"Everyone who drinks this water will be thirsty again, but whoever drinks the water I give him will never thirst. Indeed, the water I give him will become in him a stream of living water welling up to eternal life".

John Ch. 4: 13-14

To Anne,

Calum & Duncan,

thanks for the timely distractions…

Community water supplies from mudstones

by

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Abstract

Mudstone is not generally considered as an aquifer. However, many people in sub-Saharan Africa have to rely on meagre water resources within mudstones for their only water-supply. This thesis provides the first rigorous study of the factors controlling groundwater resources in mudstone environments and the methods required for finding and developing groundwater. The research was undertaken in the Cretaceous mudstones of southeastern Nigeria. The area was investigated using geophysical techniques, exploratory drilling, mineralogical analysis, test pumping and hydrochemical sampling.

The investigations demonstrate that sufficient groundwater for village water supplies can exist within the top 50 m of mudstones. The occurrence of groundwater is controlled by two factors:

1. Low-grade metamorphism. Mudstone that is unaltered (early diagenetic zone) comprises mainly smectite clay and groundwater is rare. Mudstone in the late diagenetic zone comprises mixed illite/smectite clay and groundwater is found in widely spaced fracture zones. Mudstone that has been further altered and approaches the anchizone comprises mainly illite, fractures are widespread and groundwater ubiquitous.
2. The presence of other lithologies. Dolerite intrusions within smectite rich mudstone are fractured and contain groundwater. Thin limestone and sandstone layers can also enhance permeability.

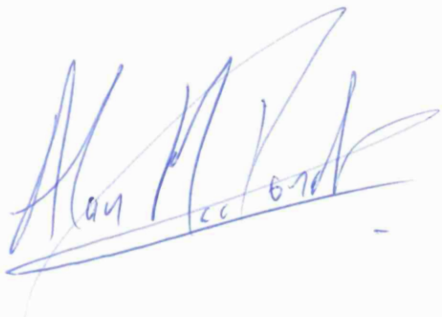
The study demonstrates a relation between ground conductivity and the degree of metamorphism of the mudstone, despite the presence of a thick tropical soil. The relation is primarily controlled by the amount of smectite within the clay. In addition, field data and novel computer modelling has demonstrated that fault zones within consolidated mudstones produce characteristic electromagnetic anomalies.

A new simple, effective pumping test, the "bailer test", was developed during the research to give an indication of borehole success. The test can be completed in under an hour and requires little specialised equipment or analysis.

In summary, sufficient groundwater for rural water supply can be found in mudstone environments with the careful application of unsophisticated technology.

Declaration

This thesis is entirely my own work unless otherwise indicated.



Alan M MacDonald

Acknowledgments

Many have contributed in one way or another to the development and completion of this thesis. First I would like to thank DFID for funding the research and BGS for paying the university fees. At University College London, John Barker, Willie Burgess and Jane Dottridge provided perceptive supervision on all aspects of the research, their wisdom and support were much appreciated. Dave McCann of the University of Edinburgh helped keep the geophysical aspects on track and his general enthusiasm for the research was most welcome. At BGS, Simon Kemp and Janice Trafford provided timely and useful laboratory analysis; Peter Rastell and Peter Ball were flexible and proficient drillers. I would particularly like to thank Jeff Davies from BGS for his firm support and erudite comments throughout the research and his companionship during the long absences from home. I would also like to thank Richard Taylor and Colin MacDonald for independent reviews of the thesis which helped improve the final output.

In Nigeria, Steven Sugden and Bitrus Kitka Goyol of WaterAid helped the research integrate with the rest of the water supply project and provided support and facilitation when required. Counsellor Vincent Edu was a tireless field assistant, interpreter and guide. All members of WaterAid and the Oju/Obi Water and Sanitation Unit provided help when required and many laughs throughout my frequent visits to Nigeria. Papa Thomas kept me alive with various forms of yam and an endless supply of clean water. The hospitality, friendship and chocolates of Sister Cobi every Sunday morning kept me sane.

Writing a thesis part-time puts high demands and extra pressures on family life. I thank Anne for being consistently supportive – particularly when Calum and Duncan arrived and free time became a thing of the past. Without Anne's help I would never have got past the first page, this thesis is dedicated to her.

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Chapter 1

Groundwater in mudstones: a source of water?

1.1 Introduction and objectives

Mudstone environments have largely been overlooked as a source of sustainable groundwater supplies, seemingly with good reason. On hydrogeology maps, they are defined as non-aquifers (Struckmier & Margarat 1995); the hydrogeological community generally accepts that they do not form good aquifers and have little potential for groundwater. Hydrogeological studies of mudstone environments have focused on the disposal of hazardous waste rather than the potential for groundwater supplies. However, many of the world's poorest and most vulnerable people live in areas underlain by these rocks. Often such people have few viable alternative sources of water, so have to rely on the meagre groundwater resources available. There is a pressing need, therefore, for hydrogeologists to examine what groundwater resources are present in mudstone environments and to determine the best methods for finding and exploiting them.

For the purpose of this thesis, mudstone environments are defined as areas that are underlain primarily (but not exclusively) by argillaceous rocks. In many of these environments, fine- to medium-grained sandstones and limestones are also present. These rocks are not excluded from the analysis, rather the whole environment is considered, whatever non-argillaceous rocks may be there. In fact, as will become apparent, the presence and frequency of other lithologies within mudstone environments often have a significant effect on the occurrence of groundwater in an area.

This thesis considers mudstone environments, not as receptacles for waste, but as a source of sustainable water supplies for rural communities. The primary goal of this research is to answer the question, "Can groundwater within mudstone environments be exploited for rural water supply?" The geographical focus of the research is sub-Saharan Africa (SSA), where rural communities have to rely on whatever water resources are available to them within walking distance of their village. The benchmark for success used in the thesis is sufficient groundwater resources and aquifer properties to sustain the yield of a handpump for about 250 people. Success translates to a yield of 6.25 $m^3.d^{-1}$, this is justified and defined in more detail in Chapter 7.

The primary goal can be divided into the following objectives:

1. To examine the controlling factors on groundwater occurrence within mudstone environments.
2. To develop appropriate methods for finding groundwater.
3. To develop a simple effective method for testing boreholes in low permeability aquifers.
4. To address the project management implications of developing groundwater in mudstone environments for community water supply projects in the developing world.

The Oju and Obi local government areas in the Benue Trough of eastern Nigeria was chosen for the research. This area is underlain by Cretaceous mudstones and the population of 300 000 suffer a severe water shortage during the five-month long dry season. There are three different mudstone groups within Oju and Obi, ranging from soft mudstones to older harder mudstones. Therefore the area is an excellent location for analysing groundwater occurrence in different mudstone environments. Oju and Obi is a rural locality with open countryside, allowing easy access for scientific equipment.

Table 1.1 shows the various elements of research that were undertaken to meet the above objectives. Some of the activities relate to more than one objective. The thesis is not an exhaustive study of mudstone environments, rather it provides a basis and model for further research into these complex and important hydrogeological environments.

Table 1.1 The project activities and how they relate to the research objectives.

objectives \ activities	drill 50 exploration boreholes	test various geophysical methods	analyse core and chip samples	undertake pumping tests in exploratory boreholes	comprehensive chemical survey	laboratory assessment of clay mineralogy	construction of base map using GIS	modelling of pumping test methods	modelling of geophysical methods using EMIGMA	discussions with WaterAid and communities
1. Where groundwater occurs	X		X	X	X	X	X			
2. Methods for finding groundwater	X	X	X			X	X		X	
3. Methods for testing boreholes	X			X				X		
4. Implications for project management							X			X

The research formed part of a Department for International Development (DFID) funded water supply and sanitation project for Oju and Obi local Governments, Nigeria (Project Number CNTR 960023A). A project team was responsible for examining the hydrogeology of the area. Therefore, other scientists were involved in collecting and analysing some of the data used in the thesis. Those involved in the project are listed below.

Project Manager:	Jeff Davies, British Geological Survey
Hydrogeologist:	Alan MacDonald, British Geological Survey
Drillers:	Peter Rastell and Peter Ball
Field technicians:	Bitrus Goyol WaterAid, Vincent Edu, Oju local government
Laboratory analysis:	Janice Trafford, British Geological Survey
	Simon Kemp, British Geological Survey
	Graham Lott, British Geological Survey
	John Bloomfield, British Geological Survey
	Eugene O'Connor, British Geological Survey
Supervisors:	John Barker; William Burgess and Jane Dottridge UCL.

The contribution of the various project staff to the different activities of the investigation (as outlined in Table 1.1) are given below.

1. *Drill 50 boreholes.* Drilling was undertaken by Peter Ball and Peter Rastell. All borehole sites were located by Alan MacDonald. Drilling was supervised by Jeff Davies for 80% of the sites, and by Alan MacDonald for 20%.
2. *Test geophysical methods.* Alan MacDonald undertook 95% of all geophysical surveys (EM34, magnetometer and resistivity) with assistance from Bitrus Goyol and Vincent Edu. All geophysical data were interpreted by Alan MacDonald.
3. *Analyse Core and Chip samples.* Jeff Davies logged 65% of core and chip samples; Alan MacDonald logged 35%.
4. *Undertake pumping tests in exploratory boreholes.* Alan MacDonald carried out 90% of pumping tests, with some assistance from Vincent Edu; Jeff Davies carried out 10% of pumping tests. All analysis was undertaken by Alan MacDonald.
5. *Comprehensive chemical survey.* Alan MacDonald took 85% of the chemistry samples; Jeff Davies 15%. Laboratory analysis was undertaken by Janice Trafford. All interpretation by Alan MacDonald.
6. *Laboratory analysis of clay mineralogy.* Samples chosen for analysis by Alan MacDonald; all analysis by Simon Kemp. Interpretation by Alan MacDonald.
7. *Construction of Base Map using GIS.* Satellite interpretation by Eugene O'Connor and Jeff Davies. Construction of GIS, data manipulation and map production by Alan MacDonald.
8. *Modelling of pumping test analysis.* All modelling undertaken by Alan MacDonald using models written by John Barker.
9. *Modelling of geophysical data.* All modelling carried out by Alan MacDonald using EMIGMA code written by Petros Eikon, Canada.
10. *Discussions with WaterAid and communities.* Discussions carried out in a series of workshops and community meetings by Alan MacDonald.

1.2 Distribution of mudstones in sub-Saharan Africa

Stratigraphic and geochemical data both indicate that fine-grained sediments, such as clay and silt, are the world's commonest sediment type comprising more than 65% of the sediment pile (Aplin *et al.* 1999). Clays and silts are deposited in a variety of environments, ranging from deltas and shallow seas to deep marine. Deposition can be complex and is influenced by rising and falling sea levels as wells as the presence and nature of terrigenous material (Reading 1996). The nature of the depositional environment usually means that sedimentary rocks occur in large basins. Examples of large sedimentary basins in sub-Saharan Africa include the Karro sediments of southern Africa, the Somali basin of East Africa, the Benue Trough and Voltaian Basin of West Africa (Selley 1997).

Figure 1.1 shows a simplified hydrogeological map of sub-Saharan Africa. This map was constructed on ArcView® using a variety of data sources (Foster 1984; Guiraud 1988; UNTCD 1988; UNTCD 1989; USGS 1997). Crystalline basement rocks form the largest hydrogeological province occupying 40% of the 23.6 million square kilometres of SSA; but consolidated sedimentary rocks occupy 32% (Figure 1.2). Considering that more than 65% of all sediments are fine-grained (see above) then about 21% of the land area of SSA may be underlain by mudstone environments.

The relative importance of each hydrogeological province is best indicated by the rural population living on each one. Rural communities are most dependent on local resources for water supply, since transportation is prohibitively expensive and difficult to manage. Using data from the World Bank (2000) and ESRI (1996) an approximation can be made of the rural population living on each rock type (Figure 1.2). Assuming that 65% of the sedimentary rocks are mudstone, up to 70 million people in rural SSA may live directly on mudstones.

1.3 A brief history of neglect

The limited groundwater research budgets available for developing countries have been targeted to understanding aquifers with greater groundwater potential, such as unconsolidated sedimentary aquifers (UNSAs) or those that are widespread, such as the crystalline basement. Research into the crystalline basement has been particularly successful. The occurrence of groundwater is now well understood and guidelines have been produced to help develop the resource (Wright & Burgess 1992). UNSAs often contain significant groundwater resources so have been extensively studied both in developed and developing countries as water sources for towns and cities (Herbert & Adams 1997). Figure 1.3 shows the number of research papers published on the hydrogeology of different rock types in Africa between 1700 and 1999. Although in excess of 200 published papers[1] which refer to the hydrogeology of crystalline basement

[1] Bibliographic analysis using Georef® from 1700 to 1999, Keywords (hydrogeology OR groundwater) AND (Africa) AND ([aquifer type])

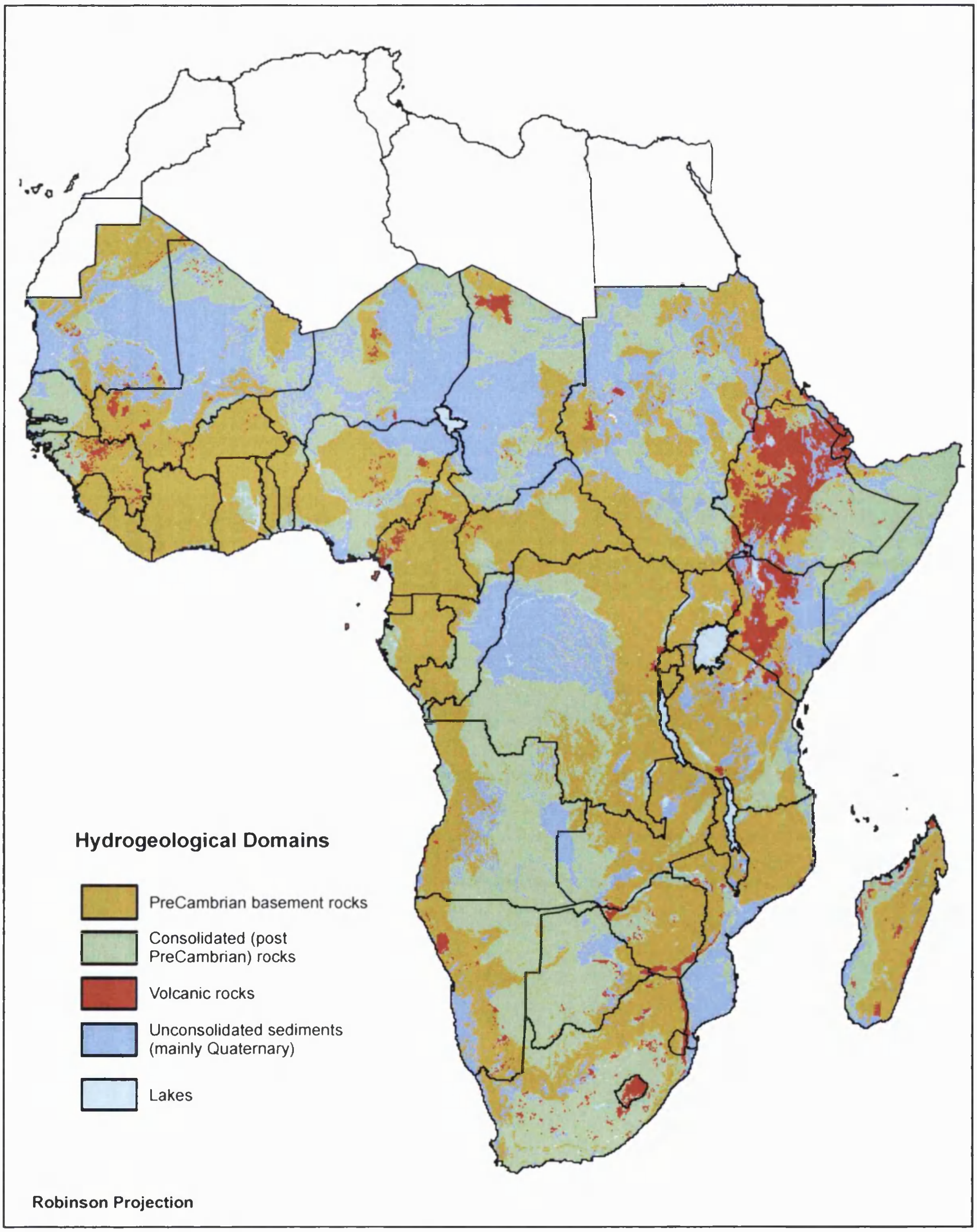


Figure 1.1. The hydrogeology of sub-Saharan Africa.

in Africa, there have been less than 30 research papers with mudstone or shale in the abstract or keyword.

During the 1960s-1980s, (and still occasionally today) groundwater was not seriously considered for rural water supply in mudstone areas, primarily because of the complexity of the hydrogeology. Instead, large reticulated water supply systems, such as are available in Europe and the USA, were proposed and sometimes developed to meet water requirements – even in rural areas. The rationale was compelling: groundwater resources were difficult to develop; technology was available to construct large dams and pipe it to areas of demand; and money for such large projects was easily available through soft loans. However, history has shown that many of these schemes are currently not working, generally because of the absence of finance and institutions to manage such large schemes and the difficulties of cost recovery for reticulated systems in rural areas. Communities are therefore forced to use unreliable and unsafe seepages and ponds within their village boundaries.

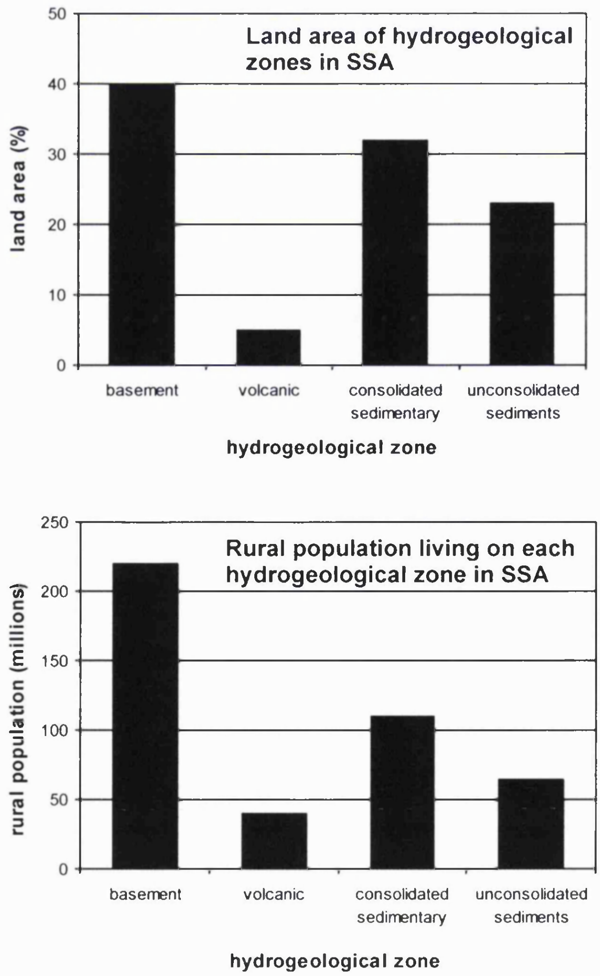


Figure 1.2 The land area and rural population of the four hydrogeological zones in sub-Saharan Africa.

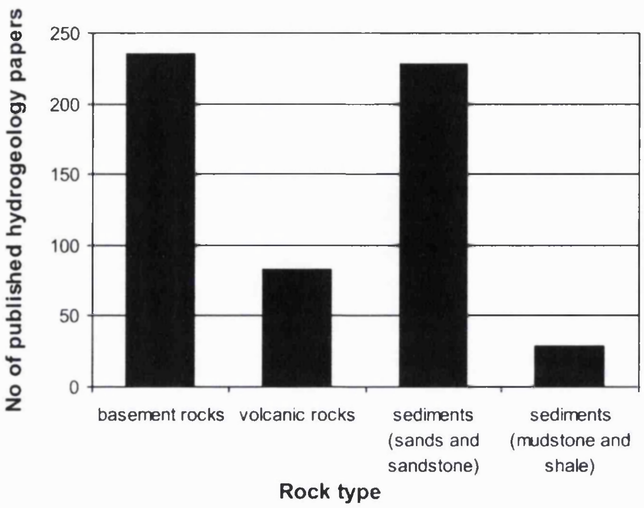


Figure 1.3 The number of research papers published on the hydrogeology of different rock types in sub-Saharan Africa.

1.4 Rationale for the current research

The main lesson learned from water projects over the past 30 years is that rural water supply is best managed and organised by the local communities who will use the water (e.g. Black 1998). For this approach to work, sustainable water resources have to exist within walking distances of communities – hence the strategic importance of rocks that contain even a small amount of groundwater. If these resources can be accessed, communities can develop and then manage them without being reliant on external agencies or funds. In this way groundwater is a resource that conforms neatly to the social science agenda of locally managed water supply. Boreholes and wells, with sufficient yield for a few hundred people, can be sited with relative ease in many environments (such as UNSAs and sedimentary basins). Even in the lower yielding crystalline basement areas, simple rules of thumb or geophysics are often sufficient to site sustainable wells and boreholes.

However, problems arise when communities are surrounded by complex hydrogeology, where groundwater resources are limited and difficult to find. In these areas simple approaches are not sufficient to site wells and boreholes. Following a social science approach, with insufficient technical input, can lead to many dry wells and boreholes. Financial resources are wasted and disillusionment and project failure can follow. Alternatives, such as rainwater harvesting and small dams are often technically difficult, expensive and difficult for local communities to manage. To have successful, groundwater-based, community water projects in these areas, the hydrogeology has to be studied in detail. With sufficient research, simple guidelines (such as those developed for the crystalline basement areas – see Chapter 3) may be developed. Therefore, it is apparent that to realise the social science agenda of locally managed and operated sources of water, the hydrogeology of complex environments, such as mudstones, has to be studied in detail.

Health statistics for Nigeria show that the highest incidences of guinea worm are in areas underlain by mudstones (National Planning Commission (Nigeria) and UNICEF 1998). The reasons for such a trend are complex, but are probably due to limited access to clean water supplies and the characteristic hydrology of these areas. Incidences of other water borne diseases may also be higher in mudstone areas.

Lack of reliable good quality water supplies is one of the prime reasons for poverty in rural Africa (DFID 2001). Therefore with the current poverty focus of aid (DFID 2000) water supply in areas underlain by mudstones becomes a high priority. It is essential that the hydrogeology of these environments is thoroughly examined before money is wasted drilling dry boreholes or constructing dry wells and prematurely raising the expectations of local communities. Only with this knowledge can simple and effective community-based water-supply projects be developed.

1.5 Guide to the thesis

Chapter 2 describes the current literature pertaining to the hydrogeology of mudstones and also discusses similarities with research into crystalline basement in SSA. The study area and research methods are described in Chapter 3, and a summary of the field data collected given in Chapter 4. In Chapter 5, the data are analysed and interpreted to put forward a model of groundwater occurrence in mudstones. In Chapter 6 a new field method for assessing the success of boreholes in low yielding environments is demonstrated. Geophysical methods for locating targets for groundwater in mudstones are discussed in Chapter 7, particular attention is given to the links between groundwater, clay mineralogy and electrical conductivity. Chapter 8 discusses how groundwater occurrence in mudstones impact on the design and management of rural water supply projects in the developing world. Comprehensive technical data are provided in a set of BGS Technical Reports. These are appended in the form of a CD-ROM. Appendix 1 gives a brief summary of these reports.

Chapter 2

A review of relevant literature

This chapter introduces relevant aspects of mudstones and discusses how these rocks can be altered by weathering processes that occur in tropical and subtropical environments. The results of permeability studies of clays and mudstones for the purposes of waste disposal are then reviewed. Synergies are then drawn with research into the hydrogeology of crystalline basement aquifers in sub-Saharan Africa. Like mudstones, basement aquifers had been thought poor aquifers; however, after much research it was shown that usable groundwater was widespread in basement environments. The Chapter is concluded with a discussion of the experience of other water supply projects in mudstone areas.

2.1 Introduction to clay minerals

2.1.1 Definitions

The unique characteristics of clays have a distinct bearing on the hydrogeology of mudstone environments. To appreciate the hydrogeology an understanding of clay sedimentology is required. Detailed discussions of clay minerals are given in Velde (1992) and Chamley (1989); a brief introduction based on these detailed texts is given here.

Historically, clays were defined as rocks consisting of grains with diameter less than 2 μm. However, clays are now more precisely defined as rocks with a sheet-like structure known as **phyllosilicate** (e.g. Chamley 1989). Clay minerals can exist at temperatures up to 250 °C. At higher temperatures, clay minerals grow and metamorphose, giving minerals of a different size and composition to clays. One of the main characteristics of clay minerals is their large surface area to mass ratio. Velde (1992) gives the analogy of a sheet of paper, which has similar ratio of surface area to mass.

2.1.2 Clay structure

Clay crystals consist of silicon, aluminium (or magnesium), oxygen, and hydroxyl (OH^-). These components combine to produce tetrahedral and octahedral sheets. Tetrahedral sheets constitute duplications of a basic tetrahedra, which has a central cation (generally silicon but occasionally aluminium or iron, Fe^{3+}) and oxygen at the four corners. Tetrahedra are joined by three oxygen atoms giving a hexagonal tetrahedral sheet (Figure 2.1). The fourth tetrahedral oxygen points normal to the sheet. Octahedral sheets have medium size cations at their centre (Al, Mg, Fe^{2+}, Fe^{3+}) and eight oxygen atoms at the corners. Individual octahedra are joined laterally (and vertically with tetrahedral sheets) by sharing oxygen. The junction between tetrahedral and octahedral sheets comprises shared apical oxygen and unshared hydroxyls (OH^-). The unshared hydroxyls are located in the centre of the tetrahedral ring.

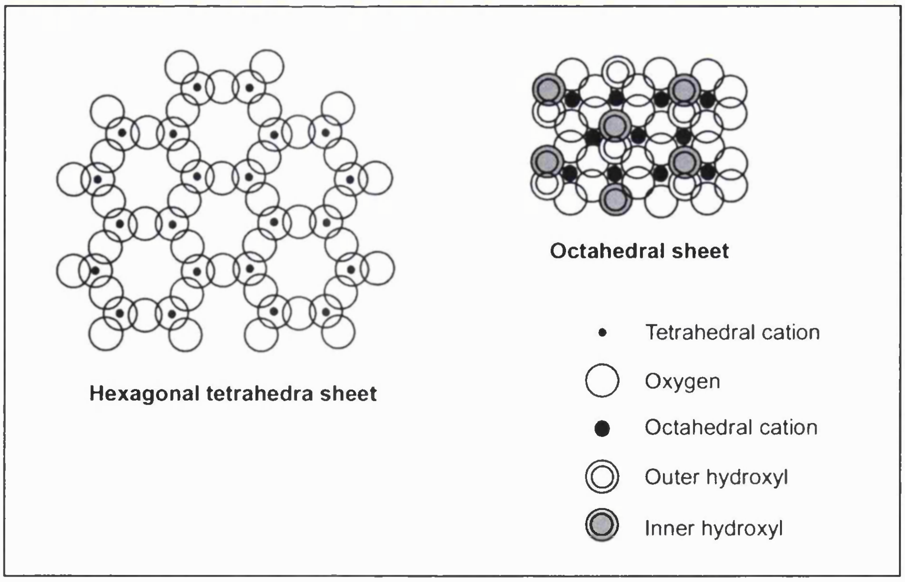


Figure 2.1 The structure of hydrous layer silicates (Chamley 1989).

There are two main ways that tetrahedral and octahedral sheets join to make a **layer**: (1) a *1:1 layer* comprises a tetrahedral sheet and octahedral sheet; (2) a *2:1 layer* comprises an octahedral sheet sandwiched between two tetrahedral sheets; one tetrahedral sheet is reversed so that apical oxygen atoms on both sheets point towards the centre and can be shared.

The space between two layers is known as an **interlayer**. If a layer is electrostatically neutral then there are no ions within the interlayer. However, many clay minerals have negatively charged layers that are neutralised by various interlayer material, such as K^+, Na^+, Mg^{2+}, Ca^{2+}, hydrated cations, or hydroxide octahedral groups. Hydroxide interlayer groups can join to give an additional octahedral sheet giving a 2:1:1 assemblage.

A **structure unit** comprises a layer and an interlayer. Depending on the type of layer and also the interlayer constituents this can vary in thickness from 7 to 18 Å (Chamley 1989). **Clay particles** are formed by the piling up of many structure units; particles are rarely more than a few micrometers in diameter, hence the convenient historical definition of the clay fraction as the rock fraction less than 2 μm in diameter. However, this fraction can contain constituents other than clay minerals, such as aluminium and iron oxide, carbonate, phosphate and organic matter.

Water adsorbs to the surface of clay particles and clay layers. Cations on the layer surfaces can also be hydrated, which pushes the layers apart making them swell (Madsen & Muller-Vonmoos 1989). 2:1 clays, such as smectite can swell to twice their volume when hydrated; 1:1 clays (e.g. kaolinite) rarely swell. In 2:1 clays, the pressures involved in swelling can be large (100 $N.mm^{-2}$) and have important engineering implications. Clays can also swell as a result of osmotic swelling: concentrations of cations within interlayers are high and where water is available it seeks to equilibrate the concentrations outside and inside and pushes the layers apart.

Cation exchange capacity (CEC) is a measure of two of the fundamental properties of clays: surface area and the charge on the surface area. CEC is reported as milliequivalents per 100 gms dry clay. Cation exchange capacity is generally measured as the number of cations on the clay surface after it is washed free of exchange salt solutions. Electrical charge is carried along the surface of clays by these cations; therefore the CEC is a good indication of the electrical conductivity of clays. This is particularly important when using geophysical methods in mudstone environments and shall be discussed in more detail in Chapter 7.

Clay mineral groups are distinguished by their structural arrangement (e.g. 2:1, 1:1 etc.) and the elements found in the polyhedral layers. These chemical substitutions tend to modify the dimensions of the clay mineral structure and consequently its behaviour. By classifying clays in terms of layer type and charge, eight groups of minerals are identified (Chamley 1989). However, the mineral groups kaolinite, smectite, illite, chlorite and palygorskite-sepiolite account for most of the clays that exist in nature. Table 2.1 describes the main characteristics of these clays.

Table 2.1 Description of the most common clay groups. For a fuller description of all clay groups see Chamley (1989) or Velde (1992). CEC from Keller & Frischknecht (1966) and van Olphen & Fripiat (1979).

Group	*layer type*	*CEC* (meq $100g^{-1}$)*	*Properties*
kaolinite	1:1	3 – 15	Mainly forms in surface environments as a result of weathering. Generally chemically pure.
Smectite	2:1	80 – 150	Swelling clays. Can easily exchange hydrated cations in the interlayer position. Mainly forms in surface environments as a result of weathering.
Illite	2:1	10 – 40	Name given by geologists to all micaceous minerals present in the clay size fraction of the rock. Often forms from very low grade metamorphism of smectite.
Palygorskite-sepiolite	2:1	20 – 60	Often called fibrous clays, since they consist of well-defined elongated fibres or ribbons. All form in surface environments from weathering. Commonly used as an industrial absorbent.
chlorite	2:1:1	10 – 40	Chlorites in sedimentary rocks form by diagenesis; low temperature chlorites can form in soils.

* Common field values are given which are generally higher than theoretical calculations or controlled measurements of pure clays because of the presence of interlayers.

2.1.3 Clay formation

Clay minerals are generally produced by the weathering of silicate minerals at the earth's surface. The chemical conditions and large amount of water present at the rock-atmosphere interface can lead to the incongruent dissolution of silicates that forms clays. These clays are generally eventually eroded and because of their small grain size often transported long distances by rivers and sea.

Sedimentation of clay material takes place in various environments such as lakes, deltas, continental shelves and the deep ocean. The chemical equilibrium achieved during the weathering process is altered in the initial stages of sediment burial, precipitating changes in clay mineralogy. Commonly, clay minerals react with the ambient solution. Various elements within the clays can be recycled depending on the presence of organic matter and the action of living organisms. However, surface diagenesis rarely produces significant quantities of new clay minerals.

When the clays are buried, the ratio of water to rock changes. Under these conditions, there are gradual changes in clay mineralogy dependent on both the temperature and the time. Metamorphism of the clay minerals can occur depending on temperature and time (pressure plays little part in the reactions). The clay minerals will recrystallise giving larger clay minerals and new silicates. At low temperatures, clays generally keep their phyllosilicate structure even if their grain size exceeds that of the clay fraction (Frey & Robinson 1999).

2.2 Permeability of mudstones

2.2.1 Introduction

Historically, much less effort has been spent understanding groundwater flow in mudstones than in more permeable rocks. The reasons are obvious: permeable rocks are important for groundwater development and the recovery of hydrocarbons. However, interest has recently arisen in low permeability rocks for a variety of reasons.

1. Aquifer response in large sedimentary basins is largely affected by the presence and nature of low permeability horizons (Neuman & Witherspoon 1972; Rushton & Thangarajan 1989; Remenda 2001).
2. Low permeability sediments may be the optimum environment for storing hazardous wastes (Lomenick & Kasprowicz, 1990).
3. Low permeability sediments have an important role in the evolution of groundwater flow systems over geologic time, thus affecting the migration of hydrocarbons and accumulation of ore bodies (Garven & Freeze 1984; Neuzil 1986).
4. Low permeability cover, such as glacial till has an important effect on limiting recharge to and contamination of major aquifers (Fredericia 1990; Klinck *et al.* 1996; Desbarats 2001).

Results from studies of low permeability sedimentary rocks are incorporated below in an assessment of permeability of clay and mudstone environments.

2.2.2 Laboratory samples

It is difficult to make accurate laboratory measurements of the hydraulic conductivity of low permeability materials. Any small leakage from laboratory apparatus can lead to the hydraulic conductivity being over-estimated. Because of the low permeability, the time taken to complete tests may be inconveniently long; it is also difficult to accurately generate and measure the very low rates of flow required to measure permeability (Neuzil 1986). There are also the problems of finding a representative sample to test. Laboratory samples cannot account for inhomogeneities and fractures at different scales to the sample volume.

Neuzil (1994) reviewed published intrinsic permeability measurements in an attempt to identify systematic variations. He only took studies that met his stringent criteria - laboratories which used natural media in an undisturbed state, where appropriate techniques were carefully applied, and where porosity was also monitored. Four of the datasets he used were from bottom muds, five were from consolidated mudstone, and one each from recent marine and lacustrine clay, glacial till and unconsolidated sediment. From these studies, K (hydraulic conductivity) varied from 10^{-16} to 10^{-8} $m.s^{-1}$ and φ (porosity) from 0 to 0.8. Neuzil (1994) found K to be broadly related to φ at the laboratory scale (Figure 2.2). Microstructural differences were also important and could account for changes of up to 3 orders of magnitude at the same porosity; e.g. clays with elongate and fibrous minerals tend to have higher permeability than those that are more platy (Gilliot 1987).

2.2.3 Field scale

If the only groundwater flow within mudstone environments was intergranular flow within clays then they could be considered as having no potential for groundwater development. However, the presence of fractures and also coarser grained units, such as thin siltstone, sandstone and limestone layers, can significantly enhance the hydraulic conductivity at the field and regional scale.

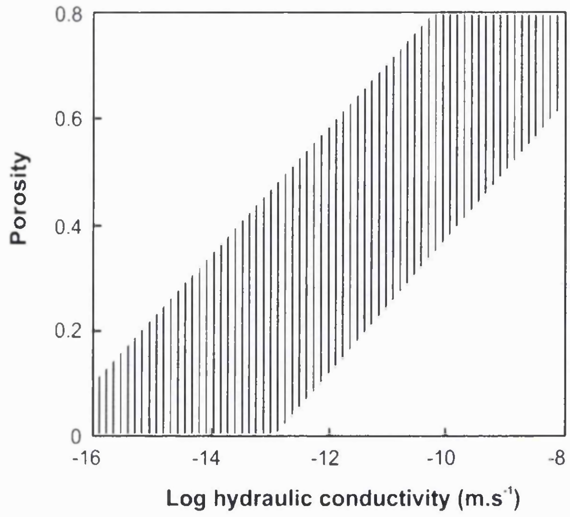


Figure 2.2 Range of laboratory derived hydraulic conductivity versus porosity for argillaceous material (from Neuzil 1994).

