British Geological Survey

REGIONAL GEOPHYSICS RESEARCH GROUP

Report 85/3

REVIEW OF GEOPHYSICAL TECHNIQUES FOR GROUNDWATER EXPLORATION IN CRYSTALLINE BASEMENT TERRAIN

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SUMMARY AND MAIN RECOMMENDATIONS

The role of geophysics for borehole siting in basement terrain is assessed in the context of the physical properties of the regolith and bedrock, and the response to fracture zones. The electrical survey methods which have been most used are relatively cheap and simple to operate but better definition can often be obtained with seismic refraction. Resistivity methods suffer from a lack of clearly defined contrast due to the widespread presence of clay minerals and to the fact that the potentially permeable zones towards the base of the regolith and in the fractured bedrock generate only a small contribution to the overall response. Velocity values seem to be controlled by water content and the mechanical state of the material rather than by lithology: this suggests that the seismic method is more likely to define variations of hydrogeological significance. EM profiling methods provide an effective means of mapping lateral changes in conductivity which can be related either to variations in the thickness of saprolite or to the presence of fracture zones within the bedrock.

There is limited evidence that a combination of IP and resistivity measurements might improve definition of the electrical section. However, IP effects have a complex origin and field trials are needed to determine which factors predominate in the environment of the regolith. As IP equipment is more expensive and the fieldwork takes longer, its use would be restricted to specfic site investigations. Similarly, the potential of shear wave seismics should be tested in the field with a view to its application in specific circumstances. Borehole logging is needed to provide in situ physical property values for correlation with ground survey data and for defining the nature of the variations with depth through the section. Induction, natural gamma and neutron logs can be obtained satisfactorily from cased sections of hole through the regolith.

In order to assess the cost effectiveness of geophysical methods relative to other siting procedures, an estimate of success rates is needed. Reliable data for comparative success rate are not available even between the different geophysical methods: in particular, the relative merits of seismic and resistivity surveys need to be established more rigorously by field studies in the same area. The concept of success rate itself needs clarification: short term yields can be misleading and such factors as specific capacity and pumping head should be considered. There is conflicting evidence as to the costs or savings attributable to geophysical surveys but, for a proper assessment, their effectiveness has to be considered in relation to other possible procedures and not simply against 'wildcat' drilling. At present, the overall benefits of geophysical surveys appear to be marginal, but the balance could be improved simply by concentrating on difficult areas and by discontinuing surveys where they are superfluous or inappropriate. Airborne geophysical data should be considered in the context of the interpretation of remote sensing imagery and aerial photographs.

CONTENTS

1. INTRODUCTION

This report forms part of a series of reviews related to the development of aquifers in crystalline basement rocks and their regolith within the context of a project being undertaken on behalf of the Overseas Development Administration. The other aspects which have been covered include remote sensing (Greenbaum,1985), the geochemistry of basement aquifers (Kay,1985) and the nature of the weathering profile (McFarlane,1985). The report is divided into three main sections: the first sets out the features of the environment which affect the response of different geophysical techniques; the second describes the merits and limitations of the methods available for groundwater exploration; the third considers what the role of geophysics should be in future exploration programmes.

The number of papers written on groundwater geophysics is relatively small and, of this, only a very limited proportion is concerned with surveys of the regolith. Considerable use has been made of geophysics, in particular of the electrical resistivity method, for siting rural supply boreholes in hard-rock terrain but the routine, in-house nature of much of this work probably accounts for the lack of publications: contact with local organizations responsible for developing groundwater resources in East and Central Africa and Sri Lanka confirmed that a large amount of resistivity data has been collected. Projects undertaken as technical assistance by international agencies and consultants are another source of more recent information though their reports are often confidential and not easily accessible. More work has been published on mapping and defining the properties of fracture zones. This has been stimulated over recent years by interest in identifying sites suitable for the disposal of radioactive waste products in such countries as Canada and Sweden. Detailed studies have involved the development of sophisticated borehole techniques for locating fractures and evaluating their hydraulic properties but there have been few innovations in the use of surface exploration methods.

Of the published bibliographies covering subjects relevant to this report those by Darracott (in press) on geophysical techniques in civil engineering; Stevenson (1982) on fractured rock; Stow and others (1976) on groundwater in developing coutries; Van der Leeden (1974) on groundwater in general, can be taken as providing a good basis for further investigations. Journals such as Geoexploration, Geophysical Prospecting and Geophysics are the source of much of the information on current activities and they have been quoted preferentially because of their wide distribution. The principles underlying the geophysical methods and their use in the field are fully described in the standard text books of which several are listed in the bibliography: only those points of specific interest are repeated here.

2. GEOLOGICAL SETTING

2.1 Aquifer occurrence

The regolith/basement aquifer can be considered as having two components which may be present independently or together. The regolith is a medium characterized by high porosity but low permeability due to the presence of a significant proportion of fine-grained material more especially in the upper part of the sequence. While the general controls of topography, climate and bedrock lithology on the weathering processes may result in a similar type of profile in a given district there can be marked lateral variations over short distances. The presence of an irregular bedrock surface is often concealed beneath a planed cover and within the saprolite the natural progression from weathered bedrock through sands to clays is commonly found to be disrupted, with blocks or boulders of fresh rock preserved at high levels and patches of clay occuring at depth. Aquifers in the regolith can usually be considered as unconfined though they may be semi-confined in part by overlying clay.

Within the bedrock itself the presence of joints and fractures may give rise to zones of high permeability but the storage is often limited. Producing fractures can be quite narrow and they need not be the dominant set: larger fractures may be discontinuous or infilled by clays or gangue minerals. The orientation of fractures is a function of the stress field in which they developed. Sub-vertical zones, which are more common except in compressional regimes, will only be intercepted by normal drilling techniques if the site is accurately located with respect to them. They may show up as narrow, laterally extensive features detectable above background noise levels but minor sub-horizontal features are especially difficult to resolve by indirect geophysical or remote sensing methods. A case of particular interest is where low angle joints or fractures are present near the weathering front, providing a zone of relatively high permeability at the base of the regolith. The ability to site wells on a transmissive layer drawing on the large storage potential of the regolith represents a primary objective for any exploration technique in this type of terrain. Recharge of the regolith will normally occur by direct infiltration towards the end of the long rains when soil moisture deficits have been made up: where the fracture system is linked to outcrop a more direct, rapid recharge mechanism may exist for the deeper aquifers.

