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UNICEF IWASH Project, Northern Region, Ghana: An Adapted Training Manual for Groundwater Development

Groundwater Science Programme

Open Report OR/11/047

BRITISH GEOLOGICAL SURVEY

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Front cover

Logging borehole chip samples using a colour chart

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This report is an adapted training manual, with specific best practice recommendations for groundwater development practitioners working in the Northern Region, Ghana. It is designed to be used in conjunction with the existing comprehensive training manual 'Developing Groundwater: a guide to rural water supply' by MacDonald, Davies, Calow and Chilton (2005). The additional guidelines provided in this supplementary report are specific to the Northern Region of Ghana, and have been informed by a review of groundwater development in the region which BGS carried out on behalf of UNICEF in 2010-2011.

The Northern Region is a difficult area in which to find and develop groundwater resources. For this reason, more resources – time and money – need to be focussed on careful borehole siting and development in order to maximise success. This includes detailed desk and field reconnaissance surveys; the effective use and interpretation of geophysical siting methods; collection of good quality data during drilling and test pumping; rigorous recording and management of data; and effective interpretation, sharing and use of hydrogeological information by all groundwater development practitioners. This report, and the associated manual 'Developing Groundwater', provide practical help for carrying out these activities effectively.

The authors gratefully acknowledge those persons who contributed to the formation of these guidelines, who include:

- UNICEF Ghana – Othniel Habila, Kabuka Banda and David Ede
- Community Water and Sanitation Agency (CWSA), Ghana – John Aduakye
- Canadian International Development Agency (CIDA) – Hydrogeological Assessment Project (HAP) – James Racicot
- All participants at the UNICEF/BGS workshop and training programme held in Tamale, Northern Region, from 7 to 18 February 2011.

1 Introduction

1.1 BACKGROUND TO GROUNDWATER DEVELOPMENT IN THE NORTHERN REGION, GHANA

The Northern Region of Ghana (Figure 1) is a particularly difficult place to find groundwater. The region is largely underlain by ancient, indurated sedimentary rocks of the Voltaian Supergroup, which were deposited in the northern part of the elongate, north to south trending Volta Basin in Neoproterozoic to early Palaeozoic times. The rocks comprise thick sequences of continental and marine silty mudstones and sandstones, with subordinate conglomerates, limestones and glacially-derived deposits. Unsuccessful water supply boreholes have been drilled throughout the region, but are particularly common in areas that are underlain by mudstones, which are usually poorly fractured.

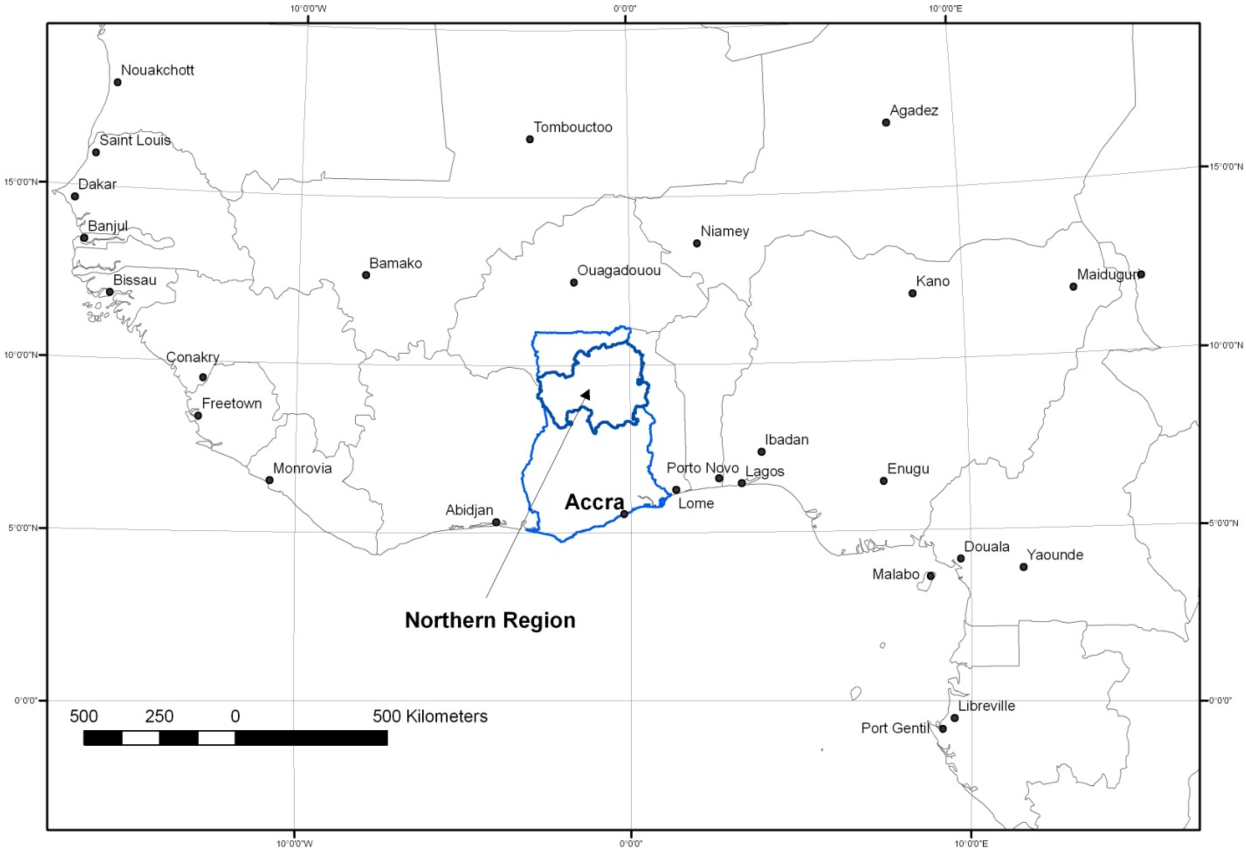


Figure 1 Location of the Northern Region in Ghana

The recent history of groundwater development in the Northern Region has included ongoing work by long-term operators in the region; large donor-led projects; and scientific research:

- Recent large projects to develop boreholes (and some hand dug wells) for groundwater supply, funded by different donors
  - European Union (EU)
  - Agence Francaise de Developpement (AFD)
  - IWASH (UNICEF)
- Ongoing borehole development by long-term operators in the region, Church of Christ and World Vision.

- Recent research:
    - The Hydrogeological Assessment Project (HAP), funded by CIDA, carried out systematic data collection during siting, drilling and testing of dedicated monitoring boreholes (CIDA 2009)
    - Not directly linked to groundwater but of direct application to groundwater development is a recent airborne geophysical survey combined with geological mapping of the Volta Basin, including a large part of the Northern Region (Jordan et al. 2009).

During 2000-2002, the British Geological Survey (BGS) conducted a detailed study of the groundwater potential of Voltaian Supergroup sandstones and mudstones in the Afram Plains region, in the southern Volta Basin (Davies and Cobbing 2002). This study followed on from even more detailed investigations carried out by BGS into the low groundwater potential of younger, Cretaceous age mudstones and sandstones in the Benue Trough region of southeastern Nigeria (Davies and MacDonald 1999). The experience gained during these, and other, projects led to the production of a comprehensive guide to rural groundwater development, ‘Developing Groundwater: a guide for rural water supply’ (MacDonald et al. 2005) (Figure 2).

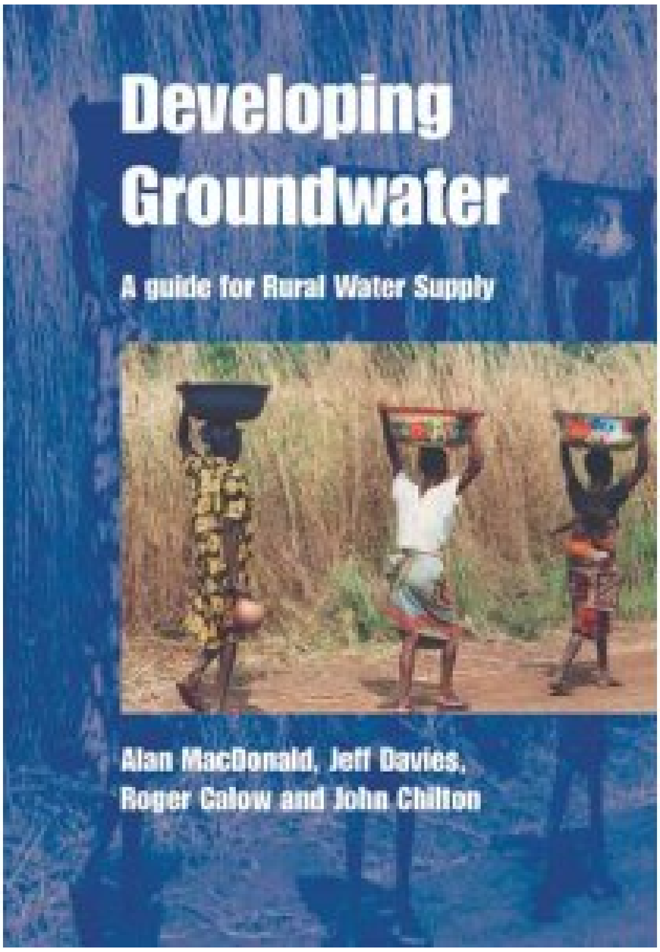


Figure 2 The training manual ‘Developing Groundwater: a guide for rural water supply’ (MacDonald et al 2005), which should be used in conjunction with this report as a comprehensive reference for groundwater development techniques

1.2 BACKGROUND TO THIS REPORT

Based on past experience investigating groundwater potential in low productivity aquifers in other parts of Ghana and in Nigeria, the British Geological Survey (BGS) was commissioned to review groundwater development practices used by consultants on the UNICEF IWASH (Water, Sanitation and Hygiene) programme in the Northern Region of Ghana; to investigate the low drilling success rates encountered by the IWASH programme; and to produce guidelines for best practice in the region. The guidelines, presented in this report, address specific aspects of, or techniques for, groundwater development that were identified as relevant to the situation in the Northern Region. They are not a comprehensive guide to groundwater development, and should be read in conjunction with other such guides, and in particular the training manual 'Developing Groundwater' (MacDonald et al.2005) (Figure 2).

The BGS project in the Northern Region was split into four phases:

(1) Situation analysis and collation of available information on current methods of groundwater development in the Northern Region, in particular in the districts where the IWASH programme operates. This involved a visit to the Northern Region by BGS experts, in November 2010, to rapidly assess groundwater development procedures and to collate available data (MacDonald and Davies 2011).

(2) Synthesis, examination and interpretation of the collated data in terms of (i) current groundwater practises; (ii) developing an understanding of the hydrogeology of the Northern Region and capturing this within a new groundwater development potential map for the Northern Region, in particular for the districts where the IWASH programme operates; and (iii) developing recommendations for improving borehole siting methods. This took place partly in the UK and partly in Ghana between November 2010 and February 2011.

(3) Based on the activities in (2), above, to develop and run a workshop and training course focussed on improving groundwater development practises in the Northern Region. This took place in Tamale, Northern Region, Ghana from 7 – 18 February 2011.

(4) Produce specific guidelines for best practice in groundwater development in the Northern Region by adapting an existing training manual, which are presented in this report.

2 Guidelines for groundwater development in the Northern Region

The guidelines presented in this report address specific aspects of groundwater development that are relevant to the situation in the Northern Region. They are not a comprehensive guide to groundwater development, and should be read in conjunction with other such comprehensive guides, in particular the relevant chapters in the manual 'Developing Groundwater: a guide for rural water supply' (MacDonald et al. 2005) (Figure 2). This manual was specifically designed to meet the needs of rural water supply project staff in developing countries, and provides comprehensive information on effective techniques for siting boreholes, assessing groundwater resource sustainability, constructing and testing the yield of boreholes, and monitoring groundwater quality. As well as the content of the 'Developing Groundwater' manual, the guidelines are based on:

- the review of current practice in the IWASH programme and other recent groundwater development work that was carried out by BGS (MacDonald and Davies 2011, Ó Dochartaigh et al. 2011), which included reviewing collected and interpreted data and visits to field areas to observe field conditions and groundwater development practises;
- discussions with individuals from UNICEF, Ghana's CWSA, and international consultants; and
- discussions with staff from key implementing IWASH partners and other groundwater development organisations at a two week workshop and training course held in the Northern Region from 7 to 18 February 2011

2.1 GENERAL GROUNDWATER DEVELOPMENT

The groundwater development problems in the Northern Region **will not be solved overnight.** A long-term plan will be needed to overcome them. The problems are complex and multi-faceted, strongly linked to the pervasiveness of low productivity, low storage aquifers across the region, and not helped by how difficult it is for groundwater development practitioners in the region to get professional support.

The Northern Region is a **difficult area in which to find and develop groundwater resources**. It should be accepted that **borehole success rates here will always be lower than in most other areas**. Particularly in areas dominated by mudstones, more resources need to be focussed on careful siting of boreholes in order to maximise potential success. This will take time and money, and includes, for example, detailed desk reconnaissance surveys and the effective use and interpretation of geophysical siting methods.

There is no magic bullet for success. There is no single technique that will find groundwater in the Voltaian Basin in the Northern Region. Improving success in this very difficult area requires effectively implementing a combination of many different approaches, such as different geophysical techniques, and making use of information from past projects, including maps of geology and groundwater potential (e.g. Figures 16 and 26). Groundwater development practitioners need a better understanding of where and how groundwater occurs in the rocks (the groundwater targets); of how to identify these targets using geological, geophysical and other surveying techniques; and how to develop groundwater effectively and sustainably once it is found. All this relies first on careful collection, analysis and interpretation of field data, and then on centrally collating and interpreting these data to develop a better regional understanding, which in turn should be used by practitioners to better inform groundwater development. The **current understanding of hydrogeology in the Northern Region is described in Section 3**, and should be a key resource for groundwater development practitioners. **It should be updated as new data, interpretations and understanding become available.**

It is important to **look at the bigger picture when siting boreholes**. It is not enough to treat each borehole to be drilled in isolation: it is vital to use all the available evidence from other groundwater investigations in nearby areas, or similar hydrogeological areas elsewhere, to help make informed choices about borehole siting and development. The key to successful groundwater development is a **detailed understanding of the regional and local hydrogeology**: what the detailed lithology of each geological unit is; what the groundwater targets are in each unit and at what depths; what the geophysical signature of each geological unit and groundwater target is. A description of the current understanding of the hydrogeology of the main geological units in the Northern Region is presented in Section 3 of this report, and is summarised in a **groundwater development potential map** (Figure 26) and accompanying table of information (Table 2). This hydrogeological understanding is based on currently available information, which is still limited for much of the Northern Region, and so it should be developed further and improved over time as more good hydrogeological information is collected and interpreted.

In the same way, geophysical surveys at each new borehole site should not be interpreted independently, but should be interpreted with reference to the results of other surveys on similar geology, and by comparing the geophysical results to geological evidence from previously drilled boreholes. A wider understanding of the relationship between geophysical results, geology, and hydrogeology across the Northern Region needs to be developed, so that practitioners can better interpret the hydrogeological meaning behind geophysical data. The HAP project began to develop this kind of systematic body of knowledge, but much more needs to be done to extend and deepen this understanding using geophysical data and (hydro)geological interpretations from ongoing borehole development.

Box 1 Key general guidelines for groundwater development in the Northern Region

Fractures in sandstones, at depths generally between 30 and 70m and rarely up to 100m, are the most important groundwater target in the Northern Region. Drilling below 100m in sandstones occasionally produces small additional yields, but there is little evidence that drilling deeper than approximately 120m in sandstones produces significant additional yields. Only small amounts of groundwater are typically found in fractures in siltstones, also typically between 30 and 70m. Groundwater is rarely found in mudstones, even where fractured. Drilling deeper than approximately 70m in siltstones and mudstones is not likely to result in significant additional yields.

Current understanding of the hydrogeology of the region has been summarised in a groundwater potential map (Figure 26).

Particularly in areas dominated by mudstones, more resources will be needed for careful borehole siting in order to maximise potential success. This may mean additional time and money for detailed desk reconnaissance surveys and effective use and interpretation of geophysical surveys.

A wider understanding of the relationship between typical geophysical values, geology, and hydrogeology across the Northern Region needs to be developed, so that practitioners can better interpret the hydrogeological meaning behind geophysical data.

In particularly difficult areas where there has been continued failure to drill successful boreholes, such as where there is unfractured mudstone, other water supply options should be considered, such as piping in water from higher potential areas at distance, treating surface water, or rainwater harvesting. A paper on rainwater harvesting in Ghana can be found at http://www.cwsagh.org/cwsa_subcat_select.cfm?tblNewsCatID=29&prodcatID=8 .

2.2 SELECTING SITES FOR BOREHOLES AND GEOPHYSICAL SURVEYS: RECONNAISSANCE DESK AND FIELD SURVEYS

The importance of reconnaissance – both desk studies and field reconnaissance – cannot be overstated, and is dealt with in detail in **Chapter 4 of the training manual** (MacDonald et al. 2005). It is the basis of good siting, where useful evidence from all relevant sources is used to increase confidence in identifying where possible groundwater targets may exist, whether these are weathered zones, fracture zones or lithological boundaries, and in selecting the most effective locations for geophysical surveys to provide the most useful information. Choosing locations for geophysical surveys should be done using all of the same kind of desk study information sources as for selecting potential sites for boreholes, not solely based on surface observations and community information.

Some of the most useful sources of information during a **desk study** are:

- Geology and/or groundwater potential maps that indicate likely geological controls on groundwater potential and/or directly show aquifer productivity (e.g. the maps in Figures 16 and 26).
- Satellite images, air photos or maps of airborne geophysical data that may indicate the presence of lineations which could be water-bearing. Depending on the type of lineation, it is often useful to **choose geophysical survey lines perpendicular to regional lineations**.
- Information from past groundwater development projects in the same area, which help in interpreting geophysical survey results. For example, yields from existing boreholes; results from geophysical surveys that show typical resistivity and/or conductivity values for the local geology; and borehole geological logs from previous boreholes (even if dry).

A **field reconnaissance survey** should concentrate on as large an area as possible – the whole of the village and surrounding area at least. Particular points to note are:

- Observe soil types and any changes across the area, which may indicate lithological changes in the rock below – e.g. soils developed over mudstones are often characteristically different than those over sandstones.
- Looking for direct evidence of the underlying geology, such as in dug pits or wells or in any rock outcrops.
- Don’t over-interpret the presence of vegetation type or anthills in terms of groundwater occurrence. While these features might indicate the presence of shallow groundwater, this may be perched and although it may be enough to provide a seasonal flow to a small shallow dug well, it is unlikely to contain enough water to provide a good yield all year round. Remember that the key groundwater flow horizons in most Northern Region aquifers appear to be between 30 and 70m deep. Few trees or anthills can access water at this depth. It is also important to recognise that indicators which might be important on sandstones or basement rocks are often no use at all on mudstones. Sandstones are more freely draining, so that water disappears quickly in the dry season and vegetation can only survive where there are significant amounts of groundwater. However, the lower permeability of mudstones means they can hold onto very small amounts of groundwater for much longer, not letting it drain away; and although there is often not enough water to supply boreholes or even shallow wells, there is enough moisture in the ground for trees and other plants to survive.

2.3 GEOPHYSICS

2.3.1 General

The use of geophysics in groundwater development is dealt with in detail in **Chapter 5 of the training manual** (MacDonald et al. 2005).

Geophysics **does not tell us where groundwater is** – it cannot directly locate productive groundwater flow zones (i.e. groundwater targets). It is one of a triangle of useful groundwater development approaches (Figure 2). When used and analysed correctly, geophysics can tell us about the geology beneath the site. Interpreting the geology can tell us about the likely types and depths of groundwater targets. Successfully interpreting changes in resistivity or conductivity seen duing geophysical surveys therefore needs a good understanding of local and regional geology and hydrogeology. The **current understanding of hydrogeology in the Northern Region is described in Section 3**, and should be a key resource for groundwater development practitioners.

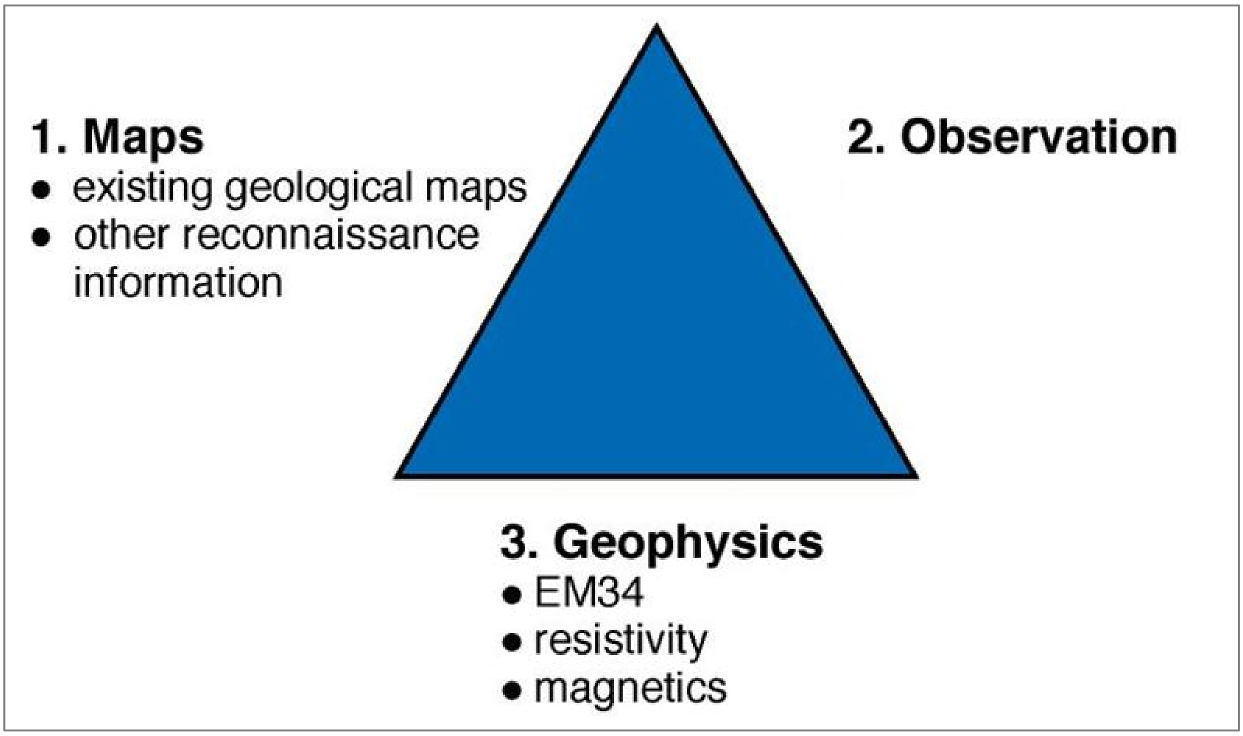


Figure 3 Geophysics is one part of a triangle of useful groundwater development approaches

The key to interpreting geology from geophysical results is to build up a **good knowledge of typical geophysical responses for different rocks** (i.e. resistivity and/or conductivity values), **in both their weathered and unweathered states**. The key to interpreting hydrogeology from geophysical results is to build up a good understanding of **what the groundwater targets are in each of these rock types and how deep they are**, as well as how these targets may show up in geophysical responses. Consultants also need to **look deeper** using their current techniques and to **analyse results correctly**.

<u>**Looking deeper**</u>**.** At the moment, geophysical methods used in the Northern Region **only assess the shallow zone from 0 to approximately 30m depth**. However, across most of the region, groundwater inflows (due to weathering and/or fracturing) are concentrated from approximately 30 to 70m depth (Section 3 in this report; CSIR 2009). Using the small

changes recommended in this report, the current geophysical equipment could provide a relatively robust picture of the geological sequence to about 60m depth – i.e. throughout the main zone of groundwater flow in the region.

Using geophysics to understand geology. Even if geophysics is looking at shallower depths than groundwater targets, it is still giving information on the geology, which can be interpreted to help identify groundwater targets. For example, if geophysics confirms that a site is underlain by sandstone, not mudstone, there is a much better chance of finding groundwater.

Analysing geophysical data correctly. The resistivity procedure currently used by most of the IWASH consultants appears to be a combination of VES and profiling, with the resulting data relating to a number of soundings at different locations along a profile. Interpretations of the field data appear to be done in a non-standard way, which would be regarded by most geophysicists as **non-valid**. More discussion of this and recommendations for alternative, more robust resistivity techniques are given in Section 2.3.3, below, and in Chapter 5 of the manual 'Developing Groundwater' (MacDonald et al. 2005). Some background on geophysical methods for finding groundwater in low permeability rocks is also given in a paper by MacDonald et al. (2001) which is reproduced in Appendix 1.