Most field studies of the hydraulic conductivity of low permeability sediments stress the importance of fractures. Regional modelling of the permeability of mudstone confining layers on various sedimentary basins in the United States have shown regional permeability to be significantly greater than laboratory measurements (Bredehoeft *et al.* 1983; Belitz & Bredehoeft 1990). The difference was attributed to fracturing and faulting. Others have directly measured the field permeability of mudstones using slug tests and pressurised slug tests. Again, increases of 2-3 orders of magnitude have been recorded (Clarke *et al.* 1989; Sen & Abbott 1991; Capuano 1993). Many different studies of glacial till also point towards a marked increase, 1-3 orders of magnitude, between fractured and unfractured till (Kazi & Knill 1973; Lloyd 1983; Herzog & Morse 1984; Bosscher *et al.* 1988; Bouma *et al.* 1989; Keller *et al.* 1988; Fredericia 1990; Fortin *et al.* 1991; Gerber *et al.* 2001). Estimates of hydraulic conductivity from fractured mudstones and clays range from 10^{-11} to 10^{-5} m.s^{-1}.

Sen & Abbott (1991) performed a direct study of the hydrogeological impact of a fault in the Jurassic age Oxford Clay. Pressurised slug tests were performed both in undisturbed areas and the fault zone. Hydraulic conductivity was found to vary from 10^{-12} to 10^{-8} m.s^{-1}, with the higher values being measured within the fault zone. Bosscher *et al.* (1988) undertook a direct laboratory study into the effect of unconnected joints in soils with high clay content. They found that when the joint orientation was within 30^{o} of the flow direction the permeability was greatly enhanced; generally the hydraulic conductivity of jointed soil was two orders of magnitude greater than unjointed soil.

However, mudstones are not always fractured in the field. From a review of a limited set of published data, Neuzil (1994) related laboratory measurements with regional values estimated from inverse analysis of various flow regimes. Using data from seven regional studies, he concluded that permeability scale dependence is not common in argillaceous material. This may be attributed self-healing of clay fractures which limits secondary permeability.

It is difficult to reconcile Neuzil's (1994) assertion with the many other studies which show significant differences between laboratory and field measurements. The implication that the extensive research indicating the importance of fractures has been undertaken improperly is unlikely. A possible explanation is that the research has actually been looking at three rather than two different scales: laboratory, field and regional. In a study of the Permo-Triassic sandstone aquifer in England and Wales, Allen *et al.* (1997) found that hydraulic conductivity measurements derived from regional models were similar to those gained from core analysis. However, pumping tests gave considerably higher estimates of hydraulic conductivity. They suggest that fractures that provide the flow to boreholes and wells are not significant for regional flow. Bredehoeft *et al.* (1983) also found a difference between regional permeability (implied from flow modelling), localised permeability from borehole tests, and intrinsic permeability from lab tests. Another possible explanation for the difference between Neuzil's (1994) review and other work is the depth at which they are considered. Much of Neuzil's work concerns deep flow within basins, while many of the other studies are of shallow weathered sequences. Higher field values of hydraulic conductivity in the weathered zone decreasing to laboratory levels below 10 – 30 m have been reported by Gautschi (2001) and van der Kamp (2001).

Several studies of clay environments have highlighted the importance of interbedded siltstones and limestones. Barker *et al.* (1988) in studying a landfill sited on shale found that an interbedded cherty dolomite provided an important flow path for contaminants. Capuano & Jan (1996) undertook pumping tests and a tracer injection test in shallow clay and silty-clay sediments of the fluvial-deltaic Beaumont Formation from the U.S. Gulf Coast. Horizontal hydraulic conductivity determined from these test was approximately 10^{-5} m.s^{-1} (1 m.d^{-1}). This value is one to three orders of magnitude larger than that of typical silts and clays, and two to four orders of magnitude larger than the vertical hydraulic conductivity measured in laboratory permeameter experiments. No water entered the boreholes until they encountered a silty-clay layer. The more permeable horizons had 17-58% fine sand within clay and silt. Furthermore, in a recent study of the effect of compaction on the London Clay, Dewhurst *et al.* (1998) found that the presence of slightly coarser material within the mudstone could increase the permeability of the resulting compacted mudstone by two orders of magnitude. Gerber *et al.* (2001) in studying a fractured till aquitard note the importance of sand and gravel lenses in increasing the hydraulic conductivity.

Few of the above studies relate the measured hydraulic conductivity to the clay mineralogy. Generally the rocks are described only as "clay" or "fractured clay". Since different clay minerals have different properties, relating clay mineralogy to fractures and hydraulic conductivity may offer further insight into the permeability of mudstone environments.

2.2.4 Fracturing within mudstone environments

The origin of fractures within mudstone environments has been subject to many studies, mostly in the context of hazardous waste disposal or hydrocarbon migration. Hydrofracturing can produce microfractures within mudstones, while larger fractures are the result of tectonic activity.

Hydrofracturing occurs when low permeability sediments are subject to burial. The increase of fluid pressure within the low permeability sediments and the very low permeability eventually leads to hydrofracturing and the release of pore fluids. These fractures tend to have closely matched walls with occasional precipitation of secondary minerals (Capuano 1993). Unlike tectonic fractures, they do not exhibit any preferred orientation (e.g. Cartwright 1994). A numerical study of compaction induced hydrofracturing showed that hydrofracturing can occur at shallow depths 400 – 1000 m and tends to be episodic (Wang & Xie 1998). Evidence for shallow hydrofracturing has also been gained from the southern North Sea (Henriet *et al.* 1991). The frequency of the hydrofracturing episodes depends on the sediment permeability and rate of deposition (Wang & Xie 1998).

The enhanced permeability of hydrofractured shales may be short lived – maybe even as short as 100 years (Roberts & Nunn 1995). Fractures can be healed by physical diffusion, or sealed by mineral precipitation (Fisher & Byrne 1990; Lomenick & Kasprowicz 1990; Hickman & Evans 1995). However, fractures can retain their enhanced permeability even after fractures have been "closed" – probably as a result of slight roughness on the fracture surfaces. Horath (1989) showed that hydraulic conductivity in siltstones with closed hydrofractures was 2-3 orders of magnitude greater than in intact siltstones for a dataset from Oregon. When erosion brings low permeability sediments back to the ground surface, the unloading may cause hydrofractures to be reactivated and dilate.

Tectonic fracturing is common in subsiding basins. Faults can both act as barriers and conduits for fluid flow. Sheared clay has lower porosity than its consolidated counterpart, therefore the permeability across fault zones can be severely reduced (Arch & Maltman 1990). However, as discussed above, there is much field evidence to suggest that fluid flow is enhanced along fault zones as a result of dilation and fracturing. (Dewhurst *et al.* 1999). As diagenetic processes and compaction progress, mudstones become more brittle and lithified, allowing fractures to remain open. Permeability can be anisotropic with little flow across fault zones, but enhanced permeability along the line of the fault (Arch & Maltman 1990).

2.3 Tropical weathering

Rock weathering has an important effect on the hydrogeology of tropical areas. The alterations can be so intense that the soil is very different from the parent material. Where rocks are soft, the intense weathering obscures most rock exposures making it difficult to identify the rock type and thus the groundwater potential. Tropical weathering occurs mainly by hydrolysis under neutral conditions, below the zone of acidic organic matter (Fookes 1997). Iron and hydrated oxides tend to remain in-situ forming characteristic red soils often referred to as "laterite" or tropical red soils. Silica can be lost by dissolution, or altered to form 1:1 clay minerals (usually kaolinite) and less often 2:1 clay minerals such as smectite. The lower soil horizons are clay enriched while the upper horizons are depleted in clay minerals and enriched in iron. Occasionally the iron rich zones can become hardened to form an indurated crust, known as ferricrete. (For an excellent review of tropical soil formation see Fookes 1997).

Three phases of tropical weathering have been identified: fersiallitic, ferruginous and ferallitic (Duchaufour 1982). Table 2.2 shows the conditions under which these soils develop.

Table 2.2 Climatic factors leading to the development of various tropical soil phases

Soil type	*Annual Temperature (°C)*	*Annual Rainfall (mm)*	*Dry Season*
Fersiallitic	13 – 20	500 – 1000	Yes
Ferruginous	20 – 25	1000 – 1500	Sometimes
Ferrallitic	> 25	> 1500	No

Fersiallitic soils. During the wet season the upper soil horizons undergo weathering; however the elements released by these process are generally retained in the profile. Smectite is the main clay produced by this process, especially where drainage is impeded. Where the parent material is clay rich (e.g. mudstone), the composition of the soil clays generally reflects the mineralogy of the parent rock.

Ferruginous soils. These soils are more strongly weathered than fersiallitic soils, although quartz orthoclase and muscovite remain largely unaltered. Kaolinite clay is predominant with subordinate smectite. Clay rich rocks will weather to kaolinite.

Ferrallitic soils. These soils are highly weathered and the final phase of development of thick soils in hot, humid climates. All primary minerals except quartz have been weathered and much of the bases have been removed – iron and aluminium remain within the profile. The iron forms nodules and pisoliths which sometimes can be indurated to form ferricrete. Below the iron-enriched layer is kaolinite, which is often mottled due to segregation of iron. Ferrallitic soils normally take about 10 000 years to develop (Fookes 1997). Ferrallitic soils can be present in areas that are currently sub-tropical or arid, where the conditions are not suitable for their development. This is probably the result of climatic shifts during Quaternary time.

There have been two documented studies made of the permeability of laterite and their effect on the groundwater resources of an area. Langsholt (1992) studied the effect of laterite on groundwater resources in southwest India. The study site was underlain by a well-developed 10-m thick lateritic profile overlying coarse-grained igneous bedrock. Rainfall was 2000-4000 $mm.a^{-1}$ distributed over 125 days. He found that groundwater levels responded rapidly to rainfall (within 10 hours) by several metres. The recharge mechanism suggested by this study was of rapid flow through preferred pathways. A similar study was carried out in Western Australia (Sharma *et al.* 1987a; Sharma *et al.*

1987b). They found that the rate of infiltration in lateritic soils was high, but was affected by land use changes.

2.4 Lessons from research into the crystalline basement

There are similarities between research into the hydrogeology of crystalline basement rocks and mudstones. Both are low permeability rocks which in the past have not been considered as significant sources of groundwater in the developed countries. They are both considered as having potential for storing nuclear waste. However, significant research into crystalline basement rocks in sub-Saharan Africa and India have shown that they can support village community water supplies. Crystalline basement rocks are now considered a highly significant strategic groundwater resource (Wright 1992). A summary of the hydrogeology of the crystalline basement is given here to help inform our study of mudstones.

Crystalline basement rocks are widely distributed throughout the world. They are highly important sources of groundwater in Africa, Asia, and South America. Like mudstones and clays, unweathered crystalline rock has very low permeability. Significant aquifers, however, develop within the weathered overburden and fractured bedrock (Wright 1992). The majority of rural water supply projects carried out in Africa are located on weathered crystalline basement aquifers. Consequently, much work has been undertaken to try to understand these aquifer systems.

Four factors contribute to the weathering of basement rocks (Jones 1985; Acworth, 1987):

- presence and stress components of fractures;
- geomorphology of the terrain;
- temperature and occurrence of groundwater;
- mineral content of the basement rock.

The resulting weathered zone (or *regolith*) can vary in thickness from just a few metres to over 90 m.

The permeability and porosity in the regolith is thought not to be constant but to vary throughout the profile (Figure 2.3). Porosity generally decreases with depth – permeability however, has a more complicated relationship, depending on the extent of fracturing and the clay content (Chilton & Foster, 1995). In the soil zone (*collapse zone*) permeability is usually high, but groundwater does not exist throughout the year. Beneath the soil zone, throughout the clay rich saprolite, permeability is low. Towards the base of the saprolite, near the fresh rock interface, the degree of weathering decreases; consequently the proportion of clay significantly reduces. This horizon, which consists of fractured and brecciated rock, has a high permeability, allowing water to move freely (British Geological Survey 1989).

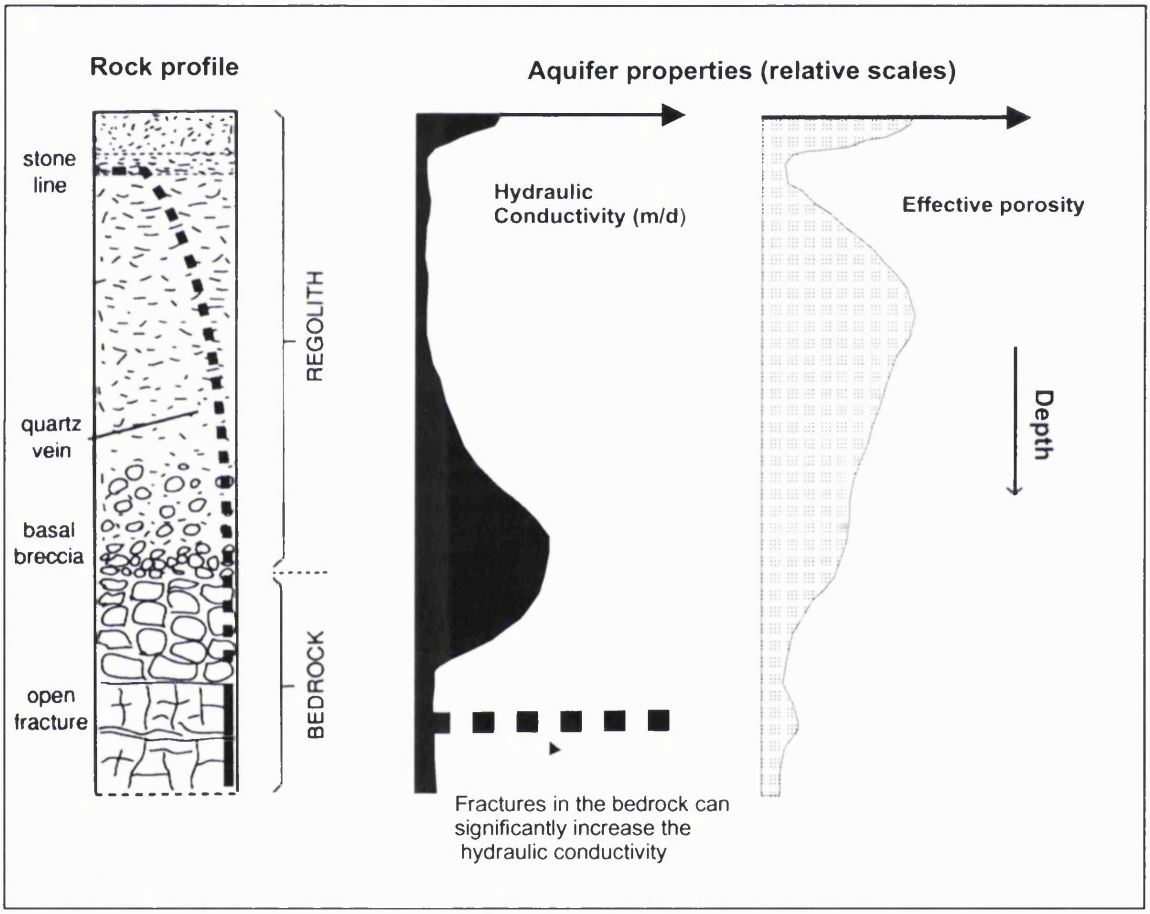


Figure 2.3 Conceptual model of the hydrogeology of the weathered crystalline basement aquifer in Africa (Chilton & Foster 1995).

Deeper fractures within the basement rocks are also often an important source of groundwater. These deep fractures are tectonically controlled and can sometimes provide supplies of up to 1 $\ell.s^{-1}$. Superficial deposits derived from crystalline basement environments can also be important sources of groundwater. In southern Africa, sand-rivers are important (Herbert *et al.* 1997). These rivers rarely contain surface water, but the thick sediment within the river channel can contain significant groundwater. In northern Nigeria, shallow floodplains known as fadamas, are important sources of groundwater in basement areas (Carter & Alkali 1996). These floodplains may be several kilometres wide and can contain 10 m of sands and gravels. They rely on annual flooding for recharge.

There are, therefore, three main targets for groundwater in basement rocks: basal saprolite; deeper fracture zones; superficial deposits (sands rivers and fadamas). The groundwater resources within these aquifers depends on how thick they are and the relative depth of the water table: the deeper the weathering, the more sustainable the groundwater. Moreover, due to the complex interactions of the various factors affecting weathering, the different aquifers may not be present at all.

Various techniques have been developed to try to locate groundwater resources within basement rocks. These include remote sensing (Lillesand & Kiefer, 1994), geophysical methods (e.g. Beeson & Jones 1988; McNeill 1991; Carruthers & Smith, 1992), and geomorphological studies (Taylor & Howard 2000). Geophysical surveys using joint resistivity and electromagnetic surveys have been found most useful in siting wells and boreholes.

Different methods have been used to abstract groundwater from basement aquifers (Figure 2.4). The most common are boreholes and dug wells. Collector wells have also been used with much success, although their distribution is at present fairly limited (Lovell 2000; Ball & Herbert, 1992). Each of these abstraction methods has its own advantages and limitations. Boreholes are quick to construct, even in hard rocks, using air rotary drilling, to depths of 100 m. However, since they are narrow they have little storage capacity and require a pump to abstract water. In addition, drilling is expensive and can limit the participation of communities. They are most useful in basement areas for abstracting water from deep fracture zones.

The main advantage of large-diameter hand-dug wells is that they have a large storage capacity. Therefore in low permeability aquifers, where the rate of flow from the aquifer to the well is slow, water can be abstracted from *stored* water in the well at a rate much greater than the permeability of the aquifer would allow. Wells also have a large internal surface area, which allows a large amount of seepage from the aquifer. Little specialist equipment is required for their construction (Watt & Wood 1979) and once completed a pump is not necessary to abstract water. However, it is difficult to construct hand dug wells in hard rock; also, since they are shallow, they can sometimes dry up, although this is often due to large demands put on the wells in the dry season, rather than

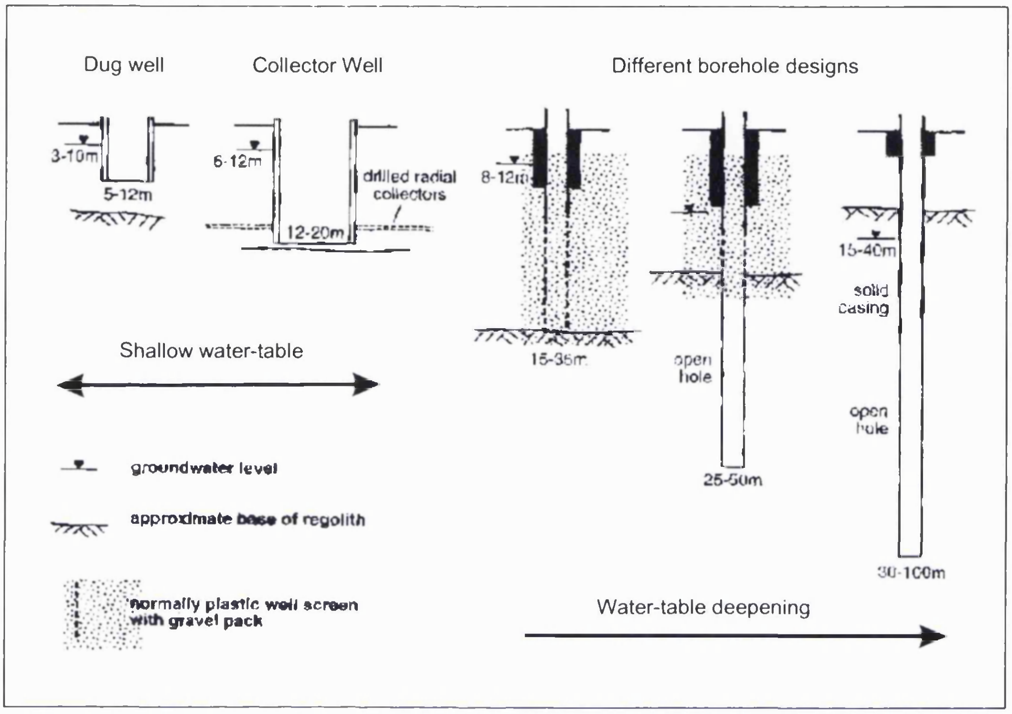


Figure 2.4 Different designs of wells and boreholes in crystalline basement areas (Foster *et al.* 2000).

natural water levels fluctuations (Calow *et al.* 1997). Wells are best used to exploit aquifers within thick, near surface, zones of weathering.

Collector wells have been designed to maximise the yield from the basal saprolite aquifers (British Geological Survey 1989). A collector well consists of a large diameter central shaft with horizontal radials penetrating the surrounding aquifer. These radials are positioned to penetrate the high permeability zone of the basal saprolite. The resulting well has a large storage, but also a high seepage rate and therefore provides a higher sustainable yield (Macdonald *et al.* 1995). However, collector wells are more expensive to construct than hand dug wells and require a specialist horizontal drilling rig. Other, less expensive methods of constructing radials would make collector wells more easily replicable.

2.5 Previous experience of groundwater development in mudstones

There have been few documented water supply programmes in areas underlain by mudstones. Of the few that have been undertaken, few data have been collected and little systematic assessment has been made of the hydrogeology. One exception is the Voltaian Basin in Ghana where several studies have been undertaken with limited success.

The Voltaian Basin in Ghana consists of interbedded siltstones, shales and sandstones. There have been many problems in this area with rural water supply. Tod (1981) states that toward the centre of the basin only 13-21% of boreholes drilled have been successful (yields >20 $\ell.min^{-1}$). Recently, a drilling programme was undertaken using aerial photographs to identify fracture zones, followed by geophysics to site the boreholes. The success rate of this programme was 13% (Iddirisu & Banoeng-Yakubo, 1993). These programmes assumed that fracture zones would be the best targets and were best exploited through boreholes. Currently boreholes are being sited using Landsat imagery and geophysics and success is thought to have increased (Teeuw 1995). Another study in the south of the basin found fracture zones within low permeability sandstones and conglomerates to be the best sites for boreholes (per Sander *et al.* 1996). The low permeability shales and siltstones were avoided. Satellite images and GIS analysis were used to site boreholes – boreholes had a marginally increased success rate within 300 m of a marked lineament.

A World Bank/UNDP project was undertaken in the Cretaceous sediments of the Benue trough in Nigeria. In fact, this project was undertaken in Oju and Obi – the same location as the study area used for this thesis. That project met with many difficulties trying to develop groundwater resources and eventually came to a pejorative end in 1993. The World Bank/UNDP conclusion from the area was to dismiss the mudstone as a source of water and focus on reticulating water into the area (Habila & Daagu 1992). One of the main problems they faced was interpreting geophysics in such a complex area; in particular the non-uniqueness of electromagnetic techniques meant that they could not distinguish the conductivity of groundwater from clay.

A review of the hydrogeology of British mudstones was carried out by Tellam & Lloyd (1981). They synthesised unpublished data from the British Geological Survey archives and reports from the mining, soil mechanic and agricultural industries. Much of the information came from domestic wells that supplied individual farmhouses. They classified British mudstones into two main classes: pre-Mesozoic and post-Palaeozoic. In the older mudstones successful wells were found where the lithified mudstones had been fractured. Highest flow rates were found in the near surface weathered zone. In the younger mudstones, permeability was mostly controlled by the presence of coarser material.

2.6 Summary and implications for present study

Research into the permeability of mudstones has shown permeability to be broadly related to porosity at a laboratory scale. Laboratory tests indicate hydraulic conductivity from 10^{-16} to 10^{-8} m.s^{-1}. The majority of field studies of mudstone permeability indicate an increase in hydraulic conductivity of 2-3 orders of magnitude at shallow depths. Shallow fractures and interbedded siltstones, sandstone and limestones can all increase field permeability. Fracturing in mudstone environments can occur as a result of hydrofracturing due to burial and tectonic activity.

From the literature it is clear that studies of mudstone permeability have focused on its ability to store hazardous waste or inhibit recharge. Therefore the low permeability scenarios have been given much of the attention, such as deep, homogenous mudstones. Higher permeability zones are only mentioned in passing, with the bulk of the work concentrating on low permeability areas. More importantly, there has been negligible published research of the importance of clay mineralogy to mudstone permeability. Most studies record only engineering factors, such as the percentage of clay. This current investigation examines the high permeability areas of mudstone and will use clay mineralogy to determine variations.

Research into the hydrogeology of crystalline basements demonstrated that highest permeabilities were obtained at the base of the regolith, where open fractures were more prevalent. Research indicated that weathering was key to the groundwater potential of basement areas. Geophysical methods are used widely to site wells and boreholes.

Geophysical methods are rarely used in mudstone environments. The few groundwater studies in mudstone areas have failed to find any successful ways of interpreting geophysical data. This stems from the non-uniqueness of geophysical methods – both clay and water have high conductivities. However, inappropriate methods of analysis are commonly applied. The success of geophysical methods in crystalline basement has led people to transfer exactly the same techniques and analysis guidelines to other lithologies without reviewing their appropriateness. Therefore there is a need to start from first principles and examine the validity of geophysical methods in mudstone environments.

Chapter 3

The Oju/Obi study area and methods of research

This chapter gives the background to the Oju/Obi area. The climate, hydrology and regional geology are described, along with other relevant information. The water supply problems of the area are also presented. The research methods used to investigate the groundwater potential in Oju and Obi are summarised in the second half of the chapter.

3.1 Introduction

An area in southeastern Nigeria was chosen as a study area to investigate the groundwater potential of mudstone environments (Figure 3.1). The area covers two local government areas, Oju and Obi, which lie within Benue State. The U.K. Department for International Development (DFID) had highlighted this area as a priority for Aid, and in particular for improved water supply and sanitation. The British Geological Survey was commissioned to develop and undertake a programme of research into the groundwater potential of the area. The knowledge and tools developed during this investigation were to be incorporated by WaterAid into a community water supply project for the area (MacDonald & Davies 2000). As discussed in Chapter 1, the study was undertaken by a team from BGS. The contributions of others to the research presented here is detailed in Chapter 1.

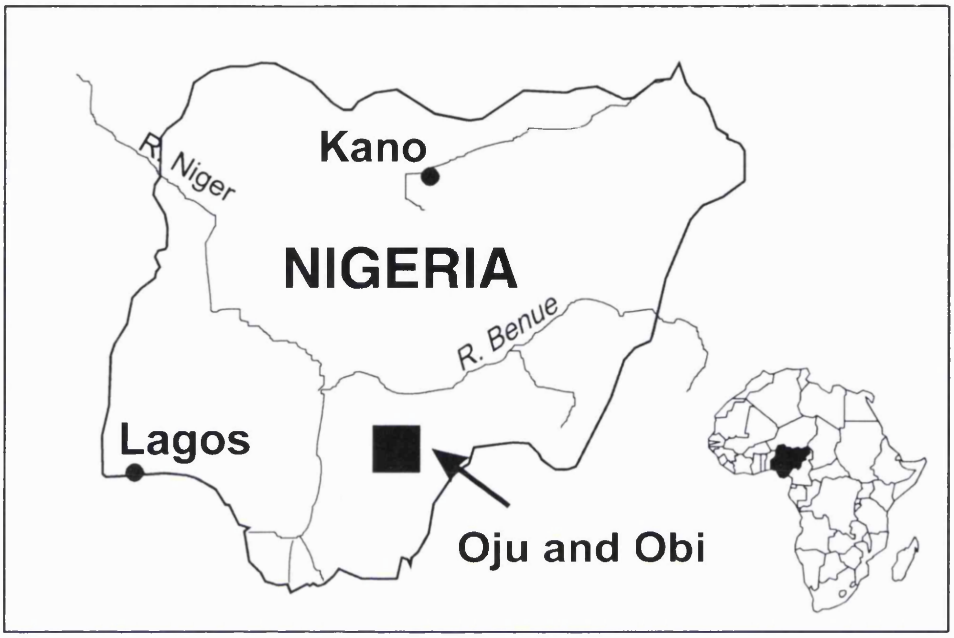


Figure 3.1 The location of Oju and Obi.

3.2 The Oju/Obi study area

3.2.1 General information

The Oju/Obi area is a remote part of Benue State in south-eastern Nigeria. The area comprises two local government areas (LGAs) that were created in 1996 by dividing the existing Oju LGA into two. Obi LGA is in the north of the area, and Oju LGA in the south. Population estimates for the combined Oju/Obi area vary between 177,000 (1991 census) and 420,000 (Morgan 1996, MacDonald & Davies 1997). For the purposes of this study, a population estimate of 300,000 is used, most of whom belong to the Igede people.

The Oju/Obi area, about 2000 km^2 in extent, can be divided into two main geographical areas: the Wokum Hills in the southwest and the central and northeastern low-lying plains. The Wokum Hills trend NE-SW and reach a height of 550 m above sea-level (asl). The plains range from 50 to 125 m asl and are gently undulating. Ferrallitic and ferruginous soils, supporting savannah woodland type vegetation, cover much of the area. The main crops grown are yams, cassava and rice. Sorghum, millet, maize, sesame seed, groundnuts and oranges are also cultivated.

Prior to this study, village locations in Oju/Obi were imprecisely known. Only a small number were shown, with limited accuracy, on the 1:50,000 scale topographic maps of the area. During the project, the majority of known villages were visited and located accurately using a Global Positioning System (GPS). The village locations and names collected were used to compile the first accurate village location map and gazetteer of the Oju/Obi area (MacDonald & Davies 1998). The distribution of villages within Oju and Obi is shown in Figure 3.2.

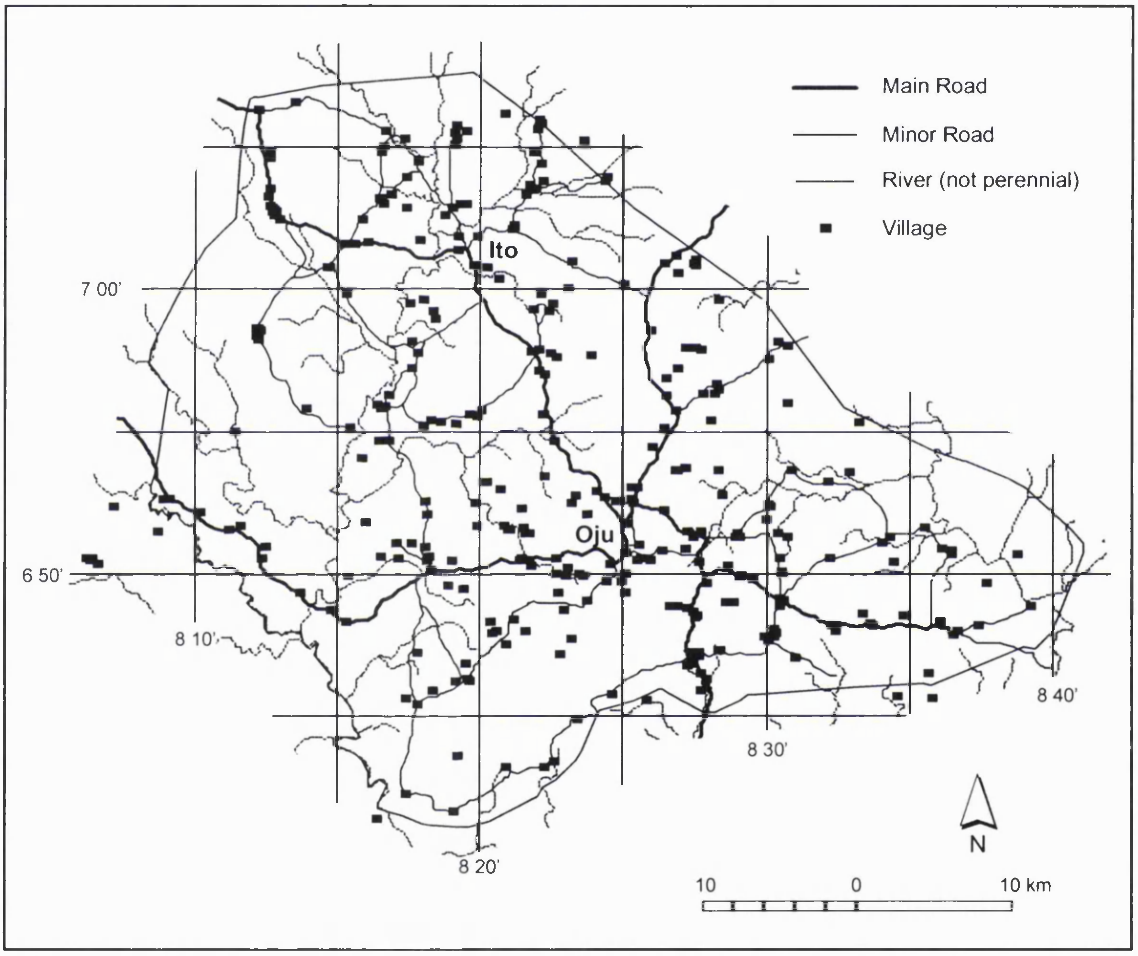


Figure 3.2 Map of the Oju/Obi area, showing the distribution of villages.

3.2.2 Climate and hydrology

The climate and distribution of rainfall has an important bearing on the water supply problems in Oju/Obi. Rainfall data collected at St Joseph's School, Ito, since 1988, indicate a mean annual rainfall of 1600 mm. Average monthly data for the period 1988 to 1993 are shown in Figure 3.3. These data indicate that the wettest months are from May to October with two months, December and January, completely dry. The annual dry season lasts four to five months, but the start of the rains can be unreliable. For example, during 1988, rainfall began in June, whereas in 1990 the first rains fell in March.

The closest meteorological index station to Oju/Obi is at Ogoja [N6° 39', E8° 42'] where rainfall data recorded from 1931 to 1960 indicate a mean annual rainfall of 1800 mm (Tahal Consultants 1982). At Ogoja there is an average of 96 rainy days per year, with only 8 rainy days during the nominal November to April dry season (a rainy day is defined as a 24 hour period with at least trace water in the raingauge). A summary of various meteorological parameters measured at index stations close to Oju/Obi is given in Table 3.1.

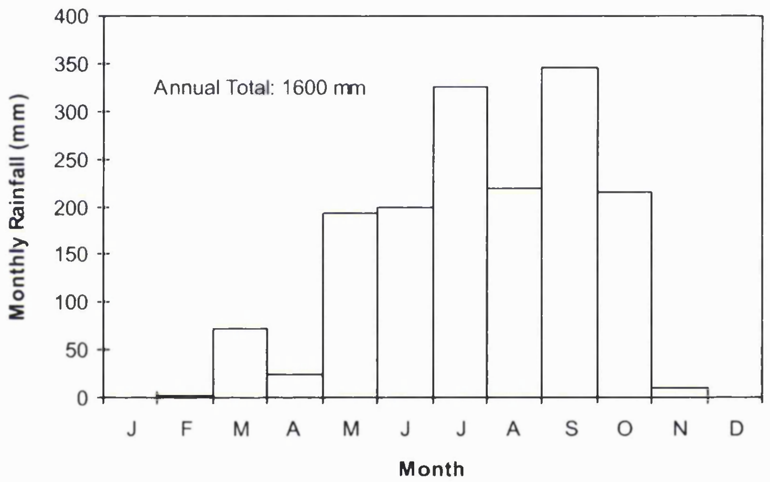


Figure 3.3 Average monthly rainfall for Ito, 1988-1993. Data from St Josephs's school.

Seasonal variations in rainfall distribution across Oju/Obi were investigated using monthly data recorded at seven stations distributed throughout the area. These rainfall monitoring stations were established, mainly at schools, at the beginning of the study. Simple plastic rain-gauges were used at the majority of the stations. These were generally located about 1 m above the roof of the school to keep it away from vandals and to avoid splashes from the roof getting into the rain-gauge. Measurements were made at these locations for one year (1997-1998). At two locations (St Joseph's School and the WaterAid Office) permanent standard metal rain-gauges were installed.

The location of the raingauges and rainfall measurements for 1997-1998 are shown in Figure 3.4. This short dataset illustrates that rainfall changes markedly across Oju and Obi. Highest annual rainfall was recorded at the stations closest to the Wokum Hills. A break in the wet season, locally known as the "August break" was observed at

Table 3.1 Average monthly estimates of various meteorological parameters from the nearest index stations to Oju/Obi.

