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New Developments in Geophysical Prospection

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Summary. The application of remote sensing to the problems of field archaeology has developed from somewhat speculative research exercises in the late 1940's to, virtually, routine procedures demanded of major archaeological field investigation. It is now accepted practice for site developers to contract for geophysical survey prior to planning so as to assess the archaeological potential of the site. Thus the methodology has "arrived" and, because of its widespread routine application, the future of scientific research in the discipline can, on the face of it, be questioned. However, developers and archaeologists now demand more complete interpretation of their sites in advance of planning decisions. This paper discusses research developments in three, inter-related, directions —area survey, vertical section sondage, and data interpretation—in which very significant progress in prospection techniques is being made. Examples of recent developments in instrumentation and methodology are presented, together with illustrations of recent achievements in data presentation.

1. Introduction

New developments in the natural sciences have frequently found application in science-based archaeology and geophysical prospection continues to benefit in this way. Developers and archaeologists now demand more complete interpretation of their sites in advance of planning decisions. The vast catalogue of "routine" data already accumulated awaits enhanced interpretation and the planning of future survey strategies will increasingly rely on

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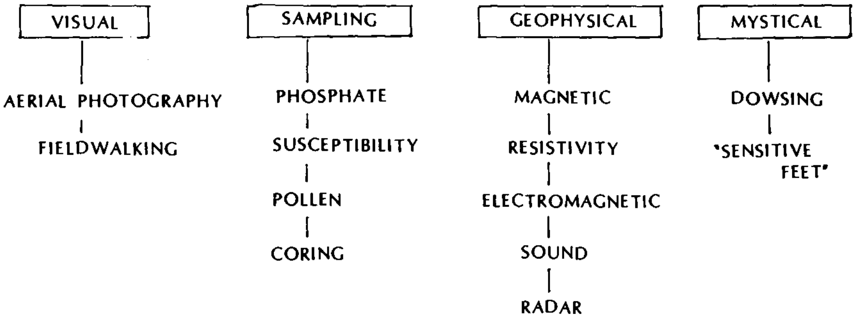


Figure 1. Archaeological prospection methods.

these improved procedures. It is, therefore, appropriate to discuss research developments along three directions:

i) area survey,

ii) vertical section sondage,

iii) data interpretation.

These are, clearly, inter-related; current and future research activities may be identified under these headings and are discussed in the following sections.

2. Area survey

Assessment of the potential of sites through area reconnaissance continues to command the greatest attention amongst archaeologists. The techniques available may be considered, somewhat arbitrarily, as "true" remote sensing through airborne and satellite cover and as geophysical, land-based, prospection.

Developments in true remote sensing have been presented in the comprehensive paper by Shennan and Donoghue (this volume) and require no further comments here, other than an endorsement of the important role of these methods in rural site assessment. The present paper, however, will be concerned with advances in geophysical prospection.

It is convenient to list methods available for site location and identification as in Figure 1, where, for completeness, aerial photography has been included. The role of scientifically-controlled field-walking, using statistically valid sampling procedures, should not be minimised, particularly in terms of site identification and history. Coupled with other scientific sampling procedures listed, field-walking can produce site information of great archaeological significance. The description of dowsing as "mystical" will be