To **maximise the amount of information**, ideally at least two geophysical methods should be used together. For example, a robust procedure would be to run one or more EM34 profiles along the lines that the reconnaissance survey identified as being hydrogeological interest; identify features that are potential groundwater targets from the EM34 results; and follow up by running VES over these features.

The currently available geophysical equipment in the Northern Region, if it is used appropriately and the results analysed correctly and interpreted with respect to the geology and hydrogeology, can provide very useful results. The introduction of more 'state-of-the-art' geophysical equipment would not, by itself, improve borehole siting success. The key issues related to geophysical siting practices are not so much related to inappropriate equipment as to the choice of technique and the lack of appropriate interpretation of geophysical results. Improved theoretical and practical training for geophysical practitioners, and increased contact with professionals in other parts of Ghana and internationally, would help improve results. Having said this, EM34 is a particularly useful technique both used alone and in combination with VES. Wider and effective use of EM34 profiling in the Northern Region could provide more information to support hydrogeological interpretations and therefore borehole siting decisions (Section 2.3.3).

Box 2 Geophysical field procedure

Careful field procedure is needed to ensure good geophysical data are collected.

Carefully maintain equipment, in particular cables, so there is no contact between metal cable (e.g. where the plastic cable cover is damaged) and the ground (Figure 4).

Take care to ensure as good electrical connections as possible in resistivity surveys (Figure 5). Although it is difficult because of the number of connections in the system, especially when equipment is old, it is critical to ensure good data collection.

Be aware of potential sources of data error, e.g. electrical current from other geophysical surveys being run at the same time.

Figure 4 Cables should be regularly inspected for damage

Figure 5 Care should be taken to ensure good connections between cables and control box during resistivity surveys

2.3.2 Resistivity

Resistivity surveys can give very useful information on the rock type and the degree and depth of weathering. They cannot reveal the presence of narrow (sub)-vertical fractures at depth below the weathered zone, which are key groundwater flow zones. Many different types of resistivity techniques are available, including various **vertical electrical sounding (VES)** techniques, which give information on the ground beneath a single point, and **profiling** techniques, which give information on changes along a line. The current most commonly used resistivity technique in the Northern Region is a combination of VES and profiling using a dipole-dipole array, which is non-standard and, based on the evidence seen by BGS, does not appear to be providing useful information. It is discussed in more detail in Section 2.3.2.2. Also used in the Northern Region is a 2D profiling system, which is discussed briefly in Section 2.3.2.3.

2.3.2.1 VERTICAL ELECTRICAL SOUNDING (VES) TECHNIQUES

More information on different VES techniques is given in Chapter 5 of the manual 'Developing Groundwater' (MacDonald et al. 2005). Each uses a different electrode configuration. The most common is the Schlumberger configuration; other common arrays are the Wenner and the offset Wenner. It is the experience of the BGS team, from working in many parts of the world, that **the Schlumberger array is easier and more robust** to carry out in the field and to interpret accurately than most other techniques; and that it is widely supported by standard geophysical literature and analysis models and software. Resistivity VES using a Schlumberger array was used to good effect in the Northern Region in the HAP project (Box 3).

Box 3 Interpreting VES data in the HAP project

Schlumberger VES was used in the HAP project with good field procedure and rigorous data interpretation. For example, field values that appeared unreasonable were rejected and the VES repeated at the same spot several times until results matched. VES data were analysed using 'RESIST' computer software (CSIR 2009) and the results were interpreted in relation to observed resistivity values from known geological units (e.g. Figures 7 and 8) and to the known hydrogeology of these units.

For example, in areas underlain by sandstone, drilling sites were selected based on the interpreted thickness of the weathered zone (with low to moderate formation resistivity), because the practitioners knew that thick weathered zones had been observed to give good borehole yields, and the transition zone from weathered to unweathered rock had also been observed to be a groundwater target. By contrast, previous studies had shown that mudstones and siltstones were associated with dry or low yielding boreholes, and with low formation resistivity, and so areas of medium to high resistivity values were preferred as target drilling points, while areas with resistivity values lower than 50 Ohm-m were avoided (CSIR 2009).

By doing this, the HAP project began to develop a systematic body of knowledge of the hydrogeological meaning behind geophysical data. This approach should be continued to develop a detailed dataset of typical resistivity and conductivity responses for all the geological units in the Northern Region, in their unweathered and weathered states. Good geophysical data should be collected during groundwater development projects and compared to borehole geological logs. In particular, more detail is needed on the geophysical responses of mudstones and siltstones (e.g. the Obosum Group and Bimbila Formation), and to specific local lithologies within these (i.e., mudstone, siltstone and/or sandstone).

The groundwater potential map (Figure 26) shows the spatial distribution of these formations and the areas where airborne geophysical data indicates that sandstones are more likely to be present, and could be used to help interpret geophysical results.

By increasing the separation distance of the electrodes in a VES, the depth of current penetration increases, providing information on the geology at greater depths (Figure 6). The maximum depth of penetration of a Schlumberger VES is related to the separation distance of the maximum outer (current) electrode (referred to as AB/2). A rule of thumb used by most geophysicists is that the **depth of penetration is between one quarter and one half of the AB/2 maximum separation**. In less resistive (i.e. more conductive) formations, the potential depth of penetration is less than in more resistive (i.e. less conductive) formations. In other words, at an outer (current) electrode separation of 100m, the results from the VES relate to a depth into the ground of about 25m (e.g. in weathered basement or soft mudstone) to about 50m (e.g. in unweathered basement or dry sandstone). **To look deeper than about 25m in mudstone, therefore, outer (current) electrode separations need to be more than 100m**.

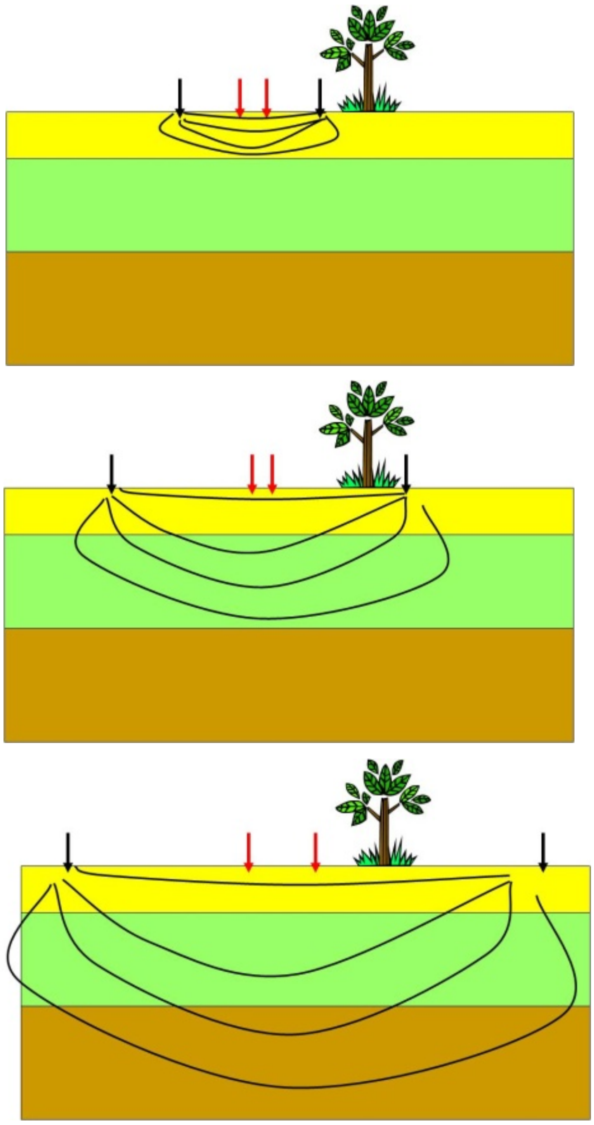


Figure 6 As electrode separation is increased in a resistivity survey, the depth of current penetration increases.

2.3.2.2 COMBINED VES/PROFILING DIPOLE-DIPOLE TECHNIQUE

The resistivity procedure currently used by most of the IWASH consultants appears to be a combination of VES and profiling, with the resulting data relating to a number of soundings at different locations along a profile. The data then appear to be interpreted using a simple plot of field data, with no modelling, as if the data related to a single vertical sounding at a fixed location. Many of the interpreted data plots have a distinct saw-tooth appearance. Under standard circumstances (outside the Northern Region), these interpretations would be regarded by geophysicists as **non-valid**, because they are unphysical (i.e., unrelated to the actual physical structure of the ground) geophysical responses.

The information from these plots then appears to be used directly to indicate the presence of fracture zones at particular depths. **This is not a valid physical interpretation of these data.** Even if carried out, modelled and interpreted correctly, **VES resistivity surveys cannot identify fractures**.

It is the opinion of BGS that the current method of interpreting the data from this technique (which involves plotting the field apparent resistivity values and directly relating them to depth) does not give physically meaningful results. We are unaware of a model for interpreting the combined VES/profiling dipole-dipole technique that is currently used by many of the IWASH consultants in the Northern Region. A model for analysing VES data is available within a free software package for interpreting geophysical data, GeoVES. This software is currently used by a number of consultants. However, the model behind this software is **unlikely to be applicable to the combined VES/profiling procedure** being used by consultants – it appears to have been designed specifically for the Schlumberger array. Before it is used, therefore, its applicability should be carefully examined, and **if the geophysical model behind this software is not directly applicable to the current procedure, either another, suitable model should be found, or another VES array for which a suitable model is available should be used.**

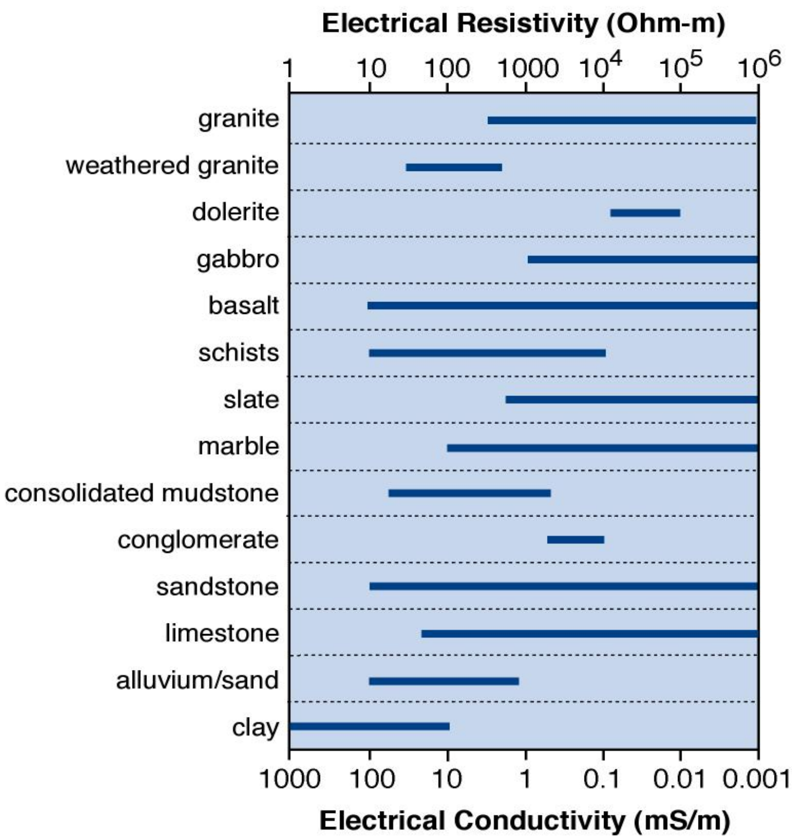


Figure 7 Typical geophysical results from different rock types

2.3.2.3 2D RESISTIVITY PROFILING (LUND) SYSTEM

A **2D resistivity profiling system** using Lund equipment is carried out on some sites in the Northern Region. This system allows for robust field procedure, and covers more ground more quickly than resistivity VES. The equipment may be considered relatively expensive but the cost is not excessive compared with other equivalent field geophysical equipment. It can achieve 60m penetration, although the maximum depth of penetration is only gained in the centre of the profile, and reduces significantly towards each end. However, it suffers from the same problems as VES in terms of getting current into dry ground, which can result in data noise.

The Lund system used is based on the ABEM terrameter, with the addition of an electrode switching system and multiple (e.g. >48) electrodes. The data collection and modelling process is computerised and produces electronic cross sections. It is important that the operator inputs the correct field parameters for each survey, for example the electrode spacing if this changes from one survey to another. Because of problems with generating enough current, there can be high levels of noise in the cross sections, which can mask real geological features, so care should be taken to ignore data noise and instead to look for large anomalies which are more likely to be real geological features. It is also useful to compare the 2D profile results with an EM34 survey over the same line, and look for features that coincide in both sets of data.

In addition, when interpreting the modelled resistivity cross sections, practitioners need to have a **good understanding of the geophysical nature of the groundwater target**s which are being searched for, such as typical resistivity values for sandstones (which have higher permeability and are a key groundwater target), and for mudstones (which have low permeability).

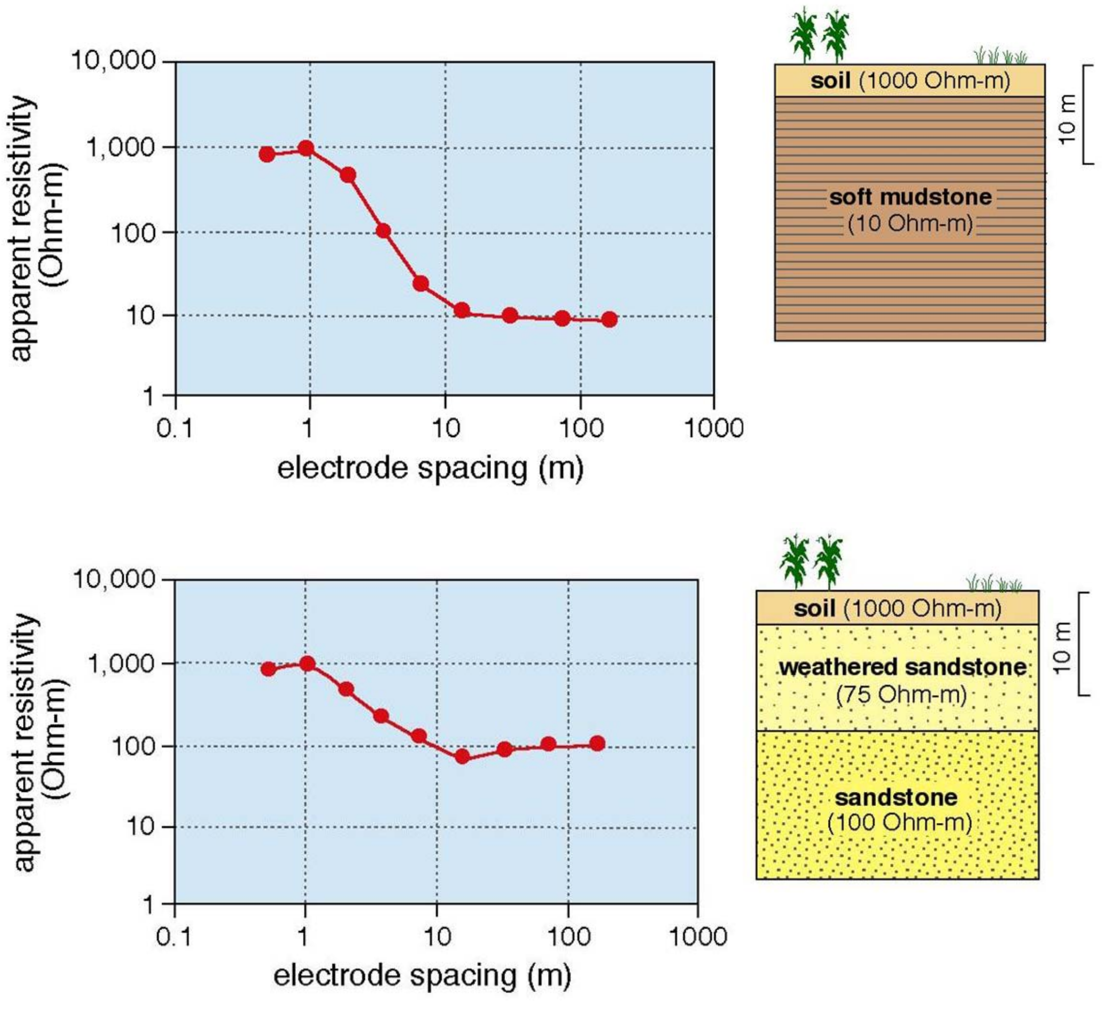


Figure 8 Examples of interpreted resistivity survey results over mudstone (top) and sandstone (base)

2.3.3 EM34

Of the many different geophysical techniques that make use of electromagnetic (EM) induction to measure the ground conductivity, EM34 is probably the most popular. Carrying out EM34 surveys is relatively quick, and the technique is very useful both in its own right and to complement resistivity surveys.

During an EM34 survey, conductivity measurements are made with the coils in both vertical and horizontal orientations (Figure 9). The depth of penetration of the method depends on both the coil orientation and the coil separation. With the coils in vertical orientation, the average depth of penetration is about 0.5 to 0.8 x the coil spacing, although the response reduces with depth. With the coils in horizontal orientation, surveys can detect vertical conductors such as faults and fracture zones, which could be water-bearing.

A good procedure is to run one or more EM34 profiles along each line that the reconnaissance survey highlighted as being of potential hydrogeological interest – such as perpendicular to regional lineations.

For each EM34 profile, run a survey at both 20m and 40m coil separations. A coil separation of 40m can give depths of penetration up to 60m into the ground (depending on the rock conductivity), and it provides a check on potential errors in measured data. Ensure that the coils are kept co-planar during measurements, to reduce any errors.

Be aware of other potential measurement errors, e.g. electrical current from other geophysical surveys being run at the same time. If the measured values change quickly (e.g. by more than 15 milliSiemens/metre over 1 to 2 stations), the readings should be repeated to check they reflect real features or are errors.

Figure 9 EM34 survey with coils in vertical and horizontal orientation

Box 4 Key recommendations for using geophysics in borehole development in the Northern Region

Geophysics **does not tell us where groundwater is.** It can tell us about the geology beneath the site. Interpreting the geology can tell us about groundwater targets.

The key to interpreting geology from geophysical results is a **good knowledge of typical geophysical responses for different rocks –** i.e. resistivity and/or conductivity values. The key to interpreting hydrogeology from geophysical results is to build up a good understanding of **what the groundwater targets are in each rock types and how deep they are**, as well as how these targets may show up in geophysical responses.

Following on from the above. Using VES soundings obtained using a single-method (e.g. the Schlumberger configuration), plot multiple sounding curves from many locations on the same graph. Group the soundings according to rock-type or other information, to obtain useful summaries of the electrical properties of the rocks.

Geophysical surveys should **look deeper** by increasing electrode separation; and **analyse results correctly**. The combined VES-profiling technique and its interpretation method that are currently used widely would be regarded by most geophysicists as **non-valid**.

To **maximise the amount of information**, ideally at least two geophysical methods should be used together. For example, run one or more EM34 profiles along the lines that the reconnaissance survey identified as being hydrogeological interest; identify features that are potential groundwater targets from the EM34 results; and follow up by running VES over these features.

Careful field procedure is needed to ensure good data are collected (Box 2).

2.4 DRILLING AND CONSTRUCTING BOREHOLES

Good practice in drilling and constructing boreholes is discussed in detail in **Chapter 6 of the training manual** (MacDonald et al. 2005).

Every borehole drilled can provide potentially useful data to support future groundwater development. Careful data collection and lesson learning during borehole development are disproportionately important in the difficult hydrogeological environment of the Northern Region.

Recording borehole information should not be done just to check on the drillers work. Information such as water strike depth, the geology at that depth, the yield and the groundwater SEC (conductivity) is all highly useful knowledge that can help ensure boreholes are properly designed and successful. Because groundwater target zones cannot be seen at the surface, the **evidence gained from drilling is vital in order to accurately locate and successfully exploit any water yielding zones**.

Following these key recommendations will help to develop a better understanding of the geology and hydrogeology of the Northern Region. Careful data collection during borehole drilling and testing; the central collection of the data; and the interpretation and use of the data by practitioners, will help build a more detailed understanding of the type and depths of groundwater targets in the different rocks.

- The rigorous collection and recording of information should be enforced by the technical specifications of the contract. Drilling supervision is best undertaken by a knowledgeable hydrogeologist. The drilling supervisor, as the consultant's representative on site, is responsible for all data collection and recording and for borehole construction.
- Maintain **good control of the drilling crew**, in order to collect good quality data, such as geological samples and groundwater flow data (Figure 10). Collecting the best data may mean drilling more slowly.

Figure 10 Working closely with the drilling crew is important to ensure good quality data are collected and recorded

Figure 11 Using a stopwatch to accurately record drilling penetration rate

Key recommendations for data collection during drilling:

- Accurately record drilling penetration rate (Figure 11). Trying to increase drilling speed by excessive hydraulic pull down can cause excessive dust production, and a non-vertical borehole. In softer rocks (e.g. mudstone, or weathered sandstone) it may better to use air flush rotary drilling with medium-toothed tricone (rock roller) bits, instead of down-the-hole hammer bits. This will produce larger rock chip samples, reduce dust, and may be a cheaper method of drilling.
- **Rock chip samples should be collected every 1m**. The supervisor should ensure that the driller tops each 1m and blows the borehole clear before re-starting, in order to clear the hole and allow the collection of an accurately-located depth sample.
- **Chip samples should be washed to show their true colour**, which is an important indicator of weathering as well as lithology, and therefore of the location of potential groundwater targets.
- Chip samples should be stored on site in a suitable manner, e.g. in sectioned sample boxes (Figure 12). These allow easy and effective logging and recording, ideally by photograph using a digital camera. An alternative to the standard sample boxes is to make 'photo logs' with a digital camera of rock chip samples stored in sectioned, marked halved plastic pipes. These photo logs clearly show rock colour changes caused by weathering or lithological changes with depth and can be combined with typed-up lithological descriptions, and stored digitally. An example is shown in Figure 16.
- **Particular care should be taken over chip sample description, or logging**. Even if the exact identification of the **lithology** or rock type (e.g. sandstone or siltstone) is uncertain, the following parameters should be fully and consistently described for each interval (ideally each 1m) of the borehole: **colour** (defined using standard charts, e.g. Munsell colour charts or other standardised chart (Figure 14), other **indications of degree or nature of weathering** (e.g. oxidation), and any **indications of fractures** (e.g. vein quartz/calcite). A hand lens should be used if possible (Figure 13).
- It is possible to preserve small sub-samples of chip samples in suitable containers (e.g. sealed plastic bags or pill bottles), labelled by depth, borehole ID and location. This data could be very useful for future geological and/or hydrogeological investigations.

Figure 12 Different kinds of marked and labelled container for systematically storing rock chip samples for logging

Figure 13 Rock chip samples from drilling should be washed and carefully examined, using a hand lens if possible

Figure 14 Using colour charts to standardise the description of rock chip samples

If water is struck in a borehole:

- Identify **each water strike zone** encountered on drilling, and measure a **representative 'blow yield'**. This can be done by channelling the discharge from the borehole through a pipe into a bucket of known volume and measuring the time taken to fill the bucket (Figure 15).
- If groundwater is struck, the SEC (water conductivity) of the water should be measured at the end of each drill rod length and at each subsequent water strike. This will give a first indication of water quality.
- If no water is struck, but there are indications of water presence – such as damp or muddy chip samples – the borehole should be left to stand overnight and then checked again. The smearing of the borehole sides during drilling can temporarily block fractures that can clear overnight, allowing water to flow in. If water is found, the borehole should be cleaned by airlift and the borehole yield measured to determine if it is high enough.

Key recommendations related to **borehole construction** are:

- Borehole screen needs to be placed accurately to coincide with all potential groundwater flow zones. This may mean **screening the whole length of a borehole**, particularly if it intercepts wholly or mostly sandstone. It is not efficient to place screen approximately, and hope that vertical flow will be induced in the formation stabilised.
- The uppermost 5 to 10 m of borehole casing should be pressure grouted to produce **an effective sanitary seal**.
- In mechanised boreholes the completed borehole diameter should be wide enough to allow the installation of a narrow tube for groundwater level monitoring. The discharge pipe from mechanised boreholes should be fitted with an in-line flow meter to allow regular monitoring of abstraction rate.