Meteorological parameter	*J*	*F*	*M*	*A*	*M*	*J*	*J*	*A*	*S*	*O*	*N*	*D*	*Annual*
Rainfall[1] (mm)	13	20	53	119	226	282	191	254	292	292	62	13	1817*
Wet days[1]	1	1	4	8	11	13	11	13	15	15	3	1	96*
Mean daily relative humidity[2] (%)	53	50	60	70	75	80	81	81	80	77	67	65	70**
Mean daily temperature[2] (°C)	25.9	28.3	30.2	30	27.7	26.6	25.9	26.1	26.2	26.6	26.3	24.9	27**
Evaporation[3] (mm)	197	214	278	249	221	188	164	182	158	176	191	189	2407*

[1]Data from Ogoja [6°39' N, 8° 42' E], 1931-1960
[2]Data from Makurdi [7° 45' N, 8° 32' E], 1952-1973
[3]Data from Lokoja and Enugu using a class A pan, 1961-1974
*annual total
**annual mean

most rain-gauge sites. Since only one year's data is available, it is unwise to draw any definitive conclusions about climate from these data.

The locations of the raingauges and rainfall measurements for 1997-1998 are shown in Figure 3.4. This short dataset illustrates that rainfall changes markedly across Oju and Obi. Highest annual rainfall was recorded at the stations closest to the Wokum Hills. A break in the wet season, locally known as the "August break" was observed at most raingauge sites. Since only one year's data are available, definitive conclusions about climate cannot be drawn.

Rainfall events can be intense. Daily records from some of the project rainfall stations show rainfall of between 50-100 mm in a 24 hour period. Often rainfall occurs in 3-4 hour downpours. Similar daily rainfall figures (maximum of 152 mm per day) have been recorded at Lokoja meteorological station (Hayward & Oguntoyinbo 1987). Swami (1970) estimated that 50-60% of Nigerian rainfall comes in rainfall events with intensity greater than 25 mm hr^{-1} – a rate that can readily cause soil erosion (Hayward & Oguntoyinbo 1987).

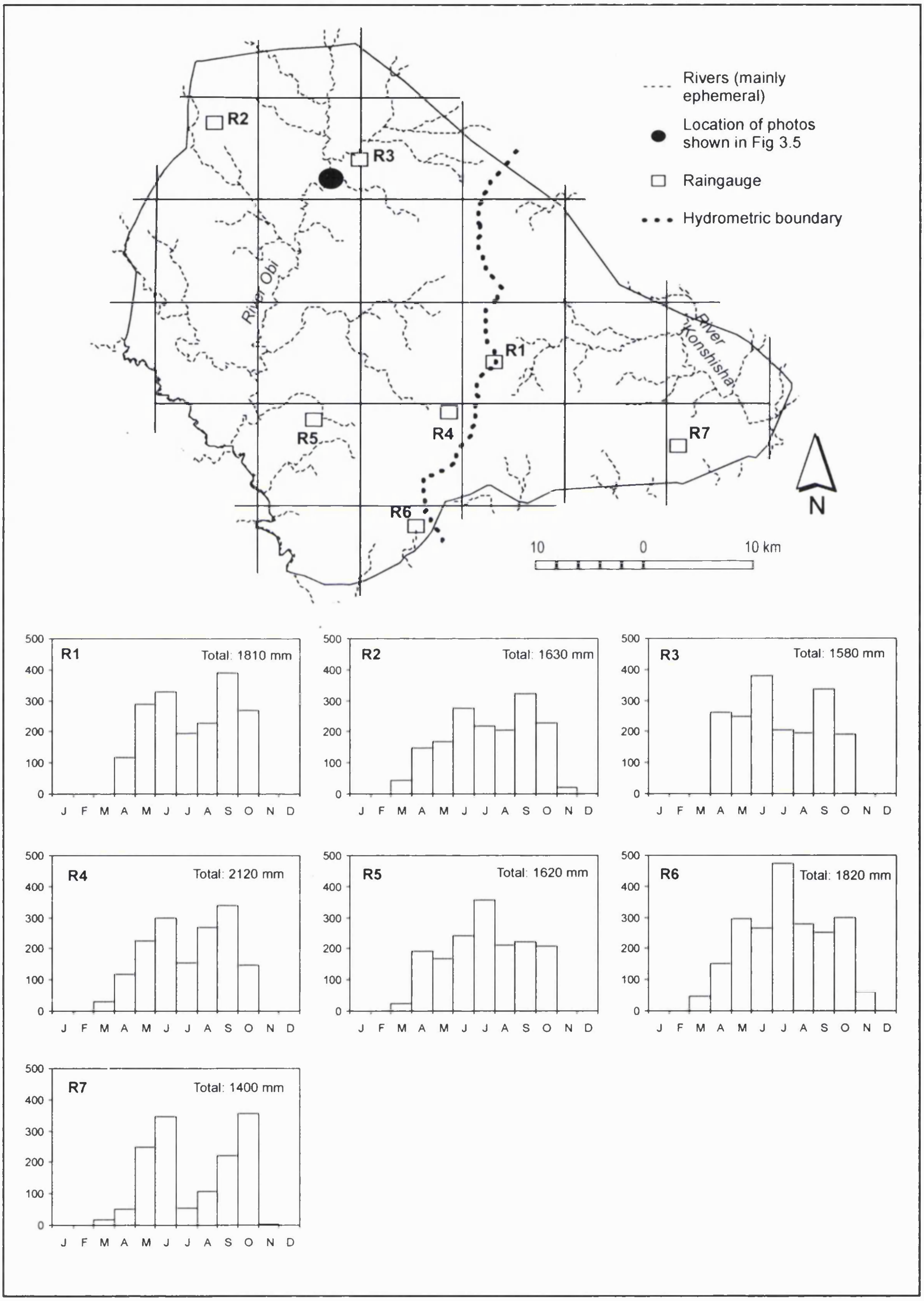


Figure 3.4 Recorded monthly rainfall across Oju and Obi 1997.

The combination of climate, soil and geology produce distinctive hydrology in Oju/Obi. During the wet season, storm rainfall causes short-term flash floods – the result of rapid surface water run-off. Most of the rivers and streams are ephemeral, drying up soon after the rains stop. There are no river gauging stations within, or close to Oju/Obi, therefore all discussion of the river system is based on visual observations made from 1996 - 1999.

Oju/Obi lies within the northern part of the Cross River Basin, which drains south to the Gulf of Guinea. The two largest rivers are the Obi, to the west and the Konshisha to the east. These rivers tend to be entrenched with limited river gravel deposits. Aerial photographs show different drainage patterns across Oju and Obi (MacDonald & Davies (1998) shows an interpretation of aerial photographs for the Oju/Obi area). In areas underlain by the low permeability mudstones, the drainage density is high and dendritic. On sandstone outcrops, the drainage density is lower.

Seasonal variations in river flow are illustrated using a series of photographs of the Obi River taken at different times of the year (Figure 3.5). During the wet season, flow in the Obi River is substantial. Following intense rainfall, the level of the Obi River rises rapidly to cause widespread flooding. River flow significantly reduces at the end of the rainy season, and by February only isolated ponds are left in the upper reaches of the main river. The lower reaches of the Obi River are perennial and supply a piped water scheme to Oju town when it is functional. All other rivers in the area are ephemeral. Most of the tributary streams dry up completely as the dry season progresses, occasionally leaving small ponds.

Throughout the area - but more commonly on the Makurdi Sandstone - river headwaters tend to form large shallow depressions. These features generally lack woodland, and are marshy during the wet season but dry during the dry season; these are similar to features observed in Central Africa, known as *dambos* (Adams *et al.* 1996). They are often used for dry season water supply. Their precise role within the hydrological system is unclear. Some authors suggest that they store only direct rainfall, others that they gain water from the surrounding interfluves. There is also doubt as to whether they contribute significantly to dry season stream flows. In Oju/Obi some of the dambos contain shallow water towards the end of the dry season.

Figure 3.5 A series of photographs showing the Obi River at various stages of the year: (1) after heavy rainfall; (2) at the end of the rains; and (3) towards the end of the dry season.

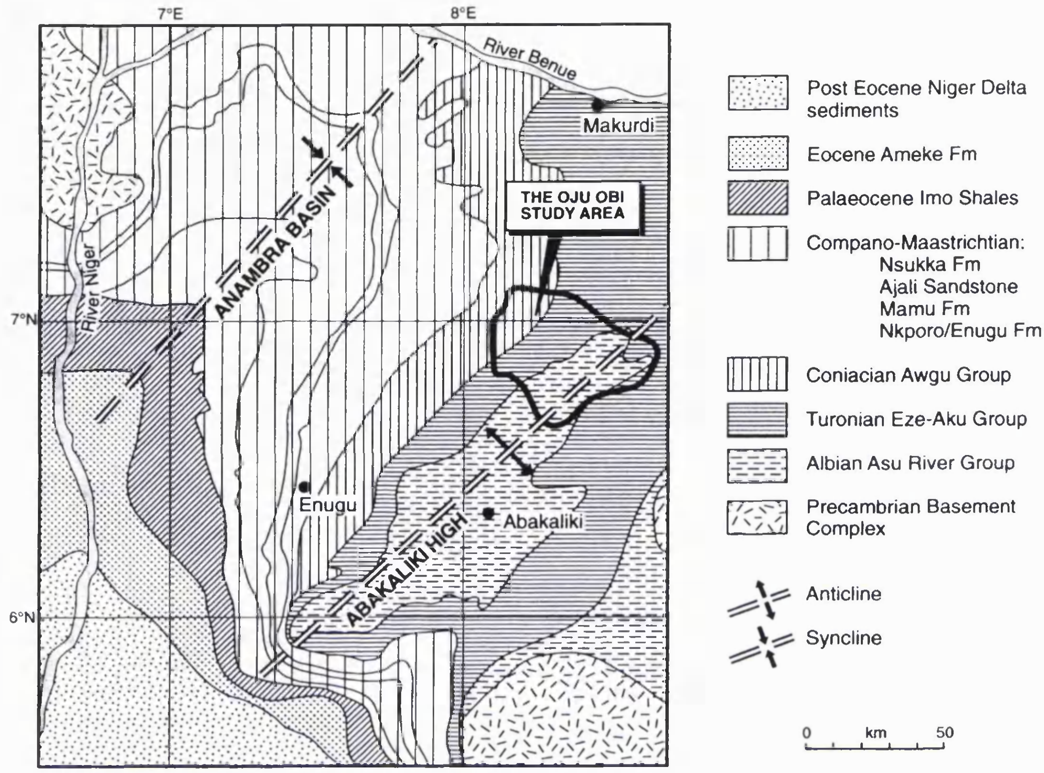
3.2.3 Regional geology

Oju/Obi is situated in the lower section of the Benue Trough. The Benue Trough is a major elongated geological rift structure infilled with Cretaceous age fine-grained, low permeability sediments deposited within a series of basins (Figure 3.6). These were deposited in deep- to shallow-marine and deltaic to fluviatile environments – often during periods of active tectonism. (Kogbe *et al.* 1978; Ofoegbu 1985) Many of the sediments have undergone low-grade metamorphism, and have been folding and faulting to varying degrees. Igneous rocks (mainly dolerite) have been intruded into the sediments. The environment of deposition and also the subsequent history of the rocks have a significant bearing on the water bearing capacities of these low permeability rocks.

Geological exploration of the Benue Trough was stimulated by the search for petroleum in the sedimentary rocks northeast of the Niger Delta. The results of exploratory work undertaken by the Shell/BP Oil Company and others provided the basis of the only published geological maps of the region, produced in 1957 (Geological Survey of Nigeria 1957a ,b).

In Pre-Cretaceous times, Nigeria consisted of an uplifted continental land-mass made up of Pre-Cambrian basement rocks which were then unconformably overlain by Lower Cretaceous Continental sediments (Kogbe 1989). The earliest dated marine transgression occurred during Albian times with the opening of the Gulf of Guinea under the Niger Delta along lines of weakness at edges of the West African and Congo cratons (Nwachukwu 1972, Petters 1978). Sinking along this linear depression (which became the Benue Trough) began by mid-Albian time and continued until late Senonian, interrupted by uplift and folding during late Albian time (Agumanu & Enu 1990).

Currently, the Benue Trough is bound by crystalline basement rocks: the Jos Plateau granites to the north and the Cameroon Basement Massif to the south (Figure 3.6). Cretaceous sediments and igneous rocks, ranging in age from Aptian to Campano-Maastrichtian, infill the trough to a depth of 3 – 6 km (Cratchley & Jones 1965; Benkhelil 1989). The distribution of these rocks within the lower and middle Benue Trough is shown on a geological map (Figure 3.6). Lower Cretaceous sediments are presumed to overlie unconformably Precambrian basement rocks along the Benue Valley (Reyment 1964). Ammonite faunas are used to subdivide the stratigraphy of these Cretaceous rocks (Reyment 1956).



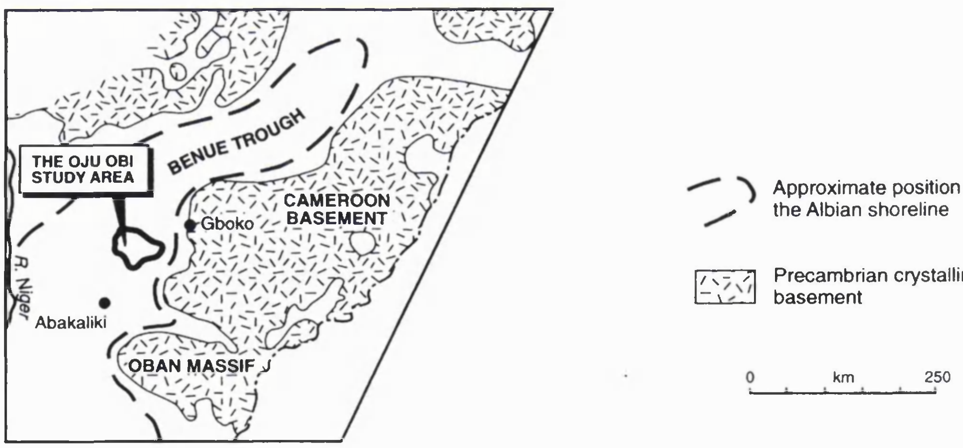


Figure 3.6 Geological map of the southern Benue Trough. Insert shows approximate limit of the Albian Sea (after Davies & MacDonald 1999).

The lithologies and stratigraphical relationships of the sediments found in the Oju/Obi area are outlined in Table 3.2. Their distribution is shown in Figure 3.7 and a cross section in Figure 3.8.

The oldest sediments present belong to the Asu River Group which crops out in the south (Agumanu 1989; Ojoh 1990). There are two distinct parts to the Asu River

Group: (1) the metamorphosed Asu River Formation which comprises hard, splintery shales, sandstones and limestones, with interbedded pyroclastic and intrusive igneous rocks; and (2) the Asu River Formation, 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.

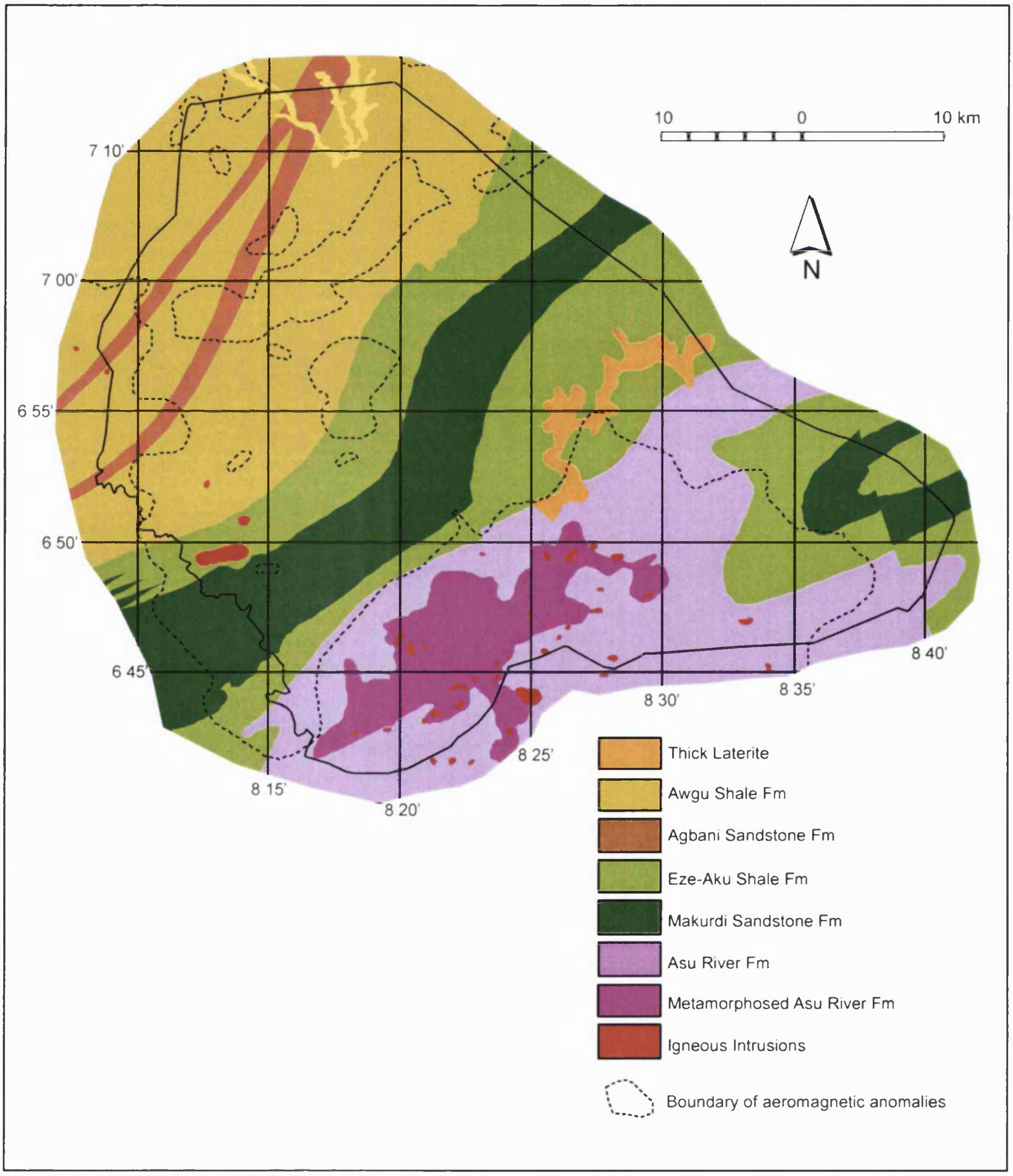


Figure 3.7 Geological map for the Oju/Obi area.

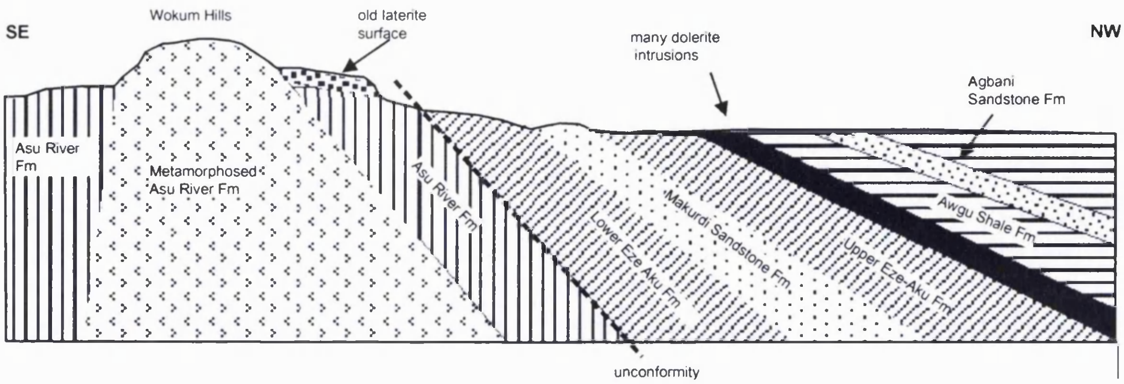


Figure 3.8 Schematic geological cross section through the Oju/Obi area.

The Eze-Aku Group overlies the Asu River Group to the north. This Group is composed of mudstones with occasional limestone, siltstone and sandstone. The mudstone is generally lithified but becomes softer towards the north (Petters 1978; Nwajde 1990; Lawal 1991). The Group is divided into two formations: the Eze-Aku Shale Formation where mudstone dominates and the Makurdi Sandstone Formation where sandstone dominates. The Makurdi Sandstone Formation comprises hard, well-cemented fine- to medium-grained sandstones, interbedded with varying thicknesses of soft shales and occasional limestones (Nwajde 1982).

The Awgu Group, in the north of the area, are the youngest rocks present. This group comprises very soft, shallow marine, carbonaceous mudstones with occasional muddy limestones and siltstones as well as a narrow band of sandstone known as the Agbani Sandstone Formation, which is generally fine- to medium-grained and moderately cemented (Agagu & Adighije 1983; Agagu *et al.* 1985; Petters 1978).

Dolerite intrusions transect the area. These igneous intrusions are associated with both pre- and post-Turonian tectonic episodes (Nwachuku 1972). Although few can be observed at outcrop their presence throughout the north of the area can be inferred from the aeromagnetic measurements (see Figure 3.7). Within the Benue trough compression folding began in Senonian time, forming a series of long, narrow folds parallel to the axis of the basin forming anticlines more than 60 km long. Ofoegbu & Odigi (1990) recognised that structural lineaments in the Benue Trough are dominantly N-S, NE-SW and NW-SE, often crossing one another forming a strong network of shearing fissures and fractures. Figure 3.9 shows major fractures interpreted from a Landsat image for the Oju area.

Table 3.2. Stratigraphic sequence of the Oju/Obi area.

Age	*Group*	*Formations*	*Colour on Fig 3.7*	*Description*
Maastrichtian				Post Maastrichtian NW-SE trending folding and faulting
Campanian				
Santonian				NE-SW trending elongate folds and faulting; igneous intrusions
Coniacian	Awgu Group	Awgu Shale Fm		Shaley carbonaceous mudstones with thin shelly limestones and sandstones
		Agbani Sandstone Fm		Fine to medium sandstones with siltstones and mudstones
Turonian Upper	Eze-Aku Group	Upper Eze-Aku Fm		Shaley mudstones and siltstone with thin sandstones and limestones
		Makurdi Sandstone Fm		Fine to coarse sandstones with siltstones and mudstone
Lower		Lower Eze-Aku Fm		Shaley mudstones and siltstone with thin sandstones and limestones
Cenomanian				Hiatus/unconformity
Albian Upper	Asu River Group	Asu River Fm		Carbonaceous shaley mudstone, limestone, sandstone and siltstone
Lower		Metamorphosed Asu River Fm		Pyroclastics and intrusives with contact metamorphosed mudstone, shale and sandstone
Precambrian Basement				N-S trending faulting

A zone of weathered material (the regolith) some 2 - 20 m thick mantles the Cretaceous age sediments of the Oju/Obi area. The regolith generally comprises a red iron-rich ferruginous soil, overlying a mottled clay horizon. In some locations a thick ferricrete has formed. The thickness and nature of the regolith is highly dependent on the geological and climatic history of the area as wells as the physical and chemical composition of the underlying geology (Fookes 1997).

3.2.4 The water supply problem in Oju/Obi

Although the Oju/Obi area receives high annual rainfall, most of this falls between April and October, leaving five months without significant rain. During the wet season most rainfall runs off as rapid surface flow or percolates through shallow permeable soils to the rivers and 'flash' floods commonly result. Wells that penetrate the shallow soils respond rapidly to rainfall and are generally full of water throughout the rainy season. At the end

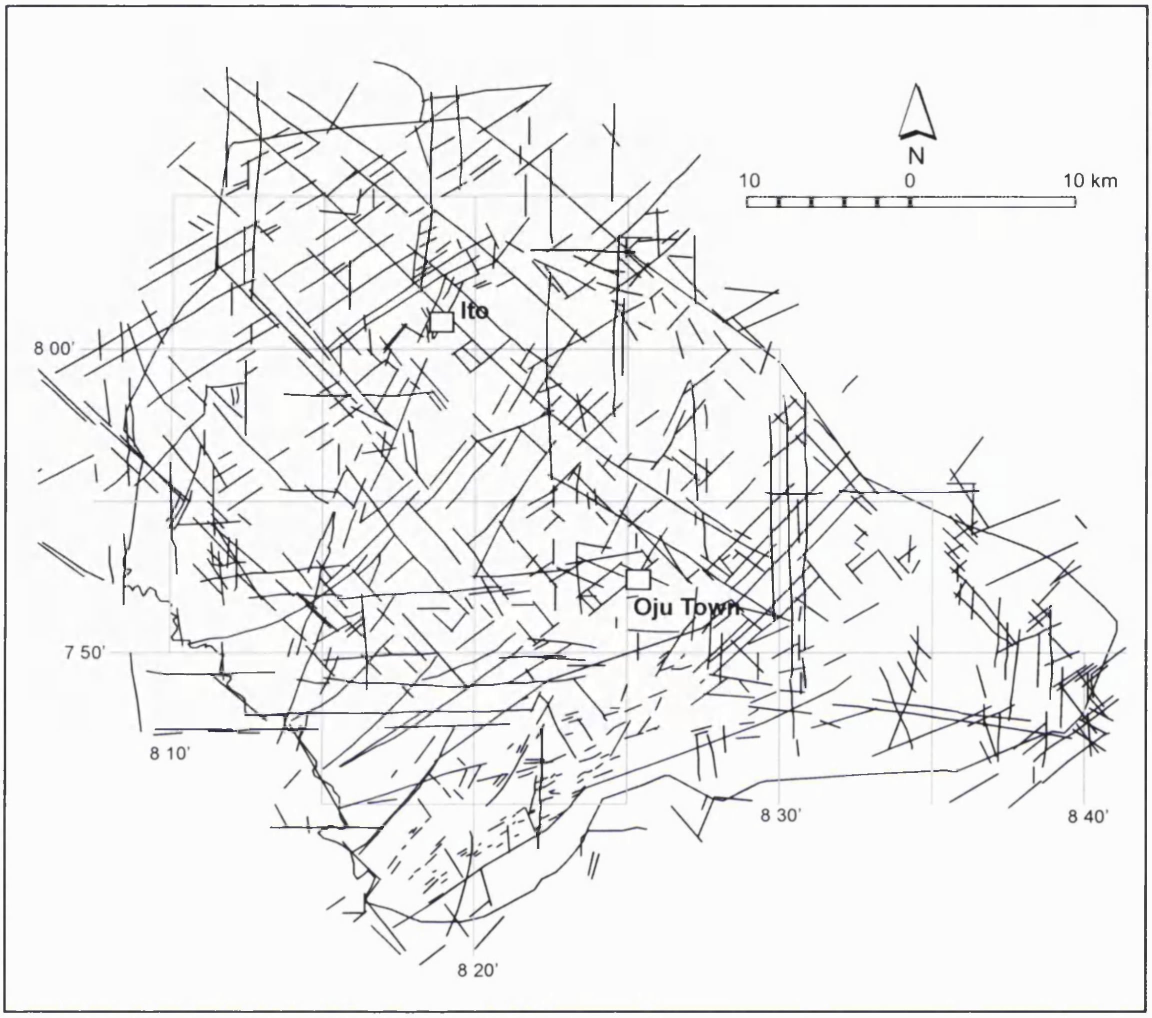


Figure 3.9 Major fracture zones across the Oju/Obi area interpreted from a Landsat image (from MacDonald & Davies 1998).

of the rains, water within the soils quickly flows out of the system, either to streams and rivers or is abstracted from shallow wells; consequently, small rivers and wells dry out.

During the dry season, community members become reliant on unprotected ponds, seepages and hollows as sources of domestic water. These sources tend to become polluted and unreliable as the dry season progresses. As local sources dry up, women and children are obliged to walk to more remote sources for water. During this period, the population becomes increasingly prone to infection by a variety of water-related illnesses, of which guinea worm and dysentery are endemic. Outbreaks of cholera and typhoid are also common. Within Oju/Obi, most of the cases of guinea worm occur in the north. The seasonal dependence on various types of water sources is shown in Figure 3.10. A brief description of the various dry season water sources is given below.

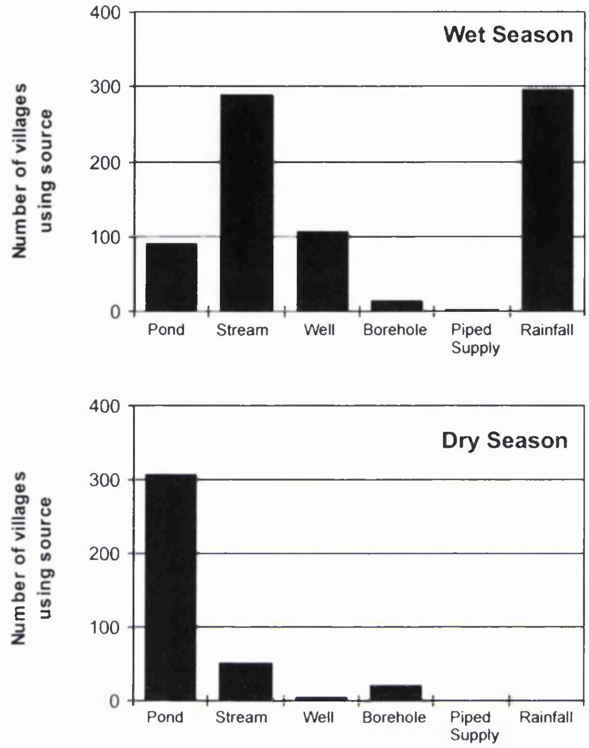


Figure 3.10 Wet and dry season water sources used in villages throughout Oju and Obi (original data from RUSAFIYA survey, 1991 reported in MacDonald & Davies 1997). Note that a village can have more than one source of water.

Stream Seepage (Figure 3.11). During the dry season stream flows diminish, and then cease, leaving isolated pools that eventually dry up. Water is then obtained from shallow pits dug into thin and discontinuous river gravel that yield small quantities of water. As the dry season continues the gravel dries out, and additional pits are excavated further down stream. Studies of stream seepages show that most water is derived from baseflow or stream banks. In the major rivers, the River Obi and Konshisha, isolated ponds and puddles can exist throughout the dry season. The importance of baseflow in sustaining these ponds is unclear. These ponds are a major source of guinea worm.

Figure 3.11 Collecting water from a stream seepage.

Figure 3.12 A pond seepage used for both drinking water and bathing.

Pond Seepages (Figure 3.12). Pond seepages are important water sources occurring within local depressions and along shallow valleys underlain by sandstones and siltstones. As the dry season proceeds, these ponds are cleaned out and deepened as the water level falls. Those that remain in use throughout the dry season often form sites of guinea worm infestation and mosquito breeding areas.

Shallow Hand Dug Wells (Figure 3.13). Unlined wells have been excavated in most communities in Oju/Obi. Although heavily used during the rainy season, many fail during the dry season. Most shallow wells are fed by inflow from shallow permeable soil layers that dewater as the dry season progresses. All wells are heavily over-pumped, contributing to their seasonal failure. Unlined wells tend to collapse due to swelling clays in the near-surface weathered zone.

Figure 3.13 An abandoned shallow hand dug well.

Boreholes. A number of boreholes had been drilled in the Oju/Obi area prior to this project. Most successful boreholes are located in the Oju area within hard and fractured Asu River Group rocks. Some boreholes supply large population groups (>1000) on a rotational basis during annual dry seasons. Unfortunately, borehole breakdowns are common. The main causes of failure are likely to be:

- erosion of pump leathers by fine sediments produced with the pumped water;
- heavy pump usage due to the low yields – this can cause mechanical damage;
- borehole collapse – poor borehole construction and completion can lead to falure.

3.3 Research methods

The Oju/Obi area is well suited as a case study for investigating the hydrogeology of mudstone environments. The geology is diverse, offering many different mudstone environments. The area is located in a sub-tropical environment, which is more representative of the conditions where mudstones are under pressure to be used for water supply than temperate climates. In addition, since the area has a pressing need for groundwater, the investigations will have a direct impact on the livelihoods of local people.

The following sections introduce the research methods and techniques used for the field study in Oju/Obi. The rationale for the methods used is also explained.

3.3.1 Base data

Base data for the area were compiled using a Geographical Information System (GIS). Using a GIS to combine spatial data has many advantages – the ease with which data sets can be compared and ability to undertake spatial analysis being among the most important. A GIS can also be used to make maps, and since all data are held digitally, these maps can be rapidly adapted to the needs of different users. For example, the data can be used to provide a simplified map for the local government and a more scientific map for professional hydrogeologists. An ESRI package, ArcView® v 3.2 (a vector based GIS with raster capacity) was chosen. This can run easily from a desktop or laptop computer, has many useful spatial analytical features.

From the available published maps, aerial photographs, Landsat TM image (LANDSAT TW 188-055, bands 4-5-7, red, green and blue, taken on 17 January 1986), and limited field surveys, the following layers of base data were interpreted:

- topographic contours from 1:50 000 topographic maps;
- roads, paths and rivers from the satellite image;
- geological boundaries from published 1:250 000 geological maps (Geological Survey of Nigeria 1957a, b);
- large magnetic anomalies from published 1:100 000 aeromagnetic maps (Geological Survey of Nigeria 1975a, b, c);
- photo-lineations from aerial photographs and satellite image;

- accurate village locations from a rapid survey using a small hand held Global Positioning System (GPS);
- borehole locations using a GPS.

The various digitised elements of the maps, images and data sets of the Oju/Obi area were combined to produce three maps (MacDonald & Davies 1998 and accompanying CD-ROM): groundwater development map; hydrogeology map; and map showing the interpretation of aerial photograph and satellite imagery. These maps were upgraded during the course of the project, as additional field data became available. The maps were produced at 1:100 000 scale and are generally accurate to about 200 m. A gazetteer of village names, GPS derived locations and approximate populations was compiled and is being used in conjunction with the Groundwater Development Map by WaterAid and the local government as an aid to planning their development programme.

3.3.2 Site selection

Selecting communities to work in can be a source of many problems. There is distinct pressure, especially from local politicians, to target the work to certain villages – usually driven by the location of friends or relatives. Even if communities are chosen for purely scientific reasons, there can be general suspicion that there is another motive at work. These suspicions and rumours can damage projects and make it more difficult to gain the trust of local communities. To try to avoid some of these issues a transparent methodology was developed with the local government and agreed by the local Chairmen. Three criteria were assessed for a subset of 50 villages throughout Oju and Obi: geology, vulnerability and access.

Geology. For the research to be effective a wide range of mudstone environments had to be tested. The basemap was used as a guide and then the geology confirmed for each of the 50 villages with a field visit. On several occasions the boundaries marked on the geological map were found to be inaccurate.

Community vulnerability. The test sites were located within or close to villages. If the test boreholes were successful, they could then be used as production boreholes. WaterAid wanted to ensure that the poorest communities within Oju and Obi were targeted first. Therefore, they developed a system for assessing community poverty and health, which they termed "community vulnerability".

Access. Much of Oju and Obi has very poor roads. Only one road is tarred and few bridges have been strengthened by steel or concrete. Consequently, some places are inaccessible to a drilling rig. Community work on roads and bridges improved access to many of these villages; however, a few remained where much investment was required to make them accessible. These were not considered as exploratory sites.

A query was set up on Microsoft Access, which ranked villages on each geological unit in terms of suitability. The test sites were identified from this list and then agreed with the local government and local communities. This process did not compromise the scientific objectives of the investigation in that each mudstone environment was investigated – this was a non-negotiable part of the site selection. However, the process did take considerably longer than if scientific criteria alone were used. The general trust and agreement that the procedure engendered was worth the time invested in the process.

3.3.3 Geophysics

Rationale

Prospecting for groundwater supplies using geophysics is well established. In Europe and the United States, research is focused on detailed 2-D and 3-D imaging techniques to track the migration of contaminants within groundwater (e.g. White & Barker 1997). Geophysical methods are also widely applied to locate groundwater in superficial deposits (e.g. Frohlich & Kelly 1985; MacDonald *et al.* 2000). Occasionally, if aquifer geometry is straightforward, some geophysical data can be interpreted to estimate aquifer parameters, such as porosity or transmissivity (MacDonald *et al.* 1999).