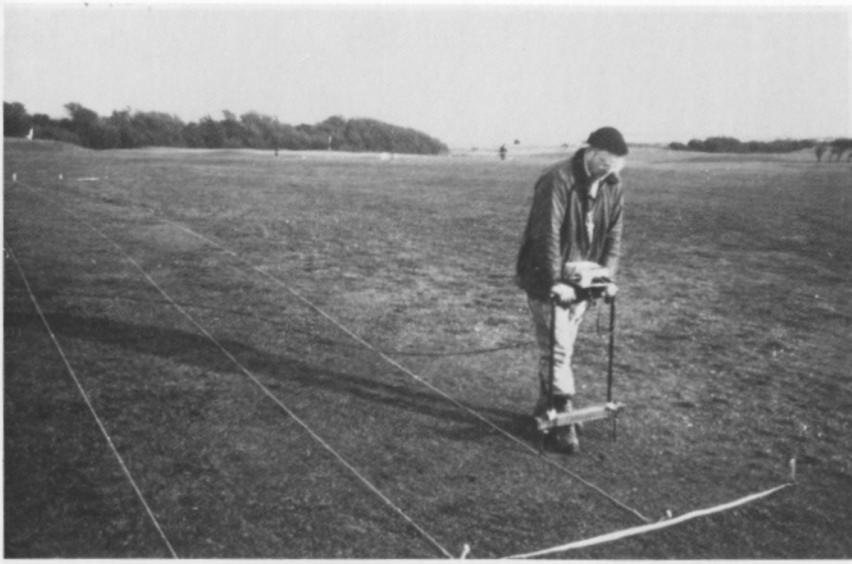


Figure 2. The twin-probe array in use with an RM4 earth resistivity system.

regarded by devotees as biased and unfair, which is certainly not intended. Indeed the technique should be viewed with an open mind, as having, as yet, no proven scientific basis, hence "mystical".

Geophysical prospection on a large scale is now an accepted procedure in field archaeology. *Earth resistance* and *magnetism* measurements carry by far the greatest work-load, with constantly improving field methodology and data-presentation. Computer-based data logging and on-site data processing are now routine, so that frequent up-dating of site strategy can be implemented. A schedule of two hectares per 12 hour day of survey is not uncommon using the techniques illustrated in Figures 2, 3 and 4. Because of this fast through-put of data, it now becomes economic to utilise the complementary nature of the anomalies detected by the two principal methods of survey. Thus a high resistivity response, coupled with a high magnetic signal is readily interpreted as an electrically impervious feature of igneous rock or human-fired structure such as a kiln. The ambiguous behaviour of resistivity measurements in the detection of ditches under different conditions of ground saturation may negate such conclusions, but this in itself offers scope for further investigative study (Clark 1990). A further research development offered by the speed of data retrieval lies in the interpretation of anomaly "shapes". Traditionally, readings of earth properties have been taken at discrete intervals, typically one metre. This sample interval gives inadequate evidence for study of the true variations of response obtained through continuous recording. However, by reducing the sampling interval to 0.25

Figure 3. Continuous earth resistance measurements with the RATEAU system and a mobile "square" array.

metre, a more realistic characteristic is obtained. Such close sampling is now entirely feasible (Figures 2, 3 and 4) in both resistivity and magnetometer surveys. In the former case multiprobe systems are in development (see section 3) which may provide interpretation of the depth and vertical characteristics of features. In magnetometry the comparison of practical and theoretical anomaly shapes provides similar information.

The simultaneous measurement of the electrically conductive and magnetic properties of the earth, using non-contact methods has been studied for the past three decades. The technique is described as an *electromagnetic method*, but, essentially, uses time-varying magnetic fields which induce secondary fields within the conductive and magnetic earth. Transmitting and receiving coils, appropriately spaced, continuously traverse without earth contact; phase and amplitude measurements of the secondary time varying fields may be interpreted in terms of magnetic and conductive properties (Scollar *et al.* 1990). Commercial systems are available to undertake such surveys, but they suffer the common limitation of linking adequate resolution with too shallow scanning depth. Alternative scanning systems may, however, be feasible. Skinner (1990) utilised a large transmitting coil which encompassed a selected area of a site and created a pulsed magnetic field which was, effectively, uniform to a useful penetration depth. The area within the loop was scanned using a smaller "search" coil to detect conducting

Figure 4. Rapid magnetic surveying with the FMl8 fluxgate gradiometer.

(metallic) or magnetically viscous bodies. Taken with corresponding magnetometer readings, the viscous anomalies can yield useful information on the archaeological significance of such features. There remains, therefore, a challenging area of study in the full interpretation of data, depending on frequency of alternating field, depth of targets and, perhaps more interestingly, their magnetic properties.

