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Technical Report WC/93/26

Project Completion Report

Groundwater exploration in southeast Zimbabwe using remote sensing and ground geophysical techniques

D Greenbaum, R M Carruthers, R J Peart, S J Shedlock, P D Jackson, S Mtetwa & B J Amos

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Groundwater exploration in southeast Zimbabwe using remote sensing and ground geophysical techniques (Project 91/8)

by

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SUMMARY

Regional and local scale investigations, involving remote sensing, ground geophysics and drilling, have been carried out in southeast Zimbabwe aimed at increasing the understanding of crystalline, hard-rock aquifers and improving borehole siting procedures. New products derived from satellite imagery that simplify interpretation have been developed and are described. Detailed field studies at a small number of locations suggest that, whilst photolineaments, thought to represent rock fractures for the most part, are an important element in borehole targeting, they are not by themselves a wholly reliable guide. The role of ground geophysical surveys in site selection is described and evaluated. A hypothesis to describe the nature and role of fracturing in this region is presented, based on the evidence of the field tests undertaken.

A strategy for medium-term groundwater development in low-rainfall areas underlain by crystalline basement, such as southeast Zimbabwe, is proposed. It is suggested that more effort is put into establishing a network of high-yielding wells at strategic locations to supplement individual village supplies during periods of drought.

The work summarised in this report was carried out under the ODA/BGS Research & Development Programme of technical assistance to the devloping countries. A full list of reports arising from the study is provided.

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1. BACKGROUND

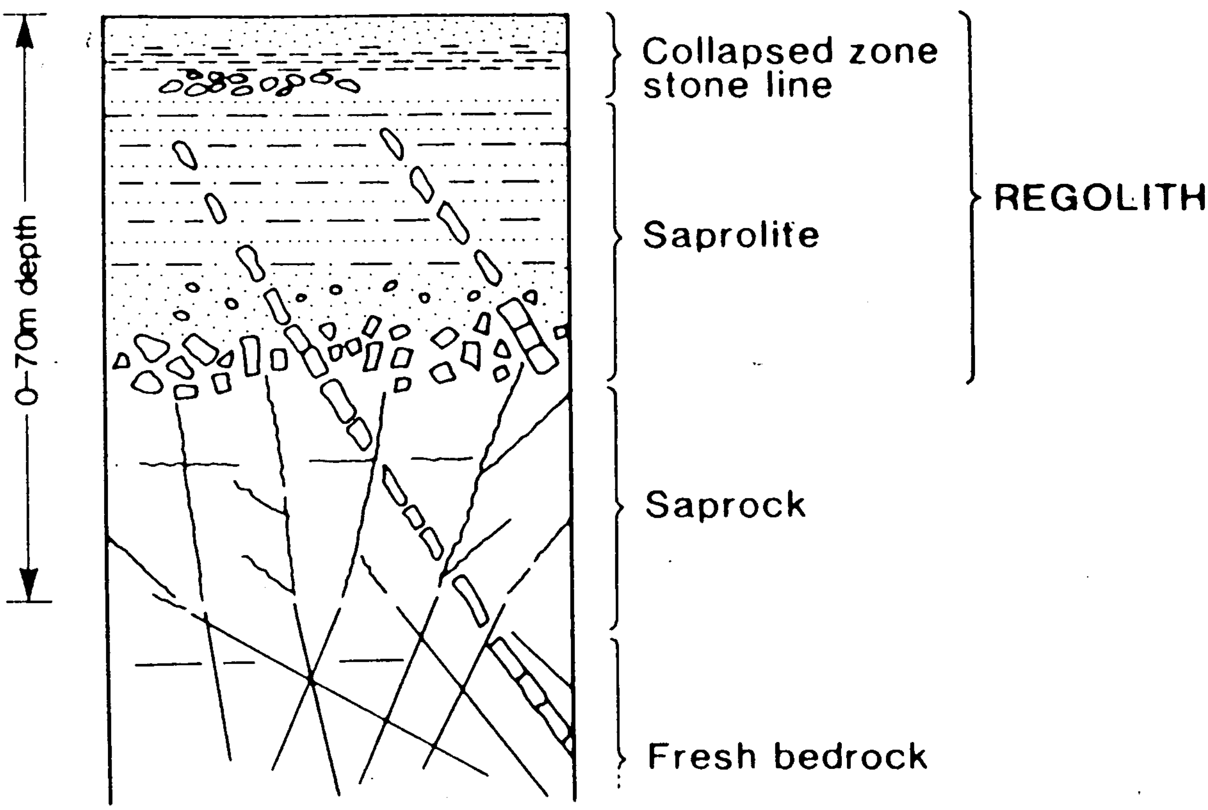
Many rural communities in arid and semi-arid areas are dependent on sub-surface supplies for the provision of drinking water. In arid and semi-arid areas underlain by impermeable crystalline basement rocks, groundwater supplies are mostly restricted to the weathered overburden (regolith) and to structural traps (e.g. fractures, fissures and intrusive bodies) (Figure 1). Groundwater exploration in these areas depends on a knowledge of both regional variations in hydrogeological conditions and local features of the geology.

Remote sensing can help delineate regional and sub-regional factors of hydrogeological relevance so that fieldwork can be carried out cost-effectively and rapidly. Satellite images and aerial photographs provide indirect information on the solid and superficial rocks, structures, geomorphology, vegetation patterns, vegetation vigour, infiltration and soil moisture, all of which have potential significance in locating groundwater. In arid areas, weathering etches out the lines of structural weakness, such as faults, joints and dykes, so that these are expressed on satellite imagery and aerial photographs as 'lineaments'. Fractures are generally considered to be passageways for groundwater movement and therefore provide important targets. Despite this, they are inadequately understood geologically, and drilling often gives poor results.

Once potential target zones have been identified on images they must be further investigated using ground geophysical methods. These indirect techniques seek to detect and map out variations in the physical properties of rocks which help characterise the sub-surface geology. In so doing they allow specific locations for drilling to be selected. This combination of remote sensing and ground geophysics provides the best approach to borehole siting presently available.

Much of southern Africa experiences unpredictable rainfall, with the result that droughts are common. The study area in southeast Zimbabwe is underlain by a varied assemblage of ancient crystalline basement rocks of mainly granitic composition (Figure 2). The chief causes of inadequate rural groundwater supplies in such terrains are poor infiltration, surface run-off and high evapotranspiration losses.

This research builds upon a knowledge of the area developed over several years during which BGS has been involved in collaborative studies with the Zimbabwe Department of Water Development. These studies, and the present work summarised in this report, have been carried out with financial support from the Overseas Development Administration (ODA) under the ODA/BGS Research & Development Programme, part of the British Government's programme of technical assistance to the developing countries. The approach and methodologies outlined below are of wider application in similar terrains and climatic environments elsewhere in the world.