In sub-Saharan Africa geophysical methods have proved an invaluable tool for siting wells and boreholes in crystalline basement aquifers (e.g. Beeson & Jones 1988; Olayinka & Barker 1990; McNeill 1991; Carruthers & Smith 1992; Barker *et al.* 1992). In particular, frequency domain electromagnetic (FEM) and direct current resistivity methods are being used regularly in many rural water supply projects. In a major review of the effectiveness of geophysical methods (mainly on crystalline basement) van Dongen & Woodhouse (1994) concluded that the use of FEM can give considerable cost savings. Surveying with FEM 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 have been developed and successfully used on many projects (Beeson & Jones 1988, Hazell *et al.* 1988, Hazell *et al.* 1992).

One of the main factors controlling the choice of geophysical equipment to test during the study was simplicity of use and easy of interpretation. Although more sophisticated methods may actually give a better image of the subsurface, their applicability to community water projects in rural Africa is limited. The aim was, therefore, to find techniques that were both simple but effective.

With this in mind, three different geophysical techniques were tested in the mudstone environment of Oju/Obi: (1) measuring ground conductivity with frequency domain electromagnetic methods (FEM) using the Geonics EM34 instrument; (2) vertical electrical resistivity sounding (VES) using the ABEM terrameter and (3) magnetic profiling (using a proton precession magnetometer). Both FEM and resistivity are well-established techniques for siting wells/boreholes in crystalline basement areas. Their operation is well understood by most hydrogeologists working in sub-Saharan Africa, and equipment is generally widely available. There is seldom requirement to use magnetic techniques, in community water projects. However, since dolerite intrusions form an important part of the geology in Oju/Obi, and the technique is straightforward, it was thought appropriate to at least test the method.

An introduction to the various methods is given here. Chapter 7 discusses the appropriateness of geophysical siting techniques in mudstone environments in considerably more detail. During the project, 75 km of FEM surveys, 50 km of magnetic profiling and 30 vertical electric soundings were undertaken (see Table 3.3 and Figure 3.14 for more details). The surveys were correlated with the geological logs from boreholes to establish methods of interpreting geophysics in Oju and Obi.

Ground conductivity (using FEM)

FEM methods measure the bulk electrical conductivity of the ground by passing an alternating electromagnetic (EM) field over and through the ground and measuring the secondary EM field produced. Figure 3.15 illustrates the basic principles. The time varying EM field generated by the transmitter coil induces small currents in the earth. These currents generate a secondary electromagnetic field, which is sensed (along with

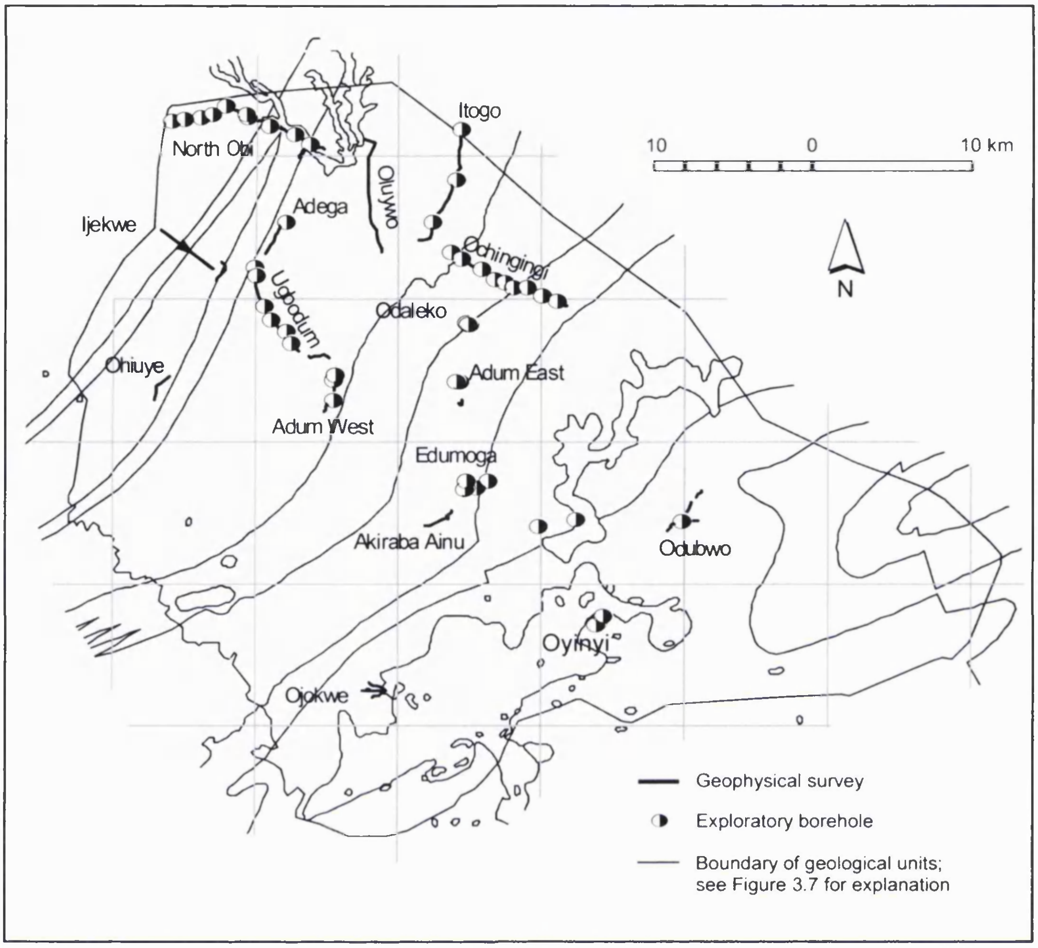


Figure 3.14 Location of exploratory boreholes and geophysical surveys across the study area.

Table 3.3 Geophysical surveys undertaken in Oju and Obi.

location	*N-ing*	*E-ing*	*Length EM34 surveys*	*Length magnetic surveys*	*No of VES surveys*	*exploratory boreholes*
Ochingingi	7 00	8 23	8.2 km	8.2 km	3	BGS 4 - 12
Edumoga	6 53	8 22	4.5 km		4	BGS 14 - 18
Adum West	6 57	8 18	3 km	3 km	3	BGS 33 - 35
Odubwo	6 52	8 30	7 km	3 km	2	BGS 1, 2 a,b
Ojokwe	6 46	8 19	5 km	4 km	1	none
Ohuiye	6 57	8 11	1.5 km	1.5 km		none
Ijokwe	7 01	8 14	1.5 km	1.5 km		none
Akiraba-Ainu	6 52	8 22	2 km	1 km	1	none
Adega	7 03	8 16	3 km		1	BGS 32
Odaleko-Adeko	6 59	8 22	3 km	0.6 km	3	BGS 3, 3a, 13, 13a
Adum East	6 57	8 22	1.5 km		2	BGS 36 - 38
North Obi	7 07	8 13	12 km	5 km	10	BGS 22 - 31
Itogo	7 04	8 02	8 km	8 km	3	BGS 47 - 50
Oluywo	7 03	8 19	8 km	8 km		none
Ugbudum	6 59	8 15	8 km	7 km	6	BGS 40 - 46
Oyinyi	6 49	8 27	3 km	1.5 km	3	BGS 19 - 21
		Total	**79.4 km**	**52.3 km**	**42**	

the primary field) by the receiver coil. The intercoil spacing and operating frequency are chosen so that the ratio of the out-of-phase (quadrature) component of the secondary field to the primary field is linearly proportional to the ground conductivity (at medium to low conductivity). This is discussed in considerably more detail in Chapter 7. The ground conductivity is calculated by assuming a linear relation with the ratio of secondary and primary fields and is known as **apparent conductivity**.

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.

Changing the orientation of the transmitter and receiver coils, and therefore dipoles, alters the response of FEM equipment (Figure 3.16). With dipoles horizontal, much of the response is from the shallow depths, and apparent conductivity is a good estimate of ground conductivity even at relatively high conductivities. With vertical dipoles (horizontal coils) much of the response is from deeper (up to twice as deep as for horizontal dipoles (McNeill 1989)), however apparent conductivity is not a good predictor of ground conductivity at high conductivities. With vertical dipoles there is also a maximum coupling between the primary electric field and any vertical conductors within the ground. This can be used to identify vertical conductors, for example saturated

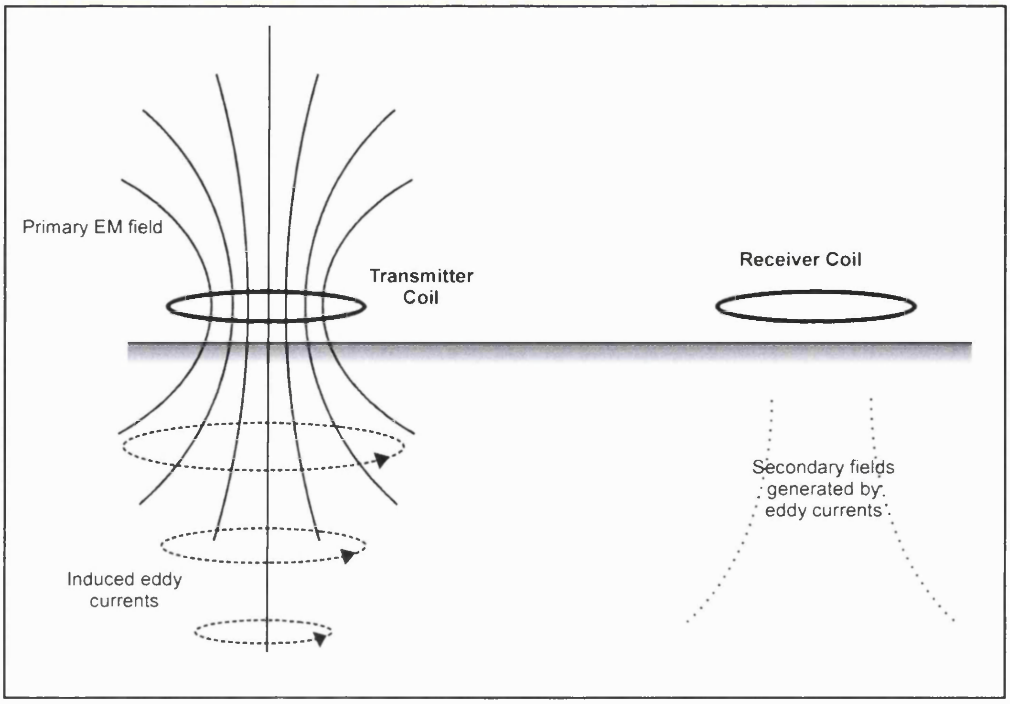


Figure 3.15 A schematic diagram of the general principles of ground conductivity methods.

fracture zones by a characteristic negative anomaly flanked by positive shoulders. 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 (Chapter 7 discusses type of response in considerably more detail).

In this study the Geonics EM34 equipment was used to measure ground conductivity. Photographs of the equipment are shown in Figures 3.17 and 3.18). Two coils are used at standard coil separations (10, 20 and 40 m) with three corresponding

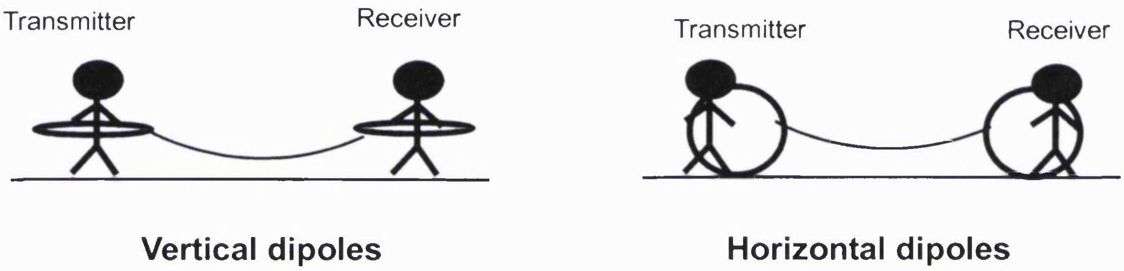


Figure 3.16 The different orientations of FEM equipment.

Figure 3.17 Geonics EM34 equipment, comprising two coils, a connecting cable, transmitter and receiver.

Figure 3.18. The Geonics EM34 equipment used with horizontal dipoles.

transmitter frequencies (6400, 1600 and 400 Hz). FEM measurements were made with coils both vertical and horizontal using a 20-m separation. The vertical coil readings reflect shallow conductivity variations while the horizontal coil readings respond to deeper layers and can also indicate conductive sub-vertical fracture zones. Measurements were taken every 20 m, reducing to 10 m or 5 m to detail significant anomalies. Apparent conductivity is quoted in this study in milli-Siemens per metre ($m.Sm^{-1}$). Conductivity (s) is the reciprocal of resistivity (ρ) measured in ohm metres, the units being linked by the relationship $s \times \rho = 1000$. (Conductivity is sometimes quoted as millimhos per metre, $mmhos.m^{-1}$, which is equivalent to $m.Sm^{-1}$).

Electrical resistivity

The resistivity technique is the longest established geophysical method used to site wells and boreholes in Africa. The technique involves passing an electrical current into the ground between a pair of electrodes and measuring the potential difference between two similar electrodes. From these two measurements, and knowing the geometry of the electrode configuration, a value of electrical resistivity can be calculated.

There are two main survey modes: profiling and depth sounding. Resistivity profiling is a relatively slow process and has largely been superseded by FEM 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 one-dimensional 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. In the present study depth soundings were used to assist with the interpretation of some FEM 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 1-2 people. Photographs of resistivity surveys are shown in Figure 3.19 and 3.20.

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.

Figure 3.19 ABEM Terrammeter and cables used for resistivity surveys.

Figure 3.20 Midpoint of a survey within a village in Oju.

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 here 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/Obi, they are easily distinguished from the poorly magnetic sediments.

The instrument used in this study is the proton precession magnetometer (PPM). The operation and principles of this equipment are explained in Breiner (1973) and Telford *et al.* (1990). The main benefits of the PPM are its portability and 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 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 highly accurate magnetic surveys 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 FEM surveys were undertaken concurrently, with the magnetometer lagging 100 m behind the FEM to avoid mutual interference. Magnetic readings were taken every 10 m, with infill to 1 m over anomalous features.

3.3.4 Drilling programme

Test sites

Two options were available for the drilling programme: (1) to drill two detailed boreholes at each test site, or (2) to drill more boreholes at each test site, but get less information from each borehole. Under the first option a production borehole would be drilled with a cored observation borehole several metres away. This would give detailed geological information and allow the possibility of carrying out pumping tests with observation boreholes. This approach was taken for the first two sites, Odubwo and Odaleko (see Figure 3.14). However, it was soon apparent from the geophysical surveys that the geology often changed markedly across a village. Therefore, carrying out a detailed study of just one part of the village would give a highly partial impression of the geology and thus the groundwater potential. For the rest of the drilling programme, the available time and resources were used to drill as many boreholes as possible.

At each test site, changes in geology could be identified from the geophysics surveys. Potential drilling sites were identified on each distinct geophysical signature.

These sites were then discussed with the local community and the final locations cleared for drilling.

Drilling and sampling methods

In all, 53 exploration boreholes were drilled throughout Oju/Obi. Various data were collected from the boreholes (see below) and, where sufficient groundwater was encountered, boreholes were constructed to permit test pumping. Boreholes with sufficient yields of good quality groundwater were fitted with handpumps by WaterAid. Locations of exploration boreholes are shown in Figure 3.14 and details given in Table 3.4.

The drilling rig used was a lightweight Dando GEOTEC-5 hydraulic top drive rig, mounted on a Bedford truck, with sufficient capacity to drill 6.5" boreholes to 100 m using 3.5" API drill rod. The drilling system uses compressed air flush with tricone rock roller bits, drag bits, coring bits and down the hole hammer; compressed air is supplied by a 600 cfm 150 psi Ingersoll Rand rotary screw mobile compressor. A second Bedford truck equipped with a hydraulic crane formed the main support vehicle.

The boreholes were drilled using tricone or drag bit through the soft weathered horizon, changing to down-the-hole hammer where the rocks became harder. Generally, the last three metres of each borehole were cored. This allowed drilling to proceed rapidly while collecting sufficient geological information for analysis. Various parameters were recorded during the drilling; these are outlined below.

Penetration logs. The time taken to drill 0.5 m intervals were recorded and plotted. Distinct hard and soft bands can be identified.

Rock chip samples. Rock chips produced during drilling using rotary air flush or down-the-hole hammer were collected at 0.5 m intervals and lithologically logged (Tucker 1980).

Core samples. Rock core sampling of the sediments and the softer igneous rocks present was undertaken using tungsten carbide insert bits and airflush. In general, up to 3 m of 3-inch diameter core was obtained from the base of most boreholes, although several were cored from the surface. These samples were stored in wooden boxes made locally. The core samples provided a true indication of the non-weathered nature of rock formations present and the degree of fracturing.

Table 3.4 Summary information on the exploration boreholes.

Bh ID	*Location*	*Northing*	*Easting*	*Geological Formation*	*Date drilled*	*Depth (m)*	*status*
BGS1	WaterAid	6 52.31	8 26.152	Asu River	17/11/97	12	screened
BGS2	Odubwo	6 52.27	8 29.87	Asu River	20/11/97	63.7	screened
BGS2A	Odubwo	6 52.27	8 29.87	Asu River	22/11/97	20.8	backfilled
BGS2B	Odubwo	6 52.27	8 29.87	Asu River	23/11/97	19.5	screened
BGS3	Odaleko	6 59.195	8 22.312	Upper Eze Aku	26/11/97	60.7	backfilled
BGS3A	Odaleko	6 59.195	8 22.312	Upper Eze Aku	29/11/97	16	backfilled
BGS4	Ochingini	7 01.700	8 21.822	Upper Eze Aku	01/12/97	12.7	screened
BGS5	Ochingini	7 01.441	8 22.166	Upper Eze Aku	02/12/97	23.4	backfilled
BGS6	Ochingini	7 01.091	8 22.847	Upper Eze Aku	03/12/97	19	screened
BGS7	Ochingini	7 00.754	8 23.313	Makurdi (sandstone)	04/12/97	16.5	screened
BGS8	Ochingini	7 00.615	8 23.666	Makurdi (limestone)	05/12/97	13.1	screened
BGS9	Ochingini	7 00.460	8 23.982	Makurdi (sandstone)	06/12/97	5.8	backfilled
BGS10	Ochingini	7 00.441	8 24.437	Makurdi (shales)	08/12/97	11.4	screened
BGS11	Ochingini	7 00.163	8 24.962	Makurdi (sandstone)	09/12/97	6.05	backfilled
BGS12	Ochingini	6 59.957	8 25.499	Makurdi (sandstone)	10/12/97	15.7	screened
BGS13	Odaleko	6 59.180	8 22.399	Makurdi (sandstone)	24/01/98	87.5	screened
BGS13A	Odaleko	6 59.180	8 22.399	Makurdi (sandstone)	27/01/98	8.3	screened
BGS14	Edumoga	6 53.418	8 22.655	Lower Eze Aku	28/01/98	27.4	backfilled
BGS15	Edumoga	6 53.651	8 23.095	Lower Eze Aku	30/01/98	29.5	screened
BGS16	Edumoga	6 53.433	8 22.342	Lower Eze Aku	04/02/98	29.5	screened
BGS17	Edumoga	6 53.393	8 22.257	Lower Eze Aku	05/02/98	29.5	screened
BGS18	Edumoga	6 53.655	8 22.352	Lower Eze Aku	07/02/98	53	backfilled
BGS19	Oyinyi	6 48.809	8 26.954	mm Asu River	10/02/98	41.5	screened
BGS20	Oyinyi	6 48.279	8 26.899	mm Asu River	12/02/98	41	screened
BGS21	Oyinyi	6 48.99	8 27.173	mm Asu River	13/02/98	38.5	screened
BGS22	North Obi	7 06.277	8 12.009	Awgu	19/02/98	23	backfilled
BGS23	North Obi	7 06.311	8 12.439	Awgu	20/02/98	23.5	backfilled
BGS24	North Obi	7 06.373	8 13.022	Awgu	21/02/98	23	backfilled
BGS25	North Obi	7 06.52	8 13.449	Awgu	24/02/98	21.3	backfilled
BGS26	North Obi	7 06.794	8 13.895	Awgu	25/02/98	23.4	screened
BGS27	North Obi	7 06.395	8 14.567	Awgu	26/02/98	23.35	screened
BGS28	North Obi	7 06.110	8 15.462	Awgu	27/02/98	23.4	backfilled
BGS29	North Obi	7 05.822	8 16.291	Awgu	03/03/98	23.6	backfilled
BGS30	North Obi	7 05.433	8 16.830	alluvium/Agbani ?	04/03/98	23.5	screened
BGS31	North Obi	7 06.395	8 14.567	Awgu	05/03/98	14.5	backfilled
BGS32	Adega	7 02.764	8 16.024	Awgu	06/03/98	32.5	backfilled
BGS33	Adum West	6 57.211	8 17.623	dolerite	09/03/98	18.5	screened
BGS34	Adum West	6 56.521	8 17.665	dolerite	11/03/98	39.5	screened
BGS35	Adum West	6 57.367	8 17.727	dolerite	12/03/98	21.5	screened
BGS36	Adum East	6 57.168	8 22.041	Makurdi (sandstone)	16/03/98	41.5	screened
BGS37	Adum East	6 57.168	8 22.041	Makurdi (sandstone)	18/03/98	18.5	screened
BGS38	Adum East	6 57.143	8 21.946	Makurdi (shales)	18/03/98	41.7	backfilled
BGS39	Elim	6 52.08	8 24.86	Asu River	23/01/99	40.5	screened
BGS40	Ugbodum	7 01.204	8 14.938	Agbani/dolerite	26/01/99	32.01	screened
BGS41	Ugbodum	6 59.809	8 15.229	Awgu	28/01/99	41.5	screened
BGS42	Ugbodum	6 59.345	8 15.499	Awgu/dolerite	29/01/99	32.05	screened
BGS43	Ugbodum	6 59.345	8 15.409	Awgu	30/01/99	31.86	backfilled
BGS44	Ugbodum	6 58.539	8 16.227	Awgu/dolerite	02/02/99	32	screened
BGS45	Ugbodum	6 59.345	8 15.499	Awgu dolerite	03/02/99	19.7	screened
BGS46	Ugbodum	7 0.842	8 14.993	dolerite	05/02/99	32.07	screened
BGS47	Itogo	7 04.287	8 22.162	Agbani/Awgu	06/02/99	31.69	backfilled
BGS48	Itogo	7 5.972	8 22.168	Agbani/Awgu	09/02/99	31.9	screened
BGS49	Itogo	7 5.972	8 22.168	Agbani/Awgu	09/02/99	10.5	screened
BGS50	Itogo	6 59.345	8 21.115	dolerite	10/02/99	31.75	screened

Analysis of rock samples

The chip and core samples taken during drilling were analysed using a variety of techniques both in the field and in BGS laboratories in the U.K.

Washed rock chip samples were logged by noting colour (using Munsell™ Colour Charts), grain size (using standard charts and a hand lens), relative hardness, and the presence of limestone (using nitric acid). Representative chip samples were placed in a core-box with depth marks, to show changes in colour with depth, then photographed and filed.

Core samples were lithologically logged using standard geological techniques (Tucker 1980) recording changes in colour, grain size, hardness and limestone content together with sedimentary structures and joint/fracture systems. Each core run was washed either in the field or at the office and photographed since core samples, especially mudstones, can deteriorate quickly. Representative samples of rock chip and core were then bagged and taken back to the U.K. for the following analyses.

- Thirty-five core samples (mainly limestone and sandstone) were sent for thin section analysis. Each sample was stained with cobaltinitrite and the dual carbonate stain Alizarin Red-S and potassium ferricyanide to distinguish K-feldspar and the various carbonate phases present. The data are presented in Lott (1998) which is described in Appendix 2 and given in full in the accompanying CD-ROM.
- Fifteen sandstone samples were sent for porosity/permeability determination using standard laboratory techniques. Permeability was determined using a gas permeameter and porosity by resaturation.
- A batch of 116 samples from a total of 17 shallow boreholes were submitted for quantitative clay mineral X-ray diffraction (XRD). Sample preparation and methods are given in Kemp (1998) and appended in the accompanying CD-ROM.

3.3.5 Pumping tests

Testing in Oju/Obi is complicated by the low permeability of the rocks. Usual pumps and techniques used on boreholes elsewhere could only be used on the higher yielding boreholes. In addition, the large number of boreholes and limited available time meant that there was only sufficient time to carry out short tests on each borehole. Carrying on the philosophy used for drilling boreholes it was judged better to have short tests carried out in all the boreholes rather than longer tests in only one or two. Simple, appropriate testing systems were devised for the Oju/Obi project. A summary of the tests carried out in all the boreholes is given in Table 3.5. A brief description of the pumping test methods used on the project is given below.

Table 3.5 Test pumping information for Oju and Obi.

Borehole	*Bailer test*	*Test 2 Duration (hr:min)*	*P-rate ℓ.s⁻¹*	*Pump*	*Analysis*	*T* (m².d)*	*Comments*
BGS1	yes					0.3	
BGS2		04:00	1.25	Grundfos	Theis Recovery	4.1	observation borehole data
BGS2B	yes	03:20	0.15	Whale	Theis Recovery	3.5	observation borehole data
BGS4	yes	00:30	0.13	Whale	Theis Recovery	0.7	
BGS6	yes	04:20	0.325	Whale	Theis Recovery	18	
BGS7	yes					0.1	borehole collapsed during test
BGS8	yes					0.4	
BGS10	yes					0.2	
BGS12	yes	05:30	0.14	Whale	Theis Recovery	1	
BGS13	yes	00:10	0.32	Whale	Theis Recovery	0.15	analysis unreliable
BGS13A	yes					0.074	analysis unreliable
BGS15	yes	05:00	0.15	Whale	Theis Recovery	1.6	
BGS16	yes	05:00	0.14	Whale	Theis Recovery	2.1	
BGS17	yes	05:00	0.15	Whale	Theis Recovery	1.4	
BGS19	yes	05:00	1.05	Grundfos	Theis Recovery	6.5	
BGS20	yes	01:00	2.9	Whale	Theis Recovery	27	
BGS21	yes	01:40	0.85	Grundfos	Theis Recovery	3	
BGS26	yes					0.02	
BGS27	yes					0.08	
BGS30	yes					0.36	marked breakaway
BGS33	yes	03:05	3.5	Centrifugal	Theis Recovery	51	
BGS34	yes	00:50	1.1	Grundfos	Theis Recovery	4	
BGS35	yes	05:00	1.15	Grundfos	Theis Recovery	23	
BGS36	yes	03:10	0.14	Whale	Theis Recovery	0.8	observation borehole data
BGS37	yes	03:20	0.14	Whale	Theis Recovery	0.8	observation borehole data
BGS39		05:00	0.13	Whale	Theis Recovery	4.0	
BGS40	yes					0.15	borehole collapsed during test
BGS41	yes					0.25	
BGS42	yes	03:40	0.11	Whale	Theis Recovery	0.8	
BGS44	yes	00:47	0.1	Whale	Theis Recovery	0.1	
BGS45	yes					0.2	
BGS46		05:00	0.65	Centrifugal	Theis Recovery	45	
BGS48		01:30	0.13	Whale	Theis Recovery	0.11	
BGS49	yes					0.04	
BGS50		05:35	0.12	Whale	Theis Recovery	2	
BER1		05:00	0.11	Whale	Theis Recovery	0.4	Extra borehole not drilled by project
BER2	yes					0.002	Extra borehole not drilled by project

*transmissivity quoted from longest reliable test at each location. Data given in accompanying CD-ROM

Bailer tests

A simple, easy to use test system was developed for giving a first approximation of the aquifer properties. The development and testing of this novel test forms a significant part of this thesis and is discussed in detail in Chapter 6. The bailer test is based on the slug test developed by Cooper *et al.* (1967). A locally constructed bailer was used to carry out the test. The amount of water extracted during 10 minutes of bailing was recorded and the water-levels then measured until they recovery to about 75% of their original level. This method differs from standard slug tests in that the water-level does not change instantaneously. (Similar techniques are used routinely in site investigations in the U.K., but are generally only interpreted qualitatively). The resulting recovery curve was interpreted using large diameter well analysis using the computer programme BGSPT[1].

Whale pumps

A simple, low permeability, test-pumping system was designed around 0.15 $\ell.s^{-1}$ capacity Whale pumps. Whale pumps are inexpensive and are powered by a car battery. The pump produces a very steady output at a capacity that roughly relates to the yield of a handpump. The lift of a single pump is limited to 6 m; two or more were connected in series to give a greater lift. The pumps were connected together with hosepipe and the yield measured accurately using a bucket and a stopwatch. The pump system is very easy to use and maintain, and can be easily carried in a landrover. When required, two sets (2 x 2) of whale pumps were installed in a borehole to produce a test yield of about 0.3 $\ell.s^{-1}$. Drawdown and recovery data from the whale pump tests were analysed using Jacob and Theis recovery methods (Kruseman & de Ridder 1990).

Higher yielding testing methods

Most of the exploratory boreholes had low yields that could be tested using the Whale pumps. For the few boreholes with yields greater than about 1 $\ell.s^{-1}$ other testing methods were used. Where water levels were very shallow, a Honda centrifugal pump (capacity of up to 4 $\ell.s^{-1}$ from a maximum depth of 7 m below ground surface) could be used. Where

[1] BGSPT is available at http://www.bgs.ac.uk/bgspt/home.html

Figure 3.21 A pumping test using whale pumps at Ochingini village.

the water level was deeper, a $1\ \ell.s^{-1}$ capacity Grundfos electrical submersible pump was used. This was powered using a 1.5 kv.a portable generator.

3.3.6 Hydrochemistry

Over 150 chemistry samples were taken from throughout Oju and Obi to assist interpretation of the hydrogeology. Two approaches were taken. First, a widespread survey was conducted of any groundwater sources available towards the end of the dry season. Samples were taken from boreholes, shallow wells, seepages and springs. This survey gave data to characterise the groundwater from the various geological units and also showed differences between various sources. Secondly, twelve different sources were monitored throughout the year. Four samples were taken (roughly every 3 months) to show the variation of water from the wet to the dry season.

Most samples were taken from sources that were being used, such as boreholes fitted with handpumps, dug-wells with rope and bucket, seepages with calabash. Samples from exploratory boreholes were taken after at least one hours pumping (borehole volume purged at least three times). Where ponds were tested samples were taken from as close to the centre of the pond as possible and several centimetres below the pond surface.

Wellhead determinations of pH, specific electrical conductance (SEC), temperature and bicarbonate content were undertaken on each sample collected. The Toledo Checkmate M90 was used to measure the temperature, pH and SEC. Total alkalinity (HCO_3) was determined by volumetric titration. Two filtered (by passing through a 0.45 μm membrane) acidified (with aristar grade concentrated nitric acid) and non-acidified 30 ml samples were obtained from each source. The GPS was used to locate accurately the co-ordinates of each sample.

Groundwater samples were submitted for analysis at BGS Wallingford. A comprehensive suite of inorganic major, minor and trace element concentrations were determined. Acidified filtered samples were analysed for major cations, sulphate and selected trace elements by inductively coupled plasma optical emission spectrometry (ICP-OES). Chloride, I, F, Br, NO_2-N and NH_4-N concentrations were determined by automated colorimetry.

3.3.7 Special considerations from working within an NGO environment

The research approach was developed to integrate with the ongoing community water project. The research budget was managed by WaterAid and monitored by social scientists within DFID. This had several impacts on the research – both positive and negative.

Scientists and engineers are often mistrusted in aid projects. This is partly due to excesses in the past, where projects were sometimes driven by engineers with little regard for the wishes of local people. The large dams and reticulated schemes built in this manner have largely been regarded as failing to meet the needs of local people. Even in community water supply projects, engineers have been blamed for using purely engineering criteria for siting wells and boreholes and so compromising a community sense of ownership. Although engineered to a high specification, these water supplies proved unsustainable. In response, the social (or "software") component of community water supply has been emphasised since the 1980s. Various techniques are routinely used to ensure community decision making and ownership thus enabling the community to maintain their water supply after the project has ended (e.g. Davis et al. 1993).

Increased emphasis of community participation and socio-economic aspects of rural water supply has been necessary and valuable. However, the importance of community software threatens to become the new dogma that is emphasised to the detriment of all other aspects of the project. Those that suggest the hydrogeology or engineering aspects of community water supply may be important are seen as regressive and consequently ignored.

Hydrogeological research was a prerequisite to any water supply programme in Oju and Obi. Otherwise there would have been little or no successful water points. However, early in the project, the requirement for any hydrogeologist was questioned month after month. This was partly due to a lack of knowledge, compounded by the innate mistrust of the scientists. These misconceptions were corrected after the scientists had gained the trust of the social scientists and eventually a robust interdisciplinary approach to the project was achieved. However, this process took a considerable amount of time to work through – a factor that should be fully costed in any interdisciplinary project.

Having to work closely with WaterAid and their local partners, the Water and Sanitation Unit (WASU) of the local government, helped dictate the research methods used in Oju/Obi. Every aspect of the research was discussed with WASU, who helped to design the geophysical surveys and choose the test sites. Much effort was spent keeping WASU informed, and making sure that they understood the rationale and methods of research. Although this was time consuming, it had many beneficial impacts on the research. Firstly, it meant that WASU could confidently prepare communities that were used as test sites. As a result, there were very few misunderstandings and relations with the local communities were excellent. Secondly, WASU members were in a much better position to accept and understand the results of the research, since they were involved in its design. Thirdly, continual dialogue with WASU kept the research from heading off on tangents which may not have had direct relevance to community water supply. Finally, the close relation with WASU meant that results of the research were communicated in ways that were relevant to their needs and skills; for example in simple maps, visual aids and workshops, rather than detailed reports.

3.4 Summary

Oju and Obi – two local government areas in Benue State, southeastern Nigeria – were chosen as a study area to investigate the groundwater potential of mudstone environments. The study formed part of a WaterAid/BGS water project funded by DFID.

1. The area is underlain by Cretaceous age rocks comprising mudstones, with subordinate sandstones, limestones and siltstones. Dolerite intrusions also transect the area.
2. Previous water projects in the area had failed to find suitable water supplies.
3. Oju and Obi are predominantly rural and have a combined population of approximately 300 000.
4. During the five-month dry season the area suffers from acute water shortages. Local inhabitants (mainly women and children) are forced to walk long distances for poor quality water.

The various data collected to investigate the hydrogeology of Oju and Obi are described below.

1. A basemap was created on GIS using published geology, aeromagnetic, and topographic maps. A satellite image was interpreted to give the location of rivers, roads and lineations. Villages were located using GPS.
2. Test sites were selected for each geological formation on the basis of community vulnerability indicators developed by WaterAid.
3. Geophysical survey methods were used at each test site. In total: 79 km of electrical conductivity (using the EM34); 52 km of magnetic surveying; and 42 resistivity soundings.
4. Several exploratory boreholes were drilled at each test site; in total 53 exploratory boreholes at 11 test sites.
5. Rock chip samples were taken every 0.5 m and core samples from the deepest 3 m of the borehole. Samples were logged in the field and representative samples taken back to the U.K for further analysis.
6. Exploration boreholes that contained water were screened and cased and various pumping tests carried out. In total 37 boreholes were test pumped.
7. Approximately 150 hydrochemistry samples were taken from existing sources and exploratory borheoles. A simple groundwater and rainfall monitoring network was established throughout Oju and Obi.

Chapter 4

Hydrogeological investigations in Oju and Obi

This chapter presents a synthesis of the geological, hydrogeological and geophysical investigations carried out in each of the geological units in the Oju and Obi area. These provide the basis for the analysis, discussions and conclusions in the rest of the thesis. The chapter does not need to be read in detail for continuity, but is better used as a reference for each of the rock units. The base data, analysis and interpretations for each study area have been collated and presented in a series of eleven BGS Technical Reports (attached in full on the accompanying CD-ROM).