Although not strictly regarded as true remote sensing, the investigation of archaeological potential through on-site soil sampling is attracting increasing attention. The use of enhanced phosphate concentrations and magnetic susceptibility of such samples is regarded as evidence for past occupation. However, the adoption of a good code of practice in the choice of technique for sampling, analysis and interpretation is long overdue as is the critical assessment of other possible parameters, such as the trace element distribution under different environmental conditions. Recent work involving the analysis of vertical cores taken at strategic intervals in the vicinity of occupation sites (Dockrill and Gater 1991) has demonstrated the potential of the sampling approach.

3. Vertical section sondage

It is doubtful whether the concept of vertical sectioning without digging would find approval amongst some field archaeologists, but the total excavation of all recognised archaeological sites is clearly impracticable. There is, therefore, a demand for methods of vertical sondage, which will give a true representation of archaeological features. It is in this direction that the main thrust of research in geophysical prospection now appears to be aimed, with the application of traditional geological methods and the development of advanced electromagnetic systems.

When a buried object is "scanned" by the probe array of a typical earth resistivity system, the form of response obtained depends on a number of factors, including the interprobe separation, object dimensions and shape and the object depth. Thus the profile obtained is unique to these four parameters, but a single scan is not adequate to obtain other than an approximate estimate of object dimensions. However, repeated scans with different probe separations (Figure 5) result in a data assemblage from which an attempt may be made to resolve the four parameters. This technique creates a so-called *pseudo-section* (Edwards 1977) which, effectively, is a model vertical section through the earth along the line of survey, into which a perturbation, representative of the object, appears. Because of the, generally, sophisticated relationship between the resistivity response and the four variables, full identification of the object from the perturbation is not easy and becomes increasingly difficult if a complex of objects exists, perhaps in non-homogeneous earth; both conditions are common in archaeology. In geological practice, the field procedures for creating pseudo-sections have been slow and laborious. However, for archaeological applications, the largest inter-probe spacing needed is seldom greater than a few metres and, with the development of fast solid-state switching devices, it has now become feasible to lay out, in the field, multiprobe systems which are switched rapidly through the relevant inter-probe spacings, with automatic logging of data and, hence, fast pseudo-section production. Research can, therefore, focus on the effectiveness of different probe systems and on new data treatment techniques, which are appropriate for the complex responses obtained from archaeological features (Plate 4). An interesting development of the multiprobe concept has been in *tomography*. Traditionally this technique of selec-

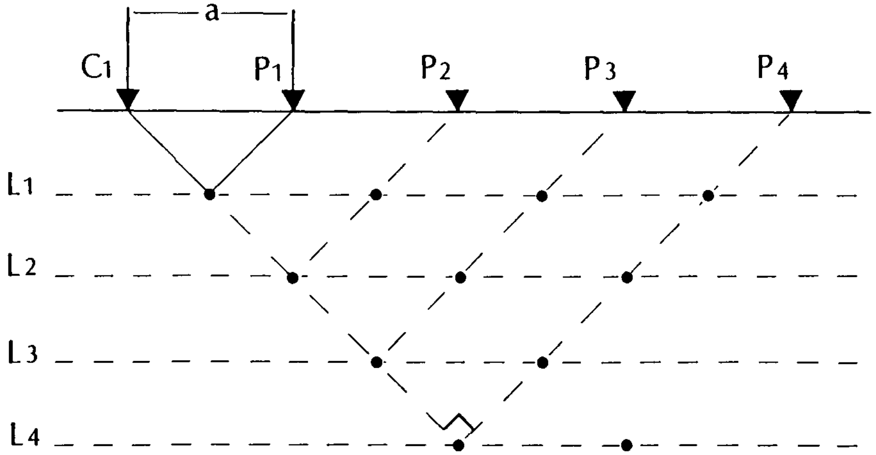


Figure 5. Pseudosection "pixels" using a multi-electrode, twin-probe array. 'Levels' (L) refer to 'pseudo-depths' with respect to interprobe spacing (CP).

tive imagery has been applied in X-radiography, but was extended to the study of softer body organs using *in situ* multi-electrode potential measurements. The latter approach has recently been applied to multiprobe systems in geophysical prospection by Noel and his colleagues (Noel and Walker 1991). However, the nature of the problem is considerably more complex than that of a controlled laboratory experiment involving "predictable" features and it may be assumed that data interpretation will encounter comparable problems to those inherent in pseudo-section theory.