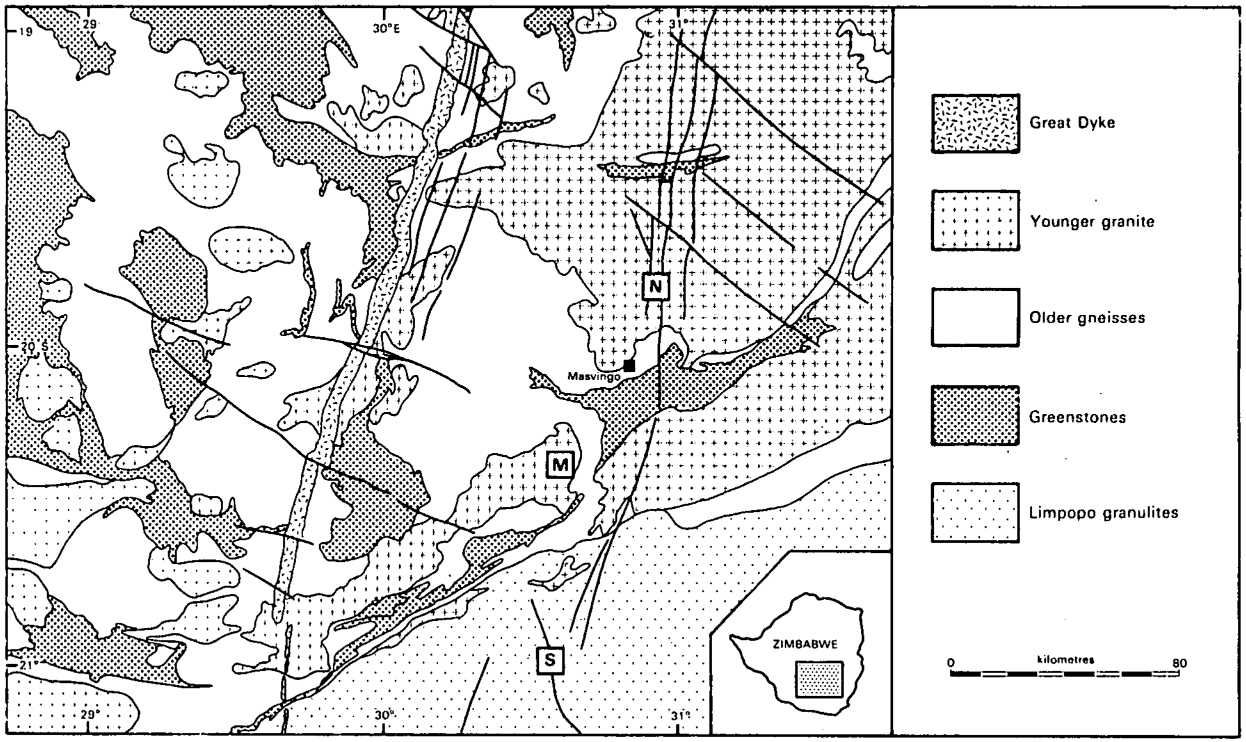
(1) Collapsed zone. This may show marked lateral variations but is generally sandy on watershed areas with illuviated clay near the base and sometimes a "stone" line; on valley slopes, colluvial material accumulates and in dambos, secondary clay materials predominate. Slope bottom laterites may also occur which can result in perched water tables. Permeabilities vary in accordance with lithology although on watersheds the collapsed zone normally occurs above the water table.

(2) Saprolite is derived by in-situ weathering from the bedrock but is disaggregated. Permeability commonly increases at lower levels due to paucity of secondary clay minerals.

(3) Saprock is weathered bedrock. Original features are likely to be more open than in the fresh bedrock and in the absence of secondary infilling, permeability could be high, but storativity low.

(taken from Wright ed 1988)

Figure 1 Description of weathering profile above crystalline basement



N Nanwi/Nemarundwe M Mhatiwa S Sarahuru

Figure 2 Location map with regional geology

2. PROJECT OBJECTIVES

The project had two major objectives:

(1) to investigate the potential of remote sensing to provide operational information at the sub-regional and local scales on the hydrogeology of semi-arid basement areas; and

(2) to characterise the sub-surface geology, especially in terms of the response of structures to ground geophysical techniques, over lineaments interpreted as fracture zones, and to determine the most appropriate techniques for siting boreholes and shallow dug wells.

These two objectives were pursued in parallel. The underlying aim was to develop a better understanding of the occurrence of groundwater in this difficult environment in order to improve exploration methods and drilling success rates.

3. REMOTE SENSING STUDIES

Methodology: The purpose of this phase of the work was to develop image processing techniques and products that highlight surface geological features and ground conditions; the hydrogeological significance of the interpreted features was evaluated through field checks. Although the methods involve the use of sophisticated image processing techniques, the final image products are easily interpreted and can be understood by non-specialists. Image processing concentrated on the reflectance properties of Landsat Thematic Mapper (TM) imagery, and especially those bands that exhibit vegetation-related variations. Images acquired in different seasons, representing a range of rainfall zones in east and southeast Zimbabwe, were compared. Image processing and analysis comprised (1) an evaluation of different band combinations; (2) the digital integration of multi-season imagery; (3) comparative studies within important land-use categories; and (4) the use of vegetation indices to map the persistence of green vegetation during periods of drought.

In dry regions, where rainfall is seasonal and erratic, patterns of vegetation can give important clues to near-surface water movement and availability. An underlying assumption here is that the distribution of healthy green vegetation on dry-season imagery provides some indication, however indirect, of variations in soil moisture or shallow groundwater. Among other things, vegetation patterns relate to the ability of plants to obtain moisture through their root systems, plants with tap roots providing the best indication of deeper, preserved moisture. Green vegetation may be mapped using using combinations of the visible and near-infrared spectral bands.

The uses of satellite imagery and aerial photographs are largely complementary since each contains unique information at different scales. Satellite imagery is of most value in regional studies for identifying large geological structures. By contrast, aerial photographs are more useful at the detailed level where high spatial resolution, stereo viewing, low cost and ready availability of data are important. Comparisons between aerial photographs and false-colour Landsat imagery were undertaken both in order to aid satellite image interpretation and to understand better how the monochrome tones of conventional black-and-white aerial photographs relate to vegetation, soil type and soil-moisture content. This understanding of conventional aerial photographs is important since they are likely to remain the basis for operational borehole site selection for some time to come.

Image products and evaluation: Three types of enhanced image were investigated: (a) digitally-merged, multi-date, change-detection images using data integrated from different seasons; (b) false-colour band combinations from a single date of acquisition; and (c) vegetation index images from dry-season imagery.

Multi-date image combinations, through seasonal differences in vegetation pattern, and possibly soil tone, can provide clues to the persistence and movement of groundwater. This was investigated by digitally combining images from the beginning, middle and end of the dry season and examining changes. It was concluded that imagery acquired during the middle to end of the dry season, when plants begin to show stress due to lack of moisture, is often the most suitable for hydrogeolgical purposes.

False colour band composites are a standard method of presenting satellite imagery. An assessment of the information content of dry-season imagery was carried out to define the best spectral bands for the discriminating surface materials and ground conditions.