4.1 Introduction

The seven different geological formations in Oju and Obi were investigated using the methods outlined in Chapter 3. Five of the formations are mudstones, and two sandstones. Test sites were also located on dolerite intrusions within the mudstones. Figure 3.7 shows the location of geophysical surveys and exploratory boreholes in relation to the different geological units. Borehole numbers can be cross-referenced with Tables 3.3-5 in Chapter 3.

Much data was generated from these test sites: detailed lithological descriptions, pumping test data, geophysical data and chemistry data. These data have been faithfully recorded, digitised and collated into a series of eleven BGS Technical Reports. The reports form part of a recognised series and will be catalogued and available indefinitely. As a further aid to the reader each report is available on the accompanying CD-ROM.

To help the reader, only an interpretation of the geological, geophysical and hydrogeological data have been given for each rock formation. Lithological information has been combined to produce simplified lithological logs, and this information has been used to provide a geological interpretation for the geophysical surveys. Pumping test data in conjunction with information collected during drilling has been used to give an interpretation of the hydrogeology of each rock formation. Regional geological descriptions given in this chapter rely on a literature review carried out by J Davies and report in Davies and MacDonald (1999).

Information regarding the tropical soil and river gravels are presented in separate sections within this Chapter. Likewise, the hydrochemical data for each rock formation have been presented together in one section to help interpretation.

4.2 The 'Metamorphosed' Asu River Formation

4.2.1 Regional geology

Within the core of the NE-SW trending Abakaliki anticline, the Asu River Group is mainly composed of Middle Albian age deep marine shales that contain an abundant ammonite fauna (Agumanu 1989). Pyroclastic and igneous intrusive rocks of the Abakaliki Volcanics Formation (the oldest volcanic rocks within the lower Benue Trough) are present within the Asu River Group. These harder igneous and metamorphic rocks now form the Abakaliki Hills that extend northeastwards into the south Oju area as the Wokum Hills and are known as the metamorphosed Asu River Formation. The andesitic tuffs, alkali and tholeiitic basalts, spilites, gabbro porphyry and diorite porphyry are related to the initial continental rifting that preceded the separation of Africa from South America during Albian times, 97-81 Ma. The shales, pyroclastic and igneous intrusive rocks were folded during Santonian time and now form the core of the NE trending Abakaliki anticline.

4.2.2 Local geology

The metamorphosed Asu River Group occur in southern Oju. They form a distinct band of hills, the Wokum Hills, which rise to 550 masl. The hydrogeological nature of the metamorphosed Asu River Group was investigated at Oyinyi Iyechi in southern Oju. Three boreholes (BGS19, BGS20 and BGS21) were drilled to about 40 m and rock chip and core samples analysed; borehole logs are summarised in Figure 4.1

At Oyinyi Iyechi the Metamorphosed Asu River Formation comprises hard, splintery, slatey carbonaceous mudstones. Subordinate calcareous meta-sandstones and limestones, thin blocky ash layers, and intrusions of dolerite and gabbro were encountered in the exploratory boreholes. Within the Wokum Hills the fine grained Asu River Group sediments have been altered by contact and burial metamorphism to have a slatey texture (Hoque 1984). Much secondary disseminated iron pyrite has been deposited mainly within sandstone layers because of the metamorphism (Lott 1998). Interbedded pyroclastic rocks and intrusions of blocks of igneous rocks into soft mudstones (e.g. as observed at Ameka) indicate that igneous intrusion was contemporaneous with sediment deposition. The rocks are highly fractured, and the fractures filled with pyrite, calcite and/or quartz.

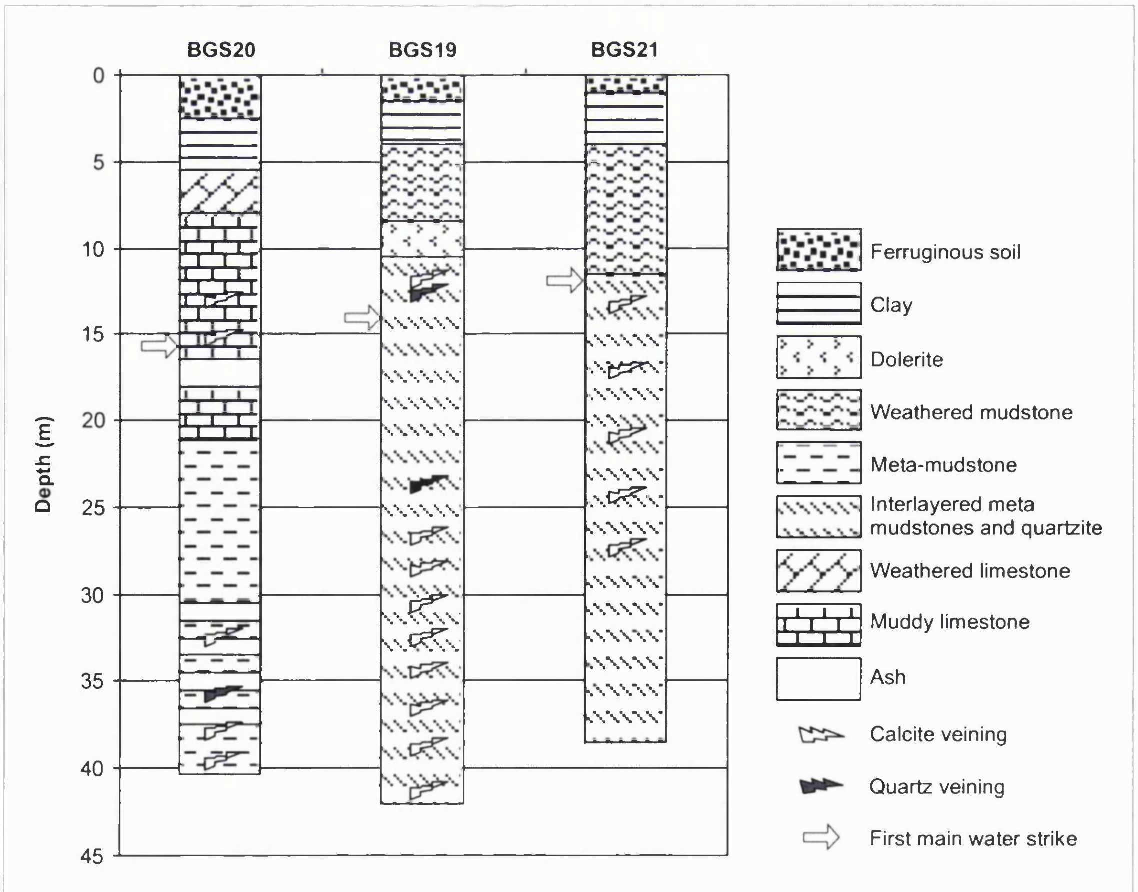


Figure 4.1 Borehole logs for the metamorphosed Asu River Formation at Oyinyi.

A thin ferruginous[1] soil has often developed over much of the metamorphosed Asu River Formation, underlain by a thin clayey layer. Ash, mudstones and igneous rocks are all exposed at the surface, discoloured by recent weathering. The shales are mainly composed of kaolinite and illite clays although interbedded ash layers appear to have weathered to soft smectitic bentonite clay (Kemp *et al.* 1998). Exposures in streambeds and gullies show the rocks highly folded and well jointed.

4.2.3 Hydrogeology

The Metamorphosed Asu River Formation forms one of the best aquifers in Oju and Obi. The rocks have negligible intergranular permeability or porosity, but the high degree of fracturing make them good aquifers. Drilling suggests that the best targets for groundwater are the blocky and highly fractured ash layers, although sufficient groundwater to supply a handpump is widely available. Fractures within boreholes and core samples remain open.

Three exploratory boreholes at Oyinyi Iyechi (BGS19-21) struck groundwater from fractures and/or weathered ash layers at depths between 11 m and 36 m. Several pumping tests were undertaken in each borehole; transmissivity varied from 4 to 40 $m^2.d^{-1}$. The borehole with the highest yield penetrated fractured ash layers, close to a river. The borehole that penetrated solely metamorphosed mudstones and sandstones had the lowest transmissivity, 4 $m^2.d^{-1}$. All three boreholes could sustain a community handpump (6.25 $m^3.d^{-1}$). The limited drilling suggests that the ash layers provide the highest yielding boreholes. As mudstone content increases, particularly where less metamorphosed, boreholes exhibit poorer yields.

4.2.4 Geophysical investigations

Several geophysical surveys were undertaken at Oyinyi Iyechi, including 3 km of EM34 surveys, 1.5 km of magnetic profiling and 3 resistivity VES. A summary of the geophysical surveys and interpretation is given in Figure 4.2.

EM34 readings are generally low (0-30 $mS.m^{-1}$) reflecting harder, metamorphosed and igneous rocks with reduced clay content. Very low EM34 readings and intense

[1] For definitions and descriptions of tropical soils see Chapter 2.

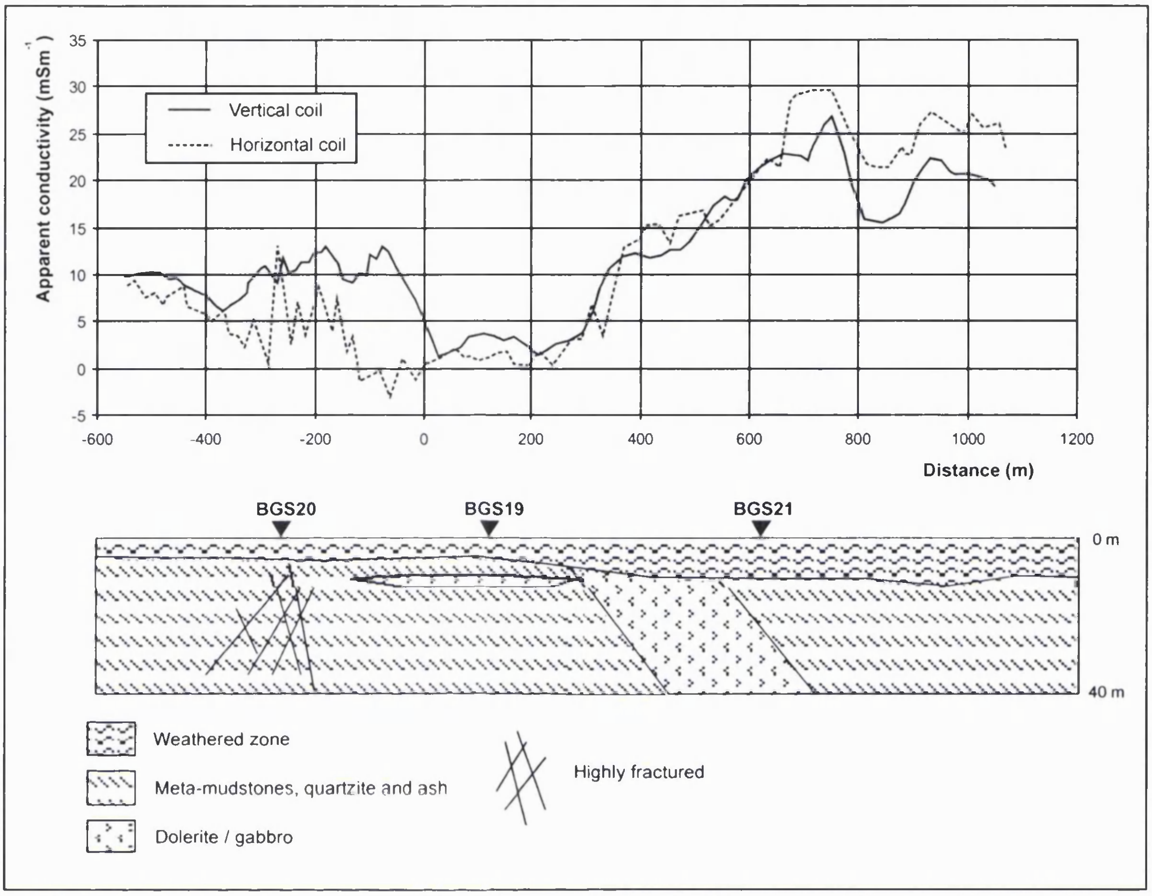


Figure 4.2 Apparent conductivity (using EM34 with 20-m intercoil spacings) for Oyinyi with a geological interpretation based on drilling and the geophysical surveys.

magnetic anomalies are associated with igneous rocks at shallow depth. Higher EM34 readings were associated with shallow weathered mudstone. Very noisy readings with the horizontal coil at -200 m are associated with much fracturing.

Resistivity soundings (VES) carried out at the three borehole sites produced distinctive profiles. At borehole BGS19, where apparent conductivity is low (< 5 mS.m^{-1}), a bedrock of resistivity 900 Ω.m was determined from resistivity. Infinite resistivity was recorded at BGS20, a site that produced much groundwater. Low resistivity bedrock (about 50 Ω.m) was recorded where mudstone was present at shallow depths.

From the geophysical investigations at Oyinyi the following general observations can be made: igneous and highly metamorphosed rocks are identified by low conductivity and high resistivity; igneous rocks can be identified by intense magnetic anomalies; weathered and non-metamorphosed mudstones give high conductivity (low resistivity) and no short wavelength magnetic anomalies. Fractured zones (or dyke swarms) give very noisy signals using EM34 with horizontal coils.

4.3 The Asu River Formation

4.3.1 Regional geology

Middle to Upper Albian age Asu River Group sediments, described by Benkhelil (1989) and (Ojoh 1990) crop-out in and around the core of the Abakaliki Anticline in the Lower Benue Trough. The Middle Albian deep marine sedimentary sequence - about 1400 m thick - is made up of sequences of slumps and turbidites. Each sequence is composed of basal sandstone slumps capped by finely laminated shales and silts or turbidites. This deep marine environment passed progressively into a shale-dominated shelf in the Upper Albian. The Upper Albian is composed of ammonite-rich, black shales with minor siltstones, limestones and sandstones.

Various sedimentary structures are present throughout the Asu River Formation. These include folded cross-bedded lamination, convolutions and micro-breccias. Other deformations are related to pore water expulsion triggered by seismic waves and fluidised intrusions; for example, sand hydro-plasticity, liquefaction, fluidisation and compaction. The distribution and intensity of the deformation structures indicate that they were produced by earthquakes associated with syn-deposition tectonic activity.

4.3.2 Local geology

The Asu River Formation occurs throughout much of central and southern Oju. The geological and hydrogeological nature of the Asu River Formation sediments was investigated at three sites: Odubwo village (BGS2, 2a, b), the WaterAid compound (BGS1) and Elim Bakery (BGS39). Detailed geological logs are summarised in Figure 4.3.

The Asu River Formation comprises moderately hard splintery mudstones and laminated coarse siltstone to very fine sandstone. The sediments have been lithified by burial diagenesis (Lott 1998). Much of the hardened mudstone has a distinct slatey cleavage and contains disseminated iron pyrite. These mudstones are commonly convoluted and folded. Seismites (rocks that have been disturbed by tectonic activity during deposition) and stress-deformed ammonites are also present. Below 10-15 mbgl the mudstone contains many fractures; many of which are filled with calcite. Cores from BGS2a show iron oxide coating fracture surfaces.

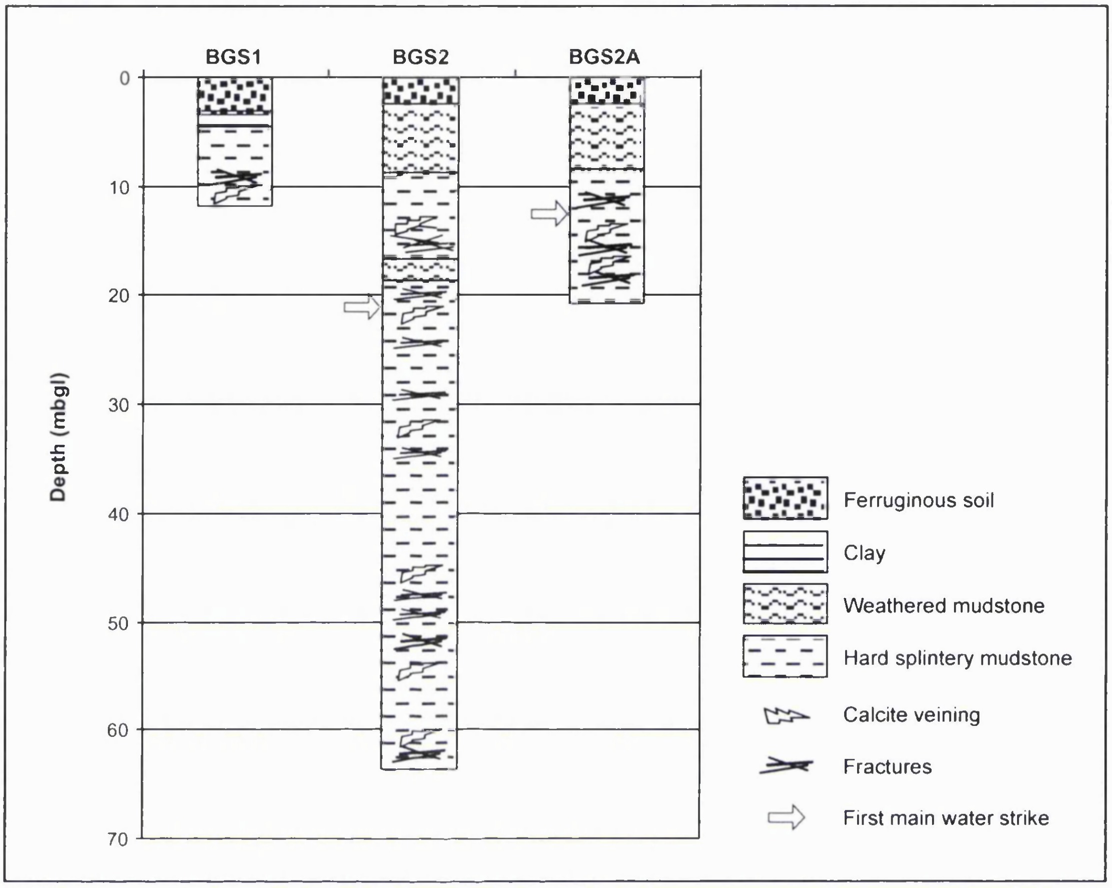


Figure 4.3 Borehole logs for the Asu River Formation at Odubwo and the WaterAid Office.

The top few metres of the mudstone are weathered and contain thin layers of kaolinite clay. Thin ferruginous soils cover much of the outcrop areas. From the few boreholes drilled, it appears that extensive weathering does not extend more than several metres. The shales are mainly composed of kaolinite and illite clays. Rocks of this formation are exposed within stream beds and gullies along the northern flanks of the Wokum Hills where they crop out as hard dark grey lithified mudstones with interbedded hard quartzitic sandstones and thin limestones. The rocks have been folded into a series of tight NE-SW trending structures.

4.3.3 Hydrogeology

The Asu River Formation has favourable hydrogeology for developing groundwater. Groundwater occurs within fractures below 10-15 m. These fractures appear to be widespread. The Asu River Formation sediments underwent lithification due to burial diagenesis and so are moderately hard. Fractures therefore generally remain open. There is no intergranular porosity or permeability within the mudstones. Shallow wells or boreholes that do not penetrate the fracture zones have poor yields.

The two deep boreholes at Odubwo and BGS39 at Elim Bakery all gave transmissivity values of about 4 $m^2.d^{-1}$. Subsequent drilling of 28 boreholes in the Asu River Group commissioned by WaterAid, demonstrated that fractures are widespread. Each borehole could be equipped with a handpump, although the local contractors did not measure yield or aquifer properties satisfactorily (MacDonald 2001). Tests in the 11-m deep borehole (BGS1) drilled at the WaterAid compound gave a transmissivity of less than 0.3 $m^2.d^{-1}$ – this borehole was too shallow to penetrate the highly fractured zone. Water in this borehole (and the adjacent hand dug well) derives primarily from the ferruginous soil.

Two measurements of storage coefficient were made at Odubwo from 4-hour long constant rate tests with observation borehole data, both giving values of 0.0005.

4.3.4 Geophysical investigations

Geophysical surveys were undertaken at Odubwo and at the WaterAid office in Oju, including 7.5 km of EM34 surveys, 3 km of magnetic profiling and 2 resistivity VES.

1. Apparent conductivity measured using the EM34 is generally low, 5-30 $m.Sm^{-1}$ (Figure 4.4).
2. Apparent conductivity increases with longer inter-coil spacings (and therefore deeper penetration). However, with very deep penetration (40-m coil orientated horizontally) conductivity reduces.
3. Resistivity VES prove a resistive soil overlying a 10-20 m thick moderately resistive (40-70 Ω.m) layer that overlies more resistive bedrock. The lower resistivity weathered zone is due to water filled fractures and clay content. A low resistivity weathered layer restricted to a thickness of about 20 m, explains variation in the measured conductivity with inter-coil spacing and coil orientation.
4. Magnetic profiling showed the presence of magnetic rocks at several locations. Unfortunately time did not permit these sites to be investigated by exploratory drilling.

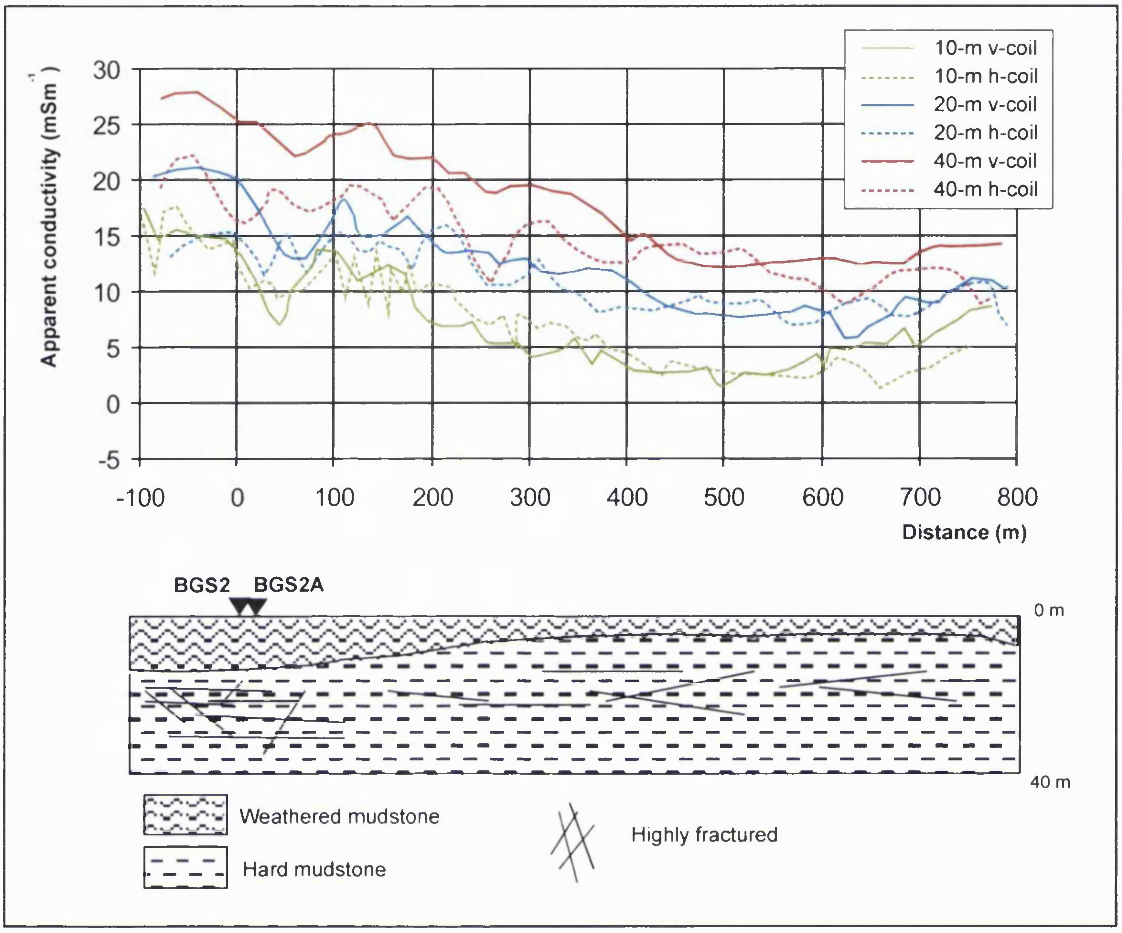


Figure 4.4 EM34 surveys at various intercoil spacings in the Asu River Formation at Odubwo. A schematic geological interpretation is also given from drilling and the geophysical surveys.

4.4 The lower Eze-Aku Formation

4.4.1 Regional geology

The broadly folded Lower Eze-Aku Formation unconformably overlies the tightly folded Asu River rocks. The junction of these formations is not observed at outcrop. The lower part of the Lower Eze-Aku sequence is composed mainly of shaley to silty mudstones whereas the upper part of the sequence contains more sand. Age determinations based on macro-palaeontological evidence indicate that the unconformity may be a distinct break, the Cenomanian Hiatus. Alternatively, Ojoh (1990) suggests, on the basis of micro-palaeontological evidence, that the sequence is continuous but attenuated. The junction may be coincident with an oceanic anoxic event during which marked species extinction occurred that was followed by a change to shallow marine conditions.

The upper part of the Lower Eze-Aku Formation consists of cyclic deposits of cross-bedded quartz-cemented sandstones at base, bioturbated calcite-cemented sandy siltstones, and black carbonaceous shaley mudstones with thin bands of bioclastic limestone at top. The sandstone is typically cross-bedded, with vertical burrows and laminated grey shale partings. The sandy siltstones are cross-laminated and bioturbated. The black shaley mudstones are blocky to well-laminated. Oyster beds up to 0.3 m thick alternate with shales. The sandstones result from sand deposition within a quiet marine environment subsequently reworked by long-shore currents. The siltstones were deposited within a delta-front, near-shore environment. The black shales were deposited beyond the delta front, in quiet anaerobic bottom conditions.

4.4.2 Local geology

The Lower Eze-Aku Shale Formation occurs in a band across northern Oju, which broadens to the northeast. Lower Eze-Aku sediments also crop out in the far east of Oju, although no drilling has yet been done to examine this area (Figure 3.14). The geological and hydrogeological nature of the Lower Eze-Aku Formation was studied at Edumoga village. Five exploration boreholes, BGS14, BGS15 BGS16, BGS17 and BGS18 were drilled to depths of between 27 m and 53 m. Lithological logs are summarised in Figure 4.5

At Edumoga, the Lower Eze-Aku Shale comprises laminated mudstone with significant inter-beds of siltstone, calcareous fine-grained sandstone and limestone. Pyrite and green chlorite are present within the sediments (Lott 1998). Some of the rocks show bioturbation although little other palaeontological evidence was found apart from prominent horizontal burrows and sole marks. The mudstone has been slightly lithified by low-grade metamorphism and is moderately hard.

The shallowest 10 m of mudstone is highly weathered with 3 m of ferruginous soil (containing iron nodules or ferricrete) overlying 2 to 3 m of plastic clay. Below the clay layer to a depth of 12 m the mudstone is soft and discoloured due to weathering. The mudstones are mainly composed of illite/smectite clays (Kemp *et al.* 1998). Fractures were found in three of the exploratory boreholes, each of which contained significant groundwater. Evidence from core and chip samples (significant vein calcite, with gypsum/barytes; slickenslides and fault breccia) shows that the fractures are associated with faults. Many of the fracture surfaces are coated with iron oxides.

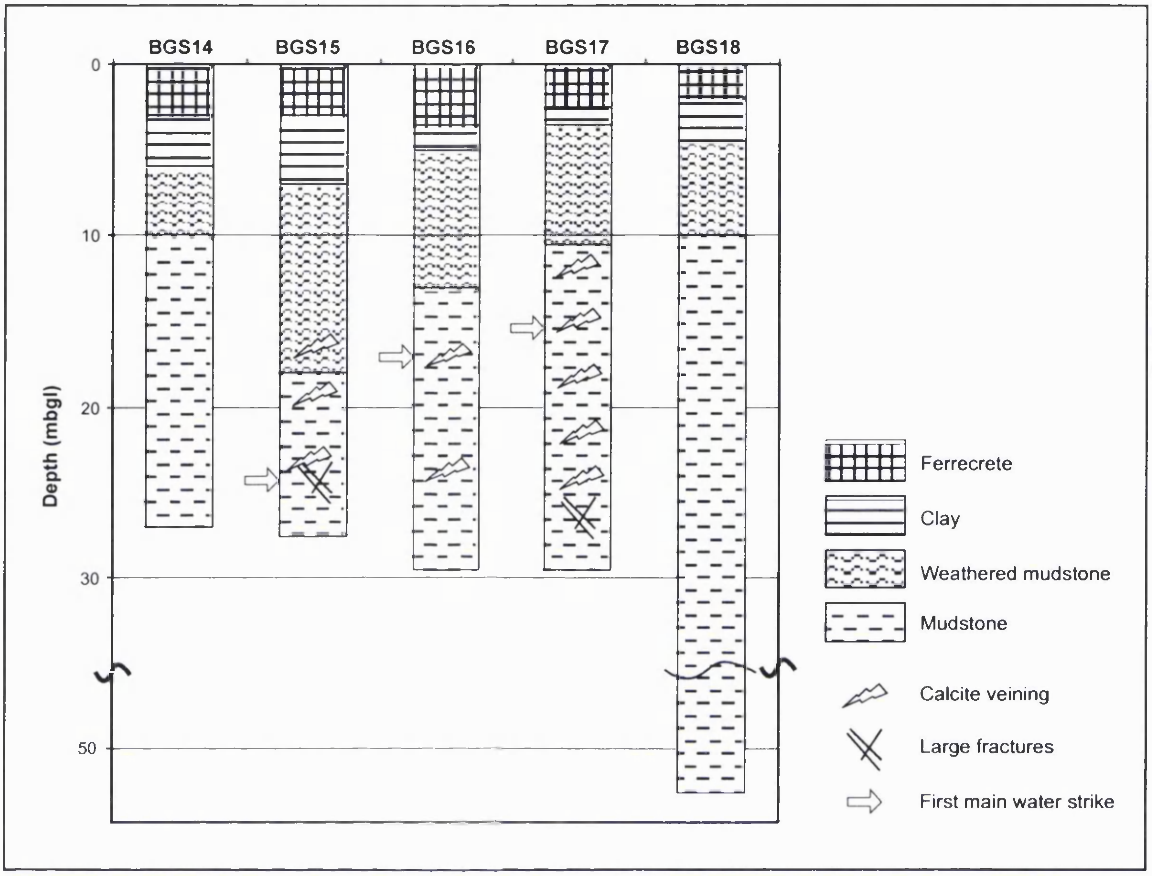


Figure 4.5 Lithological logs for boreholes drilled into the Lower Eze-Aku at Edumoga.

4.4.3 Hydrogeology

Groundwater occurs within fracture and fault zones in the Eze-Aku Shale. However, unlike the Asu River Formation, fracture zones are not widespread. The sediments are too soft for small stress-release fractures caused by weathering denudation to remain open. The lithological logs indicated that the water bearing fractures in the Lower Eze-Aku are associated with faulting and extensive fracturing. There is negligible intergranular porosity or permeability. Limited groundwater also occurs within the shallow ferricrete zone. Numerous shallow hand-dug wells exploit the water within the ferricrete but dry up shortly after the rains stop. Sustainable water supplies can only be gained from sources which encounter fracture zones below 10 m.

Of the five exploratory boreholes drilled, three (BGS15, BGS16 and BGS17) had sufficient water to carry out test pumping. Five-hour pumping tests in each borehole indicated transmissivity values of 1 to 3 $m^2.d^{-1}$.

4.4.4 Geophysical investigations

Various geophysical surveys were undertaken at Edumoga, including 4.7 km of EM34 surveys, 0.3 km of magnetic profiling and 4 resistivity VES. A summary of the geophysical surveys and interpretation is given in Figure 4.6.

1. EM34 apparent conductivity measurements are generally high (40-50 $mS.m^{-1}$) reflecting the moderately soft mudstone. From –500 to 0 m, where the apparent conductivity values are relatively uniform, the rock is generally unfractured.
2. Distinct negative conductivity anomalies or sharp fluctuations in conductivity over a short distance were indicative of highly fractured rock. Three successful boreholes were located on EM34 anomalies. Boreholes BGS16 and BGS17 were located on negative anomalies and borehole BGS15 was located where the horizontal coil recorded sharp fluctuations. Two unsuccessful boreholes, BGS14 and BGS18, were drilled in areas of flat EM34 response, indicating little likelihood of fracturing. These responses are considered in more detail in Chapter 7.

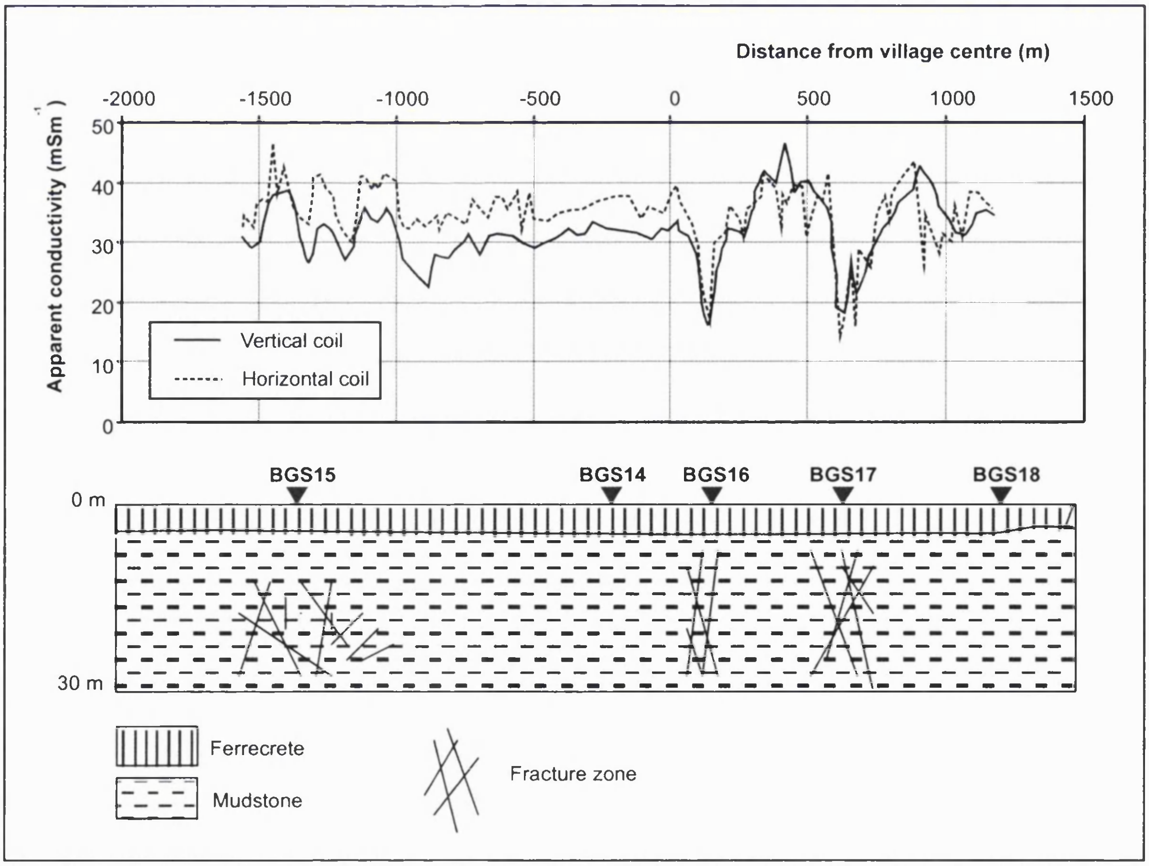


Figure 4.6 Apparent conductivity (using EM34 with 20-m intercoil spacing) for the Lower Eze-Aku (moderately soft mudstone). A geological interpretation from drilling and geophysical surveys is also given.

3. Resistivity soundings (VES) produced consistent results at all five borehole sites, detecting the near surface resistive ferricrete with underlying conductive clays, above weathered- to non-weathered mudstone that becomes more resistive at depths greater than 30 – 40 m. The VES resistivity surveys could not be used to identify vertical fracture zones.
4. Magnetic profiling was of no use in the area, since there are no magnetic rocks.

