodes themselves are 1-inch 8 BA round head brass screws which are screwed by hand into a 20 cm square $\frac{1}{4}$ inch thick Perspex plate drilled with a pattern of threaded holes that enable all the desired configurations to be obtained (see below). The screw threads are gold plated to prevent corrosion (this was done by a jeweller) and nuts, soldered in place, act as stops to ensure that the base of each head projects exactly 1 cm when the electrodes are in position. Small 0.010 inch thick phosphor bronze spring clips soldered to the resistivity meter leads are pushed on to the upper ends of the screws.

The round screw heads (dia. 4 mm) are the correct theoretical shape (Wenner, 1916) and, most importantly, it is possible to adjust their height so that they produce no distorting meniscus in the water surface when this is level with the base of the head. The fine height and level adjustment obtainable with the Lab Jacks is very necessary for this. Levelling is achieved by lining up the runway rails with their own reflections in the electrolyte.

An additional small Perspex plate, suitable for supporting two electrodes, was used for experiments with the Twin and Triple electrode configurations. When using these configurations, the especially precise levelling that is required is easily obainable by adjusting the Lab Jacks with reference to the widely spaced electrodes, rather than by the reflection method.

The holes drilled in the main Perspex plate permit the following electrode arrangements to be used:

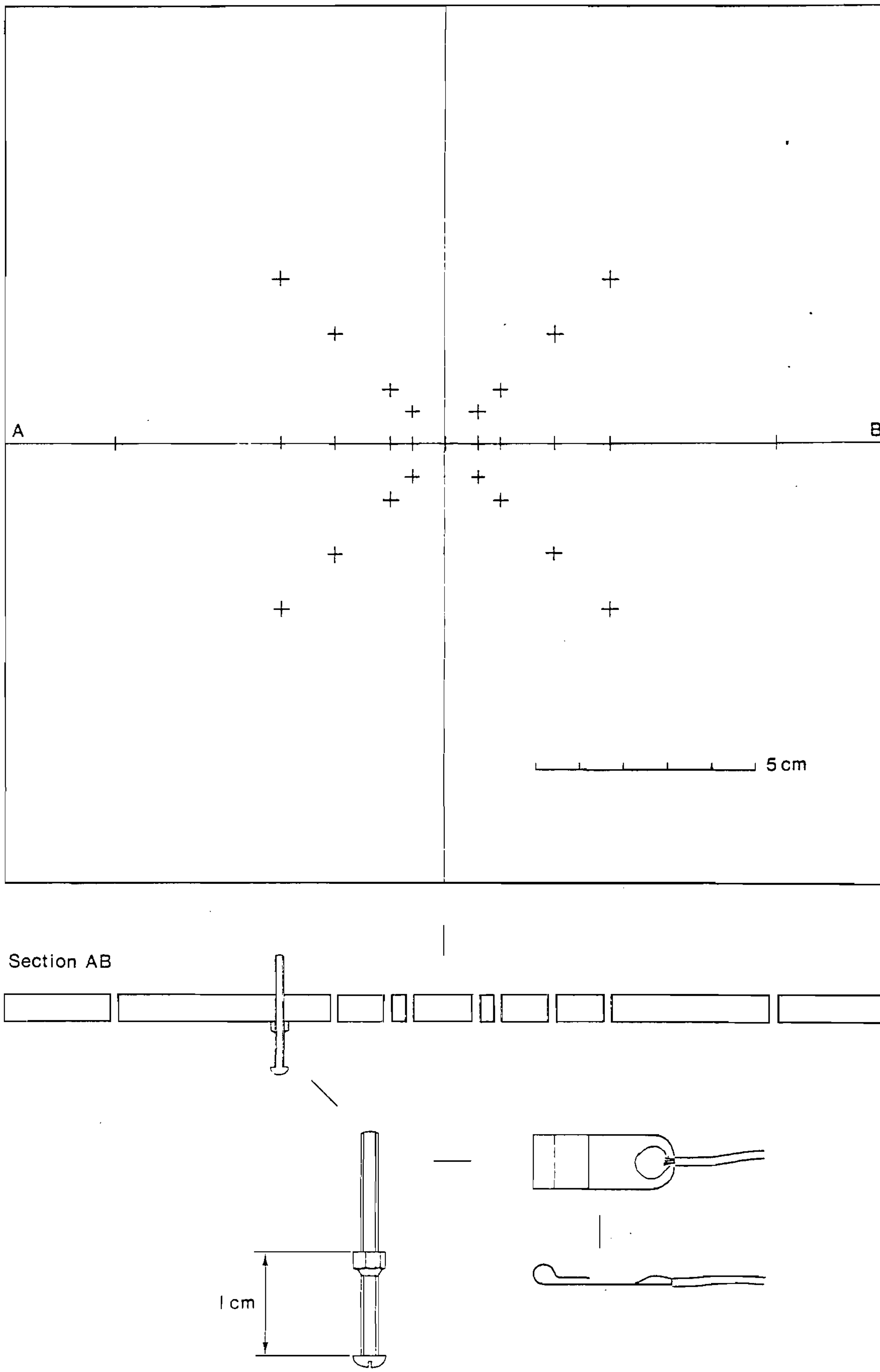


FIG. 5.4. The Perspex electrode support plate, and details of electrode (8 BA brass screw) and phosphor bronze contact clip

Linear, equally-spaced	2.5, 3.75, 5.0 cm
Schlumberger	C-C 5.0 cm; P-P 1.5 cm
	C-C 7.5 cm; P-P 1.5 cm
	C-C 11.5 cm; P-P 1.5, 2.5 cm
	C-C 15.0 cm; P-P 1.5, 2.5 cm
Palmer	C-C 15.0 cm; P-P 7.5, 11.5 cm
	C-C 11.5 cm; P-P 5.0, 7.5 cm
Square	1.5, 2.5, 5.0, 7.5 cm

The diagonal lines produced by the different Square spacings give an additional equal-spacing of 3.54 cm and also two possible Schlumberger and three possible Palmer spacings.

The two orthogonal lines scribed on the plate enable the configurations to be centred on a mark on the support frame; and they can be turned through 90° simply by lifting the plate, turning it, and dropping it back between the rails without any other adjustments.

5.1.2. THE FEATURE SUPPORT (Fig. 5.5). This consists of a bridge of the $\frac{3}{4}$ inch aluminium L-section angle (c) able to pass over the electrodes, fixed at each end by $\frac{1}{4}$ inch dia. 4 BA spacers to short lengths of wide nylon curtain track (e) that slide on the outer side of the inverted T-section rails. Small plastic-coated Terry clips, fixed to the ends of the L-section by 8 BA screws, support vertical glass rods (f) to which the simulated features are also attached by similar Terry clips fixed to them. The feature height is adjusted by sliding the clips up and down the rod, and allowance can readily be made for the electrode height so that its depth can be adjusted while out of the water.

The drive chain is conveniently anchored by 6 BA screws in the inner slot of (e), and the slots also contain the heads of the lower screws for the spacers.

5.1.3. THE ANOMALY TRANSPORT SYSTEM. To avoid slack and deadspace in this system, the chain (Meccano Part 94) is vertical when running free

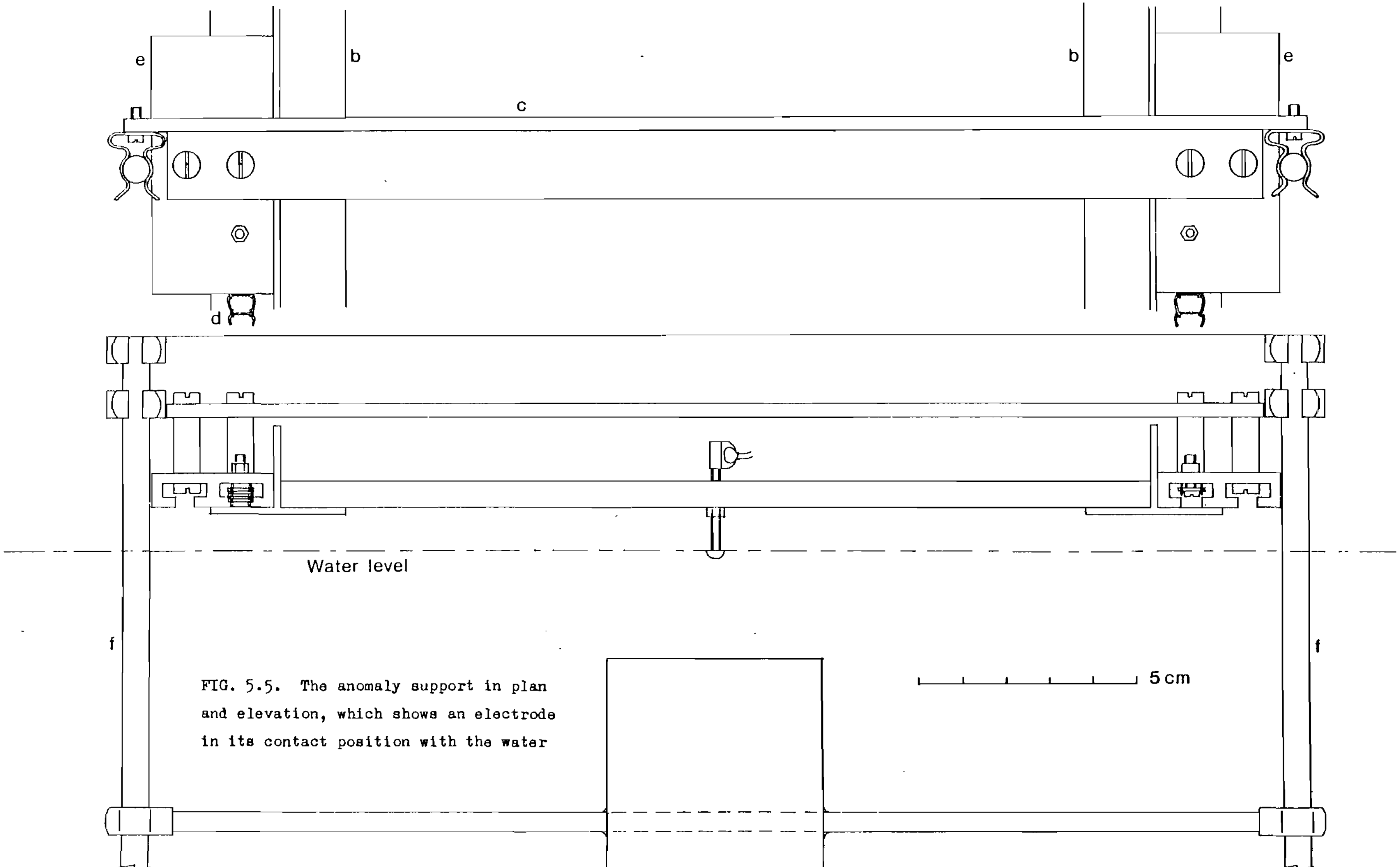


FIG. 5.5. The anomaly support in plan and elevation, which shows an electrode in its contact position with the water

and fully supported on the aluminium rails when running horizontally. The chains are linked to the recorder chart by a cross-piece of the T-section aluminium with projecting 8 BA screws arranged to engage with the end links of the chains on one side and the sprocket holes of the chart on the other. The sprocket wheels (Meccano Part 96a) at the top and bottom of the vertical chain runs are locked to the axles that link them across, to retain the chains in synchronism so that the system runs true. For the recorder chart, it was found desirable for strength and economy of paper to have a permanent backing sheet with some reinforcement of the sprocket holes attached to the screws, the pieces of chart actually used for recording being shorter and fixed to the backing sheet with paper clips; by ensuring that the sprocket holes of both sheets coincided, a useful mutual reinforcement was achieved.

This system contains so much friction that the recorder chart would be unable to move it without assistance. This is provided by a weight in the form of a 2 oz chemical storage bottle containing lead shot pulling on the cross-piece between the chains and the chart by means of a string and pulley (Meccano Part 23 with spring clip Part 35) arrangement. This weight is adjusted so that it just fails to pull the feature along, and only a small amount of extra tension is required from the recorder and chart. Because of the lack of height for the movement of the weight, the pulley system velocity ratio is $\frac{1}{2}$. The copper wire cradle for the bottle is attached to it by adhesive tape.

A PTFE spray is a suitable lubricant for the sliding surfaces. However, over-lubrication can cause a jerky 'stick-slip' motion, and this can be corrected by gentle application to the lower rails of a very soft indiarubber, which increases friction in a controlled way.

5.1.4. THE RECORDER. This is a Smith's Servoscribe Desk Model Type No. RE 511.20. The wide range of sensitivities and speeds and the flat bed design of this instrument make it most suitable for this work. It is used in the vertical position mainly to save space, although this does at the same time give the chart a straightforward run. The standard fibre tip pen supplied with the recorder, slightly blunted to give a line thick enough for reduced reproduction, and with a small additional weight (a small crocodile clip was used) to increase its pressure on the chart, was found most effective. A suitable running speed for the recorder was 120 mm/minute.

A small but essential feature is a microswitch (g), operated by the feature support, that switches off the recorder at the end of a run, so that the apparatus can be left to operate unattended.

5.1.5. FIXTURE OF FRAME TO LAB JACKS. The frame is supported on four of the standard Handy Angle round-head screws resting on inch-square pads of 1/8 inch thick rubber on the Lab Jack platforms. Coach bolts with substantial heads grip the front and rear edges of the platforms to prevent movement; the shanks of the bolts are sleeved with slightly over-length $\frac{1}{2}$ inch diameter PVC tubing, the compression of which improves the grip and helps to keep the bolts in position. The flexibility permitted by this support system prevents the inevitably unequal raising and lowering of the Lab Jacks from putting any strain on the measuring framework.

5.1.6. THE RESISTIVITY METER. This took more time than the whole of the rest of the apparatus construction, because it involved the development of a completely new automatic instrument; but this did not seem disproportionate because of the potential value of such an instrument in the field as well as in the laboratory.

At first a Martin-Clark Type 2 meter was converted from manual to automatic balancing. The out-of-balance signal was amplified to drive the potentiometer to the balance point, a signal to operate the recorder being provided by a battery and potentiometer circuit ganged to it. This was effective, though rather slow in response, but the potentiometers were rather stiff, producing a tendency for traces to be stepped and lacking in subtlety of resolution. The substitution of potentiometers with a lighter action would probably have brought about a great improvement, but instead it was decided to design a circuit of the constant current type which, after some development, proved to be fully satisfactory. This is the Martin-Clark Type 4 described in Chapter 3.

5.1.7. TANK ELECTROLYTE. This is distilled water, to avoid algal contamination, made conductive with potassium chloride, which is more stable than sodium chloride. For most experiments its resistivity was adjusted to give a basic reading of 25 ohms with a 5 cm Square Array, which gave a contact resistance of about 1.25 kilohms for each electrode, well within the tolerance of the resistivity meter. The 25 ohm reading represents a resistivity of 13.4 ohm-metres compared with 204 ohm-metres for the same reading with the full size field apparatus with probe spacing of 762 cm. It will be recalled from Chapter 2 that no scaling factor problems are to be expected from this difference.

A piece of adhesive tape on the outside of the tank serves as a marker to enable the electrolyte depth and thus any background effects, for instance from the tank bottom, to be kept constant.

5.1.8. THE SIMULATED FEATURES. All but two of these are 'linear', 25 cm long, stretching between the supports in the tank. They are as follows (Fig. 5.6):

1H. Flat sheet of high resistivity Perspex 5.0 x 0.32 cm (1/8 inch) thick. This and 1L were not so much intended to simulate specific feature types as to help in understanding anomalies caused by more complex features.

1L. Similar to 1H, but in 0.16 cm (16 gauge) thick aluminium for low resistivity.

2H. Square-section high resistivity 'box', 5.0 x 5.0 cm, made from 1/8 inch thick Perspex sheet, glued with chloroform/Perspex mixture. Its

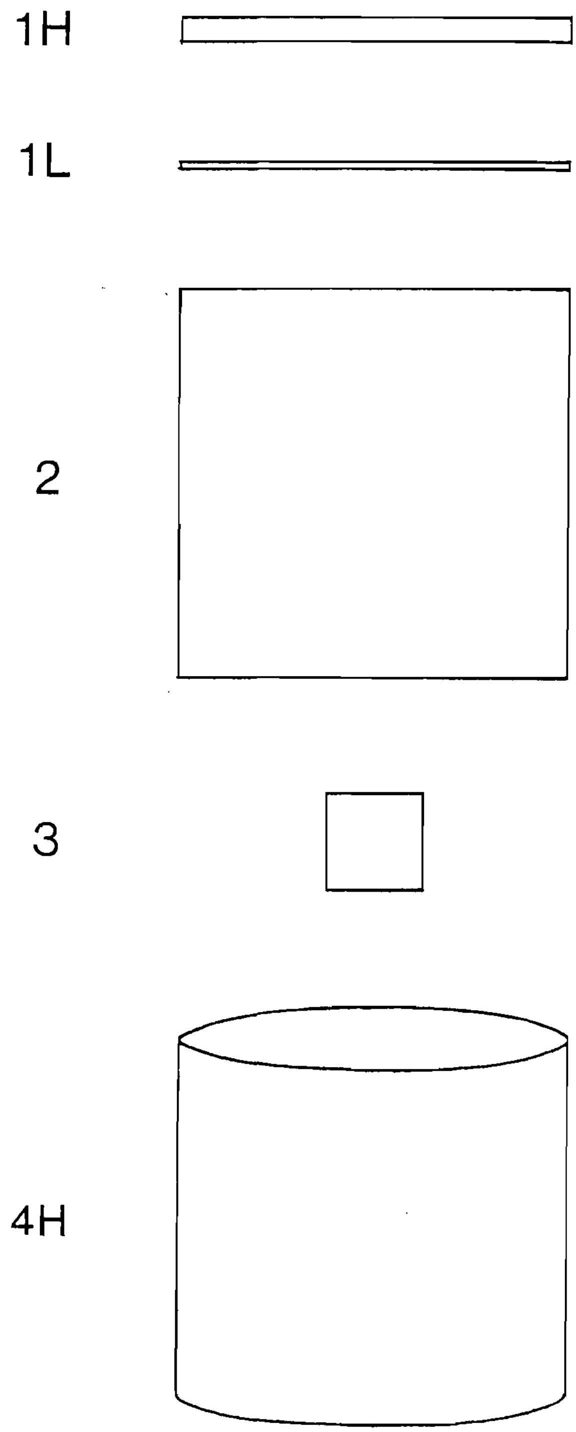


FIG. 5.6. The basic anomaly shapes used in the tank experiments. Nos. 2 and 3 represent both the high resistivity (2H and 3H) and low resistivity (2L and 3L) versions

top is formed from 1H, so that the two can be compared simply by attaching 2H to 1H using rubber bands, without disturbing any other parameter. It is used water-filled, otherwise it would be too buoyant, the water being allowed to enter on immersion through a small hole in the base. It simulates a fairly frequently encountered archaeological feature form, typically of masonry.

3H. Square-section high resistivity Perspex rod, 1.25 x 1.25 cm, representing typically a small masonry feature, or a source of high resistivity noise.

4H. Hollow cylinder of high resistivity polystyrene, 5.0 cm diameter, 5.0 cm high, made by cementing together the lower parts of two sample containers. It is supported close to its base by a 0.4 cm dia. glass rod (Fig. 5.5) which was first checked to be undetectable at its minimum depth. This simulates an isolated feature such as a pit with a loose filling. A small hole was drilled at the top and the bottom so that this too could be used water-filled.

2L. A low resistivity version of 2H made by wrapping it, combined with 1H, in aluminium foil. The foil was fixed in place by means of clear Bostik, making sure that the adhesive did not cover any of the exposed surface of the foil.

3L. A low resistivity version of 3H made by wrapping it with aluminium foil.

5H (not illustrated). A spherical feature (table tennis ball) of 3.75 cm diameter, used at the end of the experiments to check the predictions of theory for such an idealised feature, and compare them with the other feature shapes tested. It was held in position by a 0.3 cm diameter Perspex rod passed through it at a low level so as to be undetectable. It was partly filled with water to reduce its buoyancy.

Attempts to clean the aluminium of the low-resistivity features with dilute NaOH solution, to ensure maximum conductivity of the surface, were not helpful, because it was difficult to dislodge all of the NaOH after cleaning, and this affected the resistivity of the electrolyte.

The tank bottom is 14 cm below the electrolyte surface, and therefore hardly detectable by any of the probe configurations used. A sheet of $\frac{1}{4}$ inch thick Perspex, 60 x 32 cm, was used in some experiments to effectively raise the level of the tank bottom to simulate a relatively shallow, high resistivity bedrock immediately beneath the feature.

Two of the accompanying figures illustrate the different features in use. Fig. 5.2 shows feature 1H in position for use at 2.5 cm depth when the frame is lowered. Fig. 5.5 shows feature 4H in use at the same depth and passing beneath an electrode.

5.2. TANK MEASUREMENTS

5.2.1. PROBE CONFIGURATIONS. The chief arrangements tested are shown in Fig. 5.7, and their dimensions and some notes on them are set out below.

W = Wenner (Wenner α). 5 cm spacing.

Sch 1 = Schlumberger. C-C = 15 cm; P-P = 2.5 cm.

Sch 2 = Schlumberger. C-C = 11.5 cm; P-P = 1.5 cm.

This was included in some of the later experiments because, with a C-P spacing of 5 cm, it was thought to be more comparable than Sch 1 with the other configurations with 5 cm C-P spacing.

P = Palmer. C-C = 15 cm; P-P = 7.5 cm.

Palmer in fact tended to use relatively closer C-P spacings, which produce even more exaggerated responses than the tank measurements show; but the spacing used here is suitable for the tank and adequately demonstrates the characteristics of the configuration.

Sq = Square. 5 cm spacing.

DD = Double Dipole (Wenner β). 5 cm spacing.

This would more correctly be called Double Bipole, but the alliterative name of common usage is retained.

Sch-DD = 'Schlumberger-Double Dipole'. C-C = 15 cm; P-P = 2.5 cm.

This experimental configuration was achieved simply by connecting the Schlumberger in the same sequence as the Double Dipole.

CPCP = Wenner γ. 5 cm spacing.

Tw = Twin Electrode (Two Electrode). C-P = 5 cm; distance between centres of electrode pairs approximately 40 cm.

Tr = Triple Electrode (Three Electrode). C-P = 5 cm; P-P = 5 cm; distance from centre of C-P to fixed remote C approximately 40 cm.

The basic starting point for the above dimensions was an electrode separation of 5 cm for the equal-spacing configurations. In addition to the spacings detailed, W was also used at 3.75 cm for a single configuration test experiment (Fig. 5.26), and a variety of the spacings already listed as possible with the electrode plate as drilled were used for the 'optimisation' experiments described later in this chapter.

These configurations include those advocated by various workers as solutions to the problems of clear representation of archaeological features by resistivity (Sch, P, DD, Sq, Tw, Tr), which have already been briefly discussed in Chapter 4. W, with which Atkinson first demonstrated the feasibility of archaeological resistivity detection, and is still of considerable use, is retained as the basic reference and starting point. The possible alternatives of Sch-DD and CPCP arose during the tank work.

5.2.2. THE EXPERIMENTS. The experiments described below are basically in the order in which they were carried out, thus giving an indication of the development of the writer's thinking, but with some modifications to improve their logical grouping.

As already stated, the Square array was used as the reference configuration for the resistivity of the electrolyte, which was adjusted to give a 'background' reading of 25 ohms. A reason for this choice was that this compact configuration suffered insignificantly from the

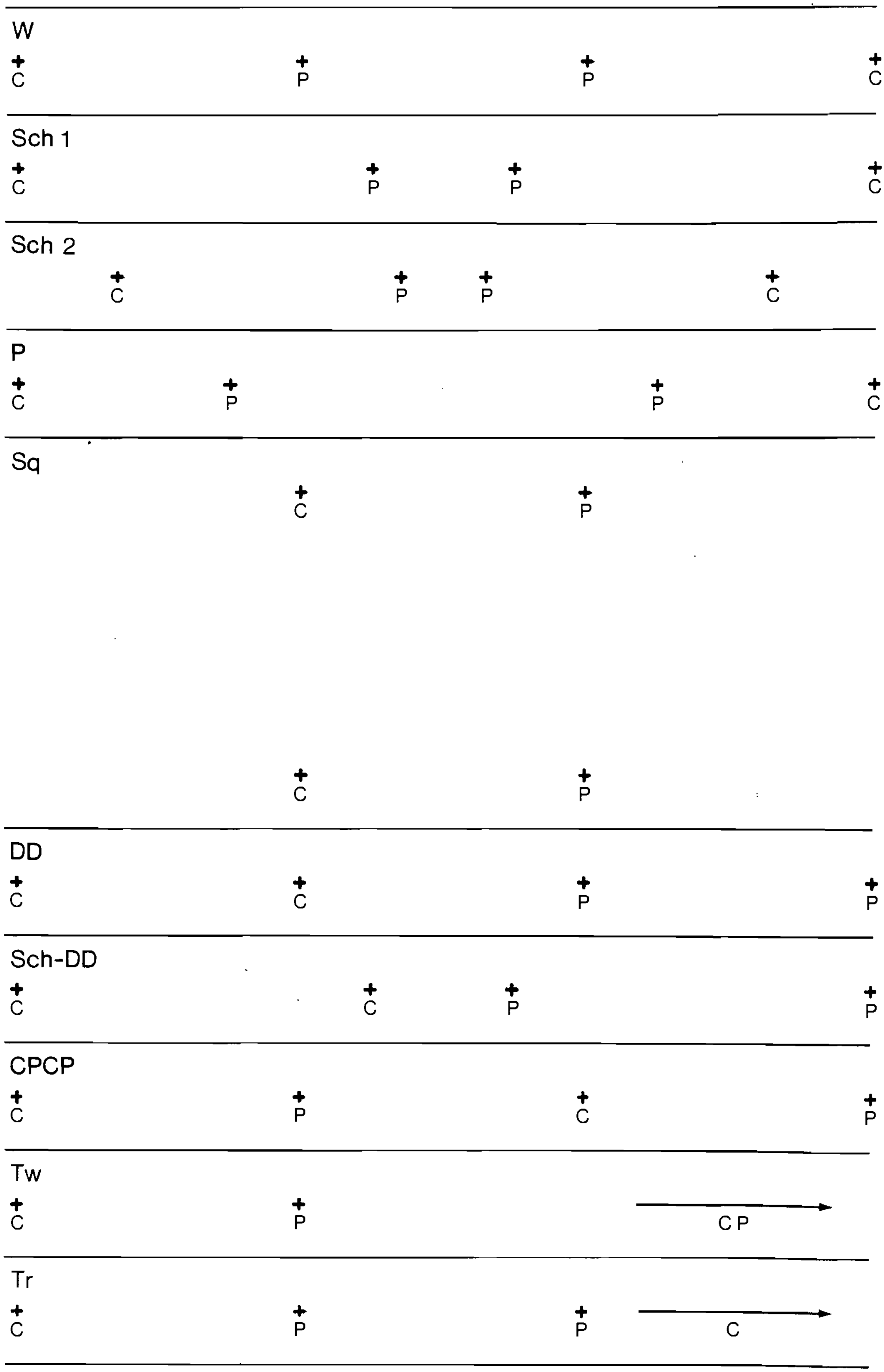


FIG 5.7. Electrode configurations used in the electrolytic tank. Scale 1:1

orientation effect described below. At this resistivity (13.4 ohm-metres), the background levels of the other configurations were noted, and their mean values are listed below alongside theoretical values for a semi-infinite homogeneous medium calculated from equations 2.7 - 2.9. Distortion due to the presence of the tank walls and base affects the wider configurations with deep current penetration, Tw and Tr, especially seriously, and was also noticeable with the more compact linear configurations as changes in background reading when the electrode assemblies were turned through 90°; and the values listed are those obtained for the 'end-on' sense of measurement (see below), in which the electrodes lie along the major axis of the tank and therefore as clear of the walls as possible. Sq was not perceptibly affected by rotation and, when the tank base was effectively raised by 6.2 cm (Fig. 5.17), reducing the electrolyte depth from 14 cm to 7.8 cm, the background level of Sq rose only from 25 to 26.5 ohms, while W rose from 45 to 50 ohms.

BACKGROUND RESISTANCE LEVELS

CONFIGURATION	OBSERVED (MEAN)	THEORETICAL
Sq	25.0 ohms	25.0 ohms
W	46.4	42.7
Sch 1	20.3	19.5
Sch 2	Not measured	19.7
P	79.9	75.8
DD	11.8	14.2
Sch-DD	47.3	50.8
CPCP	31.0	28.4
Tw	140.0	85.4
Tr	30.0	21.3

The figures that follow are photographically reduced montages of the actual traces produced by the electrolytic tank system. The vertical spacing between the major chart lines is 2 cm (equivalent to 5 ohms, unless otherwise stated), and between the minor lines, 2 mm; the horizontal spacings are respectively 6 cm and 1 cm. The simulated features, in cross-section, and their depths are shown to scale beneath the baseline of the uppermost trace (or the relevant trace) in each figure, H and L denoting high and low resistivity. Unless otherwise stated, all traces in a particular experiment were made with the same instrument and recorder sensitivities, and most of the experiments are also directly comparable.

In most cases the traces are double, comparing the 'end-on' approach in which the line of electrodes travels parallel to the direction of movement, with the 'broadside' approach, in which the line of electrodes is at right angles to the direction of movement. The respective substitution for these terms of 'crosswise' and 'parallel' as more elegant alternatives was considered but discarded because of ambiguity as to whether they meant parallel or crosswise to the feature, if an extended one, or to the direction of movement.

For convenience of reference, the experiments are described in extended captions placed alongside the relevant figures.

FIG. 5.8.

Feature 1H vertical at depth of 2.5 cm.

W, Sch 1, P, Sq, DD.

W, Sch 1, P: High, single peak with electrodes broadside.

Sq: High peak with C-C broadside.

DD: Trace with the stronger low peaks end-on.

This was regarded as equivalent to the most extreme narrow high-resistivity feature, and the double peaking effect was expected to be at its strongest; overall response was also expected to be strong because the feature would distort the current flow substantially; but the responses were, in fact, small, and the double peaking very slight, Sq and DD actually producing negative responses. An observation that continually recurs in these experiments is that W, Sch and P are closely similar in form, varying mainly in scale of response. DD, with its slight, negative response, is of no use. Bearing in mind that, in practice, the Sq values are the mean of the two curves, this configuration gives the most satisfactory response to the feature.

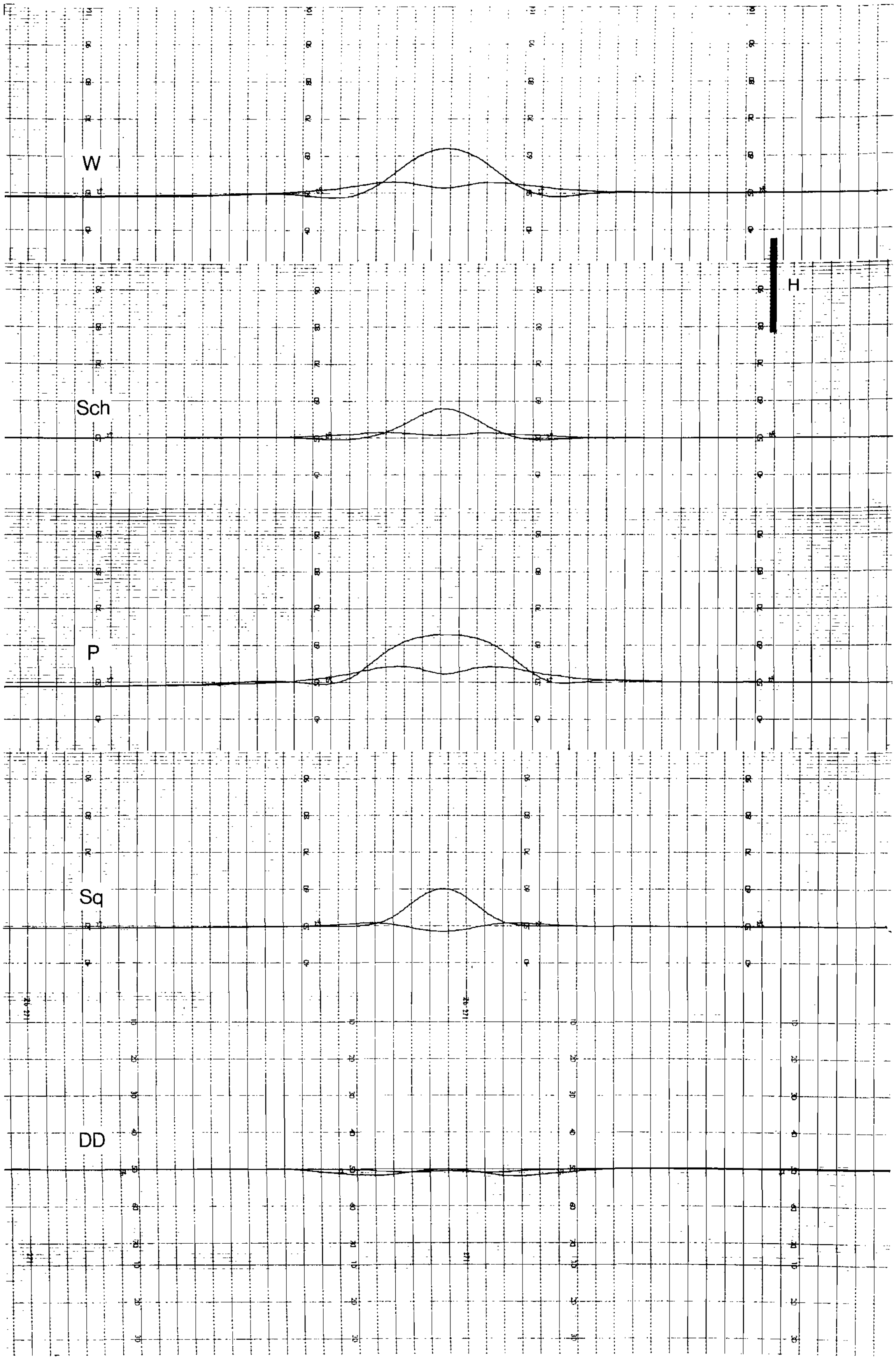


FIG. 5.8

FIG. 5.9.

Feature 1L vertical at depth of 2.5 cm.

W, Sch 1, Sq, DD, Sch-DD.

W, Sch 1: Low, single peak with electrodes broadside.

Sq: Low, single peak with C-C broadside.

DD: Smaller peak, with slower return to baseline beyond positive peaks at sides, broadside.

Sch-DD: As DD, but with stronger emphasis.

A much stronger response than with the similar high-resistivity feature (Fig. 5.8), with clearer double-peaking with W, Sch and Sq. P was not recorded because of the very large signal, similar in form to W, that it produced. This is the first experiment including Sch-DD, and its response looks encouragingly greater than DD.

The relatively strong response of the low resistivity feature in this and subsequent experiments is broadly in keeping with the theory of Lynam (1970) discussed in 2.3.3. Although his maximum factor of double response for the low resistivity version of a feature is clearly exceeded in this and other cases, extreme divergence from the theoretical conditions may be responsible.

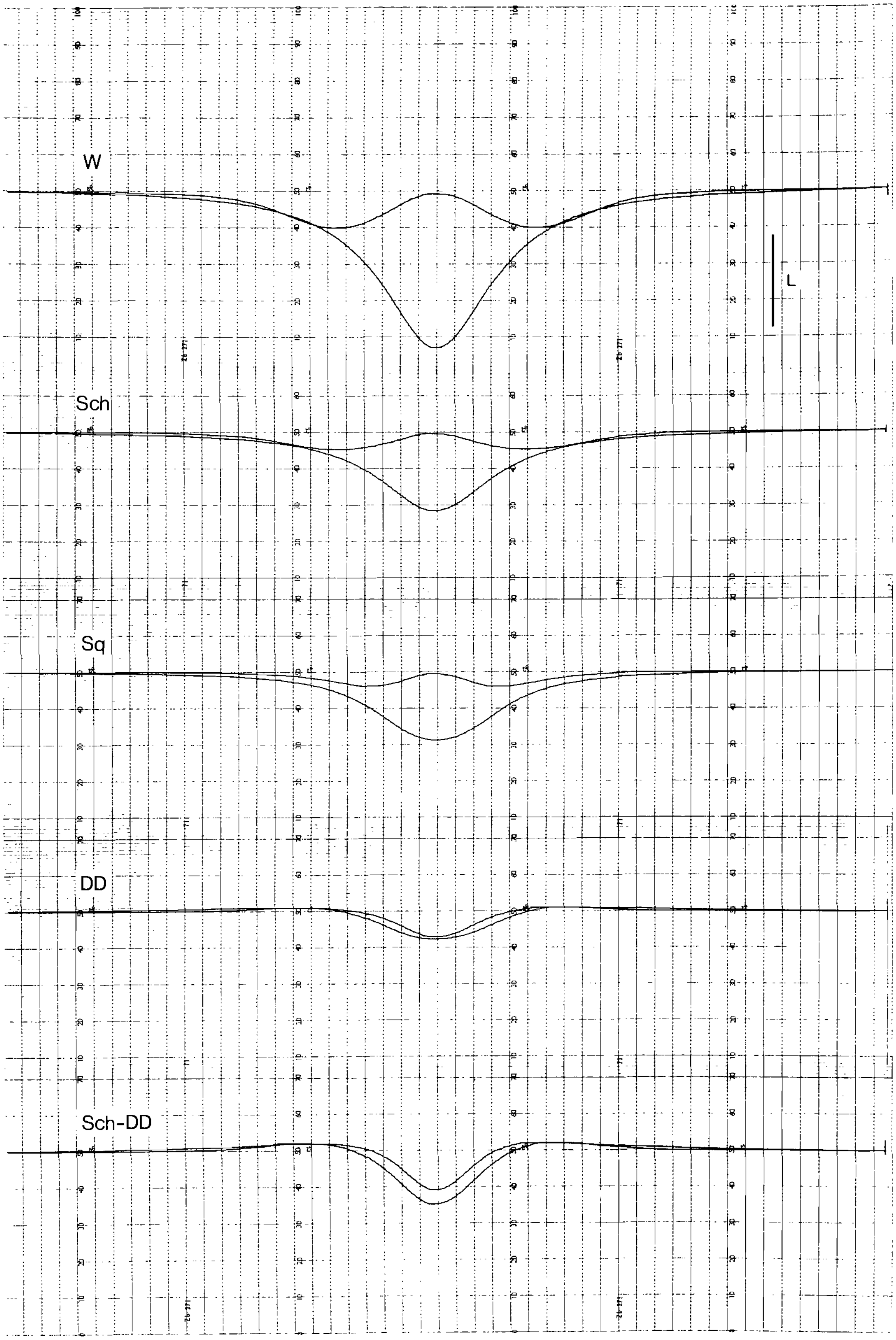


FIG. 5.9

FIG. 5.10.

Feature 2H at depth of 2.5 cm.

W, Sch 1, P, Sq, DD, Sch-DD.

W, Sch, P: Higher peak broadside.

Sq: Single peak with C-C broadside.

DD: Narrower peak, without low side peaks, broadside.

Sch-DD: As DD, but the narrow peak is also lower.

W, Sq, DD: Traced by hand from the originals, which became faded and damaged as a result of being used for display.

Strong responses, indicating that the breadth of the feature is important. Little sign of double peaking except with P and, surprisingly, Sq, but much broadening of response especially with W and P. The double peaking of Sq would again be removed by taking an average of the curves. Sch-DD looks very promising.

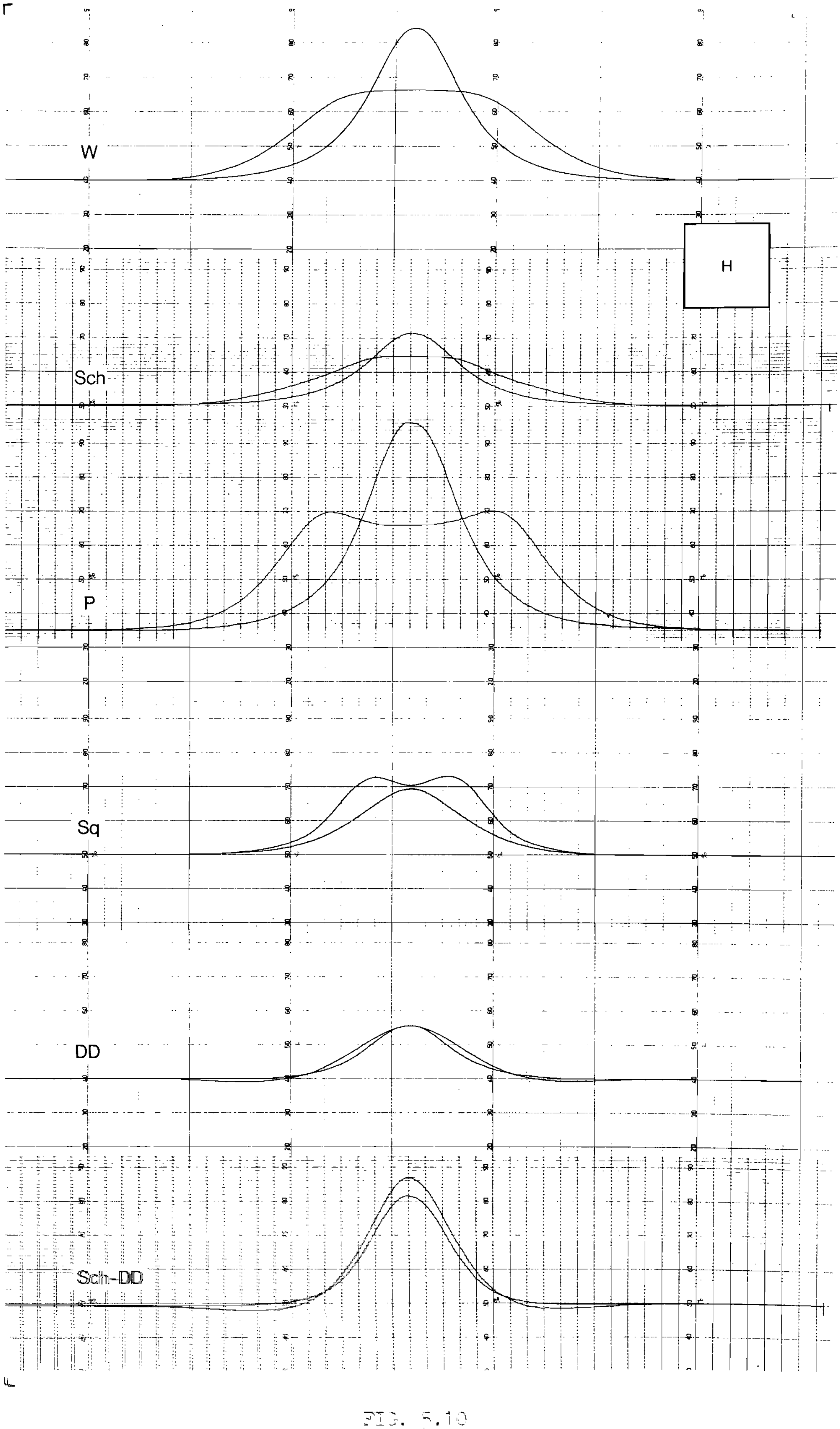


FIG. 5.10

FIG. 5.11.

Feature 2H at depth of 5 cm.

W, Sch 1, P, Sq, DD, Sch-DD.

W, Sch 1, P: Narrower peak broadside.

Sq: Lower, narrower peak with C-C broadside.

Sch-DD: Lower peak, without negative peaks at sides, broadside.

There is no double-peaking at all, except for a hint of it with Sq. W and P give the strongest responses, P most impressively so, although the peak is very broad when end-on. DD is the weakest, and Sch-DD loses its advantage over it at this depth.

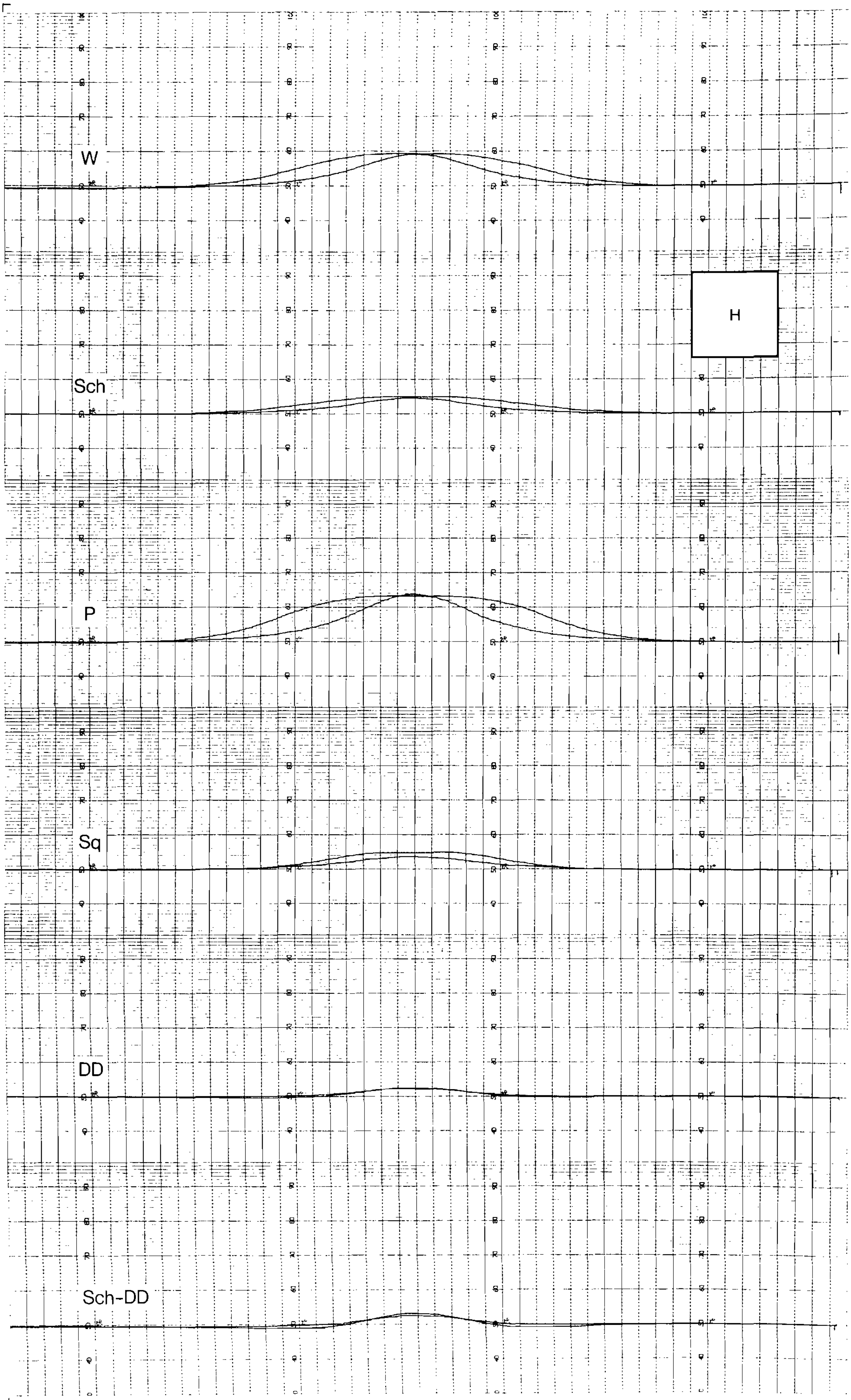


FIG. 5.11

FIG. 5.12.