The use of "echo-sounding" has excited interest from the earliest days of geophysical prospection of archaeology. *Sonic* and "shock" (*seismic*) techniques have been examined but, in general, have found limited use, primarily because of the low resolution obtained at the acoustic frequencies associated with geological applications. However, the possibility of studying buried interfaces utilising mechanical (elastic) property contrasts continues to offer promise in conditions where electrical and magnetic contrasts are low. Recent developments in high frequency transponders and in the selective use of refracted and reflected shear waves, based on geological experience, have led to practical systems for shallow surveys. At this stage, however, data throughput is slow and further study is required in the interpretation of sondages obtained from complex structures.

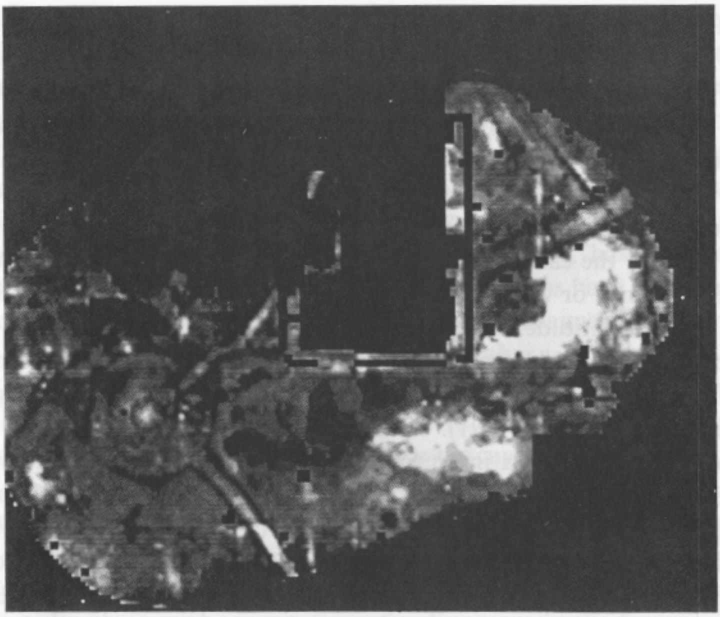
Undoubtedly the greatest potential for unambiguous sub-surface profiling lies at the high radio-frequency end of the electromagnetic spectrum, through *ground-penetrating radar*. The technique has recently generated great excitement amongst field archaeologists following a striking display of "realistic" vertical sections at an urban site in York. In fact the technique has been in use for about twenty years, primarily for civil engineering. Several commercial organisations are now offering services to archaeology in Britain and use of the technique, with varying degrees of success, has been reported world-wide. Perhaps the most significant investigations have been published by workers in Japan. Imai, Nishimura and their colleagues have carried out wide-ranging comparisons between radar and other techniques of prospection (Imai *et al.* 1987, 137; Nishimura and Kamai 1991, 757). In Plate 4 the resistivity pseudo-section of a shallow tumulus excavation is compared with the radar section, followed by confirmatory excavation.