One difficulty in trying to recognise features of hydrogeological significance is that modern vegetation patterns are to a large extent a function of land use practices. In Zimbabwe, the so-called Communal Lands, where additional groundwater supplies are most needed, are heavily overgrazed; here, natural vegetation patterns have been destroyed and on imagery the zones now appear as conspicuous 'bleached' zones. Despite this, evidence relating to run-off, drainage and infiltration remains, and can be used to understand patterns of water movement. It is concluded that such images contribute useful information when used as part of a broader study. However, the interpretation of lineaments remains their main value, as discussed below.

Vegetation index images, using a ratio of the near infrared band to the visible red band, provide an effective means of estimating percentage ground cover, or quantity of vegetation (green biomass). However, although easily calculated this ratio is not a completely reliable quantitative measure of the vegetation density.

In order to develop a better biomass estimator, comparisons were made between several different vegetation indices. This involved evaluating the influence of soil shadowing using a mathematical model in which the relative proportions of sunlit soil, sunlit plants, soil shaded by plants, and shaded plants were calculated for various vegetation densities and lighting conditions. The results showed that, whereas the presence of shadow has a marked effect on the accuracy of the ratio-based indices, it has only a minor effect on one particular index - the Difference Vegetation Index (DVI).

Whatever vegetation index is used the values are difficult to display effectively because the resulting image lacks the perspective normally provided through topographic shading. Consequently, a new presentation method was devised which allowed the DVI image to be presented in colour together with essential information on relief (Figure 3). Compared with

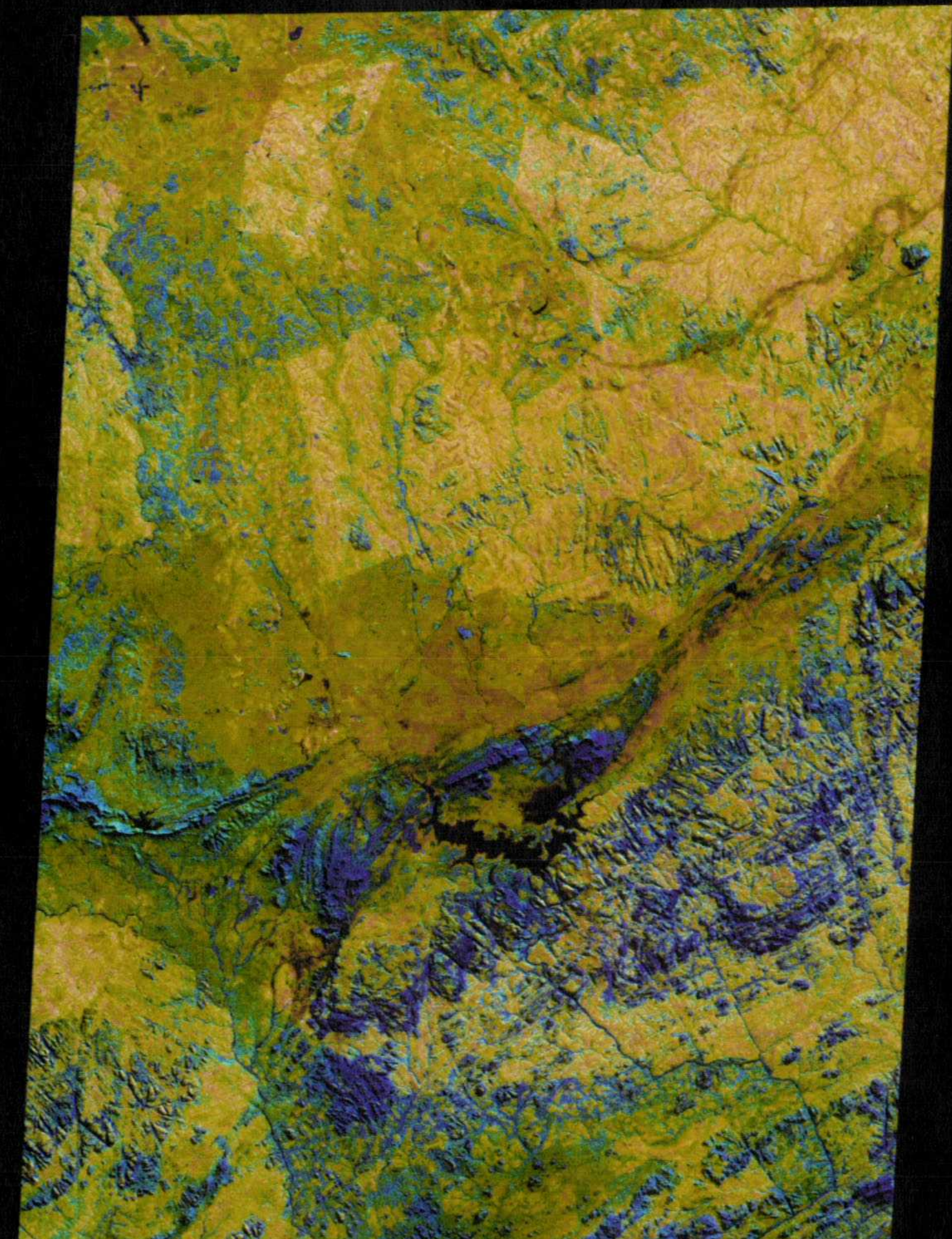


Figure 3 Difference Vegetation Index (DVI), indicating vegetation density from high (red) to low (blue), against a background of the relief

the standard false-colour composite, this image is far better at separating variations in vegetation density and is less affected by variations in soil background type.

An important use of these images is in the investigation of lineaments. By comparing false colour composites with DVI images it is possible to distinguish vegetated lineaments, which suggest the availability of groundwater in open fractures, from unvegetated ones which are more likely to be closed fractures (Figure 4).

General conclusions: The remote sensing studies were aimed at enhancing indirect evidence of groundwater occurrence from features such as soil tone and vegetation distribution. New and innovative image processing approaches have been developed leading to improved false-colour band composites and vegetation index images. These provide an important initial guide to target selection at the sub-regional level. Although there is often difficulty in distinguishing natural patterns of variations from those produced by man, satellite images are useful for interpreting vegetation vigour, and contain important, though difficult to interpret, information on soil tones, some of which relates directly to moisture and surface water infiltration patterns. At the more detailed level, however, aerial photographs remain an essential tool in site selection.