Feature 1H horizontal at depth of 2.5 cm.

W, Sch 1, P, Sq, DD, CPCP.

W, Sch 1, P, CPCP: Single peak broadside.

Sq: Single peak with C-C broadside.

DD: Lower peak, without low side peaks, broadside.

W, Sq, DD: Traced by hand from the originals, which became faded and damaged as a result of being used for display.

These traces correspond more closely than any in the previous figures to the type of response obtained from many archaeological features, for which, therefore, the flat horizontal sheet seems a good model.

These traces demonstrate especially clearly the similarity of response, varying mainly in amplitude, of W, Sch and P. Notably Sch is seen to give no improvement on W in definition, and also has a smaller response.

The double-peaking of CPCP is particularly bad end-on, and this configuration is likely to be of little value in archaeology.

Although Sq is again strongly double-peaked in one direction, the mean of the two peaks still annuls the effect.

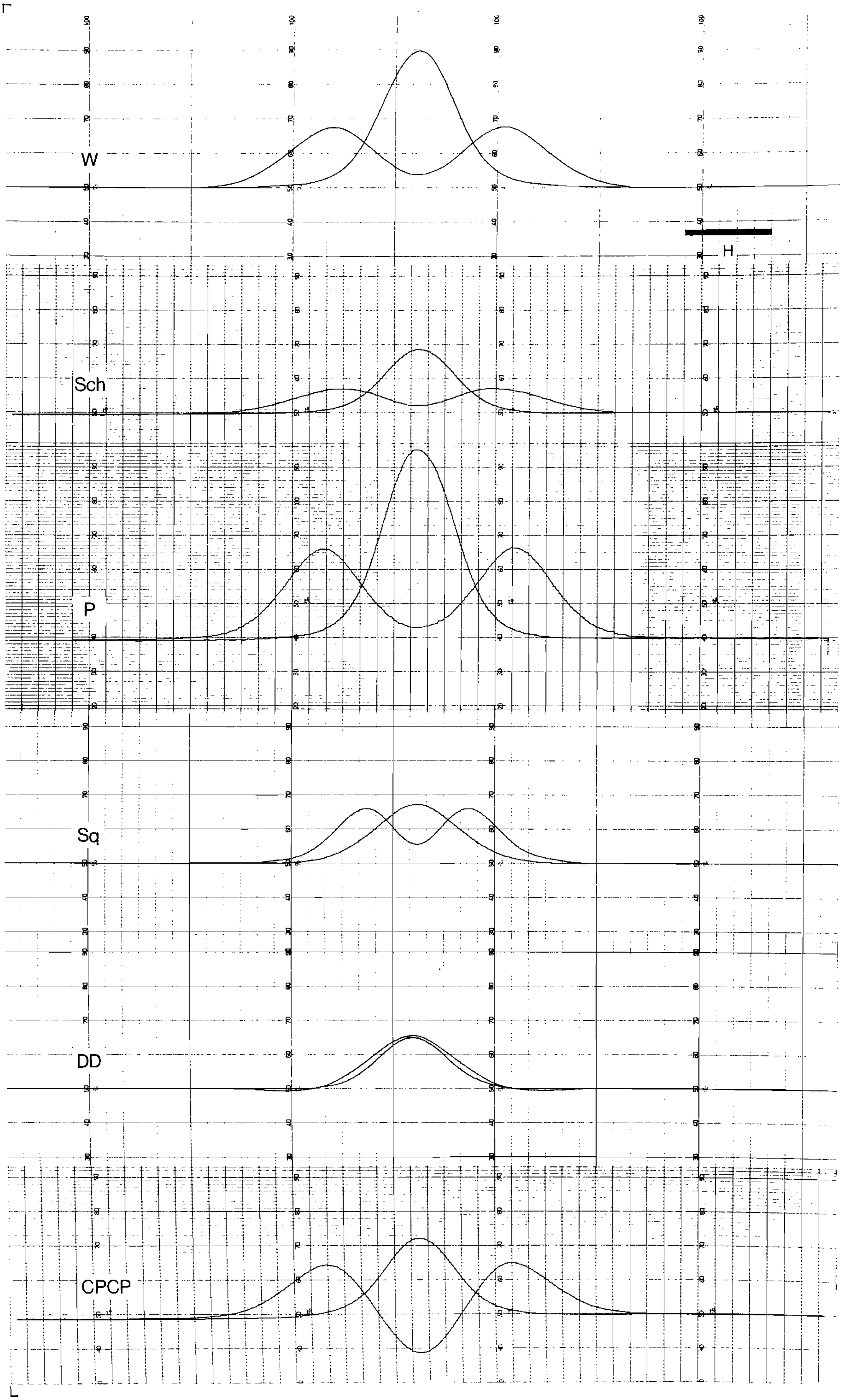


FIG. 5.12

FIG. 5.13.

Feature 2L at depth of 2.5 cm.

W, Sch 1, P, Sq, DD, Sch-DD.

P: Half sensitivity of other traces.

W, Sch 1, P: Larger peak broadside.

Sq: Larger peak with C-C broadside.

DD, Sch-DD: Narrower peak, with smaller high side peaks, broadside.

Responses, except for DD and Sch-DD, substantially greater than with equivalent high-resistivity feature (Fig. 5.10). Triple peaks with W, Sch end-on, and Sq with C-C end-on are in keeping with the theoretical treatment of Lynam. There is not a great deal to choose between the configurations for effectiveness in defining this feature, although Sch-DD is perhaps best.

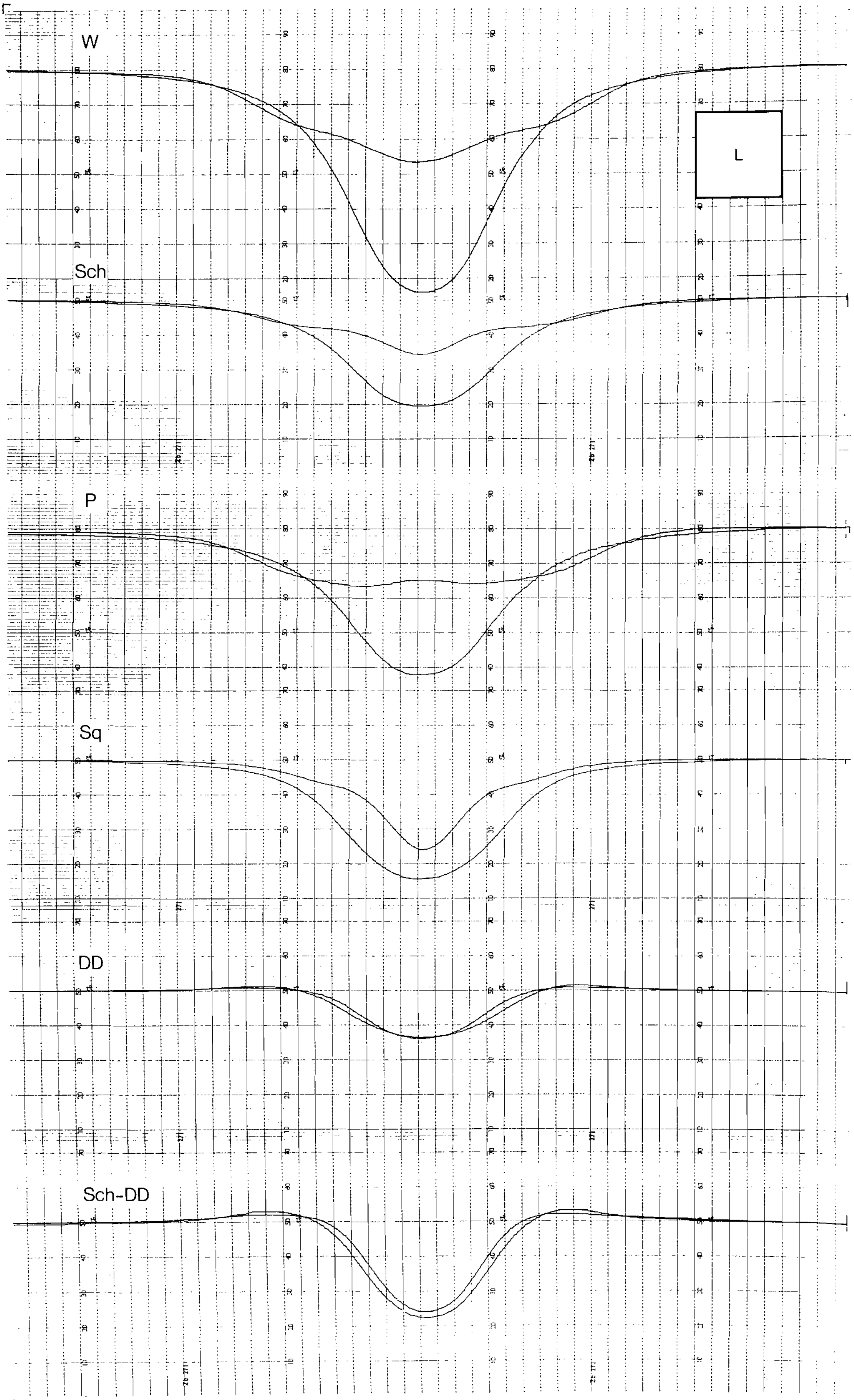


FIG. 5.13

FIG. 5.14.

Feature 2L at depth of 5 cm.

W, Sch 1, P, Sq, DD, Sch-DD.

W, Sch 1, P: Larger peaks broadside.

Sq: Larger peak with C-C broadside.

DD, Sch-DD: Smaller peak broadside.

The end-on triple peaking has disappeared from W, Sch and P (cf. Fig. 5.13). The response of DD is very slight, and with Sch-DD broadside the low peak disappears entirely, to be replaced by two high peaks: thus this configuration has a very disappointing performance.

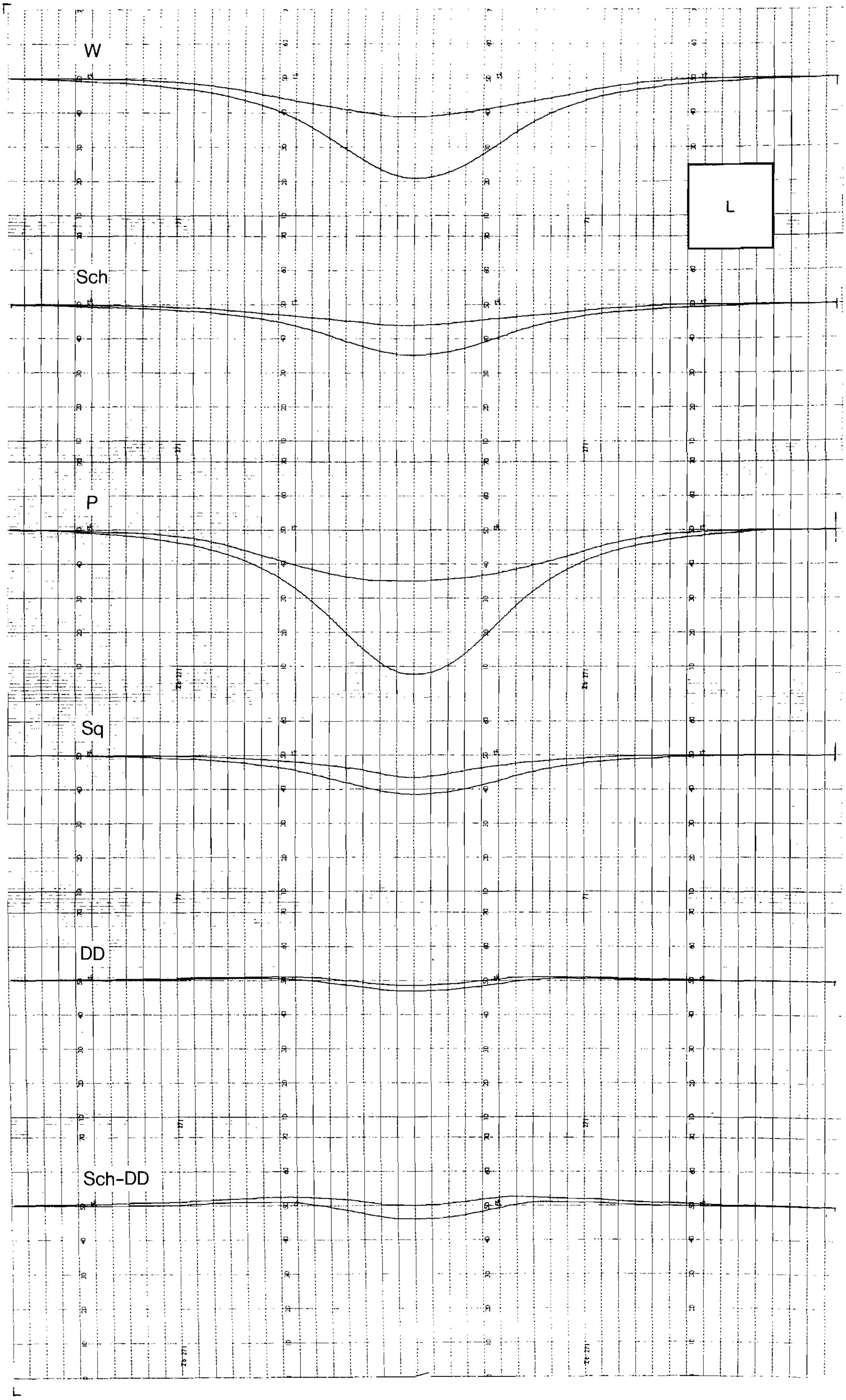


FIG. 5.14

FIG. 5.15.

Feature 1L at depth of 2.5 cm.

W, Sch 1, P, Sq, DD, CPCP.

P: Half sensitivity of other traces.

W, Sch 1, P, CPCP: Larger peak broadside.

Sq: Larger peak with C-C broadside.

DD: Larger peak, with smaller high side peaks, broadside.

The picture with W, Sch, P and Sq is very similar to that produced by 2L at the same depth (Fig. 5.13), and, although less substantial, this feature actually gave stronger anomalies than 2L with W, Sch and P: this may be due to slight difference in feature depth, which is very critical at high sensitivity, between the experiments; but there must, however, be little difference in the responses, which emphasises the dominant effect of the upper surface of the feature. Cf. the equivalent high resistivity cases (Figs 5.10, 5.12) in which, although 1H gives expectedly lower responses than 2H, the difference is very small. In both the high and low resistivity cases, it is noteworthy that the larger feature tends to smooth the multiple peaks of the end-on response.

The triple peaks of CPCP end-on confirm the unsatisfactory performance of this configuration.

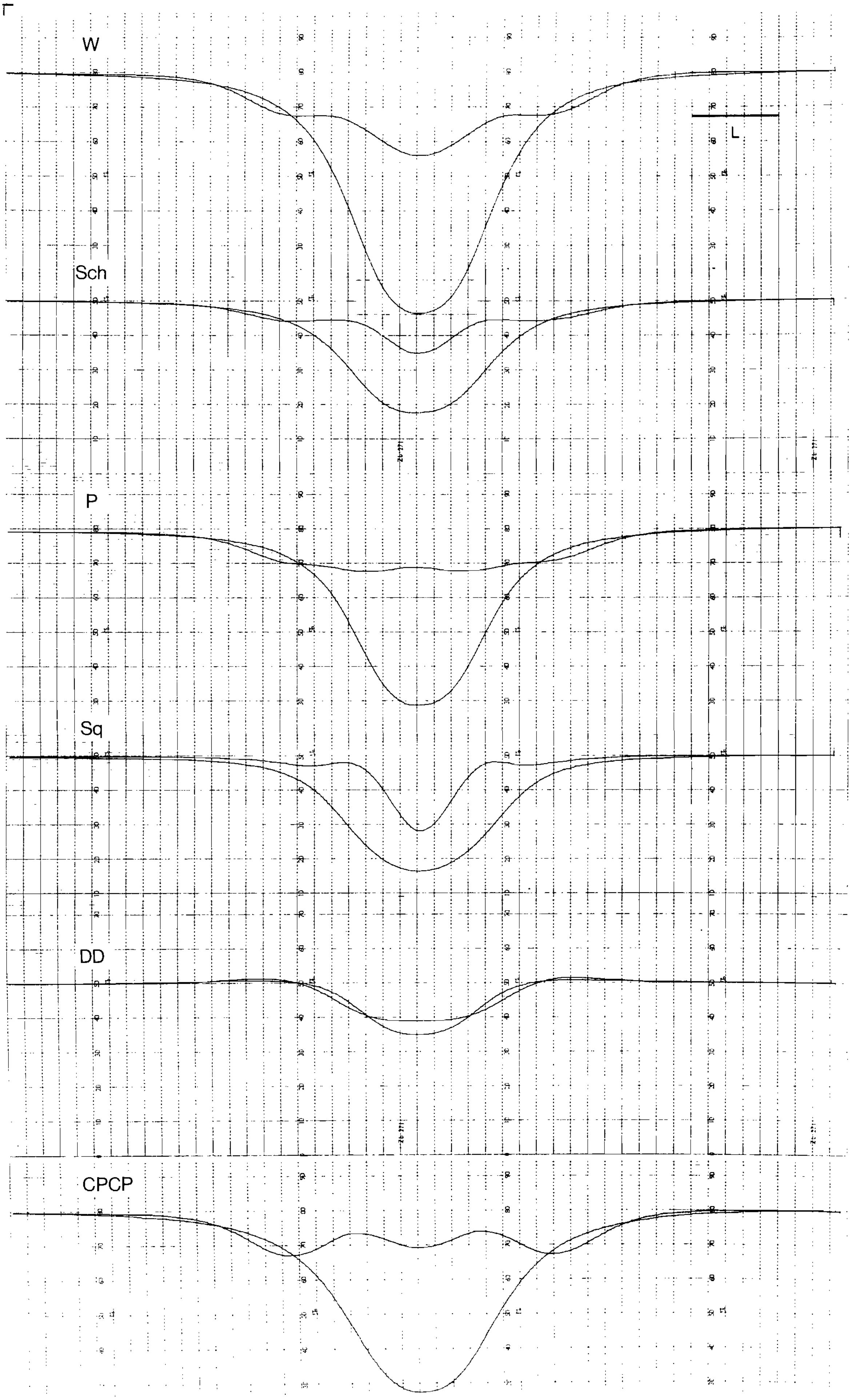


FIG. 5.15

FIG. 5.16.

Feature 4H at depth of 2.5 cm.

W, Sch 1, P, Sq, DD, Sch-DD, CPCP.

W, Sch 1, P: Single peak broadside.

Sq: Single peak with C-C broadside.

DD: Narrower peak broadside.

Sch-DD: Peaks effectively identical, but broadside lacks reversed side peaks.

CPCP: Flatter peak broadside.

This non-linear feature gives a very diminished response compared with the two linear features of the same width and depth (Figs 5.10, 5.12), and it would be hardly detectable with any of the configurations at 5 cm depth. W end-on is more double-peaked than with the comparable linear feature (Fig. 5.10), and Sch does for once define the feature better than W or P. Sch-DD is notable good, but would be expected to fall off rapidly with depth (cf Fig. 5.11). It is also observed that, as symmetry dictates, the pairs of peaks are all coincident at their centres.

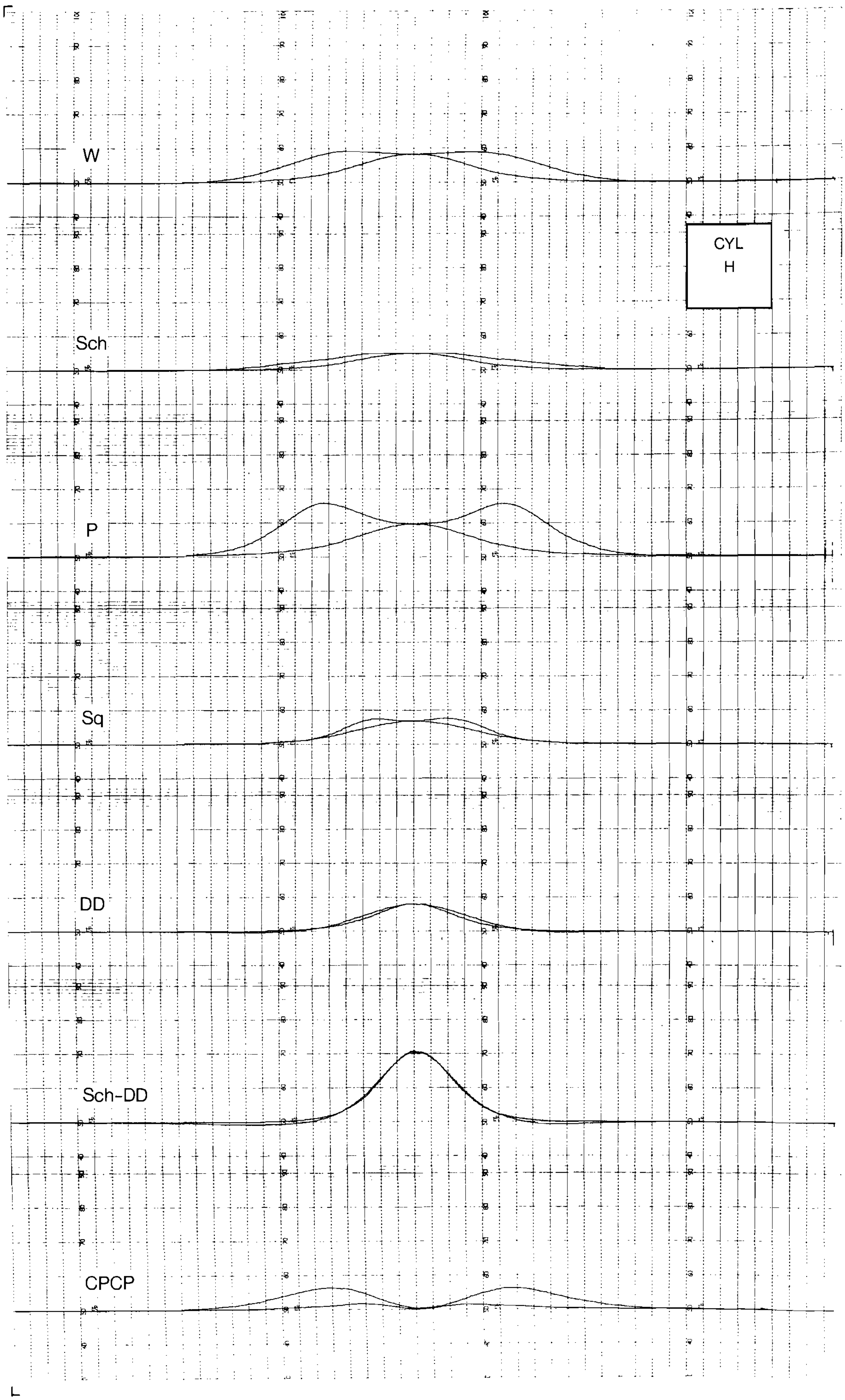


FIG. 5.16

FIG. 5.17.

Features 2H and 2L at depth of 2.5 cm, with high resistivity base.

W, Sq.

2H: W: Higher peak end-on.

Sq: Higher peak with C-C end-on.

2L: W: Larger peak broadside.

Sq: Larger peak with C-C broadside.

This experiment was performed to check whether multiple peaking was reduced when the feature, rather than being isolated in a conductive medium, was resting on a high resistivity base. A 0.25 inch thick Perspex sheet was positioned as closely as pracicable beneath the path of the feature, i.e. 1-2 mm beneath it.

In the high resistivity case, the experiment could not be performed with the flat feature giving the clearest double peaking with W (1H in Fig. 5.12), but the tendency to double-peak is clearly removed, and the end-on curve rises to a strong peak above the broadside-on peak. The originally double Sq peak (C-C broadside) also flattens.

The pattern given by the low-resistivity feature is little changed from the original without the base (Fig. 5.13) except for an increase in signal strength perhaps due to the greater resistivity contrast between the feature and the mean background value.

These results taken together confirm the theoretical prediction that the response pattern is made up of the integrated effects of the resistivities of the features (in the high resistivity case reinforced by the base) and their distances from each CP pair. This accords with the weakness of response to the vertical flat plates in contrast with the strong response when the plates are horizontal.

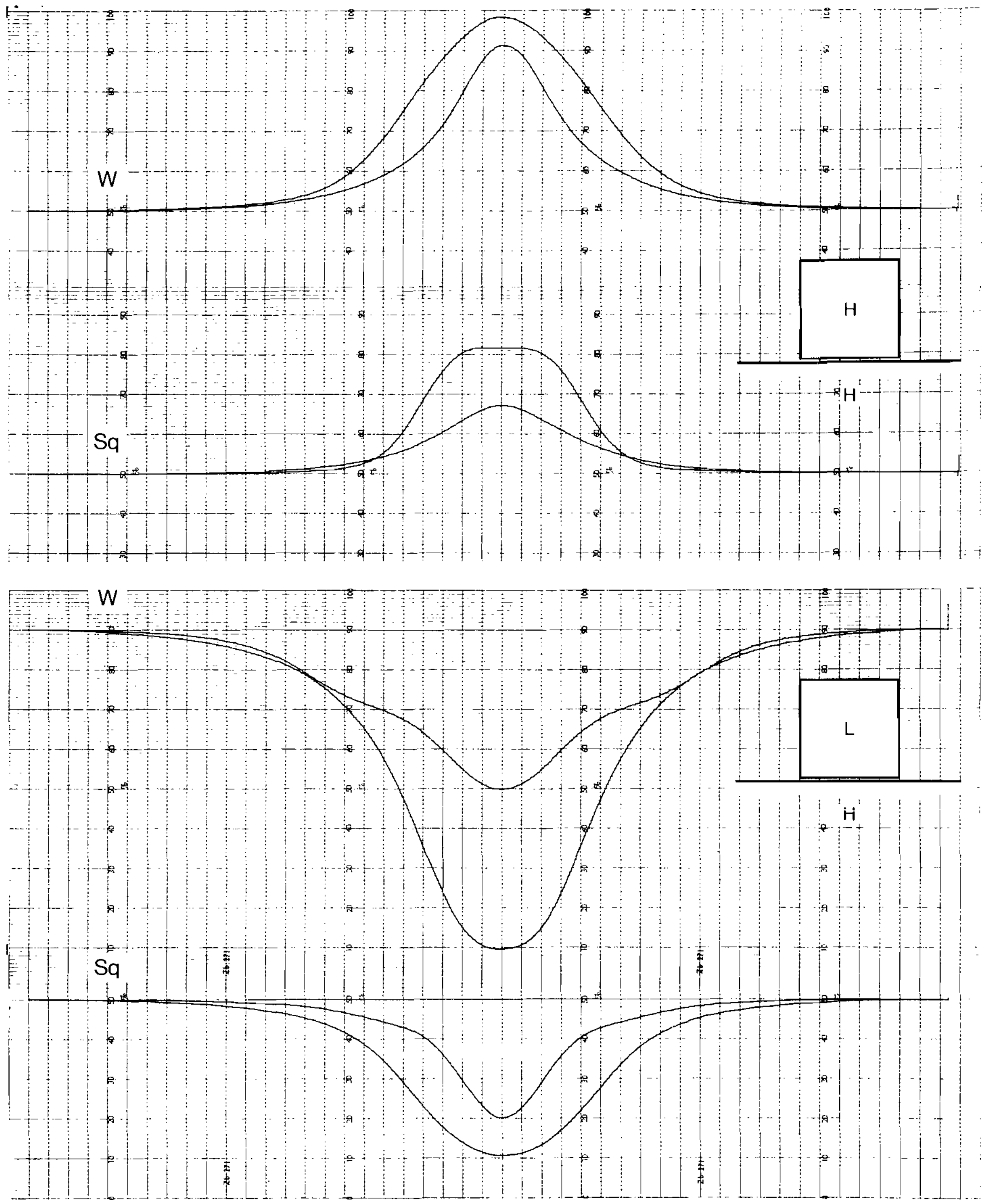


FIG. 5.17

FIG. 5.18.

Feature 3H at a depth of 2.5 cm.

W, Sch 1, P, Sq, DD.

W, Sch 1, P, DD: Narrow peak broadside.

Sq: Higher peak with C–C end-on.

With this small feature, there are some fundamental differences in response form from those obtained with, for instance, 2H (Fig. 5.10): there is a tendency for the end-on response of W and Sch to give treble peaks, and P even quadruple; and the slightly double peak of Sq has become the weaker and occurs when C–C are broadside rather than end-on. The similarity to 2L reversed is much closer. These findings were pursued in an additional experiment (Fig. 5.26), and their significance in relation to theory and practice will be discussed later in this chapter.

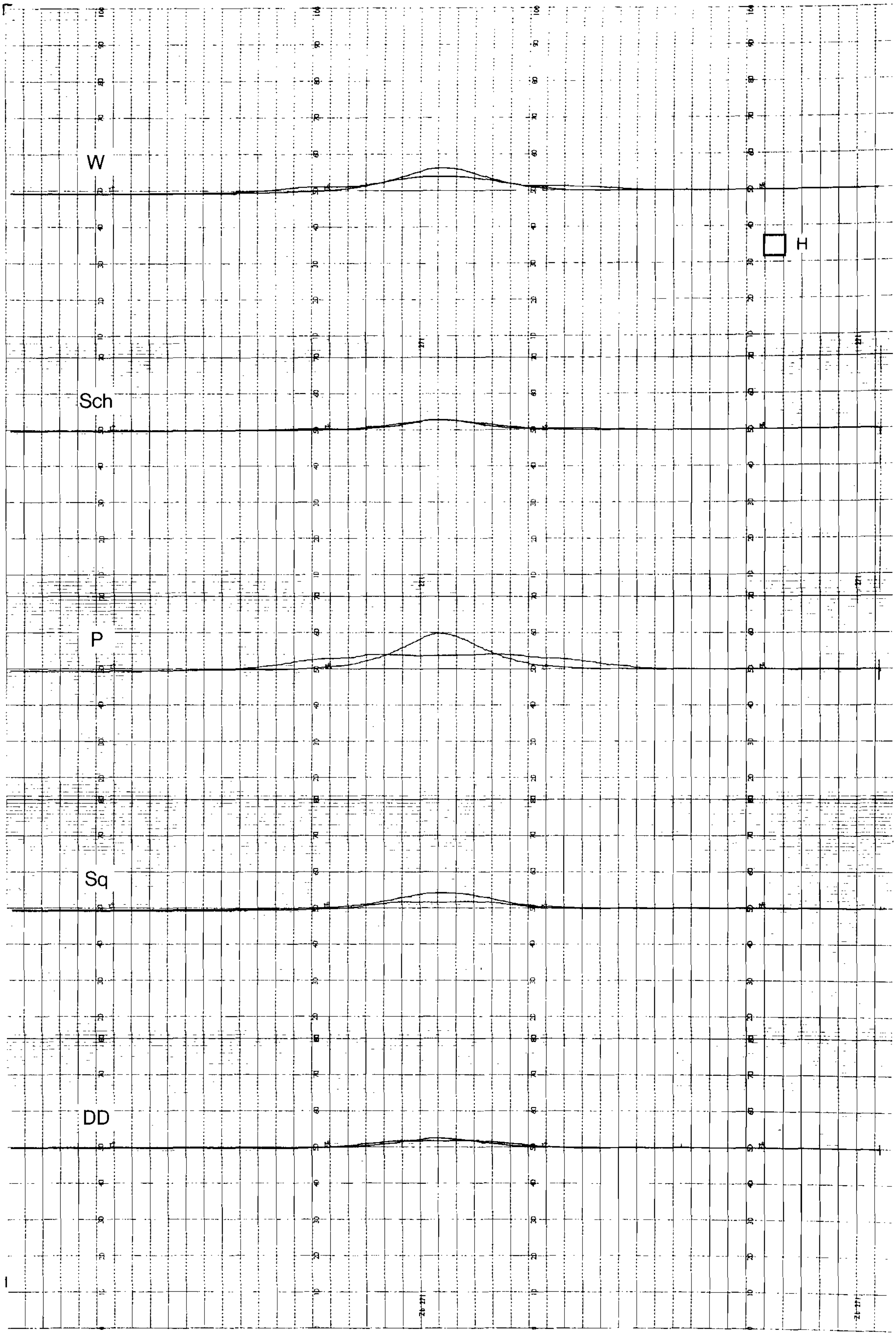


FIG. 5.18

FIG. 5.19.

Feature 3L at a depth of 2.5 cm.

W, Sch 1, Sq, DD, Sch-DD.

W, Sch 1: Larger, single peak broadside.

Sq: Larger peak with C-C broadside.

DD, Sch-DD: Larger-amplitude peak broadside.

This feature gave a very much stronger response than the high-resistivity version (Fig. 5.18), especially in the broadside direction. End-on with W, Sch and Sq, it gave much weaker responses, W and Sch being double rather than treble peaks. The superiority of DD and Sch-DD, and of Sq if averaged, is clear.

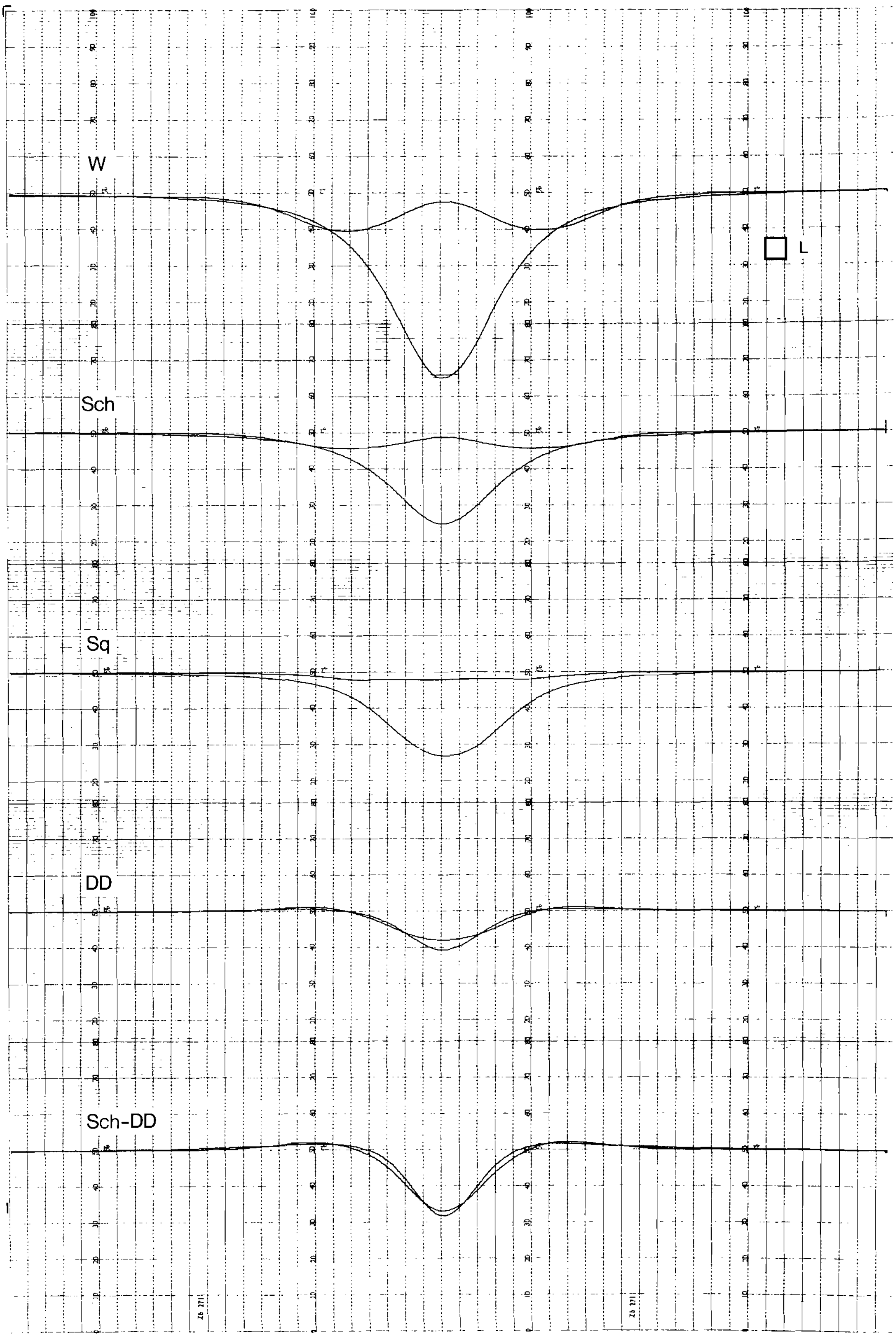


FIG. 5.19

FIG. 5.20.

Feature 3L at depth of 5 cm.

W, Sch 1, P, Sq, DD, Sch-DD.

W, Sch 1, P: Larger peaks broadside.

Sq: Larger peak with C-C broadside.

DD, Sch-DD: Upper peaks broadside.

W, Sch, P and Sq gave patterns similar to those produced by the same feature at 2.5 cm depth, but much subdued. DD is very weak and, in the broadside direction, Sch-DD gives a wholly reversed, apparently high resistivity, anomaly, so that neither of these configurations is of use in detecting this feature at such a depth.

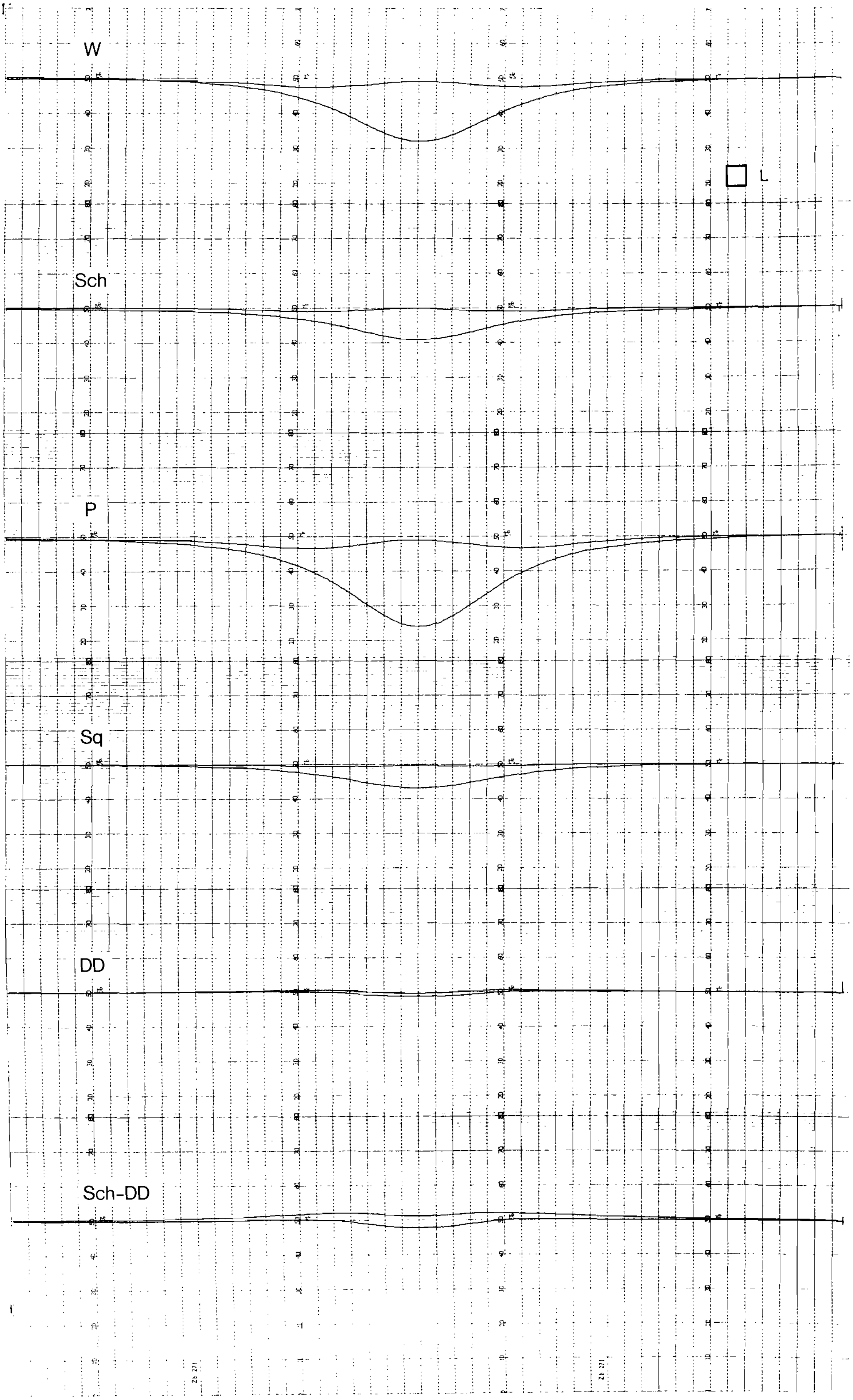


FIG. 5.20

FIG. 5.21.

Feature 3H at depth of c. 1.5 mm - just missing electrodes.

W, Sch 1, P, Sq, DD, Sch-DD.

W, Sch 1, P, DD: Simpler trace with central dip, broadside.

Sq: High central peak with C-C broadside.

Sch-DD: Trace with high central peak, broadside.

This set of traces was produced as an extreme case in an attempt to simulate the 'noise' superimposed on resistivity measurements by such surface or near-surface irregularities as deep plough furrows or large rocks. It is difficult to simulate the true conditions: probes are rarely inserted above a furrow, although this has been known to occur just after ploughing, when long cavities can exist beneath the newly-turned soil (Haddon-Reece, pers. com.); and rocks are rarely linear.

In spite of their apparent wildness, the end-on patterns in fact accord quite well with theoretical response profiles for a buried sphere as calculated by Lynam (1970); the two sides of the P pattern are interesting in being similar to separate Tw responses. The broadside patterns are basically simple, but complicated by the central dips which must be due to masking of the electrodes upsetting normal patterns of current and potential distribution as the feature passes close beneath them.

The symmetry of the traces produced by Sq means that the averaging process would smooth out the effect of this type of phenomenon very successfully.

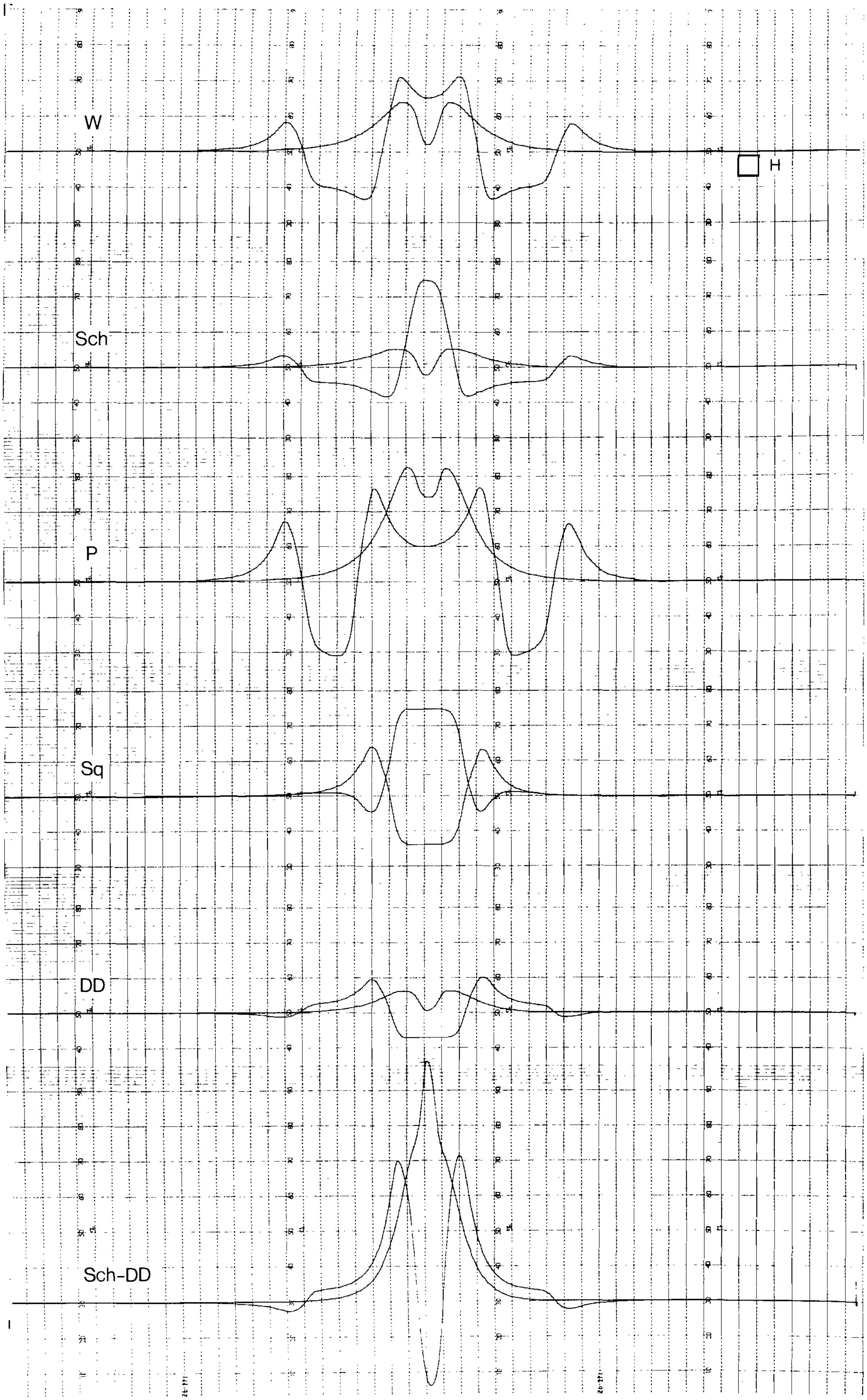


FIG. 5.21

FIG. 5.22.

Feature 1H horizontal at depth of 1 cm.