Certainly, however, it would appear that the York survey was exceptional and that there is a requirement for considerably more research into the method before its potential is fulfilled. Two aspects of the technique will justify extended research programmes. Firstly the basic physical phenomena associated with ground propagation of radio-waves in the frequency range 100–1000 MHz must be clearly assessed for the specific boundary features, both man-made and natural, associated with archaeology. The contradictory requirements of high resolution and good ground penetration should be examined in terms of optimum frequency bands and antennae arrays for different ground conditions. Radar survey techniques currently in use are reminiscent of early days of more conventional geophysical surveys with a noticeable lack of mutual appreciation of the problems of surveyor and archaeologist. There is a clear need for a rational policy of site investigation based on such understanding and close collaboration between the two. The second, and related, point is that of adequate data processing and interpretation. By the nature of the technique, data processing has borrowed from the procedures of seismic survey. On-site presentation of data, through intensity-modulated scans of depth profiles is generally unsatisfactory, in terms of ready interpretation, except for the simplest of anomalies. Attempts to utilise the sophisticated software of the seismic geologist have had limited success. It is now necessary to develop software for the specific analysis of near-surface features based on the e.m. theory of near-distance scattering phenomena at interfaces of electrical permitivity contrast. This must be coupled to a realistic approach to the practical problems of surface topography, over which the profiling is undertaken.

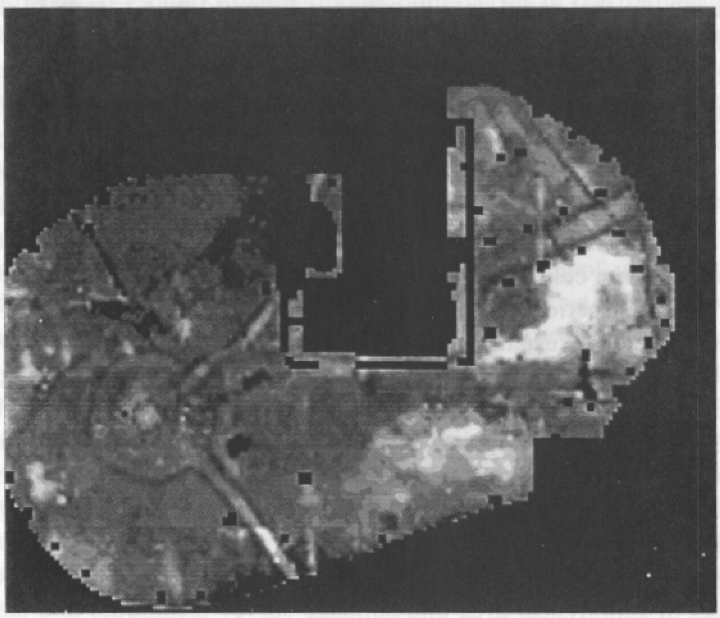
4. Data interpretation

Whatever the method adopted for geophysical survey, the ultimate goal must be to provide the archaeologist with an unambiguous display, which is identifiable in its structural context. Individual methods of survey present their own problems of interpretation, which are symptomatic of the technique employed. Thus the geophysical "fingerprint" of a simple magnetic dipole beneath the earth's surface is recognised in terms of its pattern of a "positive", partly or wholly surrounded by a negative, anomaly, dependent on the magnetic latitude. Complex magnetic features may be modelled, based on such concepts and compared with "real" magnetic surveys using, for example, data inversion and cross-correlation methods to reveal specific structures (Tsokas *et al.* 1991).

The problems of data interpretation of ground-penetrating radar have been referred to above. More generally the apparent need to smooth or filter field data so as to obtain the optimum signal to "noise" response has led to increasing sophistication in methods adopted. The availability of microcomputer-based software and graphic displays has greatly facilitated these developments, so that rapid data handling is followed by a variety of display formats embodying the large range of grey scale and false colour levels available with modern graphics (Aspinall and Haigh, 1988). Typically, following an earth resistance survey of Kirkstall Abbey by the West Yorkshire Archaeological Unit, the data handling (Cheetham *et al.* 1991) included linear and non-linear grey-scale representations (Figures 6a, b, c), together with Fourier filter and edge enhancement procedures (Figure 6d). This last treatment emphasised feature edges in a spectacular way to create a new impression of the complexity of development of this site from the medieval to the Victorian period. There is, however, a real danger in applying image cleaning, of the type usually undertaken for "ordered" images where noise is truly random, to an archaeological site. Frequently, long-term occupation gives rise to a proliferation of, apparently, random long or short wavelength features such as post-holes, pits, levelled structures etc. A quite distorted view may be given, after filtering, compared with that seen by the archaeologist after stripping the site. Such ambiguities have given rise to serious misgivings amongst archaeologists, in the use of recent radar sondages, for example. Problems of this nature, however, are there to be solved. In the past decade, advances in geophysical area and sondage survey techniques and site presentation have utilised fast data acquisition and handling developments, very effectively. Doubtless this successful exploitation will continue to benefit the cause of field archaeology into the next century when the archaeologist's