Following construction, the borehole should be **thoroughly developed to effectively clean the borehole screen**, until the **discharge water is clear and the discharge rate has stabilised**.

Figure 15 Measuring borehole yield using a stopwatch, bucket (left) and/or V notch weir (right)

26 – 27 Dark red brown and grey soft weathered mudstones

27 – 28 Dark red brown soft weathered mudstones

28 – 29 Grey and dark red brown hard siltstone

29 – 30 Interbedded grey and dark red brown hard siltstone and soft mudstone

30 – 31 Light grey hard and red brown soft siltstones

31 – 32 Dark red brown soft mudstone

32 – 33 Dark red brown and light grey variegated mudstone

33 – 34 Dark red brown and light grey silty finer bedded mudstones

34 – 35 Mainly dark brown with some light grey mudstones and dark grey siltstones

35 – 36 Dark brown and light grey shaley mudstones

36 – 37 Dark brown shaley mudstones with some light grey mudstone

37 – 38 Soft dark brown mudstones and hard grey shaley siltstone

38 – 39 Soft dark brown and grey mudstone

39 – 40 Soft shaley dark brown and grey mudstone

40 – 41 Soft shaley dark brown and grey mudstone

41 – 42 Harder dark brown and grey silty mudstone

Figure 16 Example of a detailed 'photo log' for a section of a dry borehole drilled at Kpachaa village, Northern Region, during the training course. Numbers are depth below the ground surface in metres

Box 5 Key recommendations for borehole drilling and construction in the Northern Region

Good practice in drilling and constructing boreholes is discussed in detail in **Chapter 6 of the training manual** (MacDonald et al. 2005).

Drilling deeper than approximately 70m in mudstones and siltstones is not likely to result in significant additional yields. **Drilling below this to 100m in sandstones may produce significant additional yields, but drilling below 100m even in sandstones is likely to only produce small, occasional additional inflows**. There is little evidence that drilling deeper than approximately 120m in sandstones is likely to produce significant additional yields.

Collect chip samples every 1 m; wash them; and log them carefully using standard colour charts. If possible, take photographs of the chip samples. Making 'photo logs' is very helpful in interpreting the geology.

When constructing boreholes, place screen so that it covers **all** potential groundwater flow zones. This may mean **screening the whole length of a borehole**, particularly if it intercepts wholly or mostly sandstone.

Box 6 Borehole testing

A detailed description of borehole test pumping techniques and interpretation methods is given in **Chapter 7 of the training manual** (MacDonald et al. 2005).

The data gathered during test pumping of the IWASH boreholes should be **carefully analysed to provide more information on aquifer properties**, such as transmissivity and specific capacity values for different geological formations.

Continued monitoring of abstraction rates, water levels and water quality in all boreholes, but especially in mechanised boreholes, is key to effective groundwater management. This information provides user communities with advanced warning of any problems, and is especially important where there are small borehole yields from low productivity aquifers.

Where boreholes have declined in yield or failed after several years – particularly for high yielding (e.g. mechanised) boreholes – then it may be possible to re-develop the borehole. However, the cause of falling yields should be investigated thoroughly – e.g. using a downhole camera – to show whether the failure is due to pump breakdown, borehole screen siltation or blockage, or falling groundwater levels if local groundwater storage is used up. This should be done before going to the trouble and expense of remediation work such as hydrofracturing, or siting and drilling replacement boreholes.

2.5 DATA MANAGEMENT AND INTERPRETATION

In order to improve understanding of the regional hydrogeology, which is key to improving local borehole siting decisions, there needs to be both **central collation of geological and hydrogeological information** from across the region, and **interpretation of this information at a regional scale**. Data and information collected during groundwater development projects is vital for developing this improved understanding.

A **central database** such as the CWSA DIMES system is vital in order to collate, manage and make data available. It needs to be as comprehensive as possible and to **include data from across the region**; to **include as much relevant information as possible on each borehole**; and to be **regularly updated**.

However, even a detailed database like DIMES cannot hold all potentially relevant and useful information related to groundwater development. Two key areas where different data storage systems may be very useful are in storing (1) geophysical survey data and (2) detailed geological information.

If the analysed results and hydrogeological interpretations of geophysical surveys are stored and made available centrally, they can be used by practitioners to increase their confidence in surveying new sites. For example, someone carrying out a geophysical siting survey on the Bimbila Formation could easily examine the results of previous surveys on the same formation – i.e. conductivity and/or resistivity values and patterns – along with lithological, water strike and yield information from boreholes drilled at the same sites, to indicate what they should look for in the results of the new geophysical survey to identify potential groundwater targets.

Another important step in improving understanding would be **making available detailed interpretations of drilling logs for each of the geological formations**. Although the most detailed hydrogeological information from boreholes can only be produced by drilling and interpreting cored boreholes, it is possible to obtain very useful information from the boreholes drilled for groundwater abstraction, particularly if the small changes in data collection during drilling recommended in this report are made, so that subtle details in the complicated intercalated sedimentary sequences typical to the Northern Region are not overlooked during borehole logging. One way to move towards a better regional geological understanding may be to **deposit digital copies of improved borehole logs with the Geological Survey of Ghana**, who have the expertise and regional understanding to interpret them. For example, consultants could provide a scanned version of their hand-written field log alongside a photograph of the chip samples from the field (a 'photo log' – Figure 16) and a digital copy of the summary log from the project report. Even if information from only a small percentage of new boreholes drilled was deposited in this way, it would significantly increase the amount of geological information available for study and interpretation in the future.

The wider use of maps may also help to improve understanding of groundwater potential across the region. Existing maps – geological maps, such as the one in Figure 17; or hydrogeological or groundwater potential maps such as the one in Figure 27 – can clearly show how groundwater potential may vary across an area. Creating new maps using new data can also help in interpreting and sharing information: for example, plotting the locations and results of new geophysical surveys; data from new boreholes; or the results of groundwater chemistry analyses. Creating and sharing such maps is becoming increasingly easy with the wider availability of GIS software.

3 Hydrogeology of the main geological units in the Northern Region

This summary of the current understanding of the hydrogeology of the main geological units in the Volta Basin rocks of the Northern Region is based on the assessment and interpretation of available data collated from organisations in the region and from projects such as the EU funded Mining Sector Support Programme (MSSP) programme; on discussions with Northern Region groundwater practitioners during the workshop and training; and on observations made by BGS during the two visits to the Northern Region during the BGS work.

A summary of the understanding of the hydrogeology of the Northern Region is provided by a new groundwater development potential map produced during this project, and presented in Section 3.5. The notes in the table accompanying this map will help practitioners assess the groundwater potential (Table 2).

3.1 GENERAL GEOLOGY

In order to understand hydrogeology you need to understand the geology. The geology of the Northern Region, and of the area underlain by the Volta Basin in particular (which is the focus of this study), is still relatively poorly understood. The current geological understanding is summarised here. The geology of the region is summarised in the map in Figure 17.

At the ground surface across most of the area, the rocks are covered by a layer of laterite (generally red tropical soils that are rich in iron and aluminium). When it overlies mudstones, the laterite is usually thicker – generally thought to be between 2 and 5m thick – and often nodular or tubular (formed into hollow tubes through which water can move). There is also typically a layer of kaolin clay between the laterite and the underlying mudstone. When it overlies sandstones, the laterite is typically thinner – thought to be only 1 to 2m thick, if present at all – and generally gravelly or sandy in nature.

Below the laterite, all the rocks in the region are typically highly weathered to a depth of at least 10m and often to between 30 and 60m. Few rock outcrops are visible at the ground surface, and so it is difficult to map, in detail, changes in geological units across the area; and it is impossible to have any detailed understanding of the nature of the unweathered rocks at depth. The characteristics of the rocks at depth, and lithological changes from one area to another, must largely be either inferred from remote sensing – and confirmed where possible by ground truthing – or observed from evidence gained by borehole drilling. The recent new geological mapping based on airborne geophysical sensing from MSSP has provided data that has been used to help refine the existing geological maps for part of the Northern Region, but even this was based on limited ground truthing. There has been little or no drilling for geological research in the Northern Region: what downhole information is available has been derived from drilling for water or minerals. A revised lithostratigraphy of the Voltaian Supergroup has recently been published based on recent work (Carney et al. 2010), and this paper and many other resources are available on the internet. However, even the most recent geological map and understanding still has little detail on the lithology of the geological units in the Northern Region, and in particular the interbedded mudstones, siltstones and rare sandstones of the Obosum Group and the Bimbila Formation that underlie a large part of the region.

The rocks of the far west of the Northern Region (Figure 17) are not part of the Volta Basin, and are also outside the area of the IWASH programme, and they have not been investigated as part of this project. The rest of the region is underlain by mixed sedimentary rocks of the Voltaian Supergroup, which infills one of the major sedimentary basins within the older metamorphic and igneous West African rocks. The Voltaian Supergroup forms a Neoproterozoic (late

Precambrian) to Early Palaeozoic, largely clastic, but lithologically very diverse sedimentary sequence. Mudstones, siltstones, sandstones, conglomerates and limestones occur in varying proportions across the Northern Region. They thicken progressively from west to east, where they terminate abruptly against older Precambrian basement rocks of the Buem and Togo Formations. These older rocks were once part of an ancient mountain range, which was eroded to provide the sediment that infilled the Voltaian Basin and formed the rocks of the Voltaian Supergroup (Carney et al. 2010).

The Voltaiain Supergroup can be divided into four lithostratigraphical groups: from oldest to youngest, these are the Boumbouaka, Kwahu, Oti-Pendjari, and Obosum groups. These groups are subdivided into a number of formations and members. Selected geological units are named in Table 1 (which lists the seven most widespread geological units in the are of IWASH interest in the Northern Region) and in the legend of the map in Figure 17.

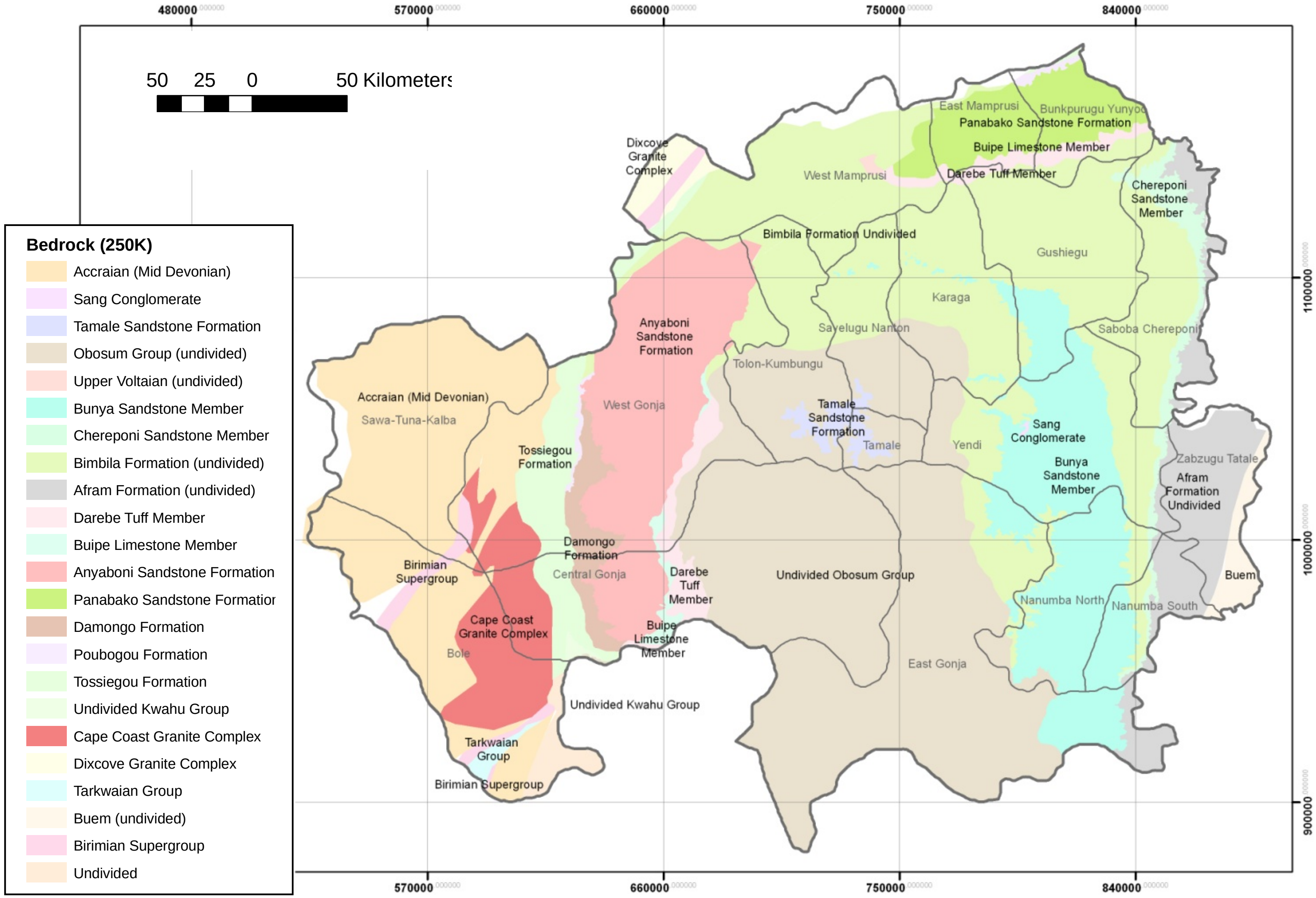
3.2 GENERAL HYDROGEOLOGY

Although there is no direct evidence yet, the unweathered rocks of the Volta Basin in the Northern Region are likely to be well-cemented and to have little primary porosity or permeability. Groundwater storage and flow in the unweathered rocks occurs mainly in fractures. Most of the rocks in the Northern Region have low or very low aquifer productivity and groundwater potential. **Borehole success rates are typically between 40 and 60%, but are as low as 20% in the lowest productivity aquifer, and generally not more than 70% even in the highest productivity aquifer** (the Anyaboni Sandstone Formation). A successful borehole is defined as one capable of supplying a hand pump: the nominal criteria for success have differed slightly across different projects and also between theory and practice, but are generally between 8 and 13.5 l/min. For the purposes of this project, an average nominal yield of 10 l/min has been taken to indicate success.

In the upper weathered zone of the rocks, particularly in sandstones and less so in siltstones, weathering of fractures can increase aquifer permeability and allow enhanced groundwater flow and storage. **Fractures in sandstones are the most important groundwater target in the Northern Region**. Only small amounts of groundwater are found in fractures in siltstones. Groundwater is rarely found in mudstones. In some formations, particularly the Bimbila Formation, it is recognised that groundwater can be found in thin zones at lithological boundaries between mudstone and siltstone.

The available information shows that **the most important zone of groundwater flows is between approximately 30 and 70m** depth. The small number of deeper boreholes that have been drilled, particularly during the HAP project – most of which have also been flow logged – generally show that there is little groundwater inflow below 70m, particularly in mudstones and siltstones. The exceptions are in sandstones which sometimes do show significant inflows up to 100m and occasional smaller inflows below 100m. **There is no evidence of significant groundwater flows at depths of over 100m**.

A preliminary reprocessing of recent airborne magnetic data by BGS has revealed the locations of what appear to be an extensive set of regionally extensive lineations that cross much of the Volta Basin, including much of the Northern Region. These have been previously interpreted as fracture zones, although they have not yet been confirmed, and there has been no investigation of them in relation to groundwater potential. If their presence is interpreted and confirmed (e.g. by controlled ground magnetic measurements and by ground geological assessment) and further work shows that they are related to groundwater-bearing features (e.g. surface geophysical surveys and drilling results show they correlate to zones of increased fracture flow), knowledge of these lineations may help define local fracture strike directions, which could improve the success of borehole siting. The subject warrants further research.



Geological map for the Voltaian Basin project area provided by BGS with permission from the Director of the Geological Survey of Ghana.

The geological units discussed in this report are summarised in Table 1.

Figure 17 The geology of the Northern Region (based on recently revised geological mapping and nomenclature; extended specifically for this project to cover the Northern Region, by reference to national geological map of Ghana at 1:1 million scale).

3.3 HYDROGEOLOGY OF INDIVIDUAL GEOLOGICAL UNITS

There are significant amounts of hydrogeological information for the seven most widespread geological units within the area of IWASH interest (effectively from the Anyaboni Sandstone Formation (which crops out in the eastern part of West Gonja district) to the Afram Formation (which crops out in Zabzugu Tatale district) – see Figure 17). A number of other units have smaller outcrops, and hence have been drilled into less often, and little is known about their hydrogeology; additionally, some of these are relatively thin, and may not be significant in terms of groundwater flow. The names and a summary of the lithology of seven most widespread geological units are given in Table 1. The hydrogeology of these seven units is then described in decreasing order of age from youngest to oldest.

Table 1 Lithostatigraphical column for the seven most widespread geological units in the area of IWASH interest in the Northern Region (after Carney et al. 2010)

Group	Formation/Member	Lithology
Obosum Group	(includes the Tamale Sandstone and Sang Conglomerate formations, but generally undivided)	The undivided Obosum Group is dominated by mudstones and siltstones, with subordinate sandstones
Oti-Pendjari Group	Bunya Sandstone Member	Dominantly grey-green. medium grained feldspathic sandstones
	Chereponi Sandstone Member	Alternating grey-green, medium grained sandstones and siltstones
	Bimbila Formation	Dominantly grey to green, weakly micaceous mudstones and siltstones with thin beds of green-grey sandstones
	Afram Formation	Dominantly grey-green micaceous mudstones and siltstones, with rare limestone and sandstone
Kwahu Group	Anyaboni Sandstone Formation	Medium to fine grained, grey to red feldspathic sandstone
Bombouka Group	Panaboko Sandstone Formation	Grey, weathering to yellow & pink, medium grained quartzose sandstone

3.3.1 Obosum Group

Dominated by interbedded, thinly-laminated and highly variegated (yellow/brown/grey/purple/green) micaceous mudstones and purplish-grey, micaceous siltstones. Rare beds of very fine-grained sandstones, and sporadic but highly distinctive beds of pebble conglomerate, particularly near the base of the group. Thinnest at its western edge, the maximum thickness is unknown but likely to exceed 400m. In the Northern Region the Obosum Group forms gently undulating terrain, with extensive formation of tubular and nodular laterite at the surface, overlying a weathered zone of kaolin clay.

The recorded boreholes in the Obosum Group are usually between 30 and 90m deep, with a small number drilled up to 150m deep. Most boreholes drilled are dry – the proportion showing any yield at all is less than 30% (Figure 20). In non-dry boreholes, recorded yields range from 2 to 1000 l/min (Figure 18), with median yields ranging from 10 to 15 l/min (based on statistics from the three main borehole datasets: the HAP database of abstraction boreholes; IWASH boreholes; and monitoring boreholes – Figure 21). In the IWASH and previous programmes, between 20 to 25% of boreholes were high enough yielding to be able to supply a hand pump – taken as a nominal yield of 10 l/min (Figure 22). Taking this value of 10 l/min to indicate success, the success rate of boreholes in the Obosum Group drilled during the HAP monitoring well programme was higher, at 50%, although only six boreholes were drilled during this programme. There is little indication that deeper boreholes consistently show higher yields (Figure 18).

The Obosum Group therefore generally forms a very low productivity aquifer. The mudstones which often dominate much of the unit do not appear to contain significant groundwater, either when weathered or unweathered. The siltstones occasionally contain water-bearing fracture or weathered-out fracture zones. Occasional high yielding boreholes have been drilled in this group, but typically only where significant thicknesses of sandstone are encountered; thin fracture zones in the sandstone are thought to be the most important groundwater targets in this case. However, not all boreholes drilled into sandstones within the Obosum Group have produced high yields, which indicate that fractures are not well-developed everywhere in the sandstone.

3.3.2 Bunya Sandstone Member (Oti-Pendjari Group)

The Bunya Sandstone Member is thought to be generally about 50m thick, and consists of minor maroon, green and grey, slightly micaceous siltstones overlying the dominant lithology of grey-green, medium-grained, micaceous, poorly sorted sandstones, which are rich in feldspar and lithic grains of quartz, red jasper and meta-volcanic rocks.

Overlying the unit there is typically thin, gravelly laterite, sometimes capped by a thin iron oxide cement.

The recorded boreholes in this unit are usually between 30 and 70m deep, with a small number drilled up to 150m deep. The deeper of these boreholes are therefore likely to have been drilled through the total thickness of the Bunya Sandstone Member and into the underlying Bimbila Formation.

Only around 40% of drilled boreholes give any yield at all (Figure 20). In non-dry boreholes, recorded yields range from 5 to 1000 l/min (Figure 18). The median yield of boreholes that were not dry is variable in the different programmes, from 7 to 180 l/min (Figure 21). Success rates in this unit in the IWASH programme (17%) were lower than in previous programmes (40%) or the HAP monitoring borehole programme (all of the four boreholes drilled) (Figure 22). There is little indication that deeper boreholes consistently show higher yields (Figure 18).

The Bunya Sandstone Member therefore appears to form a moderately to highly productive aquifer if conditions are favourable, with the key groundwater target likely to be thin fracture zones within the sandstones. However, the high percentage of dry boreholes drilled indicates that there may be great variability in the development of fractures across the unit, and that where fractures are not well-developed, yields can be negligible.

3.3.3 Chereponi Sandstone Member (Oti-Pendjari Group)

This member is thought to be 40-60m thick, and is made up of hard, possibly siliceous, dark olive-green to grey, fine- to medium-grained micaceous and lithic-rich feldspathic, arkosic sandstone.

Overlying the unit there is typically thin, gravelly laterite, sometimes capped by a thin iron oxide cement.

The recorded boreholes in this unit are typically between 20 and 70m, with an occasional borehole down to 90m. The deepest of these boreholes are therefore likely to have been drilled through the total thickness of the Chereponi Sandstone Member and into the underlying Bimbila Formation. Only around 40% of drilled boreholes provide a yield (Figure 20). In non-dry boreholes, recorded yields range from 3 to 300 l/min (Figure 18). The median yield of boreholes that were not dry appears is around 40 l/min, although the two non-dry boreholes drilled in this formation for the IWASH programme gave a lower median yield of 15 l/min (Figure 21). Success rates (boreholes yielding 10 l/min or more) were between approximately 40 and 50% in the IWASH and previous programmes (Figure 22). There is little indication that deeper boreholes consistently show higher yields (Figure 18).

The Chereponi Sandstone Member appears to form a variably productive aquifer, from low to high. The main groundwater targets are likely to be thin fracture zones, but the high percentage of dry boreholes, and the variability in yields, indicates that fractures are not well-developed everywhere.

3.3.4 Bimbila Formation

This unit consists of green-grey mudstones and siltstones interbedded with subordinate green-grey, feldspathic sandstones.

Overlying the unit there is typically tubular laterite at the surface with weathered kaolin clay below; the clay layer tends to be thinner below low-lying areas than beneath higher ground.

The recorded boreholes in this unit are typically between 20 and 80m, with an occasional borehole down to 170m. Only around 40% of drilled boreholes are not dry (Figure 20). In these non-dry boreholes, recorded yields range from 4 to 1000 l/min (Figure 18). The median yield of boreholes that were not dry is between 20 and 27 l/min for boreholes in the IWASH and previous programmes, but the ten monitoring boreholes drilled showed a much higher median yield of 85 l/min (Figure 21). Two of the monitoring boreholes had particularly high yields of 700 l/min. There is little indication overall that deeper boreholes consistently show higher yields (Figure 18); the two boreholes with yields of 700 l/min were 106 and 120m deep, but most of the deeper boreholes (120 to 166m deep) had yields of less than 20 l/min. Success rates (yields of 10 l/min or more) for boreholes in the Bimbila Formation appear to have increased from previous borehole development programmes (40%) to the IWASH programme (55%) to the HAP monitoring well programme (80%) (Figure 22).

The Bimbila Formation therefore appears to form a moderate to low productivity aquifer, probably largely dependent on the lithology. The main groundwater targets are likely to be weathered-out fracture zones in siltstones and sandstones; and it is observed that groundwater flows also occur in thin zones at lithological boundaries between mudstone and siltstone. Higher yields may also occur in thicker sandstone units.

3.3.5 Afram Formation

This unit mainly consists of olive-green to grey mudstones and siltstones, with occasional thin limestones. The formation tends to readily weather to an ochreous, ferruginous tubular laterite over kaolin clay, which is thinner below low-lying areas than beneath higher ground.