Tw, W, DD.

All measurements end-on except where stated below.

The experiment was designed to test the relationship of Tw to other configurations. Each configuration was allowed to take up its natural level and, with the electrolyte at its normal concentration (Sq = 25 ohms), the recorder was set at a chart span of 0-200 ohms to accommodate the high background level of Tw. In order to obtain adequate response at this reduced sensitivity, the relatively shallow feature depth of 1 cm was chosen.

The W trace is close to its normal level at 48 ohms, and shows normal twin peaks for this type of feature. In the trace above, one CP pair is moved away to give, in effect, a very extended Palmer. The separation is then made as great as the tank allows (37.5 cm), to give Tw trace (a), with a base level of 139 ohms.

Traces (b) and (c) are repeats of Tw to test its properties, separated artificially by means of the recorder zero adjustment. In (b), the 'moving' (left-hand) current and potential probes are interchanged, and in (c) they are turned through 90° to the broadside direction. These show that the position of the Tw peak is independent of electrode orientation and that the end-on response is the same whichever way round the electrodes are placed, but that the response increases in amplitude when the electrodes are broadside, at least with a feature of this form whose depth is 0.2 times the electrode separation.

DD is also compared, at the original recorder settings, on the separate piece of chart at the bottom. The higher peak is with the electrodes broadside.

The experiment demonstrates that, with the feature used, at this ratio of depth to electrode spacing, all the configurations produce end-on response peaks identical in amplitude and position, centred over the feature. Broadside defines the position equally well, and gives a greater and variable amplitude, the response increase over the end-on approach for the three configurations being as follows:

W (curve not drawn)	3.94
Tw	2.18
DD	1.70

Twin, in this simple case at least, can be seen as the result of expanding Wenner until it becomes two effectively independent electrode pairs; although it is more correct to see the other configurations as various ways of compounding the basic Twin.

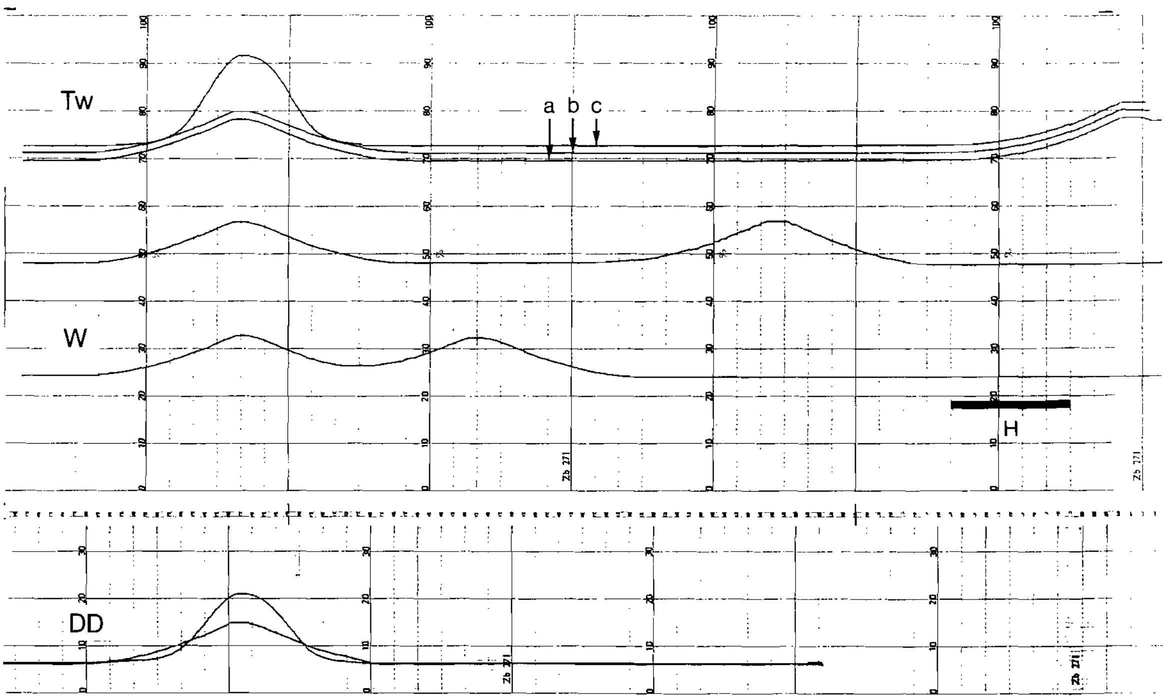


FIG. 5.22

FIG. 5.23.

1. Feature 1H horizontal at depth of 2.5 cm.

2. Feature 1H horizontal at depth of 5 cm.

W, Sch 2, DD, Tw.

1. W, Sch 2, Tw: Higher peak broadside.

DD: Narrower peak, without low side peaks, broadside.

2. W, Sch 2: Higher, central peak broadside.

DD: Lower peak broadside.

Tw: Higher peak broadside.

These two sets of measurements were made (a) to check the effectiveness of Tw in relation to DD at the two depths used as standard in this work; (b) to look at the rather narrower Schlumberger, Sch 2; (c) to measure the response to 1H at 5 cm depth, which had not previously been tested.

1. This duplicates W and DD measurements previously made (Fig. 5.12) as a check on calibration. The present response is stronger by a factor of 1.09, which is within the expected accuracy of the system. Sch 2 is slightly more compact and rather stronger in response end-on than Sch 1. The mean response of Tw is 1.5 times better than DD, and second only to W broadside.

2. The closest comparison for this is Fig. 5.11. W is strong but very double-peaked end-on. Sch 2 is very poor. With DD, the broadside peak has sunk below the end-on. Tw broadside is still the larger peak. The mean response of Tw is 2.3 times better than DD, and again approaches close to W broadside.

A slight drop to the left of Tw, away from the 'fixed' electrodes, is a normal occurrence in the tank, presumably as a result of some distortion caused by the constricted conditions.

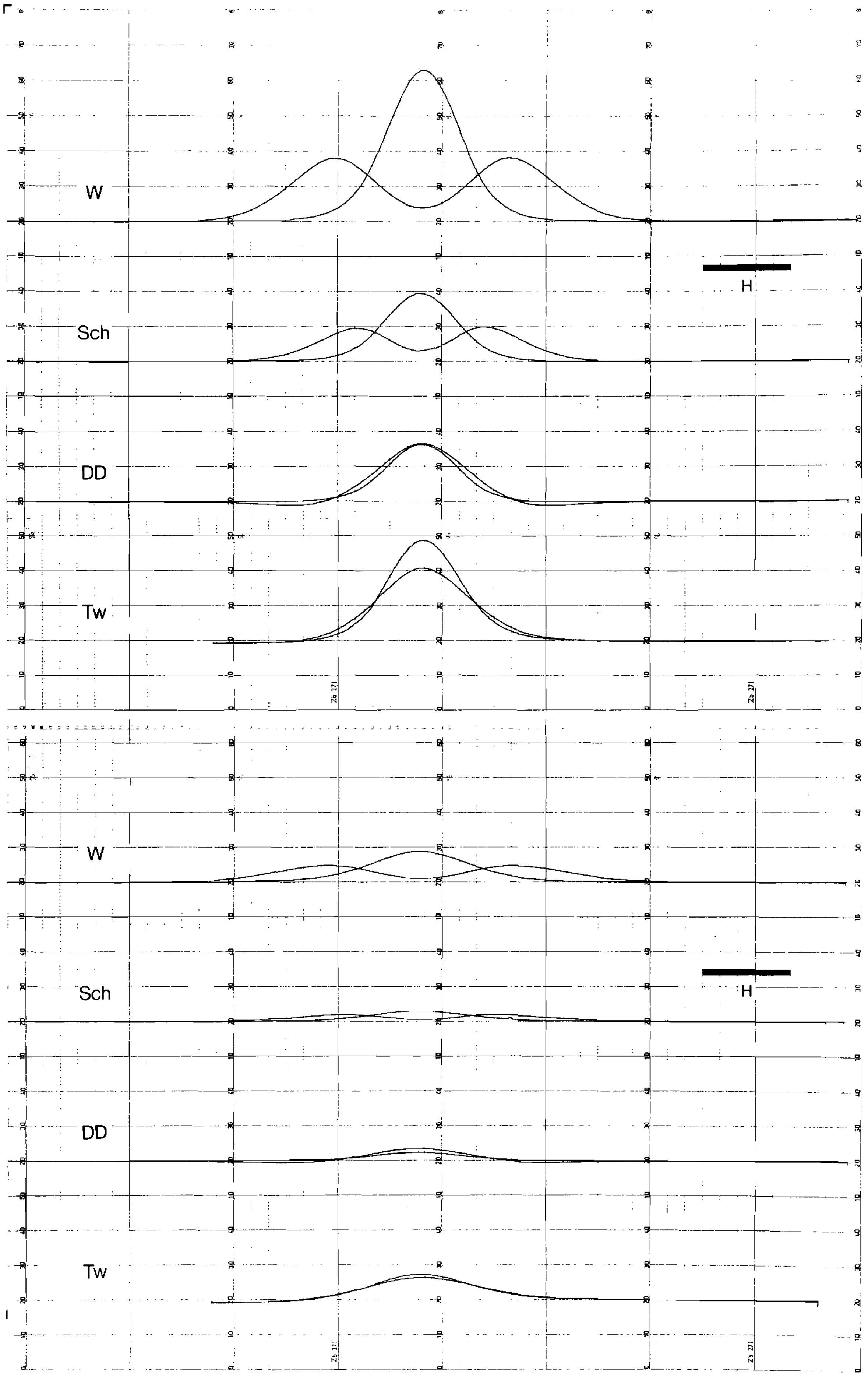


FIG. 5.23

FIG. 5.24.

Tr.

1. Feature 1H horizontal at depth of 2.5 cm.

2. Feature 1H horizontal at depth of 5 cm.

3. Feature 2H at depth of 2.5 cm.

4. Feature 2H at depth of 5 cm.

Broadside peaks all centrally positioned over the features and symmetrical.

1. Higher peak broadside. The symmetry of the two peaks is a little distorted by a slight negative peak on the end-on trace towards the remote current electrode. Sensitivity closely similar to Tw in Fig. 5.23.

2. Higher peak end-on. There is the same slight distortion of symmetry as in (1). Mean response 0.7 of Tw in Fig. 5.23.

3. The end-on peak is the bigger and is substantially displaced towards the remote electrode. The separate upper peak (artificially lifted with the recorder zero control) is the end-on trace with the CPP group turned round. It is similar in shape but lower than the 'normal' end-on trace, but is not greatly displaced. The difference between these could be an artefact of the restricted conditions in the tank. The overall response is comparable to Sq and DD (Fig. 5.10); Tw would probably be stronger (cf. Fig. 5.23).

4. High peak end-on. A comparable response to W, and much better than Sq or DD (Fig. 5.11). Tw is likely to be similar (cf. Fig. 5.23).

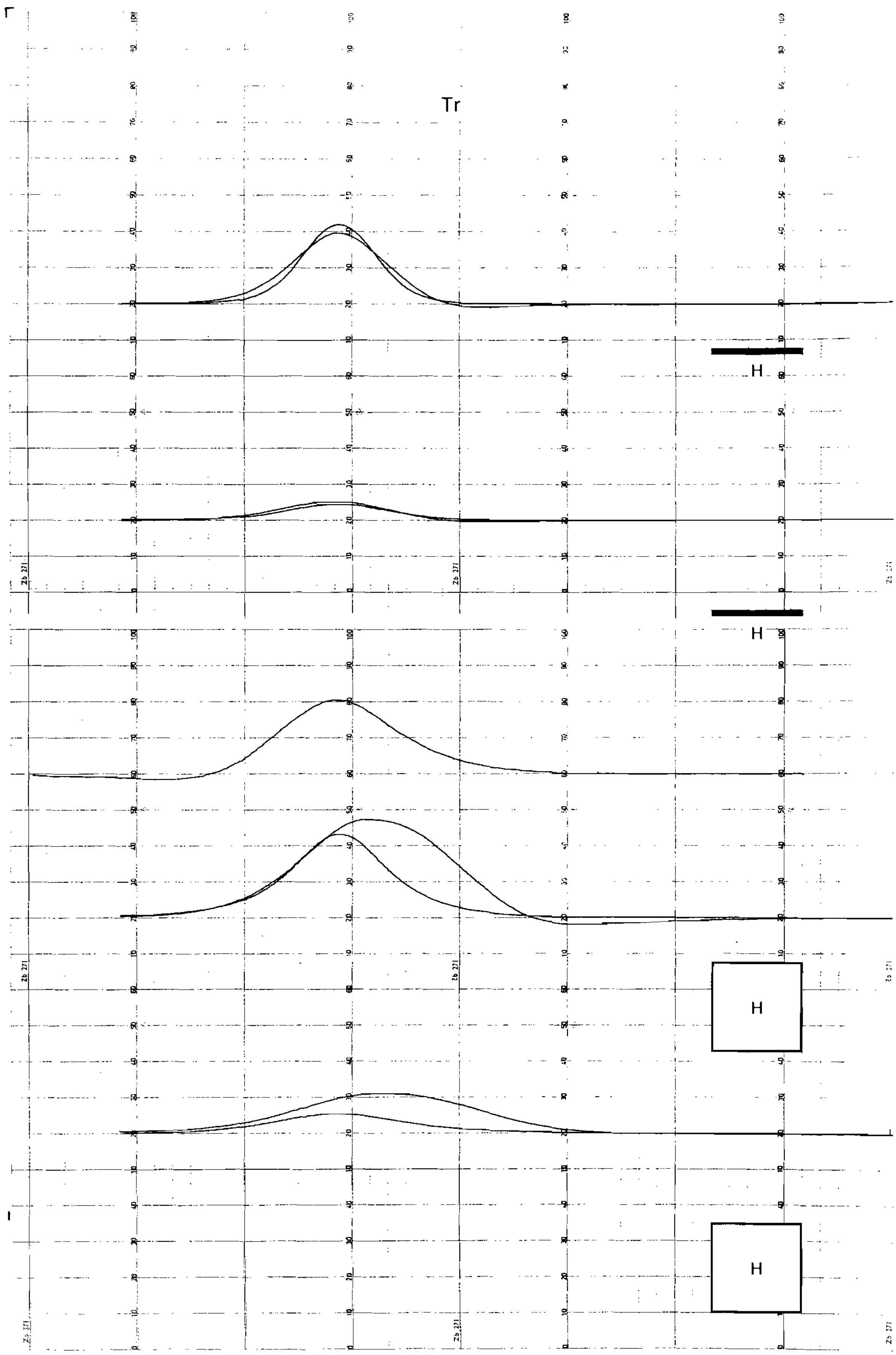


FIG. 5.24

FIG. 5.25.

1. Feature 2H at depth of 1 cm.

2. 3.75 cm dia. insulating sphere at depth of 0.4 radius = 0.75 cm.

3. 3.75 cm dia. insulating sphere at depth of 1 radius = 1.88 cm.

1. W, DD end-on.

2, 3. W end-on. Electrode spacing 3.75 cm.

This experiment was designed to compare the approximation to theory (specifically that of Lynam, 1970) of the ideal sphere and the square-section linear feature 2H. The cases were made closely comparable by having the electrode separation equal to the width of the feature. The difference between the linearity of 2H and the singularity of the sphere should be unimportant, because Lynam has shown that the effects of a sphere and a long cylinder of the same diameter are closely similar (cf. Figs 5.10 and 5.16).

The two sphere traces are in close accord with the theory. In the upper 2H trace and the upper sphere trace, the ratio of feature depth to width is the same (0.2) and, if the features were comparable in effect, the traces would be of the same shape, which they are not. Using the same theory, Haddon-Reece has calculated (Haddon-Reece, forthcoming) that DD over a sphere would give a double peak, rather than the clear single peak obtained with 2H.

Thus with this relationship between electrode spacing and feature width, the square-section feature is shown to give a much smoother response at shallow depths than the sphere, but the comparability increases rapidly with depth, as is shown by the similarity in shape between W over 2H and W over the deeper sphere. The ratio of depth to width for the deeper sphere (0.5) is the same as for 2H in Fig. 5.10, and for 4H in Fig. 5.16, with which the comparability is reasonable. The closest similarity to the sphere in curve form is provided by 2L in Fig. 5.13.

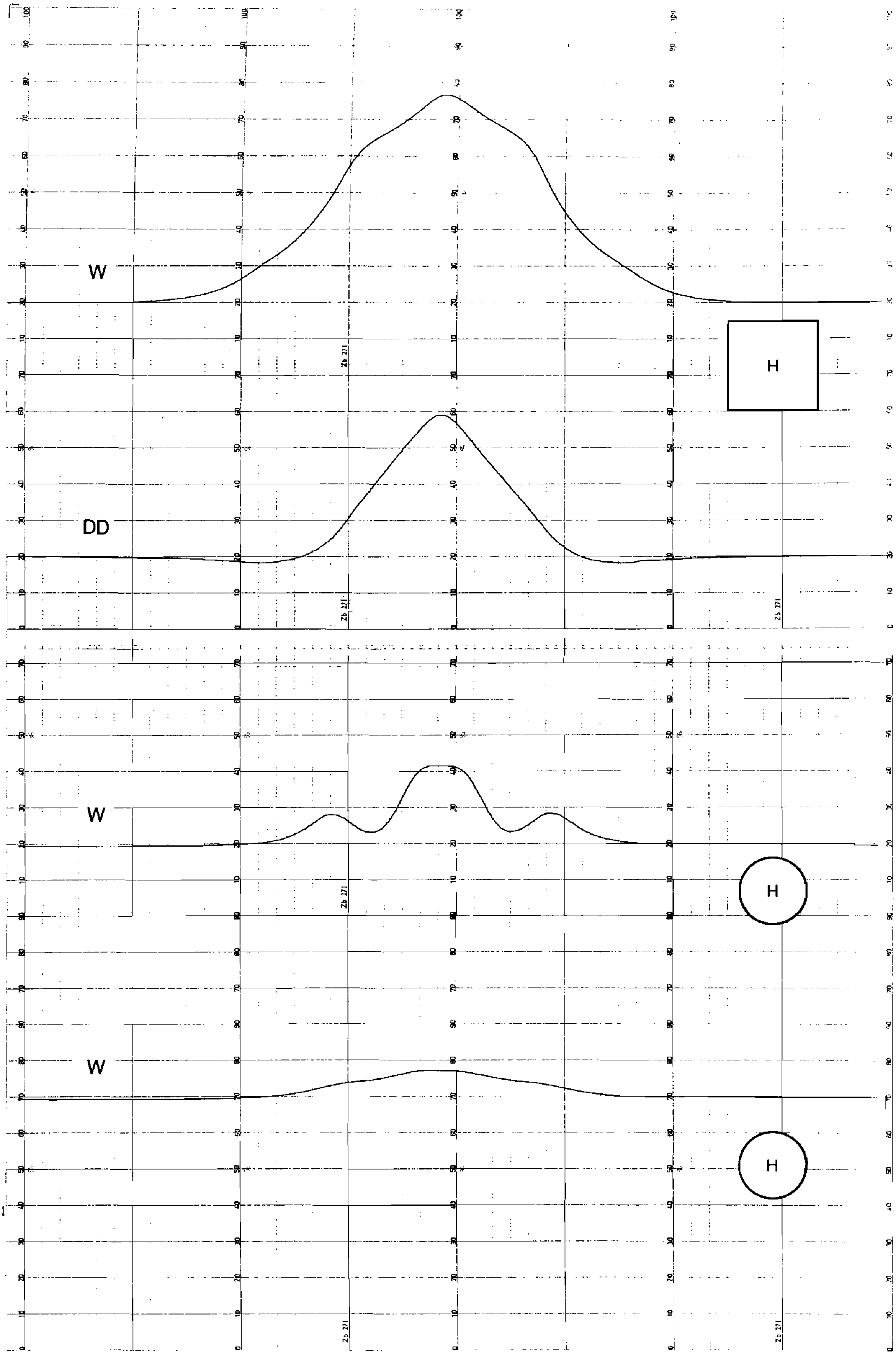


FIG. 5.25

Habberjam (1969) obtained strikingly similar results for W over a sphere.

FIG. 5.26.

Feature 3H at depth of 1 cm.

DD, W, Sq end-on.

These 'stop-press' traces were produced because previous experiments (Figs 5.18, 5.21) had suggested that this small feature was behaving much more like the theoretical sphere than were the larger ones, with the 5 cm electrode spacing. When the feature was raised to a shallow depth comparable to those assumed by Lynam for most of his theoretical calculations, this similarity was confirmed for DD and W and the traces shown, very different from those over the larger features, were produced. In these conditions, Tw would also be expected to produce a double peak similar to DD, but could not be tested because of an instrument defect. Sq, with averaging, would appear to give the most unambiguous response.

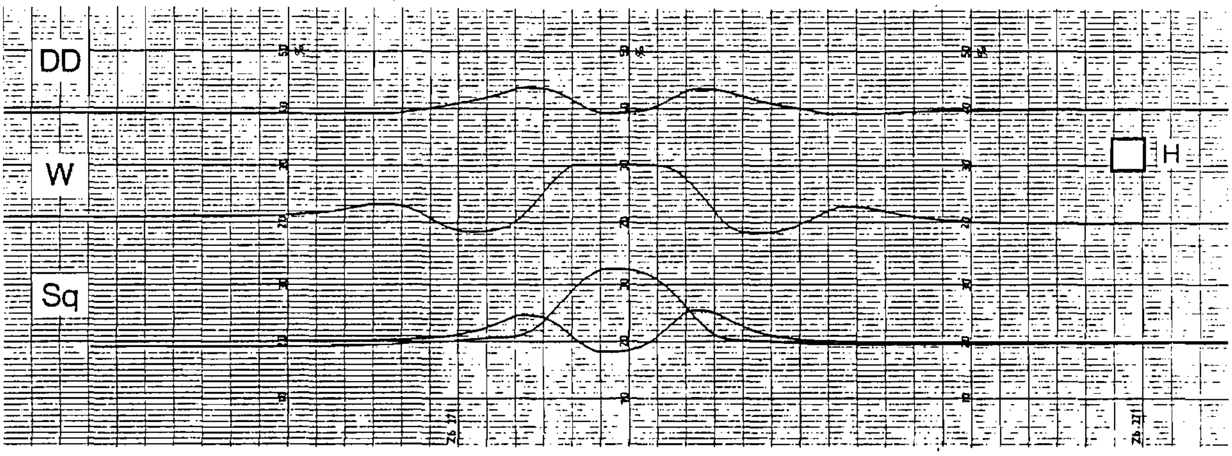


FIG. 5.26

5.2.3. OPTIMISATION OF ELECTRODE SPACING. A limited series of experiments was carried out to ascertain the probe spacings giving optimum response with two of the more promising configurations, Sq and DD. In the idealised conditions of an electrolytic tank, there are four variables: electrode spacing, and the shape, size and depth of the feature. The experiments were confined to the square-section features 2L and 3H. Families of curves were produced for feature depths of 1.25, 2.5, 3.75 and 5.0 cm for DD and 5.0, 2.5 and 1.75 cm for Sq. These curves are not illustrated.

For Sq, pairs of curves for the two orthogonal orientations were produced in the normal way, and the mean central value was used; for DD, either the central peak value or, where the response was in the form of a twin peak, the median height of the peaks and the central trough. From these were obtained the graphs shown in Fig. 5.27, in which the optimum electrode spacing is plotted against the feature depth, both in terms of the length of the feature side. The graph for Sq, being based on only three electrode spacings for each depth, is very approximate, but contains enough information to show that, like the DD curve, it is a straight line. It is interesting that the DD curve, with this type of feature at least, can become a double peak if the electrode spacing exceeds certain limits on either side of the optimum, and these limits are indicated very approximately by broken lines.

Comprehensive data of this type would be of great value in planning surveys of high quality, and need to be collected for other configurations, notably Tw.

5.2.4. ANISOTROPY WITH THE SQUARE ARRAY. The possibility of using Sq to detect features in terms of resistivity anisotropy was briefly investigated. For this, the electrodes are connected in the manner of a Wheatstone bridge, current being passed between diagonally opposite pairs, and potential measured between the other diagonal pair. Over uniform ground, current distribution is symmetrical, and zero potential difference is

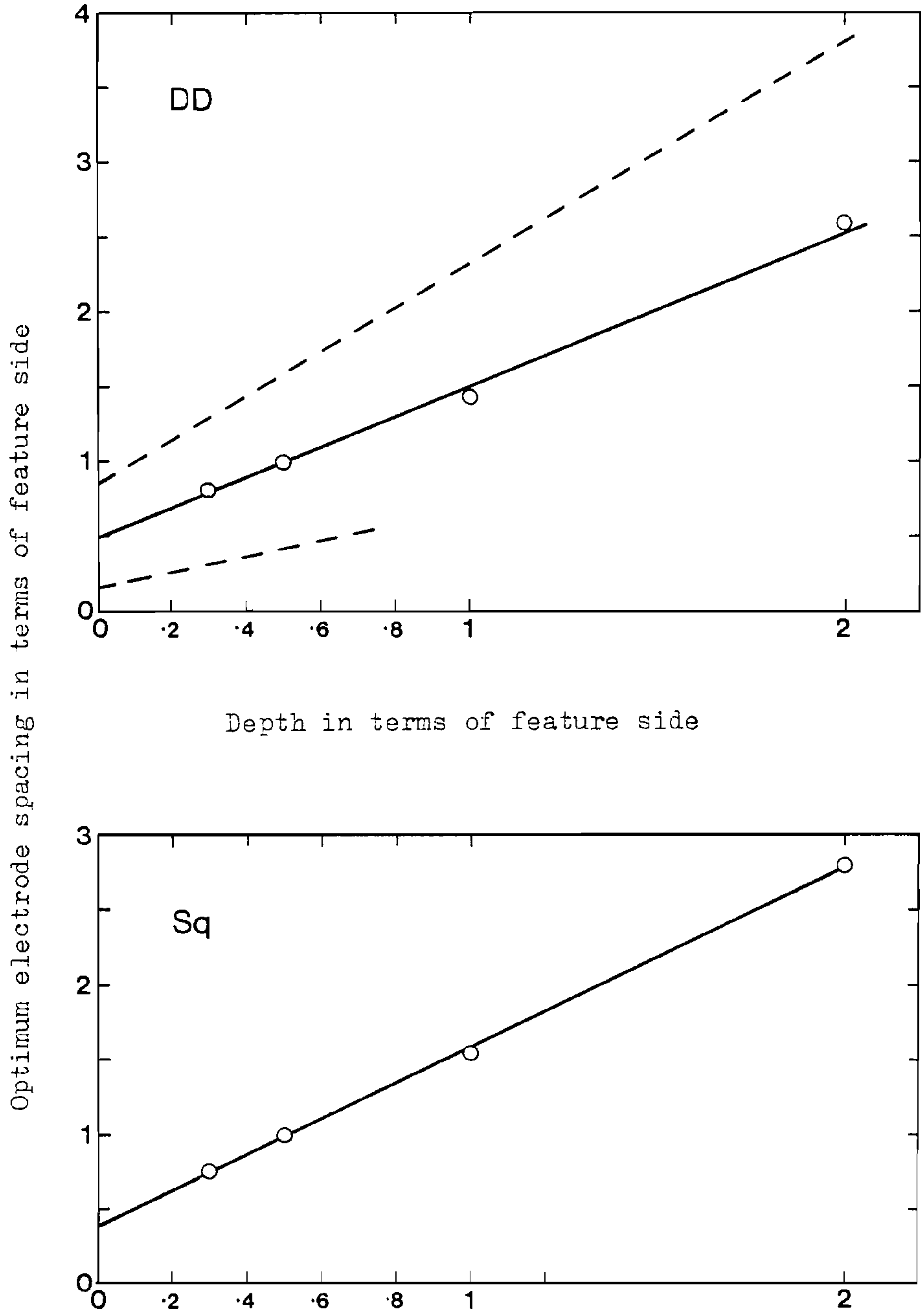


FIG. 5.27. Optimisation of electrode spacing for a square-section linear feature

recorded, but resistivity gradients will upset this balance. In the tank, feature 1H gave strong double peaks with a central reverse peak, which was annulled by averaging orthogonally in the usual way. In the field, similar experiments produced complex and uncertain results compared with those obtained when the configuration was used normally. It was therefore decided that there was little to be gained by pursuing this approach. Hesse (1966a) also considers the use of anisotropy, and, with an extended rectilinear configuration, obtained results comparing approximately with W, but in no way superior.

5.3. CONCLUSIONS

Practical experience has shown that, on many archaeological sites, discrete or linear features give twin peaks with the Wenner and related arrays (e.g. Figs 5.28, 6.17; Linington, 1967). In the electrolytic tank, the closest simulation of this was achieved with a horizontal, thin, high-resistivity feature, and it is clear that many archaeological features of a variety of shapes and cross-sections behave as though they were of this form. The reasons for this will be investigated in the next chapter.

The laminar resistivity model produces anomalies of great simplicity, even at the shallowest depths, and the anomaly form for feature 1H - a symmetrical peak centred between each CP pair - did not change basically from the greatest depth to the shallowest at 0.5 cm. Sch and P are shown to have no fundamental properties that would make either especially preferable to W, which seems a good compromise between them, and all three, with the laminar feature, show extended double peaks with the electrodes end-on. These effects are not so marked with square-section features, or indeed with the low-resistivity laminar feature 1L, so that it would seem that, in looking for low resistivity features, the choice of configuration is less critical than with high, provided the probe spacing is commensurate with, or smaller than, the feature size (see the difficulties in Fig. 5.19).

The configurations that emerge as especially successful for defining small or complex features are Sq, DD and perhaps best of all, Tw.

Sq, although somewhat cumbersome, has the advantage that readings in two directions can be easily combined. The smoothing introduced by this gives it an inherently low noise level, and any unidirectional weakness of response, common to many of the configurations, is compensated for. This can be true even if the relationship of probe spacing to feature size and depth is such that the clarity of response of even the best of the other configurations breaks down (e.g. Figs 5.21, 5.26).

DD produces a clear, unambiguous response, unless the probe spacing considerably exceeds the width of the feature, but its effective depth of detection is limited because of the increasingly subtractive effect of the alternate CP electrodes at greater depths (see equations 2.7 - 2.9). This is a valuable configuration and, when it is used in combination with W, with which it is readily interchanged, and Tw, the complementary information produced can help greatly in elucidating subsurface conditions. This is discussed further below.

Sch-DD, although extremely sensitive at shallow depths, falls off even more rapidly with depth than DD. It may prove to have applications but, as it has four moving electrodes with unequal spacing, its awkwardness is against it.

Tw arrived late on the scene, probably because, at first sight, it seems so unlikely to work, and because there is little call for a configuration with its properties except to solve the special problems of archaeology. It gives an unambiguous single-peak response like that of DD, although both break down to twin peaks when probe spacing exceeds feature size at shallow depth; but Tw has better sensitivity at depth which, indeed, exceeds that of all the tested configurations except W and P in their most advantageous orientations. Also, purely practically, it is very easy to use, especially with linked electrodes, although one must make allowance for the contribution of the fixed electrodes to the readings (see below), and the instrument used can tolerate, or compensate for, the high basic level of readings.

Tr seems to have potential that has been little tried. Against it is its tendency to give an asymmetrical response: according to the tank results, this does not seem to be serious, but Peschel (1967) showed that in theory, with a 1 m diameter sphere at 0.5 m depth (1 m to its centre), and with 0.5 m probe spacing, there is a 0.7 m displacement of the maximum response with the probes end-on. Peschel suggests overcoming this by taking the mean of two readings at each point with the probe connections reversed; this produces a rather heavily suppressed peak, but one that is at least centred over the feature. It is possible that the use of the sphere approximation emphasises the asymmetry of response, as it does other extreme effects (cf. Fig. 5.25). The three moving probes of Tr are rather more cumbersome than the two of Tw, but in its favour is the fact that it is almost as sensitive as Tw at depth, and that it gives a much lower basic reading which is dependent only on the moving electrodes. It merits further investigation.

Fig. 6.17 gives some practical illustration of the functioning of the different configurations, and may be compared with Fig. 5.22. The relative base levels of W, Sq and DD are in close accord with the theory. With C-C broadside, Sq gave a peak value of nearly 50 ohms; this was pulled down by the averaging process, but with the compensation of overall lower noise than the other configurations at this spacing. As in Fig. 5.22, the baseline of Tw is high compared with the others, and W gives double peaks over the single ditch. Tw, being biased toward deep detection, fails to detect the ditch at all at 5 ft spacing, and only produces an anomaly over the shallow berm when reduced to 0.5 m. At this spacing, the noise level is high, but this is compensated for by the strength of the signal so that, when reduced to resistivity (Fig. 6.18 and Appendix I), the noise is not so evident. The noise was probably also exacerbated by slight errors of spacing caused by the use of separate probes, although Schwarz (1967) has found that, even with linked probes, a reduction to 40 cm spacing gives excessive noise, at least in stony soil. This, and the quite abrupt onset of the response to the berm between 2.5 ft (0.762 m) and 0.5 m, indicates that probe spacing with Tw becomes very critical below about 0.75 m. It is interesting that, at 2.5 ft, although DD detects the berm while Tw does not, both produce a closely similar signal over the ditch. This is paralleled by the responses of these configurations to feature 1H at 1 cm depth in Fig. 5.22 and at 2.5 cm depth in Fig. 5.23. At 2.5 cm, the better depth response of Tw is showing in the broadside traverse (DD/Tw = 0.55), and to a lesser degree in the end-on traverse. At 1 cm, the end-on responses are identical, but the broadside response ratio has changed to DD/Tw = 0.79; and at even shallower depths, DD broadside would probably overtake Tw, whereas the end-on responses, tested to 0.5 cm depth, remain equal. On the test site, the ditch must approximate to feature 1H approached end-on, while the more extensive berm must be better simulated by the broadside approach in which all the probes are over 1H at the same time. The shallowness of the berm, and the consequent dominance of the DD response over it, must be accentuated by the fact that a major contribution to the production of the anomaly comes from the continuous rise in resistivity up to the surface (Chapter 6.4.1), a condition impossible to simulate exactly in an electrolytic tank.

The resistivity response pattern corresponding to a laminar model is by no means universal. Atkinson (1963) shows that many features, ranging from pits to walls, behave like 3H and produce a pattern with W as in Fig. 5.26. Clearly the response is to their own inherent resistivity, but it is interesting that, over a wall (Atkinson, Fig. 11), although the spurious effects are largely eliminated when probe spacing is reduced until commensurate with the width of the wall, a twin peak remains, suggesting that there is a laminar component in the moisture regime associated with the wall. Atkinson also found that a pattern similar to W in Fig. 5.26 was obtained over a low resistivity burial pit in gravel (Atkinson, Fig. 10), a situation in which the whole bulk of the pit would be expected to contrast with the well-drained material into which it was cut.

Sq and DD are perhaps supreme for shallow detection provided, with DD, that features are at least as wide as the probe spacing - Sq has been shown to be less critical. It has also been shown that Tw is able to respond well to shallow phenomena if the spacing is reduced to 0.5 m; and

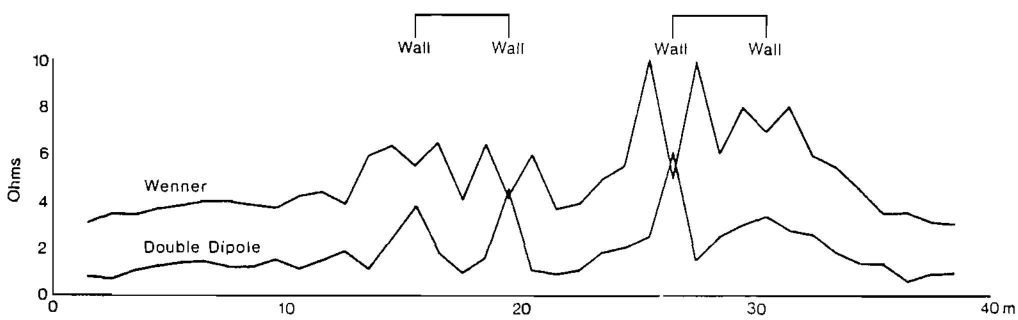


FIG. 5.28. Resistivity measurements along a line across two Roman buildings, combining W and DD configurations. 1 m probe spacing over clay bedrock

such a small spacing also much reduces the occurrence of spurious anomalies over small features. Mounting the twin probes on a frame, as is done by the University of Bradford, is convenient and also removes noise due to errors in probe spacing; and the addition of a third probe, providing the alternative of, say, 0.75 m spacing, would give the option of obtaining a comparison of shallow and deeper penetration. Schwarz (1967) has already used three probes in this manner. Such an apparatus might also be usable for Tr.

Tw remains, however, rather inconvenient for long 'search' traverses, both because of the need for a link to the fixed probes and because the resistivity of the ground in their vicinity contributes to the total reading, which therefore changes when they are moved - although this can be overcome by leaving the moving probes in their last position while the fixed probes are moved to their new position, and their spacing adjusted until the reading is the same as the last recorded for the old fixed position. For search traverses, W and DD can be used in combination by means of a simple switch on the resistivity meter. This enables a reading to be taken with both configurations at each point: a single DD peak centred between two W peaks adds conviction because a genuine feature is thus seen three times (Fig. 5.28). Also, although DD can give the clearer picture, its readings are only approximately one-third of the size of those obtained with W, which also has a better depth response, so that W can help to strengthen the credibility of some weak features.

6. WEATHER AND RESISTIVITY : THE CHALKLAND AND OTHER STUDIES

6.1. THE EXPERIMENT AT WALL

The experiment carried out on the site of the Roman fort at Wall, Staffordshire (Al Chalabi and Rees, 1962; Rees, 1962) has already been referred to in Chapter 4. It seemed that any new experiment should be related to this, the first comprehensive controlled experiment, to facilitate comparison and because of the soundness of their approach.

The site consisted of a complex of ditches, the deepest extending to 3.35 m below the surface, cut into soft Triassic sandstone and back-filled soon after their cutting with a mixture of sand, clay and turf. Probably in the seventeenth century, the area was covered with 0.6 - 1 m of pebbly sand. It has probably been pasture ever since and at the time of the experiment was covered with rough grass.

A fixed line was marked on the ground and resistivity measurements repeated along it at approximately monthly intervals from October 1959 to December 1960. The probe array used was the Wenner at 5 ft spacing, readings being repeated at 2 ft intervals along the line. Variations of anomaly size were studied in relation to recorded rainfall and estimates of evaporation and plant transpiration for the area. Because of the complexity of the site, no attempt was made to relate estimates of anomaly size to individual features; instead the 'average anomaly' of apparent resistivity, statistically related to the average difference between peaks and troughs in the curve, was obtained by taking the average difference regardless of sign between adjacent measurements.

The following correlations were studied: average anomaly and water contributed during various periods from 1 week to 6 months before each measurement; average anomaly and water contributed for periods selected from these, but ending at some time before the measurements, to test whether there was a time lag before water entering the ground percolated into the archaeological levels to produce effective anomalies. The overall correlation appeared to be best when contributed water was taken into account for a period of two to four months before the date of the measurement. Starting from the best of these results - three months and four months - the time-lag test showed good correlation by considering water contributed up to the time of the measurement and back to one month before it, beyond which correlation fell off rapidly. The best correlation was obtained by stopping at one or two weeks before the measurement and, although this was only marginally better than with no delay at all, it was concluded that, for instance, a brief but heavy rainfall would have no immediate effect on measurements.

The general conclusion was that, on a site of this nature, the maximum value of average anomaly would occur, and features be most strongly detectable, after a period of hot, dry weather when the soil had suffered an overall loss of water. A study of weather statistics showed that, as a rough rule, best results would be obtained in July, but that good conditions would be likely to exist during the period between June and September.

It is worth noting that at Wall the resistivity problems were quite uncomplicated: anomalies were always in the same sense and, even at their worst, hardly less than half as large as at their best.

6.2. THE CHALKLAND EXPERIMENT

6.2.1. DESIGN OF THE EXPERIMENT. The experiment was conceived on a broader scale over a longer period and with closer control than that at Wall. Three sites were chosen with ditches of widely graduated size (Fig. 6.1) but with similar and more typical histories than those at Wall: all had silted naturally at first, but their upper fillings were of ploughsoil and ploughwash which had finally levelled them, or nearly so. The very thorough measurement of a single traverse was abandoned in favour of the normal succession of 'leapfrog' readings at the same interval as the probe spacing, more

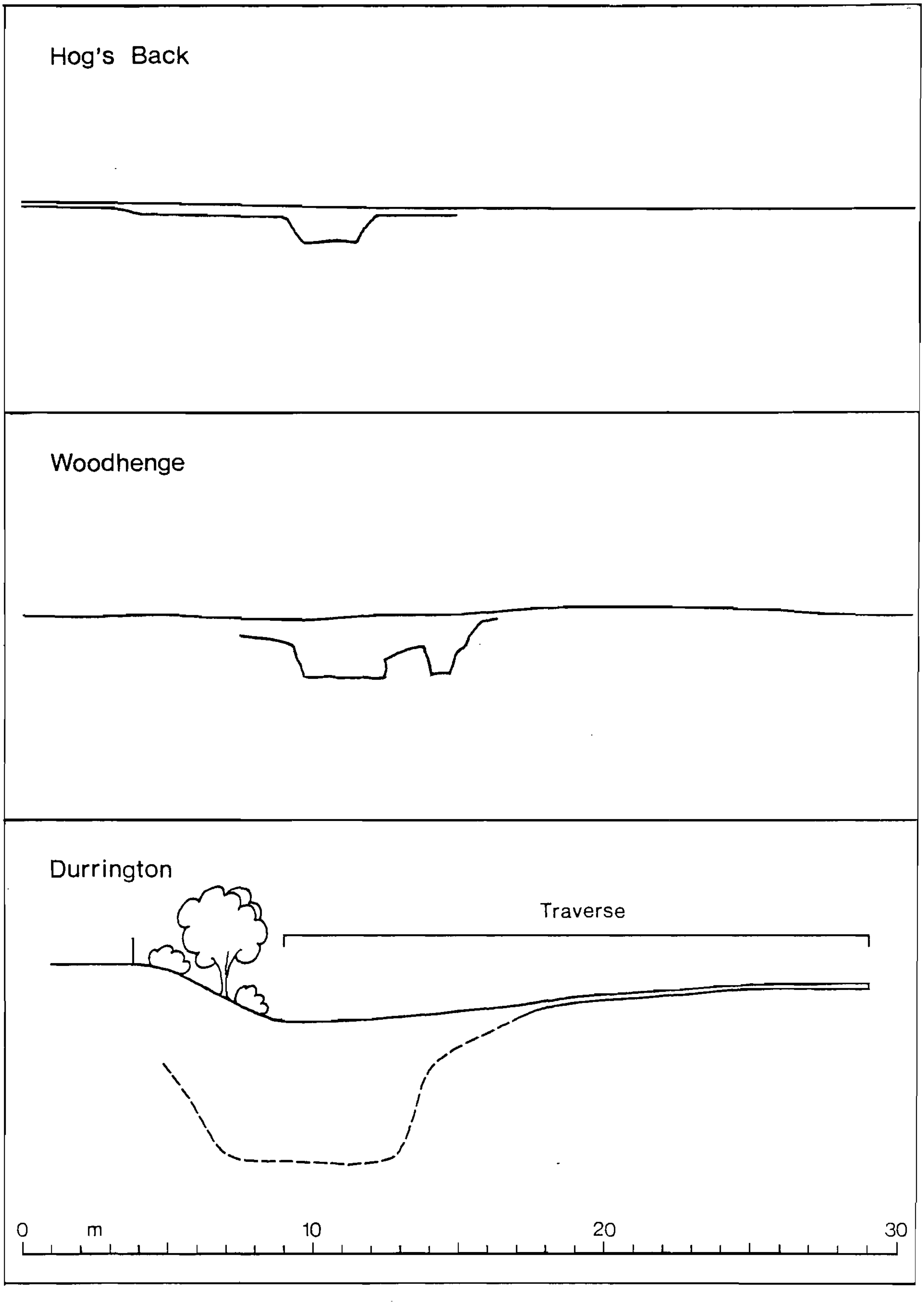


FIG. 6.1. Complete profiles and schematic sections of the three test traverses

valuable information being obtained by using the time saved to extend the work to the three sites and to make comparative measurements at two probe spacings and latterly with two configurations. Wenner measurements were made at the commonly used 1 m probe spacing and also at 5 ft for comparison with the Wall results, at roughly monthly intervals from July 1970 to January 1972. Because of the electrolytic tank results, Double Dipole readings at the same spacings were also taken for the last five months of the experiment. Interpretation was also simpler than at Wall because each ditch was single and well understood from nearby control sections. For this reason, the actual amplitudes of the anomalies have been used in calculation rather than the statistically related variations employed by Al Chalabi and Rees - which need not necessarily have referred to the features sought. As at Wall, all the sites were covered with rough grass. Most of the measurements were made with a Martin-Clark Type 1A instrument. This was calibrated with special precision for the experiment, and any necessary corrections applied to the readings.

It is unfortunate that no site with buried walls could be found in a situation suitable for long-term testing. However, it is known from experience that buildings of flint, probably the most common ancient building material on chalk, are readily detectable throughout the year (e.g. the Boscombe Roman building, Fig. 7.8), so the problem is not critical. A possible test site might be provided by one of the known buried sarsen stones at Avebury.

All three test sites lie upon the Upper Chalk formation. Woodhenge and Durrington Walls are on Salisbury Plain in Wiltshire, respectively beside and astride the A345 road 1.5 km north of Amesbury. The Hog's Back barrow is situated on the crest of this well-known ridge, the narrowest part of the North Downs, beside and partly beneath the A31 road 5 km west of Guildford.

6.2.2. DURRINGTON WALLS (N.G. SU 150435). After being engaged by the Ancient Monuments Laboratory to undertake geophysical prospecting, one of the writer's first projects was to trace the course of the ditch of the great henge of Durrington Walls in preparation for the excavations of 1967 in advance of the realignment of the A345 road (Wainwright and Longworth, 1971). The work was done with the single-handed use of the Square Array resistivity system, with some additional help from a coring tool and an Elsec proton magnetometer, and an air photograph published by O. G. S. Crawford (Crawford, 1929). The survey was carried out in the summer and, although the full circuit of the ditch was established (Fig. 6.2 is based on the plot produced), the resistivity anomalies were quite slight and sometimes surprisingly complex. Because of this, and because the ditch was likely to be as large as any to be encountered, and also because of the subsequent termination of cultivation for archaeological reasons, it was later chosen as one of the test sites for the resistivity experiments. Mainly for convenience of access, the southern sector was selected for the test traverse. Of this, the most suitable part seemed to be where the ditch cut clear across the south-west corner of the field; however, preliminary measurements in July, 1970 produced confusing results here, and a place was finally chosen where the ditch is partly overlain by a lynchet, but was strongly revealed by a lush grass mark and gave a reasonably straightforward resistivity anomaly. Control was provided by Wainwright's section 180 m to the east and by levelling and coring along the line of the test traverse (Fig. 6.3). The following description of the layers in Fig. 6.3a is adapted from Wainwright and Longworth.