Quantitative investigation of geophysical data is only practical in terms of simplified models which aim to reproduce the main characteristics of the geological situation being studied. Thus, the regolith in all its potential complexity is commonly reduced to one or two discrete, horizontal layers to which a uniform property such as resistivity or seismic velocity is assigned: additional layers representing the superficial cover and the underlying bedrock complete the model. The regolith might be subdivided on the basis of a clay-rich unit overlying sandier material, or in response to the water table. Further refinements, such as layers for weathered and fractured bedrock, may be justified where borehole control is available but even if they have distinctive properties the resolution of the methods is rarely sufficient for their presence to be deduced otherwise. If a section is considered, rather than a series of isolated data points or a single traverse, a two-dimensional model can be used to take lateral variations into account, either as dipping interfaces or appropriately shaped polygons. However, the fundamental problem remains that no data set is unique to a specific situation: within the level of accuracy of the measurements there is a range of equivalent solutions based on even the simplest models, and as the complexity is increased so in general is the number of possible solutions.

Fracture zones and intrusive dykes are treated as steeply dipping tabular bodies and the field techniques designed to detect them are often different from those used to investigate the regolith: that is, the difference between locating narrow, anomalous targets with lateral continuity, and defining the thickness and properties of an essentially horizontally layered sequence. Individual water-filled fractures will not produce a detectable response under normal circumstances but a broader zone of weakness with an increased density of fractures makes a possible target, depending on the thickness of overlying regolith.

Most geophysical surveys can be classified under one of the four headings of electrical, seismic, magnetic or gravity methods: other topics such as heat flow and radioactivity may be of interest for particular applications. The responses measured by these different techniques are controlled mainly by a specific physical property such as the electrical conductivity (or its inverse, the resistivity), seismic velocity, magnetic susceptibility or density of the formations present within the range of investigation; the results must then be interpreted and related to the local geology.

2.2 Electrical properties

2.2.1 Electrical conductivity/resistivity

Most of the common rock-forming minerals are effectively insulators and the ability of rocks to conduct an electric current arises mainly from their finite, if small, porosity and the fluids contained within the matrix. Even the most compact of crystalline rocks will for this reason show a lower resistivity, <10ohm.m, than that predicted from its mineral composition alone >10ohm.m. The development of secondary porosity by jointing and fracturing invariably results in a further reduction of bulk resistivity as measured in situ. Conductive metallic and semi-conducting minerals of <1ohm.m may be distributed within hard, compact rock so as to lower its resistivity. Graphite, pyrite, magnetite, pyrrhotite and specular hematite are ralatively common accessory minerals which tend to create conductive pathways within the rock matrix. Graphite and pyrrhotite are particularly effective in this respect while the influence of other highly conductive minerals disposed as discrete crystals may be minimal: the resistivity of a graphitic schist can be as low as 10ohm.m.

Within the weathered bedrock and regolith the conductivity is often determined by the clay content. Clay minerals are not intrinsically very good conductors but, given even a small quantity of surplus water, their cation exchange capacity can significantly increase the conductivity of the pore fluid. Of the commonly occuring clays, montmorillonite and vermiculite have the greatest number of adsorbed, exchangeable ions per unit mass, with kaolinite and illite able to provide only a tenth of this. The ability of clays to retain water by capillary action due to their fine-grained texture also has the effect of keeping resistivities low, 1-100ohm.m, in comparison with more easily drained, sandier materials when they lie above the water table. Resistivities for sands may vary over a wide range, 20-5000ohm.m, depending on their clay content and degree of saturation.

The resistivity of the superficial layer is very variable and subject to local conditions. Dry sands, light soils and indurated laterite will give high values; where the soils contain more clay or concentrations of salts due to their upward migration under conditions of high evaporation, there will often be enough retained moisture at shallow depth to reduce resistivities significantly.

The critical role played by pore fluids in these processes suggests that by determining formation resistivities it should be possible to derive information relating directly to the groundwater. An empirical formula, first established by Archie, links the bulk resistivity of a saturated rock ρ to its porosity ϕ and the resistivity of the pore fluid ρ_w:

$$\rho = F\rho_w = a\phi^{-m}\rho_w$$

where F is the formation factor, nominally a constant;
a and m are similarly constants chosen to give a fit with laboratory tests.

Also:

$$\rho_s = bS^{-n}\rho$$

where ρ_s is the resistivity of the partially saturated rock;
S is the fraction of pore space filled with fluid;
b and n are constants dependent on rock type and on whether S is above a threshold value for which a continuous film of moisture is maintained over all solid surfaces within the matrix.

These formulae were developed in the context of oil reservoir assessment. They apply to clean formations - which are free of clay - and most of the values available for the constants refer to sands, sandstones and limestones. Typical values are:

for clean sands: $a = 0.6$-1; $m = 2$;
$b = 1$; $n = 2$ for $S>0.25$;
$b = 0.05$; $n = 4$-5 for $S<0.25$;

for igneous rocks the threshold value for S may be >0.7,
with $b = 0.5$ for $S<0.7$.

In practice, the resistivity of the pore fluid may be more of an unknown quantity. The effect of the interaction between fluid and matrix is to limit in situ fluid resistivities to a maximum of about 10ohm.m even when the exchange capacity is low: for a clay-rich formation this limit may be reduced to 0.1ohm.m. Dissolved chloride ions are usually the major factor in determining fluid conductivity but other ions such as sulphate or bicarbonate may predominate locally. The chemistry of the pore water can vary over a wide range depending on local rock types, the age of the water, recharge and evaporation levels etc. The introduction of clay minerals provides a finite apparent conductivity σ_m for the matrix which shunts the resistance through the electrolyte. As discussed by Ward and Fraser (1967) the bulk conductivity of the rock may then be represented as:

$$\sigma = \sigma_w/F_o + \sigma_m$$

where σ_w is the conductivity of the pore fluid;

F_o is the true formation factor as determined for high electrolyte concentrations.

Further discussions on the relation between rock resistivity, matrix conductivity, formation factor and hydraulic properties such as transmissivity and hydraulic conductivity can be found in Ponzini and others (1984) and Worthington (1977). Empirical formula can be established for particular aquifers in relatively simple situations but they do not have a general application. The amount of data required to define the relationships appears to restrict their use to detailed, intensive surveys.

The flow of current through a layered medium is sensitive to direction with the transverse resistivity ρ_t for current flow orthogonal to the bedding always exceeding the longitudinal resistivity ρ_l parallel to it. This can be quantified using the coefficient of anisotropy:

$$\lambda = (\rho_t / \rho_l)^{1/2}$$

for which values of 2 are not uncommon. These effects may originate from layering on a microscopic or macroscopic scale, depending on such factors as texture, alterating lithologies and fracturing. Paradoxically, a resistivity array laid across, for example, a fracture zone measures ρ_l rather than ρ_t, as the current density across the plane is less than that along it: over a layered, flat lying sequence $\lambda\rho_l$ is determined and the apparent layer thickness is overestimated.