The recorded boreholes in this unit are generally between 30 and 70m. Some 50% of drilled boreholes are dry (Figure 20). In non-dry boreholes, recorded yields range from 6 to about 550 l/min (Figure 18). The median yield of boreholes that were not dry ranges from approximately 20 to 35 l/min (Figure 21). Success rates for boreholes in the Afram Formation in previous programmes were around 40%, and for the IWASH programme were 55% (Figure 22). No boreholes deeper than 70m have been recorded.

The Afram Formation therefore appears to form a moderately productive aquifer. The main groundwater targets are likely to be weathered-out fracture zones, especially in siltstones and rare limestones. These fractures are not likely to be well-developed everywhere.

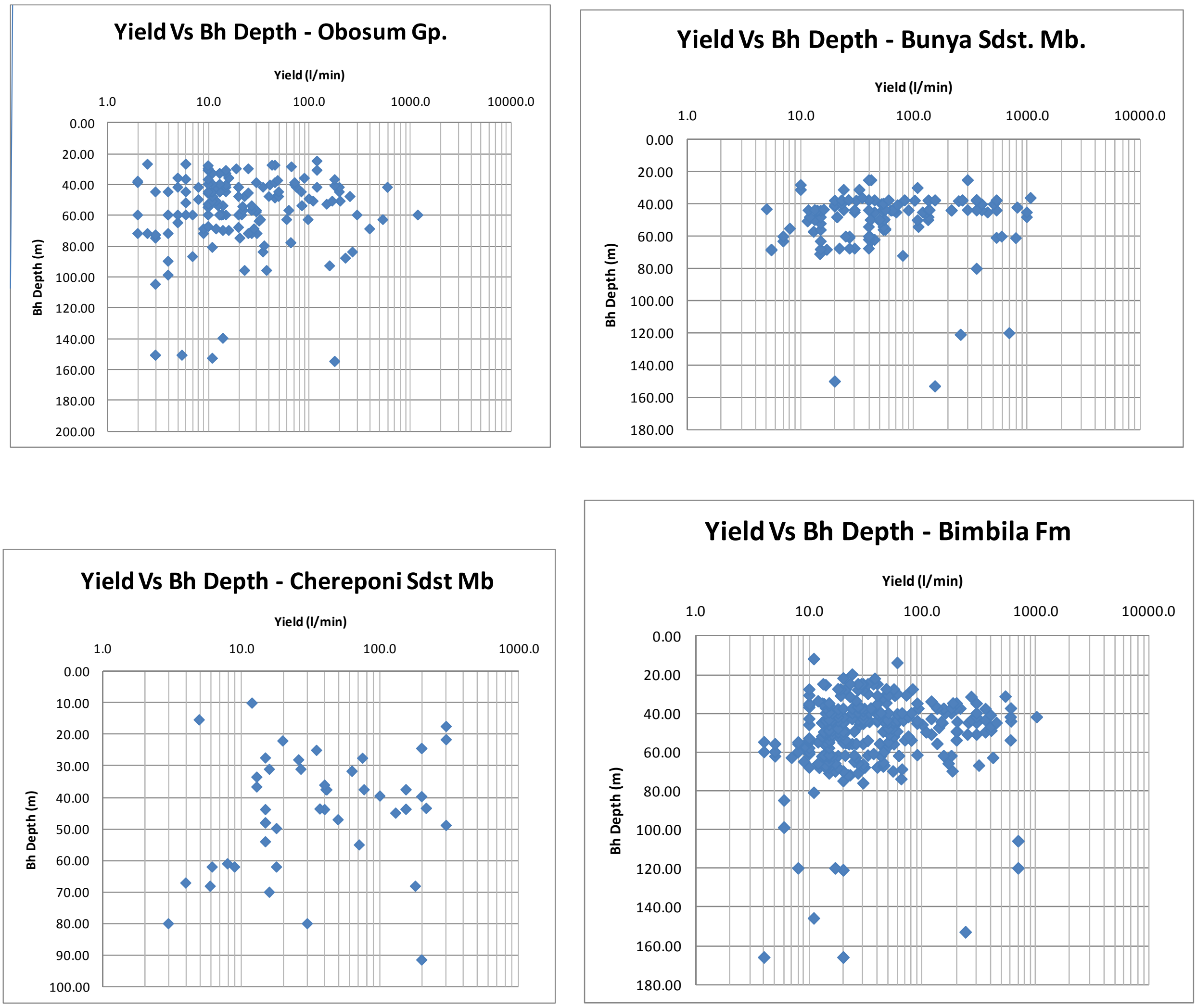


Figure 18 Borehole depths and measured yields in the Obosum Group, Bunya Sandstone Member, Chereponi Sandstone Member and Bimbila Formation. Note the different vertical scales.

3.3.6 Anyaboni Sandstone Formation (Kwahu Group)

This has been mapped as a 150-200m thick unit, comprising finer-grained, argillaceous and micaceous strata at its base, passing upwards into grey to pink, medium-grained, feldspathic, mainly sub-arkosic sandstones, which are at least partly aeolian in origin.

Overlying the unit there is typically thin, gravelly laterite, sometimes capped by a thin iron oxide cement.

The recorded boreholes in this unit are typically between 40 and 60m, with a very small number of boreholes between 100 and 120m. Some 70% of drilled boreholes provide a yield (Figure 20). In these non-dry boreholes, recorded yields range from 7 to 1000 l/min (Figure 19). The median yield of boreholes that were not dry is high, from 150 l/min in previous programmes to 260 l/min in the HAP monitoring boreholes programme (Figure 21). Success rates (boreholes yielding 10 l/min or more) are also high, from around 70% in previous programmes to 100% in the HAP programme (Figure 22). There is some indication that higher yields can be found with depth: all the boreholes between 100 and 120m had yields of between 300 and 600 l/min (Figure 19).

The Anyaboni Sandstone Formation therefore appears to form a moderate to high productivity aquifer. The main groundwater target is likely to be thin fracture zones, which are likely to become less frequent and productive with depth, but the limited evidence from the deeper monitoring wells, which have been flow logged, indicates that there can be significant inflows at depths of up to 100m, and occasional inflows below 100m.

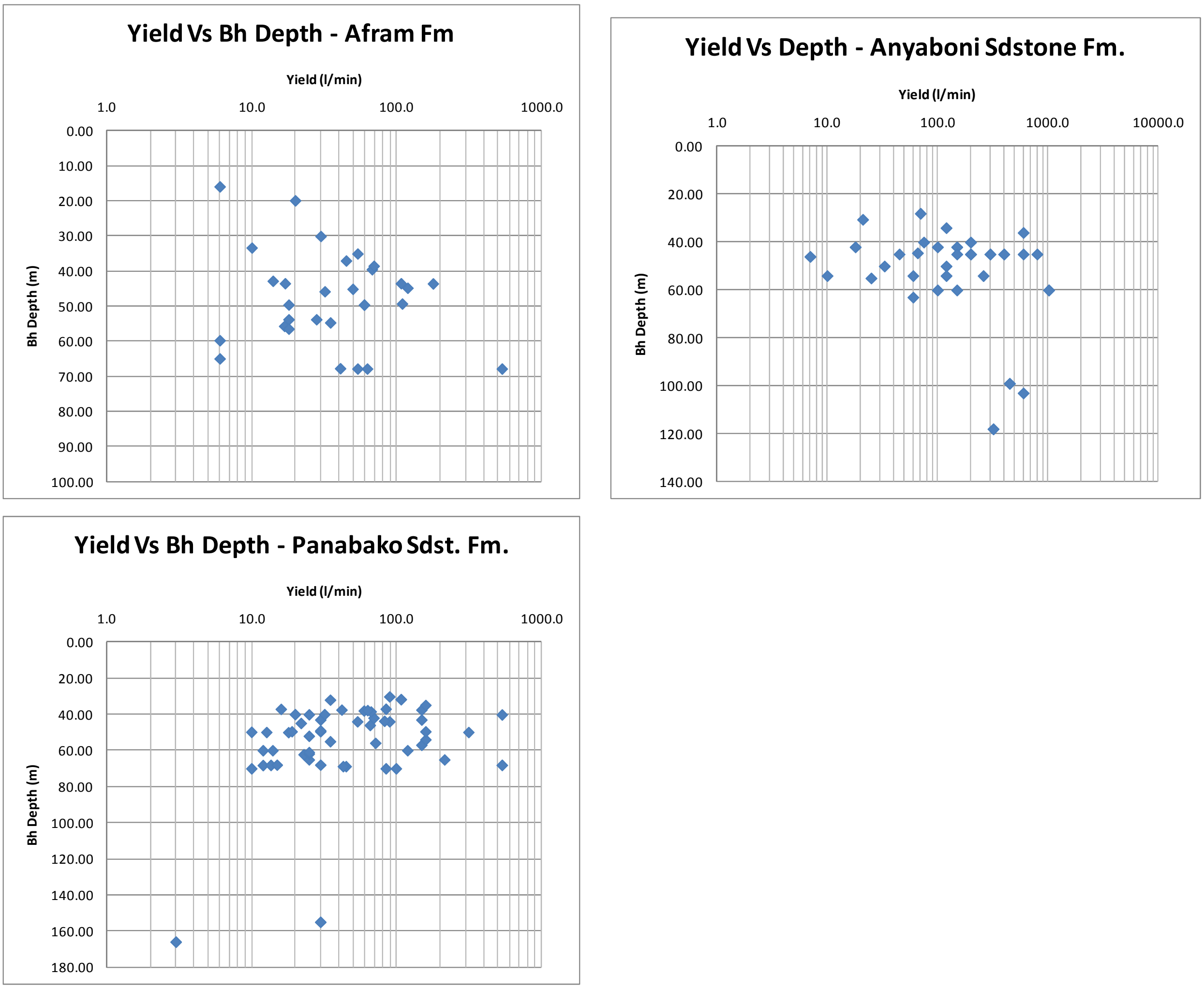


Figure 19 Borehole depths and measured yields in the Afram Formation, Anyaboni Sandstone Formation and Panaboko Sandstone Formation. Note the different vertical scales

3.3.7 Panaboko Sandstone Formation (Kwahu Group)

This unit is estimated to be 150-200 m thick, and comprises hard, well-cemented, well sorted, medium-grained, quartzose sandstones (quartz arenites or quartzites), with minor feldspar content, which are typically white or locally stained ochre.

Overlying the unit there is typically thin, gravelly laterite, sometimes capped by a thin iron oxide cement.

Of the recorded boreholes in this unit, all but two are between 30 and 70m deep, with two new monitoring wells around 160m deep. Some 40% of drilled boreholes are not dry (Figure 20), and in these boreholes, recorded yields range from 2 to about 550 l/min (Figure 19). The median yield of boreholes that were not dry is between 15 and 35 l/min (Figure 21). The two deep monitoring wells drilled in the HAP programme showed relatively low yields, with one in particular, at more than 160m deep, yielding only 3 l/min. Based on the evidence of the only two deep boreholes, there is no indication that higher yields are found with depth (Figure 19).

The Panaboko Sandstone Formation appears overall to form a moderate to high productivity aquifer. The main groundwater target is likely to be weathered-out fracture zones in the shallow zone to about 20 to 30m depth, and largely unweathered fracture zones below this, which are likely to become less frequent and productive with depth. In the two deep boreholes, flow logging showed there were small inflows below 100m, but these did not increase the yield significantly.

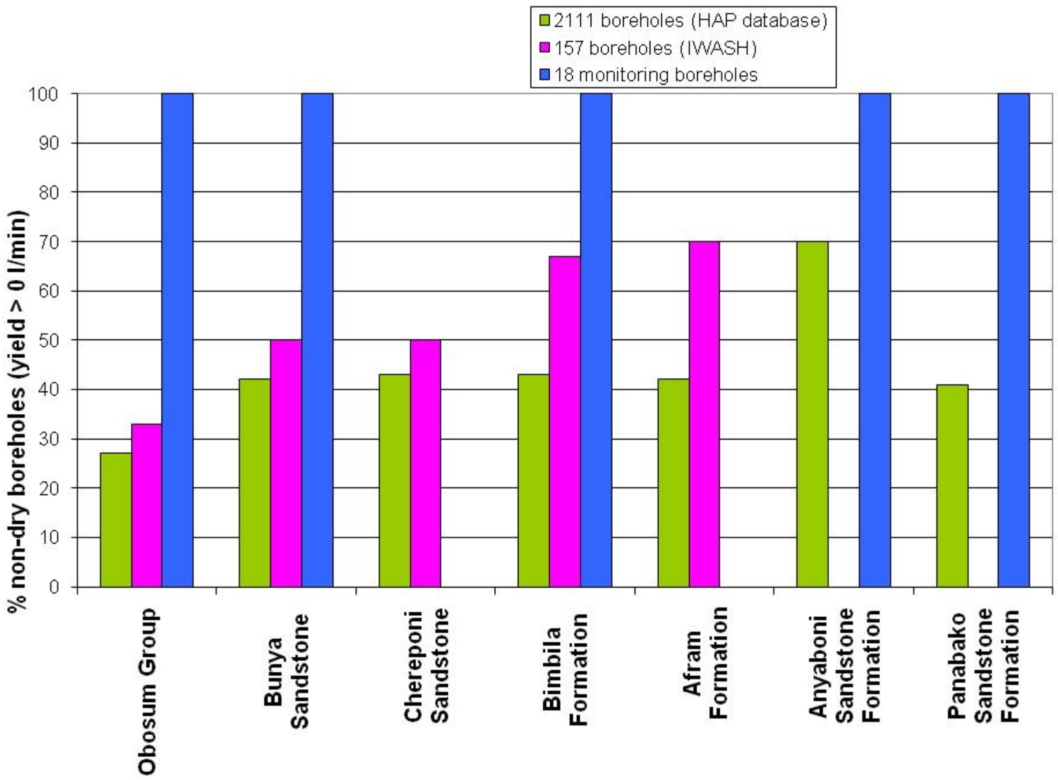


Figure 20 Percentage of non-dry boreholes (i.e. any yield more than zero) from the three main datasets (HAP database of abstraction boreholes – including data from EU and AFD projects; IWASH boreholes; and monitoring boreholes)

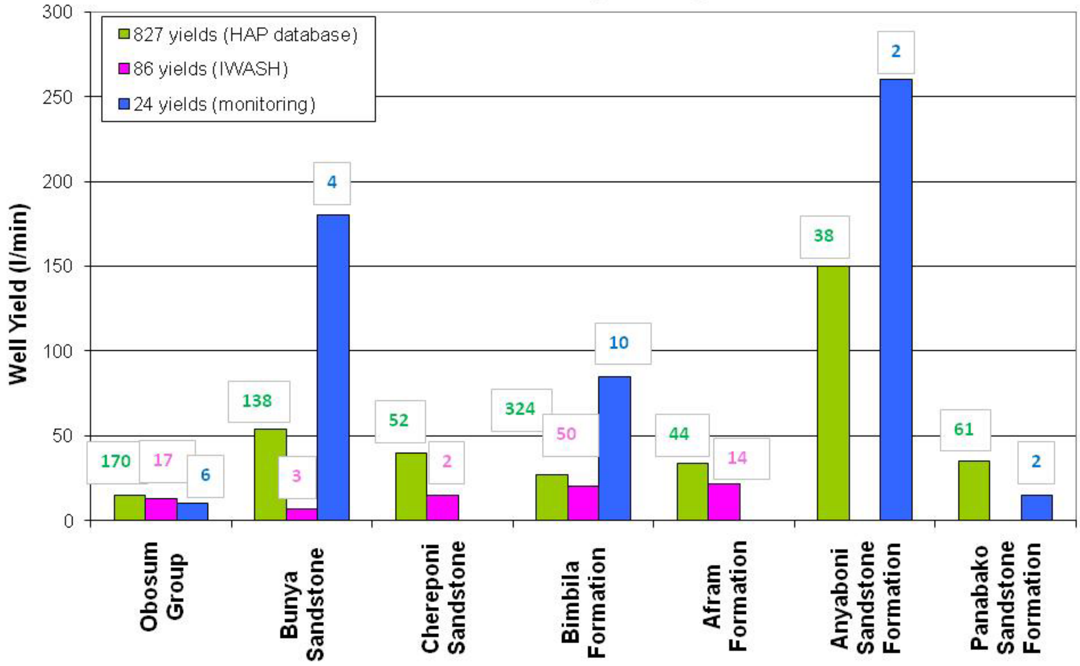
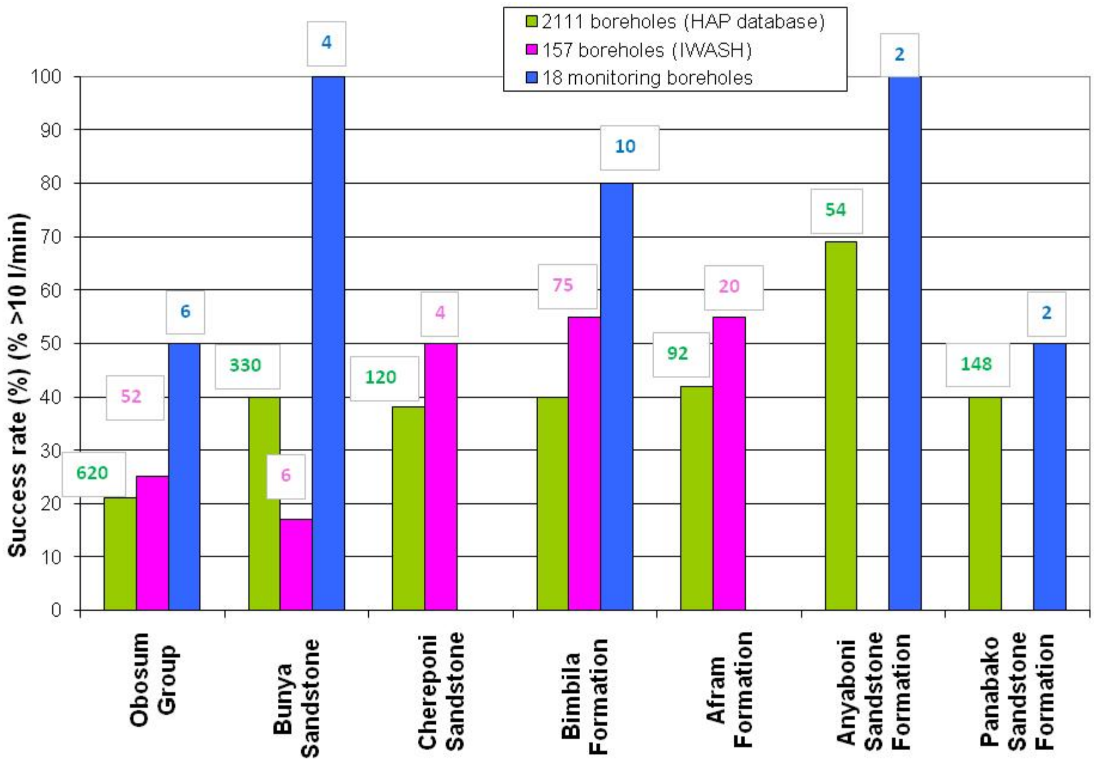


Figure 21 Median yields of non-dry boreholes by geological formation, from the three main datasets (HAP database of abstraction boreholes – including data from EU and AFD projects); IWASH boreholes; and monitoring boreholes). The number of boreholes in each geological unit is given above each bar.



Note that different borehole success criteria – defined as the nominal yield required to support a hand pump – have been used in different projects in the Northern Region, but these are generally between 8 and 13.5 l/min: 10 l/min is used here as an average.

Figure 22 Borehole success rates (boreholes yielding 10 l/min or more) by geological formation, from the three main datasets (HAP database of abstraction boreholes – including data from EU and AFD projects; IWASH boreholes; and monitoring boreholes). The number of boreholes in each geological unit is given above each bar.

3.4 GROUNDWATER QUALITY

The available chemistry data indicates there is often a difference in the degree of mineralisation of groundwaters in sandstones and in mudstones/siltstones. Groundwater from sandstones, such as the Bunya Sandstone and the Anyaboni Sandstone, appears to be generally less mineralised, with lower conductivity (measured by SEC – specific electrical conductivity). Groundwater from units dominated by mudstones and siltstones, such as the Obosum Group, often has higher conductivity, and in certain areas – such as near Tamale – very high conductivity (Figure 23).

There is only enough full major ion analysis to characterise water types for the Obosum Group, Bunya Sandstone Member and Bimbila Formation. Most of the groundwaters for which major ion analysis are available have a cation dominance by Na-K (Figure 24), with a few having no overall dominant cation. For most of the samples the dominant anion is HCO_3, or there is no dominant anion, but a small subset of groundwaters from the Obosum Group are dominated by Cl (Figure 24).

The most prominent natural groundwater chemistry issue in the Northern Region is the presence of elevated fluoride concentrations. These occur sporadically across the region, but are much more common in the eastern corridor (Figure 25). There is also evidence that fluoride is more common in sandstones than in mudstones or siltstones. There is little obvious relationship from the Northern Region data between fluoride concentrations and other parameters which are often correlated with fluoride, such as pH, Ca, HCO_3, or Na. There may be a relationship with the feldspar content of the sandstones, which is thought to be higher in the eastern part of the region, linked to the mineralogy of the basement rocks to the east which formed the sediment source for the rocks of the Voltaian Basin.