1. Modern plough soil.
2. Old plough soil and ploughwash.
4. The slow silts which formed in the sheltered hollow between the upper sides of the ditch. The deposit is a fine, grey-brown silt with a very few small rounded chalk lumps.

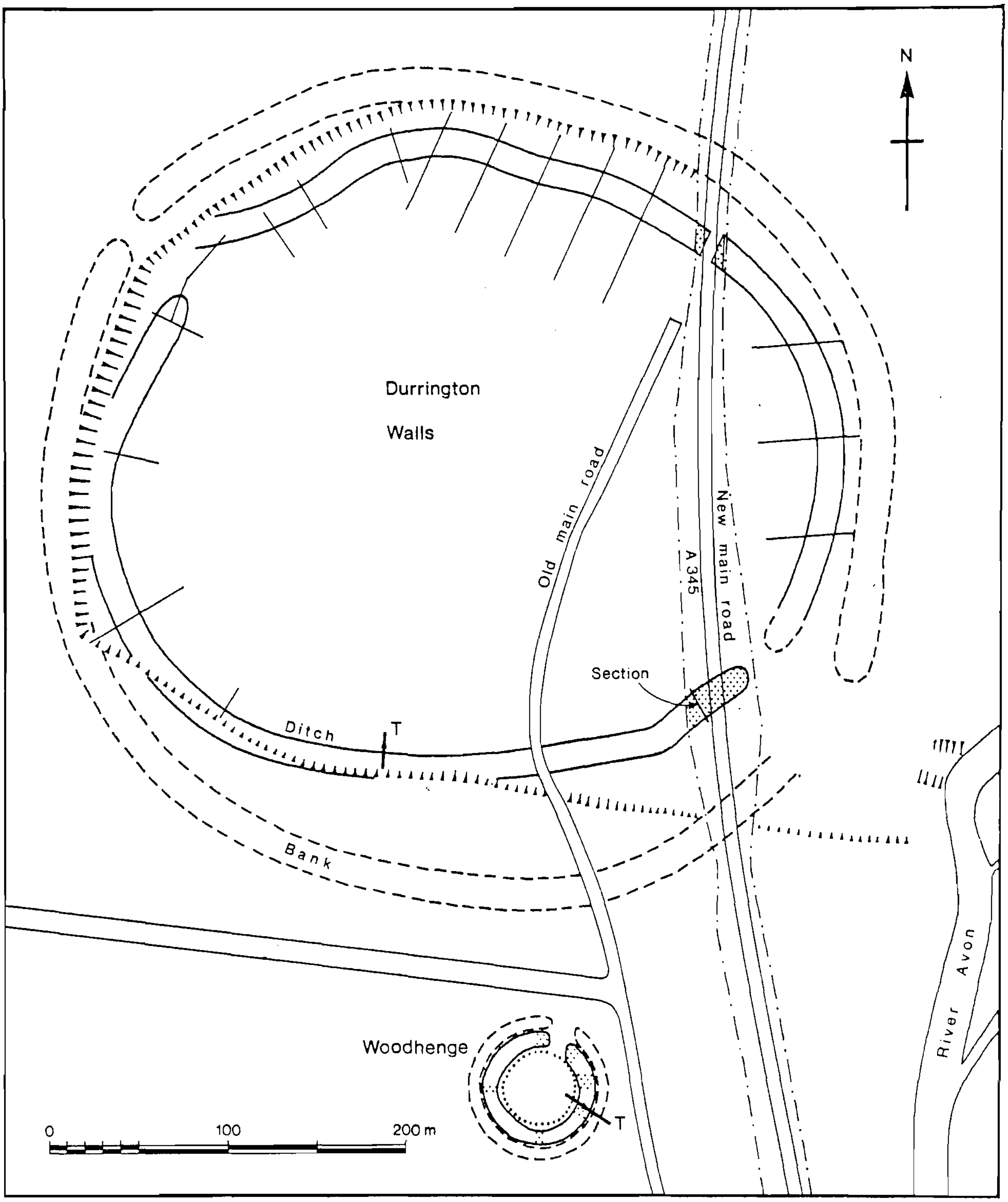


FIG. 6.2. Plan of Durrington Walls showing the circuit of the ditch as established by Square Array resistivity before the 1967 excavation. The lines intersecting the ditch mark the positions of the measurement traverses. The test traverse is marked T. Woodhenge and the test traverse there are also shown. Parts of the ditches proved by excavation are stippled.

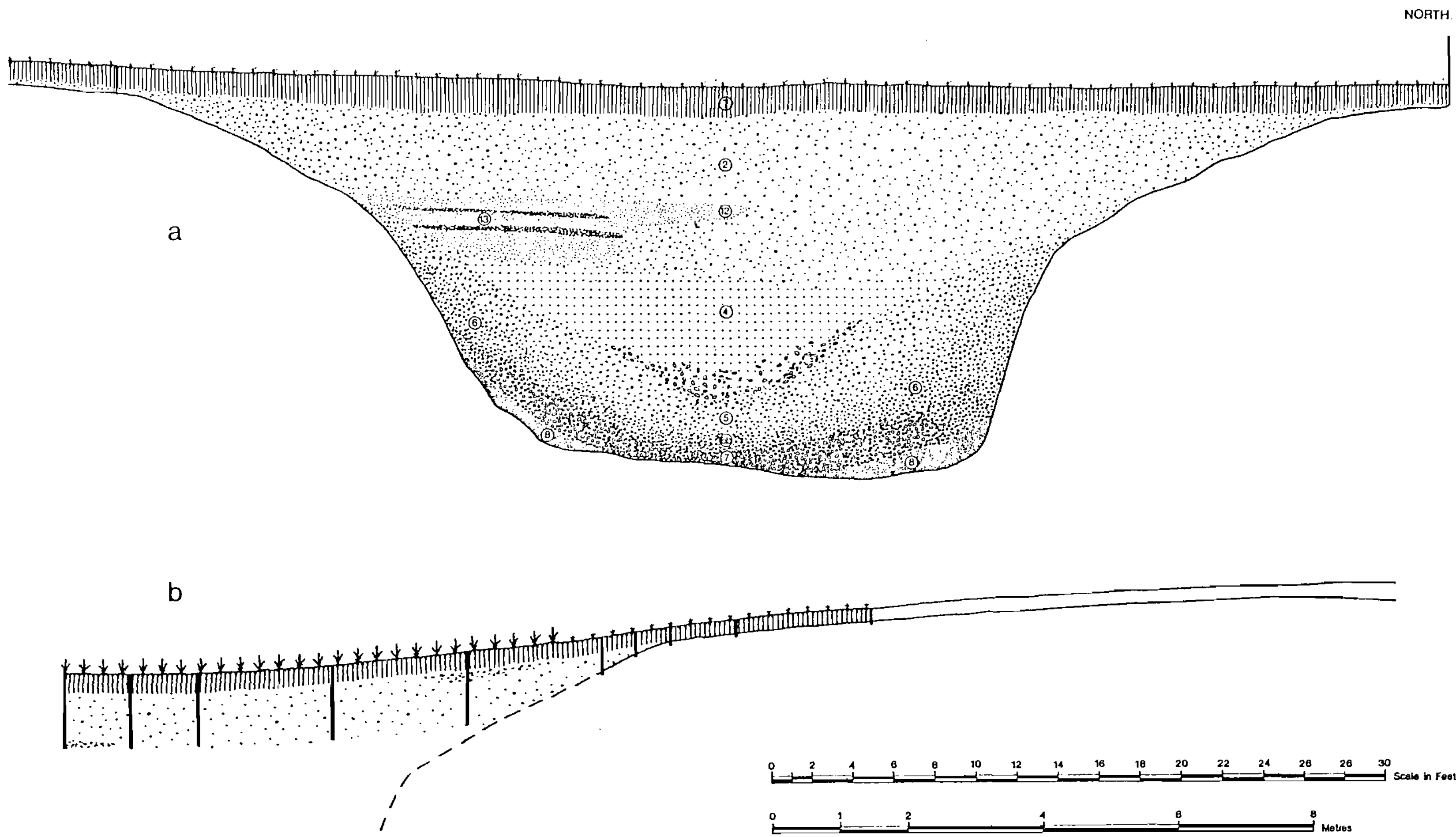


FIG. 6.3. (a) The southern section of the Durrington Walls ditch (after Wainwright); (b) The profile of the test traverse, as established by levelling, coring (heavy vertical lines), resistivity measurements and comparison with (a). The layering is described in the text

5. Brown, rather clayey soil containing rounded lumps of flint and chalk. A silt intermediate in speed between 4 and 6.

6. Chalk rubble - clean and with air-spaces near the bottom of the ditch (6b) but interspersed with rainwashed chalk and earth nearer to the sides.

7. Large angular blocks of chalk with no earth and a cellular structure. This rubble is derived from the upper sides of the ditch.

8. A fine, rather clayey grey silt deposited in the inner and outer angles of the ditch bottom. This is the rapid silt which formed immediately after the digging of the ditch.

12 and 13. Fine grey to brown silt and gravel lenses. Material of this type must have been deposited by water and the silted ditch have served as a temporary stream bed in Iron Age and Romano-British times. This may not have continued as far as the site of the test traverse.

Some layer numbers are omitted above because the numbering system also applies to another section. The coring along the line of the test traverse (Fig. 6.3b) did not penetrate below layer 2, although bands of chalk, indicated by closer stippling, were encountered within this layer. These will be discussed further below.

In addition to the resistivity measurements, the grass mark was photographed in colour on each visit to ascertain the relationship of crop marks to resistivity over this type of ditch. The results are discussed below.

Rainfall data for the Wiltshire sites were provided by the Meteorological Office, RAF Upavon, 11 km to the north. Potential evapotranspiration figures were measured at the Meteorological Office station at Larkhill, 2 km to the north-west. Although it would have been sensible to obtain the rainfall figures from this nearby station also, Upavon was chosen because of its proximity to a possible test site at Pewsey that proved to be unsatisfactory only after the essential measurements for the previous months had been supplied by Upavon, and it did not seem desirable to lose the continuity or indeed the enthusiastic support that Upavon had always given.

6.2.3. WOODHENGE (N.G. SU 150433). A section cut in 1970, mainly to obtain environmental evidence (Wainwright, 1979), provided the opportunity for a test traverse across a medium-sized ditch only about 200 m from the Durrington Walls traverse (Figs 6.2, 6.4 and 6.5b). The traverse was set out only 2 m from the section so that this would provide the best possible control without physical interference with the measurements. The layering of the section is described in Fig. 6.5b.

6.2.4. HOG'S BACK BELL BARROW (N.G. SU 937484). This was rediscovered by the writer and excavated in 1966 by the Surrey Archaeological Society under his direction in advance of the addition of a second carriageway to the A31 road. Attempts on three occasions to trace the ditch of the barrow by resistivity had produced variable and mainly poor results.

Although the new carriageway has destroyed the northern part of the barrow, the central reservation is wide here, and the old hedgerow (once the southern boundary of Windsor Forest) and part of the barrow are preserved, allowing the insertion of the test traverse as shown in Fig. 6.6. The new carriageway now overlies the northern part of the barrow as shown in this plan.

This site provided an example of the smaller type of ditch that is frequently encountered, as well as a geographical contrast with the other two test sites, 79 km away almost exactly due west. The section in Fig. 6.5a is adapted to the position and angle of the traverse from the long excavated section 7.5 m north of it. Note the berm, characteristic of a bell barrow, between the ditch and the damaged dome of natural chalk (7) formerly protected from erosion by the mound of the barrow. The name

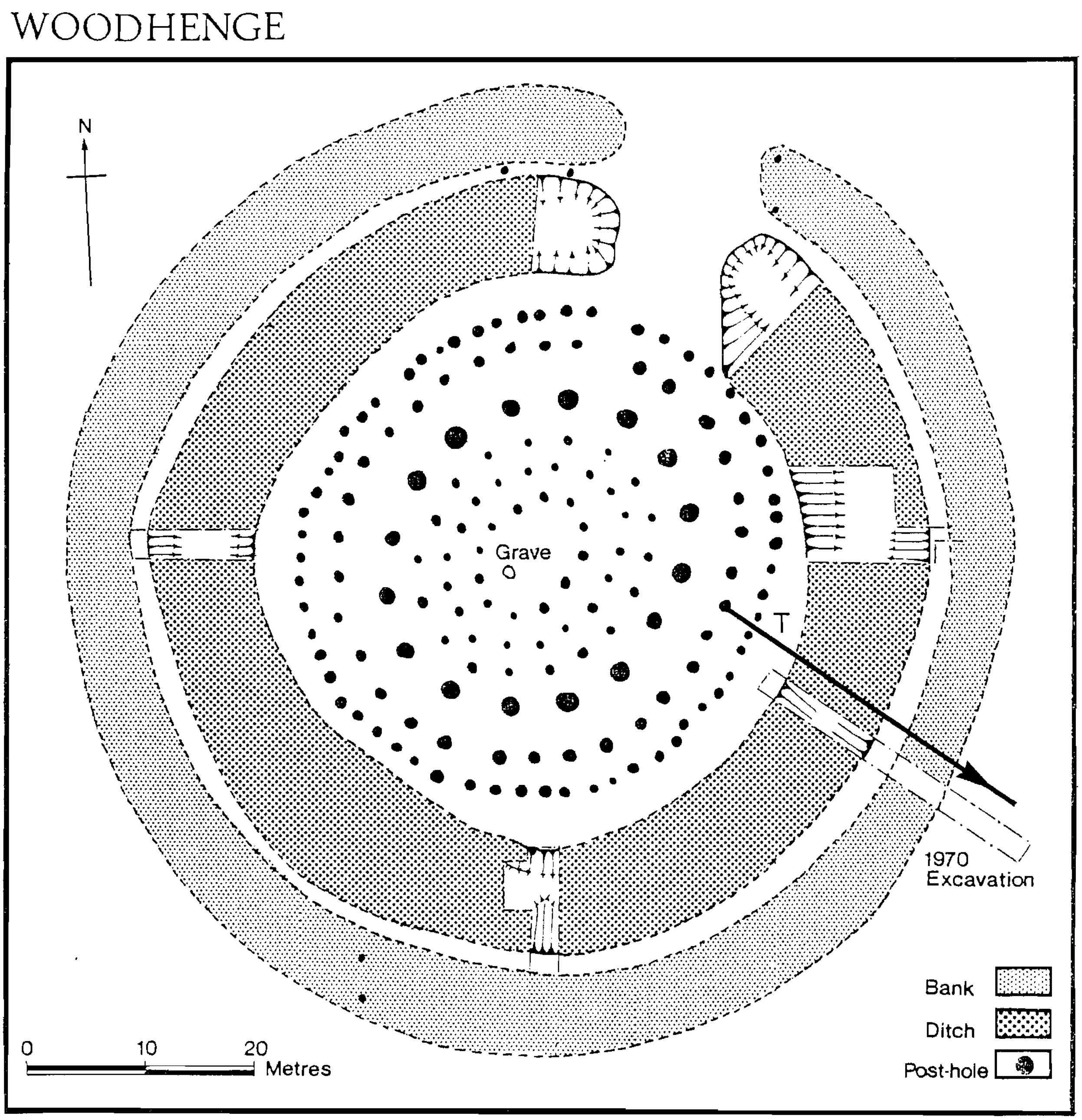


FIG. 6.4. Plan of Woodhenge, after Wainwright. The arrow marked T shows the position of the test traverse alongside the 1970 section

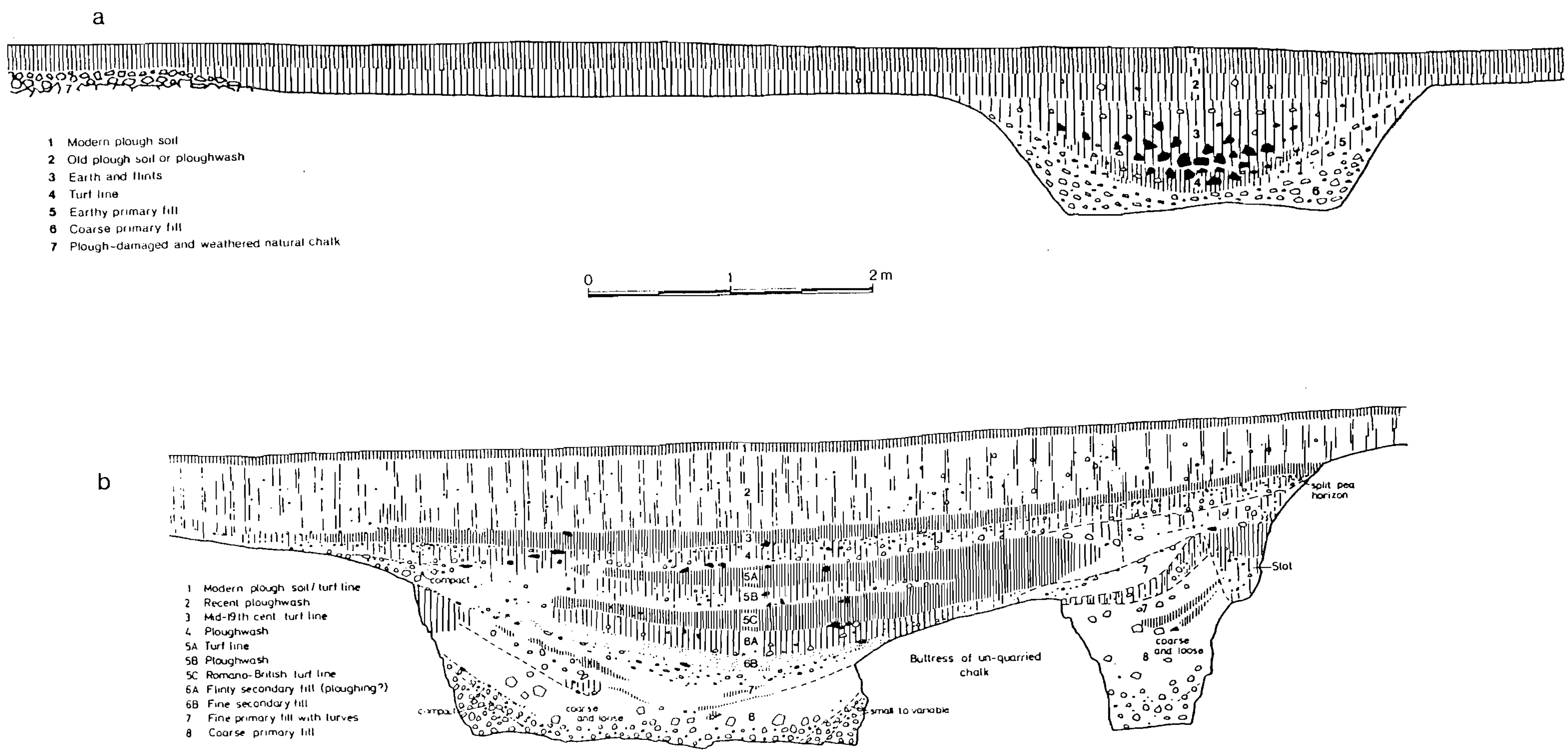


FIG. 6.5. (a) Partial section of the Hog's Back barrow; (b) The Woodhenge section, after Wainwright and Evans. Flints are shown black; chalk blocks white

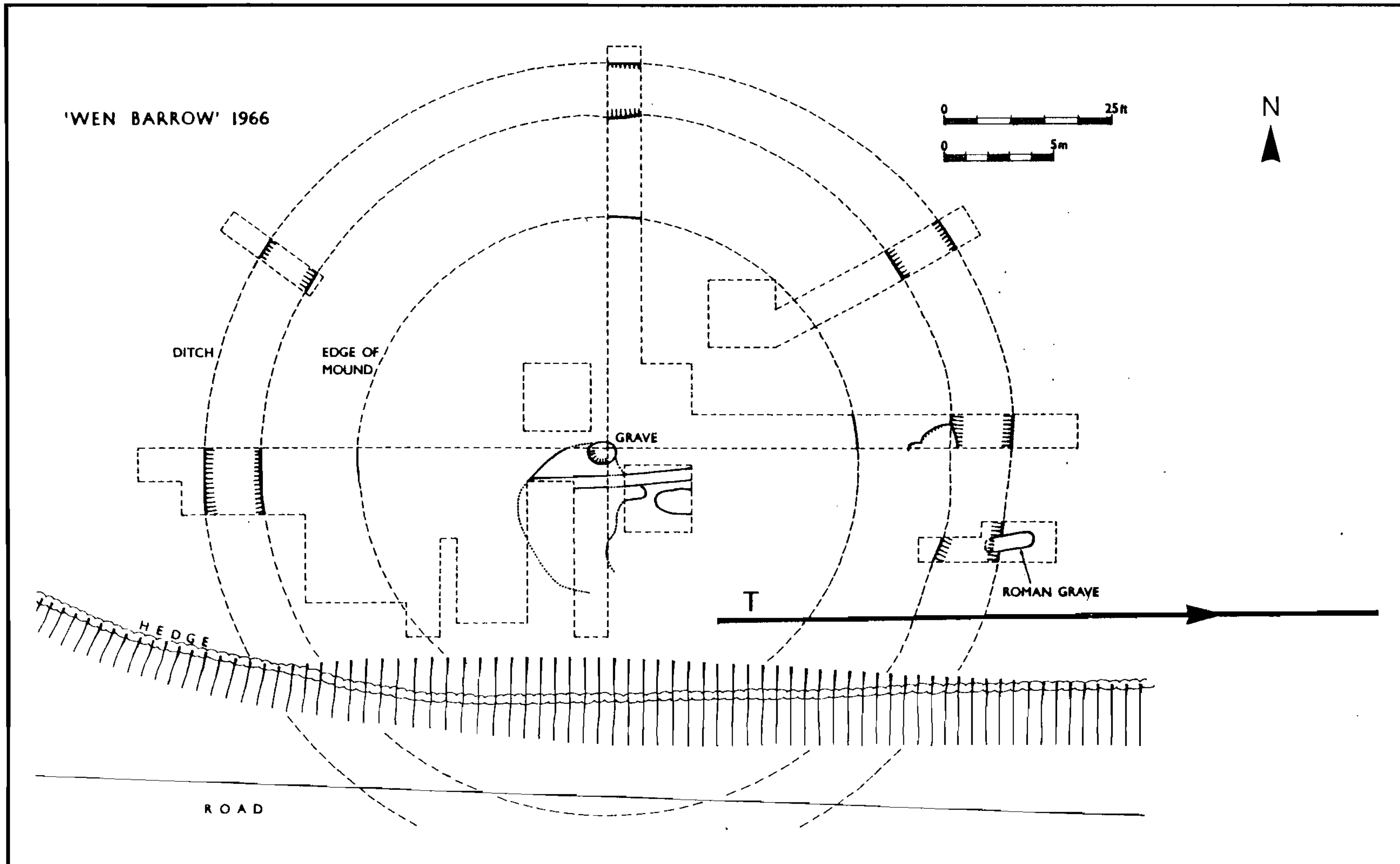


FIG. 6.6. Plan of the Hog's Back bell barrow. The line marked T shows the position of the test traverse

'Wen Barrow' is used rather speculatively on the plan because this is the derivation of the name of the parish of Wanborough in which the barrow prominently stood, and, in the absence of other known candidates, it would seem that this was the barrow that gave its name to the parish.

Rainfall data were obtained from the Ladymead pumping station, Guildford, 6 km to the ENE, and potential evapotranspiration figures from the nearest Meteorological Office station, at South Farnborough, 9 km to the north-west.

The Hog's Back measurements of 13 November 1971 were expanded into an intercomparison of probe spacings and configurations, primarily as a field check on the tank experiments; but the information obtained also proved to be of great value in understanding the nature of the resistivity anomaly caused by the ditch.

6.3. RESULTS OF THE EXPERIMENT

The monthly readings are plotted as graphs in Figs 6.7 - 6.10, with the profiles of the ditches indicated at the top of each set. As far as possible, the readings were made close to the middle of each month or slightly later. The measurement for December 1970 was delayed to 5 January because of illness, and the January measurement was therefore made later than usual to maintain a reasonable time spacing.

Anomaly sizes and water balance are shown in Fig. 6.11, which attempts a comprehensive visual summary of the results of the project. Anomaly sizes are derived from the readings obtained over the ditches at their most typical: Hog's Back at 10.5 m; Woodhenge at 10.5 m; Durrington Walls at 5.5 m (approximately). These are compared with the estimated mean resistivity level as measured over the undisturbed chalk. Water balance is shown from April 1970, although data were collected from the beginning of the year for the calculations below. The water balance figures were calculated by subtracting the potential evapotranspiration from the rainfall for each month: for the Hog's Back this required an

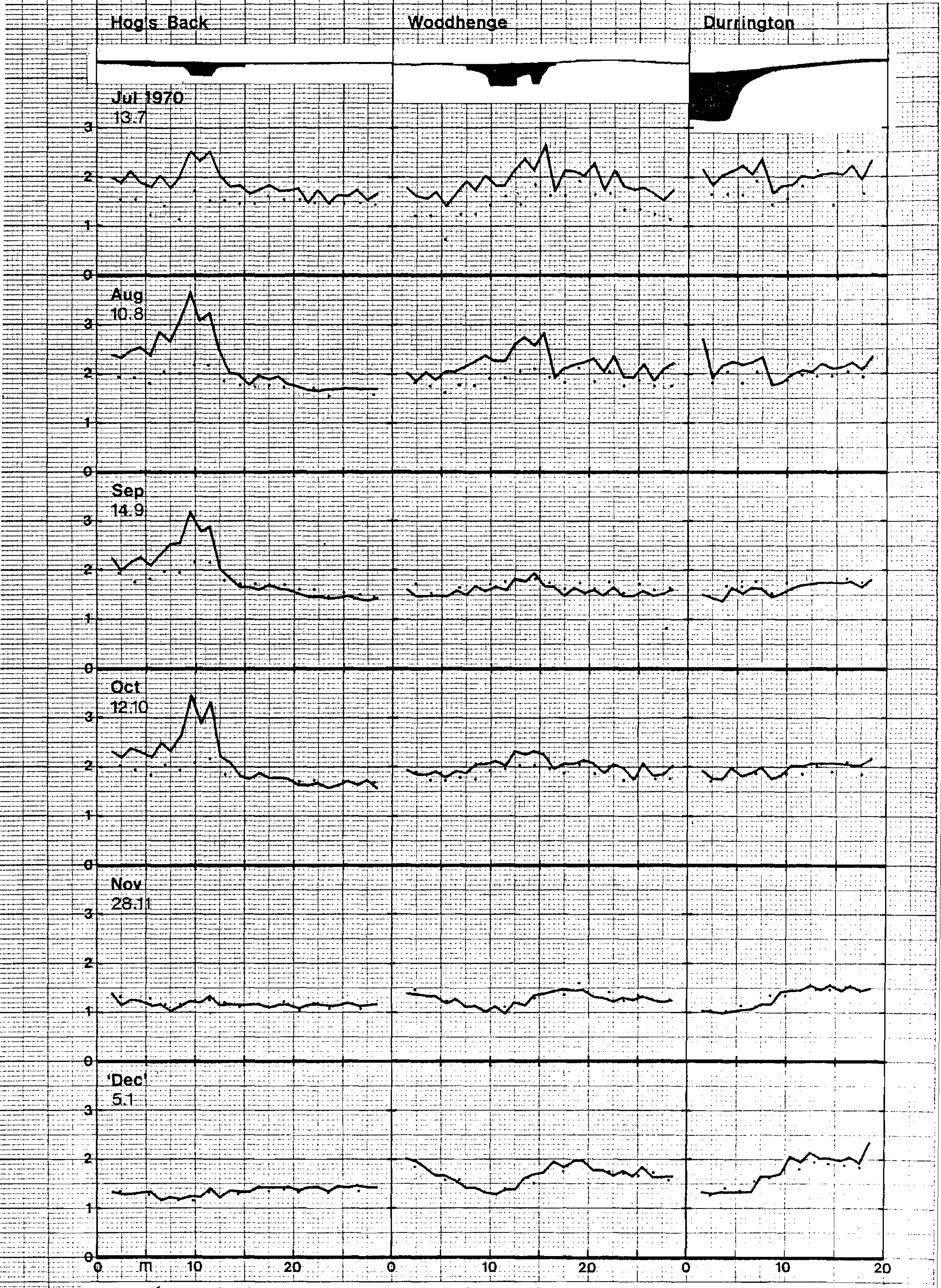


FIG. 6.7. Test traverse measurements on the three sites, July to December, 1970. Solid lines = 1 m spacing; dots = 5 ft spacing. Vertical scale is in hundreds of ohm-metres

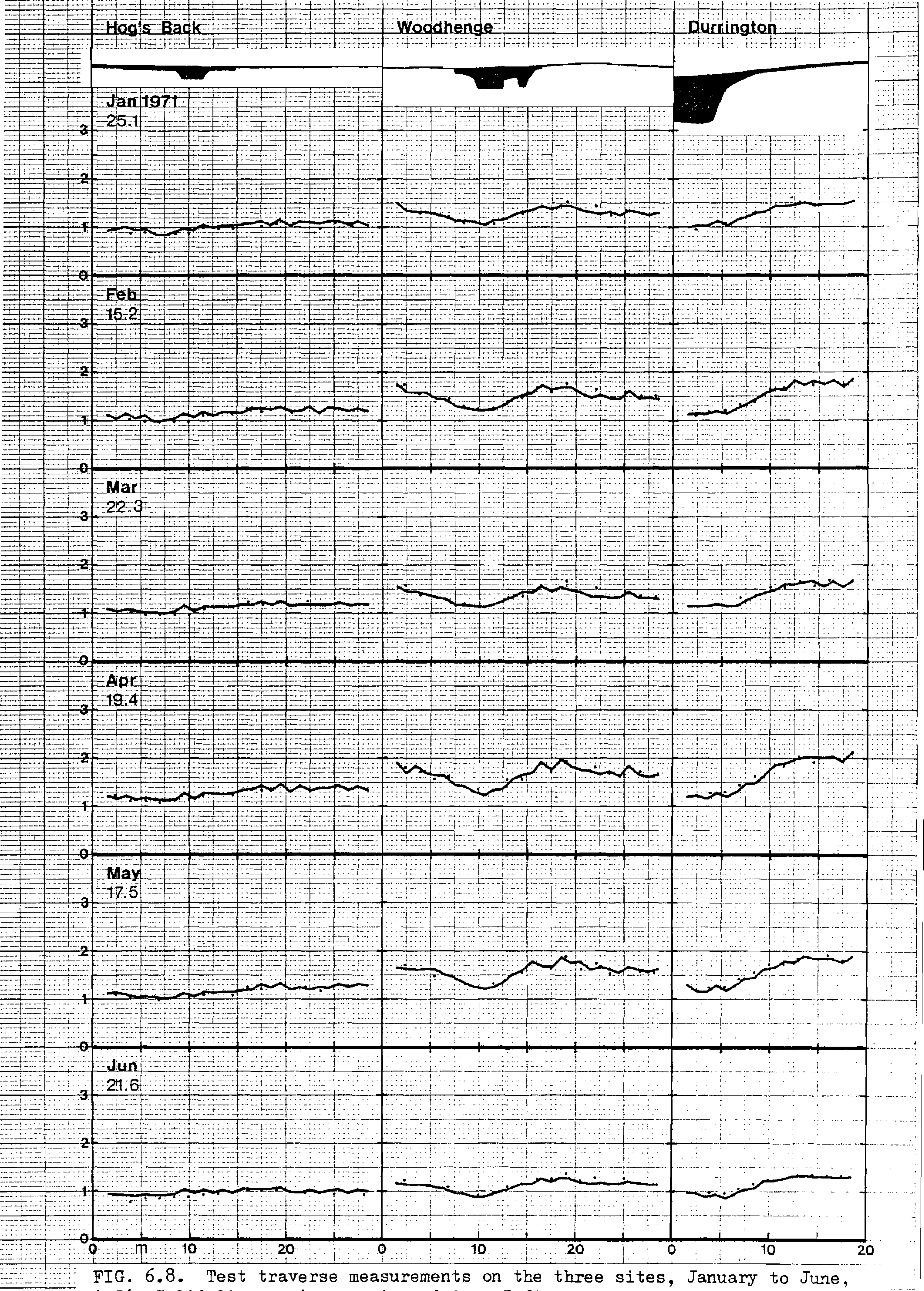


FIG. 6.8. Test traverse measurements on the three sites, January to June, 1971. Solid lines = 1 m spacing; dots = 5 ft spacing. Vertical scale is in hundreds of ohm-metres

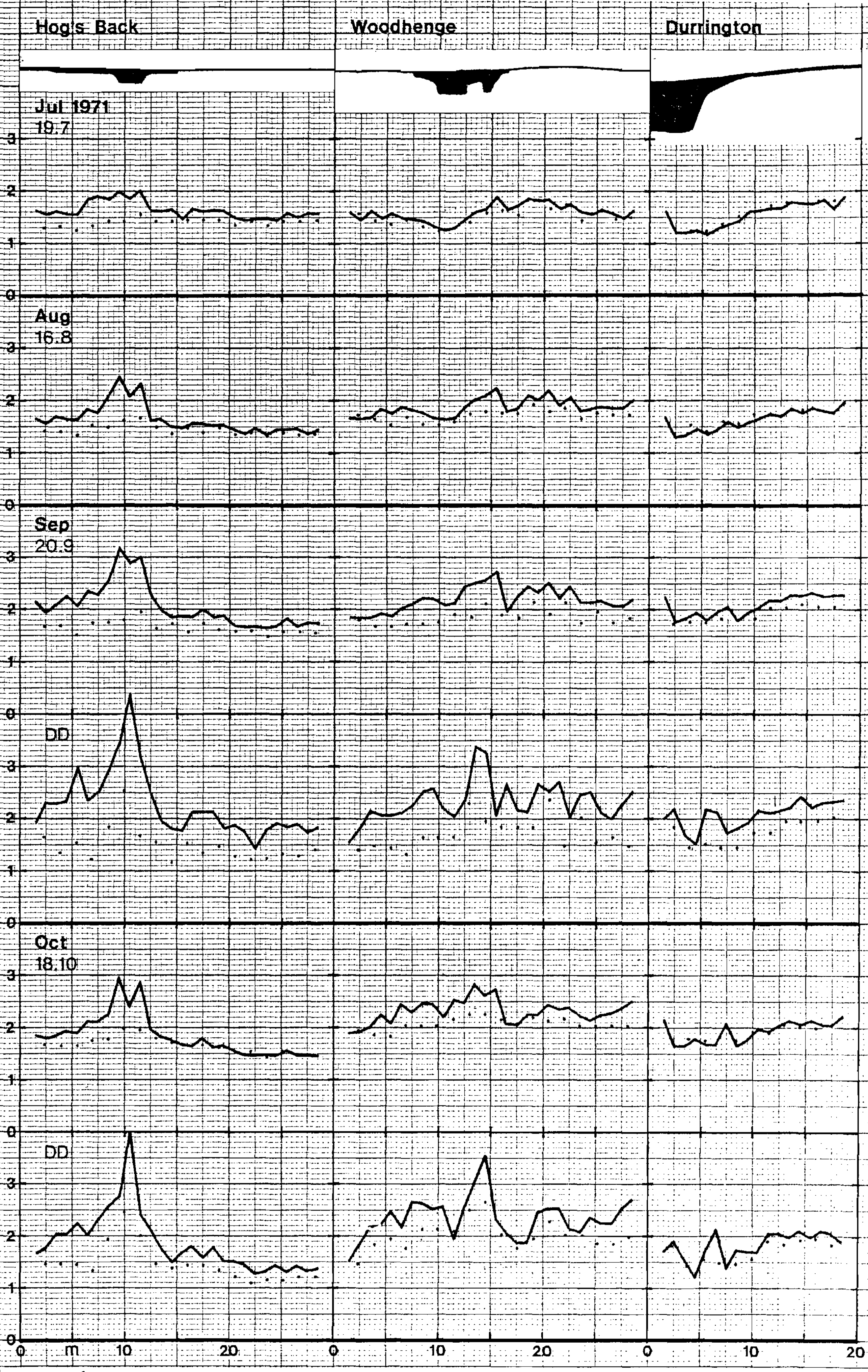


FIG. 6.9. Test traverse measurements on the three sites, July to October, 1971. Solid lines = 1 m spacing; dots = 5 ft spacing. Vertical scale is in hundreds of ohm-metres. Note the addition of the Double Dipole array from September

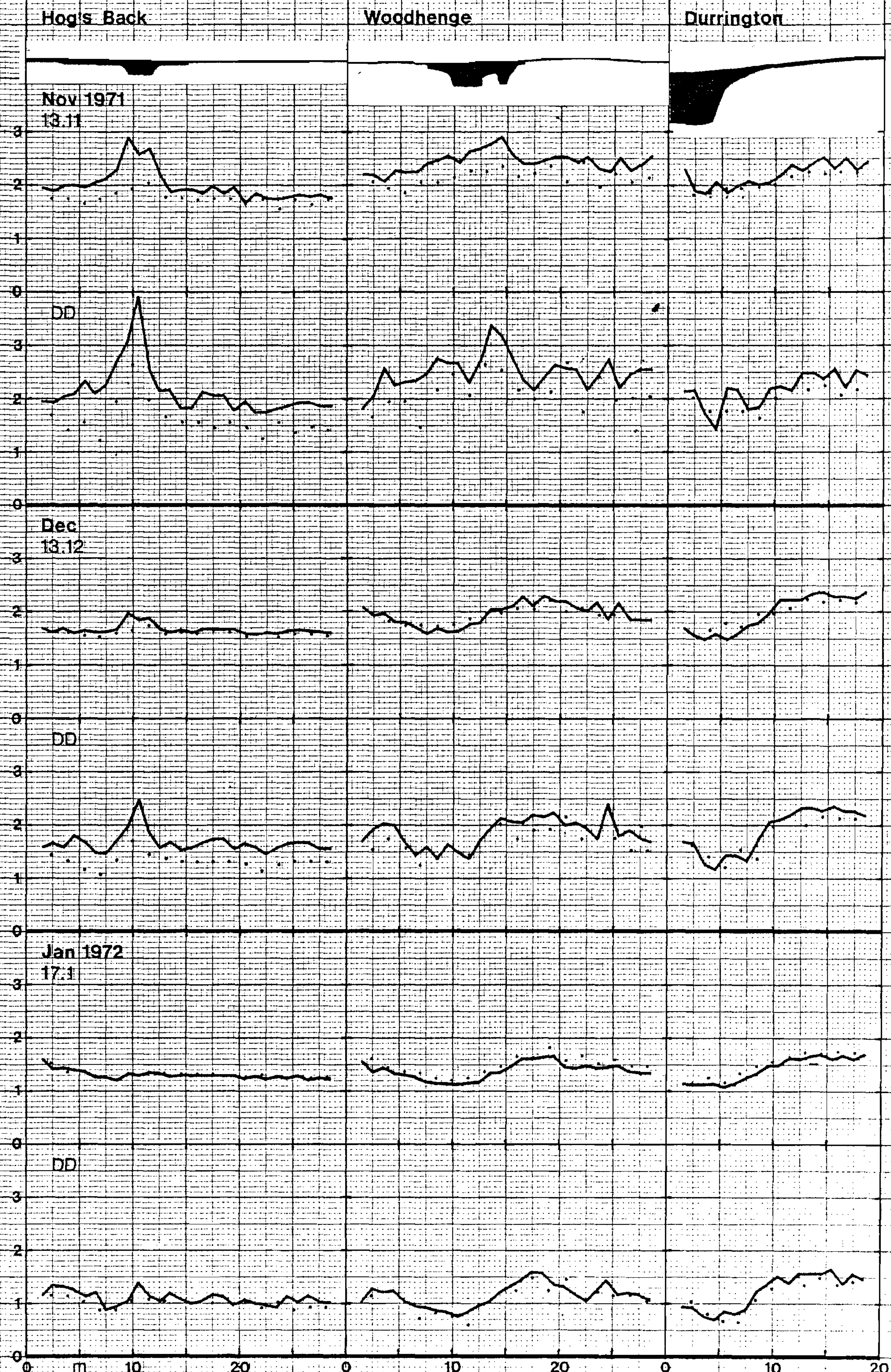


FIG. 6.10. Test traverse measurements on the three sites, November 1971 to January 1972. Solid lines = 1 m spacing; dots = 5 ft spacing. Vertical scale is in hundreds of ohm-metres. Note the addition of the Double Dipole array

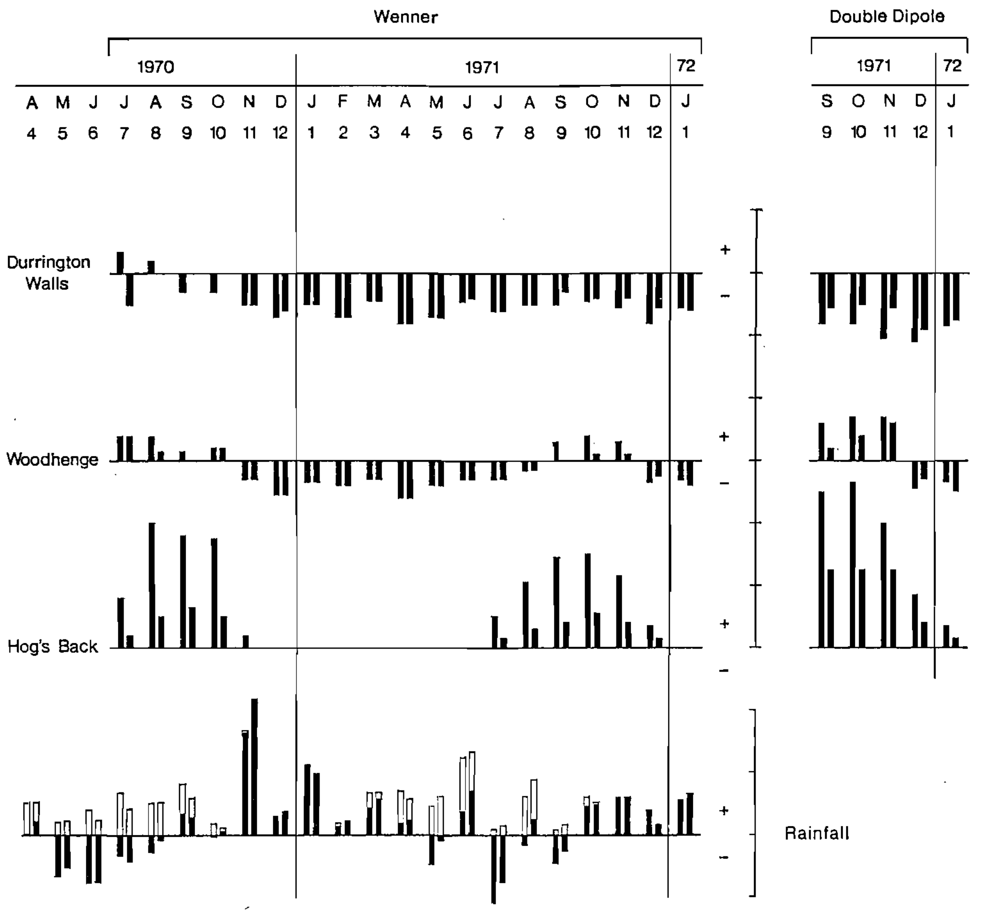


FIG. 6.11. Summary of resistivity tests on ditches in Chalk bedrock. + high, - low anomaly relative to background level. First bar of each pair, 1 m probe spacing; second bar, 1.5 m spacing. Vertical scale interval 100 ohm-metres. Water balance is shown at bottom. Open parts of bars show rainfall; black is net gain or loss of water after allowing for evapotranspiration. First bar of each pair, Durrington Walls and Woodhenge; second bar, Hog's Back. Vertical scale interval 100 mm.

adjustment to compensate for the difference in height between the site and the Farnborough measuring station (reduction of 0.9 mm/100 ft height of site above station) (Meteorological Office, 1972). Figs 6.12 and 6.13 show the same data as continuous curves smoothed by taking three-point running means; and the water balance readings, which were quite erratic, especially in 1971, are further smoothed manually.

A strikingly varied picture emerges. Except after the driest periods, the Durrington ditch gave continuously low anomalies. Woodhenge oscillated between a high anomaly after periods of net water loss to low after periods of surplus; and the Hog's Back ditch was only effectively detectable (by the Wenner configuration at least) in the dry conditions. This behaviour was broadly the same at both electrode spacings, although the 5 ft, with its deeper penetration, tended to be more sluggish in responding to the external conditions.

Fig. 6.14 compares the water balance curve (a) with the background resistivity of undisturbed chalk at Durrington Walls, measured where the soil cover was not more than 15 cm and the probes actually penetrated to the chalk, so that the effect of the soil was minimal. The difference between curves (b) and (c) demonstrates the importance of smoothing in bringing out the trends of the data. Figs 6.15 and 6.16 compare the 1 m curve in Fig. 6.14 with similarly smoothed 1 m curves for the absolute resistivities measured over each of the ditches.