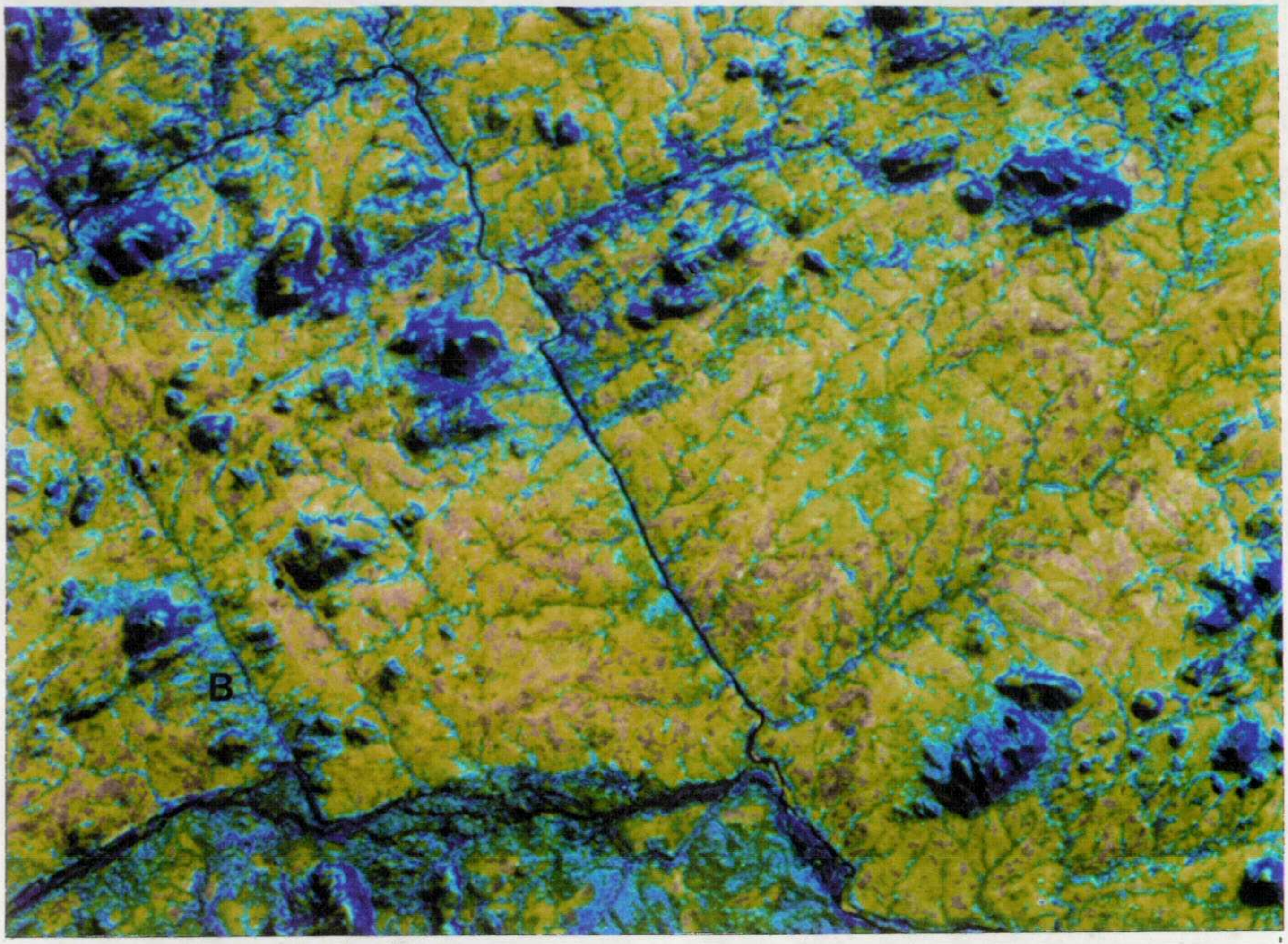
4. SITE INVESTIGATION STUDIES

Based on previous BGS investigations in Masvingo Province, and on the results of the Landsat studies, four localities were chosen (Figure 2) to cover a range of 'typical' situations. These were investigated using a combination of geophysical and geological techniques, including the collection of core samples from specially drilled inclined boreholes.

Three of the sites (Mhatiwa, Nanwi and Nemarundwe) lie within the terrain of the Younger Granites, showing characteristic flat-bottomed, open valleys (known locally as 'vleis'), a thin weathered zone and abundant outcrop both within the lower ground and as spectacular 'bornhardts'. The fourth site, Sarahuru, is on the margin of the more tectonically disturbed ground of the Limpopo Mobile Belt where gneisses predominate and the weathering is generally more pervasive.

Fieldwork was split into two phases. The first phase was devoted to geological mapping and systematic geophysical surveys; the second phase followed drilling and included core inspection, cross-hole seismic tomography, geophysical borehole logging and some additional detailed surface geophysics. Only limited work was conducted at Sarahuru due to time constraints.

Geophysical techniques: Various techniques are available for measuring specific physical parameters, such as the strength of the earth's gravity and magnetic fields, or the ease with which electrical currents flow through the ground. Measurements are usually collected at or above ground level and represent the combined response of all the materials beneath, with contributions decreasing according to distance. Specific techniques have been developed for taking measurements down boreholes, where a closer correlation can be established with the local geology.