2.2.2 Electrical polarization

While conduction can only occur if mobile charge carriers are available, the polarization effect takes place to some extent in all materials when the application of an electric field produces a separation of charge. There are various mechanisms by which this can occur at the atomic and molecular level, the most fundamental being a shift in electron orbit relative to the nucleus; the ionic bonds common in rock-forming minerals and polar molecules of which water is an example will also respond. The degree of polarizability which can be produced in different materials is determined in terms of their dielectric constant. This is frequency dependent and its affect on the conductivity measured with alternating currents at the relatively low frequencies used for geophysical exploration is usually negligible: in general terms, the dielectric constant decreases with frequency while the conductivity and displacement current increase. The range of values shown by different minerals is relatively small and it does not serve to distinguish them except in particular circumstances.

Two sources of polarization are important for geophysical techniques using very low frequencies. One is observed when conductive minerals are disseminated through a rock in such a way that current flow involves charge transfer between mineral grains and the pore fluid. The other occurs when there are variations in the mobility or velocity of ions through the electrolyte: these may be caused by an increase in viscosity through finer pores, or by particles such as clays with an ion exchange capacity which produce local distortions in the potential gradient.

The relation between the magnitude of polarization effects and the properties of the rock are considered by Ogilvy and Kuzmina (1972). A recent paper by Olorunfemi and Griffiths (1985) discusses previous work and describes their own laboratory results which show that induced polarization (IP) is proportional to the logarithm of the permeability, and inversely proportional to the logarithm of matrix conductivity for low electrolyte concentrations. Formation factors and other constants defining the relationships have to be determined empirically from sample measurements.

Iliceto and others (1982) reported some success in discriminating sands, silts and clays on the basis of a parameter derived from the analysis of IP decay curves. Whereas the total chargeability was sensitive to degree of saturation, their curve shape parameter was unaffected. However, they did not use any aqueous salt solutions as previous work had indicated that these led to a reduction in chargeability which was independent of the degree of saturation and grain size. The observed chargeability for clays was very low and changed little with water content; for loams and silt it increased significantly with water content; for sands the response peaked near 5-10% water content, though after thorough washing the values decreased consistently.

In general terms, the IP effect seems to be larger at relatively small concentrations, 1-10%, of clays occupying pore space; the higher the exchange capacity the lower the concentration required. The mechanism operating when pores are blocked by metallic conductors is often represented in terms of an equivalent resistance/capacitance circuit which provides some indications of its behaviour. Thus, the IP effect should increase with the number of blocked pores and it will also depend on grain size, current density, frequency and degree of saturation.

2.3 Seismic velocity

The speed with which seismic waves propogate through a homogeneous medium is controlled by its elastic constants and density but in a geological context other factors such as porosity, grain size and shape, confining pressure, degree of saturation need to be considered. There are two distinct types of wave: the longitudinal or P-wave in which compressional and dilatational forces act along the direction of travel; the shear or S-wave in which particle motion occurs within the plane orthogonal to the direction of propogation. Shear waves can be resolved further into SH and SV components which are parallel to or orthogonal to the ground surface. P-waves always travel faster than corresponding S-waves, typically at about twice the speed, and so the first arrivals from a seismic event will usually be in the form of P-waves. S-waves relate to the rigidity of the material through which they pass rather than to its compressibility and as a result the two wave types respond differently to changes in the medium. In particular, S-waves cannot propogate through a fluid and so they are relatively insensitive to water within a porous formation.

Compact crystalline bedrock would be expected to show P-wave velocities of at least 4km/s. These can be compared with values of about 1.8km/s for clays, 1.6km/s for water and <0.5km/s for loose sands and soils. Fracture zones and jointing within bedrock will reduce its velocity, as will the progressive effects of weathering; the presence of water, as against air, in the pore space increases the velocity, and the water table will often be a significant factor if it occurs within sandier material.

Little information is available on the practical use of shear waves for groundwater although research has been stimulated over recent years by an awareness of their application to oil exploration. Papers such as that by Helbig and Mesdag (1982) refer to the potential of shear wave observations and

Tatham (1982) gives some details of the relation between velocities and lithology as does Domenico (1984). Stumpel and others (1984) quote refraction measurements giving P-wave velocities of 0.3km/s, 1.5km/s and 2.2km/s for dry and saturated sands on boulder clay; SH-wave values were 0.15km/s in the sands both above and below the water table, and 0.45km/s for the clays. The rate of attenuation of seismic waves is also sensitive to changes in lithology and saturation and to the degree of fracturing. Newman and Worthington (1982) show the effects on both P- and S-waves in sandstones, marls and chalk sequences. A comparison of the response to P- and S-waves using both velocity and attenuation will give the most diagnostic information.

2.4 Magnetic susceptibility

The magnetic properties of rocks are attributable to the presence of at least one of only a small group of minerals. Magnetite is the most important of these minerals in that it is common as an accessary mineral, particularly in the more basic rock types, and it has a high saturation magnetization level: pyrrhotite and maghemite also have a high susceptibility which may be of local significance. While the distribution of magnetite can show marked variations within a given lithology, formations can often be distinguished on the basis of their magnetic response. If the magnetized body also has a characteristic geometry it may be possible to locate it quite precisely. Dolerite dykes are a specific example of this: they are often strongly, if not continuously, magnetized in comparison with background levels for most granites and gneisses, and they are distinguished by a series of narrow anomalies extended along stike.

The induced magnetization is proportional to the ambient magnetic field, and aligned in the same direction. There may also be a remanent magnetization locked into the crystal structure. This is usually ignored in routine fieldwork but there are occassions when it is significant: as the remanent vector is not related to the ambient field, the shape of the resultant anomaly can differ significantly from that due to the induced component alone and its effect may be large enough to give a reversed anomaly. Dykes sometimes show this effect but, in general, it is difficult to isolate the contribution from the remanent component.

Magnetite tends to be removed by oxidation to hematite in the early stages of the weathering process. Henkel and Guzman (1977) show this effect in relation to negative anomalies produced over fracture zones in basement, with a distinct reduction in measured susceptibility values. Lapointe and others (1984) also found that fractured and altered rocks gave relatively low susceptibilities. The regolith should therefore be deficient in magnetite and contribute little to the anomaly pattern except where black sands occur as local accumulations near the head of drainage channels or in dambos. The difference in susceptibility between granitic and gneissic bedrock may be no more than the variability within either rock type: a relatively subdued anomaly pattern would be expected over both, reflecting perhaps the influence of foliation and texture as well as any fracturing or intrusion by dykes.