Data in a form comparable to that of Al Chalabi and Rees was produced by calculating correlation coefficients between anomaly size and total water input over various periods before the measurements (T) and also for periods ending at various lengths of time (t) before the measurements (see table, Fig. 6.19). Assuming that resistivity change with water input approximates to a hyperbolic function, Al Chalabi and Rees compared water balance with the reciprocals of the resistivity anomalies. This was not practicable in the present work, in which the

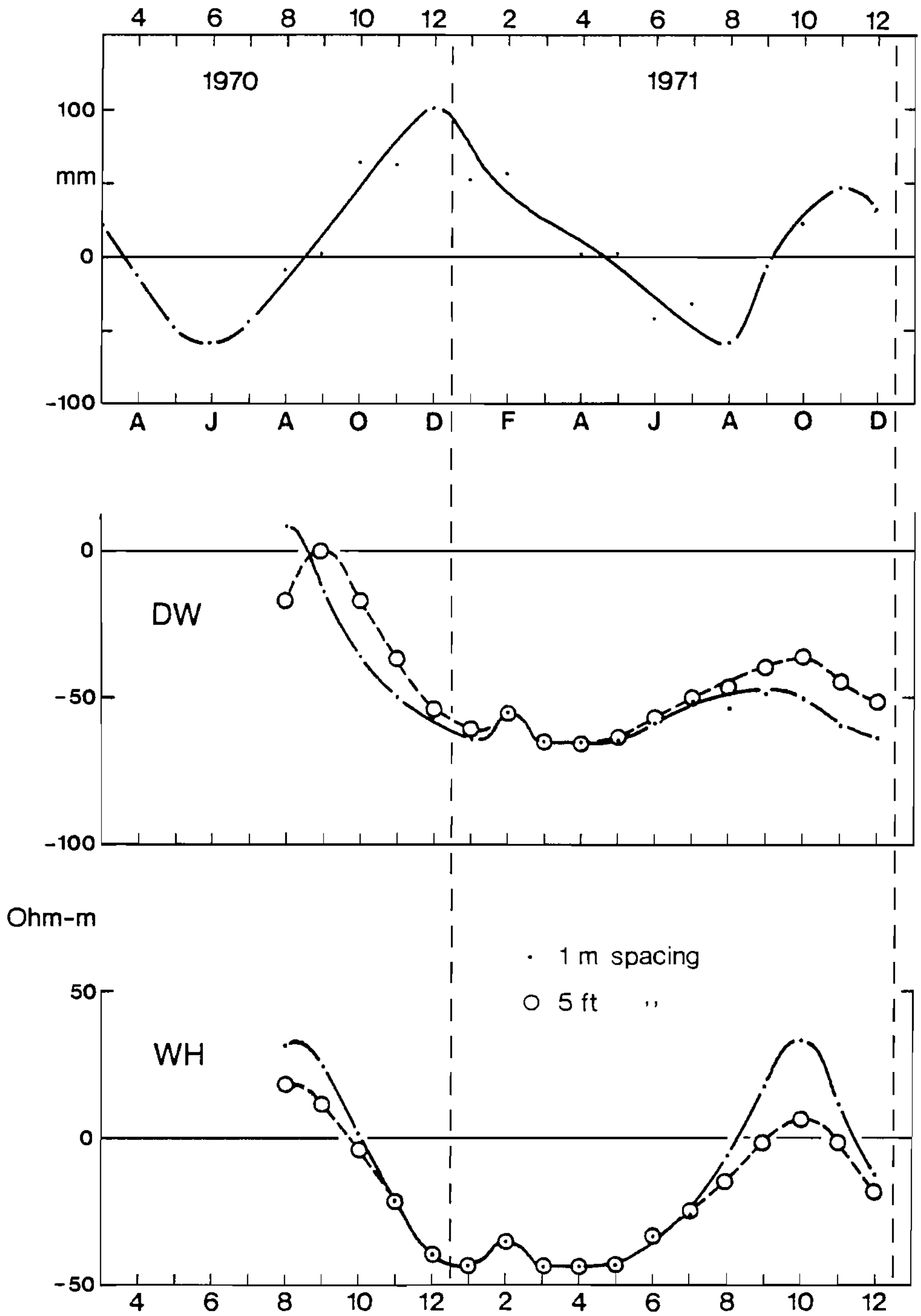


FIG. 6.12. (top) Wiltshire water balance, smoothed; (below) resistivity anomalies over ditches at Durrington Walls (DW) and Woodhenge (WH)

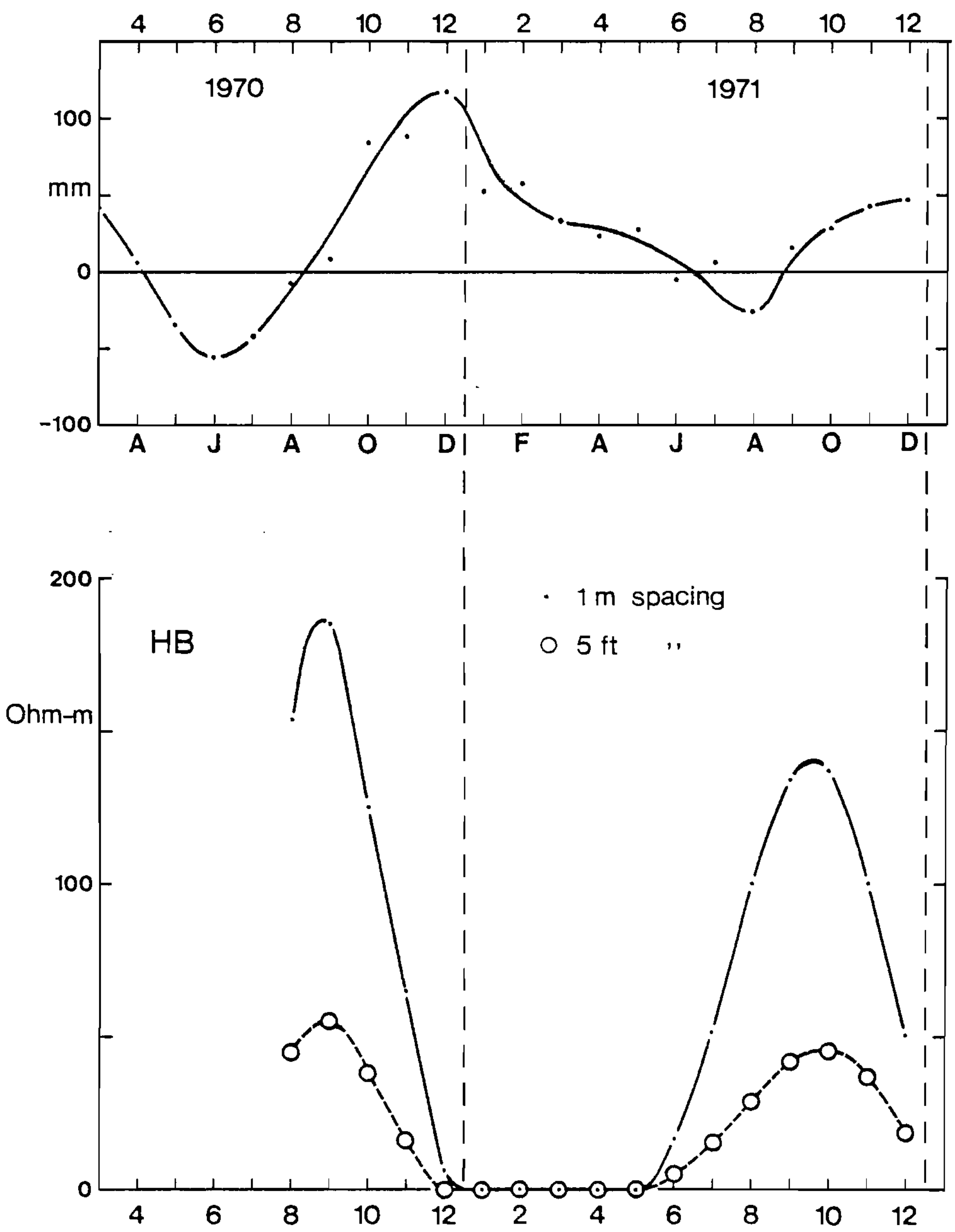


FIG. 6.13. (top) Surrey water balance, smoothed; (below) resistivity anomalies over the Hog's Back ditch

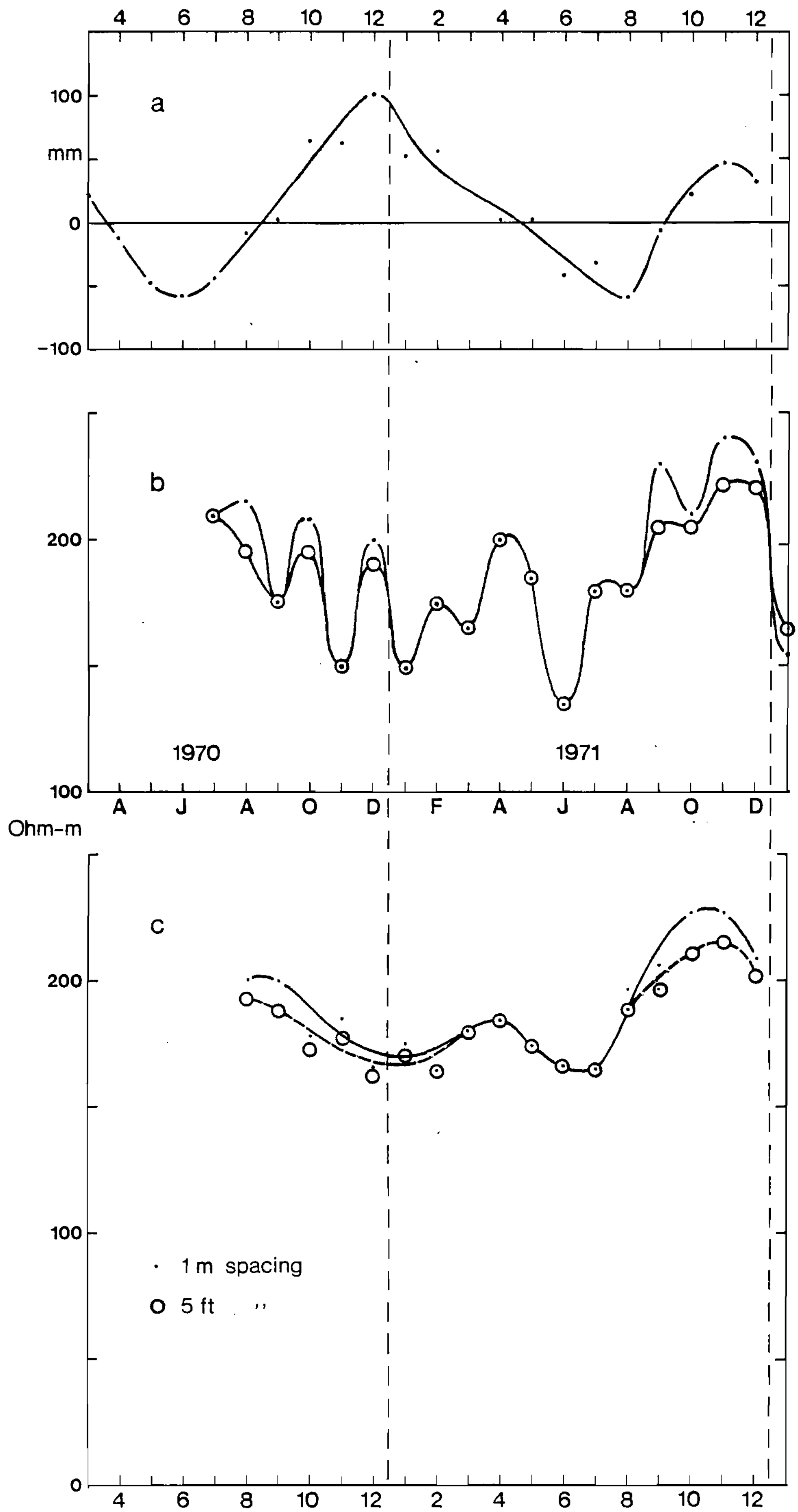


FIG. 6.14. (a) Wiltshire water balance, smoothed; (b) Chalk background resistivity, Durrington Walls, unsmoothed; (c) Chalk background resistivity, smoothed

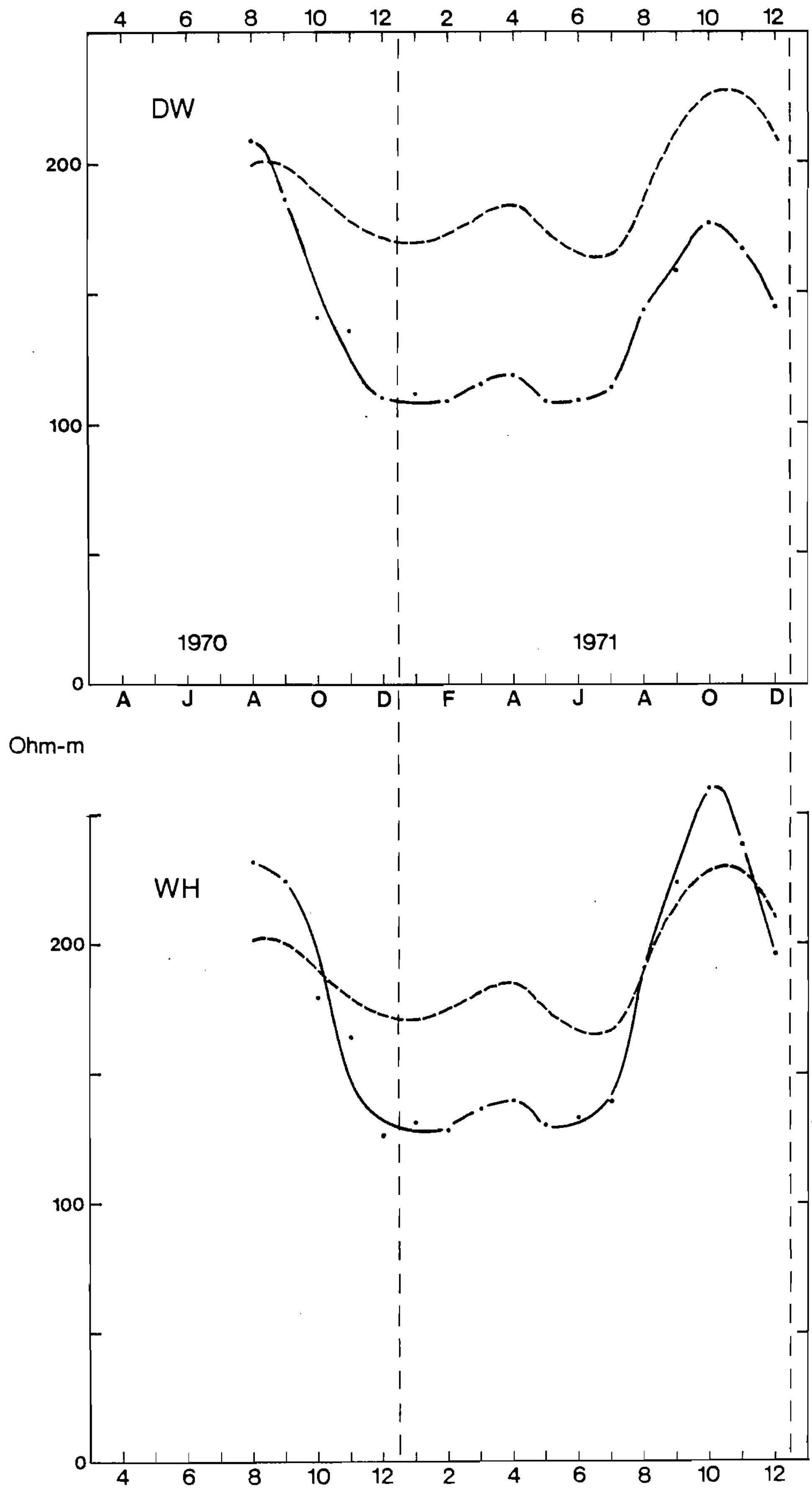


FIG. 6.15. Wiltshire: absolute apparent resistivity of ditches (solid lines) compared with Chalk background (broken line) for Durrington Walls (DW) and Woodhenge (WH), all smoothed. 1 m probe spacing

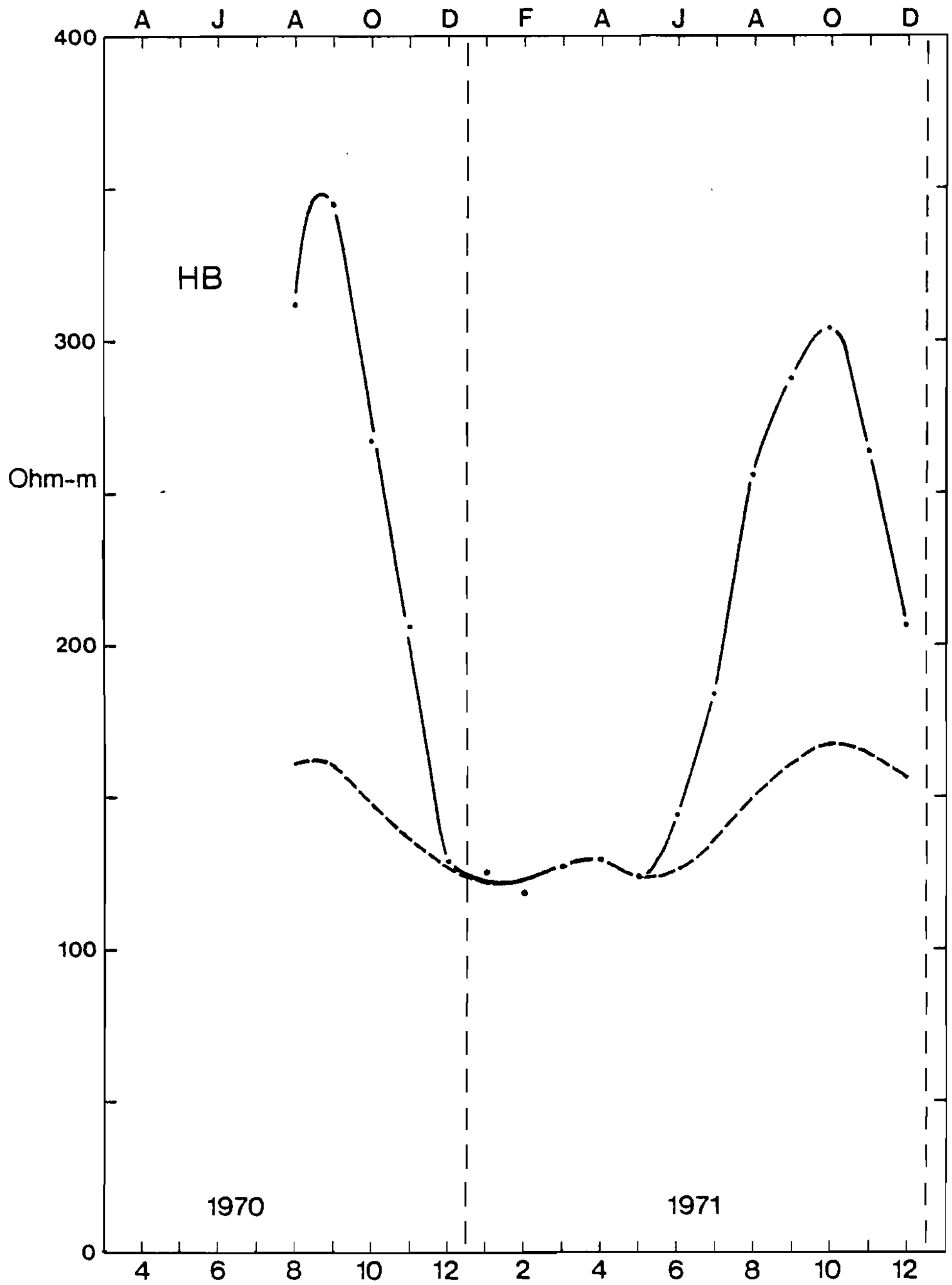


FIG. 6.16. Surrey: absolute apparent resistivity of Hog's Back ditch (solid line) compared with Chalk background (broken line), both smoothed. 1 m probe spacing

anomalies oscillated above and below zero, the reciprocals rising to infinity at the crossover point. It also seems fundamentally incorrect to make use of the reciprocal of an anomaly, which is the difference between two resistivity levels, because the reciprocal of a difference is not equivalent to the difference of the reciprocals of the same numbers. However, it should, using the assumption of a hyperbolic relationship, be valid to relate the reciprocal of the total resistivity to water input.

It has been shown that chalkland soil holds 5.2% hygroscopic water unavailable for growth, and 9.8% water at the wilting point of plants. When saturated it can hold 16.45% water (Hall and Robinson, 1945). A reasonably comparable soil cited by them is a sandy loam, and Tagg (1964) shows that, for this type of soil, the resistivity change over this range of water content is about 120 (saturated) - 200 (wilting) - 400 (hygroscopic) ohm-metres. The values observed at the test sites at 1 m spacing ranged from 110 to 350 ohm-metres, i.e. very approximately, and assuming the comparability of the soils, from saturation to between the wilting point and complete dryness. The curve given by Tagg shows that over this range there is not a great divergence from the assumption of linearity. In Figs 6.19 and 6.20 this is tested by comparing the reciprocal and linear assumptions for the Durrington Walls ditch and chalk background at 1 m spacing, and there do not seem to be systematic differences between the curves. The ditch reciprocal values do peak a month later than the linear, but the curves are very flat here and the difference is probably not significant. The anomaly relationships were therefore calculated on the linear basis, and they do produce, at their best, slightly better correlations than any published by Al Chalabi and Rees - though one must bear in mind that differences of soil or method of anomaly calculation could be responsible for this.

The correlations shown in Fig. 6.19 were originally negative, with the exception of those based on reciprocals and the first two values of Durrington Walls 5 ft. Except for the reciprocals, the signs of all coefficients have been reversed for ease and clarity of presentation. The times of best correlation are starred, those in the T column being used as the starting points for the T-t calculations.

6.4. INTERPRETATION OF THE RESULTS

The apparently wide variation in the resistivity patterns of the three ditches through the year is broadly explicable in terms of the higher porosity of the filling compared with the close-textured chalk bedrock. Such a filling might be expected to absorb more water during periods of surplus, and give it up more readily by drainage and evapotranspiration during periods of net water loss. This pattern is followed fairly straightforwardly at Woodhenge but at the other two sites it is modified by other factors; however, in Figs 6.15 and 6.16, which compare total resistivity of the anomalies with that of the chalk background, the shapes of all the curves are similar, and it can be clearly seen how the observed anomaly patterns (Figs 6.12 and 6.13), the differences in height between the curves, which look superficially very different, result simply from their degree of overlap and relative amplitude.

In the following analysis, the Hog's Back ditch is considered first. Its relative simplicity and extreme response pattern, combined with the additional information gathered from the extended series of readings taken on 13 November 1971, provide important insights into the mechanism of resistivity anomaly production, in this type of circumstance at least, and the interpretation of the other two sites is considered in the light of these.

6.4.1. HOG'S BACK. The high resistivity of this ditch following net water loss, and its lack of a low response in winter conditions, must be due to the small cross-section of water-retentive material (Fig. 6.5a, layers 3 and 4) that it contains. At first sight, the explanation seemed to be that the anomaly was the result of the drying-out of these layers by a combination of evapotranspiration above and drainage into the coarse-textured primary silt below, aggravated by the large number of high-resistivity flints present and the fact that the primary silt is near enough to the surface for its high resistivity to be directly detectable by the instrument. The data obtained from the work carried out on 13 November 1971, summarised in Figs 6.17 and 6.18 (and already discussed in the context of probe configurations in Chapter 5), require that this interpretation be modified and extended as enumerated below.

1. In Fig. 6.17, the response at 5 ft of Twin is nil, and of Wenner and Double Dipole poor, although in each case at least two readings should be fully affected by the ditch which is deep enough to have a substantial influence on the measurement. This indicates that the mean resistivity of the ditch filling is not very high.

2. There is a steady increase in response as probe spacing narrows, with a possible step change between 5 ft and 1 m; therefore the driest material is close to the surface.

3. The double peaking of W remains at its closest spacing of 2.5 ft, although at that spacing either one reading must be fully over the ditch or two successive ones should be equally influenced by it. This indicates that there must be a continuous gradient of increasing dryness reaching a maximum at the centre of the ditch; and the persistence of simple double peaking indicates that the response is to an effectively horizontal laminar feature.

4. At 2.5 ft, and to a lesser extent at 1 m, a 'shoulder' appears on the left-hand side of the W, Sq and DD peaks, but is absent from Tw. It appears, however, on Tw at 0.5 m. The compact configurations, with relatively shallow current penetration, are clearly detecting the berm of the barrow, where topsoil depth reaches 0.4 m, only 0.15 - 0.2 m deeper than normal, whereas it is undetectable by Tw except at very narrow spacings. This

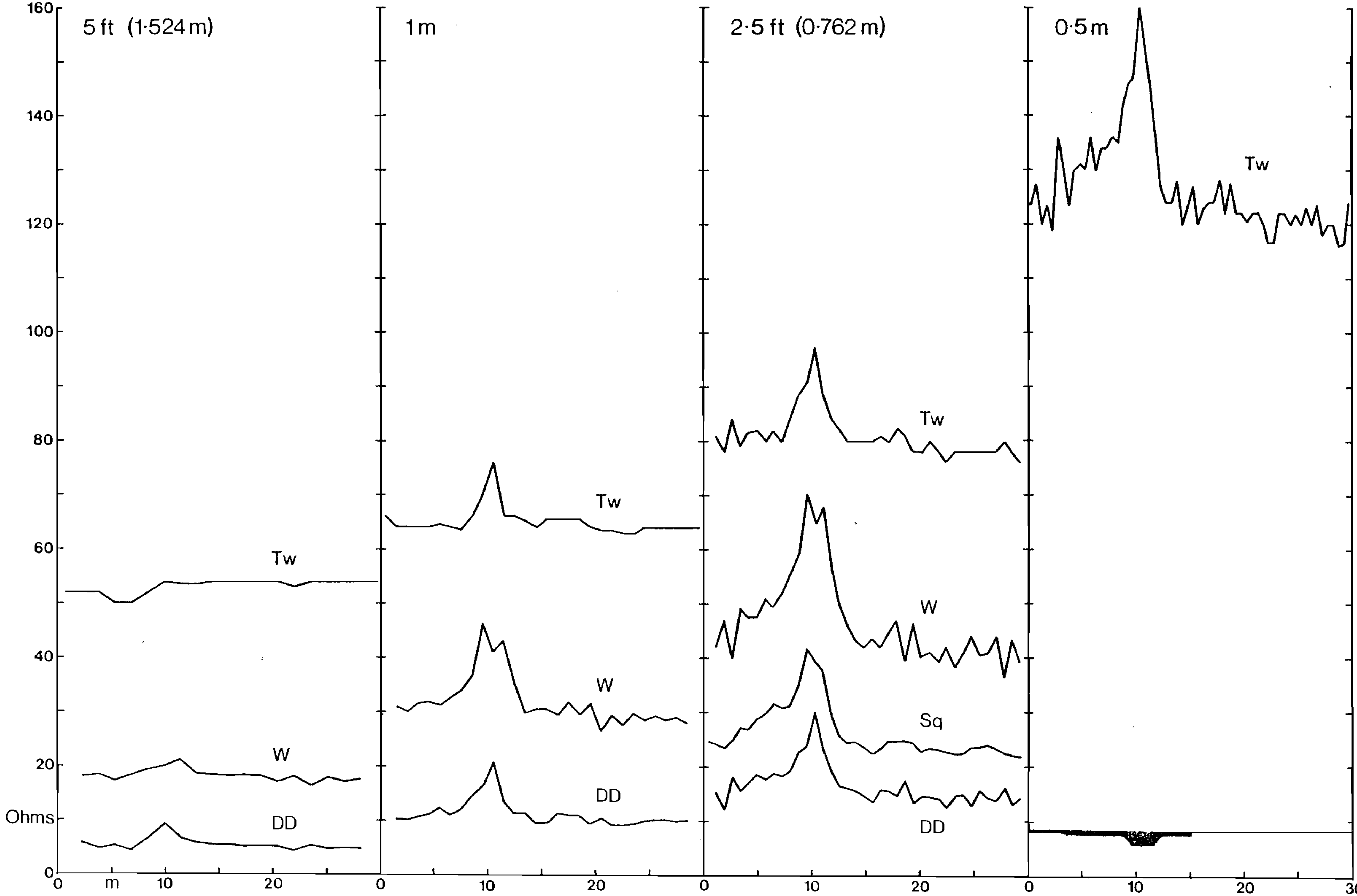


FIG. 6.17. Hog's Back: measurements on 13 November 1971 repeated with various configurations and probe spacings. Raw data

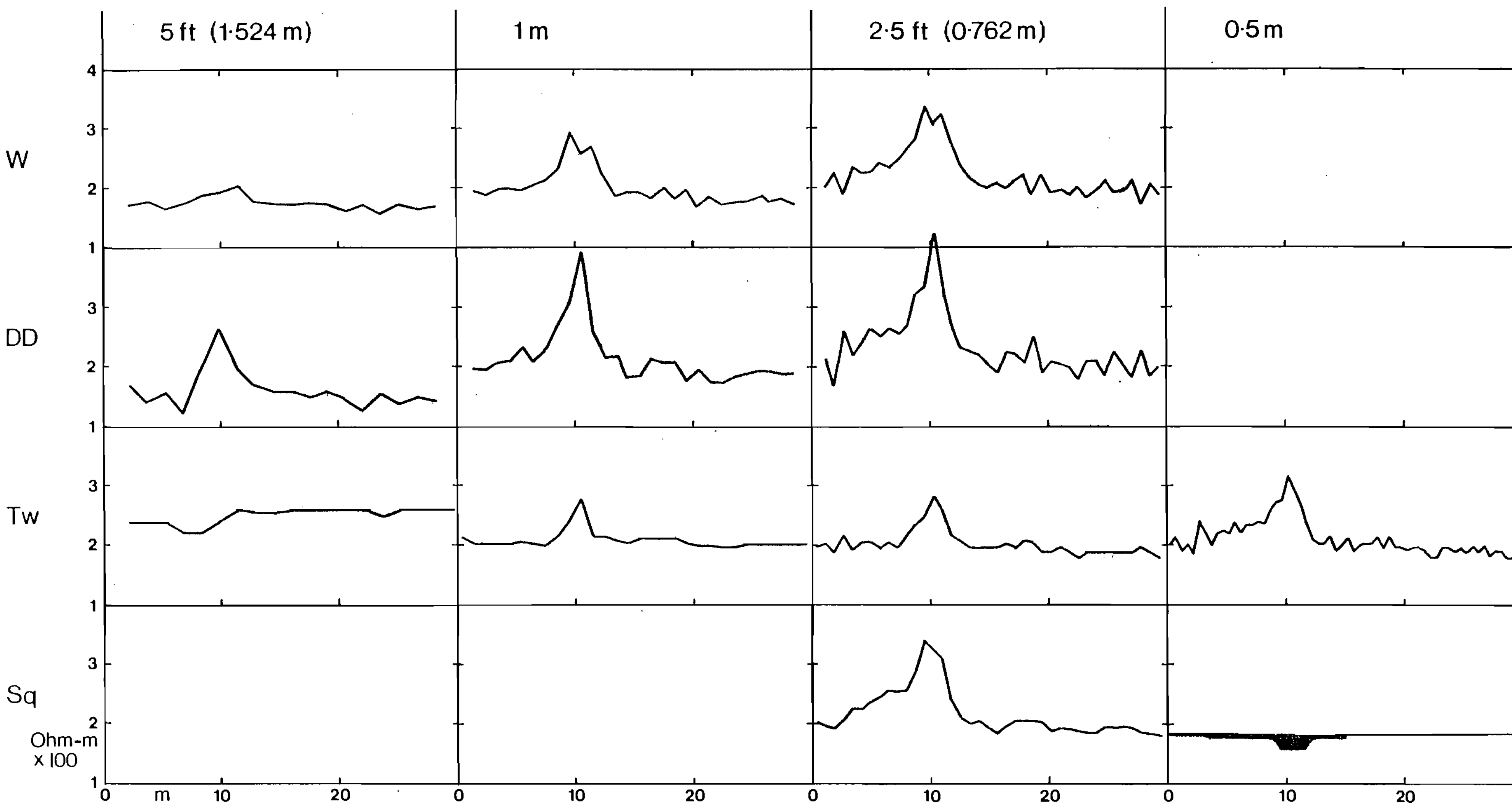


FIG. 6.18. Hog's Back: measurements on 13 November 1971 repeated with various configurations and probe spacings. Data converted to apparent resistivity values

confirms the very high sensitivity of the narrow-spacing compact configurations at shallow depths, compared with the bias of Tw toward deep penetration. It has been calculated by Parasnis (1962) that 70.6% of the current (in homogeneous earth) does not penetrate deeper than the spacing of the current probes which, bearing in mind the noisiness of practical measurements, may be regarded as the effective limit of detection (see also Fig. 4.1).

In summary, the evidence from the Hog's Back ditch shows that, in this type of case at least, resistivity sees not so much the feature itself as its drying effect on the layer of soil over it, or rather the action of the feature in impeding the replacement of moisture lost by evapotranspiration. (1) shows that the mean resistivity of the ditch contents is not high, and that layers 3 and 4, even when acting as a barrier to water movement, retain enough water to compensate for the high resistivity near the surface and of the primary silt. Water retention must be aided by the well established facts that its transfer by capillary action in soils is slight (Hall and Robinson, 1945; Russell, 1957), and that a coarse layer impedes drainage from a close-textured layer overlying it by reducing the hydraulic conductivity (Hillel and Talpaz, 1977; Clothier, Scotter and Kerr, 1977); and the effect of the retained moisture must be emphasised by the high sensitivity of resistivity measurement (already demonstrated theoretically and in the electrolytic tank) to low resistivity features. Fig. 6.21 attempts a visual summary (at the same scale as Fig. 6.5a) of the likely water regime within the ditch section in the form of notional 'contours' of resistivity increasing toward the surface.

The virtual absence of any anomaly in conditions of saturation indicates that the high and low resistivities of the layers in the ditch continue to cancel one another in these conditions, and the removal of the superficial drying effect is decisive. A very small positive anomaly does in fact tend to persist, but this is commensurate with the noise level of the Wenner readings, and would not be of practical use. However, as Figs 6.10 and 6.11 show, the Double Dipole at 1 m spacing was particularly effective for the Hog's Back ditch; it actually extended the period (at least to January 1972) when it was detectable, and might well have been able to detect it throughout the period of suppression. This is probably due to a combination of the fact that evapotranspiration does not entirely cease even in conditions of excess water input (Hall and Robinson, 1945), and the particular effectiveness of DD at shallow depths. By comparison with Woodhenge (below), the similarity of the ditch resistivity to that of the background is unlikely to be due to the general saturation of the upper layers, but to a genuinely delicate balance of resistivities within the components of the ditch filling which may be common among ditches of about this size. There do seem to be slight variations on either side of zero anomaly depending on the nature of the fillings; for instance, a comparable ditch at Tadworth (Clark, 1977) tended to give a very slight low anomaly in the same conditions: perhaps the large number of flints in layer 3 of the Hog's Back ditch tip the balance the other way.

6.4.2. WOODHENGE. Here the soil filling is deep enough for its low resistivity to be dominant throughout the periods of water surplus when the Hog's Back ditch is suppressed. In these conditions, the anomaly due to the ditch is a broad low displaced rather to the left of the deepest part of the comparative section. This is probably due to a combination of three factors: the ditch is actually turning in this direction; layers 2 and 3 remain deep beyond the main margin of the ditch on this side; and the buttress of unquarried chalk, and the relatively sterile fill between it and the side of the ditch, must continue under the traverse line, creating conditions similar to those in the Hog's Back ditch, which is of similar depth. In the dry part of the year, the low anomaly is slowly diminished and eventually reversed, while a high peak, like that over the Hog's Back ditch, develops over the buttress and sterile fill. There is also a tendency, as in August 1971 (Fig. 6.9) for positive peaks to develop over the berm-like extension of the ditch to the left (probably a ramp produced by a combination of weathering and erosion by the plough), and over what remains of the bank to the right: 10-20 cm of chalk lumps beneath about 20 cm of soil.

The layers in this ditch, including the uppermost, contain three turf lines separated by ploughwash. These probably have particularly good water retention, aiding the production of a low resistivity anomaly. Without them, the ditch might have behaved more like that on the Hog's Back.

6.4.3. DURRINGTON WALLS. The anomaly pattern at Durrington Walls is similar to that at Woodhenge, except that the variations are less extreme and the whole profile is 'lower'. Evidently this massive ditch is buffered against water loss by the good water absorbence of layer 2 and the absorbence and retentivity of layer 4 - the two layers having a total depth of about 4 m - above the drainage barrier of the coarse lower silts. The fine silt of layer 4 probably forms a particularly effective water reservoir. It is notable that, even in the very dry conditions of July and August 1970, the 5 ft spacing never gave a 'high' anomaly, showing that it was penetrating to water reserves less accessible to the 1 m spacing, and absent from the smaller ditches. As discussed in 6.4.4, the 1 m spacing was more rapidly responsive to weather conditions here than with either of the other ditches, indicating that the upper part of layer 2 at least, being simply ploughsoil, is relatively close textured, while in the smaller ditches the more water-retentive material of old turf lines is included in the measurements. At Durrington Walls the drying of the open-textured upper levels must also inhibit evaporation from the lower levels (Hillel and Talpaz, 1977), further emphasising the contrast in their water contents and increasing the isolation of the water retained below. However, although more responsive to contributed water, the 1 m spacing normally gave low anomalies which must have been due to some direct response to the water stored at lower levels.

This analysis is supported by observations while making the auger borings to establish the upper part of the ditch profile (Fig. 6.3b) on 28 April 1972. Under relatively dry soil, the top of the chalk layer at 0 m was extremely wet, with 2.5 cm of very wet soil above it - a direct demonstration of a coarse layer acting as a barrier to downward movement of water. At 2 m the soil became distinctly damper below 95 cm, and at 4 m below 90 cm. At 6 m (apparently over the weathering ramp, where the relative textures of the layers were probably reversed) increased wetness was less noticeable.

Apparently confused readings at Durrington Walls following dry conditions, e.g. July 1970 and October 1971, with high peaks at 6 - 7.5 m, must be due to the drying-out of the shallow filling over the weathering ramp; indeed, the occurrence of this peak is evidence, not produced by the coring, that the profile here is comparable to that of the excavated section (Fig. 6.3). A similar rise at the beginning of the traverse may be due to the chalk layer mentioned above which is probably the buried tail of the lynchet in one of its phases of development (Fig. 6.1) Between these effects, there is little room, in this narrow part, for the real ditch anomaly to be produced at all in dry conditions. It was almost certainly such phenomena that led to the difficulty in selecting a test site in July 1970.

It should perhaps be added here that the position of the traverse was chosen so that the drying effect of trees on the lynchet would be minimal: the nearest tree was a small elder 2.5 m up the bank from the zero point, the foliage of which hardly overlapped the traverse.

6.4.4. CORRELATION WITH WATER BALANCE. Figs 6.12 - 6.16 summarise the relationship of water balance to anomaly production. In them it is tempting to see the phase difference between the water balance and resistivity curves as the interval necessary for the water status at any time to produce a corresponding resistivity effect; but there is in every case an almost immediate response by the resistivity curve, in the form of a reversal of slope, at times of changeover between water gain and deficit. This is supported by the correlation coefficients (Figs 6.19, 6.20) which show response periods considerably longer than the phase differences.

Fig. 6.14 shows that there is a modest oscillation in the resistivity of the Wiltshire chalk, the deeper chalk detectable at 5 ft spacing being very slightly more stable throughout the year than the shallower detectable at 1 m spacing. The pattern is similar in Surrey (Fig. 6.16) but more subdued, possibly due to some difference in the texture of the chalk (or even the texture or thickness of the overburden), because the precipitation patterns and amplitudes are very similar. That the climatic changes are greatly smoothed by the chalk is shown by the poor correlation with the precipitation figures.

The ditch fillings, and therefore the sizes of the anomalies, are more responsive to the changes in water balance (Figs 6.12, 6.13). At Woodhenge and the Hog's Back the 5 ft response is diminished but synchronous with the 1 m; only at Durrington Walls is there a time lag between the two, which has been discussed above. Thus the correlation curves for both 1 m and 5 ft for Woodhenge and Hog's Back peak simultaneously (Fig. 6.20), at about 4 months and 4½ months respectively. This shows that both are responding to the mean full period of water deficit, and to a similar period of water gain until 'field capacity' (maximum water retention in equilibrium with drainage) is reached. The correlation for the Hog's Back is noticeably better throughout, because of the simple relationship there between water deficit and anomaly production.

The Durrington Walls 5 ft anomaly shows a long-term correlation with water input that may not even have reached its maximum at 6 months, the longest period considered. This is in keeping with the stability of the lower layers of the ditch (but see below). The 1 m correlation peaks relatively early at 2 - 3 months, but the correlation is poor; however, the total apparent resistivity over the ditch at 1 m spacing correlates well at 5 months, and the contrast between these results emphasises the slow overall responsiveness of the ditch filling to external factors, compared with the variations, often quite short-term, that occur close to its surface. The physical implications of this behaviour have already been briefly considered in 6.4.3.

Clearer and more practically useful information is given by the graphic presentation in Figs 6.12 and 6.13. These show that the high resistivity anomalies on the Hog's Back increase as long, and only as long, as the water deficit conditions favourable to their production persist, while low resistivity anomalies at Durrington Walls and Woodhenge tend to level off after about 4 months of water gain either because field capacity is reached, or because of the downturn in the rate of increase of water input. In the calculations above, the time correlation for the Hog's Back is thus probably more the result of the accident of nature that defines the length of the water deficit period, while the poor correlation for Durrington Walls reflects the struggle of the correlation expression to deal with data which, although showing a clear response to water gain, are sluggish in response to water deficit.

The minor peaks at February 1971 in the anomaly curves for Durrington Walls and Woodhenge (Fig. 6.12) are the result of the running means including relatively small anomalies for January and March, both due to suppression of resistivity contrasts by heavy rain during the week previous to the measurements. In this context it is interesting to

WATER	HOG'S BACK		WOODHENGE		DURRINGTON WALLS				WILTS CHALK	
T	1 m	5 ft	1 m	5 ft	1 m	5 ft	1m total	1m total recip.	1 m	1 m recip.
1 week	.240	.158	.013	.006	.023	-.293	.279	.256	.396	.409
3 weeks	.465	.383	.175	.209	.109	-.113	.403	.458	.496	.546
1 month	.439	.409	.329	.328	.357	.066	.533	.548	.438	.480
2 months	.696	.642	.664	.662	.606*	.293	.681	.642	.406	.423
3 months	.800	.752	.809	.751	.596	.487	.742	.721	.509	.496
4 months	.872	.847	.839*	.829*	.600	.621	.756*	.761	.527	.508
5 months	.880*	.859*	.824	.821	.548	.650	.743	.800*	.596*	.575*
6 months	.861	.834	.804	.795	.448	.705*	.688	.739	.578	.545
t										
-1 week	.889*	.878*	.865	.844	.657	.740				
-3 weeks	.834	.813	.873*	.852	.724*	.748*				
-1 month	.819	.806	.866	.853*	.655	.714				
-2 months	.704	.715	.756	.740		.666				
-3 months	.489	.521	.515	.558		.520				

FIG. 6.19. Correlation coefficients between anomaly size and water input for various periods before each measurement

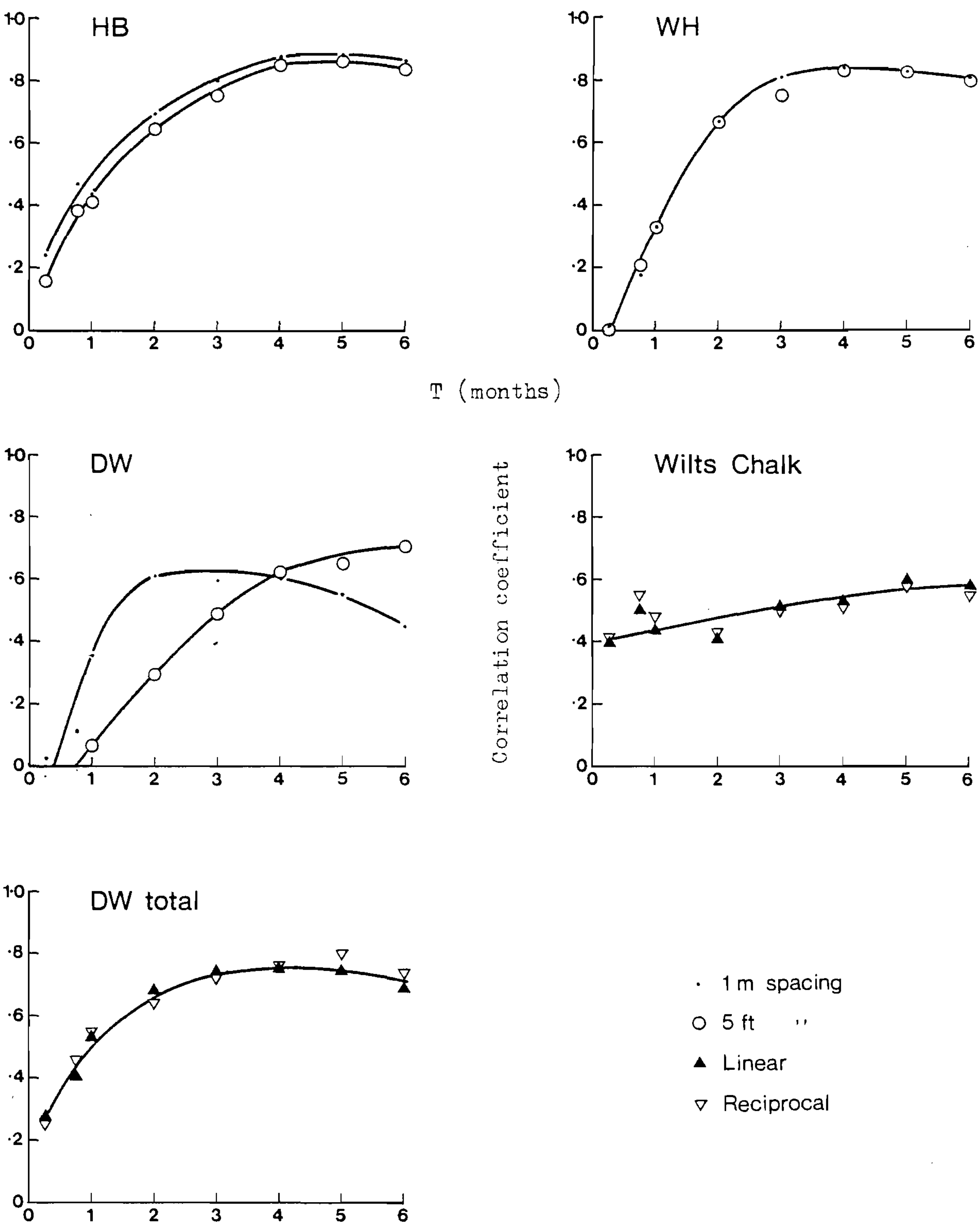


FIG. 6.20. Correlation coefficients between anomaly size and water input during T months before each measurement (from data in Fig. 6.19)

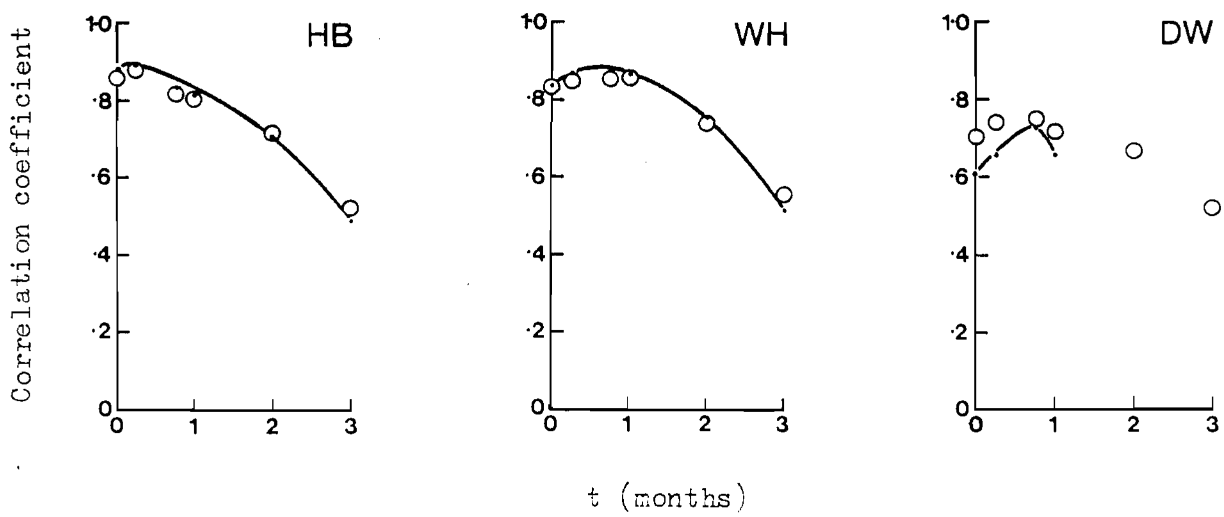


FIG. 6.21. Correlation coefficients between anomaly size and water input during T-t months ending t months before each measurement (from data in Fig. 6.19). Symbols as in Fig. 6.20

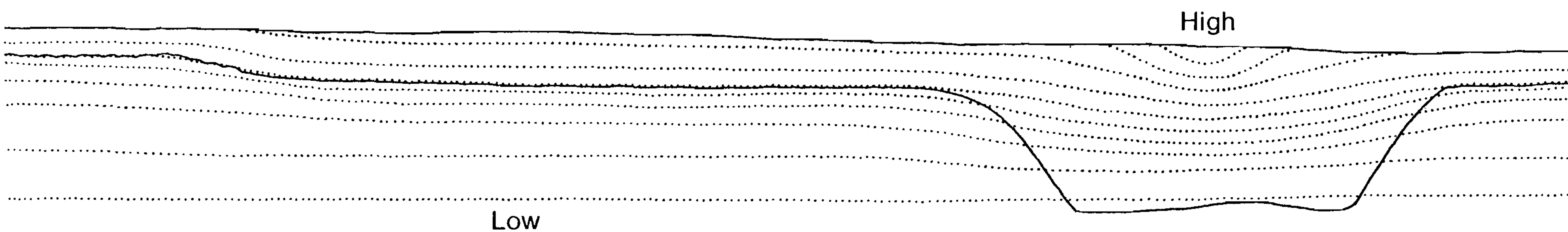


FIG. 6.22. Approximate form of vertical water content/resistivity contour distribution for the Hog's Back section, as deduced from the work described in this chapter. Cf. Fig. 6.5a

consider the T-t correlations in Figs. 6.19 and 6.21. For the Hog's Back these show an improvement if the week previous to the measurement is discounted; for Woodhenge and Durrington Walls about three weeks. Al Chalabi and Rees interpreted this as meaning that weather during the period t up to the time of measurement should have little effect on anomaly size, because its contribution to anomaly production was relatively slight. However, the input of rain prior to the Wiltshire measurements of January and March 1971 produced an immediate effect in opposition to the long-term effect of rain. Thus the fall in correlation as T-t tends to zero must be in part at least a reflection of the disturbing effect of such recent rain, which therefore cannot be ignored.