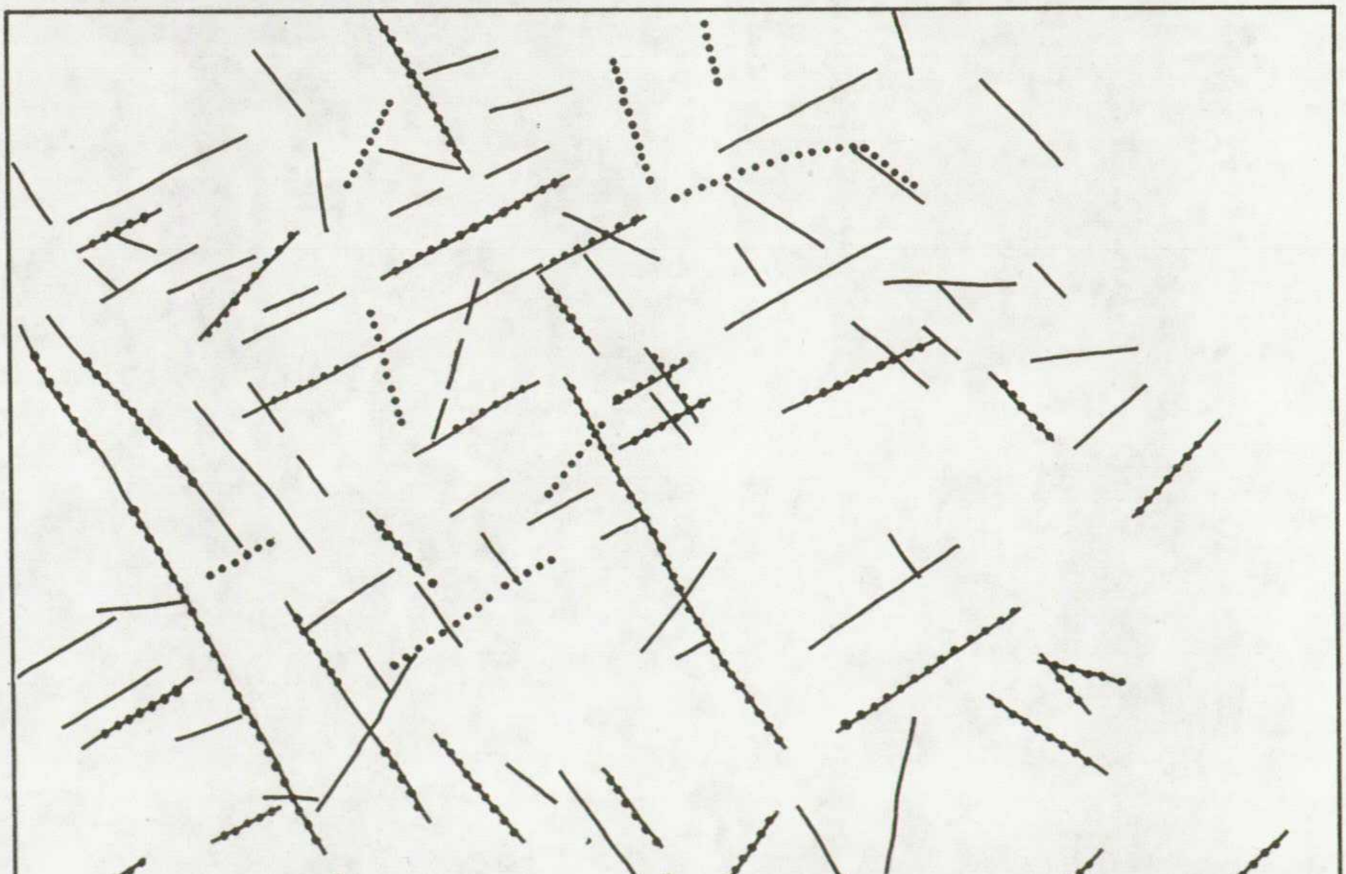


Figure 4 1: 100,000 scale extract from Figure 3 together with lineament interpretation. Lines interpreted from ordinary false colour composite and dots from above DVI image: coincident lineaments are more likely to

Geophysical results must first be interpreted in terms of the distribution of physical properties within the sub-surface, and then placed within a plausible geological context. A primary aim is to map any responses which could be associated directly with photolineaments and, if possible, to interpret the source of the anomalies. The mapping of the sub-surface bedrock profile is also important in regard to locating local depressions for the optimum siting of dug wells. The confidence of the geophysical interpretation usually increases if complementary data sets are available; e.g. a combination of techniques reduces the ambiguity inherent in any one method.

In this study data were collected using electrical resistivity, electromagnetic (EM), seismic and magnetic techniques, including recently developed time-domain EM. Electrical (including EM) methods respond most directly to the fluid content of the sub-surface and may also indicate groundwater quality; they are the standard tools for groundwater investigations. Recent advances in technology have led to increasing use of EM equipment, particularly for detecting lateral variations in more detail. Sophisticated 3-dimensional computer modelling programs were also developed to predict the type of resistivity and EM response that could be expected in this environment.

Geophysical survey results: The most impressive geophysical anomalies occurred at the Sarahuru site where the combination of EM and magnetic data proved particularly effective in delineating the main feature (see Figure 5). This was attributed to the presence of a large basic dyke or dipping sill, overlain by thin, highly conductive, black soils. The EM data complement the magnetic results as they respond mainly to the less-magnetic weathering products derived from the intrusion and indicate the presence of other zones which may represent associated fracturing; they also give clear evidence of the superficial nature of the main conductor.

At other sites, the responses, though more subdued, showed resistivity and electromagnetic anomalies coincident with, or offset parallel to the photolineaments. These anomalies are distinguished mainly by their linearity (Figure 6) and can be largely explained in terms of variations within the cover of weathered material such as thin, grey conductive clays. These clays are responsible for the darker tones on aerial photographs along drainages marking lineaments. Occasionally, the streams cut through the clays to reveal outcrop which produces corresponding resistivity highs. Detailed modelling of resistivity profile data confirmed that the observed anomalies near the lineaments could be reproduced by variations within the uppermost 10-15 m of the sequence, with any response from underlying bedrock fractures being suppressed.

None of the anomalies detected indicated the presence of a major zone of fractured bedrock extending to depth. The lineaments themselves often coincide locally with resistivity highs, or their margins, suggesting that quartz pegmatites and lateral variations within the granite, as well as shallow bedrock, are significant. A prominent magnetic 'low' at Mhatiwa, parallel to, but offset from, the lineament by up to 70 m (Figure 7) was interpreted as a probable pegmatite-rich zone. Drilling on the actual photolineament found no evidence of fracturing; this emphasises the need for caution in using photolineaments as evidence of the underlying structure.