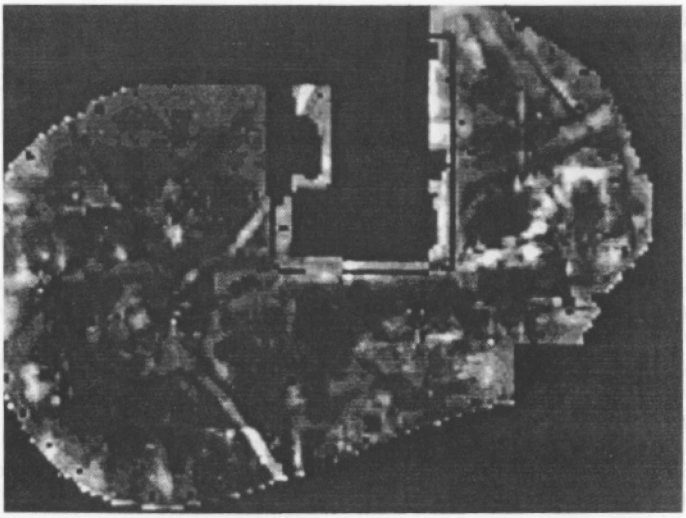


(a)



(b)

Figure 6. Kirkstall Abbey, W. Yorks: earth resistance grey-scale presentations. (a) linear: range black-white, 40–100 ohm. (b) non-linear to enhance contrast. (c) high pass Fourier filter. (d) high pass Fourier filter with edge enhancement. To the west (left) of the excavated guest house is a Victorian band-stand with radiating paths: to the south lies the kitchen area: to the east a Victorian garden scheme overlies earlier buildings. The production of 'artefact' edges is suspected in Figure 6.



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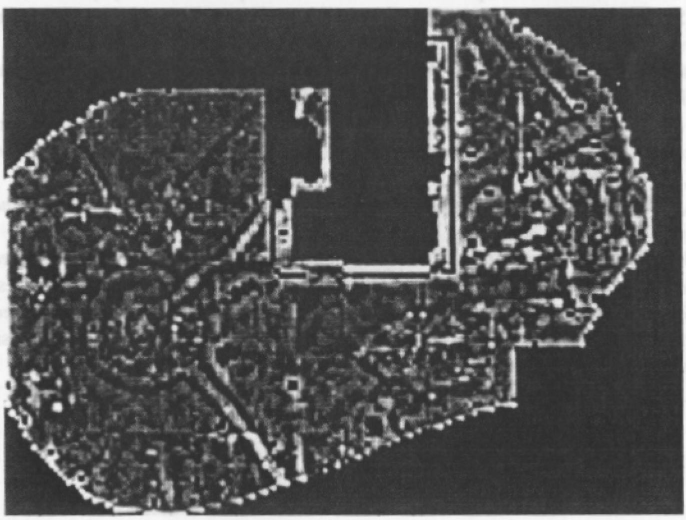

(d)

dream (or nightmare) of "peeling off" successive occupation layers on a site, without digging, may be an achievable goal.