Fracture zones, the best targets for groundwater, can be identified using the EM34. Negative-going anomalies, or rapidly fluctuating readings with the horizontal coil are likely to indicate the presence of significant fractures.

4.5 The Makurdi Sandstone Formation

4.5.1 Regional geology

The Makurdi Sandstone forms part of the Turonian Eze-Aku Group. They occur across more than 1000 km^2 of territory extending from the Makurdi area to central Benue State. In the type section at Makurdi they form a thick sequence of felspathic sandstones interbedded with marine carbonaceous mudstone and limestone (Nwajide 1986). Poorly-sorted, feldspathic sandstone alternates rhythmically with clay-silt layers. Several-fining upward cycles of deposition have been recognised in the Makurdi Sandstone Formation. Away from Makurdi, the sandstones generally become thinner and fine-grained.

4.5.2 Local geology

The Makurdi Sandstone Formation occurs in a band across central Oju/Obi and roughly corresponds to the boundary between the two local government areas. It forms a prominent ridge at Adum East and Ochingini where the thickest and youngest sandstone crops out. The Makurdi Sandstone is a series of fluviatile sandstone units interbedded with black to dark grey carbonaceous mudstones, siltstones and thin muddy limestones. The sandstone bodies become thicker and more competent higher up the sequence (i.e. towards the northwest). In some instances, the sandstones form high ridges, enhanced by the silcretisation of the near surface sands while the softer mudstones are eroded to form valley like depressions. The Makurdi Sandstone outcrop is also characterised by a series of shallow dry valleys that have formed perpendicular to the strike of the formation.

Because of the shallow water table in these valleys, they form valuable sources of domestic water during the dry season.

The hydrogeological nature of the Makurdi Sandstone was investigated at several locations in Oju and Obi. Six exploratory boreholes were drilled into the Makurdi Sandstone at Ochingini (BGS7, BGS8, BGS9, BGS10, BGS11 and BGS12), two at Odaleko Adiko (BGS13, BGS13a) and three at Anyoga Adum East (BGS36, BGS37 and BGS38). Simplified lithological logs of some of these boreholes are shown in Figure 4.7.

The studies confirm that in Oju and Obi, the sandstone mostly comprises fine- to medium-grained sandstone interbedded with mudstone and occasional thin limestone layers. The sandstone layers vary in thickness from several millimeters to several metres. Sandstone layers are commonly cross-bedded. Load cast features and evidence of bioturbation are also present. Much feldspar is present within the sandstone, although quartz remains the dominant mineral. At Adum East the sandstones are muddy and silty

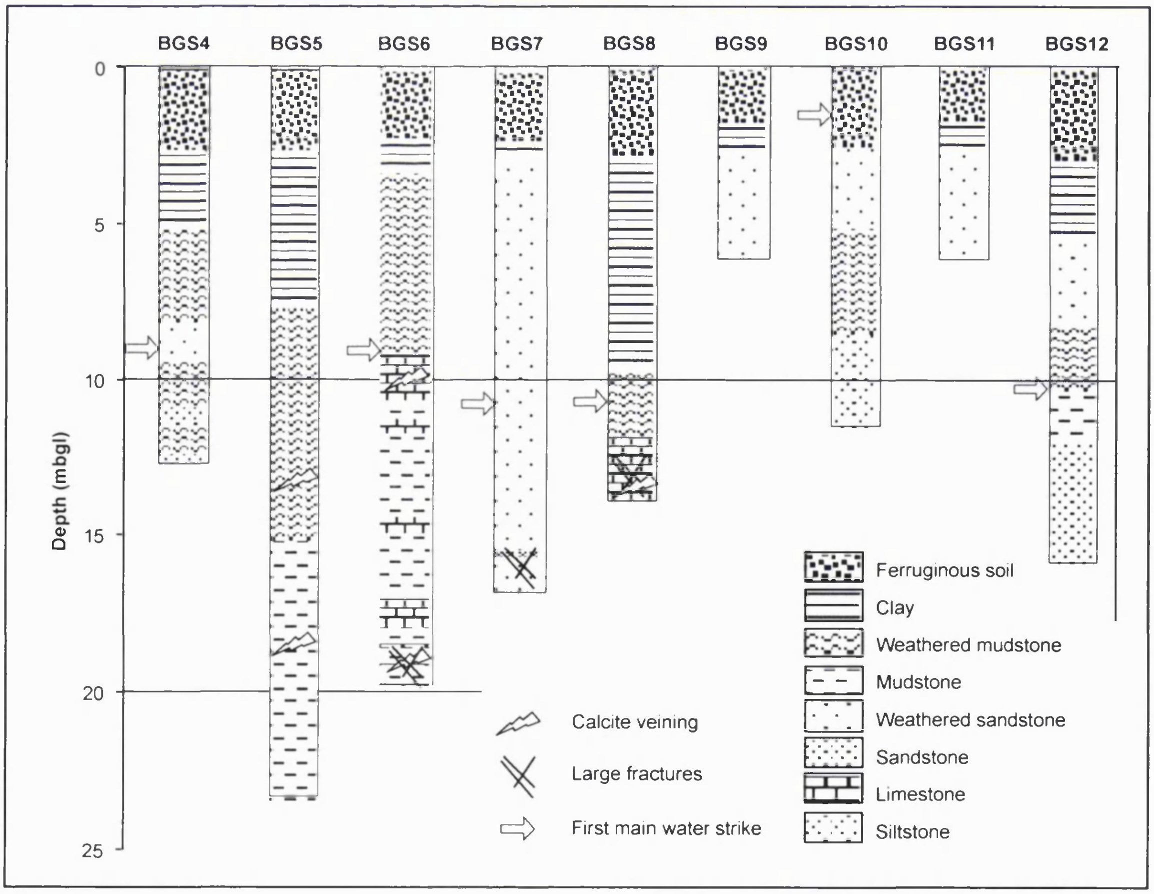


Figure 4.7 Lithological logs for exploration boreholes drilled into the Upper Eze-Aku (BGS4-6) and Makurdi Sandstone Formation (BGS7-12) at Ochingini.

and contain much mica. The sandstone is generally very hard and well-cemented. Limestone layers, such as those noted at BGS8 are commonly shelly and muddy and contain vertical fractures.

A traverse of six boreholes drilled across the outcrop of the Makurdi Sandstone at Ochingini illustrates the variability of the sandstone. Several distinct bands of sandstone are present near the top of the formation which commonly form ridges. Interbedded between these sandstones are thick (possibly several hundreds of metres) sequences where mudstone dominates. Towards the base of the Makurdi Sandstone, sandstone units become much more common, and the interbedded mudstone layers become thinner.

A deep borehole drilled 83 m into the Makurdi Sandstone (BGS13) provides some detailed information about the upper part of the formation (Figure 4.9). Fining upwards sequences, 4-7 m thick, of coarse- to fine-grained feldpathic sandstones capped by black carbonaceous mudstone were observed. A 20-m thick layer of soft, friable homogeneous sandstone was penetrated from 60 to 80 mbgl which appeared to have been deposited under deeper fluviatile conditions.

The rocks are highly weathered over the uppermost 10–12 m. In the shallowest 2-3 m a red ferruginous soil is generally developed. Weathering in the mudstone produces thick clay sequences, with illite/smectite clay to 8-10 mbgl (e.g. BGS8). During the dry season the illite/smectite clay layer tends to crack on drying. Weathering in the sandstone produces a thin clay layer (kaolinite/illite) and discoloured, kaolinised sandstone is present beneath the clay (Kemp *et al.* 1998). At Odaleko and Adum East, silcretised bands are present at depths from between 5-15 mbgl. These thin bands are products of weathering and are extremely hard. Fractures are often present at the base of the weathered zone (from 8-15 mbgl). These fractures are iron-stained and generally allow groundwater seepage. Leaching of feldspar minerals within the weathered zone enhances the porosity of the sandstone.

4.5.3 Hydrogeology

Prior to this study, the Makurdi sandstone was believed to be the best aquifer in the Oju/Obi area. However, drilling at Adum East, Odaleko and along the traverse line south east of Ochingini showed that the sandstone is complex, highly variable and interlayered with thick mudstones. The best targets for groundwater are fractures at the base of the weathered zone (8-15 m deep) and fractured limestone layers where present.

The sandstone has moderate porosity. Core samples taken from seven boreholes gave measurements of porosity varying from 9% to 34 % (median value 16%). Sandstone porosity is enhanced within the weathered zone by dissolution of feldspar crystals leading to the formation of intergranular voids. Unfortunately, these voids may not be well interconnected so that although porosity is high, hydraulic conductivity is often low. Hydraulic conductivity (measured using a gas permeameter) from core samples from the seven boreholes varied from less than 10^{-4} $m.d^{-1}$ to 0.7 $m.d^{-1}$ (median 0.001 $m.d^{-1}$). These measurements indicate a very large range in sandstone hydraulic conductivity. Most samples had insufficient intergranular permeability to provide significant flow in the aquifer. .

Eight pumping tests were carried out in the Makurdi sandstone. Transmissivity estimates ranged from 0.07 $m^2.d^{-1}$ to 1.5 $m^2.d^{-1}$, with a median value of 0.4 $m^2.d^{-1}$. Higher transmissivity values were found in most exploratory boreholes that penetrated sandstone to a depth of more than 12 m. These measurements are much higher than the intergranular permeability would predict. Hence the importance of fractures increasing the transmissivity of the sandstone. Poor yields were measured at BGS10 and BGS38 – both boreholes penetrated thick mudstone layers. Poor yields encountered in BGS7 were due to fine sand clogging the borehole.

4.5.4 Geophysical investigations

Many geophysical surveys were undertaken at Ochingini, Odaleko and Adum East. In total approximnately 10 km of EM34 surveys, 5 km of magnetic profiling and 7 resistivity VES were conducted over the Makurdi Sandstone Formation. These surveys have been correlated with lithology from the exploratory boreholes. Typical EM34 measurements from the different lithologies are shown in Figure 4.8.

1. When the underlying rocks are primarily sandstones the apparent electrical conductivity using a 20-m coil separation is between 10 and 20 $mS.m^{-1}$. Vertical and horizontal coil measurements are similar.
2. Apparent conductivity values in excess of 30 $mS.m^{-1}$ are indicative of the predominance of mudstones. Measurements taken with the vertical coil are often greater than with the horizontal coil.
3. Limestone bands could not be distinguished using geophysical techniques.

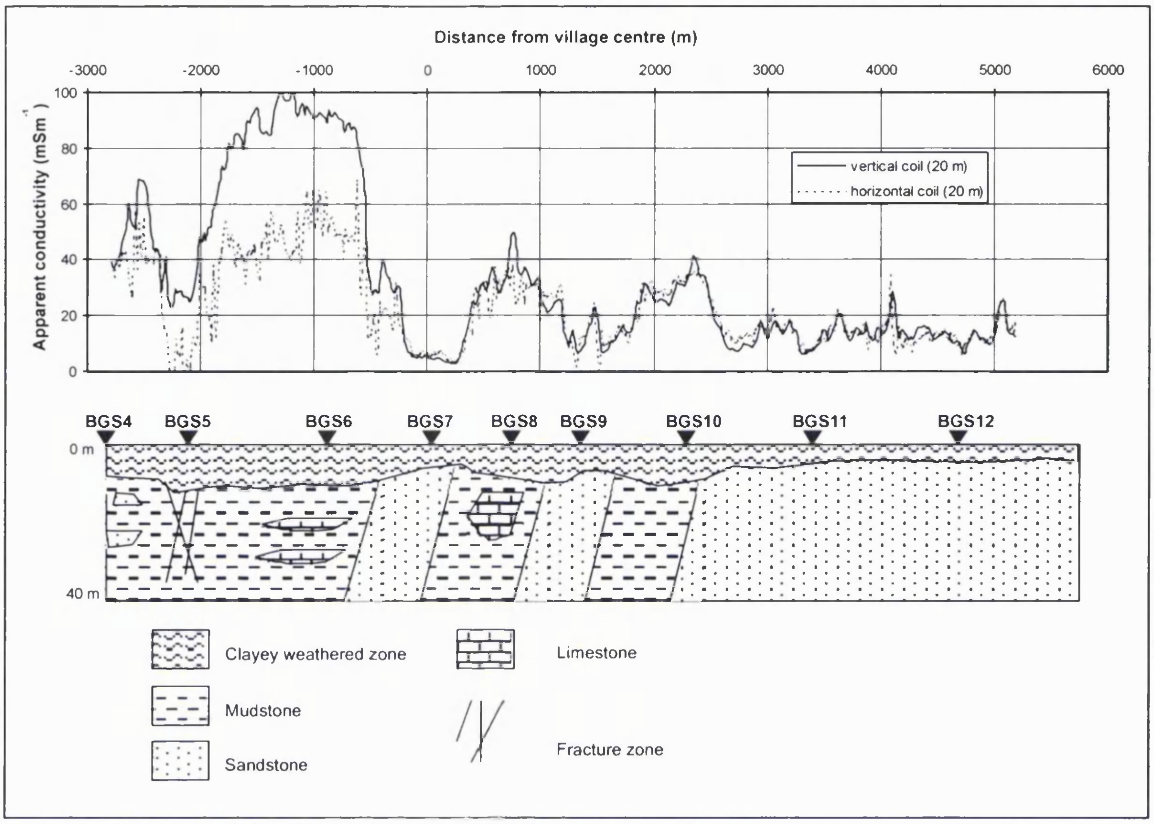


Figure 4.8 Apparent conductivity (from EM34 with 20-m intercoil spacing) for the Upper Eze-Aku (-3000 to -500 m) and Makurdi Sandstone (-500 to 5000 m) at Ochingini. A schematic interpretation is given from the results of drilling and the geophysical surveys.

4. From the investigations carried out, none of the geophysical methods could identify if the sandstone contained fractures.
5. Magnetic profiling is of little use in the Makurdi Sandstone since there is little difference in the magnetic properties of the various lithologies.
6. Resistivity surveys carried out over sandstone and mudstone showed similar profiles: resistive surface layer, conductive middle layer (about 5-10 m thick) and resistive (>80 Ω.m) bedrock. Across the sandstones the middle layer had a resistivity of about 30 Ω.m; across the mudstones this fell to less than 10 Ω.m.

4.6 The upper Eze Aku Formation

4.6.1 Regional geology

The Turonian to Coniacian Upper Eze-Aku Formation comprises bluish black calcareous marine and fluviatile shales with subordinate limestone, calcareous and non-calcareous sandstone and siltstone (Amajor 1987). The black shales are highly carbonaceous, thinly laminated and often pyritic, suggesting anaerobic bottom conditions during deposition. The limestones comprise oyster beds and occur as thin bands that alternate with shales. The sandstones resulted from sand transport into a quiet water marine environment, below the wave-base, with subsequent reworking by long-shore currents. The siltstones were deposited by slow and continuous settling of fine materials over a long period while its sandy variations indicate storm deposits in a subtidal environment. The black shale and interbedded limestone was deposited further offshore than the siltstone in a quiet basin.

4.6.2 Local geology

The Upper Eze-Aku occurs in southeastern Obi. The geological and hydrogeological nature of the Upper Eze Aku formation was investigated at two areas; west of Ochingini (BGS4-6), and Odaleko Adiko village (BGS3, 3a). It may also have been intersected in one of the boreholes in Adum West (BGS34). A summary of geological logs is given in Figures 4.7 and 4.9.

The Upper Eze-Aku Formation comprises soft grey/black carbonaceous mudstones with thin fine- to medium-grained arkosic sandstones and thin, hard, muddy and shelly limestone bands. Limestone bands are generally less than 0.3 m thick. Cores of limestones obtained from BGS6 contained vertical fractures lined with crystals of iron pyrite and calcite. Thin muddy limestone were also encountered at Odaleko Adiko where they were approximately 0.3 m thick. Polygonal vertical fracture systems may extend throughout the limestone bands forming useful zones of secondary permeability. The limestone bands are interbedded with mudstone and siltstone. Soft, black carbonaceous shales and muddy sandstones and siltstones are found higher in the sequence at BGS5 and BGS4 respectively. The changes in sediment type indicate a move from prodelta conditions where limestones were deposited within muds, through more muddy conditions to active deltaic conditions when fluvial sands were deposited within muds.

The shallowest 10-15m in the Eze-Aku Shale is highly weathered. The soil is generally red and ferruginous, although occasional it is covered with sandy soils. Several metres of clayey ferruginous soil are underlain by illite-smectite rich clay (Kemp *et al.* 1998).

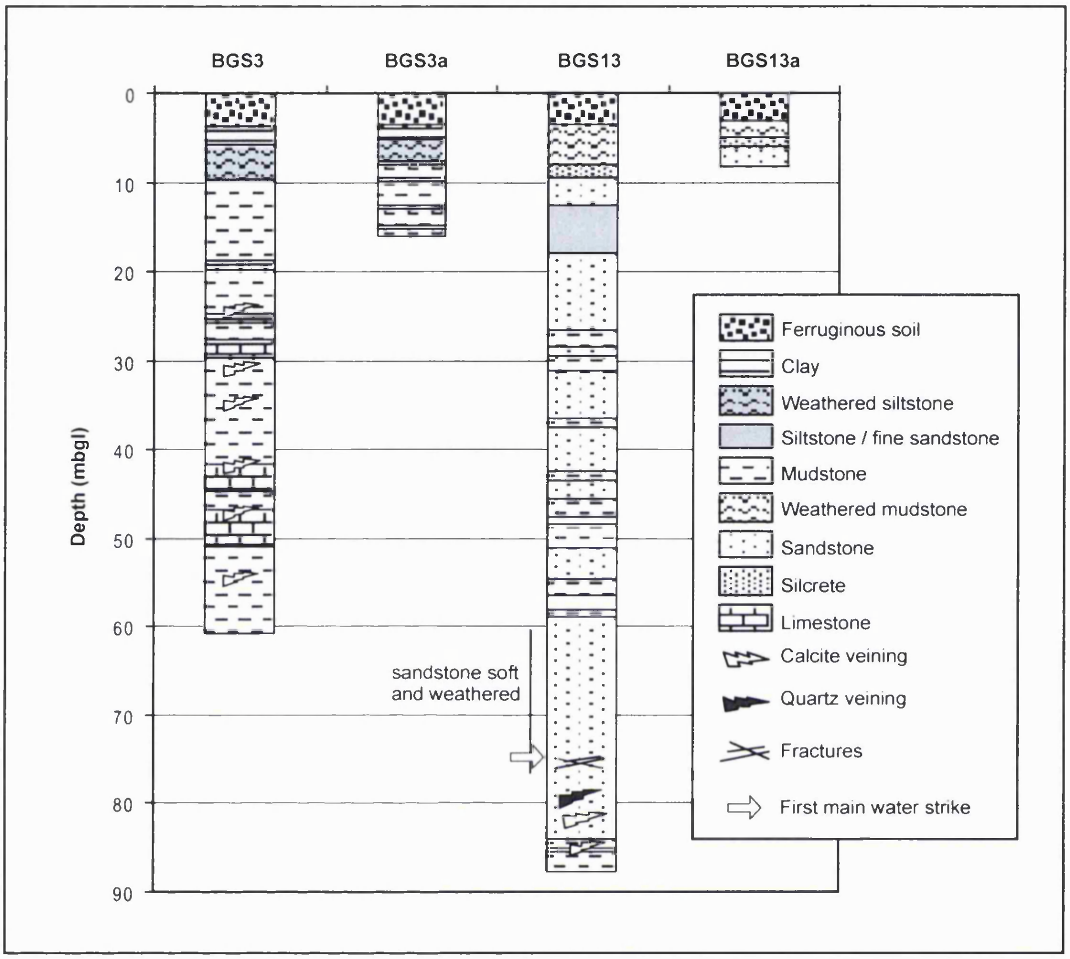


Figure 4.9 Lithlogical logs for the Makurdi Sandstone and Upper Eze-Aku Formations at Odaleko Adiko.

4.6.3 Hydrogeology

Groundwater occurs within thin limestone and sandstone layers in the Upper Eze-Aku Formation. The limestone layers are thin (0.3 m) but may be extensive as they are observed occasionally at outcrop. These limestone bands often contain fractures (as in BGS6). Groundwater within the siltstones and mudstones may provide groundwater storage, which slowly seeps into the limestone layers and then transported to boreholes. Sandstones, where they occur, are similar to the Makurdi Sandstone. In fact, the thick sandstone layer at Ochingini occurs within the area mapped as Upper Eze-Aku rather than the Makurdi Sandstone.

The large fracture zone encountered in BGS5 contained no usable groundwater. The core and chip samples showed much calcite and occasional slickensides (Figure 4.7). However the borehole was dry. Further analysis of the clays in the Upper Eze-Aku

Formation indicates a much greater proportion of smectite than in the Lower Eze-Aku Formation. Therefore, the mudstone may be too soft to contain open fractures. This is discussed in more detail in Chapter 5.

Analysis of core samples from BGS4 gives porosity values of 26%-34% and intergranular hydraulic conductivity of 0.004 $m.d^{-1}$. Pumping tests gave a transmissivity of 0.7 $m^2.d^{-1}$. These results suggest that the fractures within the sandstone provide most of the groundwater flow. These aquifer properties are marginal for a handpump yield from a borehole, but should be sufficient for a large-diameter-well. Pumping tests carried out in fractured limestones at BGS6 gave transmissivity values of 14 $m^2.d^{-1}$. However, boreholes drilled in the muddy limestones at Odaleko Adiko (BGS3 BGS3a) were abandoned and backfilled since yields during drilling were very low. Only where the limestone is competent and fractured can good yields be sustained.

4.6.4 Geophysical investigations

Approximately 6 km of EM34 surveys, 4 km of magnetic profiling and 2 resistivity VES have been used to investigate the Upper Eze-Aku. Typical geophysical signals are given in Figure 4.8 along with a rough interpretation.

1. Generally the apparent conductivity of the rocks is high (> 40 $mS.m^{-1}$) which reflects the abundance of illite/smectite clays in the weathered zone. Lower apparent conductivity (< 40 $mS.m^{-1}$) is associated with interbedded sandstone and mudstone.
2. The limestone layers are too thin to be identified using standard geophysical methods There is therefore no way of knowing whether limestones are present without drilling or digging a well.
3. Fracture zones were identified from negative anomalies. However, these fracture zones are not good targets for groundwater since the mudstone is too soft for the fractures to remain open.
4. Resistivity soundings at BGS3 showed a moderate resistive soil overlying 1-2 m thick low resistivity (>15 Ω.m) layer, followed by 40 Ω.m bedrock, these observations are consistent with the EM34 measurements.

The geophysics of the Upper Eze-Aku is complex. Sandier horizons can be identified as having lower apparent conductivity with the EM34. However, the main target for groundwater, thin limestone layers, are not easily identified.

4.7 The Awgu Shale Formation

4.7.1 Regional geology

Based on estimates made on surface exposures, the Awgu Shale is approximately 900 m thick. The formation was deposited in a shelf environment; pollen data suggest a late Turonian to Santonian age (Agagu *et al.* 1985). Foraminiferal evidence indicates that the maximum water depth in the Lower Benue Trough was probably attained during this period. However, interlayering with sandstones and occasional development of cross-stratification in some of the sandstone units, indicate that the shelf was still relatively shallow. The occurrence of abundant planktonic foraminifera (at a time of species extinction) indicates open marine conditions; this is further corroborated by the abundant ammonites and pelecypods. The generally low-diversity bentonic microfauna of the limestone bands in the exposed sections of the Awgu Formation might also be indicative of shallow-water near-shore marine conditions.

The sandstones and dolerite intrusions found within the Awgu Shales are discussed in separate sections.

4.7.2 Local geology

The Awgu Shales underlie much of Obi. The hydrogeological and geological nature of the formation was investigated at three locations: between Ijegwu and Ameka (BGS22-31), Ugbodum (BSG40-46) and Itogo (BGS47-50). These sites were also used to investigate the Agbani Sandstone and the dolerite intrusions. A summary of lithological logs for north Obi is given in Figure 4.10.

Awgu Shales consist of dark grey to black, soft, highly carbonaceous, well-bedded fissile mudstones with commonly occurring thin (0.5 m) interbeds of muddy shelly limestone and calcareous mudstone. There are also occasional layers of fine- to medium-grained, moderately sorted sandstones referred to as the Agbani Sandstone. This Agbani sandstone is discussed in Section 4.8.

The black shales are very soft and contain much carbon. They are laminated and often break into thin layers when dry. In the upper part of the Awgu Shale, some pyrite is found. In the lower part of the Awgu Shale (towards the southeast) the shales are grey and less carbonaceous. Thin silt and limestone layers are common, but are not hydrogeologically significant. At BGS26 a core of limestone obtained from 21.5 m depth

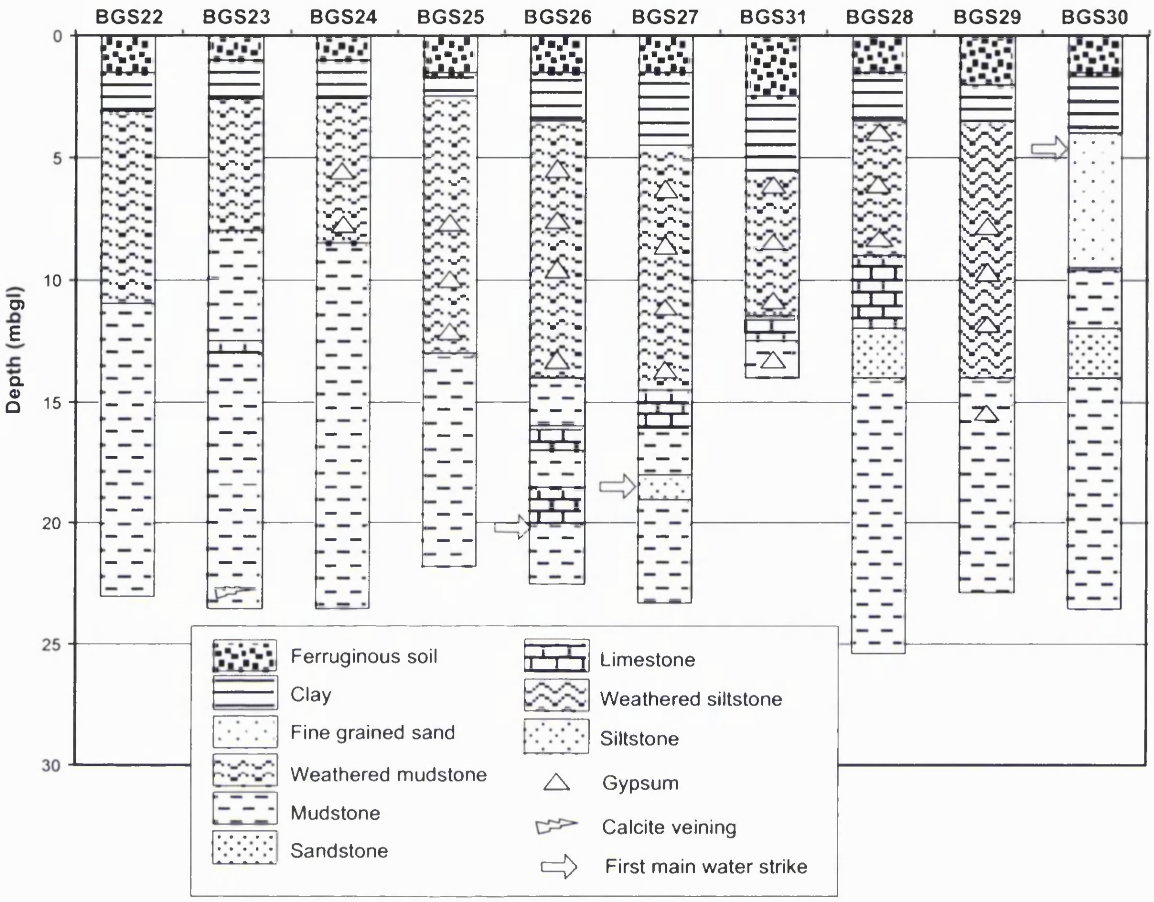


Figure 4.10 Lithological logs for boreholes drilled into the Awgu Shale Formation in north Obi.

was composed of hard shelly limestone. This limestone was deposited as an oyster-bank deposit in brackish-water without much current activity.

Gypsum is found within the weathered zone of the Awgu Shale. Core samples from borehole BGS31 demonstrate that gypsum occurs frequently as a secondary deposit in vein (selenite) and nodular (anhydrite) forms within the weathered zone. The Awgu Shale is mainly composed of smectite clay; within the weathered zone, some of the smectite has been altered to kaolinite.

4.7.3 Hydrogeology

Negligible potable groundwater exists within the Awgu Shales. The mudstone is too soft to contain open fractures. Sufficient groundwater for rural water supply is only found within thin sandstone layers and dolerite intrusions – these are discussed in Sections 4.8 and 4.9 respectively.

Sufficient groundwater was found within thin limestone and siltstone layers in BGS26 and BGS27 to carry out bailer tests. However, these tests gave transmissivity values of 0.01 to 0.02 $m^2.d^{-1}$, much too low for successful boreholes or wells. Even the small amount of groundwater that exists is of poor quality and not suitable for drinking; the poor quality is associated with gypsum in the weathered zone (see Section 4.12). During the wet season, groundwater is found within the shallow tropical soil. The ferruginous soil is permeable and groundwater can flow to shallow wells and springs. However, shortly after the end of the rains, the soil dries out and boreholes and wells fail. This seasonal behaviour is discussed in more detail in Chapter 5.

4.7.4 Geophysical investigations

Approximately 25 km of EM34 and magnetic surveying has been carried out in Awgu Shale areas; 20 resistivity surveys have also been undertaken. An example of an EM34 survey and corresponding interpretation is given in Figure 4.11.

1. EM34 readings are very high (80-140 $mS.m^{-1}$). VES resistivity surveys show a corresponding low resistivity (< 6 Ω.m). Apparent conductivity values are generally high due to saline water within the mudstone and the high smectite clay content of the mudstone.
2. The large difference between the EM34 readings taken with the vertical coils and horizontal coils is mainly due to the different responses of the coil orientations at high conductivity. The response of the horizontal coil becomes significantly non-linear at conductivities greater than about 50 $mS.m^{-1}$ (see Chapter 7).
3. All the resistivity surveys indicated a surface layer (usually several metres thick) of a few hundred Ω.m followed by thick very low resistivity layer of about 6 Ω.m. The similarity is probably due to the shallow clay layers masking any changes with depth.

4.8 The Agbani Sandstone Formation

4.8.1 Regional geology

The Agbani Sandstone occurs within the Awgu Shale. The presence of cross-bedded sandstones, interbedded with the Awgu Shales, suggests that the Agbani Sandstone was

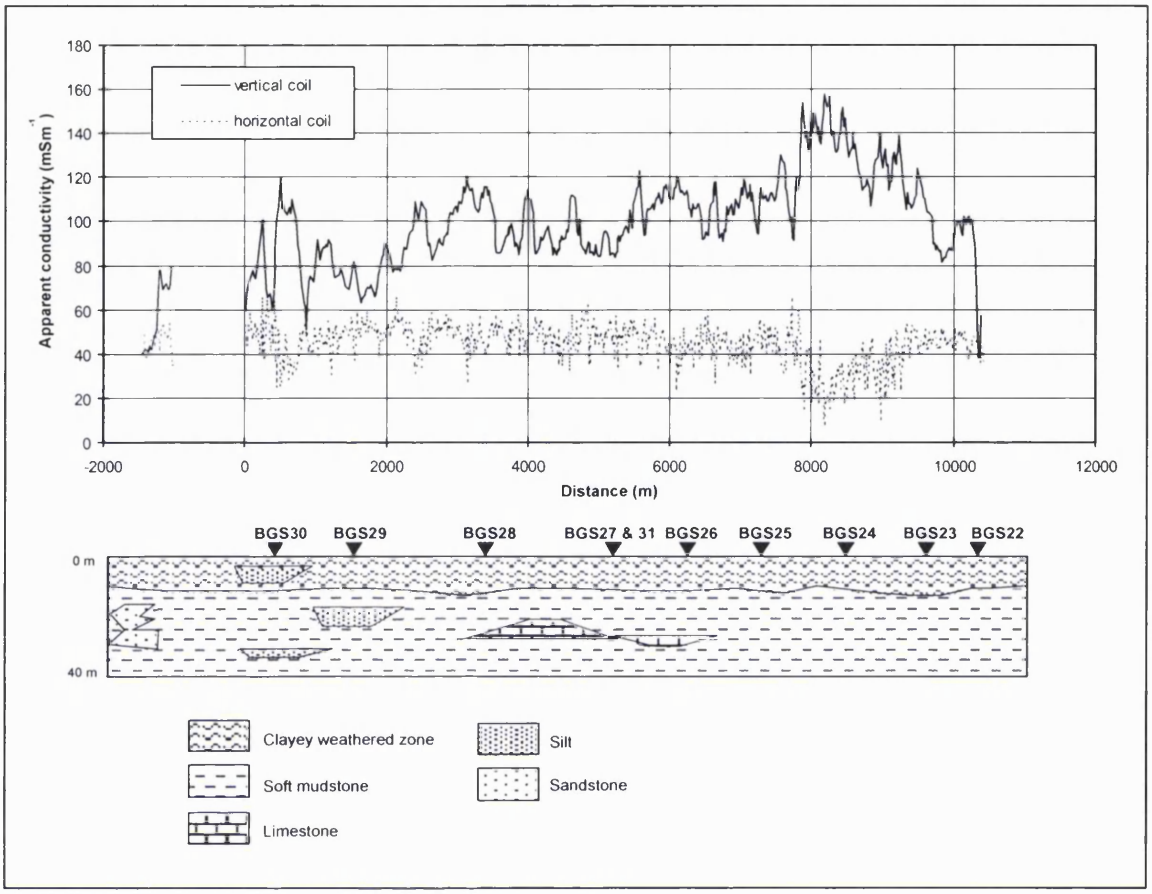


Figure 4.11 Apparent conductivity for the Awgu Shale across north Obi (measured using EM34 with 20-m intercoil spacing). A schematic interpretation from the lithological logs is also given.

deposited in a shallow marine shelf environment. In this section, the Agbani Sandstone is taken to represent any significant sandstone layers within the Awgu Shale.

4.8.2 Local geology

The Agbani Sandstone occurs in north and west Obi. According to the geological map it occurs in two thin bands that cross Obi from northeast to southwest. However, from field observations sandstone often does not occur where the geological map indicates (Figure 3.7), and vice versa. The geological and hydrogeological nature of sandy horizons within the Agbani Sandstone Formation was investigated in four areas: the eastern end of the Ijegwu to Ameka traverse (BGS26-31), Itogo (BGS47-49), Ugbodum (BGS40) and Echuri (hand dug wells constructed by WaterAid). Several of these investigations found very little evidence of Agbani sandstone. Logs of boreholes that penetrated sandy horizons within the Awgu Shale at Itogo are given in Figure 4.12.

Non-weathered cores of Agbani Sandstone obtained from BGS40 show light grey, fine- to medium-grained, clay rich, feldspathic sandstones with interbedded dark grey shaley mudstones. The sandstones are crudely cross-bedded and bioturbated. A borehole drilled close to Ameka on a location marked as Agbani Sandstone, encountered fine-grained silty sandstones interbedded with greater than 50% mudstone. Unfortunately, no access was available to drill at other sites within the Agbani Sandstone.

At a stream exposure near Echuri, weathered Agbani Sandstone comprised soft yellow fine- to medium-grained sandstone interbedded with highly weathered soft mudstone. Samples from hand dug wells at Echuri indicate medium grained highly weathered sandstone with much kaolinite clay. Hand dug wells into sandstone at Oliywo encountered interbedded sandstones and shales.