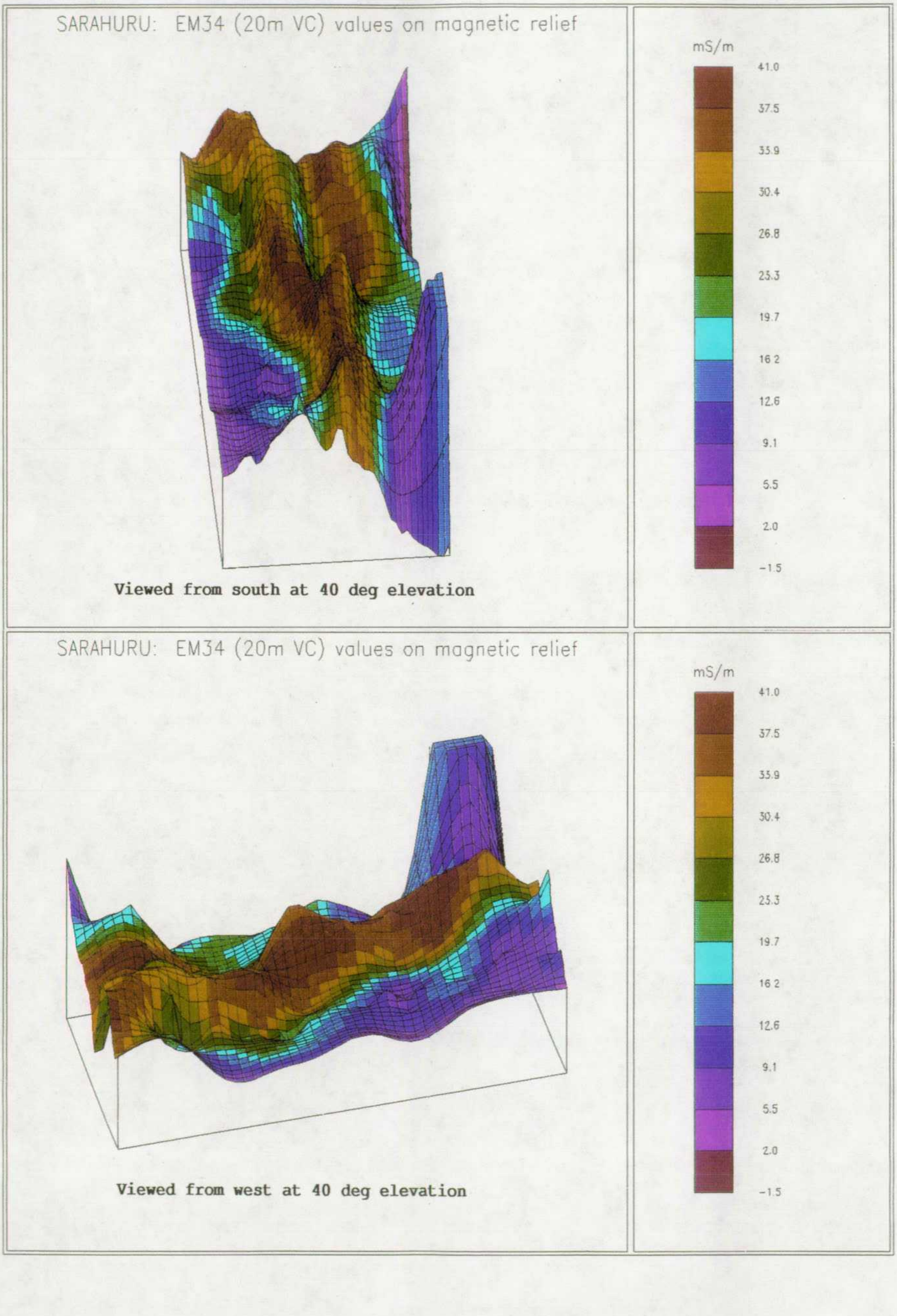


Figure 5 Combined plot of EM34 and magnetic data from Sarahuru

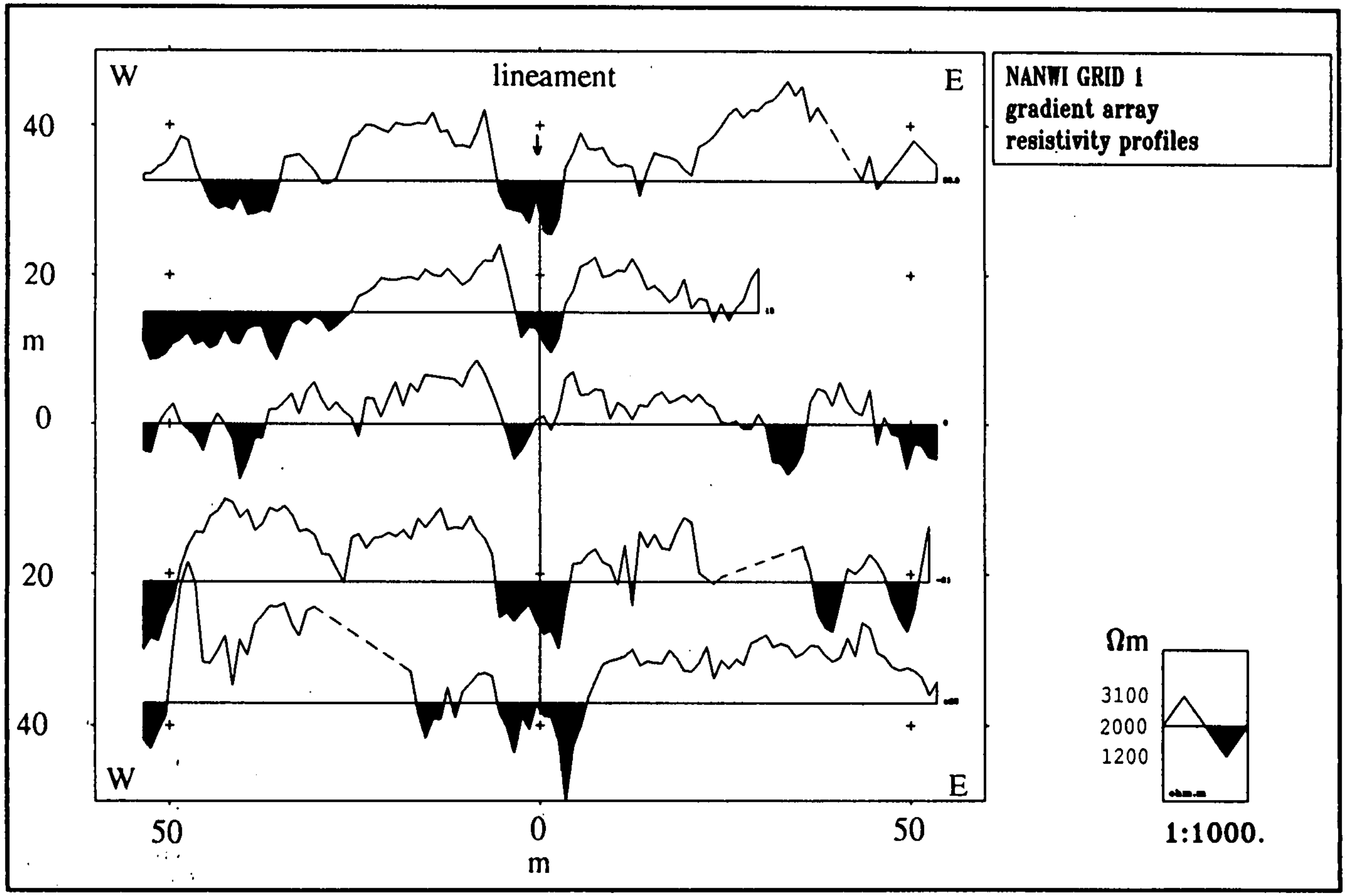


Figure 6 Nanwi: gradient array resistivity data covering borehole sites

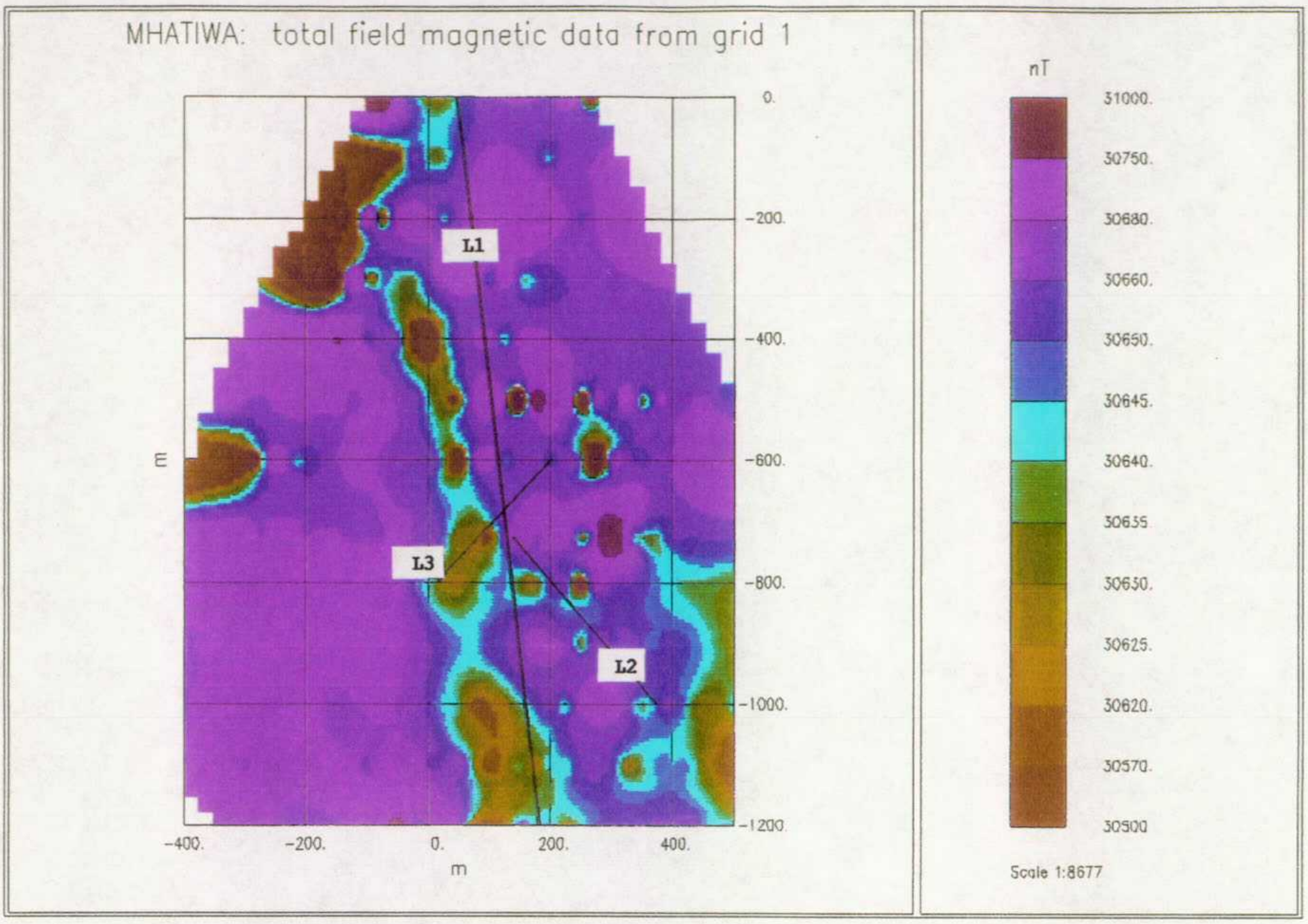


Figure 7 Filled contour map of magnetic results from Grid1, Mhatiwa

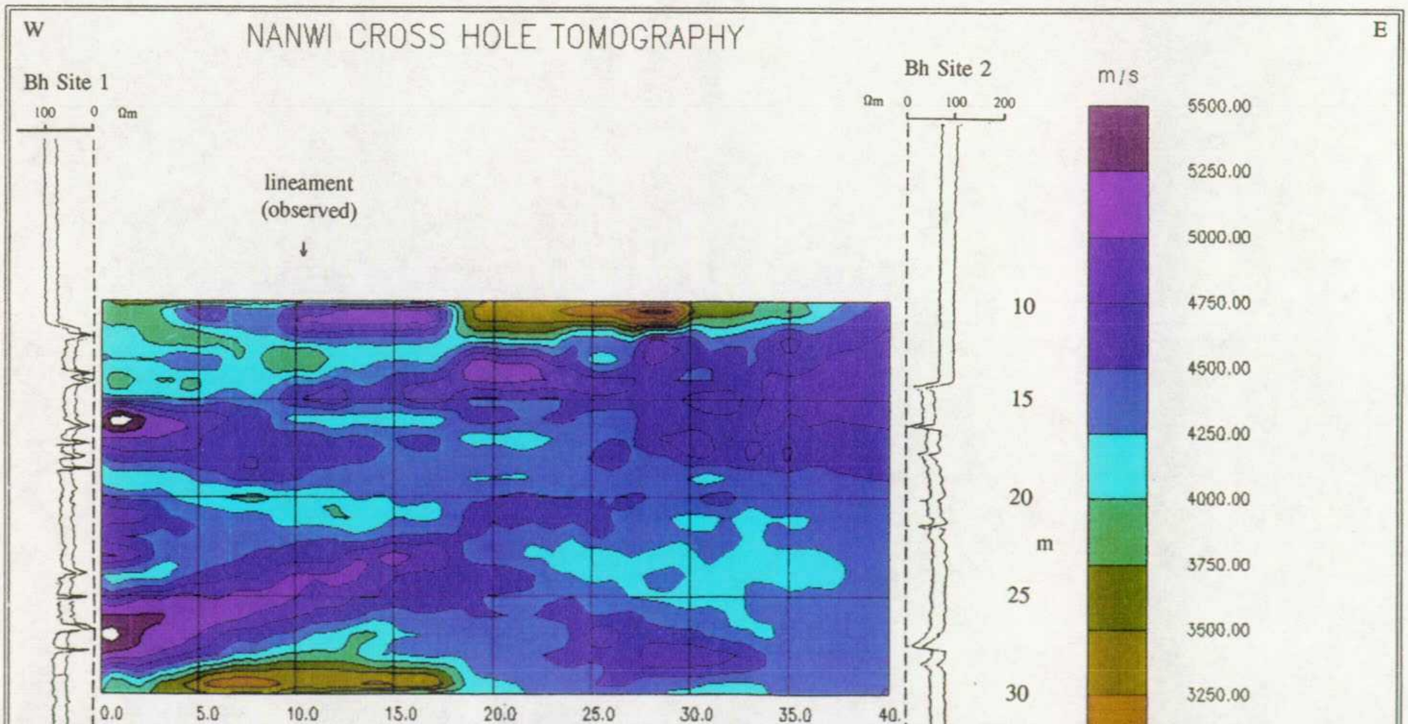


Figure 8 Seismic tomogram between Sites 1 and 2 with micro-resistivity logs

Drilling results: Inclined holes were drilled to provide core across interpreted fracture zones, and vertical deep and shallow air hammer holes for cross-hole tomography. Both the inclined and vertical holes were used for geophysical logging. Boreholes were sited along photolineaments, in all but one instance where the geophysical indications were relatively favourable.

No evidence was found of significant fracturing below a depth of about 15 m. In two cases it was apparent that steep zones of increased fracturing/fissuring/veining were intersected which might represent permeable materials. The existence of such zones provides a physical explanation for the photolineaments but their restricted development does not conform with the conceptual idea of a major, permeable zone. At the northerly Mhatiwa site, the lineament corresponds to silicic replacement and pegmatite infilling of a fracture. Of the other cored boreholes, one yielded massive rock throughout and evidently did not intersect the expected structure, while in the remainder, indications of even a weak fracture zone were equivocal.

Coring through the productive lineament at Nanwi confirmed the more open nature of the rock mass here without providing conclusive evidence regarding the geometry of the fracture system. However, consideration of all the borehole data around this site supports the view that enhanced fracturing is not restricted to a narrow, steeply-dipping zone identifiable as a photolineament but extends laterally, with sub-horizontal connections. Significantly, inferred correlations between geophysical logs, together with the seismic tomography results (Figure 8), suggest that sub-horizontal fracturing could be important, in producing what amounts to a composite fractured aquifer system.

General conclusions: Site-specific studies involved detailed geophysical surveys and drilling at a small number of localities along lineaments, identified from imagery and photographs. Although relatively simple in concept, the 'structure' of the shallow basement involves components with variable properties, whose boundaries are often very irregular and indistinct. Despite the resulting ambiguities in the interpretation, the geophysical data can highlight specific features to guide the siting programme. It is important to ensure that geophysical studies are fully integrated into any exploration programme so that the results can be assessed on a continuing basis in terms of the nature of the regolith and local groundwater regime as determined by drilling.