2.5 Density values

The bulk density as measured in situ represents a combination of grain density, porosity and degree of saturation. Within bedrock the mean grain density can usually be related to the silica content: as the acidity increases the density is reduced with quartz replacing heavier minerals. A density of 2.67t/m^3 is regarded as a representative value for rocks of granitic composition, increasing to perhaps 2.8t/m^3 in a more basic gneiss and to 3.0t/m^3 for fresh dolerite. The presence of joints and fractures will reduce the bulk density unless they have acted as the host for mineralization: the change in bulk density is proportional to the effective porosity and to the difference between the grain density and the density of the infilling material.

Weathering of the fresh bedrock, either by chemical alteration or mechanical breakdown will reduce the bulk density although there are circumstances in which the removal of material in solution may leave a residual deposit of high density mineral. The density of clays is usually higher then that of sands and gravels but the observed values are sensitive to variations in porosity and degree of saturation, to the extent that the potential overlap in ranges, 1.5-2.5t/m^3 is almost complete. Given a progression from weathered/fractured bedrock, though sands to clays nearer the surface, the tendency for the lower levels to be water saturated will reduce the density contrast between the sands and clays. The gradational and irregular nature of the processes forming the regolith also implies that its bulk density will show little coherent variation and that the most distinctive contrast is likely to occur near the weathering front.

3. GEOPHYSICAL EXPLORATION TECHNIQUES

3.1 General considerations

Geophysical methods are directed towards the measurement of a specific, characteristic property of the geological section. The received signal will, in general, be a composite response which contains information on all the material between the observation plane and the effective range of investigation. While survey techniques can be focussed to some extent to concentrate on particular targets it is obviously a prerequisite that the physical property serves to distinguish the target from the surrounding material, and that the signal level returned is high enough for the response to be resolved from background variations or ambient noise levels. In this respect both the contrast in the property value and the size of the target relative to its distance from the observation plane have to be considered: the seismic response differs somewhat in being more sensitive to the interface between zones while most of the other techniques are influenced by the volumes of material involved. One subdivision of methodology can be made between airborne, ground and borehole surveys in terms of the scale of operations; anomaly resolution; definition of properties within the sequence; equipment. Some of the basic techniques employed have much in common but borehole logging can involve a more specialized approach.

In considering the application of any technique to surveys for basement aquifers it is necessary to bear in mind the cost effectiveness of the operations. This will be covered in more detail in Section 4 but it should be noted that, for rural water supply, the relation between drilling costs, success rates and geophysical survey costs appears to be delicately balanced. Whereas in oil or mineral exploration surveys the risk capital element is small in comparison with the potential rewards of success, there is much less flexibility for experimentation in the context of groundwater surveys. For this reason the techniques applied need to be well established or adapted from methods developed for other purposes. The fact that few qualified geophysicists are concerned with supervising or undertaking surveys for routine borehole siting has also restricted the application of newer ideas, and it explains why, in some cases, the use of outdated resistivity methods is continued without a real appreciation of their capabilities and limitations.

Realistic objectives for geophysical surveys in basement terrain can be listed as:

1. defining the depth to hard, compact bedrock;

2. indicating the depth to water and variations in the composition of the regolith which might relate to permeability;

3. fixing the location of dykes and fractures and of intersecting trends;

4. mapping variations in bedrock lithology.

Depth to 'bedrock' is the parameter of basic importance to which surveys are directed routinely: it relates to maximizing the saturated thickness in exploiting the regolith and, indirectly, to the occurrence of fracture zones within the underlying rock. In practice, there may be a gradual transition to massive bedrock and the geophysically defined interface will represent the average of both vertical and lateral variations near this level.

3.2 Resistivity surveys

There are two standard forms of resistivity survey. In the first, the electrode array is expanded about a fixed central point to obtain information primarily on variations with depth; this is commonly referred to as resistivity sounding. In the second, the electrode spacings are constant and the array as a whole is moved along a traverse to map lateral variations. Both Wenner and Schlumberger array configurations are used, though the latter is probably more widely adopted these days. The Wenner array has the advantage of giving a stronger signal for a given depth of investigation but the Schlumberger array is more convenient logistically and the data are less susceptible to distortion from near-surface inhomogeneities. Barker (1981) describes a multicore cable system based on the Wenner array which reduces the problems due to variations in the superficial layer while significantly improving on the efficiency of field-work.

The dipole-dipole array is rarely used, mainly because of the low received signal level and the consequent need for more expensive, less portable equipment. However, it is well suited to providing sectional data for two-dimensional modelling surveys and it has long been the standard array in IP surveys for mineral reconnaissance. Griffiths and Turnbull (personal communication) report the development of the multicore cable system to allow measurements of pseudosections with a Wenner array.

Interpretation of resistivity soundings presumes a one-dimensional sequence of homogeneous, isotropic layers in order to derive layer resistivities and thicknesses. This can be done by matching apparent resistivity data against standard sets of auxiliary, and 2-4 layer, master curves but a more reliable approach is to compare the results with values calculated for a specific model which can be modified as required. This is easily achieved with a small micro-computer using the linear filter technique proposed by Ghosh (1971). Automatic curve matching programmes, such as those described by Zohdy (1974) and Koefoed (1979), can also be run on small machines.

Curves obtained over hard rock terrain are characterized by a minimum corresponding to a relatively conductive regolith, bounded by a resistive cover and underlying bedrock. In some cases this central zone can be resolved into two components, with the deeper section suggesting either sandier material in the saprolite, or the presence of a transition zone through weathered bedrock: typical resistivity values range from 15ohm.m to 250ohm.m. The existence of any thinner, discrete layers within, or at the base of the regolith is suppressed and, even where a lower section is identified, the range of equivalent solutions prevents its accurate definition: both of these effects add to the uncertainty in fixing a depth to bedrock. The parameter that can be defined most reliably in these circumstances is the total conductance of the units overlying resistive bedrock, using the graphical method of Orellana (1966) or interpreted model parameters: this will emphasize the presence of conductive clays rather than zones of immediate hydrogeological interest but it may give a more reliable indication of variations in the regolith.

One difficulty in assessing the reliability of such interpretations is the shortage of studies which review them in terms of subsequent drilling results. This arises in part because the geophysics tends to be used only semi-quantitatively for routine site selection: also, the borehole control itself may be lacking in detail or simply be too unreliable for defining variations in the saprolite and in the transition zone to compact bedrock. Another factor which affects the sounding curves and their interpretation is the presence of lateral variations in total conductance over the length of the array, that is over a distance of typically 200-400m depending on the depth to bedrock. Irregular data points are easily identified but more subtle distortions of the curve may be attributed wrongly to horizonted layering.