6.5. CROP MARKS

In the course of the resistivity tests, neither the Hog's Back nor the Woodhenge ditches produced a crop mark - or rather a grass mark - visible from the ground, except that, in dry periods, the grass over the Woodhenge ditch was just detectably lusher than that beside it. At Durrington Walls a very clear mark occurred, indeed it was mainly the clarity and definition of this that led to the final choice of position for the test traverse; and, as the crop mark mechanism is related to that of resistivity, it seemed worthwhile to monitor the behaviour of this during the experiment. Some discussion is also appended on the crop mark that led to the discovery of Woodhenge, and other crop marks close to that site.

6.5.1. DURRINGTON WALLS. Colour photographs of the mark were taken in October 1970, and on each monthly visit to the site in 1971, excluding January, all from exactly the same spot, and notes were also taken. The status of the field was that it had recently been taken out of cultivation (as previously mentioned). It had been seeded with grass, and was cut for hay yearly. The mark consisted of this grass, with a proportion of wild plants, contrasting with the ground over undisturbed chalk, 18 to 25 cm deep in the vicinity of the ditch, where the grass

a

b

FIG. 6.23. The Durrington Walls grass mark, looking east on (a) 12 October 1970; (b) 15 February 1971. The test traverse is in the middle distance. The lynchet that partly overlies the ditch is on the right, and the embankment of the new road built after the excavation can be seen in the distance

grew relatively thinly with few other plants mixed with it. The progress of the mark is chronicled below.

13.7.70. Mark mostly lodged; colour contrast reduced by general dryness of the conditions. Lodging of the crop in the south-west corner of the monument, visible on an air photograph taken in May 1924, was one of the phenomena that enabled Crawford to trace parts of the ditch (Crawford, 1929).

10.8.70. Grass cut about two weeks previously. For the effect of this, see below.

14.9.70. Mark beginning to become re-established.

12.10.70 (Fig. 6.23a). A good contrast between the lush mark and the yellowish grass over the undisturbed chalk. Contrast seemed to be increasing.

28.11.70. Mark had lost colour contrast, but remained as contrast in grass height.

15.2.71 (Fig. 6.23b). Frost and snow. Mark visible as long grass.

22.3.71. Mark reduced to rather battered-looking long grass without colour contrast: everything very light brown.

19.4.71. Mark showing well as strong green mark in new grass.

17.5.71. Everything very green and lush, but mark a little darker and longer than the rest.

21.6.71. Field recently cut but not cleared, but the mass of light brown cut stems of the grass over the ditch quite distinctive compared with the shorter green grass visible over undisturbed ground where the cuttings were more thinly spread.

19.7.71. Cuttings cleared. Mark noticeably greener than rest of field.

16.8.71. Much like previous month.

20.9.71. Mark very green compared with the rest of the field.

18.10.71. Mark showing as lush, rather yellow, light-coloured vegetation compared with the rest of the field, which was rather brown. Grass over ditch 20 to 25 cm high, considerably taller than elsewhere.

13.11.71. Similar to previous month. Mark quite silvery-looking.

13.12.71. Field generally light brown, but mark lighter and still with taller grass and distinctly visible.

The first and second of these observations, for 13 July and 10 August 1970, coincide with the only time when high resistivity anomalies were obtained - at 1 m spacing - and the loss of colour contrast indicates that the grass was feeling the strain of this. Otherwise the mark maintains its greenness in contrast with the background for much of the growing season and even in winter is visible because of the length of the dead grass. And again, at the height of the 1970 summer the lodging made it visible.

The limit of the mark was at 17.2 m on the resistivity traverse, and its breadth is indicated in Fig. 6.3b by the tall plant symbols. In spite of the apparently indeterminate position of this limit in relation to the ditch, it was sharply defined and did not vary. It may perhaps therefore be presumed that the depth of soil at the limit of the mark - about 0.8 m - represents the greatest depth to which the grass roots can penetrate in search of moisture: and it must be freedom of ramification rather than the moisture percentage in the soil that allows strong growth to occur in the drier months. Although in drought conditions the chalk can contain a greater percentage of water than the soil filling the ditch, the roots cannot penetrate the chalk to obtain it.

6.5.2. WOODHENGE. The unusual nature of this site, originally thought to be a disc barrow, was recognised from the air by Squadron Leader Insall, V.C. His first observation was in December 1925, when only indeterminate chalk marks were visible in the ploughsoil. He later wrote: 'In [the following] July, when the wheat was well up over the site, there was no further doubt. Five or six or perhaps even seven closely-set rings of spots appeared, and were photographed. I climbed on to a hayrick in the same field a few days leter, and although a few dark patches could be seen in the standing wheat, no pattern was visible, and they would have passed unnoticed. From the air the details of the site were as clear as on the photograph, if not clearer' (Insall, 1927). M. E. Cunnington (1929) adds: 'Having been shown the photographs by Squadron Leader Insall, a visit was made to the site in the beginning of August, when the taller deeper coloured growth of the wheat forming a continuous band along the course of the ditch, and tufts over the pits, were clearly seen, but without the advantage of a bird's eye view it was not possible to see on what plan they were arranged.

'Photographs of the site had been taken from the air in previous years, but had shown only the circle of the earthwork itself, always plainly discernible on the ground. A photograph taken later in August after the wheat was carried, also showed nothing, although on the ground it was possible to trace some of the larger holes by the deeper colour and stronger growth of the stubble. It was a fortunate chance that Squadron Leader Insall should have seen the field just when the wheat most plainly revealed the secrets hidden at its roots.

'We were told by the farm workers that the peculiar and irregular way in which the corn grew at this spot was always noticeable at harvest time, for the corn grew so thick in patches that it got beaten down and consequently difficult to reap.

'The earthwork lies in the corner of a large open arable field, and at the time the photograph revealing the rings was taken, the whole field including the earthwork was covered with a fine crop of wheat, nearly at its full height. It will be realised, therefore, that what is seen on the photograph was due to irregularity in colour or growth of the wheat covering the actual surface of the ground. The soil here is only a few inches deep over the chalk, into which the long fibrous roots of the wheat penetrate with difficulty. On the other hand, wherever a hole has been dug down previously into it, the disturbed chalk disintegrates and becomes comparatively soft, and is moreover generally mixed with soil, so that the long rootlets penetrate, and finding congenial conditions, the corn grows better than on the surrounding undisturbed ground... It was, therefore, realised at once that the dark spots shown on the photographs probably represented pits of some kind, just as the dark ring enclosing them represented the taller and deeper coloured growth of corn over the filled-in ditch.'

The photograph taken by Insall on 30 June 1926 is shown in Cunnington (1927 and 1929) and also in Clark (1940). Prints from the original negative of this and a near-vertical shot taken at the same time were also kindly lent to the writer by the Air Photographs Unit of the National Monuments Record (NMR Nos. SU 1543/131 and SU 1543/132). On these photographs, there is a lighter band along the centre of the dark crop mark of the ditch. The obvious explanation for this is that it represents the beginning of the summer drying-out process, but, according to the resistivity, at least where the test traverse was placed, such an effect would be expected to develop eccentrically - cf. July 1970, Fig. 6.7. In 1971, a more typical year but still relatively dry, the ditch anomaly in July (Fig. 6.9) is still low; also, on the photographs, the comparatively insubstantial post holes and slighter ring ditches, probably of barrows, are all dark. Cunnington sectioned these and showed that the majority are similar in shape and filling to the Hog's Back ditch, though most are smaller, yet all showed as dark marks in the crop. The darkest mark was produced by the outer ditch of Cunnington's Circle 1, which was unexceptional apart from the fact that it contained a deeper and cleaner chalk rubble primary filling than the others, in which the rubble was more contaminated with soil. It seems inescapable that this ditch was benefiting from the condition of clean chalk rubble in some way; and the dark edges of the Woodhenge crop mark seem to have overlain the sides of the deep part of the ditch where the chalk rubble produced by the primary silting process was closest to the surface. R. Palmer (private communication) states that many crop marks on the Chalk behave in this way, with especially strong growth defining their edges. It thus seems likely that the crop is able to make use of moisture accumulated at the interface between the rubble and the finer soil above it by the mechanism discussed above (6.4.1); and it is even possible that, in conditions of increasing water deficit, some or all of this moisture may be derived from the chalk blocks themselves and from the chalk sides of the ditch, predominantly in the vapour phase: the large surface area of the blocks should be conducive to this, and the warm conditions encouraging to both upward movement of the water in the bedrock, and vaporisation. By some such processes, a lush crop is able to survive, sometimes indefinitely, after resistivity readings are detecting the relative dryness of the upper part of the filling in contrast with the undisturbed chalk; but in extended drought these conditions break down, and the ditches become parched. This has occurred on a photograph of the same field taken on 18 July 1930 (NMR No. SU 1543/155), and photographs taken by P. Goodhew, at the height of the drought of 1976 (RCHM, 1979; NMR Nos. 1543/167 and 1543/168), not only show all the circles and the ditch of Woodhenge as parch marks of dramatic clarity (though the outer ditch of Circle 1 remains the least parched), but also reveal many slighter ditches, probably of Romano-British fields, never previously seen. Thus it seems that a ditch may be too small to produce a positive growth mark, but still capable of producing a parch mark in conditions of extreme stress - which is reminiscent of the resistivity behaviour of the Hog's Back ditch. The fact that the marks existed at all demonstrates the ability of the undisturbed Upper Chalk to retain and deliver moisture steadily even in such conditions.

6.6. OTHER CLIMATE STUDIES

6.6.1. LONDON CLAY (N.G. SU 985505). This study, on a bedrock type not previously investigated, was conceived as complementary to the chalkland work. It was relatively brief, the features less well understood, and the weather less carefully monitored, so that it might be usefully extended at a later date. It was carried out during 1975 at the University of Surrey, Guildford, initially by M. D. Janes as part of a final year B.Sc project in the Department of Physics (Janes, 1975), and the measurements were completed by his supervisors, A. G. Crocker and the writer.

A farm called Deer Barn once stood at the foot of the northern slope of Stag Hill, which is entirely of London Clay, and was demolished when the university campus was created. Guildford Cathedral stands on the crest of the hill. Careful use of maps enabled the site of the farm to be relocated, and a 25 m test traverse was laid out across part of it. A substantial high anomaly over approximately the first 10 m of the traverse proved to be suitable for the measurements: although it was not possible to ascertain its exact cause, it was probably a pond backfilled with a mixture of rubble and clay. 1 m W and DD were used for all the measurements, which were repeated monthly from February to November 1975. The instrument used was a Martin-Clark Type 2. As expected on clay, background resistivity was always low, never exceeding 15 ohm-metres in spite of the drought of that year. The strength of response followed a pattern very similar to that of the Hog's Back ditch, the best response being from June to November, peaking in September when the anomaly reached 214 ohm-m above the base level with W and 296 ohm-m with DD. It was at its weakest in May (W = 12 ohm-m; DD = 18 ohm-m), just before the commencement of the rise in mid-June. In February, March and April, it was at a quite constant level of about W = 15 ohm-m; DD = 23 ohm-m. Although, unlike that on the Hog's Back, the anomaly never disappeared, it was only in the driest conditions, on 7 September, that some slight additional anomalies, possibly caused by wall foundations of farm buildings, appeared. By 15 September, after heavy rain for several days, these again disappeared, and the main anomaly was reduced from the peak level given above to W = 82 ohm-m; DD = 113 ohm-m. The consistently higher values given by DD are also reflected in the relative base levels of the two configurations, and are therefore likely to be due to a gradient of general dryness toward the surface rather than shallowness of the feature causing the anomaly. Over the strongest part of the main anomaly there was a coincidence of double peaks with W and single peaks with DD, especially in the driest conditions, and the small anomalies exhibited a similar tendency.

6.6.2. FRANCE. An experiment was carried out by Hesse near the Centre National de la Recherche Scientifique, Garchy, Pouilly-sur-Loire, Nievre, in central France, during the years 1962-63 (Hesse, 1966a). The bedrock was limestone with a soil depth of up to 30 cm, apparently with a cover of short turf. A test traverse, for which 1 m W was used, was laid out across a feature which subsequently proved to be a covered, air-filled stone sarcophagus in a grave pit; its anomaly was always high with respect to the background, and at its best in the form of very distinct twin peaks. Maximum response again occurred during the latter part of the year, certainly from August to October: figures are not given for July.

It is especially interesting that Hesse's experiment coincided with one of the coldest winters of the century. Measurements during a brief thaw after ten days of heavy frost from 11 January 1963, when the ground temperature remained between 0° and -10°C, showed a rise in base level from about 80 ohm-m to 500 ohm-m, and the anomaly due to the feature was largely obliterated by parasitic peaks. The freeze continued almost uninterrupted until 5 February, and even on 12 February the resistivity base level had only fallen back to about 250 ohm-m, and the parasitic effects were still stronger than the anomaly caused by the sarcophagus. On the other hand, the effect of a more normal period of frost in December 1962, lasting four days with minimum air temperatures between -5°

and $-10^{\circ}C$, was not detectable. It is possible that most of the difficulty was due to the frost causing high contact resistance; and the continental climate of central France probably exacerbated its effect: Russell (1957) states that in the fairly typical English conditions at Rothamstead, Herts, there is very little temperature variation between summer and winter at depths as small as 20-30 cm, and that a grass cover has a considerable effect in smoothing out extremes of temperature.

6.7. CONCLUSIONS

6.7.1. OPTIMUM RESISTIVITY CONDITIONS. The periods for best detection of features of various sizes and types on different bedrocks are summarised in the table, Fig. 6.24. It shows that, with the exception of the larger ditches on Chalk, there is a quite close similarity in periods of optimal response for a wide variety of bedrock types and patterns of weather, with a 'core time' common to all the sites of July-September. This may prove to be broadly applicable to the bedrocks of north-west Europe. Further experiments are required, for instance on gravel, although in the meantime tentative extrapolation from the present data is perhaps permissible: on the basis of texture, one would expect that gravel would behave rather like the sandstone at Wall. Work has not been done on pits, which may probably be considered as similar to ditches, providing allowance is made (for instance) for the better water retentiveness of those with a closer-textured filling. However, on all the bedrocks so far studied, except the Chalk, conditions have proved not to be critical because features - except for the slightest - are detectable throughout the year (with the possibly general exception of heavy and prolonged freezing as in the winter of 1963), and there is evidence that this is also true of stone structures on Chalk: the Roman building at Boscombe, described in the next chapter, was surveyed in continuous rain in February, yet gave anomalies up to 120 ohm-metres.

The ideal time to survey a site on Chalk with ditches and other

SITE	BEDROCK	FEATURE	DIMENSIONS	ANOMALY TYPE	MEAN BEST MONTHS	PEAK MONTHS
WALL Staffs	Triassic Sandstone	Ditches	Width variab. Depth 3.4 m max.	Low	June – September	July
HOG'S BACK Surrey	Upper Chalk	Ditch	Width 2.5 m Depth 1.1 m	High	July – November	September
SURREY UNIVERSITY	London Clay	?Rubble ?Walls	Width c. 10 m & 0.5 m Depth ?	High	June – November	September
POUILLY Nievre	Limestone	Stone coffin	Width c.0.5 m Depth c.1.5 m	High	?July – October	?October
DURRINGTON WALLS Wilts	Upper Chalk	Ditch	Width 17.7 m Depth 6.0 m	Low	December – June	March – April
WOODHENGE Wilts	Upper Chalk	Ditch	Width 6.3 m Depth 2.1 m	Low/High	December – June	March – April

FIG. 6.24. Optimum times for detection of features of various sizes and types on different bedrocks

features of varying or unknown size is rather difficult to choose. One survey during the first half of the year and another in the second would be ideal, but often difficult or uneconomical to achieve. For a single survey one must choose the second half of the year when all sizes are detectable, even though the large are relatively weak and the intermediate unpredictable. Providing the onset of rain is not too relentless, as it was in November 1970, good results may be obtained in December when the larger ditches are giving reliably low anomalies, and those of the small ditches still remain high. At Woodhenge, the high anomalies caused by the unexcavated chalk buttress and a last remnant of the bank revealed the presence of the ditch when the filling was least detectable in summer and autumn. From December to May 1971 the ridge was lost in the normal low ditch anomaly, so that surveys at different times of the year over such a ditch could be used to ascertain its outline as well as information about its more detailed structure. In this way, as with the use of suitable configurations or probe spacings to define the berm of the Hog's Back barrow, resistivity can be used to produce information of great subtlety.

The production of anomalies can be predicted most reliably if the soil water balance is monitored. As already discussed, high resistivity anomalies on Chalk (small ditches) seem to increase as long as the water deficit conditions favourable to their production persist, while low resistivity anomalies (large ditches) tend to level off after about 4 months of water gain. For practical purposes, it is probably best to consider the time lapse required from the onset of favourable conditions to the production of a clear anomaly. If this anomaly is defined as 25 ohm-m with Wenner, the times for 1 m and 1.5 m (approx. 5 ft) probe spacings are as given in the table, Fig. 6.25. This will also apply to probe spacings of equivalent penetration with other configurations, with some modification to allow for the fact that, for instance, Double Dipole gives a more effective definition of small features than does Wenner.

FEATURE & CONDITIONS	PROBE SPACING	TIME FROM ONSET	REMARKS
Large ditch (DW) (Water gain)	1 m 1.5 m	1 month 2 months	Not critical except after very dry periods
Medium ditch (WH) (Water gain)	1 m 1.5 m	3 months 3 months	Long delay because of need to wait until high anomaly is reversed
Small ditch (HB) (Water deficit)	1 m 1.5 m	1 month 2.5 months	Long delay at 1.5 m because this spacing is unsuitably large for the feature

FIG. 6.25. Time from onset of appropriate water balance to production of 25 ohm-m anomaly for the Durrington Walls, Woodhenge and Hog's Back ditches, using the Wenner configuration

6.7.2. THE NATURE OF RESISTIVITY ANOMALIES. In combination with the electrolytic tank work (see 5.3), this study has shown that small ditches in Upper Chalk behave essentially as horizontal laminar features of high resistivity. The laminar effect has also been observed over a variety of high resistivity features on clays and limestones, and largely explains difficulties with probe configurations such as the Wenner which produce a double response to such features. It seems not to be confined to narrow features, but it is probably almost entirely confined to features giving high-resistivity anomalies because of their peculiar interaction with the evaporation pattern of the soil. Low resistivity features tend to behave more three-dimensionally and, as the electrolytic tank work has shown, even if laminar in form tend to give more coherent anomalies with arrays such as Wenner.

The laminar effect seems to be largely due to interaction between the feature and evapotranspiration mainly caused by overlying grass or crops, and on bare ground would be expected to be much diminished; indeed the response of resistivity measurements to archaeological features generally would probably be suppressed in such conditions, in which experimental measurements would be desirable.

6.7.3. CROP MARKS AND RESISTIVITY. The crop mark behaviour of the larger ditches parallels their resistivity response quite closely, but the smaller ditches seem able to continue to support a lush mark at the same time as resistivity anomalies are beginning to rise. This must mean that the better rooting conditions provided by the fillings, combined with deeply stored water, are the dominant effects with the crop, while resistivity measurement readily penetrates the relatively damp chalk, detecting the water in it which is inaccessible to the roots, except as it gradually reaches the surface of the chalk mass. Thus the upper filling of the ditch, depleted of moisture by the roots themselves, stands out in contrast as a high resistivity anomaly. The moisture reserves of the larger ditches, however, tend to counteract this imbalance, most effectively in the case of the massive ditch of Durrington Walls.

Evans and Jones (1977) report the appearance of crop marks only after the potential soil moisture deficit has reached 50-90 mm, on terrace sands and gravels in Staffordshire and Kirkcudbrightshire. On the Chalk, the positive crop marks clearly begin in less extreme conditions, and it would seem that the parching effect is more closely allied to their findings.

7. APPLICATIONS AND DEVELOPMENTS

7.1. SURVEYS WITH THE OPTIMUM PROBE CONFIGURATIONS

Some of the most effective work carried out with the Wenner configuration before this study has already been briefly described in Chapter 1. Below are given some examples of surveys made with the Square and Twin configurations. In spite of its potential, the Double Dipole has not yet been so extensively used, at least in Great Britain, probably because of its relative inconvenience compared with Tw. However, its use in combination with W for test traverses is now established, and was very effective, and more convenient than Tw, for the large Grime's Graves survey (7.1.3).

The material used below has been chosen to include comparisons with magnetic surveys to demonstrate the relative merits of the two methods: there is a bias, however, in favour of resistivity because, as it is the slower method, it tends to be used only where it is likely to be most effective. A great many highly successful magnetic surveys have been used to cover areas vaster than could be economically surveyed by resistivity but, as the second part of this chapter will attempt to show, more rapid resistivity methods are imminent which will significantly increase its competitiveness with magnetic survey.

The opportunity is also taken below to demonstrate a variety of methods of presenting survey results, with some discussion of their appropriateness in the different cases.

7.1.1. SQUARE ARRAY SURVEYS WITH 2.5 ft (0.762 m) PROTOTYPE

EAST WANSDYKE. At the crossing of the dyke by the Ridgeway on the Marlborough Downs, Wilts, the Square Array was used, during small-scale excavations by Green (1971), to examine two causeways across the ditch to ascertain whether either was original. Both were accompanied by gaps in the bank and one, called Red Shore, was the causeway that actually carried the supposed ridgeway route through the dyke. A single traverse

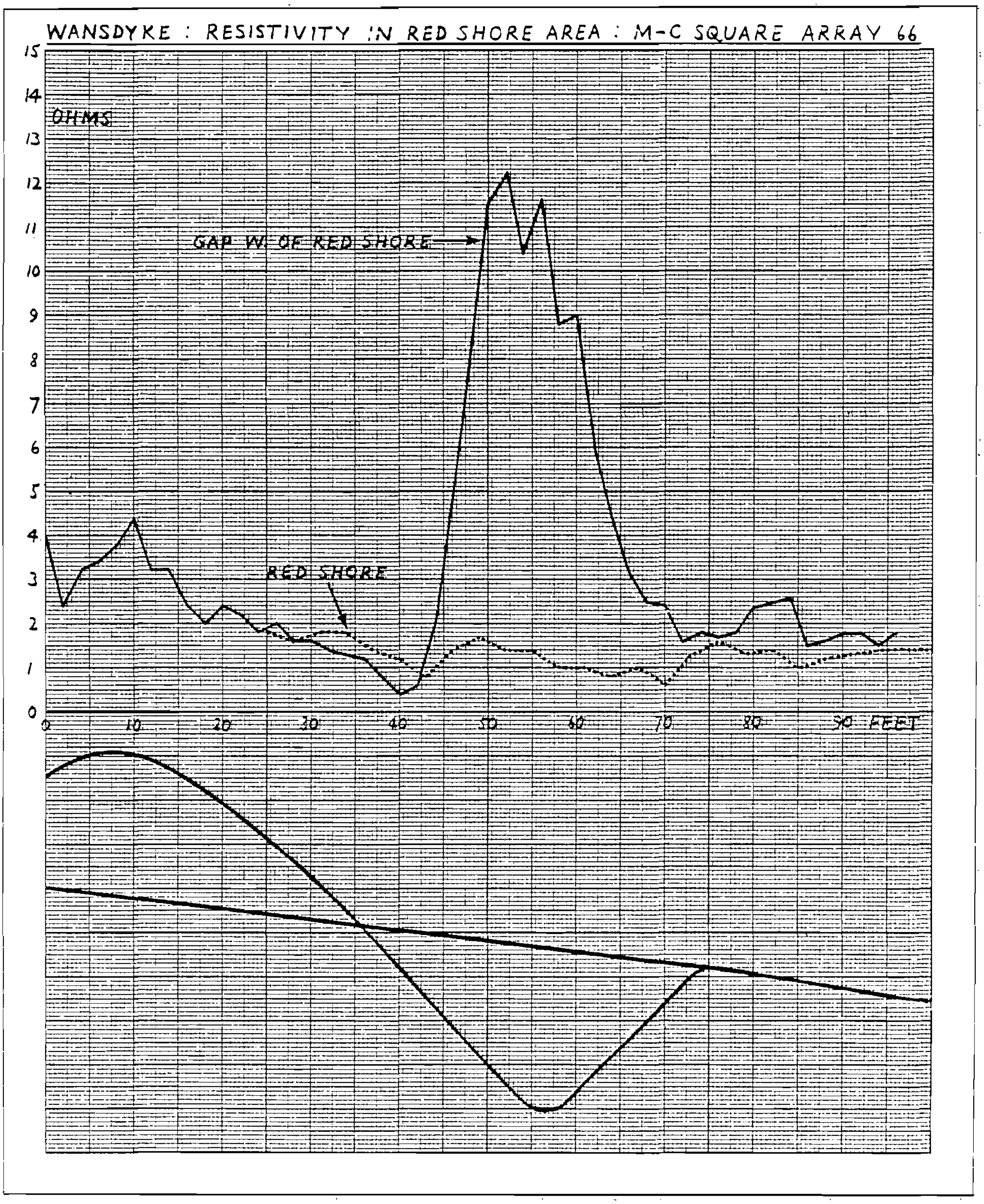


FIG. 7.1. Original graphs of resistivity measurements along two gaps through Wansdyke, slightly reduced. The lower curves show schematically the profile of the bank and ditch superimposed on the profile of the gaps

was put along the axis of each causeway, at right angles to the dyke and substantially overlapping the ground on either side. The results are shown in Fig. 7.1. The base resistivity level is low because, although the bedrock is Chalk, it carries a thin capping of low-resistivity Clay-with-flints. The resistivity results clearly show that there is no change over the Red Shore causeway, but a very substantial rise over the other, indicating that this causeway is largely composed of chalk blocks interspersed with air gaps, derived from the throwing-down of the bank. Thus it seems that the Red Shore gap is indeed original. This technique has also proved useful for checking whether gaps in the defences of the Surrey hillforts Anstiebury, Holmbury and Hascombe Hill were original entrances (Thompson, forthcoming). These forts stand on Lower Greensand hills, and the sandstone blocks of which the ramparts are largely composed produce resistivity patterns similar to those of the chalk blocks in Wansdyke.

BURTON FLEMING. This site, on the Yorkshire Wolds, was part of an extensive cemetery of square Iron Age barrows, of which only the ditches and central graves had survived the plough (Stead, 1976). These lay in a shallow valley containing a subsoil of chalk gravel, with some admixture of glacial material, over the Upper Chalk bedrock. A 100 ft square was surveyed intensively at 2.5 ft spacing with the 2.5 ft Square Array, after the Wenner configuration, at wider spacing, had produced inconclusive results, and a magnetic survey (Elsec proton magnetometer) had responded only in one small area, to what proved to be a concentration of natural magnetite particles of glacial origin.

The result of the survey is shown in Fig. 7.2, where it is compared with a plan of the subsequent excavation. Use is made of the 'dot density' method of representation (Scollar and Krückeberg, 1966), each reading being represented by a group of randomised dots proportional in number to the difference between the reading and a base level typical of undisturbed ground, giving an overall 'half-tone' effect that aids the

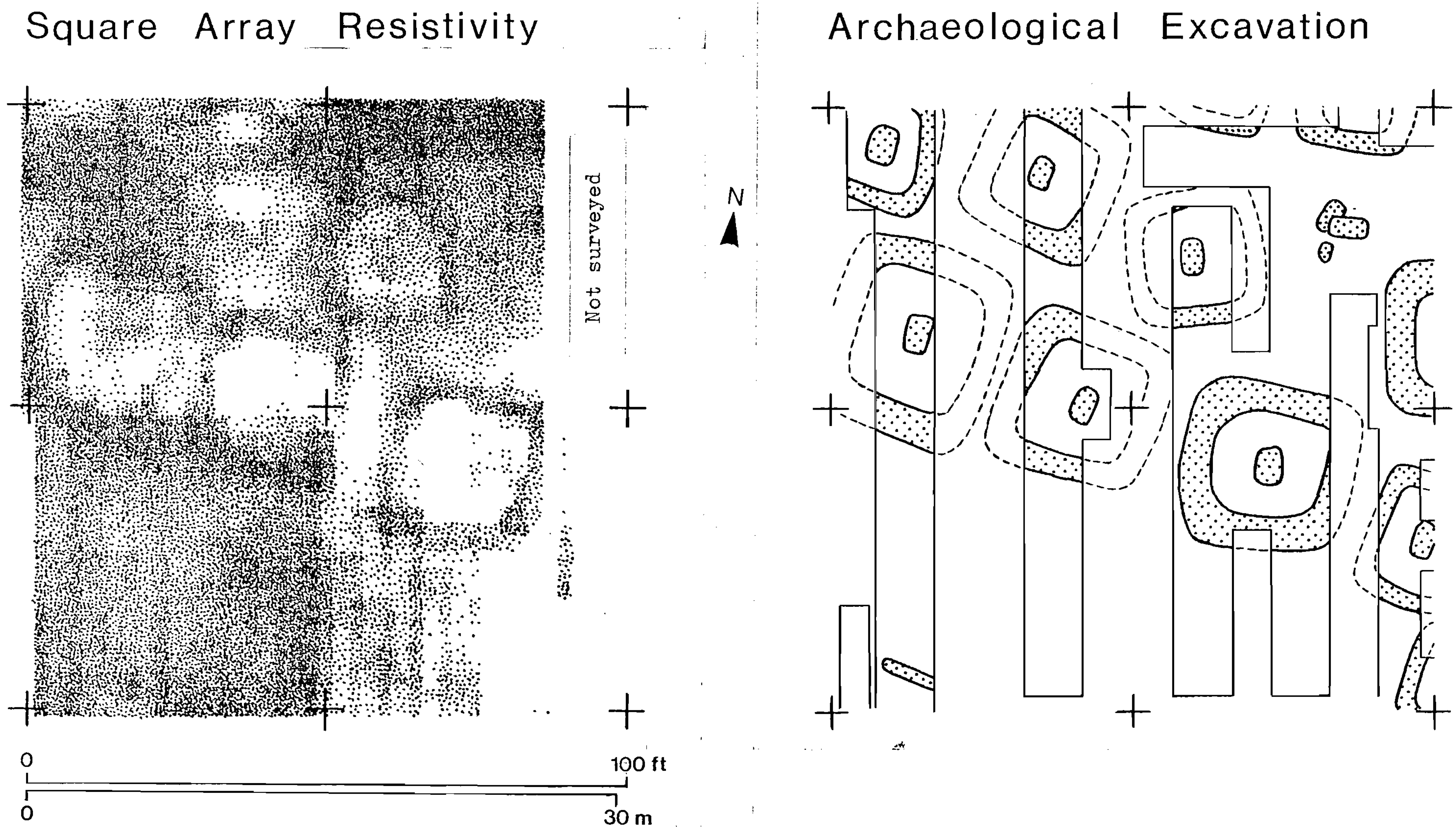


FIG. 7.2. Burton Fleming: dot density plot of survey compared with results of subsequent excavation

eye in subtleties of interpretation - as well as being readily acceptable and comprehensible to archaeologists. The best definition of buried remains is obtained by careful selection of the base level and of the rate of increase of dot density: a good general rule is to make zero density level at the mode or mean of the readings, or at a suitable value between these limits (the more anomalies there are, the more displaced and inappropriate the mean will be, and the data may become bimodal), and to allow the density to increase to total blackness at two standard deviations, either above the base level or below it, depending on whether high or low values are significant.

The present survey took place in early October, 1967 when the water retention of the ditches, though slight, was rather better than that of the open-textured subsoil, so that low readings were significant. The base level was chosen to give the best definition of the barrow in the bottom right quadrant of the area: few ditch readings diverged by more than 3 ohms below the base level of 18 ohms, so dot size and density were adjusted to saturate at 15 ohms. The dotting was done manually with a felt-tip pen, using 10 dots per ohm.

The quadrant mentioned was the first surveyed, in showery conditions which, immediately affecting the background resistance level, caused the 'stripy' effect in this part of the plot. The survey was completed after an interval of two days during which there was more rain, so that the level of the whole of the rest of the plot is too low, especially at the top edge of the survey where the effect is aggravated by deepening topsoil close to the edge of the field. More sophisticated data treatment, designed to overcome such problems, is discussed later in this chapter.

The graves show poorly, if at all, because the subsoil they contain was, in the nature of things, put back immediately after being dug out, and so differs little from the undisturbed ground. It is interesting that the corners of the barrows tend to be best defined, because in this position both the readings forming the Square Array mean value are strongly affected by one arm of the ditch or the other.

COTTAM. This site (Stead, 1979), like Burton Fleming which is only a short distance away, consists again of a group of square barrows on Wolds Upper Chalk geology, but there are interesting differences between them. The ditches at Burton Fleming were undetectable with a magnetometer able to resolve down to ± 1 nanotesla, but those at Cottam were clearly detectable with this magnetometer, giving anomalies frequently as high as 8 - 10 nT, peaking at 14 nT, and low resistivity anomalies of 2.5 - 3 ohms from a base level of about 6 ohms - up to 50% reduction in apparent resistivity. The barrows were more monumental in scale than those at Burton Fleming, the largest being almost twice as wide; the ditches, beneath topsoil about 30 cm deep, were similar in width to the Hog's Back ditch but rather deeper. Their low resistivity response was probably in part due to the hardness of the Chalk here, caused by filling of the Foraminifera cells, which make up half its bulk, with calcite (Sorby, 1879), whereas in the southern Chalk they are empty, thus allowing the water retentivity to be higher. Also, there is probably a Boulder Clay component in the Wolds soil, giving it relatively low resistivity and high magnetic susceptibility.

Figs 7.3 and 7.4 compare dot density plots of the magnetic and resistivity surveys. Although these were made at twice the reading interval (5 ft) of that at Burton Fleming, and coarser dots (at only 5 per ohm for the resistivity survey) were used for economy in plotting, the effect is just as clear because the barrows are relatively large and the readings present a strong contrast with an uncomplicated background. This is especially obvious in the magnetic plot, but the resistivity plot seems more diffuse because the starting level for plotting was made deliberately high to bring out subtle features. This has been effective in revealing traces of the graves in the two easterly barrows, but it has again, as at Burton Fleming, shown up the deepening soil at the

COTTAM: MAGNETOMETER

FIG. 7.3. Dot density plot of the Cottam proton magnetometer survey. Scale 1/500: the survey is 200 ft square

FIG. 7.4. Dot density plot of the Cottam resistivity survey. Low values plotted. Scale 1/500

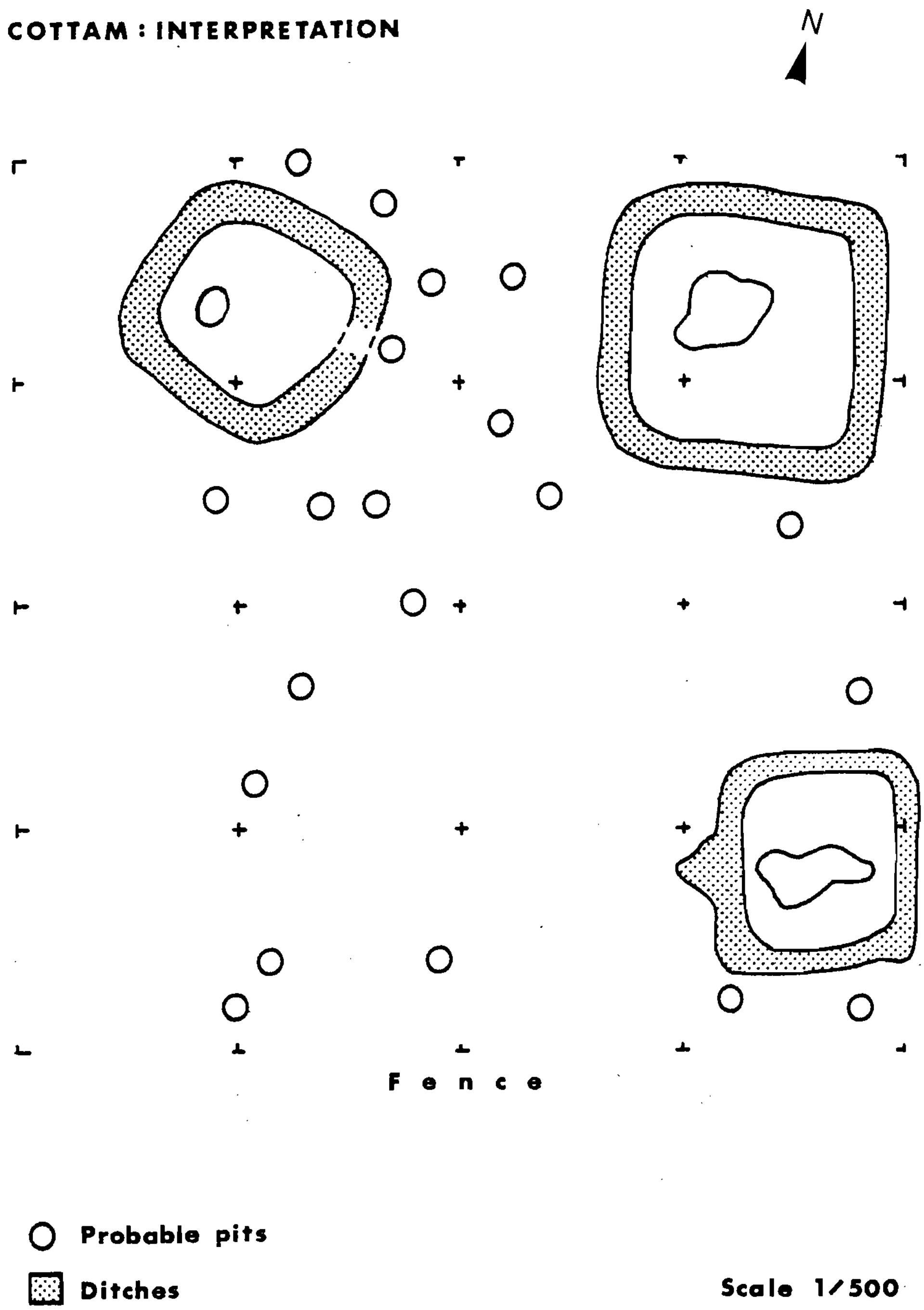


FIG. 7.5. Interpretative plan of the Cottam barrows based on the magnetic and resistivity surveys.

southern edge of the field. The interpretation (Fig. 7.5) combines the information from both surveys, probable pits being marked between the barrows where resistivity amd magnetic anomalies coincide. Subsequent excavation confirmed the effectiveness of this survey (Stead, 1979).

SHARPE HOWES. This survey, again on the Yorkshire Wolds, was done in mid-September 1967, the same year as Burton Fleming. A round barrow being excavated by T. C. M. Brewster appeared not to have an encircling ditch, but a series of quarries at the cardinal points. Three had been sectioned, but it was required to check that they were indeed discrete pits without further excavation. Square Array surveys were made at 2.5 ft reading intervals, and, as there was little likelihood of background resistivity variations of significance over the small areas involved, and the features were strongly defined, contouring was chosen as the most suitable and graphic method of representation, with an interval of 2 ohms. All the quarries were successfully defined. Fig. 7.6 shows (a) the plot of the north quarry, alongside (b) a computer contour plot used as an aid to its production. Fig. 7.7 shows the much larger west quarry. Only the contours fitting in best with the excavated sections have been selected for the final plots. There is a noticeable tendency for contours to turn inwards on approaching the trench sides because of the effect of the trench both as an infinite resistivity feature and in drying out the adjacent soil.

BOSCOMBE EAST FARM. A gas pipeline trench across the Upper Chalk downland of Salisbury Plain in Wiltshire cut through the heavily plough-eroded foundations of several walls of Roman date, partly overlying a substantial Iron Age ditch. To establish the plan of the building, a survey was made with the Square Array on a 1 m grid, partly in February and partly in April, 1970. Background reading levels were about 7 - 10 ohms, and hardly changed between the two surveys; and over the building readings rose to a maximum of 22 ohms.