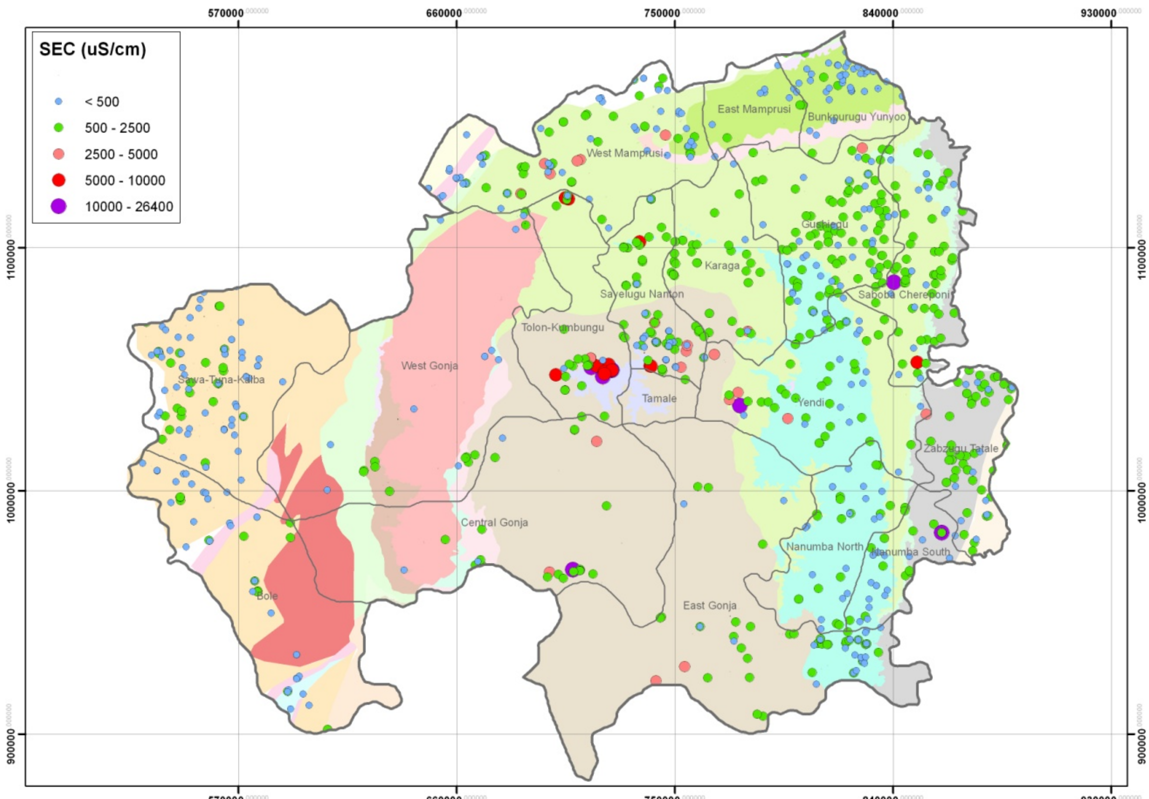


Figure 23 Groundwater conductivity (SEC – specific electrical conductivity) across the Northern Region

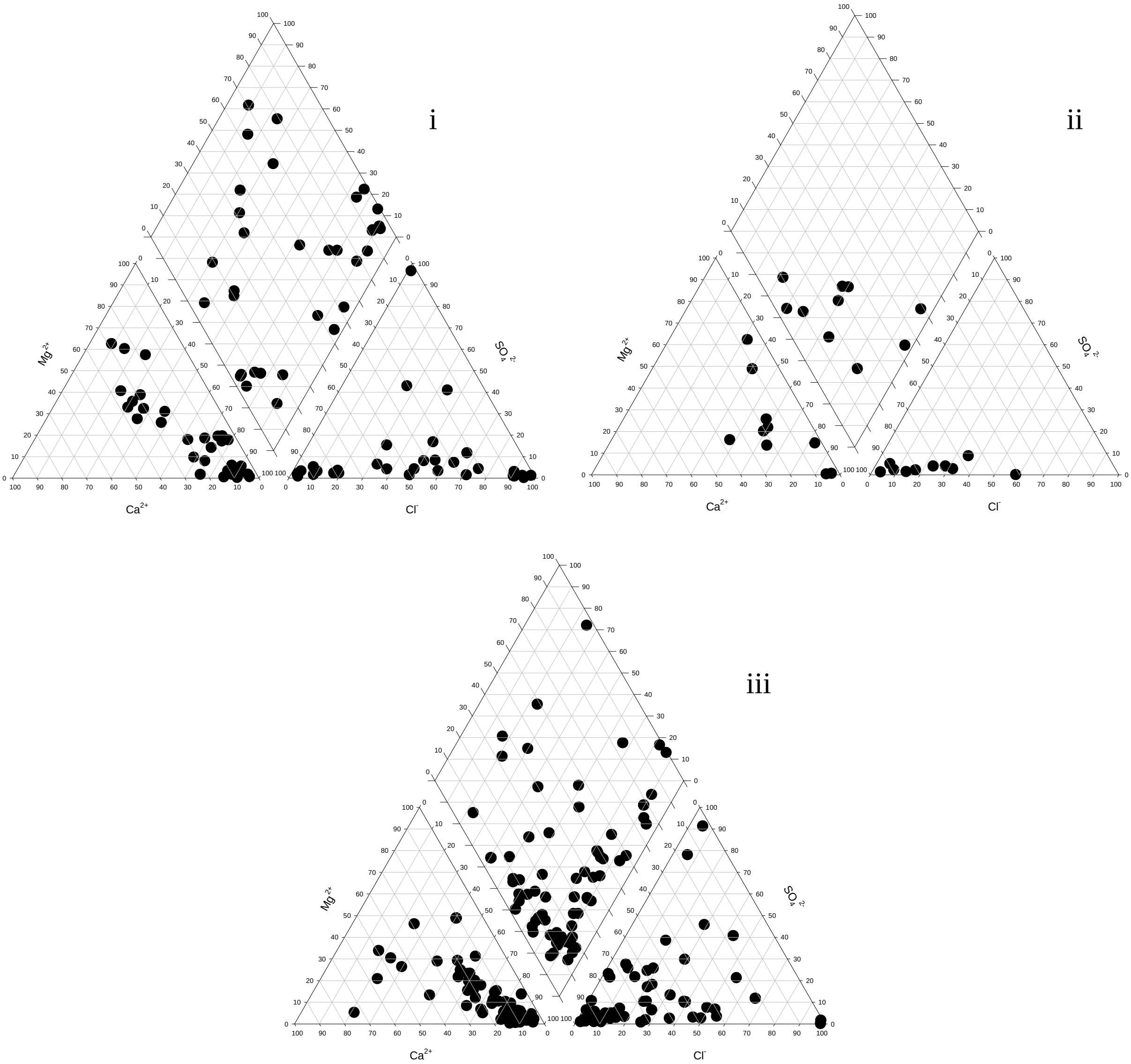


Figure 24 Piper plots for (i) the Obosum Group, (ii) the Bunya Sandstone Member and (iii) the Bimbila Formation

Nitrate is the most commonly recorded pollutant of groundwater in the region, although recorded instances of high nitrate concentrations are still rare and isolated (Figure 26). They are thought by most practitioners to be linked to the increasing use of artificial fertiliser by farmers, although there may also be a link between increased nitrate concentrations and local contamination by human and/or animal waste.

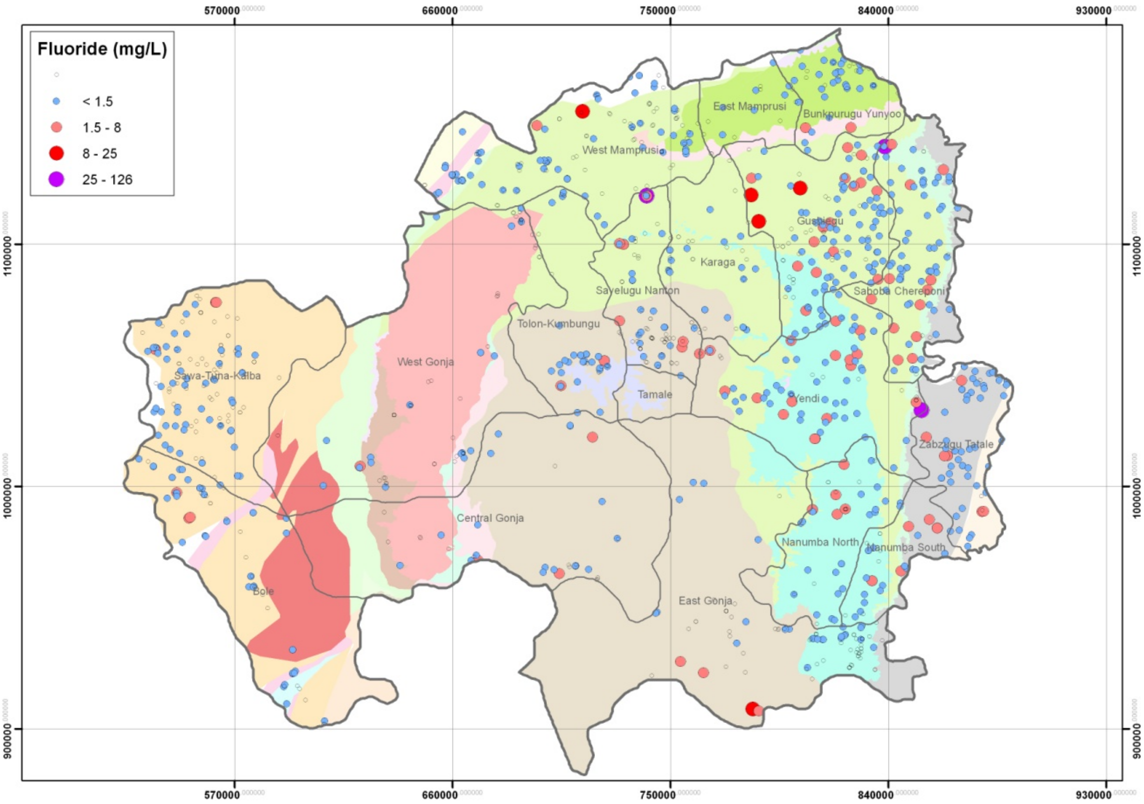


Figure 25 Fluoride concentrations in groundwater across the Northern Region

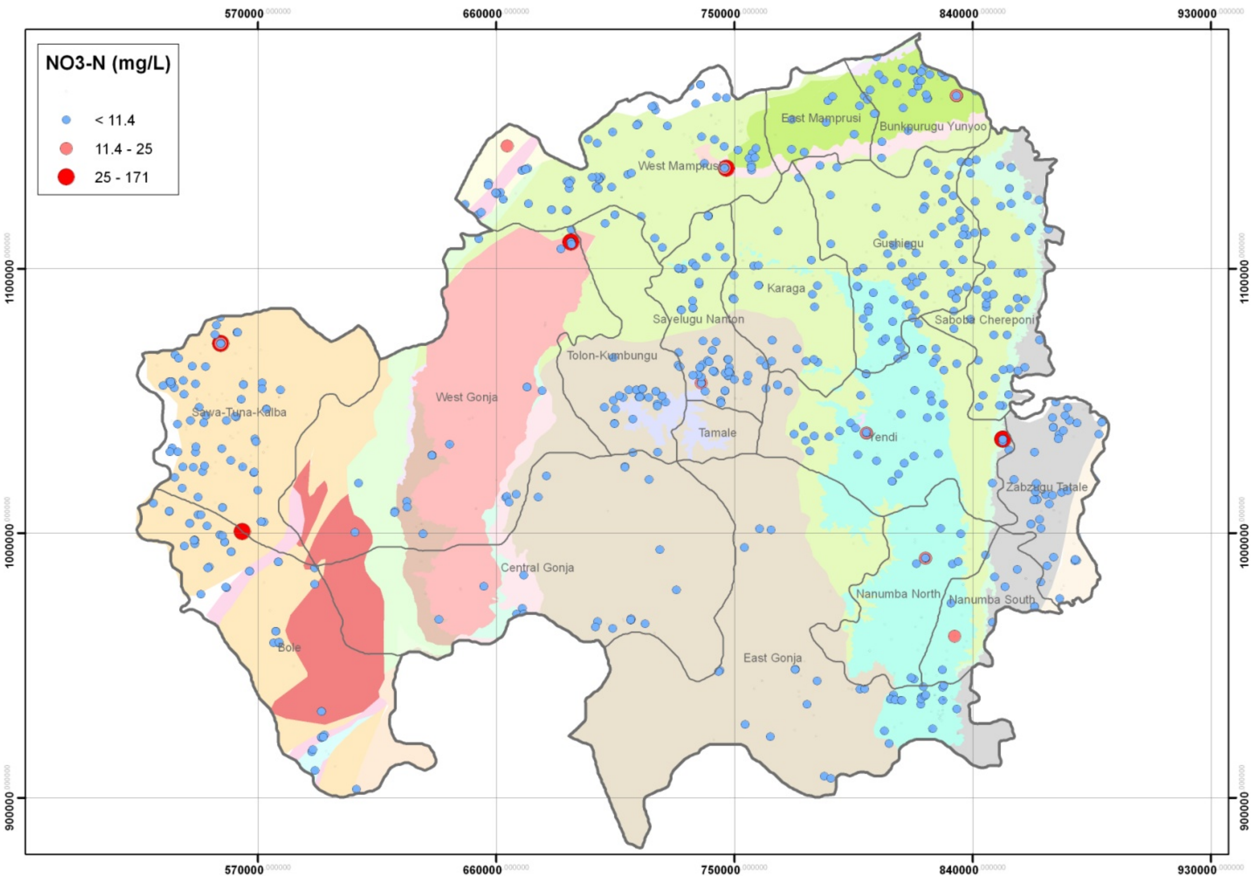


Figure 26 Nitrate concentrations in groundwater across the Northern Region

3.5 A GROUNDWATER DEVELOPMENT POTENTIAL MAP FOR THE NORTHERN REGION

A map of the different geological formations in the Northern Region has been produced (Figure 27), together with an attribute table indicating groundwater development potential in each geological formation, and recommendations for appropriate development techniques (Table 2). The map highlights known variations in aquifer productivity (i.e. potential groundwater yield) and relevant groundwater development issues in different geological units. It was created by BGS and refined by feedback from Northern Region groundwater practitioners and by observations made by BGS during the two visits to the Northern Region as part of this project. The map can directly help groundwater development practitioners to select locations for groundwater development.

Each geological formation has been categorised as having either Low, Moderate or High groundwater potential, based on the recorded yields of boreholes drilled into the geological formations in the Northern Region, and corresponding in general to:

Low groundwater development potential: <15 l/min

Moderate groundwater development potential: 15-80 l/min

High groundwater development potential: >80 l/min

If borehole yields in a geological formation vary significantly, the groundwater potential is given two or more categories, with the first named reflecting the most common category. For example, Moderate to High groundwater potential describes a formation which generally has Moderate potential but sometimes has High potential; while High to Moderate groundwater potential describes a formation which generally has High potential but sometimes has Moderate potential. One of the formations – the Chereponi Sandstone Member – shows very variable yields, and has been classed as having Low to High groundwater potential.

The map focuses on the seven main geological formations that underlie the central and eastern parts of the Northern Region, where the IWASH programme has been operating. Most of the boreholes in the region have been drilled into these formations, and so most hydrogeological information is available for them. Other minor formations occur in this area, but they cover a relatively small area, and little hydrogeological information is available for them.

It also has an overlay highlighting the areas where airborne geophysical data (electromagnetic/EM coverage) indicate there are more likely to be sandstones at depths of less than 100m. Because fractures in sandstones are thought to be a critical groundwater target in the Northern Region, a better knowledge of where sandstones might be could significantly improve borehole siting success. However there been no ground truthing of this information, and so at present it must remain only a potential indicator of the presence of sandstone.

Another potential use of the airborne geophysical data would be to add, as another overlay on the groundwater potential map, the regionally extensive lineations identified from the reprocessed magnetic data during the current project. These have been tentatively identified as fracture zone, although there has been no ground truthing or hydrogeological investigation of these features yet, so it is not yet known whether they do have hydrogeological significance. However, it could be an important subject for future research.

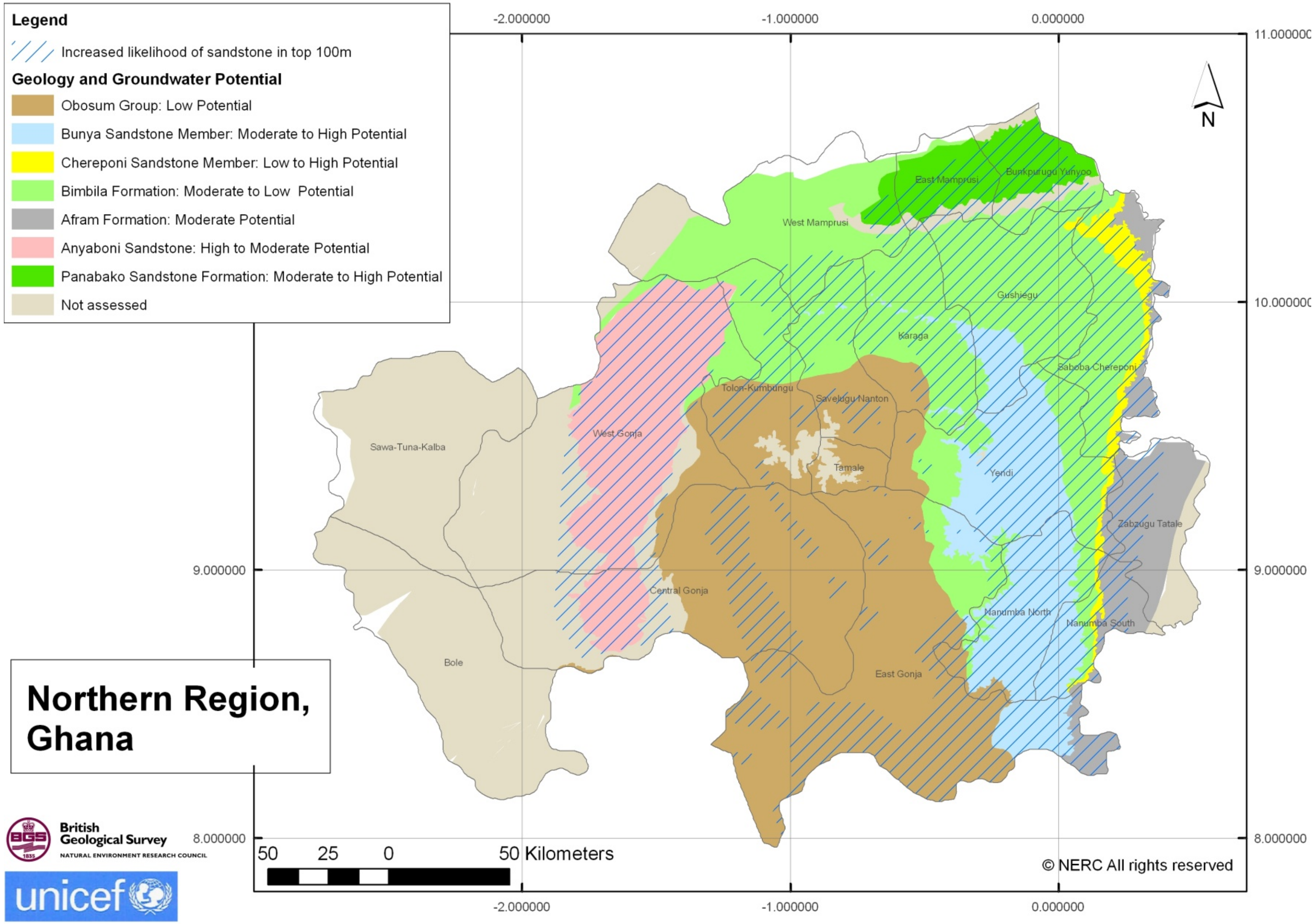


Figure 27 Groundwater development potential map for the Northern Region

Table 2 Attribute table showing groundwater development potential in the main geological units of the Voltaian Basin rocks in the Northern Region

Geological Unit	Lithology	Weathered Zone	Main Groundwater Targets	Typical Groundwater Potential[1]	Typical success rate	Typical depths of successful boreholes	Natural groundwater quality	Recharge Potential
Obosum Group (un-differentiated)	Dominantly mudstones and siltstones with subordinate sandstones	Highly weathered to <5m. Clay layer below laterite is thinner below low lying areas than higher ground. Slightly weathered to 30-60m	• Weathered fracture zones, especially in siltstones, to 30-60m • Thin fracture zones in rare sandstones, to 80-100m	Low	20-25%	30-80m	Typically Na/K-HCO_3 to Na/K-Cl type. SEC generally moderate & occasionally very high. Variable F from low to high	In mudstones: little infiltration through clay; low acceptance potential. In rare sandstones, higher infiltration and acceptance potential
Bunya Sandstone Member (Oti-Pendjari Group)	Dominantly grey-green. medium grained feldspathic sandstones	Highly weathered to 7-15m. Gravelly laterite to <5m, sometimes capped by thin iron oxide cement. Slightly weathered to 20-30m	• Thin fracture zones; frequency decreases with depth	Moderate to High	40-60%	30-70m	Typically Na/K-HCO_3 type. SEC generally low, occasionally moderate. Variable F from low to high	High infiltration through thin, gravelly laterite, except where cemented. Relatively high acceptance potential
Chereponi Sandstone Member (Oti-Pendjari Group)	Alternating grey-green, medium grained sandstones and siltstones	Highly weathered to 7-15m. Gravelly laterite to <5m, sometimes capped by thin iron oxide cement. Slightly weathered to 20-30m	• Thin fracture zones, especially in sandstones; frequency decreases with depth	Low to High	40-50%	20-70m	Generally low, occasionally high SEC. Generally low F	High infiltration through thin, gravelly laterite, except where cemented. Relatively high acceptance potential
Bimbila Formation	Dominantly grey to green, weakly micaceous mudstones and siltstones with thin beds of green-grey sandstones	Highly weathered <5m. Clay layer below laterite is thinner below low lying areas than higher ground. Slightly weathered to 30m, occasionally 60m	• Thin zones at lithological boundaries from green-grey mudstone to chocolate - brown siltstone) • Thin weathered fracture zones, especially in siltstones and rare sandstones. Frequency decreases with depth but significant inflows to 90m and occasional inflows below 100m	Moderate to Low	40-55%	20-80m	Typically Na/K-HCO_3 or no dominant type. SEC occasionally very high. F generally above WHO standard & occasionally very high	In mudstones: little infiltration through clay; low acceptance potential. In sandstones, higher infiltration and acceptance potential
Afram Formation	Dominantly grey-green micaceous mudstones and siltstones, with rare limestone and sandstone	<5 m. Clay layer below laterite is thinner below low lying areas than higher ground. Slightly weathered to 30m, occasionally 60m	• Weathered fracture zones, especially in siltstones and rare sandstones, to 30-60m	Moderate	40-55%	30-70m	SEC generally moderate. F generally high and occasionally very high.	Little infiltration through clay; low acceptance potential.
Anyaboni Sandstone (Kwahu Group)	Medium to fine grained, grey to red feldspathic sandstone	Highly weathered to 7-15m. Gravelly laterite to <5m, sometimes capped by thin iron oxide cement. Slightly weathered to 20-30m	• Thin fracture zones. Frequency decreases with depth but can find significant inflows to 100m and occasional inflows below 100m	High to Moderate	>70%	40-60m	Generally low SEC and low F	High infiltration through thin, gravelly laterite, except where cemented. Relatively high acceptance potential
Panaboko Sandstone Formation (Kwahu Group)	Grey, weathering to yellow & pink, medium grained quartzose sandstone	Highly weathered to 7-15m. Gravelly laterite to <5m, sometimes capped by thin iron oxide cement. Slightly weathered to 20-30m	• Weathered fracture zones to 20-30m • Thin to 0.5m thick fracture zones below this. Frequency decreases with depth but occasional inflows below 100m	Moderate to High	40-60%	30-70m	Generally low SEC and low F	High infiltration through thin, gravelly laterite, except where cemented. Relatively high acceptance potential

Box 7 Associated notes for map and attribute table

These notes are designed to accompany the groundwater potential map and attribute table, to explain some of the terms given in the map and table, and to support groundwater development practitioners when planning and carrying out borehole siting work.

[1]**Groundwater potential** is an overall function of groundwater storage, yield and residence time (length of time groundwater remains in the geological unit, i.e. the rate of throughflow).
The qualitative values given in the table correspond in general terms to: Low: <15 l/min
Moderate: 15-80 l/min
High: >80 l/min

[2] **Success rate** refers to the percentage of boreholes yielding more than 10 l/min, the nominal minimum yield for a hand pump.

[3]SEC – specific electrical conductivity of water

Geophysical techniques: applicable to all the geological formations, but careful field procedure is needed and results must be interpreted in relation to the known geology and hydrogeology, and the scientific basis and limitations of each technique. This needs a good knowledge of typical resistivity and conductivity values for key geological units in their weathered and unweathered states; and a good understanding of potential groundwater targets. Ideally, more than one method should be used and the results compared to identify features that coincide in each result, to increase confidence.

EM34. Rapidly covers ground; non-invasive. 20m coil penetrates to ~15-30m, and indicates thickness of weathered zone. 40m coil penetrates to ~30-60m, and can indicate base of thick weathered zones, bedrock lithology, and the presence of large vertical fracture zones below the weathered zone. When interpreting, look for the base of large anomalies in the 40m coil (deep) results.

2D resistivity profiling: Rapidly covers ground. Indicates bedrock lithology and thickness of weathered zone to a maximum of ~60m in centre of profile. Invasive; can be difficult to get current into dry ground, and depth of penetration decreases rapidly away from centre of profile. Data noise is common in dry ground and can hide deep geological features; when interpreting, look for large features which are more likely to be real.

VES: Can confirm thickness of weathered zone and bedrock lithology, e.g. over features identified by EM34 or 2D profiling. Invasive; can be difficult to get current into dry ground. The Schlumberger array is simpler to carry out and interpret than the Dipole-Dipole array. Whichever array is used, continuing to wider electrode spacings (e.g. AB/2 >=100m) gives deeper penetration; and the correct model must be used to process the data. Interpret the resulting curve in relation to the most appropriate conceptual model for the known geology at the site.

The geological linework on the map is available as a GIS shapefile with hydrogeological attributes in an associated table, and a separate shapefile of the overlay showing where there is increased likelihood of sandstone in the top 100m. An image file and a pdf file version of the map, with the overlay, are also available. The pdf version is designed to be printed with the attribute table on the reverse and suitable for use in the field. All these digital files are available in the CD-ROM attached to this report.