Following on from their earlier work, in which they pointed out the discrepencies between resistivity interpretations and drilling results, Ballukraya and others (1981 and 1983) reported a correlation between the depth to water strikes given on drilling records and the occurrence of discontinuities or 'breaks' in sounding curves at equivalent half current electrode separations. They attributed this to the occurrence of the aquifers as thin, locally sub-horizontal, conductive layers within bedrock; this means that the breaks can be distinguished from the effects of lateral inhomogeneity by the fact that they occur at the same electrode spacing when the array centre is displaced: While the authors admit that relation is empirical and lacking a theoretical basis, it is difficult to discount their analysis of more than 800 borehole records. Other semi-empirical approaches to the interpretation of sounding curves have been promulgated, such as the inverse slope method of Sankaranarayan and Ramanujachary (1967), which apparently can give better results than curve matching techniques in some situations. Certainly, an empirical technique which proves effective is better than an abused analytical treatment of the data. However, as Keller (1968) indicates, its limitations have to be considered.

To summarize, it can be said that while sounding results may help in categorizing different types of regolith in relation to lithology, as described by Palacky and Kadekaru (1979), Palacky and others (1981), and in giving general indications of the nature of the regolith and depths to bedrock, they also suffer from serious limitations: the resolution is inadequete for picking out any zones of higher permeability near the base of the saprolite or in transitions through broken bedrock; the depth to water is not usually identified; quantitative analyses are subject to gross errors and do not show consistent agreement with drilling results, as seen for example in Carruthers (1981) on data from Malawi. It is not clear that the units of specific interest do have distinctive resistivities and this can only be confirmed by detailed borehole studies which include coring and geophysical logging.

Resistivity profiling is being superceded to some extent by the use of EM (electromagnetic) equipment which has several theoretical and logistical advantages. However, the resistivity method uses simpler, more widely available equipment and it allows flexibility in power output and electrode spacing while providing results which are directly comparable with sounding data. Bose and Ramakrishna (1978), Buckley and Zeil (1984), McDowell (1979) and Peart (1981) discuss its application to groundwater surveys in India and Botswana as a means of mapping both fault zones and areas of deeper weathering in basins of decomposition. In the latter case the gradient array, with the current electrodes fixed at a wide separation and only the potential dipole traversed within the central section, is an efficient technique; for narrow, vertical features the Schlumberger array gives better resolution. The length of the array is selected with reference to the depth at which the features of interest are expected to occur - to maximize the response and lateral resolution while keeping interference and masking effects in the overlying layers to a minimum. For the simple, two-layer case, traversing at two electrode spacings will define the weathering profile over resistive bedrock: the closer spacing fixes the resistivity of the regolith; the wider spacing gives the total longitudinal conductance. The use of at least two separations is needed in general to check that anomalies do not originate within the upper layers rather than at the bedrock interface.

Lateral effects within the regolith or bedrock can be identified in sounding curves either as discontiniuties, if the array is expanded across the feature, or by a change in curve shape between arrays sited along it and offset from it (Bro and others, 1980-81). Another technique is to expand the array along different azimuths about a fixed central point. Mallik and others (1983) suggest plotting apparent resistivities in plan for each current electrode separation: for an isotropic medium the values will join as circles; otherwise the ratio of the length of major to minor axis of the ellipse gives a measure of the anisotropy, with the fractures lying along the major axis (see also Keller and Frischknecht, 1966 pp 36-39). Fractures will not usually give a large response and even this suffers rapid attenuation through a conductive overburden. They are most likely to be detected as a broader zone of weakness within the bedrock, associated with deeper weathering.

3.3 **EM profiling**

An EM signal can induce current flow within the ground, avoiding the need for grounded cables. This is a significant advantage in arid areas where electrode contact resistances are high enough to restrict the effectiveness of resistivity surveys by reducing current flow and increasing noise levels. Other advantages of EM systems include their better horizontal resolution of anomalies and more efficient fieldwork. The use of inductive coupling also means that conductivity mapping can be carried out by airborne surveys.

The EM methods have been developed primarily for mineral exploration in which very conductive ore bodies are the target, but the same equipment can be effective in groundwater surveys. Palacky and others (1981) give a comprehensive account of their experience with horizontal-coil EM traversing, and they show the importance of defining the borehole site precisely with respect to the anomalies if better yields are to be obtained. They used a standard moving source/receiver system with a coil separation of 50m and operating frequencies of 444Hz, 1777Hz and 3555Hz which enabled them to detect fracture zones at depths of 30m and to distinguish granitic from volcano-sedimentary bedrock. VLF (very low frequency) signals provided similar information on the location of conductive zones but as the method relies on transmissions from distant, fixed stations it could not be used effectively in areas where the strike direction prevented good coupling.

Poddar and Rathor (1983) illustrate how VLF results can give information on the resistivity and thickness of the weathered layer over granite-gneiss: Carruthers (1980) includes some additional examples. Henkel and others (1983) show the application of horizontal-coil EM and VLF to mapping faults and fracture zones in Sweden: they operate the EM at an unusually high frequency, 18kHz, with 60m coil spacing, as the response to relatively poorly conductive, sheet-like bodies is enhanced at large induction numbers (proportional to frequency and coil separation) in the absence of a masking clay cover.

The Geonics EM34-3 instrument was designed specifically for conductivity mapping. It is another moving source/receiver system but it operates over the relatively low conductivity range of 1-1000mS/m with a higher sensitivity than conventional equipment: the out-of-phase signal component is calibrated to give a direct read-out of apparent conductivity. The coils are oriented to lie in the same horizontal or vertical plane at spacings of 10m, 20m or 40m for which the respective operating frequencies are 6400Hz, 1600Hz and 400Hz. With vertical coils the effective depth of investigation is reduced significantly but the data are less susceptible to mis-orientation errors: with the coils horizontal there is better coupling with sub-vertical bodies which may show up as characteristic anomalies superimposed on background conductivity levels.

The Scintrex SE-88 Genie is another recently developed system which can be applied to geological mapping and groundwater exploration. Again it employs a moving source and receiver but in this case, two frequencies are transmitted simultaneously and their amplitudes compared at the receiver: no interconnecting cable is required and the measurements are insensitive to geometric errors. Coil spacings of 6.25-200m can be used with four operating frequencies between 112.5Hz and 3037.5Hz.

The attenuation of EM waves is proportional to the ground conductivity and the signal frequency so that a conductive overburden will restrict the information that can be obtained from fracture zones beneath it. The VLF response in particular can be reduced sharply as the operation frequencies are 15-25kHz. Deeper penetration may be obtained with the Turam system which measures the amplitude ratio and phase difference between a pair of receiver coils: the signal is transmitted typically at 220Hz or 660Hz through a long grounded cable, or a rectangular loop laid out on the ground, which remains fixed whilst the receiver coils are traversed over lines orthogonal to it.