SHARPE HOWES : North Quarry

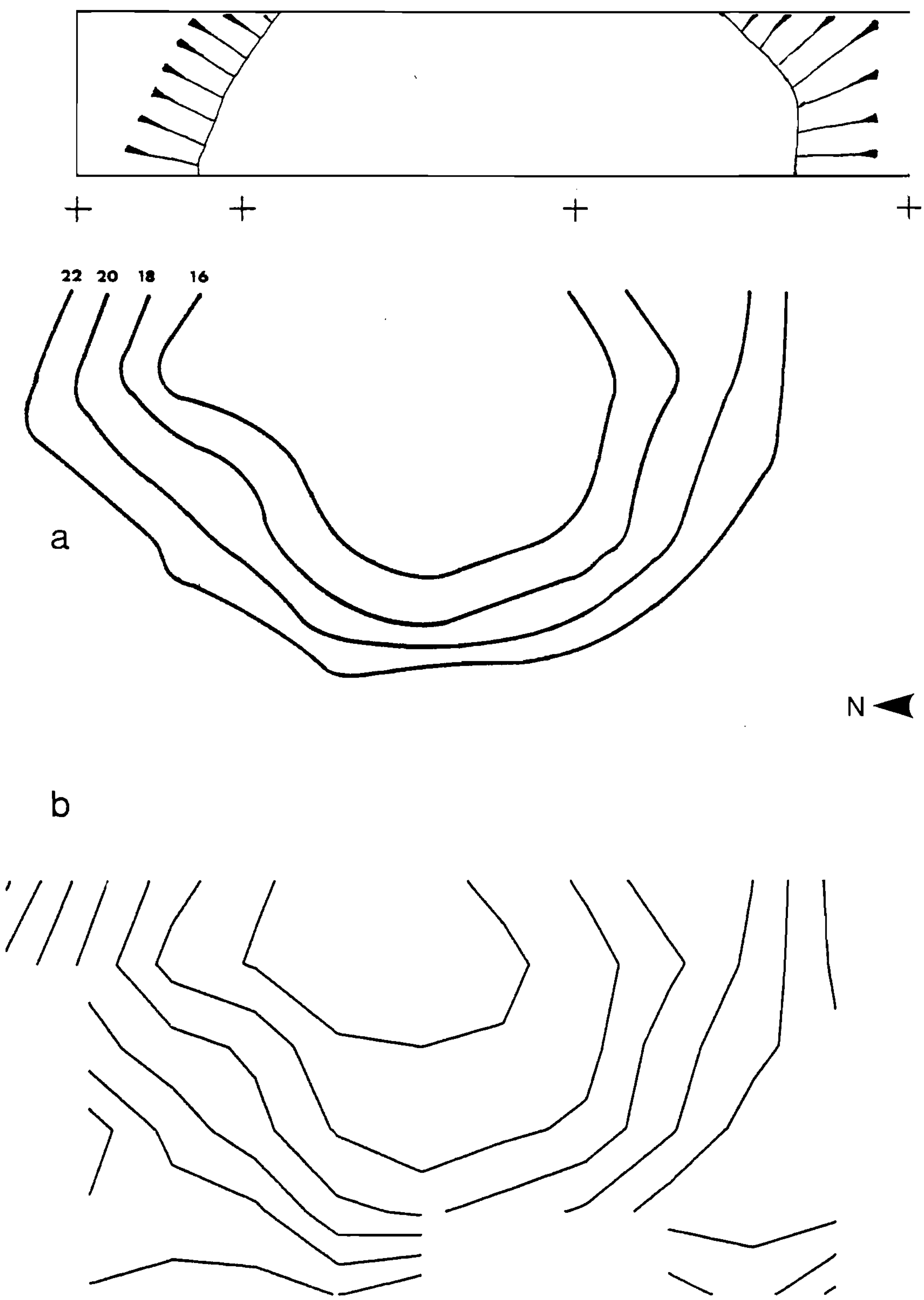


FIG. 7.6. Sharpe Howes barrow. (a) Section and resistivity contour plot of north quarry; (b) Computer contour plot used as basis for (a). Scale 1/60. Contour interval 2 ohms

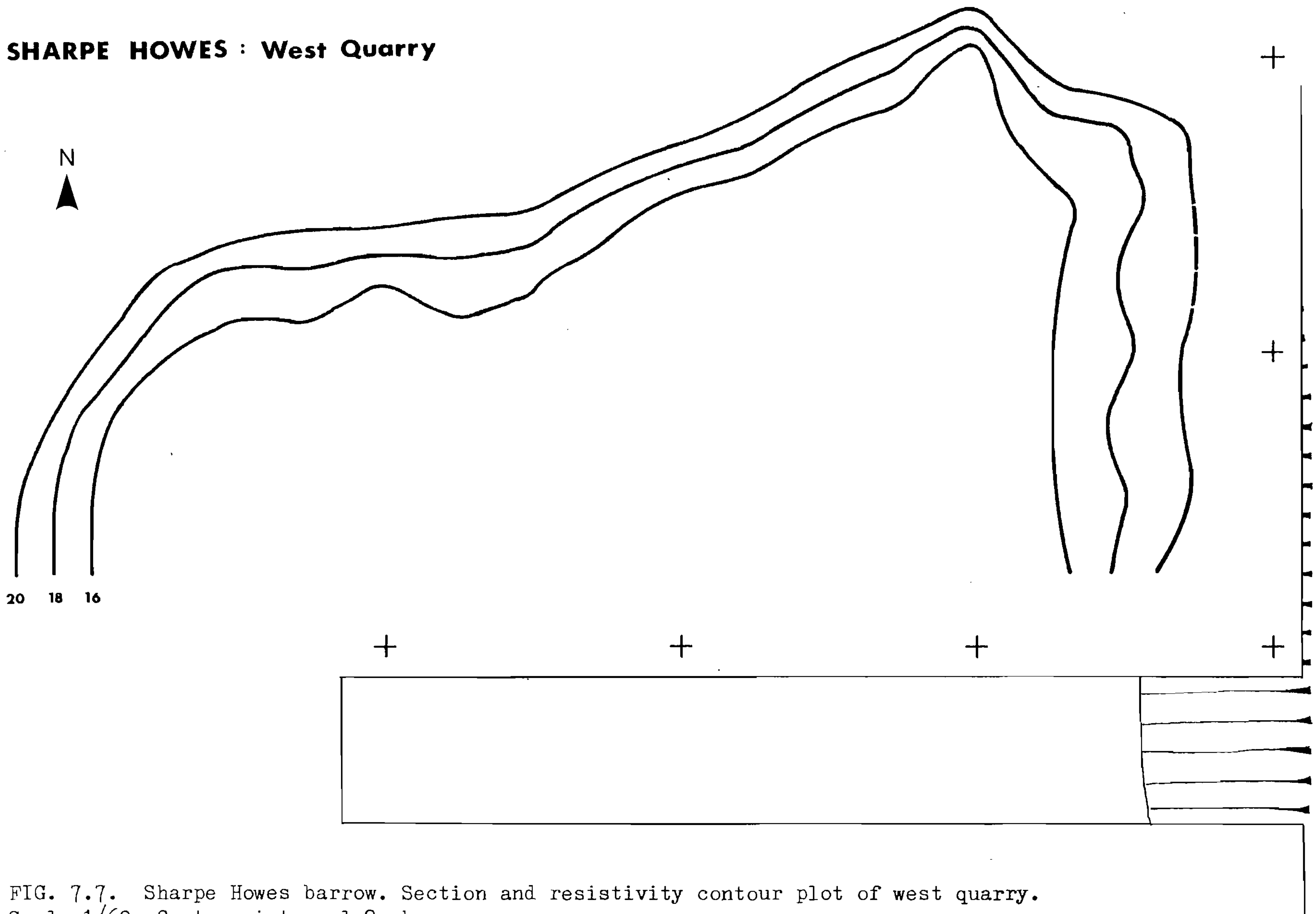


FIG. 7.7. Sharpe Howes barrow. Section and resistivity contour plot of west quarry.
Scale 1/60. Contour interval 2 ohms

Fig. 7.8a shows an initial dot density plot superimposed on a plan of the walls cut by the pipe trench, as interpreted from sections on either side of the trench. The walls were of flint and mortar at a depth of about 20 cm. An interesting detail is that the sections of the southernmost piece of wall did not have the same staggered relationship as the others, but the survey subsequently explained this as due to the trench cutting the building exactly at its corner here. The plot was produced by computer, using an arbitrary starting level as previously described. It revealed the shadowy plan of a corridor building which seemed to have the corridor on the north-east side (although this was oddly interrupted by a cross wall) and a possible verandah on the south-west downhill side.

A drawback of plotting from an arbitrary base level is that, as already mentioned, variations in background resistivity due to geological or topsoil depth changes are likely to make some parts of the picture too dark and others too light, obscuring the variations of archaeological origin. Once the data are in a computer, this can be overcome by filtering routines of varying sophistication (Bartlett, 1979). In the present case, a simple filter was used (Scollar, 1959) whereby from each reading is subtracted the average of a group of surrounding values, and the resultant differences, knows as residuals, are plotted. This in effect sets up a separate, localized, base level for each reading, emphasising the narrower resistivity gradients likely to be archaeological in origin at the expense of the broader background changes. If the distance between the central and surrounding readings is suitably chosen, the size of anomaly passing through the filter can be defined, and a specific type of archaeological feature can be selectively emphasised in the presence of others.

The plan of the Boscombe building was greatly clarified by this treatment (Fig. 7.8b). The picture was much improved by using a very

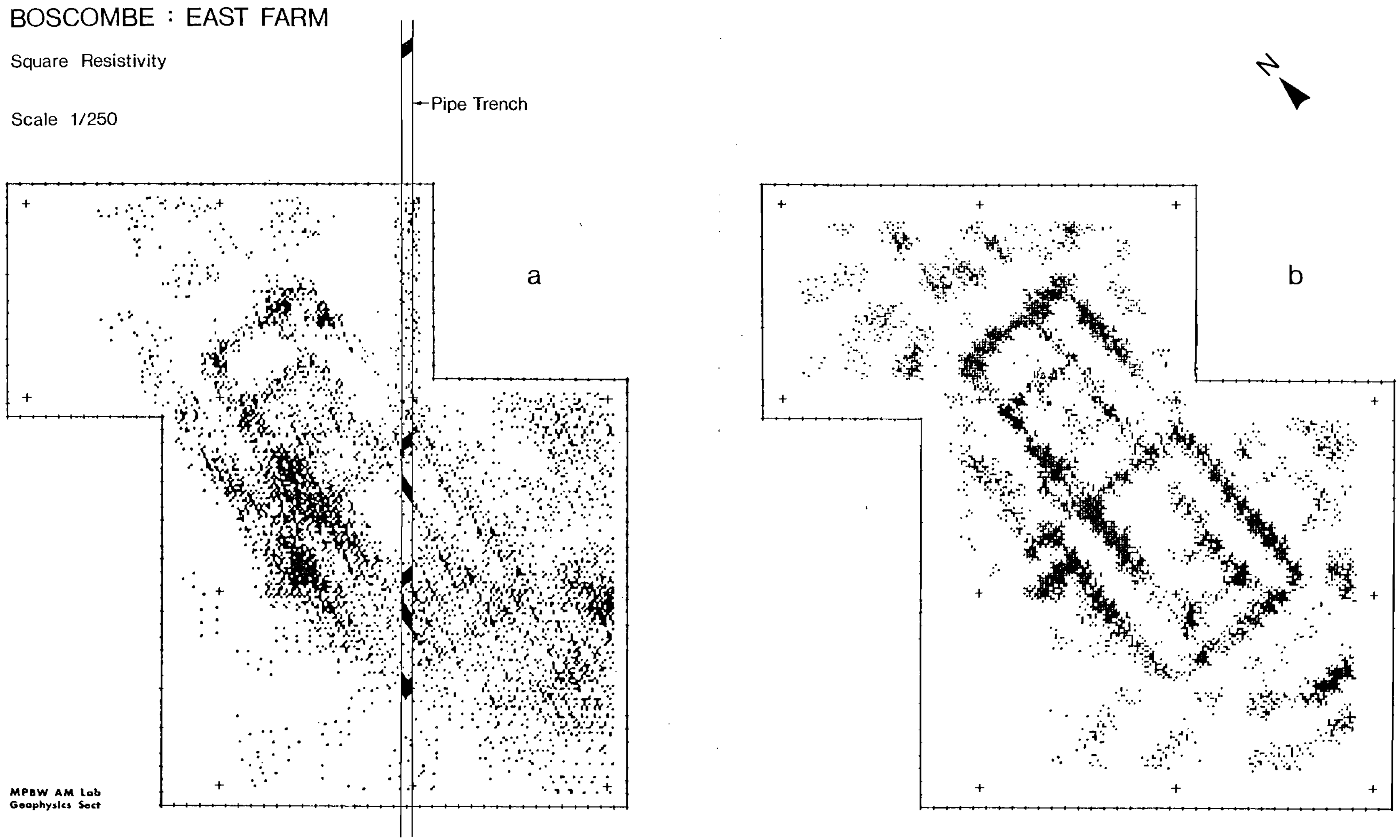


FIG. 7.8. Computer dot density plots of Roman building (a) before and (b) after filtering. The marginal ticks are at 1 m interval, the same as the reading interval

simple filter in which the mean of the four immediately adjacent readings was subtracted from each reading, but the final plot was obtained with a filter of double this spacing using the mean of a square of eight readings - the more values used, the less is the chance of the mean being affected too much by one rogue reading, or by those that lie over the feature itself and are thus of similar value to the central reading. In Fig. 7.8b half the 'verandah' was rejected by the filter because it was too wide and the building emerged as consisting of two blocks, one wider than the other and with a porch-like extension on the south-west side. The wall across the corridor showed that the two blocks were probably of different periods, the wall presumably being demolished to its foundation when the building was enlarged. A small selective excavation confirmed this interpretation, and revealed that the part of the 'verandah' that had been filtered out was a mass of rubble used to consolidate the Iron Age ditch when the building was erected. Furthermore the filtered plot showed clearly walls which were difficult to distinguish from rubble in the excavation. The half-tone effect of dot density is capable of considerable subtlety, encouraging the eye in recognising sometimes the most fragmentary patterns - for instance the few dots filling the gap in the north-east wall in Fig. 7.8b are acceptable to the eye as representing the wall even though they reflect only a minute resistivity contrast where the wall remains were too slight even to be noticed in the side of the pipe trench.

7.1.2. TWIN ARRAY

SHALFORD EAST MANOR. The site of this probably fourteenth century house at Shalford, Guildford, Surrey, was discovered by the writer in 1960. It is in a field, normally pasture, beside the flood plain of the River Tillingbourne, and lies on the Atherfield Clay. It was at first thought to be an iron-working site because of the presence of a couple of blocks of slag on the surface, but trial excavation by the Surrey Archaeological

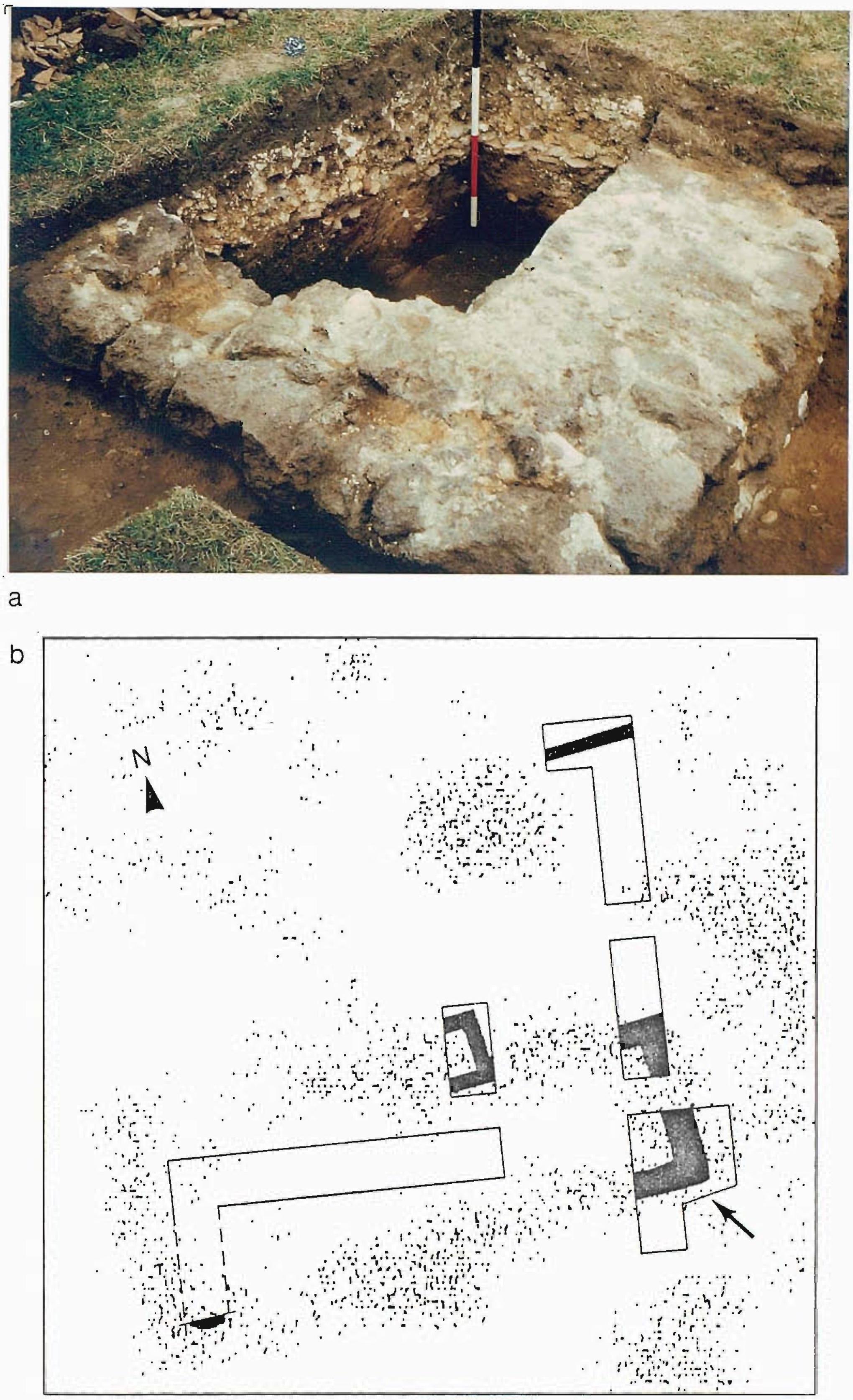


FIG. 7.8A. Shalford East Manor. (a) The iron slag foundation. (b) Walls as revealed in the trial excavation, superimposed on the dot density plot of the subsequent resistivity survey (see Fig. 7.9). The west wall was just missed by the uncompleted trench through the middle of the building. The arrow shows the direction of the photograph in (a)

Society revealed the foundations of a building constructed from mortared blocks of slag that must have been derived from an unknown site. Such a structure seemed suitable as a test bed for comparing magnetic and resistivity detection, and the first comparative survey, carried out by students taking the final year Archaeometry Option of the Physics Department of the University of Surrey, on 19 November 1977, is reported here.

The main feature revealed by the trial excavation was the massive foundation of the east end of the building (Fig. 7.8A). Just sufficient information was obtained about the rest of the building to show that it broadened toward the west, and there was evidence that some of the foundations at least were slighter. A sleeper wall of a separate timber-framed building, probably a kitchen, judging by the associated finds, was found 7.1 m to the north. The foundation of the east end of the main building was up to 0.9 m thick; the sleeper wall was 0.36 m wide.

The resistivity survey, using the Twin Array at probe spacing and reading interval of 1 m, covered an area 20 m square; the magnetic survey, with an Elsec 1 m baselength fluxgate gradiometer, using the same reading interval, was curtailed on the west side because of lack of time. For the resistivity survey, the fixed probes were set at 2 m spacing to ensure that they were brought to an acceptable level on the 50 ohm scale of the Type 2 Martin-Clark meter used, but in the event the readings on this low-lying clay-based site were unusually low and this need not have been done. The background resistance reading level was about 16 - 18 ohms, and typical readings over the building foundations were 22 - 24 ohms. Magnetic anomalies were typically 4 - 6 nT, rising to as much as 18 nT for individual extreme readings over the massive east foundation.

The two surveys are plotted side by side as computer-produced dot densities in Fig. 7.9; both were treated in the same way, using a 3 m radius, 8-element filter, the residuals being plotted from the mean to

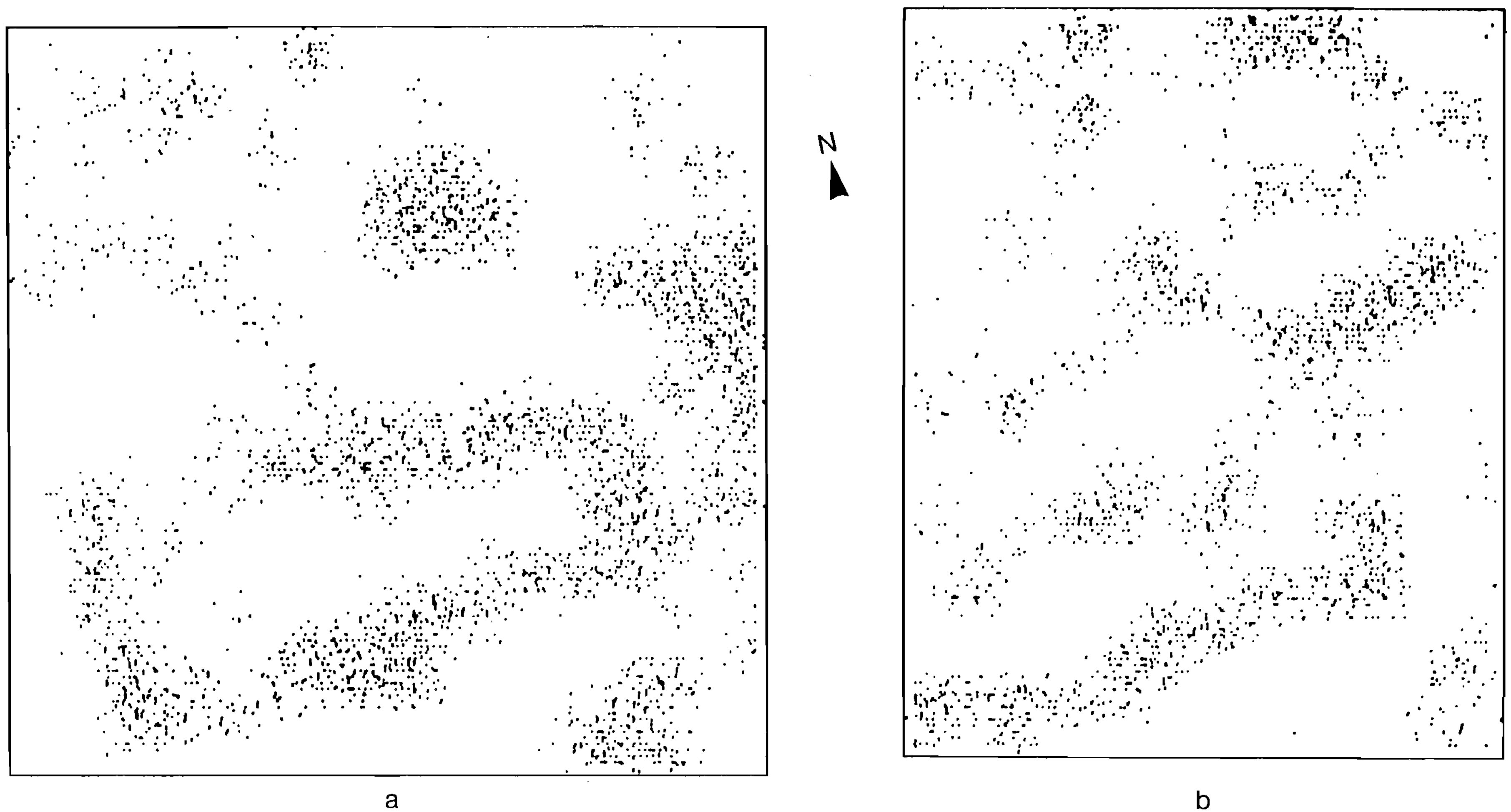


FIG. 7.9. Shalford East Manor. Computer dot density plots of (a) resistivity survey; (b) magnetic survey, using a 3 m radius, 8 element filter in each case. The resistivity survey is 20 m square. The magnetic survey is displaced 0.5 m to the north, and curtailed on the west side

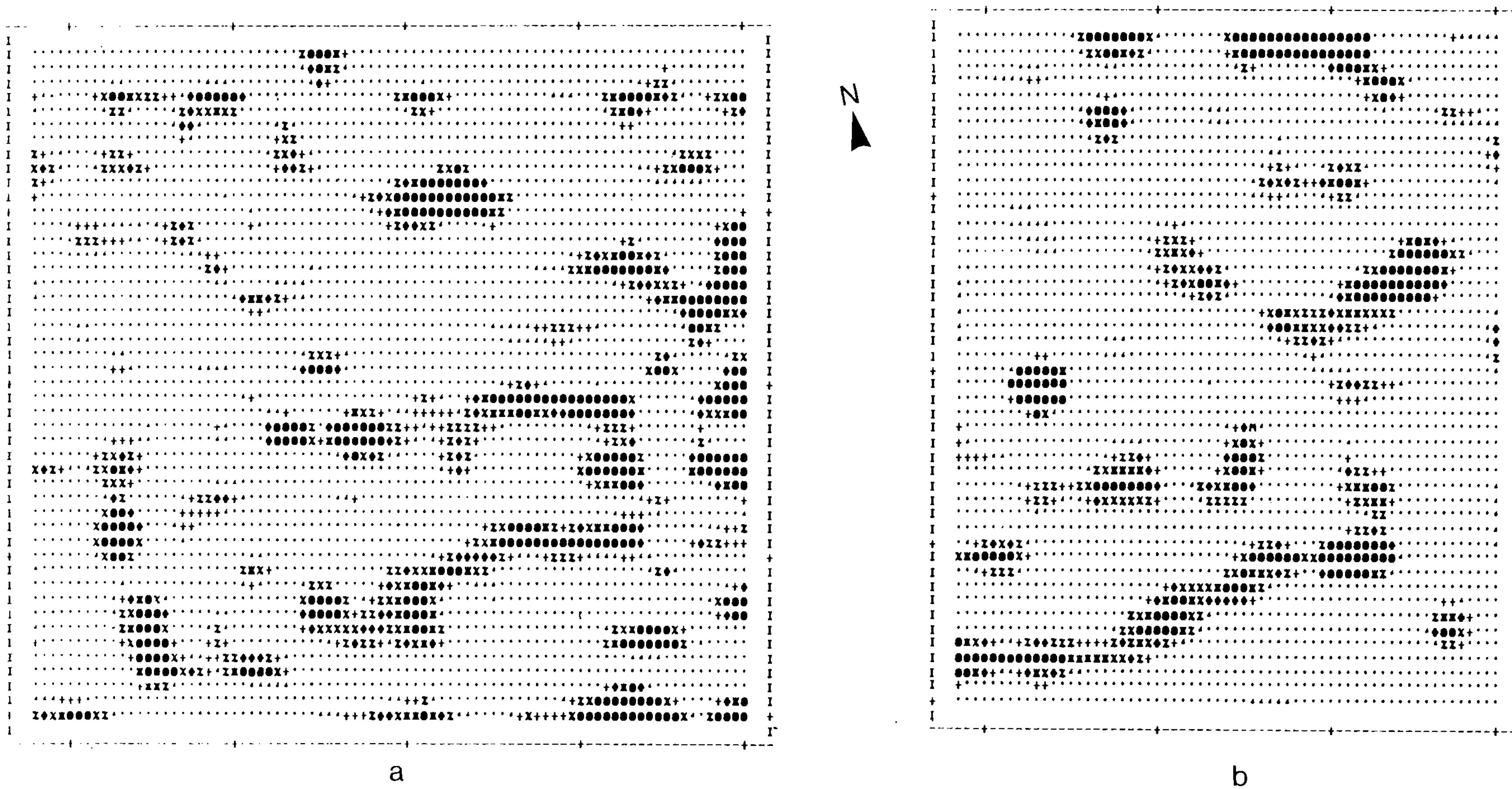


FIG. 7.10. Shalford East Manor. Computer symbol density plots of (a) resistivity survey; (b) magnetic survey, using a 2 m radius, 8 element filter in each case. Scale 1/200

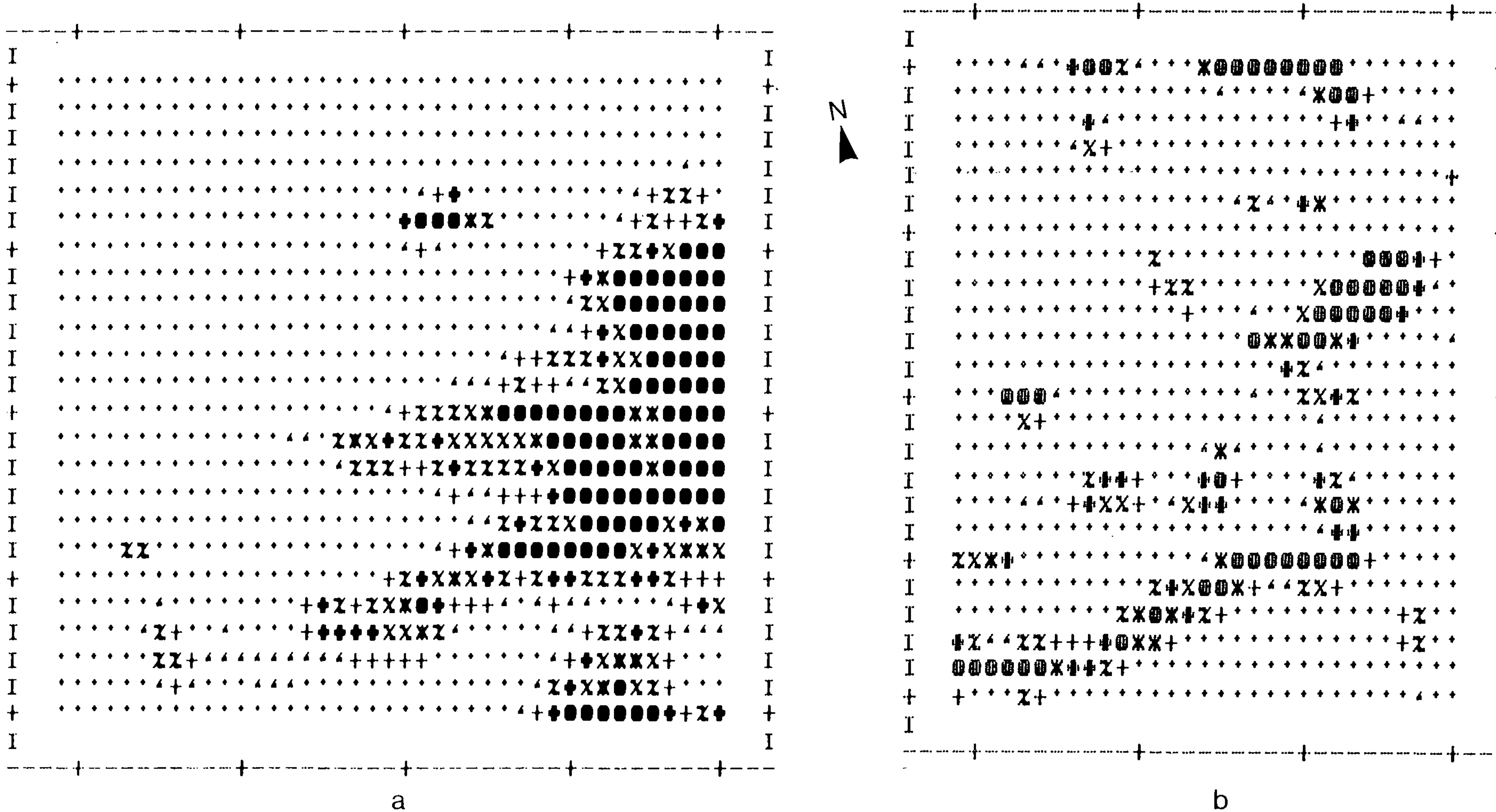


FIG. 7.11. Shalford East Manor. Unfiltered computer symbol density plots of (a) resistivity survey, (b) magnetic survey. Plotting from mean to mean + 1.5 standard deviations in each case. Scale 1/200

mean + 1.5 standard deviations. The resistivity plot quite clearly shows the basic shape of the building which is superimposed on the excavation plan in Fig. 7.8b. The definition of the magnetic plot is not so good, probably in part because of the random orientation of the slag blocks, although this effect was not as serious as expected, possibly because the inherent magnetism of the slag is not very great, so that the more orderly effect of 'temporary' magnetisation by the Earth's field due to their magnetic susceptibility may be making a significant contribution. Neither plot shows the kitchen building with any clarity, although other, probably significant, substantial anomalies are present. Fig. 7.10 compares the two surveys as symbol density plots produced by a line printer: these are stronger but, having fewer density levels, lack the interpolative subtlety of the dot density plots, and the use in this case of a narrower filter of 2 m radius may also have been less suitable.

It should perhaps be pointed out here that a magnetic gradiometer tends to be 'self-filtering', producing a level baseline unless there are localised magnetic anomalies; but resistivity measurements are always responsive to background variation and more generally in need of filtering. This is well demonstrated by Fig. 7.11 which shows as coarse symbol-density plots the results of plotting the Shalford magnetic and resistivity surveys without filtering: the magnetic plot differs little from the filtered version in Fig. 7.10, but the resistivity plot is very heavy to the east of the building, which would not be recognisable without prior knowledge of its presence. This difference in response of the two types of measurement is also demonstrated by Fig. 7.21.

Further experiments are planned for the Shalford site.

GUILDFORD PARK MANOR. This moated site, once a Royal hunting lodge and now mostly the lawn of the present farmhouse, was surveyed with the Twin Array before excavation under A. G. Crocker in 1973, using, as at Shalford. 1 m for both probe spacing and reading interval. The site is on London

FIG. 7.12. Guildford Park Manor. Manual dot density plot. The plotting cells (i.e. individual readings) are 1 m wide

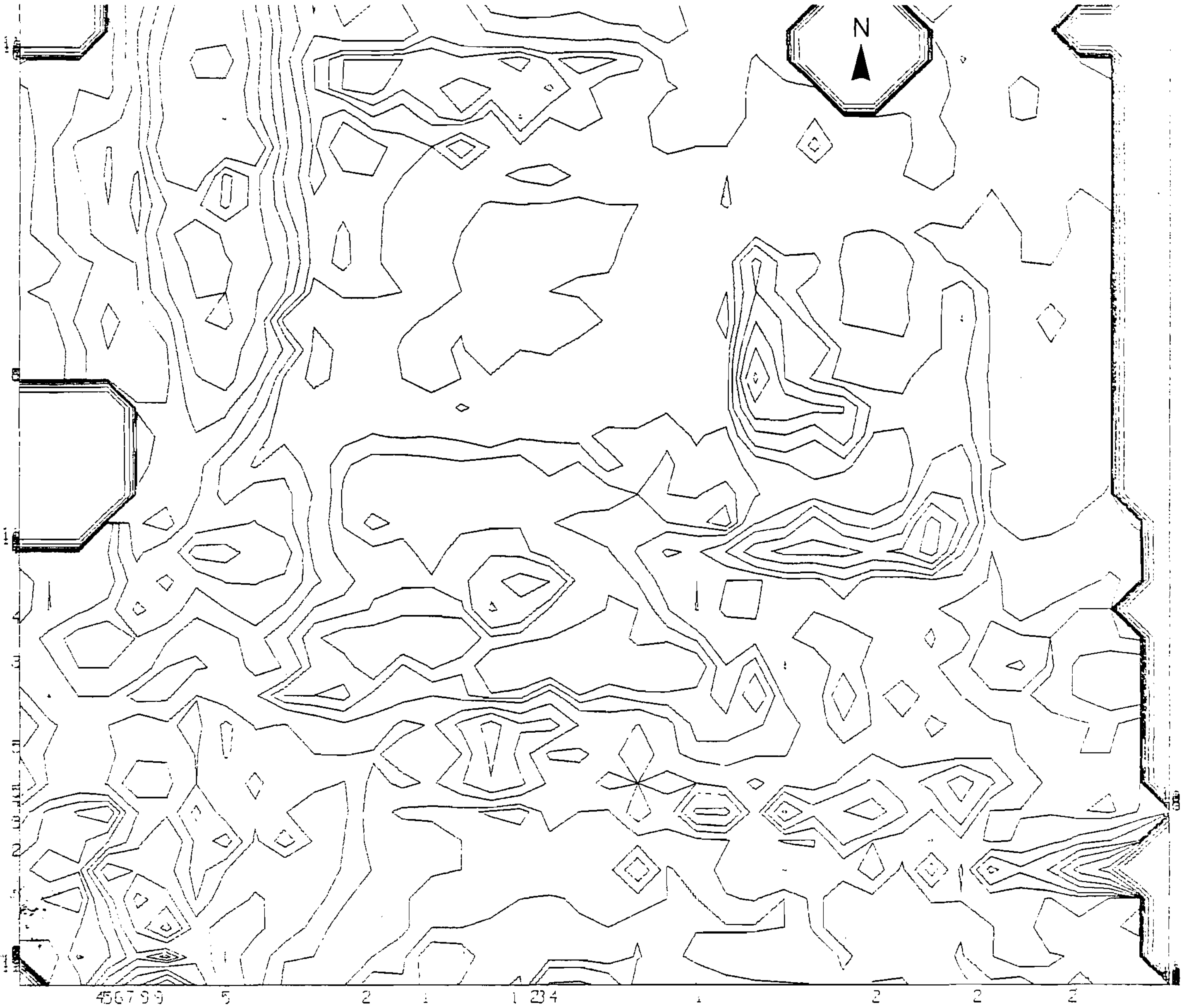


FIG. 7.13. Guildford Park Manor. Computer contour plot. For scale see Fig. 7.12

Clay. Part of the survey is shown (Fig. 7.12) plotted by manual dot density (by R. Lock) and by computer contouring (Fig. 7.13) to compare the effectiveness of the methods. The contour interval is 1 ohm; high readings are shown as increasing density in the dot plan, which was a direct plot without filtering. The main building is to the right, and the backfilled part of the moat runs up the plots on the left. Gaps in the survey caused by obstacles are heavily outlined in the contour plot. The building - which was not the main subject of the excavation but was confirmed by a small trial trench - stands out clearly on the plots, both of which suggest that it is divided into two equal parts by a major internal wall. The continuity of the walls is rather more obvious in the dot density than in the contour plot, and might have been further improved by a different selection of dotting steps and background level, or by filtering - the optimum is conveniently chosen by experiment, providing the speed of a computer is available. The contour plot also might have been improved by such adjustment; but one of its disadvantages is that it makes no immediate visual distinction between areas of high and low readings, as does the dot density.

The high readings over the moat were not in keeping with a backfilling of natural clay, and it was surmised that it had been backfilled with rubble from the demolition of the buildings. Excavation confirmed that this was so.

CORBRIDGE. This site, in the grounds of Corchester School, just outside the north wall of the Roman fort and supply base of Corbridge, Northumberland, was surveyed because of the possibility of development. There was known to have been development in this direction in Roman times, during a period of expanding civilian occupation (Birley. 1954).

An automatically recorded magnetic survey was made with the fluxgate gradiometer, and a resistivity survey with 1 m Tw (Bartlett, 1976), the latter over a smaller part of the area because of its relative slowness.

Both surveys were plotted twice by computer as dot densities, comparing positive and negative representations in each case. The positive plots were made to saturate at mean + 2 standard deviations, the negative at mean - 1 standard deviation. All plots were treated with a 3 m radius filter.

Both surveys produced highly responsive results. The original traces of the magnetic survey (see 7.2.2 for method) are shown as a montage in Fig. 7.14. Numerous substantial peaks suggest the presence of industrial activity especially in the eastern two-thirds of the area. Both the positive and negative dot density plots (Fig. 7.15), made from data recorded at 1 m interval on the Microdata logger (see 7.2.3) in parallel with the trace recording, confirm this picture, although the negative plot perhaps over-emphasises minor effects because of too rapid saturation. All the magnetic plots show roughly east-west bands of differing clarity; most are relatively clear of anomalies and probably represent roads or streets, while that at the top of the survey is either a road with substantial side ditches, or simply a ditch system, possibly enclosing the area of activity. The resistivity survey (Fig. 7.16), covering only the southern and western parts of the area, is dramatically clearer, especially the negative plot. A road or street, with a sharp bend at its western end, runs across the survey area; from it run, northward and southward, side alleys defining modules or '*insulae*', mostly either 20 ft or 30 ft wide. The street and alleys are not well defined on the magnetic dot density plots (they might have been improved by further treatment), but the traces confirm them as magnetically quiet strips, as would be expected. The traces also indicate that there is more industrial activity south of the street; on its north side, the modules may represent rectangular shops end-on to the street as discovered elsewhere at Corbridge, but it is possibly significant that the 30 ft module width is also shared by army granaries and workshops on the site.

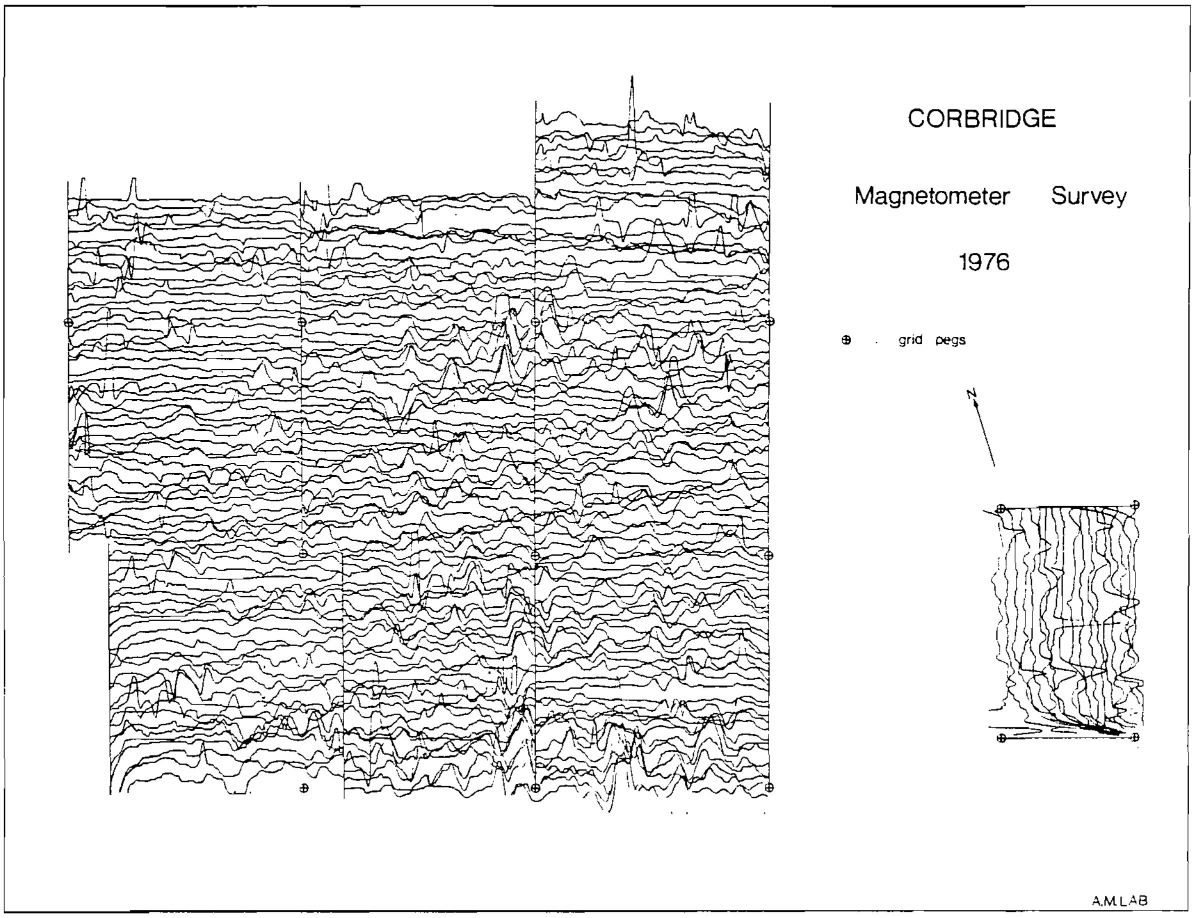
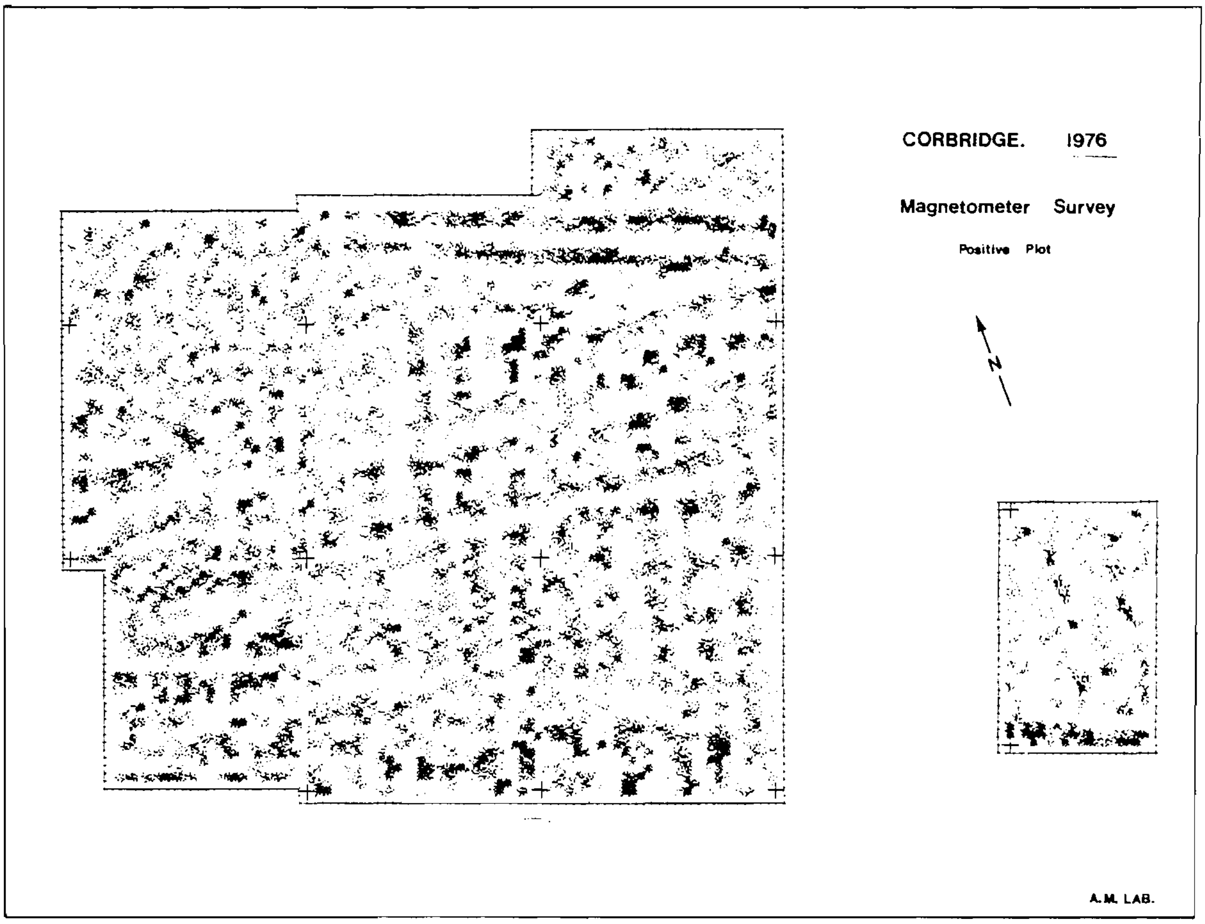