4 Improving hydrogeological understanding in the long-term

Key recommendations for long-term improvements in hydrogeological understanding in the Northern Region, which will bring increased borehole success, are:

- Bring data together from all groundwater projects, collate it centrally, make it easily available to all practitioners, and interpret it with a regional perspective. Move away from the current tendency to take a site-specific or local view, where individual borehole sites are largely investigated in isolation, without reference to wider hydrogeological understanding or results from previous geophysical studies and drilling logs. Ideally, future projects will allow more geophysical surveying across wider areas, and the regional interpretation of results, so that datasets are built up of typical geophysical responses for the rocks in the region. More use should also be made of resources such as geological and groundwater maps, and databases of existing boreholes.
- Reduce pressure on contracts to cut costs by siting and drilling boreholes quickly, which encourages short cuts in reconnaissance, geophysical surveying, detailed data collection during drilling and effective borehole development, and in the long run reduces borehole success. This may mean accepting that in the short term, individual borehole development could cost more.
- Promote and support professional communication between groundwater practitioners in the Northern Region and across Ghana and further afield. Groundwater practitioners in the Northern Region, especially those working in the private sector, are often isolated from the wider hydrogeological community, and one consequence of this is a lack of deeper understanding of some of the groundwater development techniques being used, in particular geophysics. Sharing experience with other professionals in Ghana, as well as further afield, will help practitioners to increase their understanding, skills, and success rates. Particularly useful is likely to be more opportunities for sharing experience between the private sector and universities, where groundwater experts typically have more opportunity to develop a deeper understanding of hydrogeology and learn about new and/or alternative techniques. However, promoting interaction between all groundwater practitioners – in the private sector, government agencies, NGOs and universities – would be a very positive step towards improving professional skills, particularly among more junior staff.
- Future research issues that could lead to a step change in understanding the hydrogeology of the Northern Region:
    - The recent new airborne geophysical data for the sedimentary rocks of the Voltaian Basin provides considerable scope for investigating controls on groundwater targets. For example, it may be possible to use EM data to predict the presence of sandstones at shallow depth; or to use reprocessed magnetic data to identify lineations which may be water bearing. However, more work is needed to investigate just how useful these new datasets could be in improving borehole success. A research project to site, drill and test new boreholes on targets that were identified from the airborne geophysical data would start to show whether the airborne data could be used in this way.
    - A programme to drill and investigate in detail a series of targeted, deep, cored boreholes would provide direct information on detailed lithological changes, weathering styles and depths; and on the occurrence, distribution and nature of water bearing fractures and other groundwater targets.

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Appendix 1 Geophysical methods for locating groundwater in low permeability sedimentary rocks

Pergamon

Journal of African Earth Sciences, Vol. 32, No. 1, pp. 115–131, 2001

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0899-5362/01 $- see front matter

Geophysical methods for locating groundwater in low permeability sedimentary rocks: examples from southeast Nigeria

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ABSTRACT—Geophysical techniques have long been used to help locate rural groundwater supplies in crystalline basement environments. However, as local communities (particularly in sub-Saharan Africa) look to increasingly marginal aquifers for supply, many of the standard procedures for locating groundwater become inappropriate. Areas underlain by low permeability sediments (such as shales and siltstones) are particularly difficult for locating groundwater resources. In response to these difficulties, this study was commissioned to assess both the groundwater potential and methods for siting wells and boreholes in low permeability sediments in Oju, southeast Nigeria.

The Oju area suffers from an acute water shortage during a five-month dry season. Low permeability Cretaceous shales, siltstones and sandstones, with occasional intrusions of basic igneous rocks, underlie the area. Three main targets for groundwater have been identified: (i) sandy units within the shales; (ii) fracture zones in areas where the shales are lithified; and (iii) fractures associated with dolerite dykes and sills. The geophysical techniques used to identify these groundwater targets comprise frequency domain conductivity using the Geonics EM34, vertical electrical resistivity sounding (VES) and magnetic profiling (using a proton precession magnetometer). Three areas were studied in detail using a combination of geophysical surveys, exploratory drilling of the characteristic geophysical anomalies identified and test pumping.

In the interbedded shale and sandstone areas, sandstones were distinguished as low conductivity zones (<20 mmhos m^{-1}) using elecromagnetic and resistivity techniques. In the lithified mudstones, fracture zones were readily identified using electromagnetic methods as negative anomalies or smaller amplitude 'noisy' profiles. Dolerite intrusions within soft shales were identified by their lower electrical conductivity and distinct magnetic anomalies. © 2001 NERC. Published by Elsevier Science Ltd. All Rights Reserved.

RÉSUMÉ—Les méthodes géophysiques sont couramment utilisées pour permettre la localisation des ressources en eaux souterraines dans des contextes de socles cristallins. Toutefois, comme les collectivités locales (en particulier dans Afrique sub-saharienne) comptent pour leur approvisionnement, sur des aquifères de plus en plus mineurs, de nombreuses procédures conventionnelles de recherches ne sont plus appropriées. Les secteurs renfermant des sédiments à faible perméabilité (tels que des schistes argileux et des grès fins) sont particulièrement difficiles à traiter pour la localisation des eaux souterraines. Pour résoudre ces difficultés, cette étude a été commandée pour évaluer, à la fois, le potentiel hydraulique souterrain et aussi les méthodes pour positionner les puits et les forages dans les sédiments peu perméables à Oju, Sud-Est Nigéria.

La région de Oju subit une sévère pénurie en eau pendant les cinq mois de la saison sèche. Son sous sol est constitué de sédiments faiblement perméables, schistes argileux, grès fins et grès d'âge crétacé,

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avec des intrusions peu fréquentes de roches magmatiques basiques. Trois cibles principales concernant les eaux souterraines ont été identifiées: (i) des unités sableuses dans les schistes argileux; (ii) des zones fracturées dans les secteurs ou les schistes sont lithifiés; et (iii) les fractures associées aux filons doléritiques et aux sills. Les techniques géophysiques utilisées pour identifier ces aquifères souterrains incluent des analyses de conductivité en utilisant le Geonics EM34, les sondages verticaux de résistivité électrique (VES), et des profils magnétiques (utilisation d'un 'proton precession magnetometer'. Trois secteurs ont été étudiés en détail en combinant les reconnaissances géophysiques, le forage exploratoire des anomalies géophysiques charactéristiques et des tests de pompage.
Dans les interstatifications schisto-gréseuses, les grès se distinguent comme des zones de faibles conductivité (< 20 mmhos m^{-1}) avec des techniques de mesures électromagnétiques et de résistivité. Dans les argilites lithifiées, les secteurs fracturés sont aisément identifiés avec méthodes électromagnétiques comme des anomalies négatives ou des perturbations de plus faible amplitude du profil. Les intrusions de dolérites dans les schistes argileux plus tendres sont détectés par leur plus faible conductivité électrique et par des anomalies magnétiques marquées.

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INTRODUCTION

Surface geophysics can be an invaluable tool for siting wells and boreholes in crystalline basement aquifers throughout sub-Saharan Africa. (e.g. Beeson and Jones, 1988; Olayinka and Barker, 1990; McNeill, 1991; Barker *et al.*, 1992; Carruthers and Smith, 1992). In particular, frequency domain electromagnetic (EM) and direct current resistivity methods are being used regularly in many rural water supply projects (van Dongen and Woodhouse, 1994). Surveying with EM and resistivity equipment is generally straightforward. The equipment is simple to use and qualitative analysis, without the need for computers or a high level of expertise, is often sufficient for site selection purposes. Specific methods of interpreting the data to locate groundwater within crystalline basement areas have been developed and successfully used on many projects (Beeson and Jones, 1988; Hazell *et al.*, 1988, 1992).

Much of Africa is underlain by rocks other than crystalline basement; and in these areas, despite the contrasting geology, the same survey and interpretation techniques are often applied. Unfortunately, the very techniques that have proved so useful in crystalline basement areas can consistently identify inappropriate borehole or well sites when taken out of context. Frequently, this has caused water engineers to distrust geophysical methods or led them to conclude (incorrectly) that no groundwater exists in certain areas. Alternative (surface) water supplies, however, are expensive to exploit safely and require a high level of infrastructure and management to make them sustainable. Locating groundwater, therefore, remains the primary objective of most rural water supply projects, even where the geology is complex and the hydrogeology unfavourable.

As part of a joint project with WaterAid, which is funded by the UK Department for International Dvelopment (DFID), the British Geological Survey (BGS) has been investigating the potential for groundwater in a predominantly shale area in southeastern Nigeria (Figs 1 and 2). Prior to this study, little was known about the hydrogeology of the area or how to locate any groundwater that might exist. Even outwith the study area little is known about the ground-water potential of low permeability sediments; these are more often studied to assess their potential for storing hazardous waste (e.g. Lomenick and Kasprowicz, 1990; Neuzil, 1994) rather than their ability to meet the water supply requirements of rural populations. As part of the BGS investigations, the applicability of various geophysical techniques was tested for siting wells and boreholes, and some results of the study are detailed below. The authors believe these results are of particular interest because each of the characteristic geophysical signatures identified has been tested by core drilling.

BACKGROUND

General

Oju is a remote part of southeastern Nigeria that experiences severe water shortage during the annual

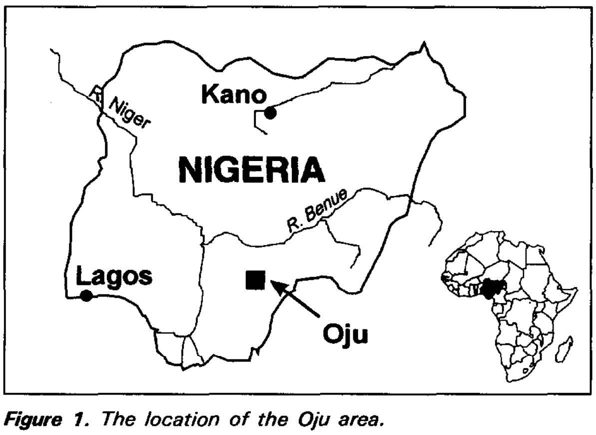

Figure 1. The location of the Oju area.

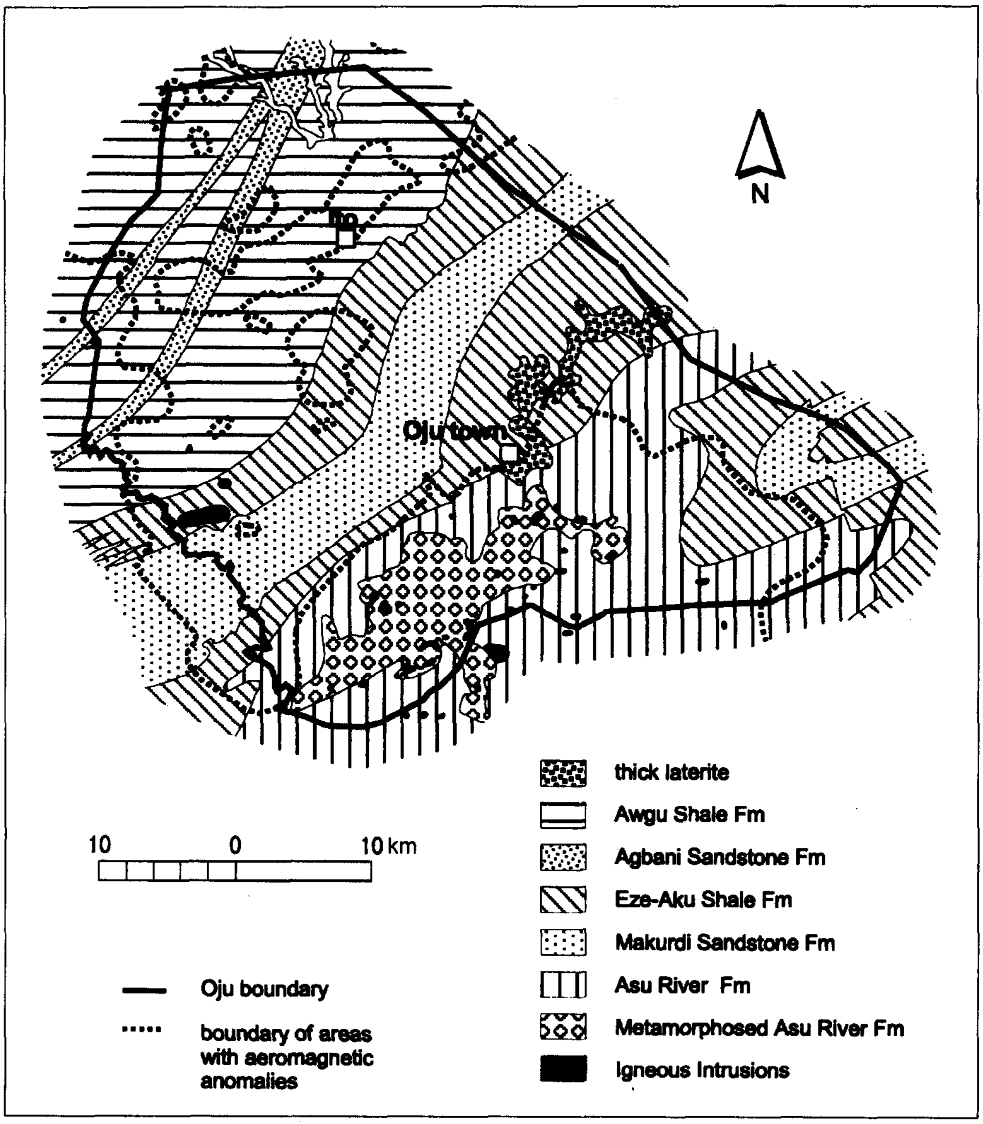

Figure 2. *Simplified geological map of Oju. Fm: Formation.*

dry season. Mean annual rainfall for the years 1988–1993 was 1600 mm (Davies and MacDonald, 1999). The rainy season generally lasts from April to October, leaving five months with very little rainfall. During the dry season, unprotected ponds, seepages and hollows are the primary sources of domestic water. These sources become less reliable towards the end of the dry season and many fail altogether. Consequently, women and children have to walk long distances (often >10 km) to get limited supplies of generally poor quality water. Inevitably, much of the population of Oju (~300,000) is badly affected by a variety of water-related illnesses, of which guinea worm, dysentery and malaria are endemic; outbreaks of cholera and typhoid are also common (Morgan, 1996).

The Oju area is generally flat, with a few hills in the south. Vegetation comprises deciduous and semi-deciduous woodland with tall grasses (savannah woodland). Much of the tree cover has been cleared for farmland. However, dense vegetation still exists in some places such as along river valleys and at sacred sites that have been left as virgin woodland. Within the villages, large trees (usually mango or fucus) have been left to provide shade.

Geology

The Oju area is located within the Benue Trough, a failed rift that formed during the initial splitting of the African and South American continents which formed the Atlantic Ocean. Over 800 km long and striking northeast, the Benue Trough is infilled with 3–6 km of folded marine and fluviatile sediments of Cretaceous age (Benkhelil, 1989). The Oju area is located towards the eastern edge of the lower

Table 1. Simplified stratigraphical sequence of the Oju area

Age	Geological Unit	Comments and Description
Maastrichtian		Post Maastrichtian northwest-trending folding and faulting
Campanian		
Santonian		Northeast-trending elongate folds and faulting
Coniacian	Awgu Shales Agbani Sandstone	Soft carbonaceous shale with shelly limestone and siltstone Fine- to medium-grained sandstone with some Siltstone
Upper Turonian Lower Turonian	Makurdi Sandstone Eze-Aku Shale	Fine- to coarse-grained sandstone with silt-stones Shale and siltstone with thin limestone and sandstone horizons
Cenomanian		Hiatus
Upper Albian Lower Albian	Metamorphosed Asu River Group Asu River Group	Hard splintery shales with meta-sandstones interbedded with pyroclastic and igneous intrusive rocks Moderately hard, lithified shale with occasional limestone and sandstone
Precambrian basement		North-south-trending faulting

section of the trough, where the majority of the sediments were deposited in a shallow marine to deltaic environment. The stratigraphy of the rocks present is shown in Table 1.

Figure 2 shows the outcrop of the main geological units in Oju. According to Ojoh (1990), the oldest sedi-ments present belong to the Asu River Group that crops out in the south. There are two distinct parts to the Asu River Group:

i) the metamorphosed Asu River Group, which comprises hard splintery shales, sandstones and limestones with interbedded pyroclastic and intrusive igneous rocks; and

ii) the non-metamorphosed Asu River Group sediments, composed of hard deep marine shales, sandstones and limestones deposited in a tectonically active environment. These sediments show convoluted bedding and have been lithified by the effects of burial.

The Eze-Aku Formation overlies the Asu River Group to the north. This formation is composed of mudstones with occasional limestone, siltstone and sandstone; the mudstone is generally lithified but becomes softer towards the north. Significant sandstone horizons are present within the Eze-Aku Formation, the most extensive is known as the Makurdi Sandstone. This comprises hard well-cemented fine- to medium-grained sandstones, interbedded with varying thicknesses of soft shales and occasional limestones. In the north of the area are present the youngest rocks, the Awgu Formation. These comprise very soft shallow marine carbonaceous mudstones with occasional muddy limestones and siltstones and a narrow band of sandstone known as the Agbani Sandstone, which is generally fine- to medium-grained and moderately cemented.

The structure is dominated by the northeast-trending Benue Trough and associated northeast-trending elongate folds (Cratchley and Jones, 1965). Analyses of aerial photography and landsat imagery confirm the dominant trend with faulting normal or sub-parallel to this. A secondary northern trend is associated with activity along earlier faulting in the underlying Precambrian basement. Pre-Turonian tectonism caused intensive fracturing and folding of the Asu River Group. The later Santonian and Maastrichtian tectonism caused less intensive fracturing and folding of post-Asu River Group sediments in the Oju area.

Dolerite intrusions transect the area. These igneous intrusions are associated with both pre- and post-Turonian tectonic episodes. Although few intrusions can be observed at outcrop, their presence throughout the north of the area can be inferred from the aeromagnetic map (see Fig. 2).

Prolonged exposure of the Cretaceous sediments to a sub-tropical climate has altered the near surface layers to a complex fersiallitic soil and associated weathered saprolite (Fookes, 1997). The upper zone is generally 1–5 m thick and comprises a 1–3 m zone of Fe and Mn nodules, sometimes consolidated into a ferricrete. This typically overlies several metres of smectitic or illitic clays with subordinate kaolinite.

Hydrogeology

The soil and rock types present in Oju, combined with the distinct wet and dry seasons, produce a characteristic hydrogeology. In general, the top few metres of the fersiallitic soil are highly permeable, several orders of magnitude greater than the underlying rocks. During the wet season, most of the rainfall flows through the fersiallitic soils to the rivers. This results in flash flooding and ensures that all wells and boreholes are full of water. As the rains end, the upper soil zones dry out, rivers generally stop flowing and wells and boreholes dry up rapidly. Even the deeper wells and boreholes often fail as the dry season progresses, since most of the rocks beneath the fersiallitic soils have both little storage capacity and negligible permeability. The gravels in the bottom of rivers, which are often a good dry-season source of water in other parts of Africa (e.g. Herbert *et al.*, 1997), contain little groundwater in Oju. This is due to the local geology and hydrology, which allow only thin and intermittent river gravels to develop.

Detailed investigations of the hydrogeology have shown that, although limited, groundwater does exist in Oju in three different types of environments. These environments can be difficult to locate but at least one usually occurs within walking distance of most villages. The three main targets are described below and shown schematically in Figs 3 and 4.

Fracture zones within the Asu River Group and older Eze-Aku Shales

The Asu River Group and metamorphosed Asu River Group both comprise hard splintery shales. Fractures within these rocks are fairly common and generally remain open regardless of their orientation. Much horizontal fracturing is associated with the base of the weathered zone in a similar fashion to that seen in the crystalline basement (Acworth, 1987; Wright, 1992). These fractures are probably caused by unloading and are enhanced by dissolution. The Eze-Aku Shales, although considerably softer, also contain open fractures. These tend to be more widely spaced than in the Asu River Group and are associated with faults. Test pumping of boreholes located in fracture zones indicate transmissivity values in the range 0.5–5.0 $m^2 d^{-1}$.

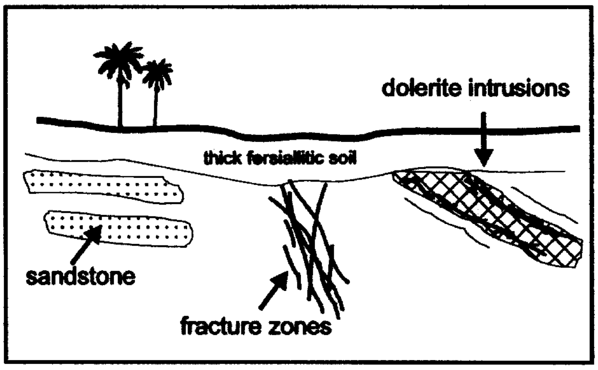

Figure 3. Schematic diagram of the three main groundwater targets in the shales of Oju: sandstone layers, fracture zones within the harder shales and dolerite intrusions. .

Sandstone and limestone layers within the younger Eze-Aku Shales, Makurdi Sandstone and Agbani Sandstone

Sandstone is present within the younger Eze-Aku Shales, Makurdi Sandstone and Agbani Sandstone Formations, generally inter-layered with thick shales. The thick soil covering and generally flat topography make it difficult to identify these sandstone units by field observation alone. The sandstones are fine- to medium-grained and can be highly consolidated. Their permeability is generally insufficient for successful boreholes, but the sandstones can support hand dug wells where they are constructed deep enough to provide a large seepage area. Transmissivity estimates from boreholes drilled into the sandstone are generally <0.3 $m^2 d^{-1}$. Occasional thin limestones (<0.5 m), although rare, provide sufficient water for boreholes with hand pumps.

Dolerite intrusions within the Awgu Shale

Throughout the north of the area, mainly where underlain by Awgu Shale, there is negligible potential for groundwater from the sediments. This formation is too soft for fractures to remain open, and sandstones or limestones are uncommon. The main targets for groundwater in this area are dolerite sills and dykes, and the baked shale contact zone. The edge of the dolerite is generally highly fractured and contains many mesolite crystals. Transmissivity values in excess of 30 $m^2 d^{-1}$ have been calculated from boreholes sited on dolerite sills.

METHODS OF INVESTIGATION

General

Three different geophysical techniques were chosen to identify groundwater targets in the Oju area:

i) frequency domain conductivity using the Geonics EM34 instrument;

ii) vertical electrical resistivity sounding (VES); and

iii) magnetic profiling (using a proton precession magnetometer).

Both electrical conductivity and resistivity are well-established techniques for siting wells/boreholes in crystalline basement areas. Their operation is well

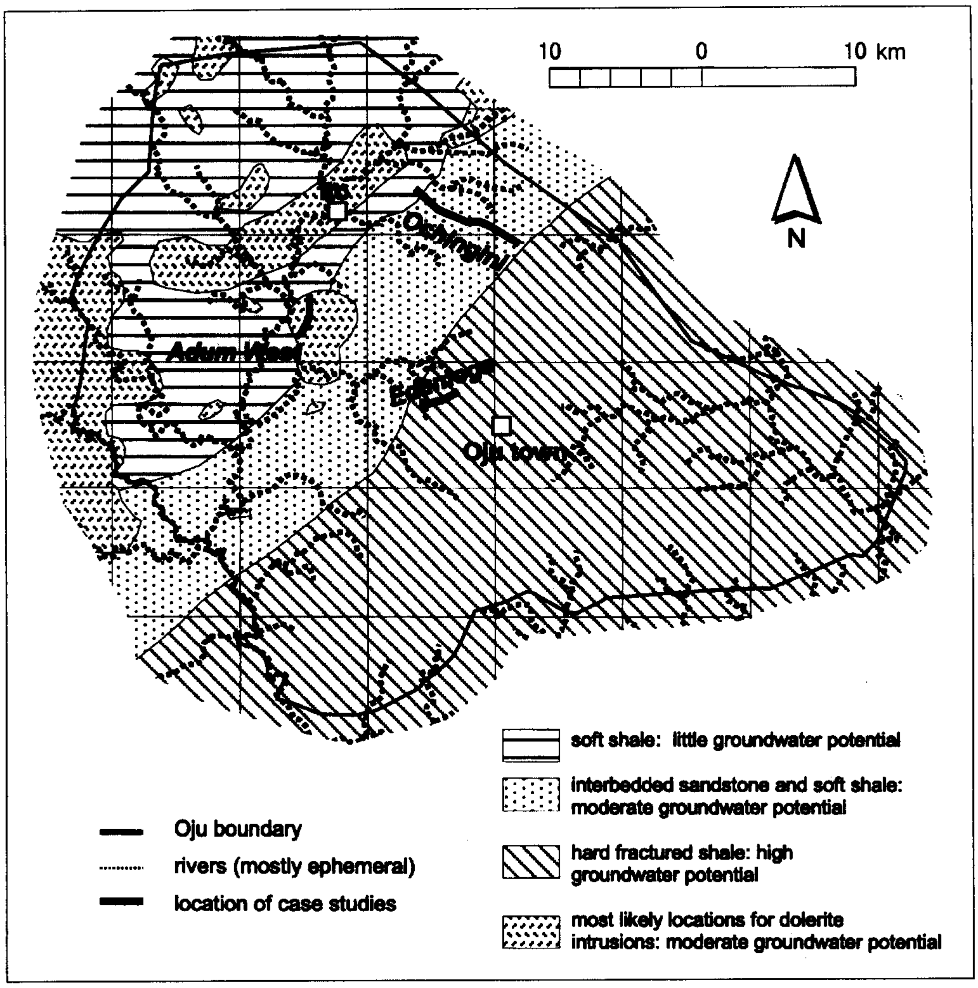

Figure 4. *Simplified hydrogeological map of Oju (adapted from MacDonald and Davies, 1998). The locations of the three 1case studies discussed in this paper are shown.*

understood by most hydrogeologists working in sub-Saharan Africa, and equipment is generally widely available. Magnetic techniques are generally less applicable to hydrogeological investigations. However, since dolerite intrusions are such an important hydrogeological target in northern Oju, it was thought appropriate to test the method there.