A limited amount of quantitative interpretation is possible with EM data to provide estimates of the thickness and conductivity of the weathered layer if it is isotropic, but Palacky and others (1981) point out the difficulties with this. Model studies can be used to demonstrate the type of variations that occur, as for example Villegas-Garcia and West (1983): a more empirical approach is to calibrate observed values at control points provided by drilling or resistivity soundings. Anomalies attributable to sub-vertical features such as fault zones or dykes can be modelled as tabular bodies, with due allowance for their geometry, depth below conductive overburden etc. Angle of dip is critical if the borehole has to intersect a narrow permeable zone below water table and this will still be the case if inclined holes are drilled.

Instrumental problems remain in obtaining variable frequency EM sounding data over the required range despite the potential advantages relative to resistivity methods: Poddar (1983) provides an example of this use. The main developments now relate to time-domain techniques which are proving very effective; the latest equipment under development should provide a depth sounding capability at the relatively shallow levels needed for work in basement terrain.

3.4 IP surveys

Very few examples of surveys of the type relevant to the situation of basement aquifers are available. The work that has been published is mostly concerned with alluvium or granular rocks, and an assessment of excessive groundwater salinity, though Ogilvy and Kuzmina (1972) do show results from surveys over basalts using both profiling and sounding techniques to distinguish weathered, fractured and fresh bedrock.

In general, the IP response is more difficult to interpret than resistivity data as changes in resistivity will, of themselves, affect IP values. Roy and Elliott (1980) make the point that it is the ability to pick out additional features not resolved with resistivity alone which justifies the use of IP. Elliot and Lauritsen (1977) put forward a method for interpreting IP sounding curves on the assumption of no resistivity contrasts: Nabighian and Elliott (1976) require that the resistivity layering be fully defined for their procedure: another approach is suggested by Patella (1973) though Roy and Elliott (1978) comment on some limitations with this. A qualitative indication of the presence of different layers is given by inflections and turning points in the sounding curve.

Results relating specifically to regolith/basement terrain are required before a satisfactory assessment of the IP method is possible but it might add significantly to the interpretation of resistivity data: the results are, to a degree, complementary and resistivity data are always obtained as part of the IP survey. IP data might help in:

defining the water table, with a maximum response from the capillary fringe;

differentiating heavily weathered, clay-rich material from zones with a sandy texture, either as lateral variations or an increase in chargeability with depth;

outlining zones of saline water in the aquifer;

indicating the base of the weathered rock;

showing variations in the bedrock related to lithology or, perhaps, fracturing. Fractures might give a lower response due to weathering out of polarizable minerals, or a higher response if a suitable clay/silt infill is formed.

This number of possibilities might suggest that the results will be too ambiguous to give any useful information but, in practice, one or two of these mechanisms are likely to predominate.

3.5 Seismic refraction surveys

The seismic refraction method is potentially one of the most effective geophysical technique available for defining the hard rock aquifer, and the main questions relating to its use are concerned with costs, time, availability of equipment and qualified staff. A paper by Ovaskainen (1984) makes a convincing case in support of seismic surveys in terms of both a higher success rate of borehole sites, and improved well efficiency in the form of lower pumping heads and greater specific capacity. Three layers were usually identified:

a superficial layer with a P-wave velocity of <0.8km/s;

a heavily weathered, clay/rich or silty zone of 0.5-1.1km/s when dry, 1.0-1.9km/s if water saturated;

a deeper, less weathered zone of 1.7-3.5km/s in broken and decomposed to fractured rock, increasing to 4.8km/s in more compact, fractured bedrock.

The velocities for fresh rock were >4.5km/s but the gradual increase towards these values means that no specific interface can be defined. Sites were chosen mainly on the basis of low velocity zones in the deeper refractor, found on lines limited to 200-800m in length. Borehole results confirmed the reliability of the interpretations with interface depths consistent to better than 10% and significantly higher specific capacities at sites classified as being the more promising. These results from Kenya were obtained over granitic, volcanic and sedimentary rocks for which the velocity profiles showed little difference in relation to the lithology.

Seismic results from Nigeria (Omorinbola, 1983) were equally convincing in defining interfaces corresponding to the water table and the weathering front as correlated against observation wells. The unsaturated zone gave a velocity of 0.8-1.1km/s, with 1.5-1.8km/s for the saturated regolith and 2.8-3.2km/s in the underlying bedrock: the intermediate zone effectively defines the saturated thickness. As no mention is made of well yields or specific capacity, the hydraulic characteristics of the regolith remain undefined: by implication, the bedrock here is relatively homogeneous and adequete water supplies can be derived from the regolith. With saturated thicknesses typically >15m the situation may be analagous to that described by Chilton and Smith-Carington (1984) in Malawi where geophysical surveys were not necessary. However, borehole programmes in the same district of Nigeria have resulted in low success rates and it may be that fracture zones are in fact important although they have not been identified from these seismic surveys.

Bro and others (1980-81) give a comprehensive account of their methodology for locating fractured basement aquifers in Mali. They emphasize the need for seismic data to resolve the ambigiuties attached to the results of electrical surveys. Low velocity zones in the deep refractor can be used to define the fractured rock and locate boreholes with the necessary precision. While anomalies are often apparent in the resistivity profiles they do not characterize the fracture zones as such.

Interpretation techniques for seismic data are well established but in this type of shallow investigation extra care is needed to avoid errors due for example to near-surface inhomogeneities. Burke (1970) and Domzalski (1956) consider these problems in some detail. Simple solutions based on plane, dipping interfaces may be adequete as a first approximation but, in general, methods which allow for irregular refractor surfaces and lateral velocity changes are necessary to give accurate results: Sjogren (1984) describes various procedures, to which can be added the reciprocal method of Hawkins (1961), requiring adequete coverage of each refractor for a full analysis.

The relation of S-wave to P-wave surveys is similar to that between IP and resistivity techniques. P-waves, being the first energy arrival at the geophone, are easier to define than the later onset of S-waves. This problem is mitigated by transmitting preferentially SH mode waves which do not convert into other wave types: the SH response can be enhanced further by reversing the impact direction and stacking signals at the recorder with opposite polarity. In order to be able to store sufficient data and to process it effectively the equipment needs to be more sophisticated than for P-wave surveys.

Seismic reflection surveying represents an extra level of complexity: shallow reflection arrivals can be recorded in favourable circumstances from depths of >20m (Hunter and others, 1984) but at the present stage of development the method is not considered applicable to regolith/basement aquifer studies. The shorter wavelength of S-waves gives, potentially, a higher resolution. However, their main advantage lies in complementing P-wave data, to give some extra information on the nature of the materials - the ratio of velocities from clays may be diagnostic - and interface depths.