Throughout various parts of the Awgu Shale, the weathered zone is sandy, but the bedrock is mainly mudstone. This has been observed along the Itogo traverse (BGS47, 48, 49), and in a river valley next to Ameka (BGS30). The sands are fine-grained, well-

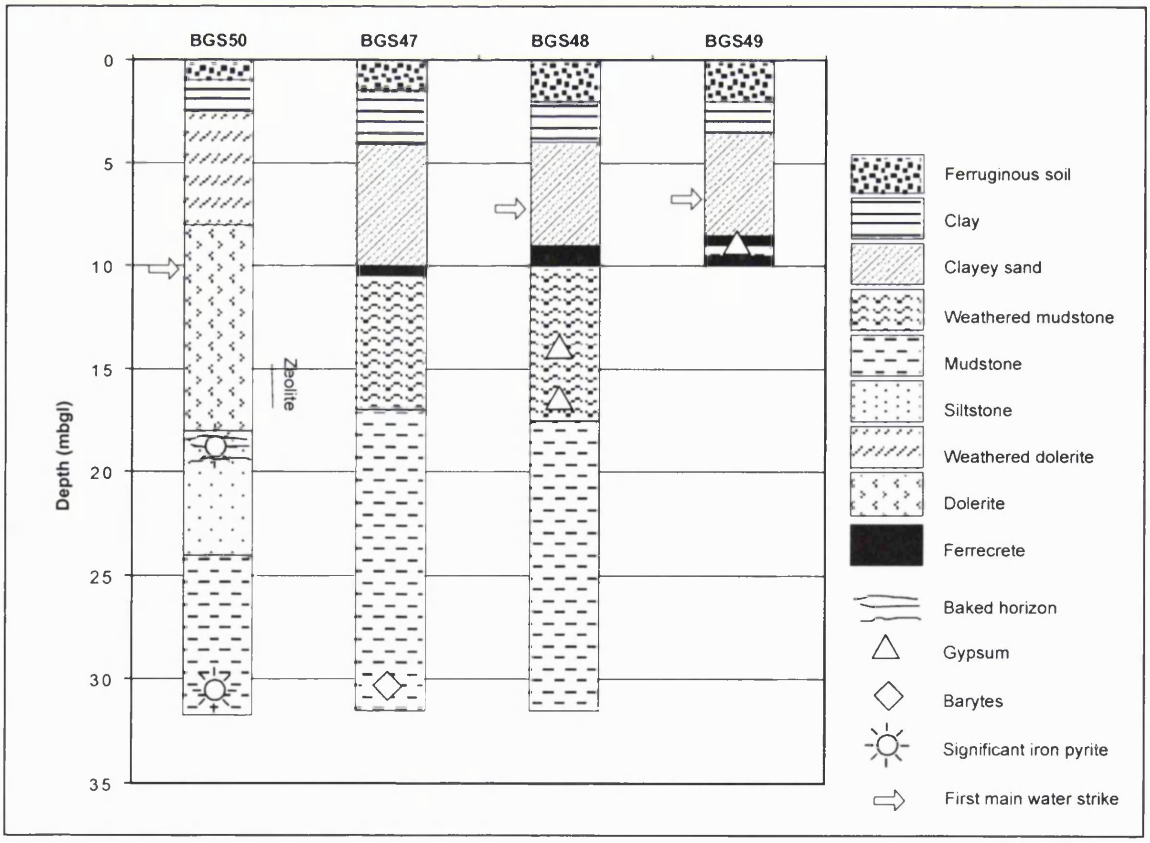


Figure 4.12 Lithological logs for exploratory boreholes at Itogo. BGS47-49 encountered sandstone within the Awgu Shale.

rounded and often collapse during drilling. The sands are very clayey with the clay composed of more than 60% smectite (Kemp *et al.* 1998). Along the Itogo traverse, a pronounced gravelly ferricrete layer is present at the base of the sands (about 8-10 m). These sands may be remnants of weathered Agbani Sandstone: the sand grains are more resistant to weathering than the clay so after thousands of years of weathering they would be concentrated within the weathered zone. An alternative explanation is that they are remnants of fossil sand dunes that covered the area during the Pleistocene Age (Nichol 1999). These sands dunes may have been reworked to form alluvium in some of the valleys (e.g. BGS30).

4.8.3 Hydrogeology

The hydrogeology of the Agbani Sandstone is complex, and could not be fully characterised during this study. Potentially, however, it could form a strategic water resource in north Obi. Groundwater occurs mostly within the weathered zone where the sandstone has been weathered to fine sand. Groundwater may also exist in fractures within the more competent sandstone. Only one exploratory borehole penetrated the unweathered Agbani Sandstone (BGS40). This borehole collapsed during development and much fine sand entered through the screens. Therefore, the transmissivity of 0.15 $m^2.d^{-1}$ measured from the pumping test is probably an underestimate. Two existing boreholes with hand pumps penetrate the Agbani Sandstone at Ameka and Oluywo, but were not working during the fieldwork of this study (1996-1999). The local communities claim that, when working, these boreholes could easily sustain the yield of a hand pump. They may have failed due to corrosion from brackish water or ingression from fine sands.

Several exploratory boreholes were drilled into the sandy layers within the weathered zone. These gave transmissivity estimates of 0.05 - 0.36 $m^2.d^{-1}$. Most of these boreholes appeared to get most water from a thin ferricrete layer at about 10 m depth. Throughout Obi, there are examples of shallow wells that exploit water within the sandy weathered zone (e.g. Adega, Oluywo, Itogo Iyaho). Many of these wells remain operative until March, and several operate through to the end of the dry season. As a result, the best location for a well within the sandy weathered zone would be in a valley – close to a source of recharge.

4.8.4 Geophysical investigations

EM34 equipment can be used to distinguish between Awgu Shale and Agbani Sandstone. A characteristic signal for the sandstone was produced in areas of known Agbani Sandstone occurrence adjacent to wells at Udegi, Ameka and Echuri. At these locations both the horizontal- and vertical-coil conductivity values fall to about 30 $mS.m^{-1}$ and do not vary much over the outcrop. Figure 4.13 shows a typical EM34 response of sandstone within the Awgu Shales.

Resistivity surveys carried out on the Agbani Sandstone at Ugbodum, showed a resistive (200 Ω.m) weathered zone overlying a resistive bedrock (50 Ω.m). Where the bedrock was mainly mudstone, the conductivity was less than 10 Ω.m.

Therefore, EM34 (using 20-m intercoil separation) can distinguish sand within the weathered zone. Resistivity surveys (or EM34 with 40-m coil separation) can be used to identify sandstone at depth.

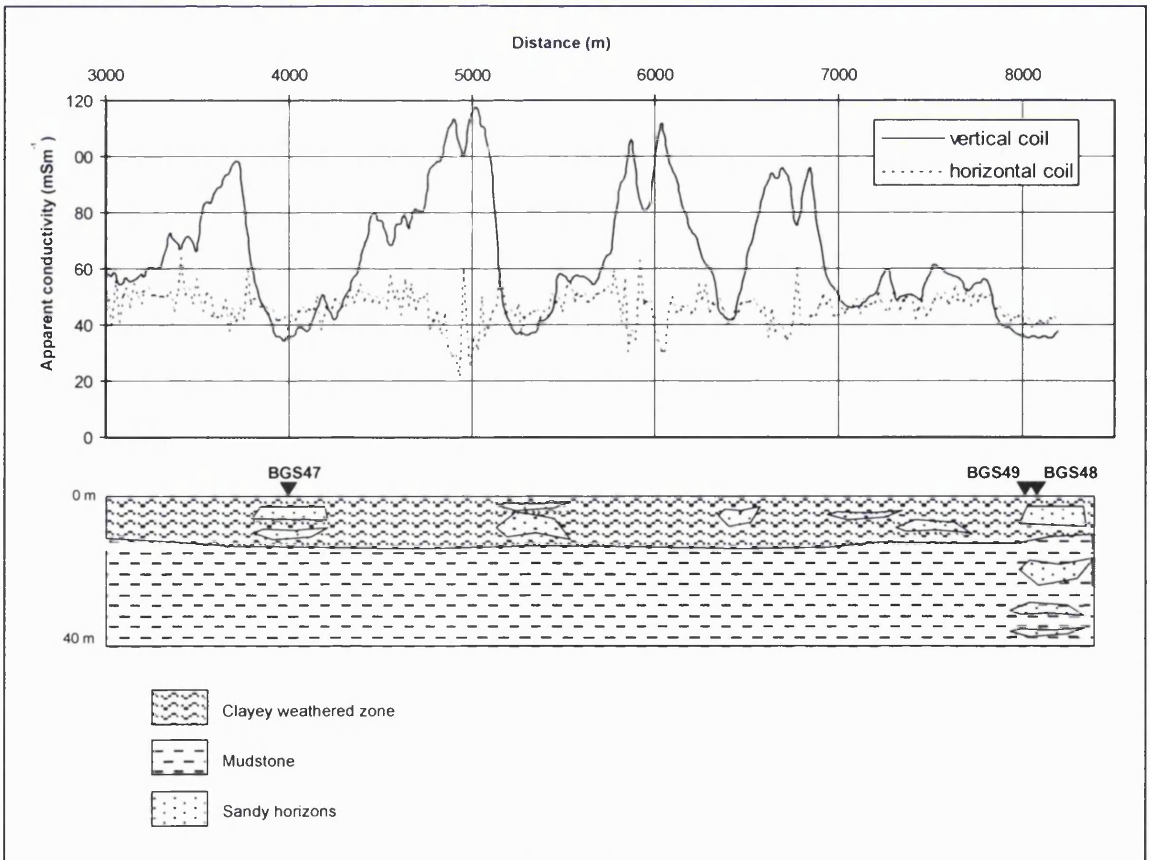


Figure 4.13 Apparent conductivity (using EM34 with 20-m intercoil spacings) for the Itogo area, where sands are present within the Awgu Shale (soft mudstone). A schematic interpretation is also given using information from the exploratory boreholes and the geophysical surveys.

4.9 Dolerite intrusions

4.9.1 Regional geology

Dolerite intrusions of various sizes occur within most of the lithological units present within the Benue area. Much of the intrusive activity occurred in Turonian times. The occurrence of the larger intrusive bodies can be interpreted from anomalies shown on the aeromagnetic surveys of the region.

4.9.2 Local geology

Within the Oju/Obi area, dolerite intrusions of various sizes appear to occur within the metamorphosed Asu River Formation and within the Upper Eze Aku and Awgu Shale Formations. Dolerite/gabbro bodies crop out at numerous locations within the central core of the Wokum Hills. Hydrogeologically however, the presence of dolerite is much more important within the Obi area where the surrounding geology contains negligible groundwater. In Obi, dolerite outcrops have been noted around Ito town and Adum West. Anomalies within the aeromognetic map can also indicate the presence of dolerite. The dolerite was investigated at three locations: Adum West (BGS33-35), Ugbodum (BGS40, BGS42, BGS44-46) and Itogo (BGS50). Simplified lithological logs of boreholes at Adum West are shown in Figure 4.14.

The dolerite occurs generally as hard dark blue/green fine-medium grained basic igneous dykes and sills. These are intruded into the mudstones, siltstones and sandstones of the Awgu Shale, Agbani sandstone and Ez-Aku Shale. At Adum West and Ito, the dolerite is highly fractured and zeolite crystals (mainly mesolite) have grown in some of the fracture surfaces. At Ugbodum the dolerite intrusions are much thinner than those at Adum West. In addition the dolerite is finer grained and zeolite layers are thinner, especially where the sediments are sandier. Consequently, there are less fractures in the thinner dolerite intrusions. Another thin dolerite sill was encountered in the Itogo traverse (BGS50, Figure 4.12) and was observed to be medium to fine grained containing zeolite growths.

The sediments at the edge of the dolerite intrusions have been baked. The mudstones become harder and change to a light grey/white colour. Very little water was found within the baked horizons.

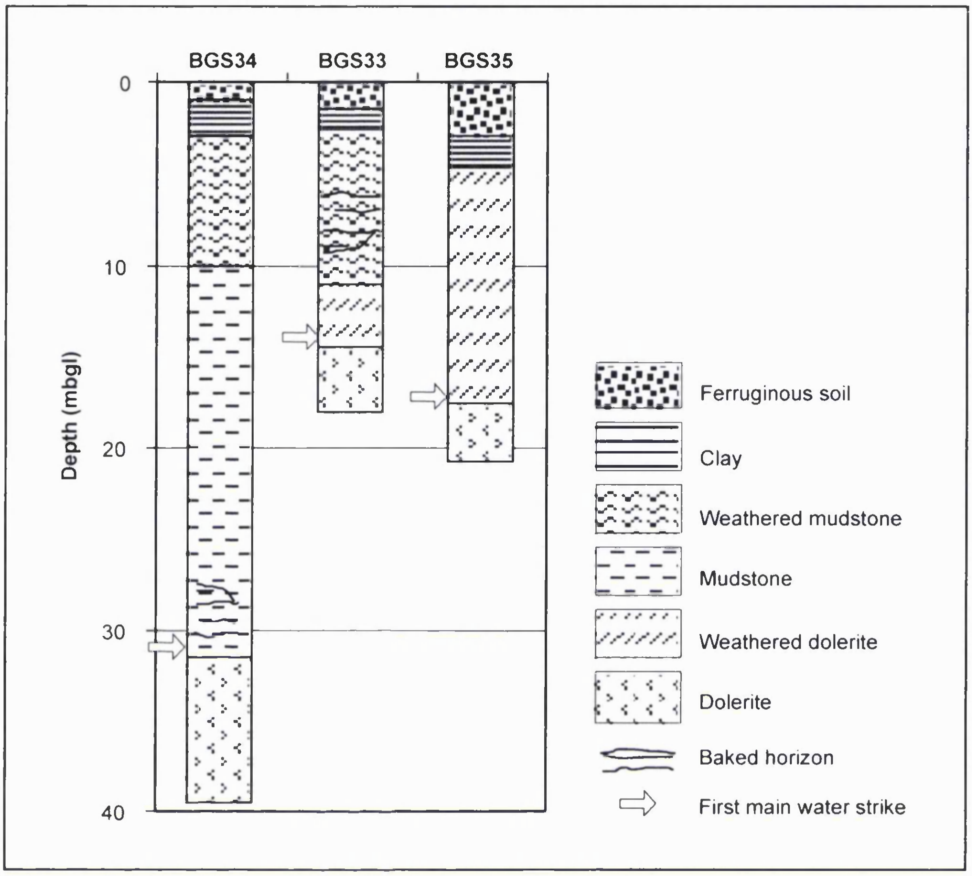


Figure 4.14 Lithological logs for exploratory boreholes that penetrated dolerite at Adum West.

At the surface, the dolerite weathers to form smectite clay (Kemp *et al.* 1998). Typical black/green clayey soils develop. Dolerite is easily identified in riverbeds, where it forms a hard dark grey rock with no bedding features and spherical weathering.

4.9.3 Hydrogeology

Groundwater exists within the dolerite found in Obi. Groundwater occurs in fractures that have formed close to the edge of the intrusions. These fractures often have growths of zeolite along their surfaces, and have void spaces of up to 10 mm. Greater frequencies of open fractures appear to have formed where the dolerite has been intruded into mudstone (BGS33-35), rather than sandstone (BGS40). Very little water was found within the baked shales or sandstones at the edge of the intrusions.

At Adum West, where the dolerite is highly fractured, and zeolite is present, transmissivity values of 20 - 60 $m^2.d^{-1}$ were calculated from pumping tests (BGS33, BGS35). These measurements show that the boreholes can provide high yields. Where the dolerite was encountered at 30 m depth, transmissivity of 5 $m^2.d^{-1}$ was measured, sufficient to sustain the yield of a handpump.

At Ugbodum, various thin dolerite intrusions were investigated. In two of the boreholes (BGS40 and BGS44), the dolerite had been intruded into sandstones; transmissivity values of 0.15 - 0.3 $m^2.d^{-1}$ were measured. Another very thin dolerite intruded into mudstone gave a transmissivity values of 0.7 $m^2.d^{-1}$.

Remote from the main dolerite intrusions at Adum West and Ito, the greatest yields were found where the dolerite occurs in valleys. Two boreholes (BGS46, BGS50) were tested giving transmissivity values of 30 and 2 $m^2.d^{-1}$ respectively.

4.9.4 Geophysical investigations

Various geophysical surveys have been undertaken to identify dolerite intrusions. A typical EM34 and magnetic survey over a dolerite intrusion is shown in Figure 4.15. A summary of the main geophysical characteristics is given below.

Where dolerite is close to the surface, the apparent conductivity is moderate (< 60 $mS.m^{-1}$). There is sufficient contrast with the very high readings of the Awgu Shale to make the dolerite easily identifiable. Vertical coil readings with 20-m intercoil spacing are generally about 40 $mS.m^{-1}$. However, the surveys indicated that in some places (e.g. Ito) apparent conductivity could be lower (10 $mS.m^{-1}$) and in others (e.g. part of Adum West) higher (50 $mS.m^{-1}$) depending on the degree of weathering of the dolerite.

Large magnetic anomalies (100 nT) are encountered where the dolerite is close to the surface. The magnetic field often varies significantly within a few metres with no obvious anthropogenic explanation (i.e. no steel roofs or bikes).

Where the dolerite is at depth (20 – 30 mbgl) the electrical conductivity measured using the 20-m intercoil spacing is high, reflecting the conductivity of the Awgu Shale within the weathered zone. However, subdued magnetic anomalies of 10 - 20 nT are still observed.

Resistivity surveys over dolerite give a different profile to those over Awgu Shale. The surface resistivity may be low due to the smectite in the black dolerite soil. However, the less weathered dolerite bedrock give resistivity values of greater than 50 Ω.m – which is easily distinguishable from the Awgu Shale with resistivity values of less than 10 Ω.m. Even at depths of greater than 20 m, where the EM34 cannot easily

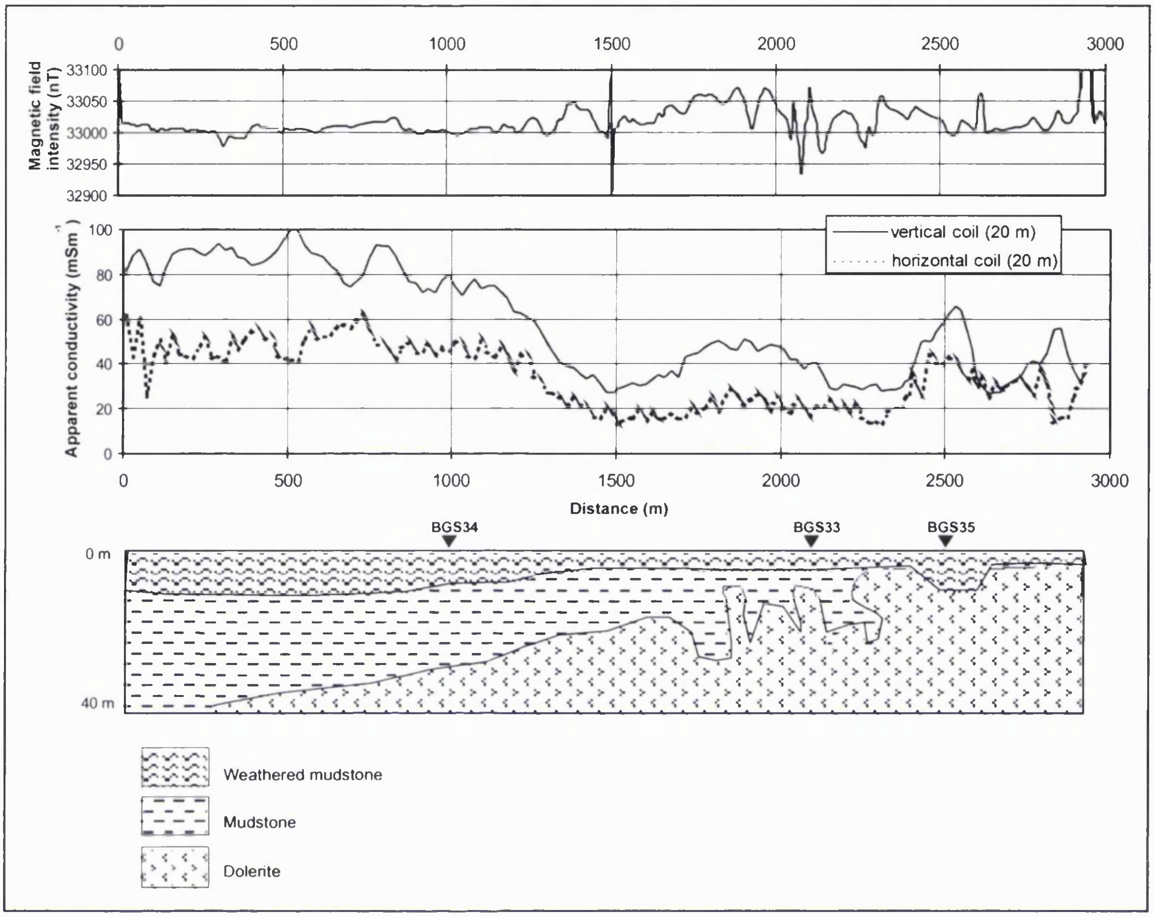


Figure 4.15 Geophysical surveys and schematic lithological interpretation for dolerite intrusions at Adum West.

distinguish dolerite, resistivity soundings can be effective. EM34 with 40-m intercoil spacings of 40-m can easily distinguish dolerite at depth (Itogo traverse).

4.10 River gravel and alluvium

4.10.1 Alluvium

There is very little alluvium within the Oju and Obi area. However, in the upper reaches of the Obi River, occasional pockets are found – possibly from reworked dune material (Nichol 1999) or eroded from the Agbani Sandstone. A 5-m thick deposit of water-bearing river alluvium, composed of interbedded fine-grained sands and clays above weathered Awgu shales, was investigated in borehole BGS30 located south west of Ameka, Obi. Test pumping showed that there was sufficient water in the sand for a hand-dug well. Similar fine sand is also found along some of the rivers in northern Obi

Alluvium can be located with a combination of geophysics and field observations. It is only found on flood plains along the sides of rivers. Since the sands have lower clay content than the weathered mudstone of the Awgu Shale, the apparent electrical conductivity measured by the EM34 is lower.

Boreholes are not appropriate for exploiting the groundwater in alluvium since the fine-grained sand readily passes through the slots in the screens to block boreholes. Hand-dug-wells are more appropriate but must be constructed carefully to avoid the sides collapsing. When designing wells it must also be appreciated that the alluvial plain will flood for part of the year. Groundwater quality within the alluvium is good, although the permeable soil and shallow water-table make the groundwater vulnerable to pollution.

4.10.2 River gravel

In many parts of the world, and particularly southern Africa, riverbed deposits are a useful source of groundwater (Herbert *et al.* 1997). Some ephemeral rivers contain so much sediment they are called *sandrivers* and water continues to flow through the sediment even in the dry season. In Oju, abstractions from dugouts and ponds in riverbeds are important sources of water in the dry season.

To try to estimate the size and nature of the water resources within the river bed deposits a study was undertaken during March 1997. Five different rivers were visited and augering undertaken to assess the thickness and nature of the gravel. This study is reported in MacDonald and Davies (1997). The conclusions of the study are given below.

1. The river gravel deposits of the major rivers are thin ($<< 1$ m), intermittent and have little groundwater storage.
2. Thin gravels (< 1 m) occur along small river valleys developed on the Asu River Group outcrop. Such gravels contain small amounts of groundwater early in the dry season that quickly diminish as the dry season progresses.
3. More sustainable seepages found along river beds at the height of the dry season are sustained by groundwater.

River gravels are not a major source of sustainable water in Oju/Obi, but they form an important source of water for many communities during the early part of the dry season. The quality of this water is generally good, but highly vulnerable to pollution. As the dry season progresses, the gravels dry out. People then move further downstream or to places where shallow pits can be excavated through to the water-bearing rock beneath.

4.11 The tropical soil

4.11.1 Geology

A 2 - 20 m thick regolith overlies the Cretaceous age sediments of the Oju/Obi area. The regolith generally comprises a red iron-rich ferruginous soil, overlying a mottled clay horizon, followed by a clay rich zone containing weathered bedrock (see Chapter 2 for a description of tropical soils). The thickness and nature of the regolith depends on the physical and chemical composition of the underlying geology. Table 4.1 gives average thickness of the different regolith layers for the various rock units found during the exploration programme.

Table 4.1 Average thickness and composition of the weathered zone of the hydrogeological units in Oju/Obi.

Formation	*Upper Layer*	*Clay layer*	*Weathered Bedrock*
Metamorphosed Asu River	0-3 m clayey soil with weathered bedrock	2-3 m illite, kaolinite clay	2-8 m clayey bedrock
Asu River	0-3 m, weathered bedrock, some haematite, and manganese nodules	0-2 m illite, kaolinite clay interlayered with competent mudstone	0-6 m clayey bedrock
Lower Eze-Aku	2-4 m many iron-manganese oxide nodules, sometimes bonded into hard ferrecrete	2-4 m illite/smectite and kaolinite clay	4-12 m weathered olive green clayey bedrock
Makurdi Sandstone	2-3 m sandy soil with many haematite and manganese nodules	0-2 m sandy clay – mainly kaolinite with some illite.	5-15 m weathered, orange and red sandstone with kaolinite clay and hard silcrete bands
Upper Eze-Aku	2-3 m clayey soil with many haematite nodules	2-5 m kaolinite, illite smectite clay	4-8m weathered olive bedrock
Awgu Shale	1-2 m very clay red soil with occasional haematite and manganese nodules	2-4 m kaolinite and smectite clay	6-10 m soft very clayey olive bedrock
Agbani Sandstone	2-4 m hard haematite and manganese nodules	3-4 m sandy clays (no clay analysis done)	4-8 m clayey olive sandstone with red bands
Dolerite	0-3 m nodular hard ferrecrete with hanatite and manganese nodules	2-4 m mottled clays – mainly smectite	3-15m soft weathered dolerite

From Table 4.1 several generalisations can be made. The tropical soil is mainly made up of 0 - 3 m of red clayey soil with variable quantities of iron and manganese oxide nodules. Below the red clayey soil are 2 - 4 m of mottled clay, with generally more kaolinite clay in the upper zones and smectite, illite or illite/smectite clay in the lower zones – depending on the geology. Below the distinct clay layer is generally 5 - 15 m of weathered bedrock, where the rock is competent (i.e. bedding features are preserved) but the rock is soft, discoloured and clayey. Ancient and thicker ferricrete layers occur around Oju town, forming an area of high ground that has a prominent escarpment along its northern boundary.

4.11.2 Hydrogeology

The thick tropical soil present throughout Oju/Obi has an important bearing on the hydrogeology. The shallow nodular zone can be highly permeable, particularly where the nodules have been bonded into a hard tubular ferricrete. During the rainy season, water flows through the most shallow few metres to the rivers, causing extensive river flows and flooding. Shallow traditional wells tap this water source and can supply high yields when the shallow zone is saturated. However, as the rains stop, the shallow tropical soil quickly dries out and water-levels in the wells rapidly decline. Highly permeable ferricrete may pose a problem for latrines. Rapid groundwater flow from latrines to wells may cause contamination. This is discussed further in Chapter 5.

The clay zone beneath the shallow ferruginous soil impedes the downward movement of groundwater. Therefore, recharge to the fractured aquifers is reduced. However, rainfall may percolate slowly through the clays providing some measure of recharge, as happens in the glacial clays in northern latitudes. Also the clays can be fractured and contain significant discontinuities which enhance recharge.

4.12 Hydrochemistry

This section provides a broad overview of groundwater chemistry as it relates to geology and the sources from which the samples were taken. The data refer to the individual sections on each geological formation, but are combined into one section for ease of reading. Approximately 150 water samples have been taken from boreholes, wells and seepages throughout Oju/Obi. Analysis of these water samples has aided interpretation and understanding of groundwater flow within the aquifer units. In this section only waters taken during the dry season are considered; further analysis is given in Chapter 5. All chemistry data are given in the Appendix.

The chemistry of groundwaters found in Oju/Obi is complex. A Piper diagram showing all the samples taken from Oju and Obi is shown in Figure 4.16. A map showing the specific electrical conductance (SEC) is shown In Figure 4.17. Clearly, the chemistry is strongly related to the geology. Variations within each geological unit are due to local variations in geology and also the source from which the sample was taken (this is discussed later in this section).

Groundwater within the Asu River Formation and metamorphosed Asu River Formation does not change markedly from place to place; TDS is approximately 500 mg.$\ell^{-1}$and pH around 7. The groundwaters are calcium-bicarbonate type. Dissolved iron concentrations can be slightly high (> 1.5 mg.ℓ^{-1}). Groundwater found within the

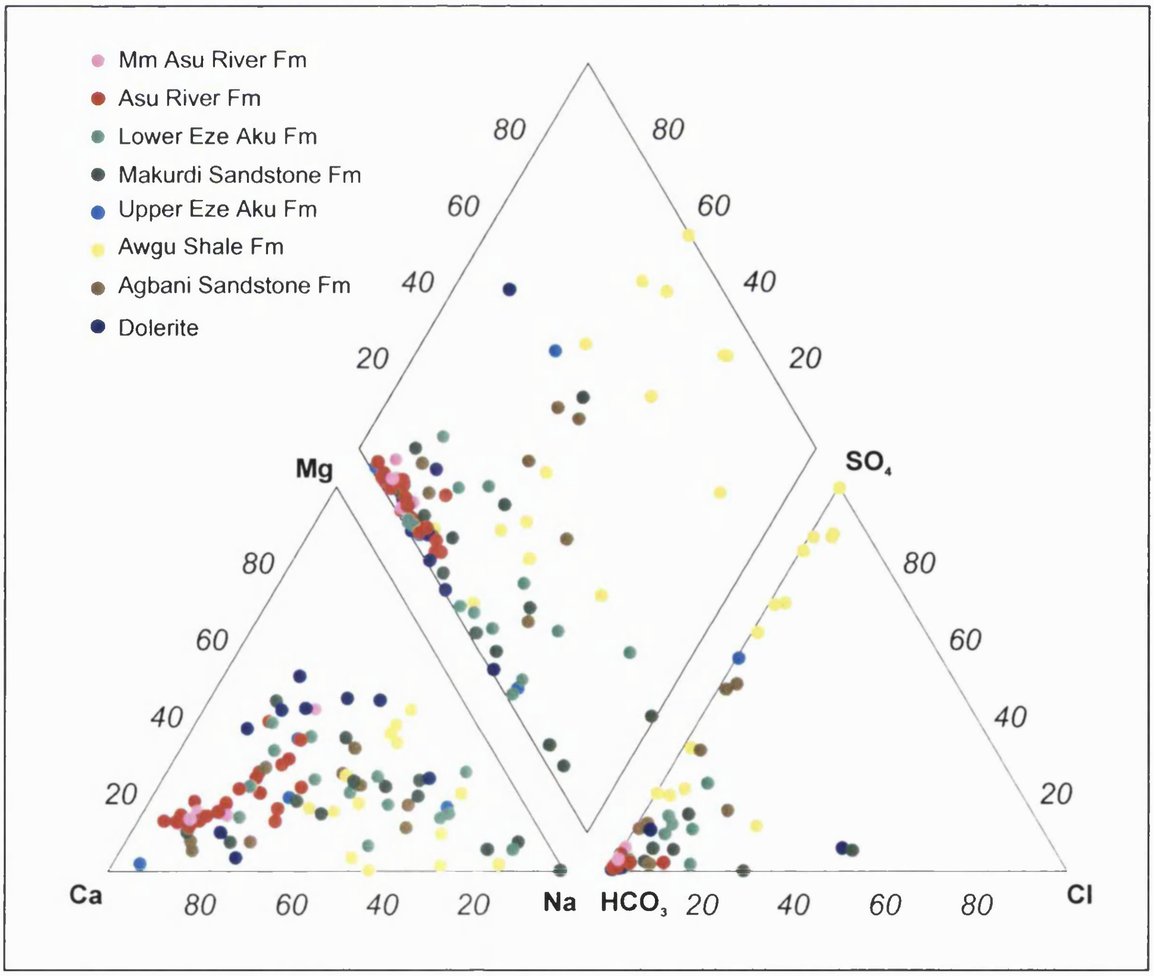


Figure 4.16 Piper diagram of water samples taken in the dry season (January-April) throughout Oju and Obi.

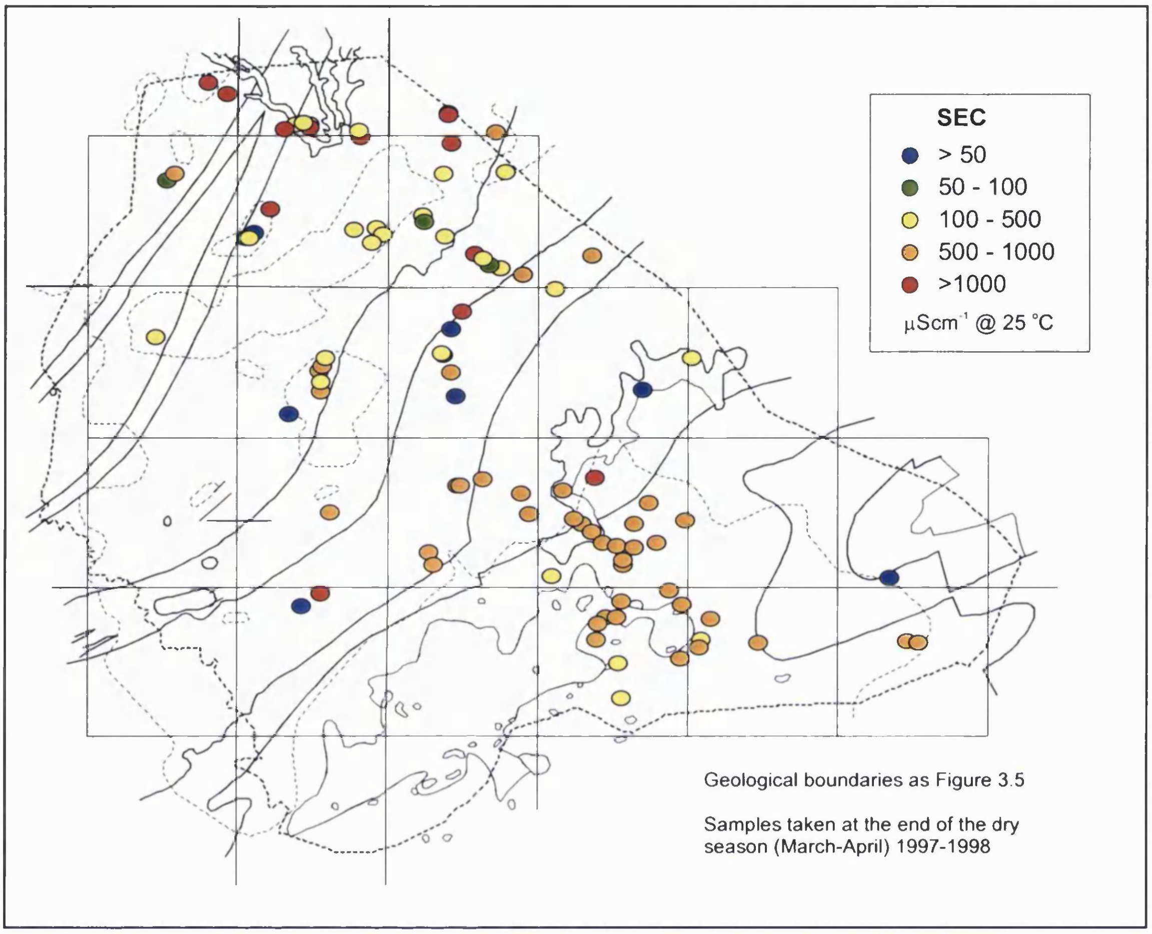


Figure 4.17 Specific electrical conductivity (SEC) for dry season groundwater samples throughout Oju and Obi. SEC is broadly related to TDS.

dolerite intrusions is similar, but has a lower TDS (usually 400 mg.ℓ^{-1}), and is calcium/magnesium bicarbonate type.

Groundwaters from the Lower and Upper Eze-Aku and Makurdi Sandstone Formation have broad similarities. Groundwater is broadly calcium/sodium bicarbonate type; although slightly elevated sulphate and chloride are sometimes observed (Figure 4.16). The sodium rich waters tend to have lower TDS and reflect more the composition of rainwater. The TDS is highly variable and related to the source type. For example, wells and seepages tend to have lower TDS than boreholes (see below).