Surface geophysics provides useful information on variations within the weathered zone and solid bedrock. The best results are obtained where there is a direct link between the near-surface weathering profile and underlying structures, or where the structures are substantial features in themselves. The techniques can detect major open fracture systems as well as areas where the regolith is thick enough to sustain hand-pump yields by itself. In other, less well-defined situations, the geophysical data tend to improve general success rates and provide indications of water quality, without guaranteeing the results at any one location. The techniques are not generally capable of resolving the smaller-scale features which may be critical to the success of a particular borehole. As a minimum contribution, routine geophysical surveys (EM and resistivity) eliminate extensive areas of shallow, massive bedrock from further consideration. In favourable situations, the form of the bedrock surface can also be mapped with sufficient reliability to guide collector well siting.

Further technological advances in ground-probing radar and EM surveying are likely to provide additional exploration tools in the near future, but an understanding of the local environment will still be a key factor in their successful application. Computer models confirm the likely difficulty of resolving specific fracture-related anomalies from the geological background variations. The difficulties in modelling the 3D EM response will also be solved in the near future, allowing the range of suitable operating conditions to be set more rigorously.

The predominantly closed nature of steep fissures as observed in core is consistent with the relatively poor success rate for boreholes in the Masvingo area. Yet, it is necessary to explain why some boreholes along lineaments *do* give good supplies. A possible explanation is that, although steep shear planes do not typically form open structures *over their full extent*, conduits formed by fluid movement exist within some of them, perhaps developed preferentially at the intersections of cross-cutting fracture planes. If this model is correct, then the chance of a narrow borehole intersecting the open, water-bearing part of the fracture system is slight. This would also explain the difficulty in identifying successful sites on the basis of geophysical evidence which generally reflects the bulk properties of the rock mass.

What emerges from the drilling, resistivity logging and tomography is that the existence of sub-horizontal fracturing may be as important for borehole siting as the lineaments and their associated steeply-dipping fissures. These flat-lying fractures probably correspond to the surface-parallel 'sheeting', which is common in granitic terrains and thought to be a product of tensional unloading and pressure release associated with erosion. Such fractures are most abundant in the near-surface zone where the lithostatic loading is least. The intensity of flat-lying fractures may also be higher near to steep fracture zones, due to a general weakness in the rock mass. Although tensional fractures tend to form open structures, they have not previously been regarded as significant groundwater traps because individually they are of limited extent and rarely have a direct surface connection.

Based on these ideas, a conceptual model that takes account of both the sub-vertical and sub-horizontal fractures to explain the existence of successful sites, is proposed. It is suggested that, even where a steep fracture zone possesses only restricted permeability, its intersections with open sub-horizontal fissures form a 3-dimensional network of interconnections such that the rock mass as a whole acts as a fractured aquifer. Not only does this imply increased storage but, since the horizontal fractures form part of an interconnecting fracture system, the target zone for siting a borehole may be regarded as extending farther away from the lineament itself. This linkage of shallow-dipping fractures also helps explain how multiple water strikes can occur within a single vertical borehole.

It should be noted that although this hypothesis is consistent with observations, it cannot be *proved* on the basis of the available data. Nevertheless, if correct, it fully justifies the continued targeting of lineaments despite the evidence that the vertical zones are often inadequate in themselves to act as aquifers.

5. RECOMMENDATIONS: A POSSIBLE STRATEGY FOR RURAL WATER SUPPLY

The severity of the recent drought throughout southern Africa, combined with ever increasing demands for both domestic and irrigation uses, has emphasised the need for a re-think of the long-term approach to rural water supply. Based on several years of research on basement aquifers in southeast Zimbabwe, we are of the opinion that what is needed is not just a better understanding of the geological controls (which are complex and variable), but also a new look at the overall strategy for exploiting limited groundwater resources.

The scattered nature of population distribution in rural Zimbabwe presents a problem for any borehole siting programme. Because large numbers of individual boreholes are needed, each serving only a few families, and since each must be sited within carrying distance of the community, severe constraints apply to site selection. During routine siting programmes little time is allowed for photogeological and geophysical siting (typically half a day) and some of the more promising targets are necessarily excluded because of distance. These restrictions contribute to the high drilling failure rate. Pump maintenance for large numbers of boreholes also presents a major logistical challenge. Breakdowns due to overpumping, which are more common in the case of low-yielding boreholes, only serve to exacerbate the problem. The net result is that at any given time large numbers of pumps are likely to be unserviceable.

It seems unlikely that major improvements can be achieved wholly through new 'rapid siting' methods, although systematic remote sensing combined with ground geophysical surveying can provide a higher success rate under certain conditions. Rather, we now believe that significant increases in drilling success rate can only be achieved if (1) the most promising sites are targeted, and (2) more time is allowed to properly investigate each site.

The proposed strategy involves the establishment of a network of reliable, higher-yielding boreholes, each capable of providing a sustained supply during periods of severe shortage. Where appropriate, collector wells rather than conventional tube-wells should be constructed. Such a network would be superimposed upon the existing borehole system at a spacing that would permit supplies to be 'accessible' to the majority of communities during times of drought. The new network, once established, would complement and not supersede existing boreholes under 'normal' rainfall conditions. High-yielding sites could be monitored to avoid over-exploitation and take priority for maintenance in order to ensure their effectiveness during periods of severe shortage. The higher producers could be fitted with a motorised pump and have storage and possibly limited distribution facilities built.

The regional borehole/well network would be based upon some nominal spacing to be decided, but actual sites would depend on the distribution of local communities, communications networks (roads, tracks) and *the existence of favourable geological settings*. The new network would take as a starting point existing good producers that have a record of sustained yields during periods of drought; it is anticipated that, where suitably located, these would be upgraded. Having established a basic network and identified target areas requiring new high-yielders, studies would be carried out to locate the most favourable drilling sites. This would involve the identification of 'significant' lineaments (those having larger catchments and showing preserved dry-season vegetation), and would require the systematic use of satellite imagery and aerial photographs (see Greenbaum, 1992), and ground reconnaissance. This would be followed by detailed ground geophysical surveys at selected sites, and eventual drilling. Proper documentation of site investigations and monitoring of subsequent well performance is essential for identifying the key elements in site selection and improving the efficiency of subsequent work.

Clearly, the above scheme is no more than an outline concept which would require further thought and planning. What is proposed is not an 'immediate' solution but one that will show results in the medium term (5-10 years). Such a programme could form the basis of a Technical Cooperation development project. An aid project of this type would not only provide a means of establishing a more stable rural water supply network without disrupting the essential ongoing work, but it would allow for the continued development of practical siting procedures arising out of this and other past studies carried out by BGS on behalf of ODA.

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Requests for the BGS Technical Reports prepared by the project should be addressed in the first instance to: Head, International Division, British Geological Survey, Keyworth, Nottingham NG12 5GG, United Kingdom (Telephone: 44 (0)602 363100; Fax: 44 (0)602 363474; Telex: 378173 BGSKEY G)