3.6 Magnetometer surveys

Proton magnetometers provide a rapid and accurate means for mapping anomalies in the earth's total magnetic field (more correctly, the flux density). They are not susceptible to instrumental drift and so it is only necessary to make allowance for diurnal variations, which may be negligible in comparison with the amplitude of anomalies of interest. Their application to groundwater exploration has been limited to delineating dykes; apart from a few exceptions.

Birch (1984) describes the use of Werner deconvolution and Fourier spectral analysis in the routine processing of magnetic profile data to give estimates of bedrock depth where the magnetization of the overburden is insignificant. Taking the thin vertical dyke as the model for calculating source depth he gives several examples where the results agree approximately with seismic refraction data. While such estimates may give a guide to bedrock depth they are not reliable enough to be used independently. Collar (1979) shows several procedures for interpreting individual anomalies from profile data which can be used if a microcomputer is not available for 2-dimensional modelling: Satpathy and Kanungo (1976) provide another example from hard-rock terrain in India.

Henkel and others (1983) have traced fault belts with the help of the negative anomalies that can occur as a result of oxidation processes. These do not define individual fractures but relate to broader zones of weakness. In contrast, the anomalies due to dykes are often quite distinct and if surveyed in sufficient detail they can yield information on depth to upper surface, dip and width. Various types of compound anomalies are possible in association with dykes, depending on the lithologies and on the relative effects of chilled margins and local fractures on weathering processes: for example, a central core of strongly magnetized rock may lie within a broader, negative feature.

While dykes have great significance locally for well siting in such countries as Botswana (Enslin, 1950) they do not occur throughout basement terrain. Mapping contacts and changes of lithology within the bedrock is a more general application of the magnetic method where the contrasts in magnetization are sufficient.

3.7 Gravity method

Consideration of the likely density profile through the regolith and the relatively small scale of the features of significance, points to few situations in which the gravity method would be appropriate. Eaton and Watkins (1970) show that gravity surveys have an application to delineating volumes of porous unconsolidated sediments but the necessary density contrasts are rarely found in the regolith. Gravity data can help in terms of mapping the larger-scale structures such as faults or geological boundaries, and if the information is already available it should certainly be considered for the appraisal of a new development area, along with remote sensing and aerial photography.

3.8 Airborne geophysics

The high cost of airborne surveys means that they can seldom be justified in the context of groundwater exploration alone. However, many countries now have at least a partial coverage because of interest in locating mineral and oil reserves. Aeromagnetic surveys are the most extensive because they have general application and impose fewer constraints on such parameters as terrain clearance: EM and radiometric data may also be collected in areas of greater prospectivity.

Various types of EM system are in use: multifrequency; INPUT, the acronym for the induced, pulse transient method, operating that is in the time domain; and VLF. While they have been designed for the detection of conductive ore bodies rather than for geological mapping purposes, it is often possible to extract valuable information on the overburden, fractured zone, variations in lithology, structural trends. Examples of this application are provided by Fraser (1978), Palacky (1975,1981), Sengpiel (1983), Sinha (1983), Eriksson (1983).

Hult (1983) shows how regional dislocation systems can be analysed from aeromagnetic data using techniques similar to those described by Greenbaum (1985) for remote sensing, bearing in mind that the geophysical information is essentially line data which tends to suppress the influence of trends parallel to the flight direction. Buckley and Zeil (1984) show that the presence of dykes may be picked up on aeromagnetic maps; Henkel and Eriksson (1980) comment on the use of airborne magnetic and VLF data for mapping fractures.

Two significant advantages of airborne data are: first, the rapid, systemmatic coverage of large areas; second, the scaling effect which allows for the correlation of apparently isolated anomalies along regional trends. Because of the limits on resolution and the possibility of position-fixing errors, airborne surveys are not a substitute for ground traverses but they can provide a basis for selecting targets for detailed ground follow-up work.

3.9 Borehole geophysics

Borehole logging provides a means of correlating directly the physical properties of the material with lithological descriptions over a vertical section: the geophysical data may also define contacts more accurately in the absence of cores, pick out marker beds which serve to correlate results from other holes and provide information on variations around the borehole. Keys (1970,1971) gives details of the methods and their application to groundwater.

Unfortunately, the two parameters of immediate concern for surveys of the regolith, that is the resistivity and sonic velocity, cannot usually be determined through casing; variations in resistivity can be logged opposite slotted casing below static water level and conductivity values can be measured in the absence of metal casing by induction logs. Natural gamma logging is one standard technique which will give some information on clay content in a dry, cased hole if due allowance is made for differences in absorption on the count rate as the borehole design varies. Neutron logging, which is related to porosity, is also possible in cased holes.

A full suite of logs can be obtained in open hole sections. Soonawala (1984) points out that the location of fractures and of changes in salinity presents few difficulties but the evaluation of the lateral extent, continuity and hydraulic properties of fractures is less straight forward. The July 1984 issue of Geoexploration and the proceedings of a workshop on radioactive waste disposal (Nuclear Energy Agency, 1982) contain a number of papers relating to this subject. Some of the techniques now being developed involve tube-waves, generated at fracture intersections and propagated along the borehole wall/fluid interface; cross-hole and hole-to-surface measurements of acoustic energy, EM fields and resistivity; radar; as well as assessments of the more familiar formation density, neutron and temperative logging data. The possibility of extracting useful information from a failed well is obviously attractive, more especially in a heterogeneous environment where a successful well may be sited within a few metres of a dry hole.

4. GEOPHYSICAL SURVEYS FOR BOREHOLE SITING

4.1 Survey considerations

Two related problems have to be addressed in considering the role of geophysics in these circumstances. The first concerns the applicability of methods currently available; that is, whether the aquifers are associated with distinctive physical properties, either of themselves or as secondary features of their mode of occurrence, which can be detected by geophysical techniques. The second is a question of economics and the relative effectiveness and costs associated with different exploration techniques such as wildcat drilling, remote sensing, aerial photography, geomorphology, geophysics. The term 'basement terrain' does not define a unique geological setting and it would be surprising if these problems could be answered in simple terms. Given the absence of any general solutions a procedure for deciding on the best siting techniques is needed which can be adapted to particular circumstances. Geophysics is only one aspect of this.

The first point has been considered in the previous sections. It is not clear whether the regolith can be treated as a well-stratified sequence on a local scale or if it is essentially heterogeneous but the tripartite subdivision typically provided by geophysical interpretations seems often to be an oversimplification when compared with the hydrogeology. However, in the absence of a thicker, more predictable regolith profile of the type found in parts of Malawi, the depth to more compact rock and the occurrence of fracturing in its upper layers are significant parameters which geophysics may help to define.