Electrical conductivity (EM34)

The EM34 conductivity meter comprises a transmitter and receiver coil, and operating consoles. It is a two person portable device that directly measures terrain conductivity. Three standard coil separations (10, 20 and 40 m) are used with three corresponding transmitter frequencies (6400, 1600 and 400 Hz). These frequencies are sufficiently low that the electrical skin depth in the ground is always greater than the intercoil spacing. In this condition, virtually all the response from the ground is in the out-of-phase component and is directly proportional to ground conductivity at the lower end of the range. The equipment may be operated with both coils either vertical or horizontal; the selected orientation gives significantly different response with depth. The effective investigation depths for the two modes are ~0.75 and 1.5 times the intercoil spacing, respectively (McNeill, 1989).

The EM34 measures the bulk conductivity of the ground in units of millimhos per metre (mmhos m^{-1}). Conductivity (s) is the reciprocal of resistivity (ρ) (measured in ohm metres); the units being linked by the relationship $s \times \rho = 1000$. Over a sub-horizontally layered earth, the response will represent a weighted mean (related to depth) of the formations within the range of investigation. The three main factors controlling the electrical conductivity of the ground are the porosity, the presence and nature of pore fluid, and the clay content.

The EM34 can also be used to identify vertical conductors, for example saturated fracture zones. When the coils are oriented horizontally, there is maximum coupling between the primary electric field and the conductor, which produces a characteristic negative anomaly flanked by positive shoulders (Fig. 5). In this situation, the observed values do not indicate ground conductivity as such, but the form of the anomaly can be analysed to estimate the nature and dip of the putative fracture zone.

In the present study, EM34 measurements were made with the coils in both vertical and horizontal orientations at 20 m separation. The vertical coil readings reflect shallow conductivity variations, while the horizontal coil readings respond to deeper layers and can also indicate substantial conductive sub-vertical fracture zones. Measurements were taken every 20 m, reducing to 10 m or 5 m for increased detail over significant anomalies.

Electrical resistivity

The resistivity technique is a long established geophysical method used to site wells and boreholes in Africa. There are two main survey modes: profiling and depth sounding. Resistivity profiling is a relatively slow process and has largely been superseded by EM conductivity traversing for detecting lateral variations. Resistivity depth sounding (VES) involves expanding the current electrodes at logarithmic intervals, thereby exploring to greater depths. VES assumes a 1-D section and can distinguish between various horizontal geo-electrical layers. Methods combining both profiling and depth sounding are now available and can give good insight into the geology. However, such surveys are complex and require specialist equipment and interpretation. For this reason, they are not generally appropriate for small rural water supply projects. The depth soundings in the present study were used to assist with the interpretation of the EM34 anomalies. The Offset Wenner electrode configuration was used (Barker, 1981); this array minimises the effect of shallow inhomogeneities and allows surveys to be conducted rapidly by one or two people.

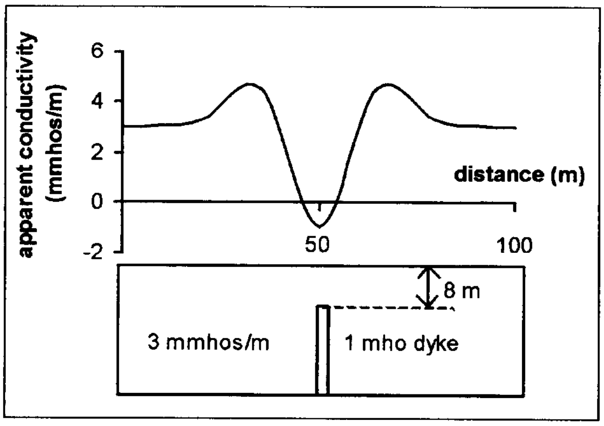

Figure 5. Typical EM34 anomaly (horizontal coils) over a thin vertical conductor (from McNeill, 1980).

High contact resistance between the electrodes and the ground surface is one of the main difficulties in hot arid climates. The electrodes must be hammered in securely and water added to improve contact with the ground in order to pass sufficient current for the signal to be measured reliably.

Magnetic profiling

Magnetic methods in geophysical exploration involve measuring the local strength of the Earth's magnetic field. Variations in the field strength can be complex and highly localised, reflecting contrasts in the magnetic properties of rocks and their geometry. The most important magnetic property is susceptibility, which is a measure of how strongly magnetic a rock will become in the inducing Earth's field. The susceptibility of rocks is determined mainly by the amount of ferrimagnetic minerals present. In general, sedimentary rocks have low magnetic susceptibility, while basic igneous rocks are characterised by high susceptibilities. In many cases, the magnetisation of rocks depends on the present magnetic field. However, residual magnetisation of rocks can also be important. Residual magnetisation results when a magnetic material is cooled below the Curie point and, therefore, is often present in igneous rocks (Telford *et al.*, 1990). The direction of the Earth's magnetic field at the time of cooling is locked into the rock, which contributes to the overall magnetisation recorded in surveys today. Due both to the residual magnetisation and the present-day magnetic susceptibility of the dolerite intrusions in Oju, they are easily distinguished from the poorly magnetic sediments.

The instrument used in this study is a proton precession magnetometer (PPM). The operation and principles of this equipment are explained by Breiner (1973) and Telford *et al.* (1990). The main benefits of the PPM are its portability, ease and speed of operation. Surveying can be carried out quickly and requires only one person. Measurements are accurate to about 0.1 nT, which is more than adequate for groundwater surveys of large anomalies such as the dolerite dykes. The sensor is carried on a long pole to keep it away from sources of cultural noise and rubble on the ground surface and remote from the operator and console.

In detailed magnetic surveys, where the results are to be contoured, it is necessary to correct the observed data to account for the diurnal changes in the Earth's magnetic field. In the present study, this was not necessary as the short wavelength anomalies sought were readily distinguishable from the effects of time variation.

Generally, the magnetic and EM34 surveys were undertaken concurrently, with the magnetometer lagging about 100 m behind the EM34 to avoid mutual interference. Magnetometer readings were taken every 10 m with infill to 1 m over anomalous features.

CASE HISTORIES

Examples have been chosen to illustrate the use of geophysics in identifying the three different groundwater targets that exist in Oju. In each of the case studies, an initial EM34 traverse (several kilometres long) was carried out, followed by resistivity sounding and magnetic profiling, where appropriate. After analysis, various sites were identified for drilling. Boreholes were drilled at favourable and unfavourable sites to provide both calibration data and a better understanding of the relation between geophysical response and the hydrogeology. Rock chip samples were logged and analysed and core samples taken from the last few metres of every borehole. Various pumping tests were carried out on any boreholes that contained water; water samples were also taken from successful boreholes.

Ochingini: locating sandstones

The village of Ochingini lies to the northeast of Oju (Fig. 4). Several shallow hand-dug wells exist here, none of which are perennial. The wells tend to be <5 m deep and frequently collapse below about 2 m due to swelling clays. Data were collected along an 8 km traverse passing through the village and perpendicular to the general strike of the geology (Davies and MacDonald, 1999). The geology map indicates that this traverse should cross both the Eze-Aku Shale and the Makurdi Sandstone.

The Ochingini EM34 profiles (Fig. 6) indicate three contrasting conductivity environments characterised by background values of:

i) about 10 mmhos m^{-1} (e.g. between 3000 m and 5000 m);

ii) about 30 mmhos m^{-1} (e.g. between 500 m and 1200 m); and

iii) vertical coil values approaching 100 mmhos m^{-1}, approximately double the horizontal coil values (e.g. between −500 m and −2000 m).

In environments (i) and (ii), the horizontal and vertical coil values are closely matched, suggesting a uniform conductivity distribution with depth; whereas in type (iii), the high conductivity causes marked differences in coil values. The strong negative-trending horizontal coil values centred at -2200 m (which were even stronger when repeated at 40 m intercoil separations) may indicate a series of vertical conductive features or may be associated with very low conductivity at depth.

Figure 7 shows the lithological logs for the nine boreholes drilled along the traverse. The area comprises inter-layered sandstone, mudstone and limestone. Overlying all lithologies is a 1–2 m thick fersiallitic soil, usually comprising Fe and Mn pisoliths (nodules) bounded by red clay. Below the soil layer, there is generally a few metres of clay; the clay layer tends to be thicker where the bedrock comprises mainly of mudstone. Weathering extends to below 10 m. Weathered mudstone comprises very soft clayey material with occasional remnants of bedding features from the original mudstone; weathered sandstone is primarily discoloured sandstone with occasional kaolinite clay.

The lithological logs confirm that the lower conductivity values (10 mmhos m^{-1}) reflect shallow sub-cropping sandstones (boreholes BGS7, BGS9, BGS11, BGS12) while the presence of shallow, thicker clays and/or weathered mudstones (boreholes BGS8 and BGS10) is indicated by intermediate conductivity values (30 mmhos m^{-1}). The highest vertical coil values encountered (approaching 100 mmhos m^{-1}) reflect a thick sequence of weathered mudstone (BGS6). Preliminary clay analysis suggests that these very high conductivity readings probably reflect a greater proportion of illite/smectite clay (Kemp *et al.*, 1998).

The broad negative anomaly at -2200 m was tested by borehole BGS5. Drilling did not identify any source for very low conductivity at depth, which could explain the negative horizontal coil readings. However, there was a high proportion of vein calcite encountered in the borehole that suggests fracturing within the mudstone, although the borehole was dry. Vertical fractures may be filled with fault gouge and clay, which provides significant changes in the electrical conductivity profile, causing complex electromagnetic coupling that may produce negative anomalies. Even if this interpretation is correct and the negative measurements are associated with fracturing, it appears that the mudstones here (Upper Eze-Aku) are too soft to support open water bearing fractures and these conductive zones are not suitable targets for groundwater. An interpreted cross-section based on the conductivity profiles and borehole control is shown in Fig. 8.

Test pumping was carried out on six of the boreholes (BGS4, BGS6, BGS7, BGS8, BGS10, BGS12). Each of the sandstone boreholes has a sufficiently high yield to support a large diameter well. Well construction would require pneumatic hammers to get through the hard sandstone layers; but, in the long term, such wells are likely to be more sustainable than boreholes. Wells are much easier to maintain than boreholes and are not subject to the ingress of fine sands, which can quickly put boreholes out of action. High yields were also found in the limestone layers proved in

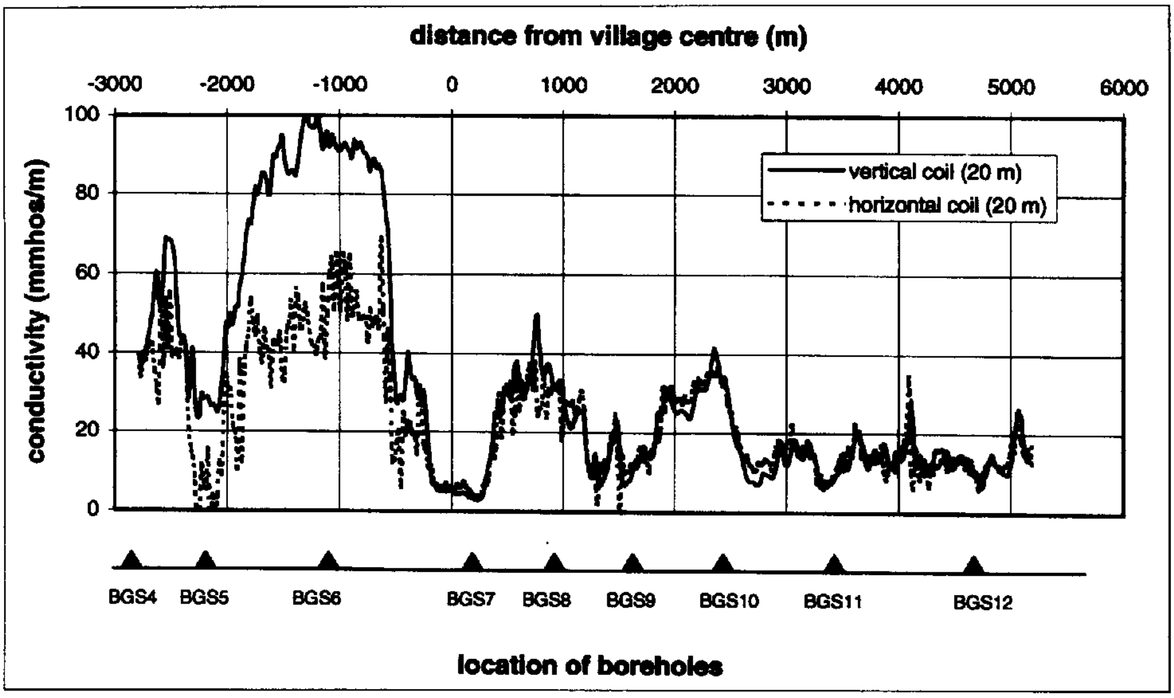

Figure 6. EM34 traverse at Ochingini. The locations of the test boreholes are also shown.

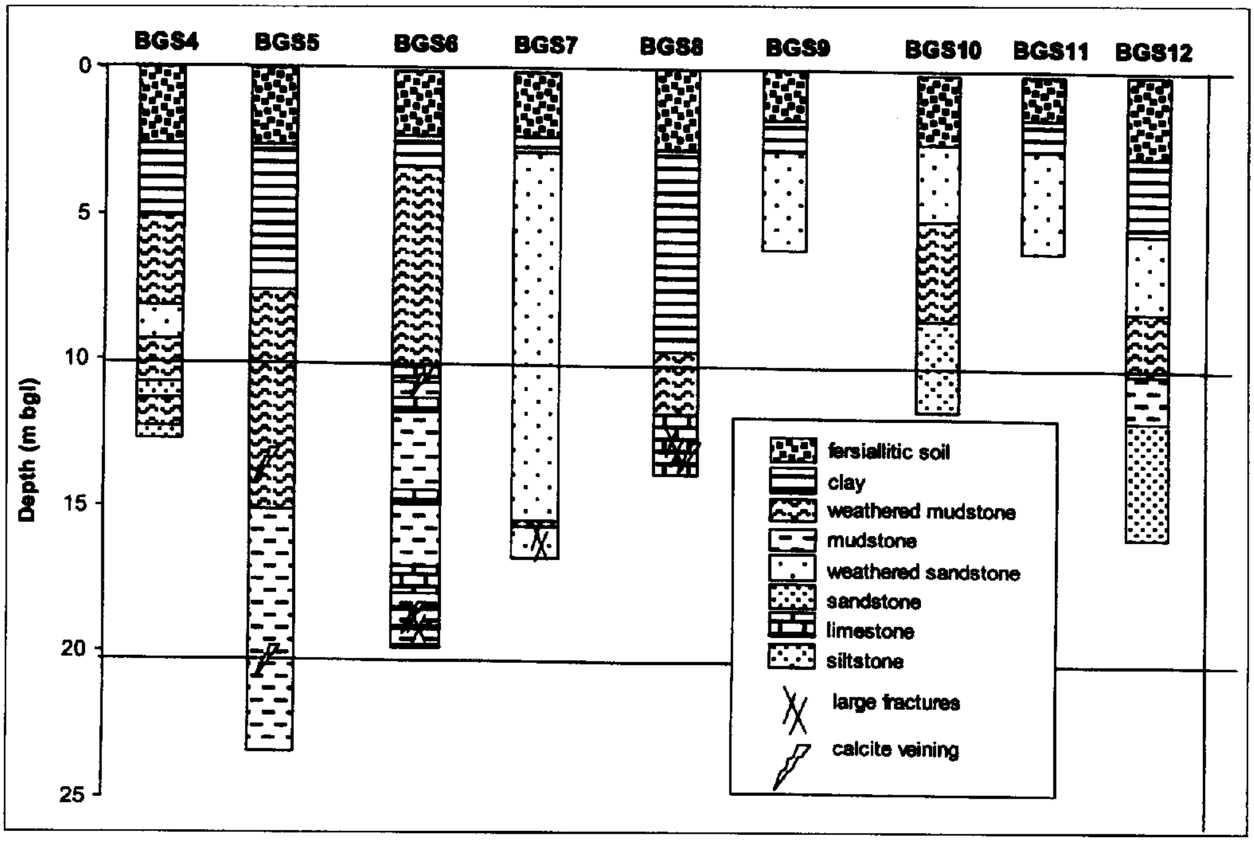

Figure 7. Ochingini borehole logs.

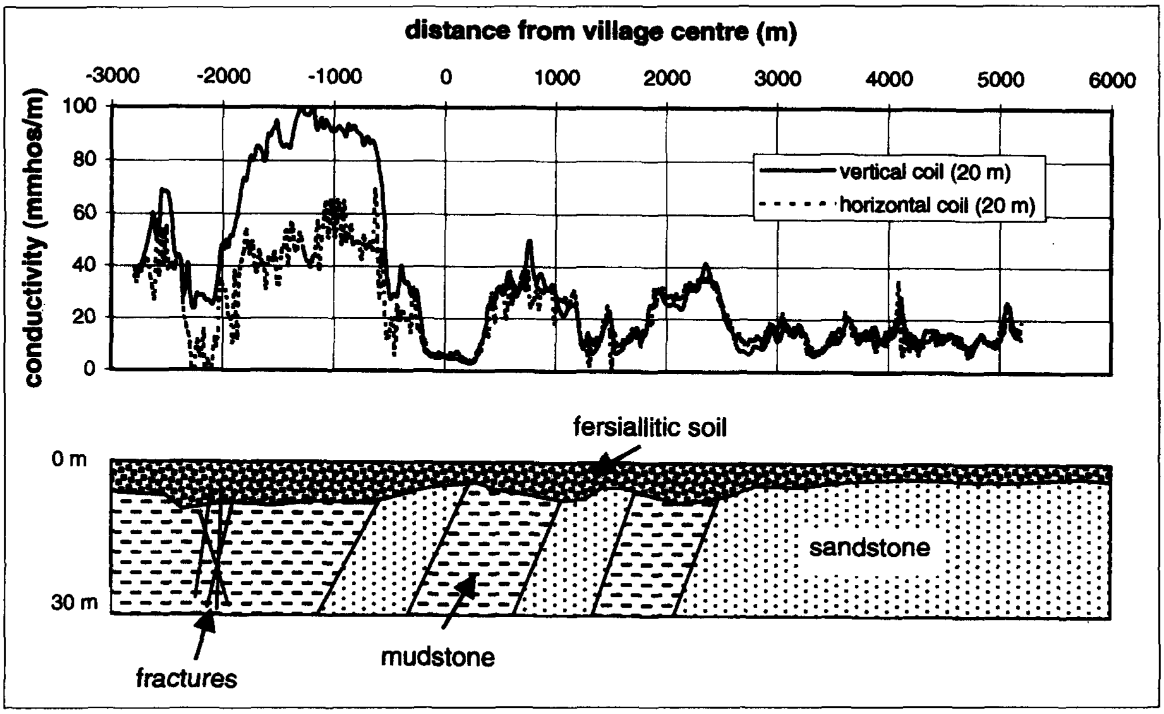

Figure 8. Hydrogeological interpretation for Ochingini.

boreholes BGS6 and BGS8. Unfortunately, these layers are too thin and flat lying to be identified using the geophysical methods commonly available; therefore, the sandstones remain the best targets for groundwater in this area.

Fracture zones within the harder mudstones: Edumoga
Edumoga Village lies in the centre of Oju and is underlain by mudstones of the Eze-Aku Shale Formation (Fig. 4). There are several wells in the village, typically about 5 m deep, which also tend to collapse below 3 m due to swelling clays. No wells last throughout the dry season, and soon after the rains have stopped water has to be taken from small dugouts in the nearby ephemeral river. As the dry season proceeds, the dugouts are made progressively further downstream. Approximately 4.5 km of EM34 traverses and four resistivity soundings were made in and around Edumoga Village (Davies and MacDonald, 1999).

The main Edumoga EM34 traverse measured conductivities typically in the range of 30–40 mmhos m^{-1} (Fig. 9). Generally, horizontal coil values exceed those of the vertical coil, implying increasing conductivity with depth. In addition, two striking negative-trending anomalies where recorded in both horizontal and vertical coil orientation with values approach 15 mmhos m^{-1}. Five sites were identified for test drilling (Fig. 9). Boreholes BGS16 and BGS17 were located on the two negative anomalies, another two (BGS14, BGS18) were sited where there were no significant anomalies and the last (BGS15) was located where the EM34 profiles, especially the horizontal coil values, display particularly rapid excursions.

The lithological logs of these five boreholes, drilled and tested at Edumoga, show a similar geological arrangement along the traverse (Fig. 10). The soil comprises 2–3 m of nodular permeable ferricrete, which overlies 1–4 m of clay. The bedrock comprises moderately soft mudstone with interlayered siltstones, fine sandstone and muddy limestone. The mudstone is discoloured and clayey, typically down to about 10 m. However, despite the similar lithologies and extent of weathering, two of the boreholes were dry, while the other three gave sufficient yields for a hand pump. Closer examination of the cores and rock chip samples provides the reason. The successful boreholes (BGS15, BGS16, BGS17) all contained evidence of fracturing below the weathered zone in the more competent mudstone. Each of these boreholes contained significant quantities of vein calcite, which is often a good indicator of the presence of faults. Slickensides were also observed in the cores of both BGS15 and BGS17, while core samples from BGS17 established that the borehole had penetrated a fault breccia. Very limited evidence of fracturing was found in the two dry boreholes. An interpretation of the EM34 traverse is shown in Fig. 11.

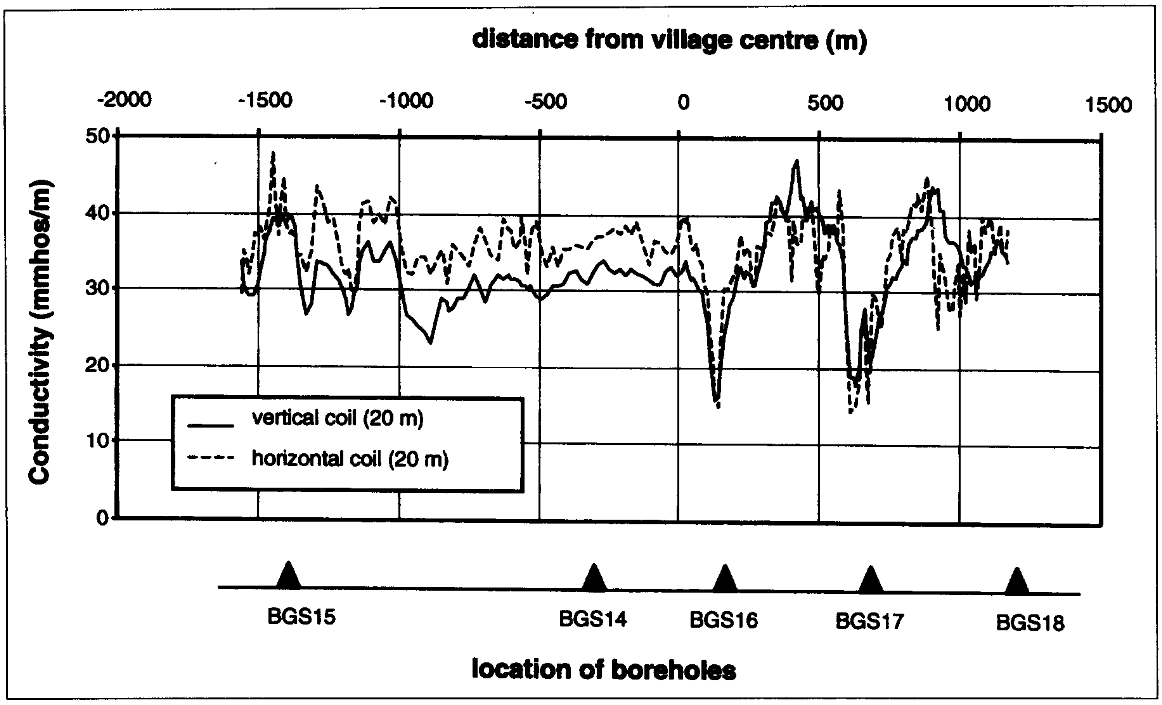

Figure 9. EM34 traverse at Edumoga and the locations of the five test boreholes.