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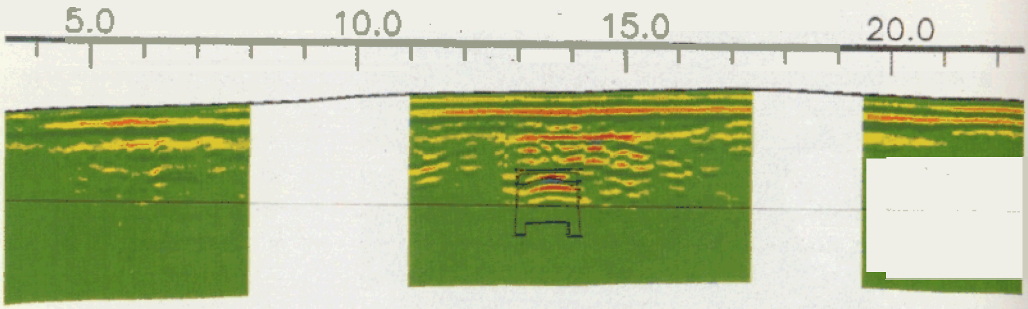
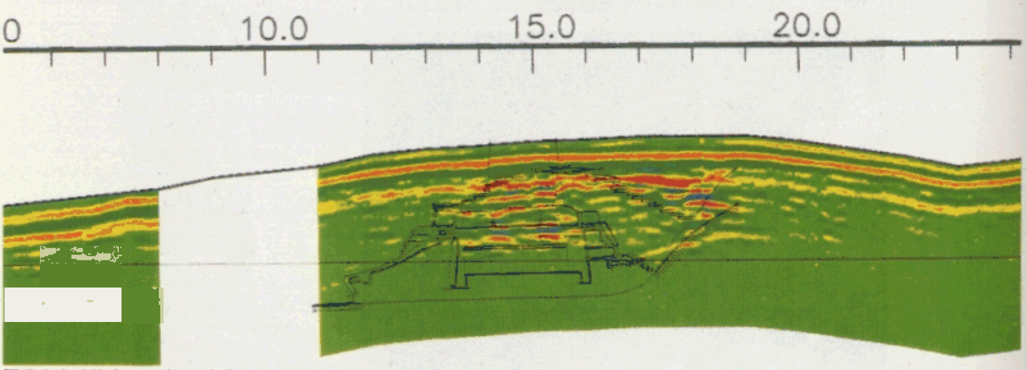
PLATE 4



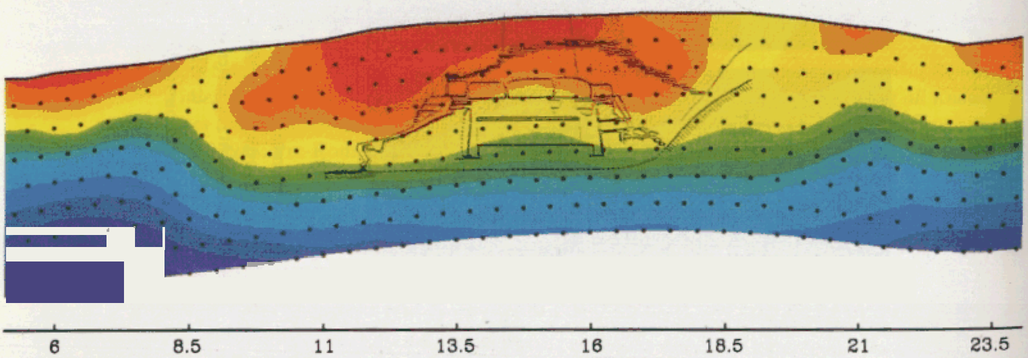
阿武山古墳地中レーダー　東西セクション

Ground probing rader surveying of *Abuyama* tumulus(E-W section)



阿武山古墳地中レーダー　南北セクション

Ground probing rader surveying of *Abuyama* tumulus(N-S section)



阿武山古墳電気探査　南北セクション

Resistivity surveying of *Abuyama* tumulus(N-S section)

Ground-probing radar sondages and resistivity pseudosection over a shallow tumulus. (a) radar E-W section. (b) radar N-S section. (c) twin-probe pseudosection, N-S. Subsequent excavation features are superimposed.