Electrical survey data, which are most sensitive to the occurrence of water, do not relate readily to the specific yield of the regolith. There are examples of surveys which show better agreement with water table and bedrock depths but there is no evidence of a consistent, quantitative association of well yields and specific capicity with resistivity values and interface depths interpreted from sounding curves. The results do discriminate against sites where shallower bedrock occurs or where thicker, conductive clays are likely to restrict recharge and aquifer thickness, and on this qualitative basis borehole success rates should be improved. On the other hand, Ovaskainen (1984) has presented data which show that seismic velocities from the deeper section of the regolith can be related directly to drilling success and well performance; depths to static water levels and an interface corresponding to a change to less decomposed saprolite were also confirmed by drilling. Given the association between the bedrock profile and the intensity of fracturing, any method which provides information on both aspects has obvious advantages. An equivalent approach in two-dimensions for resistivity data does exist but the resolution is lower and the ambiguity in interpretation is greater.

In general, a better interpretation can be made if different geophysical techniques are used over a survey area rather than if results are available from only one: the data referring to distinct properties are complementary and so a clearer understanding of the geology may be gained by noting similarities and differences between the data sets. Soonawala (1984) and Olsson and others (1984) describe their approach to site investigations for radioactive waste disposal in fractured crystalline rocks; this includes magnetic, EM, electric, gravity and seismic ground surveys following analysis of any airborne data.

Groundwater supply surveys in rural areas have to be less ambitious to compete against drilling costs: a combination of magnetics with electrical methods is sometimes found, as for example Satpathy and Kanungo (1976), but only rarely are seismic and resistivity results available for comparison. This makes an assessment of their relative cost effectiveness very difficult. For example, the drought relief programme in Victoria Province, Zimbabwe (Hydrotechnica,1984) relied exclusively on EM and resistivity for geophysical surveys; Ovaskainen (1984) quotes only seismic refraction data; Bro and others (1980-81) did use resistivity methods as a means of selecting sites to be covered by seismic profiles for locating fractures and contact zones but there is no quantitative comparison. No field data are available for evaluating IP or shear wave seismics in this environment.

4.2 Economic considerations

Farr and others (in press) have proposed a method for comparing different siting methods on the basis of marginal costs. This requires figures for average production borehole drilling and search technique costs, and an estimate of the success rate for each method. It is difficult to pre-judge what the success rate will be without first using a method: there is little reliable evidence for reference and local factors in any given area are likely to be significant. Some interesting comparisons are possible by considering the minimum success rate a method would need to viable in competition with wildcat drilling. Figures for Botswana based on about 6km of resistivity/magnetic traverse per site, supported by some sounding data and control boreholes within the survey area, suggest that with a wildcatting success rate of 45% an improvement of 10% would justify the geophysical surveys. However, an approach based on aerial photography and the known geology would probably be preferred.

Part of the difficulty lies in defining the criteria for success rate. Referring again to Ovaskainen (1984), the benefits of seismic surveys relate not only to meeting a minimum yield requirement as, for example, significant reductions in pumping head should extend the life and reduce maintainence costs of the pumps. His figures indicate that geophysical survey costs were about 10% of the sum for drilling a dry hole to 70m depth, while the success rate increased by 30-40% in some areas and specific capacity values invariably increased. The limit for a successful hole was set at a minimum sustainable yield of 0.12l/s for a hand-pump stroke rate of 45 per minute, but nearly half of the holes into granite produced at more than 0.5l/s with a specific capacity in excess of 0.02l/s/m. In Zimbabwe, the yield limit of 0.25l/s was reduced, because of the acute water shortage, to a specific capacity of 0.003l/s/m at which level a success rate of 76% was achieved; nearly 80% of the values were below 0.1l/s/m. Bro and others (1980-81) attribute increases of 25-30% in the success rate to the use of geophysics, with average yields raised by 50% to 1.25l/s.

The daily charge rate for geophysical site surveys is made up from amortization, transport, staffing and a relatively small component for consumables such as batteries and perhaps explosives. Capital costs can be high for new equipment, at up to about $50,000 for a 24-channel enhancement seismograph system, $5,000-$15,000 for EM and resistivity sets, $3,000 for a proton magnetometer: there may also be problems over spares and servicing of sophisticated electronic equipment. A significant proportion of the costs arises from the time spent at each site and the travelling involved. Ease of access and the density of wells required in the project area will limit the savings that can be made in travel time and costs but there are obvious advantages in maintaining a base camp within the immediate area if it can be operated conveniently.

Under favourable circumstances it should be possible to survey two sites per day using resistivity/EM/magnetics, but a more realistic average would be closer to one site per day, especially if seismic refraction was involved; more time will be needed in problem areas or where higher yields are essential. Depending on the drilling techniques being used, one field crew could find the sites for two rigs on this basis. The level of operations and staffing will obviously need to be scaled to meet requirements and available resources. Ideally, a hydrogeologist should ensure that survey lines are located with due consideration for geomorphological controls, aerial photography and any other relevant information; field work and data collection would be undertaken by competent technical officers and labourers (up to 2+4) working to a geophysicist responsible for compiling and interpreting the data from two survey teams.

The choice of survey techniques has to be made at an early stage of work in a new area. Seismic velocities appear to correspond with the mechanical state of the rock rather than to lithology, but resistivity values are more sensitive to local factors such as the type of bedrock and dominant clay mineral in the saprolite; water chemistry may also be important and it can raise specific problems, perhaps a sulphate-rich water for which a pyritized bedrock source might be traced. Initially, a combination of resistivity soundings with EM and magnetometer traverses would be recommended for rapid reconnaissance, followed up with seismic refraction if practical and if additional control is needed.

The priorities in many cases should be to do the minimum necessary to avoid sites with shallow bedrock, and to pick out lateral discontinuities associated with fractures and deeper weathering. The length of traverses may be restricted by access or siting requirements but a knowledge of the average distance between major joints and fractures for the local bedrock would be significant for setting a preferred lower limit: in difficult areas for locating aquifers, the length and number of traverses can justifiably be increased, bearing in mind that the extra costs need to be reflected in improved success rates relative to other siting procedures.

Dijon (1982) illustrates the need for a continued review of survey techniques in the light of drilling results. Whilst accepting the use of geophysics in particular areas he considers that 30-40% of the 'fairly expensive' geophysical programmes in some projects could have been substituted by interpretation of aerial photographs, without much reduction in success rates; in arid areas with saline groundwater the interpretation of resistivity data were misleading. These conclusions arose out of experience gained from United Nations groundwater projects on crystalline rocks in twelve African countries: resistivity surveys were undertaken in eight of these, together with a much lesser amount of seismic refraction in six; magnetometry was restricted to Botswana. Experience from Malawi (Chilton, 1984) also demonstrates that the role of geophysics must be assessed critically in relation to development programmes.

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