FIG. 7.14. Corbridge. Magnetic traces. The grid pegs are 30 m apart



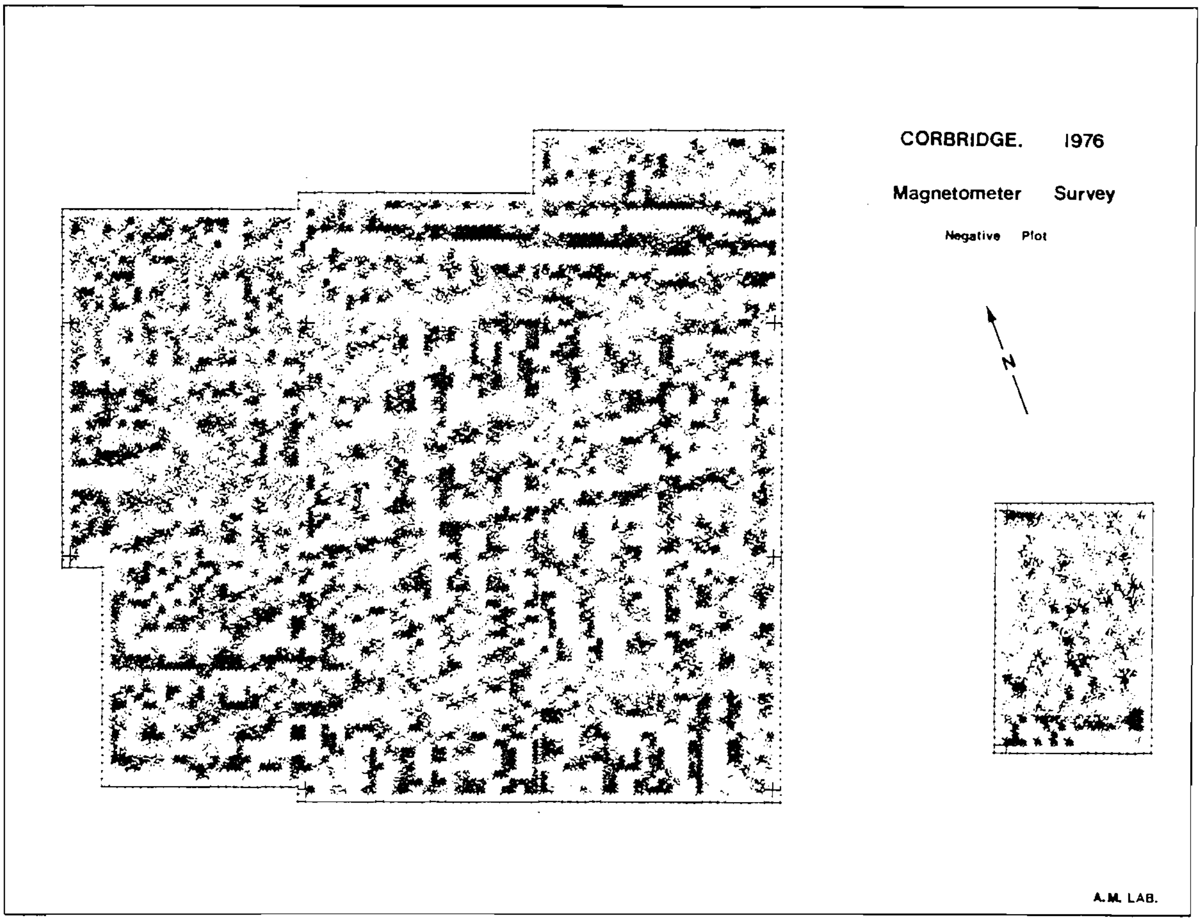
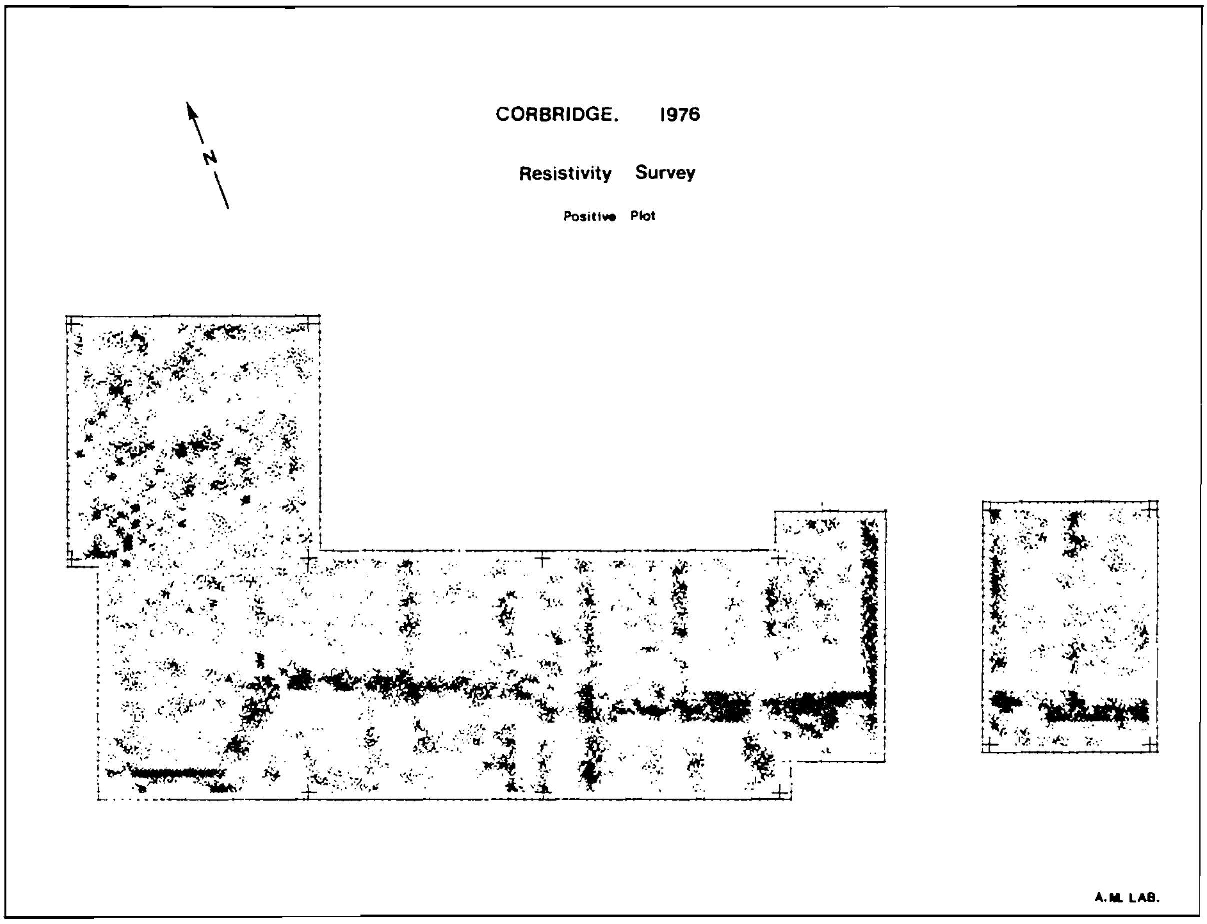


FIG. 7.15. Corbridge. Dot density plots of the magnetic survey. Same scale as Fig. 7.14



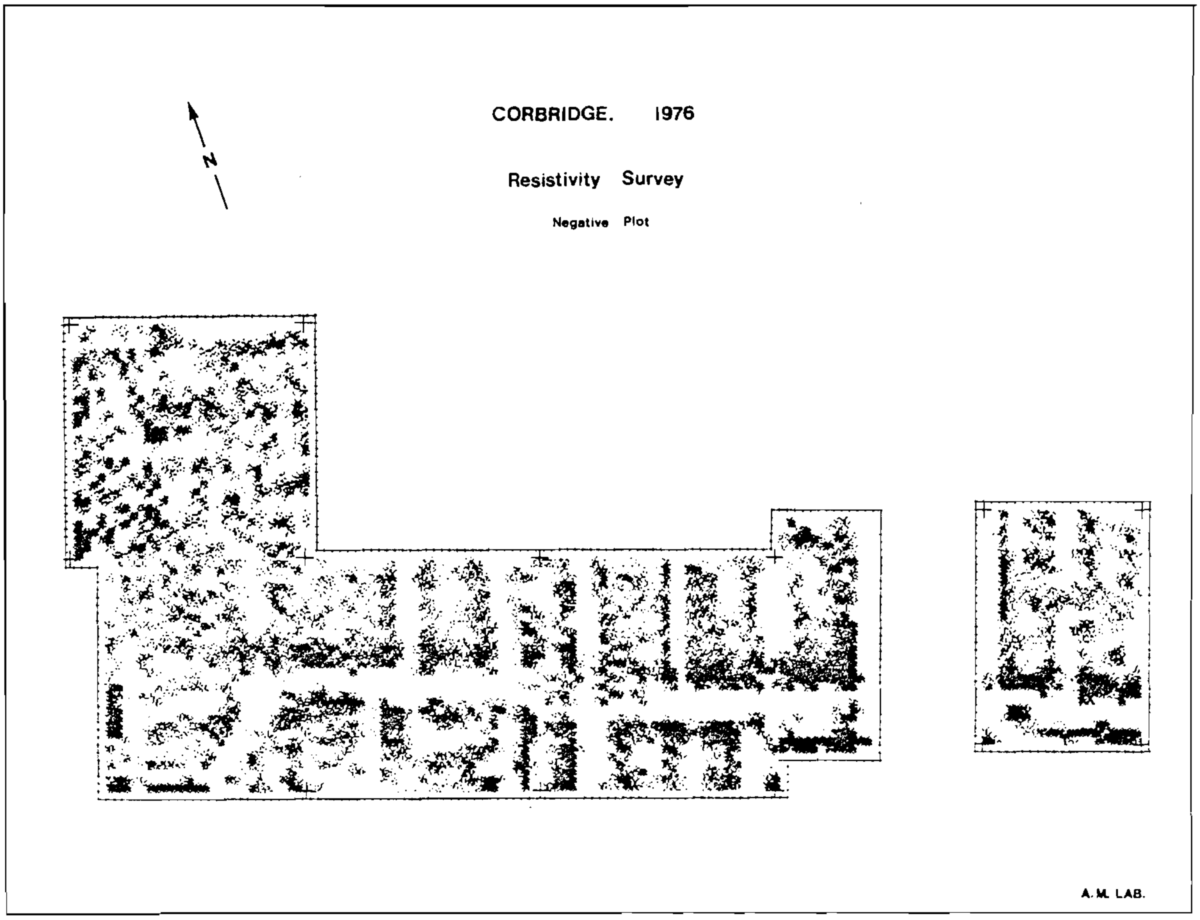


FIG. 7.16. Corbridge. Dot density plots of the resistivity survey. Same scale as Fig. 7.14

This is a good example of the power of magnetic and resistivity surveys used in combination to produce complementary information that can greatly illumine the archaeology of even a complex site without excavation.

The resistance level over the street typically rose to about 28 ohms above a base level of about 20 ohms.

THE GIANT OF CERNE. At the instigation of Yorkshire Television, an extensive resistivity survey has been carried out on this well-known Dorset hill figure cut into Upper Chalk, primarily in an attempt to obtain information about any lost features that might add to the evidence for its identity and date. Making full use of the results of the research described herein, the survey has been conducted with the optimum spacing of the Twin Array - 0.5 m - and at the optimum time of year for the detection of shallow features (cf. the berm of the Hog's Back barrow), to produce a detailed map of soil depth variations over much of the figure, with readings at 0.5 m spacing. Coring at selected points has confirmed the validity of the picture which is in the process of computer treatment at the time of writing. Some lost features do indeed seem to be emerging, especially in the region of the figure's conspicuously empty left arm. Magnetic and electromagnetic surveys have proved ineffective because of the low magnetic susceptibility of the soil. Gravett (1971) has already examined the Long Man of Wilmington, Sussex, briefly with similarly promising results, and the Red Horse of Tysoe has also responded well to resistivity survey.

7.1.3. DOUBLE DIPOLE.

GRIME'S GRAVES. One of the most extensive resistivity surveys so far carried out in Britain was undertaken under the writer's supervision by A. Millett and assistants on behalf of the British Museum at the Neolithic flint mining complex of Grime's Graves, Norfolk, to map any extension of the area of pits beyond those still visible at the surface. It was also especially desired to detect any traces of domestic occupation on the site. Much of what is written below is taken from the writer's contribution to the publication produced after the first part of the survey, 3,330 sq. m, had been completed (Sieveking et al, 1973).

The massive shafts of Grime's Graves seemed ideal subjects for resistivity detection. Being packed for much of their depth with chalk rubble containing much air space, they were expected to have a distinctively high resistivity compared with the solid chalk into which they were cut. On the other hand, they were expected to be fairly sterile magnetically, and poor subjects for this type of detection; therefore, any occupation deposits, with their well-known effect of enhancing soil magnetism, might well have been detectable among them, and it was decided to carry out a basic resistivity survey complemented by a magnetic survey.

Initial experiments over levelled pits visible as grass marks close to the main complex were made with the Wenner and Double Dipole arrays at 1 m and 2 m spacing. The instrument used was the Martin-Clark Type 2. Low values were obtained in all cases, although it had been expected that the 2 m spacing, with its commensurate depth of penetration, would have been affected by the rubble filling of the lower parts of the pits. At the time it was assumed that the upper soil filling was damper throughout, but the present research suggests that it too was mainly dry, but that a damp interface with the rubble was being detected. It also seemed that if a spacing wide enough to penetrate to the rubble were to be used, there might be too much loss of detail, which, in our ignorance of what the site might produce, we were unwilling to risk at this stage. The 2 m spacing, which also permitted quite rapid ground coverage, seemed a good compromise, and the survey was carried out using W/DD at this spacing. The tests and the main survey took place in conditions of net water loss.

The survey proceeded in parallel with excavation, and comparison of the two made it clear that interpretation was going to be difficult: downhill across the site, there was an overall geological change from

Chalk to a deepening overlying deposit of sand, and the subsoil was much affected by fissures of various widths caused by glacial action, many similar in size to archaeological features; thus there were increasing background resistivity values combined with changes in anomaly strength and possible confusion with natural features. Dry contact conditions also tended to cause occasional erroneous readings. Fairly sophisticated computer treatment was therefore adopted: experiments were made with 'band-pass' filters to reject effects likely to be both larger and smaller than the pits - substantial geological changes, minor glacial fissuring, and individual erroneous readings for instance. The best overall effect was obtained by setting the upper limit with a filter in which the average of a ring of eight readings at a radial distance of about 8 m from each measurement point was subtracted from the central reading. The resulting residual values were further treated with a filter of about 2 m radius, the residuals of this being subtracted from the first set. Values passing between the limits thus defined by these two filters were plotted at a density of 10 dots per ohm, with a maximum of 25 dots per reading for saturation. Comparison of plots of positive and negative residuals showed that the most convincing pattern was produced by the former which, rather than showing the pits themselves, seemed in most cases to reveal the rings of upcast material around them. A line of small contiguous pits seemed to define the limits of mining activity where the sand was becoming increasingly deep, and a linear, possibly opencast, mining pattern seemed to be detectable over parts of the area.

Subsequent excavation showed that the limit of activity as defined was probably correct, while one of the apparently large pits was in fact a shallow depression in the natural chalk containing a cluster of minor pits and working floors: this might, in retrospect, have been expected, because the major pits of the true Grime's Graves type would have been difficult to obliterate by the subsequent ploughing to which the site had been subjected at some period in the past.

The computer treatment was confined to the DD measurements, but straightforward contour plots of both the DD and W readings were prepared by Millett. The survey was later considerably extended around the periphery of the known pits, but the full evaluation of it and the different plotting methods in relation to the excavation carried out has not yet been completed. It can be said, however, that this difficult survey, subtly interpreted, has added considerably to our understanding of Grime's Graves. Magnetic surveys over parts of the same ground were also successful, as hoped, in defining occupation sites in preference to pits, although the occupation was slight and the magnetic anomalies commensurately so.

7.2. METHODOLOGICAL DEVELOPMENTS

7.2.1. WENNER/DOUBLE DIPOLE SWITCHING. The use of these two configurations in combination is one of the simplest developments to arise from the

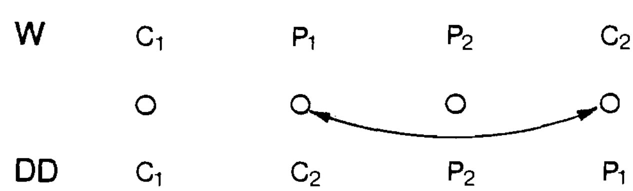
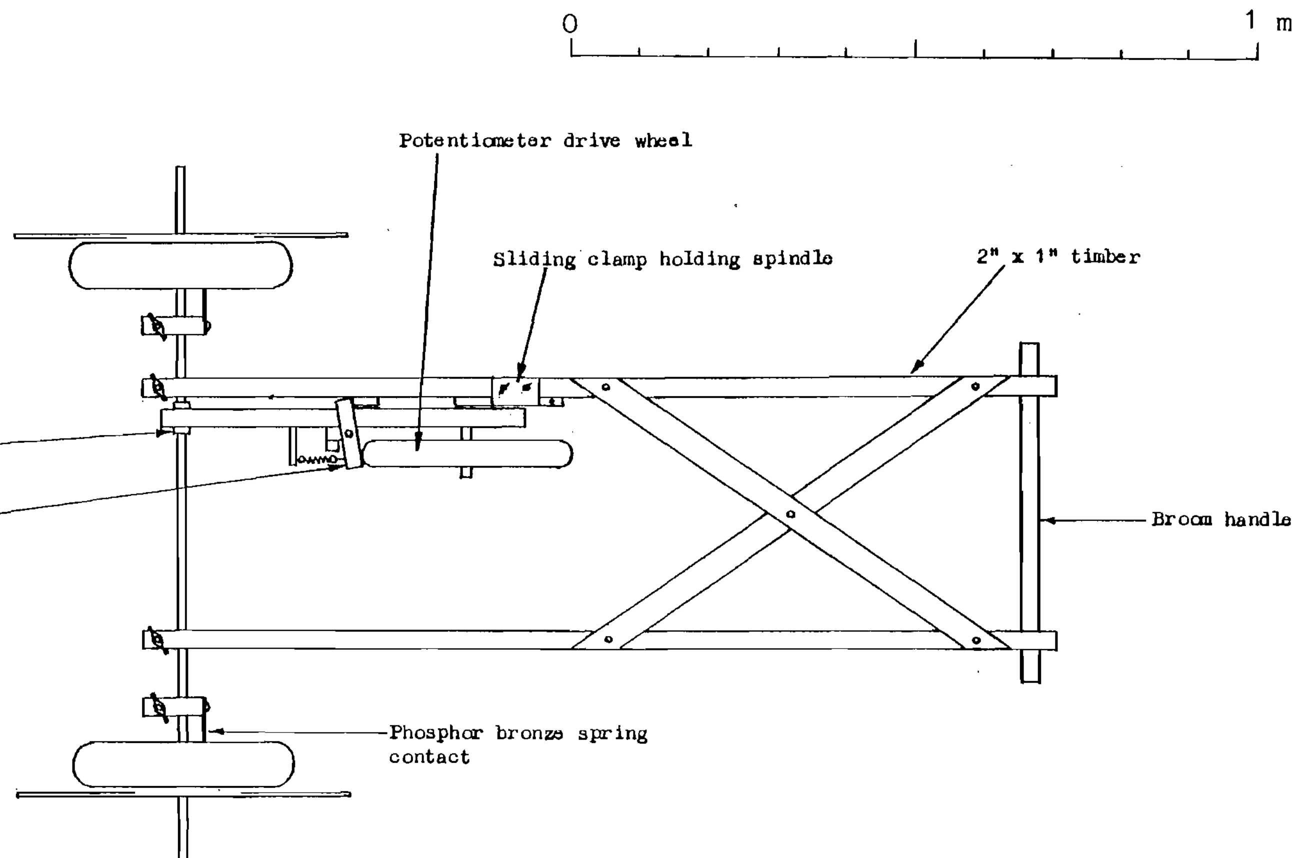


FIG. 7.17

research described herein. The inclusion of a changeover switch for this purpose for the first time in the Type 2 Martin-Clark meter has been mentioned in 3.2.2; the effect of using the two configurations together is described in 5.3, and examples of the use of the combination are given in 7.1.3 and Fig. 5.28. The necessary interchange of electrode connections is illustrated in Fig. 7.17, and is achieved by means of a straightforward double-pole two-way toggle switch on the instrument face.

7.2.2. WHEELED RESISTIVITY. This was designed to produce high-speed resistivity surveys by exploiting the Twin configuration in combination with the Martin-Clark Type 4 constant current resistivity meter and the Ancient Monuments Laboratory automatic survey plotting system normally used with the fluxgate gradiometer (Clark and Haddon-Reece, 1973; Clark, 1975). In this, a succession of traverses at 1 m interval and 30 m long, are recorded as traces on an X-Y plotter (Smith's Servoscribe M). The distance signal is produced by the instrument carrier moving, as he walks, a line which passes over two pulleys supported by tripods at each end of the traverse run, one of the pulleys being geared to a potentiometer that controls a battery output to produce the X signal on the recorder. The recorder traces are proportionately stepped on automatically in the Y direction in preparation for each traverse. The survey plot is thus built up as a series of parallel traces deflected by the response of the instrument to buried archaeological features, giving a pseudo-relief effect (e.g. Fig. 7.14; Fig. 7.21a).

The Twin configuration, requiring only two moving ground contacts, is eminently adaptable to wheeled operation, and a prototype apparatus was designed by the writer and kindly constructed in the workshops of the Department of Physics, University of Bradford. The original drawings are reproduced as Figs 7.18 and 7.19, and the actual apparatus, slightly modified from these, in Fig. 7.20. Rubber-tyred wheelbarrow wheels were used, to each of which was attached a duralumin plate with a radial series of flat mild steel blades designed to ensure, as far as possible, continuous contact with the ground, maximum contact area and ease of insertion, which was further facilitated by sharpening as shown in Fig. 7.19. Each wheel thus formed a single electrode with the critical dimension, the probe separation (Aitken, 1974), kept constant. Separate spikes were used in preference to continuous discs, because of the smaller tendency of the spikes to ride up over stones and even vegetation; they were made square-ended because it was thought that their slicing action would ensure their insertion, but a point might have been preferable. Electrical contact with the wheels was made by means of short sprung levers with phosphor bronze ends in contact with brass discs on each wheel, protected by flanges from the grosser soil contamination, and



Parts positioned on spindle with, say, split pins

Provision for wheel separations of 0.6, 0.8 and 1 metre

FIG. 7.18. Original design for wheeled resistivity apparatus

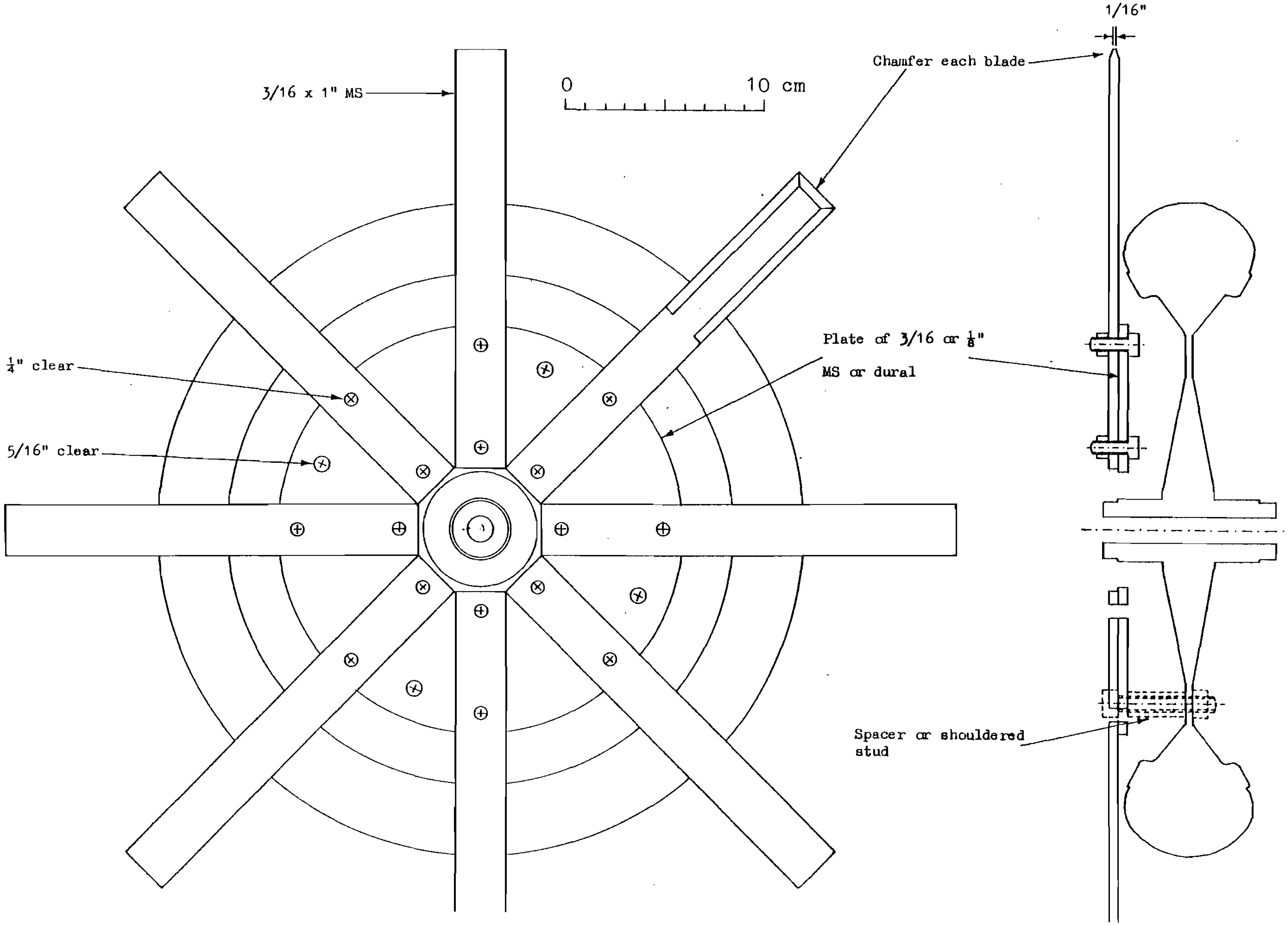


FIG. 7.19. Wheeled resistivity apparatus: details of ground contacts

FIG. 7.20. The wheeled resistivity apparatus in use. To the left can be seen one of the tripods of the distance transducer system

best seen in the photograph of Fig. 7.20. The built-in distance transducer, in the form of a wheel linked to a potentiometer on a trailing arm, was not constructed, and the magnetic potentiometer system was used, rather awkwardly, for the trials. The version of this system shown in use in Fig. 7.20 is an early one consisting of a simple stretched resistance wire and contact, rather than the cord, pulleys and rotary potentiometer version that succeeded it and has been described above.

Fig. 7.21 compares sets of traces of an area 30 m x 15 m at the Iron Age site at Gussage All Saints, Dorset, on Upper Chalk with some Clay-with-flints (Wainwright and Spratling, 1973), surveyed (a) by fluxgate gradiometer, (b) by the wheeled resistivity system. Anomalies due mostly to pits tend to be more strongly defined in the magnetic survey, showing only as minor depressions in the resistivity survey, for which the conditions, in the early part of the year, were not ideal; nevertheless, there is a pattern of fluctuation in resistivity which reflects subtle variations in bedrock depth not detected by the magnetometer. The two plots demonstrate well the basic flatness of the gradiometer response (see 7.1.2) compared with that of resistivity, which, as so often, changes across the width of the survey area. It is also interesting that both surveys show 'spikes' which look very similar, but in fact are of quite different origin: in the case of the magnetic survey, they are caused by superficial recent iron, e.g. horseshoes, while in the resistivity survey they are caused by momentary loss of contact when one wheel or the other is lifted by stones (the site is very stony) out of contact with the ground. (c) shows the lowest traverse of the resistivity plot repeated three times to demonstrate reproducibility.

In spite of these encouraging initial results, the wheeled system has not been subsequently used. The reasons are as follows: (1) The apparatus requires much effort in operation, and would benefit from the addition of a motor which, in addition to providing the motive power,

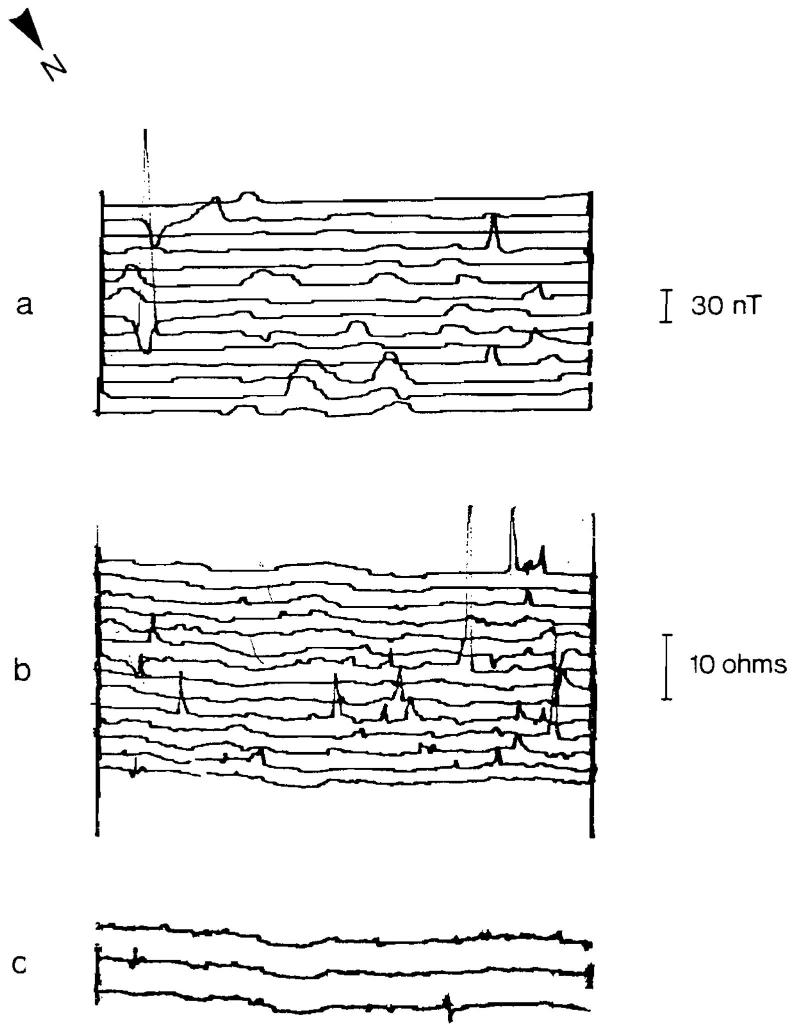


FIG. 7.21. Continuous trace recording. Two surveys of the same 30 x 15 m area (a) by fluxgate gradiometer, (b) by wheeled resistivity. (c) demonstrates the reproducibility of the lowest resistivity trace. The original traces were 15 cm long. The instrument sensitivity settings are shown to the right: the background level of the resistivity traces was approximately 39 ohms

would add weight and thus improve contact, especially in dry conditions and on hard ground. (2) Because of the almost routine need for filtering, for which resistivity surveys must be converted to digital form, individual readings have so far proved most convenient. (3) The existing distance transducer is unsuitable. None of these is a major impediment, but time has not been available to overcome them. If fully developed, this system would certainly prove useful, especially if used in parallel with automatic logging of data for subsequent treatment if required.

7.2.3. STEPPED TWIN ARRAY SURVEYS WITH AUTOMATIC RECORDING. Considerable use has been made in the Ancient Monuments Laboratory of the Microdata Miniature Incremental Data Logger Model 200. This is a weatherproof portable instrument designed to collect data at fixed time intervals determined by an internal clock, or collection may be initiated by an external switch. It has twelve data channels, most of which are normally inhibited in our work, and a third possible mode of operation is to allow it to run freely and to record the instrument signal on channel 1 and a distance signal on channel 2, while inhibiting the remainder: this allows readings to be collected at intervals of about 0.6 m at a steady walking pace: it is ideal for fluxgate gradiometer surveys with a distance transducer, and would also be suitable for wheeled resistivity. The logger accepts analogue signals up to 4 V, converting them to digital form, for which 256 levels are available, stored on a standard-sized magnetic tape cassette.

A resistivity recording system, well adapted to one-man operation, has been designed using Tw combined with the external call switch option and a Martin-Clark Type 4 constant current instrument. Because of its weight, the logger is placed on the ground off the survey area. The electrodes are mounted on a frame with the resistivity meter and actuating switch, and a liquid crystal readout which enables the survey to be visually monitored.

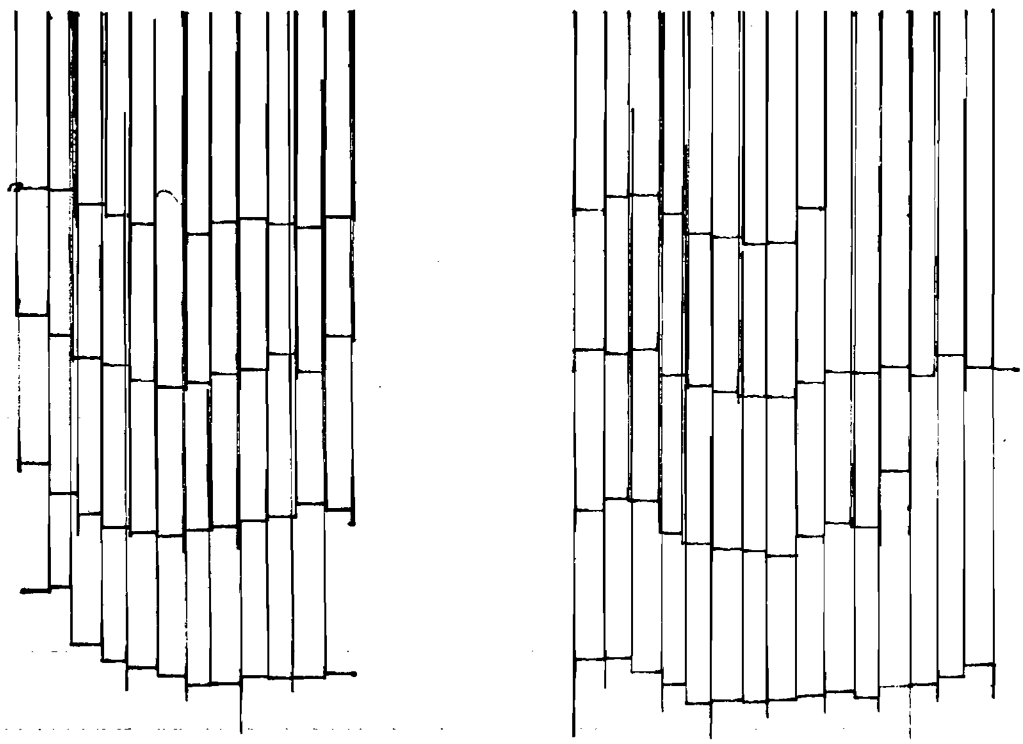


FIG. 7.22. Automatic recording of separate readings by means of an X-Y plotter. Two sets of traces from a survey beside York Minster.

An earlier version of this system made use of an X-Y plotter in place of the data logger, and an example of the traces produced with this is shown in Fig. 7.22. Separate probes were used, and stepping in the X direction was achieved with a hand-held box containing a rotary potentiometer advanced a fixed amount by a manual rotary switch with detente at every reading position. The vertical lines on the traces are caused by open circuit conditions between readings. The traces were separated manually by means of the recorder Y zero control, and were widely spaced to avoid the confusion between them to which this stepped form of presentation is especially prone. The 'instant hard copy' record provided by the plotter is, as with magnetic surveys, so useful as a guide to the progress of a survey that it will probably be added as an option to the recording system with the data logger.

A fourth surveying system at an early experimental stage makes use of the recording apparatus described above, but short probes are attached to the bottom of the operator's shoes or boots, while the length of his pace is regulated by a rope between them. This has the advantages that a survey may be conducted at a steady walking pace, and the full weight of the body is automatically applied to the probes at the instant of insertion. Also, tapes for measuring along the traverses can be dispensed with and replaced by guide markers at the ends of the traverses. The unusual physical sensation of walking with hobbled legs is rapidly overcome: the psychological sense of indignity perhaps rather more slowly.

8. SUMMARY OF CONCLUSIONS, AND RECOMMENDATIONS FOR FUTURE RESEARCH

8.1. CONCLUSIONS

8.1.1. RESISTIVITY METERS. Although developed manual-balance instruments such as the Martin-Clark Type 3 will probably remain in use for a considerable time, the future probably lies with the constant current principle exemplified in the Martin-Clark Type 4, which is essential for rapid survey systems such as those described at the end of the last chapter. As mentioned in 1.1, the introduction to archaeology of contactless instruments may be possible, although the subtle adjustment of detection parameters obtainable with probes may be more difficult, or impossible, to achieve with these.

8.1.2. PROBE CONFIGURATIONS. The configurations found most effective, in order, were Twin Electrode, Double Dipole, Square Array and Wenner, with the possible addition of the Triple Electrode, which would merit further investigation. Tw and DD gave unambiguous single peaks for a wide range of feature forms, sizes and depths; this was also true of Sq, provided pairs of orthogonal readings are averaged at each measuring station. Indeed Sq, used in this way, is probably the most consistently effective of all (e.g. Fig. 5.26), but its penetration is more limited than that of Tw, and it is less flexible than DD, and can be more inconvenient to use in difficult, e.g. dry or stony, conditions.

A horizontal, high resistivity laminar feature, equal in width to the probe spacing, was found to simulate the behaviour of many archaeological features. W, like other configurations, produced double peaks over this, indeed the feature seemed unique in that the response of most configurations to it took the form of a simple peak between each CP pair at all depths. W also gave double peaks over the high resistivity isolated cylinder and with the narrower low resistivity features, but merely a broadening with the high resistivity square-section feature of side equal to the probe spacing. With the low resistivity horizontal laminar feature equal in width to the probe spacing, and with high resistivity features narrower than the probe spacing, W gave a triple peak of subdued form more closely in accord with the theory for spherical forms. As low resistivity features tend to be soil-filled excavations and thus in the broader category, it would therefore seem that the choice of configuration for their definition is not so critical as for high resistivity features which tend to be narrow (e.g. walls) or apparently so (e.g. the Hog's Back ditch) and thus poorly represented either by the extended triple or double peaks. In spite of its tendency to complexity of response, W remains useful as a compact array with good penetration, useful in combination with DD, with its better definition but shallower penetration.

The above remarks apply to the use of the linear arrays end-on. When used broadside, all give unambiguous single peaks.

The depth penetration of the configurations is related to the separation of the current probes and is thus, in decreasing order, Tw, W, DD/Sq.

With Tw and DD, the response to a three-dimensional feature can become double-peaked beyond certain limits of probe spacing : feature depth : feature side ratio. This was determined experimentally for DD, and is shown in the optimisation diagram (Fig. 5.27), which also includes Sq. It was found that Tw can be used effectively for relatively shallow work with a spacing of 0.5 m, at which peak twinning would be minimal and of little effect in producing a misleading representation of the shape and position of buried features. For instance, Lynam (1970) shows theoretically for a sphere (always an extreme case) that twinning is virtually absent at all depths for a sphere of radius equal to the probe spacing; for the same sphere at double the probe spacing, twinning becomes seriously noticeable when the depth to the top of the sphere is less than 0.8 times its radius.

8.1.3. CLIMATIC EFFECTS. An extended experiment was conducted over ditches of three sizes, filled mainly with ploughsoil, on Upper Chalk sites in southern England. The results, explicable in terms of the balance of precipitated water, and the porosity and water capacity of the fillings, differed strikingly with ditch size, to the extent that the ideal times of the year for detecting large and small ditches were shown to be mutually exclusive and their anomalies opposite in sense: except in very dry conditions, the great ditch of Durrington Walls always gave low readings, which were particularly clear during winter and the first half of the year, following a period of net water gain by the soil; while the small Hog's Back ditch was obliterated by the winter rains, but appeared as a strong positive anomaly in the second half of the year following a net loss of water. The intermediate Woodhenge ditch behaved in a confusingly intermediate manner, changing from negative to positive each year, but was most reliably detectable when Durrington was also at its best. The finding are summarised in Figs 6.11, 6.12 and 6.13, and a discussion of the best times and conditions for surveys is given in 6.7.1.

Although it was not systematically collected, there is evidence that stone structures - at least of non-absorbent stone such as flint - on the same Chalk bedrock are detectable throughout the year. Other experiments summarised show that features of various types on sand, clay and limestone bedrocks are all most clearly detectable in conditions of net water deficit, and this probably applies to the stone structures on the Chalk. An attempt at a comprehensive resumé of the known findings is given in Fig. 6.24.

The work on the Yorkshire Wolds, reported in 7.1.1, shows that one should be cautious when extrapolating any of these experimental conclusions in detail over large distances, even when dealing with the same nominal geological formation.

In the course of the climatological work, the opportunity was taken to monitor the development of grass marks over the features being studied, and to examine records of the previous appearance as crop marks of these and adjacent ditches. The lush mark over the large ditch of Durrington Walls was found to parallel its low resistivity response. For small ditches, there is evidence that lush marks persist after their resistivity anomalies become high, and that they become parch marks only in extreme conditions. Intermediate phenomena - as with resistivity, though different in pattern and timing - occur over the intermediate ditch of Woodhenge. Attempted explanations of these patterns of behaviour are given in 6.5 and 6.7.3.

8.2. RECOMMENDATIONS FOR FUTURE RESEARCH

8.2.1. CONFIGURATIONS. Further electrolytic tank studies would be desirable to complete aspects of the work rather cursorily treated here, e.g. the vertical cylindrical feature, especially in its conductive form, which would closely simulate many archaeological pits. Further study of the conductive horizontal laminar feature would be rewarding, as well as laminar features both broader and narrower than the electrode spacing. The work should be concentrated on the more successful configurations - Tw, DD, Sq and W - and Tr should be further investigated. A greater attention to shallower feature depths would also be desirable, especially as it has been shown that many anomalies originate very close to the surface; and Fig. 5.26 shows how complex response can become in such conditions.

Tank work should be compared with theoretical approaches, and attempts made to overcome the problems of relating the two - as exemplified by Fig. 5.25. Simulation by the use of conductive paper (Teledeltos) is also of some value, either with a field plotter, enabling one to examine potential distribution, or, simply by using a resistivity meter making contact with one edge of the paper as if it were the surface of the earth, it is possible to obtain a good qualitative impression of anomaly forms, feature shapes being created with great ease by cutting out or painting them with conductive paint.

8.2.2. OPTIMISATION OF ELECTRODE SPACING. This study should be extended to Tw, and less importantly W, to complete the work started on DD and Sq, and the work on these should be further checked and refined.

8.2.3. CLIMATIC EFFECTS. These studies need to be extended to gravels, and more thorough work on clay and limestone bedrocks would be desirable. Stone and chalk foundations on a sandstone base are notoriously difficult to detect, and merit a special study, with which it would also be desirable to include gravel. Once these basic rock types have been studied, the work might be extended to more localised regional types and conditions, of which a good example is the Lower Chalk of the Yorkshire Wolds, which is harder and probably less water-retentive than that studied in southern England, and has a soil apparently modified by a glacially transported component (see 7.1.1). Tests over a wider variety of feature types and conditions, including, if possible, bare ground, would be of value, both on the bedrocks already studied, and on others.

The seasonal soil moisture distributions laboriously and tentatively deduced from the work described here should be tested either by laboratory measurements on samples taken from borings, especially into ditches, or by measurements in the borings themselves, for instance by the neutron scattering technique.

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APPENDIX I. RESISTIVITY CALCULATIONS WITH THE TWIN CONFIGURATION

Because readings obtained with this configuration are predominantly the sum of effects due to the soil resistivity beneath the moving probes and also the fixed probes, the computation of the apparent resistivity (ρ_m) of the ground beneath the moving probes is less straightforward than with the configurations in which all the probes are moved. Two alternative methods of solving the problem are given below.

METHOD 1 : USE OF TWO FIXED PROBE SPACINGS

The contribution of the fixed probes to the readings is calculated by observing the change in any one reading when the spacing of the fixed probes is changed by a known amount. Consider (Fig. I.1) fixed probes

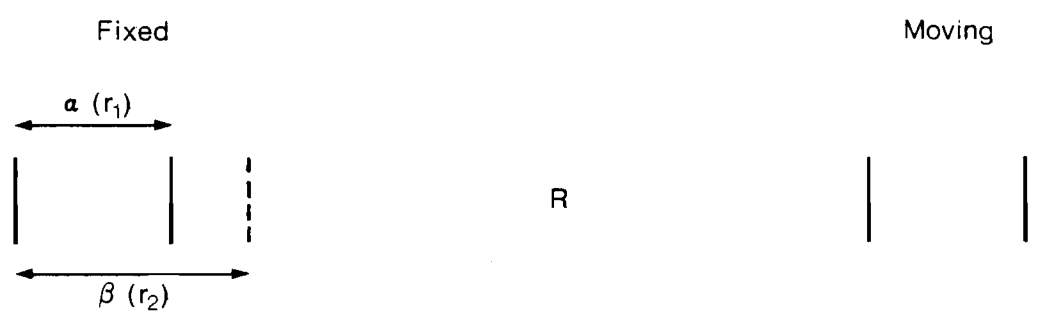

FIG. I.1

with an initial spacing α, giving a contribution r_1 to the total measured resistance R_1, and a second spacing β giving a contribution r_2 to a total resistance R_2. Then, assuming that the ground beneath the probes is of uniform resistivity ρ_f,

$$2\pi\alpha r_1 = \rho_f \quad ; \qquad r_1 = \frac{\rho_f}{2\pi\alpha} \tag{I.1}$$

and $$2\pi\beta r_2 = \rho_f \quad ; \qquad r_2 = \frac{\rho_f}{2\pi\beta} \tag{I.2}$$

Subtracting (I.2) from (I.1),

$$r_1 - r_2 = \frac{\rho_f}{2\pi\alpha} - \frac{\rho_f}{2\pi\beta}$$

$$2\pi(r_1 - r_2) = \frac{\rho_f}{\alpha} - \frac{\rho_f}{\beta} = \frac{\rho_f(\beta - \alpha)}{\alpha\beta}$$

Whence $$\rho_f = \frac{2\pi a\beta(r_1-r_2)}{\beta-a} \qquad (I.3)$$

Substituting (I.1) in (I.3),

$$r_1 = \frac{\beta(r_1-r_2)}{\beta-a} \qquad (I.4)$$

Now $(r_1-r_2) = (R_1-R_2)$, and we can therefore write

$$r_1 = \frac{\beta(R_1-R_2)}{\beta-a} \qquad (I.5)$$

The contribution to the total reading R_1 from the moving probes is R_1-r_1 and, if their spacing is α, then the apparent resistivity of the ground beneath them is

$$\rho_m = 2\pi a(R_1-r_1) \qquad (I.6)$$

METHOD 2 : PARTITIONING OF MEASURED RESISTANCE

A position of the moving probes is found where they overlie undisturbed ground, and where it is assumed that the apparent resistivity is equal to that beneath the fixed probes, so that the reading R_0 can be equally divided between the two, and the resistivity beneath the fixed probes is therefore

$$\rho_f = 2\pi\alpha \frac{R_0}{2} \qquad (I.7)$$

At any position of the moving probes, the apparent resistivity beneath them will then be

$$\rho_m = 2\pi\alpha \left(R-\frac{R_0}{2}\right) \qquad (I.8)$$

where R is the reading at that position.

APPLICATION OF THE METHODS

The two methods were tested in the preparation of Fig. 6.18. Reliable data for more than one fixed probe spacing were available only for α = 1 m (β = 0.5 m) and α = 2.5 ft or 0.762 m (β = 0.5 m). For α = 1 m, Method 1 gave a background level (at 25-26 m along the traverse) of ρ_m = 201 ohm-metres, exactly the same as that obtained by Method 2. For $\alpha = 2.5$ ft at the same position, Method 1 gave $\rho_m = 177$ ohm-metres, while Method 2 gave 187 ohm-metres.

It was decided to use Method 2 for the plotting of Fig 6.18 because (a) it was the only method available for all spacings, and gave rather better consistency of background level between the 1 m, 2.5 ft and 0.5 m spacings; (b) it was suspected that Method 1 might be subject to errors due to the different penetrations of the α and β spacings at the fixed probe end giving different values for ρ_f because of resistivity gradients in the ground, especially difference in resistivity between the topsoil and the natural chalk.