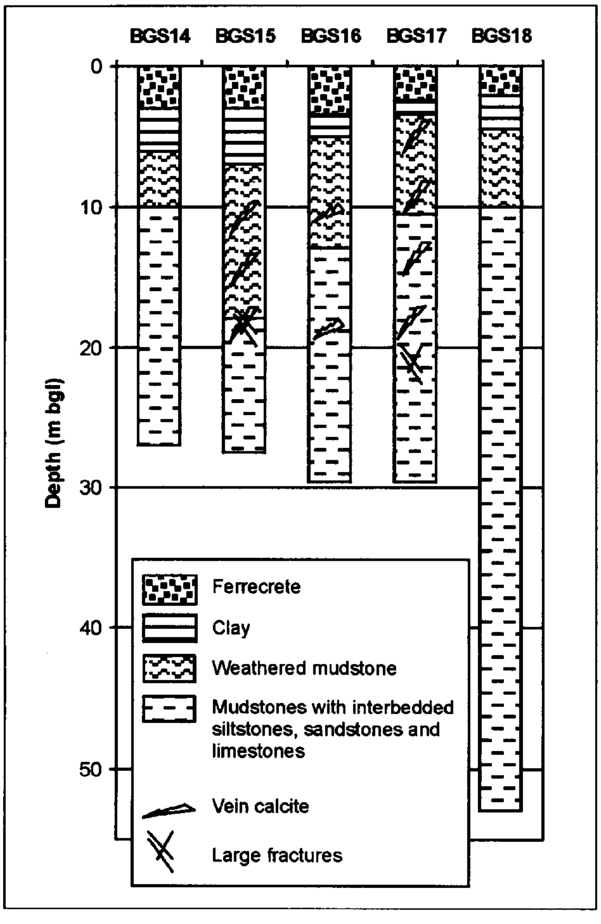

Figure 10. Edumoga borehole logs.

Thus, it appears that productive fracture zones in the Edumoga area may be characterised on EM34 profiles by either sharp excursions of horizontal coil values (BGS15) or by well-defined negative-trending horizontal and vertical coil values of similar amplitude (BGS16, BGS17). This latter type of anomaly differs from the classic EM34 response to narrow vertical con-ductors in which the vertical coil readings are little affected (reflecting the minimal electrical coupling with the target in this mode), while the horizontal coil values show a well-defined trough, occasionally with minor positive shoulders (Fig. 5). However, real geological environments produce much more complex geology than single vertical conductors. As computer modelling of electromagnetic coupling becomes more powerful, increasingly realistic scenarios will be able to be modelled. An alternative explanation of the local conductivity lows in the Edumoga profile, supported by their considerable width compared to the coil separation, is that they reflect discrete zones of reduced conductivity. This, in turn, may imply the presence of harder mudstone or an increase in the interbedded sandstone and limestone. However, subsequent geophysical information does not support this possibility. Resistivity soundings were made at four of the borehole sites (including BGS16 and BGS17) and these indicate a consistent three-layer geoelectrical section: high resistivity material (soil) overlying a few metres of low resistivity clays (10–20 ohm m) with bottom layer resistivities in the range of 20–33

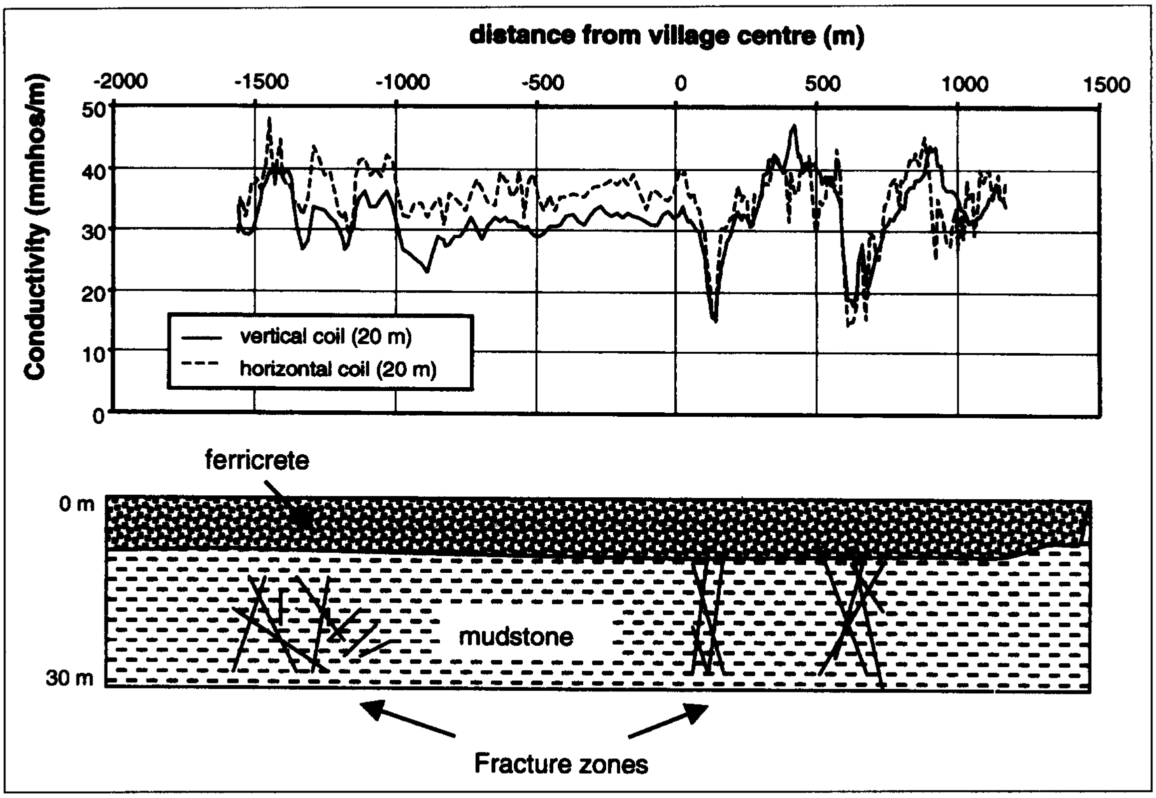

Figure 11. Hydrogeological interpretation for Edumoga.

ohm m (50–30 mmhos m^{-1}). Over such a geo-electrical section, the anticipated EM34 horizontal and vertical coil readings would exceed 30 mmhos m^{-1}. Thus, it appears that the two well-defined negative EM34 responses reflect 3-D electromagnetic coupling rather than a change in 1-D electrical conductivity profile.

The rapidly fluctuating horizontal coil values, that appear to reflect faulting at the site of BGS15, probably reflect variations in the depth of weathering and the presence of sub-vertical fractures. McNeill (1989) reports similar high frequency fluctuations of horizontal coil data and ascribes them to the combined effect from multiple conductive fractures.

In summary, the EM34 proved useful at identifying water-bearing fracture zones in the lithified mudstones, siltstones and limestones at Edumoga. These fracture zones were identified as either pronounced negative-trending anomalies or a rapidly fluctuating response in the horizontal coils. Where conductivity values were relatively consistent laterally, the mudstone was unfractured and contained no groundwater. Resistivity soundings in this area clearly identified the nature of the lithological depth profile (ferricrete, clay, mudstone).

Adum West: finding dolerite intrusions

Adum West is a large dispersed village in a remote part of Oju located on the outcrop of the Awgu Shale (Fig. 4), which has very little potential for groundwater. There is only one well in the village, which is shallow and dries up soon after the rains stop. During the dry season, the only water sources are stagnant pools and dugouts in the river Obi, 2 km away. The aeromagnetic map revealed several magnetic anomalies near the village (Figs 3 and 4). However, the topography is very flat, and there is no indication of dykes on satellite imagery or aerial photographs. A 3 km EM34 and magnetic traverse was made through the centre of the village to try to identify dolerite intrusions (Davies and MacDonald, 1999).

The resulting data (Fig. 12) reveal two characteristic geological environments:

i) relatively conductive country rocks (the soft Awgu Shales) containing no significant shallow magnetic material, extending between 0 and ~1200 m; and

ii) much less conductive background, heavily intruded by magnetic material as shallow sills with occasional dyke-like bodies, extending between 1200 and 3000 m.

Three boreholes were drilled on this traverse: two were sited to test the magnetic features (BGS33, BGS35) and the third to test the more conductive lithologies (BGS34). Figure 13 shows the lithological logs for these boreholes. BGS33 and BGS35 proved shallow dolerite (at depths of 11 and 4 m, respectively), while BGS34 penetrated soft mudstone before intersecting dolerite from about 32 m to the total depth of 39 m.

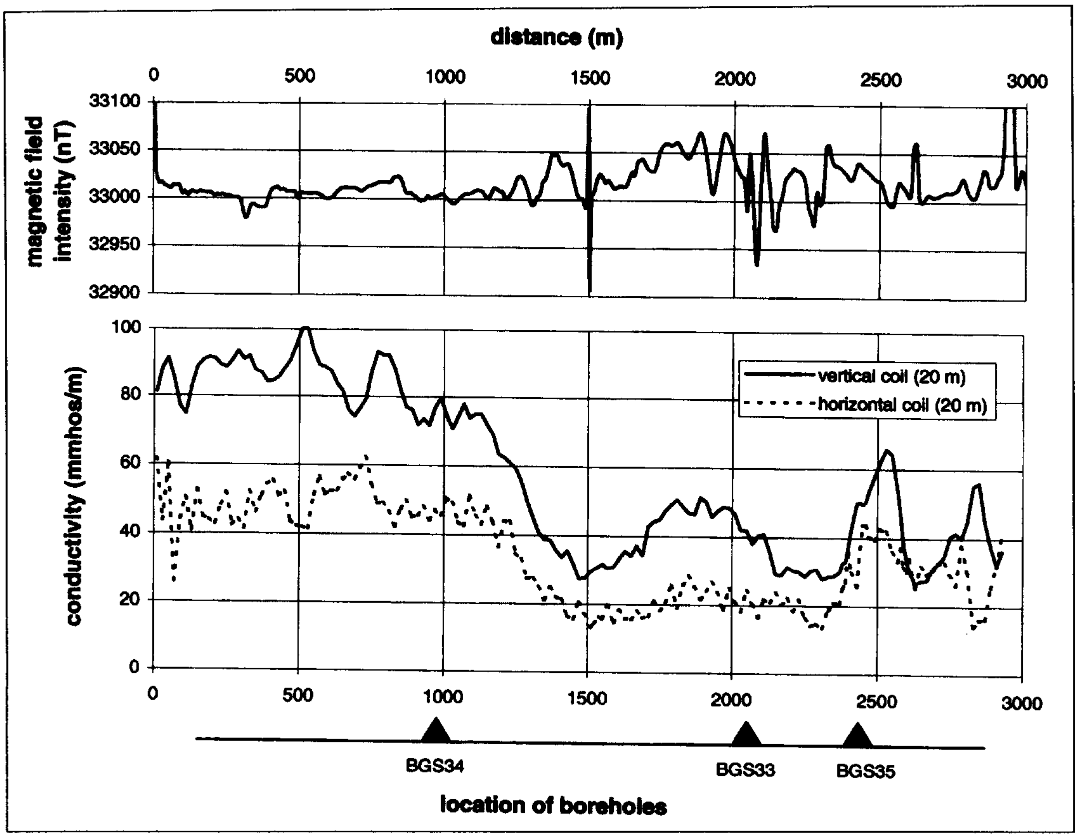

Figure 12. EM34 and magnetic profiles for Adum West and the locations of the three test boreholes.

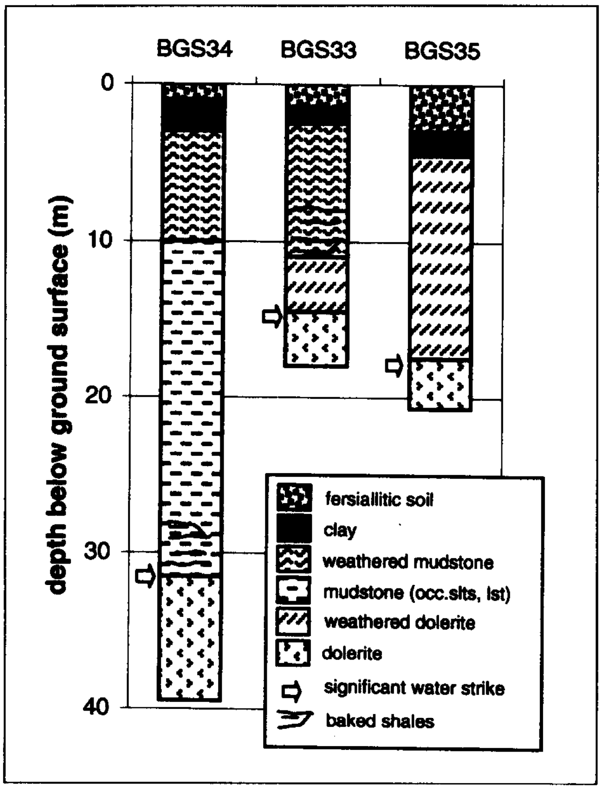

Figure 13. Adum West borehole logs.

Abundant groundwater was found in all three boreholes, with the highest yield coming from BGS33. Pumping tests gave estimates of transmissivity greater than 25 $m^2 d^{-1}$ for BGS33 and BG35 and of about 5 $m^2 d^{-1}$ for the deeper borehole, BGS34. These aquifer properties exceed the requirement for a hand pump. In fact, if necessary, these boreholes could be used as a well field to supply a much larger population. Significantly, the majority of the groundwater was found within the dolerite, rather than in the surrounding baked shales. The dolerite was highly fractured and had frequent zeolite growth (mainly mesolite) within the void spaces. Water quality from the boreholes was good and well within the World Health Organisation (WHO) recommended limits for drinking water.

Modelling of the magnetic data indicate a broad sill underlying the area, dipping to the south. To the north (from 1300–2600 m), the sill is heavily intruded with dykes. The dykes and sill have a susceptibility of 0.01–0.02 SI and exhibit remnant magnetisation (Fig. 14). The uniform reduction in conductivity associated with the noisy magnetic profile also favours the presence of extensive shallow flat-lying intrusions. From the limited drilling, it appears that the main groundwater target in the area is fractures affecting the upper surface of sills, where weathering is not too

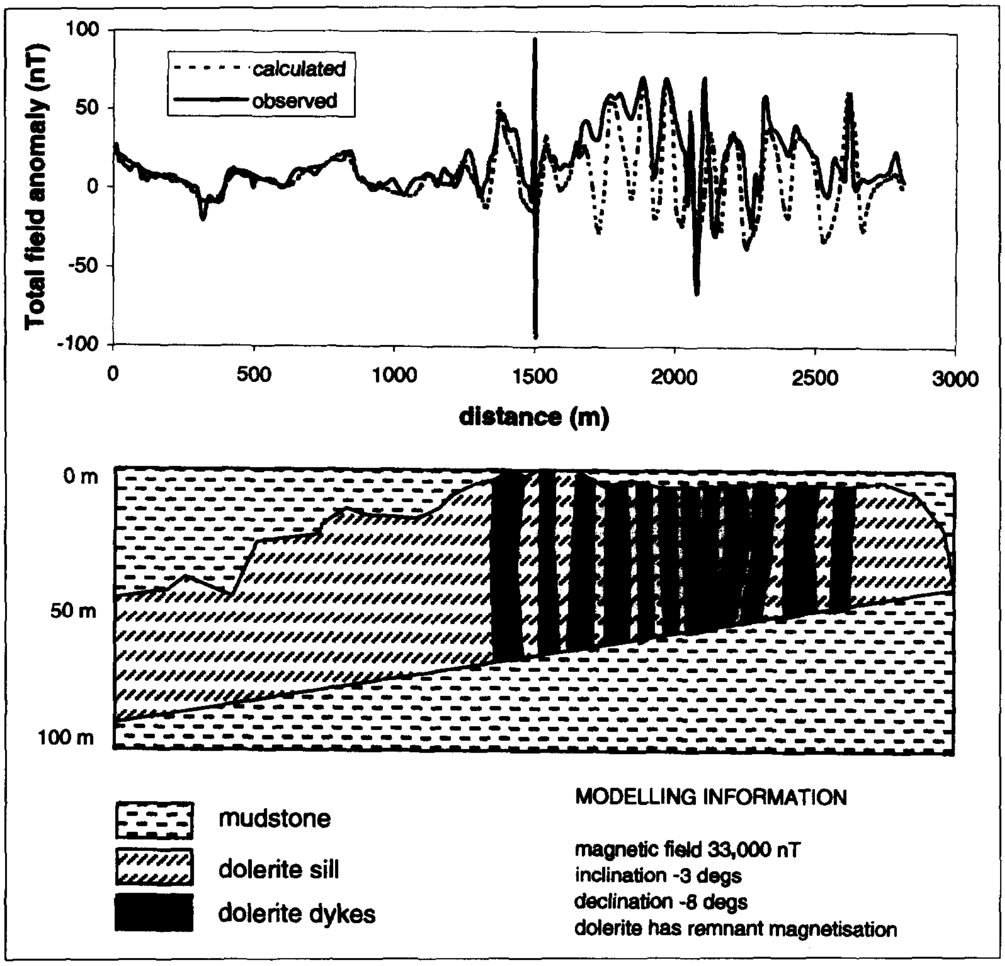

Figure 14. Modelled interpretation of magnetic anomalies at Adum West.

far advanced. Boreholes drilled anywhere to intersect this surface are likely to be successful. However, boreholes located on sub-vertical dyke-like bodies are unlikely to be successful since the fracturing at either edge of the dyke will be difficult to intersect in the absence of detailed modelling. Thus, in this environment, the dykes are a more difficult target than the sills.

The higher conductivity values associated with the quieter magnetic profile reflect the thick mudstone sequence proved in BGS34. The magnetic profile here, while much subdued, still displays short wavelength excursions of +/-20 nT, which, according to the modelling, reflects a sill-like body extending across the area at depth. A resistivity depth sounding centred on BGS34 also identified a change in lithology at depth; low resistivity (< 10 ohm m) reflecting the mudstone, overlying a higher resistivity (190 ohm m) layer corresponding to the dolerite and baked shale. Other resistivity depth soundings made in areas of the Awgu Shale, where there was no dolerite at depth, all indicate bedrock resistivity of below 10 ohm m (Davies and MacDonald, 1999).

DEVELOPING SURVEY TECHNIQUES

A main objective of the Oju study was to develop appropriate methods for siting boreholes and wells in low permeability sedimentary environments. These techniques had to be simple, effective and easily replicable by local teams working in the area. Ideally, simple interpretational rules of thumb would be developed, similar to those that have been so effective throughout the crystalline basement areas of Africa. However, the complex geology and hydrogeology of Oju requires geophysical interpretation that is specific to the local geology. As the case studies have shown, the potential groundwater targets and their specific geophysical signatures change radically with the geology. Consequently, before using geophysical methods to site boreholes or wells in a village, the particular geological unit underlying the village has to be known.

A systematic method for identifying the groundwater potential of a village and then siting wells and boreholes has been developed for Oju, in conjunction with Oju local government and WaterAid. This method has been called 'geological triangulation' by the authors. Most community water projects now have a large sociological and health component and project workers are, therefore, used to the idea of triangulation, or the process of substantiating information from various sources. Using several techniques to understand the substrata is also fundamental to geology. Using the same term 'triangulation' helps to bridge the gaps between the technical and sociological aspects of water supply projects.

Prior to drilling, information about the groundwater potential of a village can be gained from three different sources: maps, observation and geophysics. Map and observation information help to identify the type of hydrogeological environment of a village and, therefore, which geophysical signatures are most likely to indicate conditions favourable for groundwater. Below is an outline of the geological triangulation method developed by the project staff in Oju (see Fig. 15).

i) Village sites must first be plotted accurately on maps. This is done by measuring the co-ordinates of the villages using a hand-held Global Positioning System (GPS). Compound maps were created for the area using published geology maps, aeromagnetic maps and satellite images (MacDonald and Davies, 1998). These give a guide to the geology, and the location of dolerite intrusions and satellite lineations.

ii) It is essential to spend a few hours in each village examining rocks and discussing ground conditions with community members. Busy geophysical teams often have little time to do this, but local staff can easily be trained in the basics of geology. There are many health and sociological baseline studies carried out in villages, and adding a technical component to these existing surveys is fairly straightforward. Local wet and dry

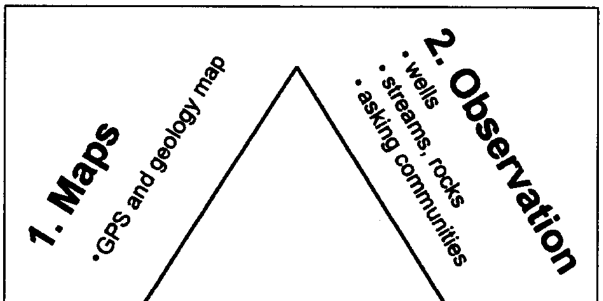

Figure 15. *The geological triangulation method used for assessing groundwater potential and siting boreholes and wells in Oju.*

season sources of water can be noted and rock samples collected from any exposures or well spoil heaps near the village. This information is used to confirm the map data. Because of the complex highly variable geology, the maps were found to be inaccurate about 50% of the time.

iii) Once these observations have been completed, geophysical surveys can be undertaken in the village. The interpretation of the geophysical surveys is guided by the anticipated geology. In the harder rock areas, where the mudstone has been metamorphosed, EM34 and resistivity can be used; higher conductivities in these areas usually imply deeper weathering and, therefore, groundwater. Where the mudstones are softer but still lithified, EM34 can be used to identify conductivity anomaly lows that generally correspond to water-bearing fracture zones. In areas where sandstones are thought to be present, long traverses using EM34 are appropriate. Within Oju, conductivity values <20 mmohs m^{-1} generally indicated sandstone. Where dolerite is believed to be present, magnetic profiling and EM34 should be used together. Shallow dolerite is readily identified by the combined data; to identify dolerite at depth, resistivity depth soundings should be used.

The above methodology requires the flexible use of geophysics in Oju. Our initial investigations have given sufficient information to enable WaterAid and local government staff to interpret geophysical surveys carried out throughout much of the Oju area. In some areas, geophysics has been used only to confirm what has been gathered from maps and observation. In other areas, much more detailed surveys have been carried out to try to identify a possible target somewhere within village boundaries. In a few villages, geophysics has been used to rule out the possibility of finding groundwater. In this manner, resources are not wasted and expectations are not raised unnecessarily.

SUMMARY AND CONCLUSIONS

Geophysical methods have made a valuable contribution to the identification of groundwater resources in the low permeability sediments of southeastern Nigeria. The hydrogeology of this area is complex and quite different to that in the crystalline basement areas found throughout much of Africa. Consequently, the interpretation methods developed for crystalline basement areas were generally inappropriate for this area, except for the hard mudstone areas in the south. The case studies presented here illustrate the use of geophysics to identify three main types of hydrogeological target present in Oju. Since these targets are often widely spaced, rapid survey techniques, especially EM34, were found most useful. Resistivity sounding was used to help interpret the EM34 profiles but generally did not add a significant amount of information to the results.

In the interbedded shale and sandstone areas, sandstones were distinguished as low conductivity zones (< 20 mmhos m^{-1}) using EM34. In the lithified mudstones, such as those found at Edumoga, EM34 was used to identify fracture zones. These gave negative-trending anomalies or lower amplitude 'noisy' horizontal coil profiles. Dolerite intrusions, within the soft shales of the Awgu Formation, were identified using both magnetic and EM34 surveys. The intrusions had lower electrical conductivity than the shales and gave distinct magnetic anomalies.

A simple methodology, known as geological triangulation, was developed with the project staff in Oju. This combined map and observation data to select the most appropriate geophysical survey and interpretation techniques to be carried out at any village. These guidelines must be reviewed as more data are collected in these areas.

Groundwater does exist within the complex low permeability sedimentary rocks of southeastern Nigeria. The systematic study of the effectiveness of various geophysical siting techniques in Oju has allowed the development of a straightforward method for siting wells and boreholes. Although these methods may need to be refined as more data become available, WaterAid have sufficient information to develop a rural water supply project in an area once avoided for its apparent lack of groundwater.

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