Groundwater within the Awgu Shale and Agbani Sandstone have the highest TDS of all groundwater in Oju and Obi. As discussed earlier in this chapter, the permeability of these formations is low, and there has consequently been less flushing of existing waters. The dominant cations are bicarbonate and sulphate; the main anion is sodium, although calcium and magnesium concentrations can also be high.

Several general statements can be made about changes in groundwater chemistry from different sources. This is discussed in more detail in Chapter 5.

1. Waters from seepages tend to have low total dissolved solids (TDS) contents, suggesting the water is young and probably rainwater. Waters taken from shallow wells also tend to have low TDS contents. As the dry season progresses, TDS increases, indicating that the shallow laterite layers are drying out and increased contribution of deeper groundwater to flow.
2. Borehole waters tend to have moderate TDS contents (about 500 $mg.\ell^{-1}$). The quality does not change much throughout the year since waters are abstracted from deeper sources unaffected by seasonal variations.
3. Shallow groundwater from wells and seepages can have low pH (< 5). These waters tend to have a low TDS content and low pH, conditions under which heavy metals, such as aluminium, can be taken into solution. Higher nitrate and ammonia were observed in some shallow wells located within villages.

4.13 Summary

The hydrogeological surveys carried out in Oju/Obi have shown groundwater to exist in three different ways within Oju/Obi

1. *Fracture zones within the Asu River Group and Lower Eze-Aku Shale Formation.* The Asu River Formation and 'Metamorphosed' Asu River Formation both comprise hard splintery shales. Fractures within these rocks are common and generally remain open, regardless of their orientation. Much horizontal fracturing is associated with the base of the weathered zone. The Lower Eze-Aku Shale Formation, although softer, contains open fractures. These tend to be more widely spaced than in the Asu River Group and are associated with faults. The hard, splintery shales can be distinguished by low apparent conductivity (< 30 $mS.m^{-1}$). Fracture zones in the Lower Eze-Aku Shale Formation can be identified by negative-going or noisy anomalies in EM34 surveys.

2. *Sandstone and limestone layers within the Upper Eze-Aku Shale Formation, Makurdi Sandstone Formation and Agbani Sandstone Formation.* The sandstones are interlayered with thick shaley mudstones. The location of sandstone units from field observation alone is difficult due to the thick soil cover and flat topography. Geophysics, however, can be used to distinguish between sandstones and mudstones. The sandstones

are fine- to medium-grained and sometimes silicified. Intergranular permeability is low, but fractures are common between 10 - 15 m depth. Thin limestones (0.3 m), where fractured, can be permeable (transmissivity > 10 $m^2.d^{-1}$). Yields from the Agbani Sandstone Formation are variable due to the sandstones containing a high proportion of smectite clay. Clay free sandstone is easily distinguished from mudstone by measuring bulk conductivity with EM34 equipment. Sandstones have low apparent conductivity (<20 $mS.m^{-1}$)

3. *Dolerite intrusions within the Awgu Shale Formation.* Within the northern area there is little potential for groundwater development from underlying Awgu Shale Formation mudstones. While fractures do not remain open within the soft mudstone, thin water-bearing sandstones and limestones are uncommon. The main sources of groundwater in this area are dolerite intrusions. The dolerite occurs as sills and dykes that are often fractured. Where the dolerite is thick, high yields can be obtained. Where dolerite is thin highest yields are obtained along valleys and where the dolerite has intruded into mudstone. Surface indication of dolerite outcrops are limited to soil type and occasional stream exposures. Dolerite intrusions are best located as anomalies on regional aeromagnetic maps that are ground truthed using a combination of magnetic and EM34 surveys.

Chapter 5

The hydrogeology of mudstone environments

The data collected during the study in Oju and Obi have shown that significant groundwater resources exist within low permeability sediments. This chapter puts the results of the Oju study into a wider context and develops a conceptual framework for the existence of groundwater in mudstones. Geological, hydrogeological and hydrochemical data presented in Chapter 4 are drawn on within this analysis. Clay mineralogical data are introduced within this chapter to help broaden the interpretation. Estimates of storage and recharge to low permeability sediments are also suggested from modelling and chloride analysis.

5.1 Factors controlling permeability distributions

5.1.1 Transmissivity patterns from Oju and Obi

To test for systematic patterns in transmissivity within Oju and Obi, transmissivity measurements from the different hydrogeological units are compared in Figure 5.1 and Table 5.1. Only test boreholes drilled to more than 15 m are included. For the purpose of the analysis, mudstone units within the Makurdi Sandstone have been designated Upper Eze-Aku; boreholes that penetrated very thin dolerite sills (< 1 m) within the Awgu

Shales have also been distinguished from boreholes penetrating larger dolerite intrusions. Transmissivity values have been calculated from the longest reliable dry season pumping test for each borehole. For example Theis recovery analysis from 5 hour whale tests would be used before a bailer test. Boreholes which were too low yielding to test using standard pumping test methods have been included in the analysis to minimise data bias; they have been assigned a nominal transmissivity of 0.01 $m^2.d^{-1}$.

A strong correlation between transmissivity and geological formation is evident in Figure 5.1. Highest transmissivity values are found within the metamorphosed Asu River Formation, the Asu River Formation and the dolerite. Lowest transmissivity values are found within the Awgu Shale Formation. Large variations in transmissivity are found within the Upper and Lower Eze-Aku Formations

Table 5.1 Transmissivity of different hydrogeological units in the Oju and Obi area.

			Transmissivity ($m^2.d^{-1}$)		
	Code	*No of tests*	*minimum*	*maximum*	*geometric mean*
metamorphosed Asu River Group	mmA	3	3.0	27	7.90
Asu River Group	Asu	3	2.5	4	3.30
Lower Ezu-Aku	LEA	5	0.01	2	0.22
Makurdi Sandstone	MSS	5	0.1	1	0.37
Upper Eze-Aku	UEA	5	0.01	18	0.04
Awgu Shale	Awg	11	0.01	0.25	0.02
Agbani Sandstone	Agb	4	0.01	0.4	0.10
thin dolerite in Awgu Shale	A+D	3	0.06	0.8	0.17
dolerite	Dol	5	2.0	51	13.0

The detailed geological logs of the boreholes (as described in Chapter 4) provide a first indication of why some boreholes have higher yields than others. For example, fractures at a depth of 12-35 m within both the metamorphosed Asu River Formation and Asu River Formation are responsible for the high transmissivity measurements. The lack of open fractures within the Awgu Shale results in the very low transmissivity measurements. The geological logs show that the high range of measurements in the Lower Eze-Aku is again due to the presence of fractures: boreholes that penetrate fracture zones have higher transmissivity than those with little evidence of fracturing. The high range in the Upper Eze-Aku is due to the presence of thin limestone bands within the mudstone. Where limestone is present (and fractured) transmissivity can be high; where limestone is absent, transmissivity is very low.

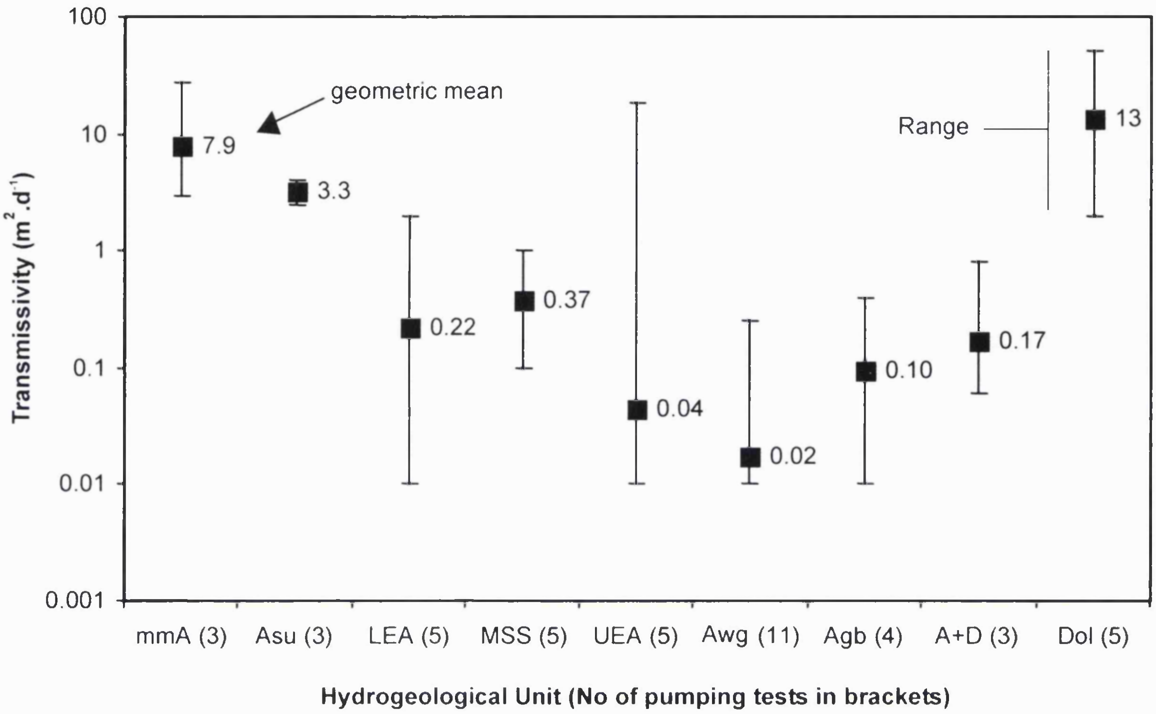


Figure 5.1 Transmissivity of different hydrogeological units in the Oju and Obi area. Codes are explained in Table 5.1

However, the geological logs alone give little indication of why some mudstone units are fractured (and therefore permeable) and some are not. In the following sections, the effect of two factors on groundwater occurrence within low permeability sedimentary environments is explored – very low-grade metamorphism and the presence of other lithologies (such as thin sandstone layers or dolerite intrusions).

5.1.2 Diagenesis and low-grade metamorphism

To help put the Oju/Obi mudstone environment in a wider context, clay analysis for various representative boreholes was undertaken. These clay analyses were also used to help provide a basis for interpreting the geophysics data (see Chapter 7 and data in Appendix). Figure 5.2 shows the proportion of different clay types in poorly weathered samples from representative mudstone boreholes (sandstone and dolerite samples are discussed in the next section). Laboratory analyses were undertaken by Kemp *et al.* (1998).

The samples show a definite pattern. The Awgu Shale is composed mainly of smectite clay, the Upper and Lower Eze-Aku formation of interlayered illite/smectite clays and the samples from the Asu River Group of illite clay.

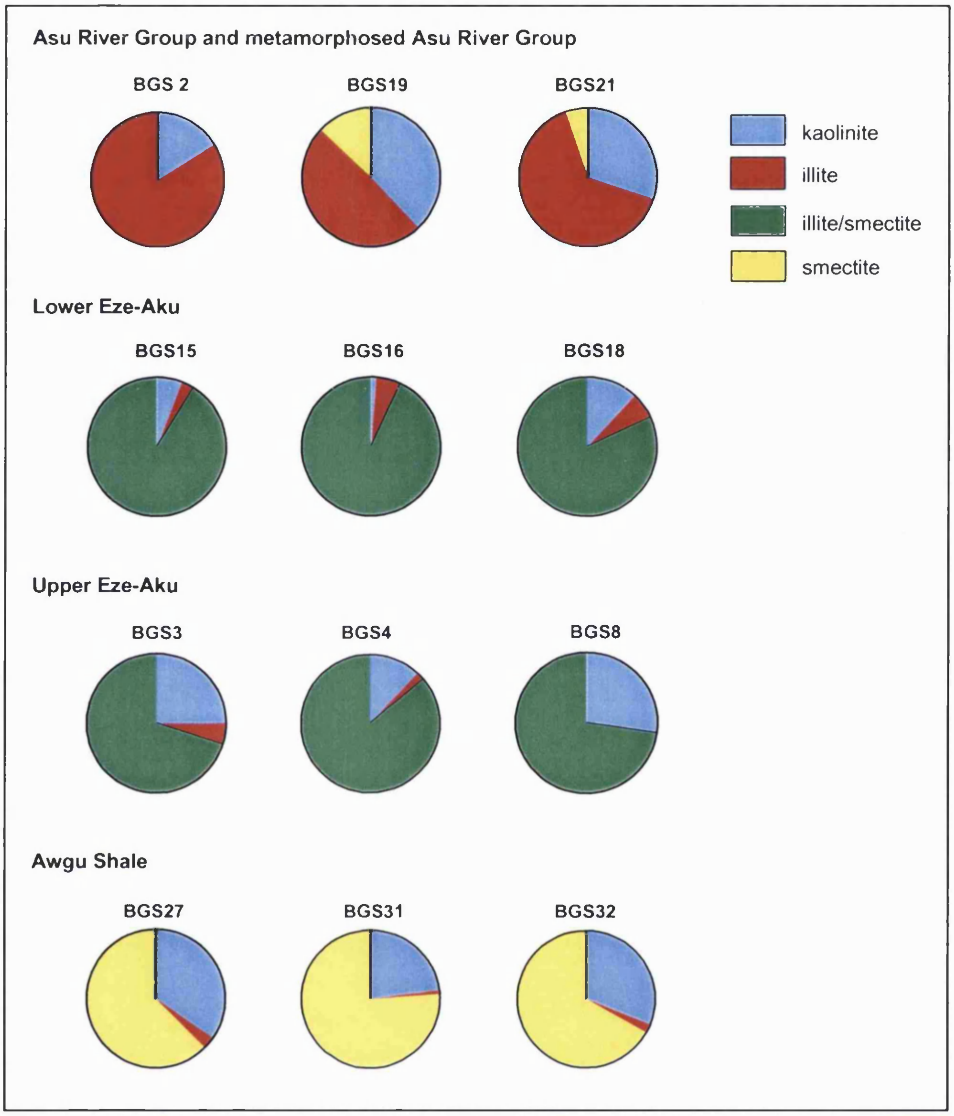


Figure 5.2 Clay mineralogy of unweathered mudstones.

It is not surprising that the Awgu Shale is comprised of smectite. Smectite is the main clay mineral formed by erosion in warm temperate and tropical environments; the conditions Nigeria would have been experiencing during the Cretaceous Age (Chamley 1989). In addition, non-erosional sources of clay minerals, such as volcanic ash and glass also give rise to smectite clay. The depositional environment of the Upper and Lower Eze-Aku, and also the Asu River Group would not have been very different from that of the Awgu Shale, and almost certainly the initial dominant clay mineral of all these mudstones was smectite.

The progression of smectite → illite/smectite → illite is indicative of different stages of low-grade metamorphism. At low temperatures (<300 °C), pelitic and metapelitic rocks exist in a series of metastable structural and chemical states. The main driving force for these reactions is temperature, although strain energy can also be important. The reactions are not reversible. The classic study of Hower *et al.* (1976) in the Gulf of Mexico showed that the transformation from smectite to illite took place at about 90 °C (a depth of 3-4 km). Intermediate stages of mixed layer illite/smectite clays are again metastable and often highly structured (Merriman & Peacor 1999). Figure 5.3 shows the expected clay mineralogy and physical properties of metapelites at various grades of metamorphism. The reactions are a movement towards a more ordered state, with larger crystals and less defects. Pore water is expelled during these reactions.

In Oju and Obi, the clay mineralogy of the various geological formations is consistent with the pattern of metamorphism discussed above. The youngest mudstone, the Awgu Shale, has not suffered any late stage diagenesis and is still largely unaltered

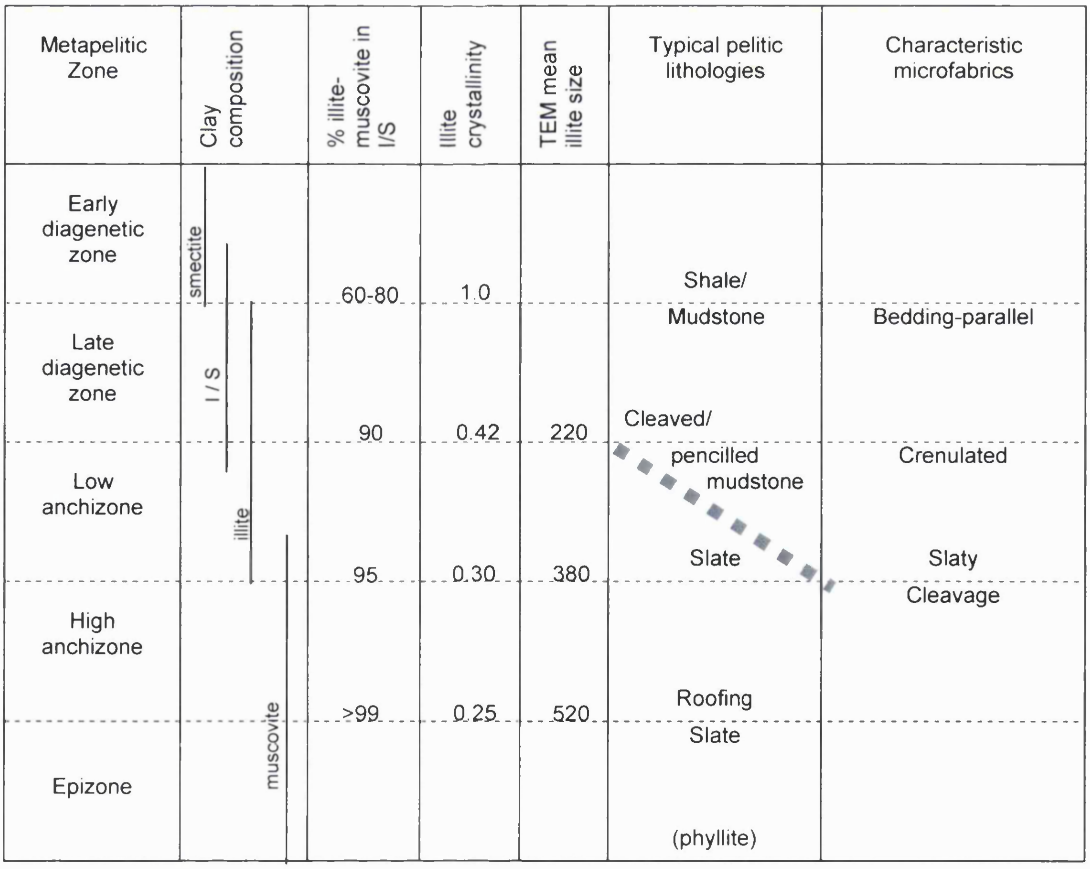


Figure 5.3 Metapelitic zones and indicators of smectite–I/S–illite–muscovite progress (after Merrimor & Peacor 1999).

smectite clay. The Eze-Aku Group has been subjected to burial. Rock samples show a degree of fissility (see detailed geological logs in accompanying CD-ROM) and the clays are mixed layer I/S, with older samples generally having less smectite layers. The oldest mudstone, the Asu River Group, has been subjected the highest grade of metamorphism. Not only have the mudstones been deeply buried (some estimates suggest as deep as 3200 m (Akande & Erdtmann 1998)) but they have been subjected to tectonic strain. The corresponding high proportion of illite, little smectite and the well-developed slaty cleavage suggest a low to high anchizone grade of metamorphism.

The metamorphic model provides a major step towards understanding variations in transmissivity between different mudstone formations. In Chapter 2 it was noted that mudstones must be fractured to enhance their permeability sufficiently to be of use as an aquifer. Mudstones that have not undergone late diagenesis, still have a high component of smectite clay. Because of its low negative charge, smectite clay has unique properties of water absorption and swelling – any fractures that might be generated within the smectite can be quickly healed. Therefore, unaltered mudstones have little potential for groundwater.

Where mudstones have been buried and subjected to low to high anchizone grade metamorphism, illite clay dominates the clay mineralogy. Illite has a much higher negative charge than smectite, and therefore binds interlayer ions closely. Illite does not swell, and often has large crystals (>100 Å). This makes illite mudstones stable and resistant to weathering (hence the durability of roofing slate). Any fractures at shallow depths within the mudstone will generally remain open. This is clearly observed in the Asu River Group where fractures are widespread. Boreholes drilled within the Asu River Group (often at random) encounter fractures which sustain high yields. The transformation from I/S to illite clay, although explaining why fractures, once formed, remain open, cannot account for the widespread generation of fractures. However, the brittleness of illite dominated mudstones ensure that they are easily fractured. Tectonic stresses, erosional unloading or even the reactivation of old hydrofractures may give rise to stresses that create the fractures (Singhal & Gupta 1999).

Mudstones that have been subjected to late diagenesis, but not deep burial, comprise mixed layer illite/smectite clays. The ratio of smectite to illite is crucial within mixed layer I/S clays. Where illite dominates, fractures are likely to remain open and enhance the permeability of the mudstone. However, if diagenesis has not proceeded far, smectite will dominate the mixed layer I/S clays and secondary permeability will not develop. The exploratory boreholes in the Upper Eze-Aku Shale showed that permeability was greatly enhanced by large fault zones, giving transmissivity values of 1 to 3 $m^2.d^{-1}$. However, boreholes that did not penetrate large fracture zones had very low transmissivity (akin to those in the Awgu Shale).

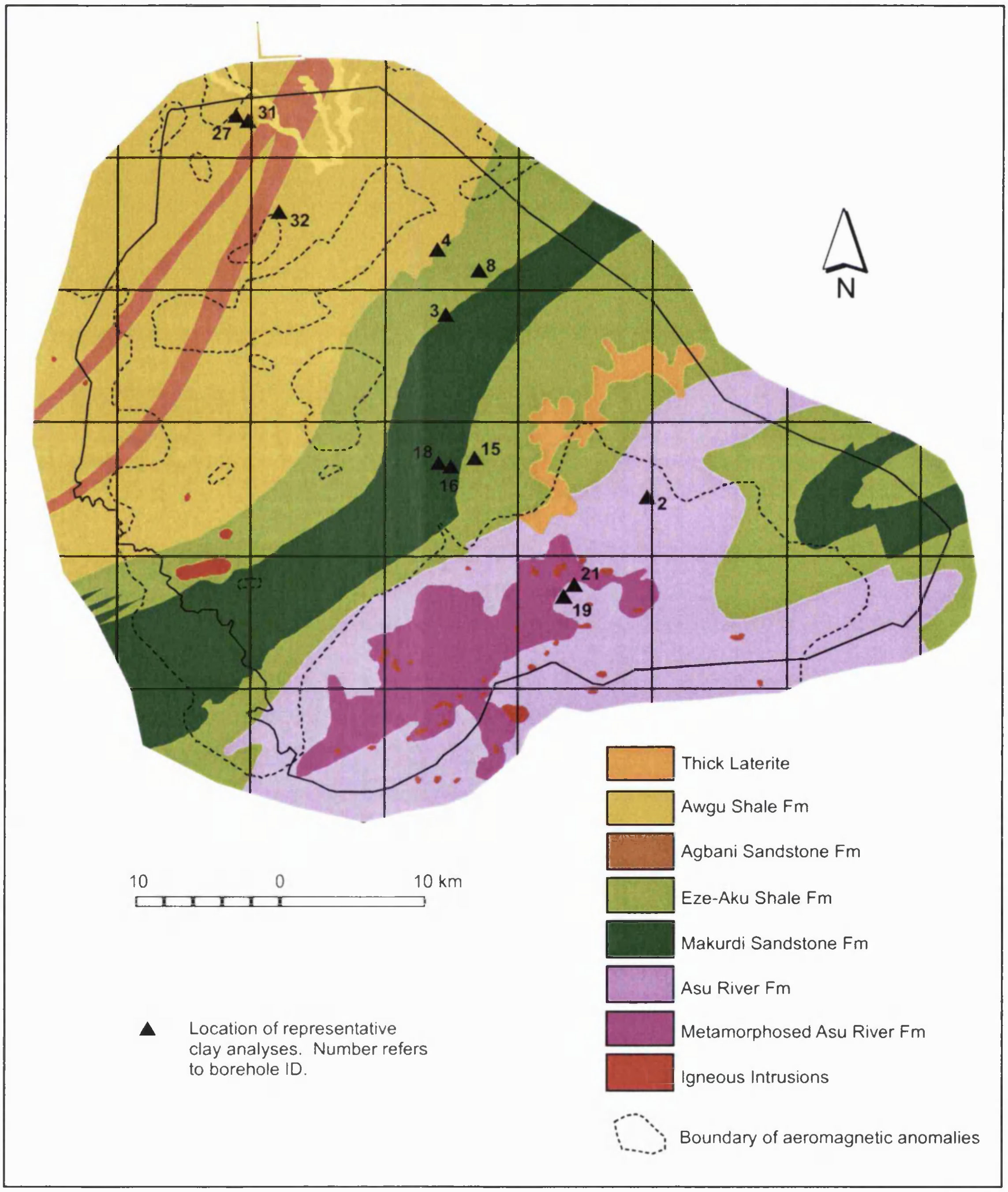


Figure 5.4 Location of boreholes used to study the effect of low-grade metamorphism on mudstone hydrogeology.

To test how well the data from Oju and Obi fit this conceptual model some further analysis was undertaken. This analysis focused on trying to uncover the degree of low-grade metamorphism *within* the illite mudstones and the I/S mudstones. For several samples of the Asu River Group and metamorphosed Asu River Group illite crystallinity was determined. Illite crystallinity is a measure of the size and order of illite crystals, and therefore the degree of metamorphism (see Merriman & Peacor 1999). For samples within the mixed I/S clays of the Upper and Lower Eze-Aku, the relative proportion of illite within the mixed clay was established by modelling (data in Appendix). Only boreholes that struck water from mudstone were included in this analysis (see Figure 5.4 for borehole locations) all sandstone, limestone and dolerite boreholes were excluded. The analyses were checked against the results of a similar study of burial metamorphism in the Benue Trough (Akande & Erdtmann 1998).

Figure 5.5 shows the transmissivity from boreholes penetrating the upper 20-40 m of mudstone, related to degree of low-grade metamorphism. It is clear that as metamorphism increases and the smectite content reduces, transmissivity increases. For unmetamorphosed, smectite-rich mudstones, transmissivity is consistently low. As metamorphism proceeds to the early-late diagenetic zone boundary, higher transmissivity

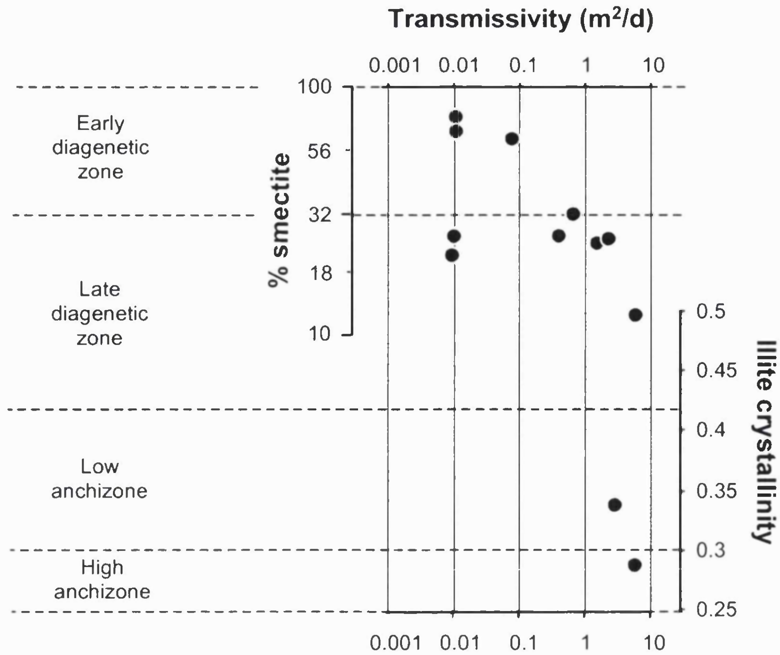


Figure 5.5 Transmissivity related to degree of metamorphism of mudstones in Oju and Obi, using %smectite and illite crystallinity as indicators.

values are possible within the mudstone since large fractured zones remain open; the variance remains high however, since transmissivity is still low away from the large fractured zones. Where metamorphism has proceeded well into and beyond the late diagenetic zone, the mudstones are sufficiently competent for widespread small fractures to remain open and transmissivity can be consistently high.

Variations in transmissivity data from Oju/Obi are therefore explained by considering the extent of low-grade metamorphism. This conceptual model is transferable to other mudstone areas.

5.1.3 The presence of thin sandstone and limestone layers

The presence of geological material other than clay particles has an important effect on the hydrogeology of mudstone environments. Thin bands of sandstone and limestone can significantly enhance permeability (see Chapter 2). In this section I examine how the presence of other lithologies affected the hydrogeology of Oju and Obi, and also suggest how this has a wider implication.

Three test sites were located in areas that had significant sandstone or limestone beds interlayered within the mudstone: Ochingini, Odaleko Adiko and Adum East. Two others penetrated thin sandstone layers: Itogo and the north Obi traverse.

Ochingini, Odaleko Adiko and Adum East, are all within the Eze-Aku Group. This Group comprises interlayered sandstone, mudstone and limestone. The Group is subdivided into the Makurdi Sandstone Formation where the sandstone layers are dominant, and the Eze-Aku Shale Formation where mudstone is dominant. The geological logs show that the sandstone layers can be anything from less than one millimetre to several metres thick.

Comparison of laboratory analysis of hydraulic conductivity and field measurements of transmissivity indicates that in most of the boreholes fracture permeability is the dominant method for groundwater flow (see Chapter 4). Careful examination of core samples indicates thin fractures in many of the sandstone boreholes at about 8 – 20 m. Similar conditions have been found subsequently by WaterAid when constructing hand-dug wells. Figure 5.6 shows a sub-vertical fracture from the core of BGS7. One or two of these small fractures may be providing the majority of the flow within the aquifer. For example, a pumping test on BGS36 indicated that 60% of flow

Figure 5.6 Photograph showing sub vertical fracture (far left) in a core from the Makurdi Sandstone (BGS7, 16 m).

within the borehole came from a fracture at 11 m (see data on CD-ROM). The small fractures transport water stored within the sandstone matrix to the well/borehole.

Evidence from the exploratory boreholes and subsequent hand-dug wells constructed throughout Oju and Obi indicates that fractures appear to be widespread over the outcrop of the sandstone. They appear to be at the base of weathered zone – few fractures of significance have been found below 20 m. Boreholes that have been constructed to depths significantly below the weathered zone have encountered groundwater with high TDS (BGS13, BGS36).

Constructing boreholes within fine-grained sandstone requires careful drilling and construction. Without the correct gravel pack and screen, the borehole can rapidly be filled with fine sand, leading to failure. In Oju and Obi, since the fractures are shallow, hand-dug wells are a much better option than boreholes for exploiting the available groundwater.

Thin limestone layers were also found to contain significant groundwater in Oju and Obi. Where the limestone was fractured, significant groundwater was found. A good example is BGS6. Here a thin (< 0.3 m) limestone layer is present within mudstone. A five-hour pumping test indicated transmissivity of about 18 $m^2.d^{-1}$. Unlike the sandstone, however, limestone has no matrix storage. Groundwater sources from the limestone may be unsustainable, unless a significant interconnected fracture system exists, or the mudstone is sufficiently permeable to allow slow vertical seepage into the fracture system. Rushton and Thangarajan (1989) showed that vertical seepage through clay layers providing recharge to thin sandstone aquifers was possible in India. Similar mechanisms were also found in the London Clay (Egerton 1994) and the muddy layers of the Lower Chalk in England (Allen *et al.* 1997).

Thin sandstone and limestone layers therefore have a significant impact on the local hydrogeological conditions in Oju and Obi. Since the required yield for community water supply is low, a thin layer that contains one or two fractures can be sufficient to supply a borehole or shallow well provided sufficient groundwater storage is available in the surrounding rocks (see later in this Chapter). Such interlayers are common in mudstones that have been deposited in deltaic or shallow sea environments. Even deep marine mudstone can contain coarser material and limestone because of turbidites (Reading 1996).

Drift deposits can also be of significance as sources of rural water in areas where the underlying rock has poor aquifer properties. In northern latitudes, glacial drift is occasionally used for local water supply, where surface water is of poor quality (Jones & Singleton 2000). Alluvium may also be present where there are sandstone or basement rocks upstream. In parts of Africa, blown sand deposits can be present, forming a thin aquifer several metres thick (Nichol 1999). These small aquifers can be highly significant in storing sufficient groundwater to supply a village through a prolonged dry season. Research into drift aquifers, is a large topic, and is not covered in any more detail within this thesis.

5.1.4 Dykes and sills

Some of the most productive boreholes in Oju and Obi penetrated dolerite intrusions found within the soft smectitic mudstones of the Awgu Shales. This was one of the most surprising results of the groundwater investigations. Usually, dykes and sills are avoided as they rarely contain groundwater and often act as impermeable barriers to groundwater flow (e.g. Bromley *et al.* 1994, MacDonald *et al.* 2000). On the rare occasions that the presence of dykes and sills has been found to increase borehole yields, the main factor has been increased fracturing in the host rocks due to metamorphism (Ventriss *et al.* 1982).

In Oju and Obi, however a clear pattern emerges: boreholes that penetrate thick dolerite intrusions (such as at Adum West or Ito) contain significant groundwater. Enhanced yields are also found in other boreholes that penetrated thinner intrusions, particularly in valleys (see Figure 5.1).

The geological logs of the Adum West boreholes contain interesting information about the dolerite. The majority of groundwater was not found in the metamorphosed and disturbed rock next to the intrusions. The groundwater was found *within* the dolerite. The dolerite was highly fractured with significant void spaces which allowed the growth of several millimetre long mesolite crystals along the fracture walls (Chapter 4). At two of the boreholes, BGS33 and BGS35, the dolerite was shallow, highly fractured and contained much mesolite; transmissivity values of in excess of 20 $m^2.d^{-1}$ were measured at these two boreholes. At another borehole, BGS34, the dolerite was encountered at 31 m depth; there was little zeolite and transmissivity was only 4 m^2d^{-1}. Subsequent modelling of the geophysical data showed that an extensive dolerite sill was present in the area (see Chapter 7).

The other exploratory boreholes targeting dolerite, encountered much thinner intrusions – some only a few centimetres across. Much less zeolite had developed along the edges of these intrusions and fracturing is generally less developed. Pumping tests from these boreholes indicate that, although aquifer properties are enhanced, transmissivity is not universally as high as that recorded in the larger intrusions. The two boreholes with highest transmissivity (BGS50 and BGS46 see Chapter 3 and 4) were sited where the smaller dolerite intrusions were found in valleys.

Why are the dolerite intrusions so fractured in Oju and Obi? The most likely reason is the high porosity and low permeability of the Awgu Shales into which the dolerite was intruded. At the time of intrusion the mudstones would have undergone little change since deposition and therefore would have a high porosity and contain large quantities of interstitial water. As the dolerite was intruded, the interstitial water would have turned to steam, which would not have been able to dissipate quickly, because of the low permeability of the mudstone. The resulting high pressures and rapid cooling could have caused the extensive fracturing observed at the edges of the intrusions. Subsequent circulating fluids would have given rise to zeolite growth of the fracture surfaces. This hypothesis is supported by data from BGS40, which found little fracturing and no increase in yield from dolerite intruded into sandstone.

5.2 Seasonal variations in mudstone environments

In arid and subtropical environments, where there are distinct wet and dry seasons, corresponding changes in groundwater availability depend on the nature of the hydrogeology. In large sedimentary aquifers groundwater availability and chemistry change little throughout the year. However, smaller aquifers (such as basement, shallow alluvium or low permeability sediments) are generally dependent on annual or recent recharge and therefore borehole yields and chemistry can change season to season (Calow *et al.* 1997).

In Oju and Obi, changes in hydrogeology throughout the season are an important part of community life. During the wet season, shallow wells and boreholes are full and high yielding. River and stream flow is also high and often there is widespread flooding. However, as the rains end and the dry season progresses, many streams and rivers cease to flow and most wells and boreholes dry out. In an attempt to quantify and analyse these changes, several parameters were monitored throughout the seasons (Figure 5.7).

5.2.1 Water-level and transmissivity variations

Groundwater levels in Oju/Obi are generally fairly shallow (see Figure 5.8). During the wet season, water-levels can be 2 m below ground surface, and even in the dry season are rarely deeper than 10 m. The water-levels follow the rainfall pattern throughout the year, sometimes exacerbated by the effect of pumping. In some sources (e.g M3 and M4 in Figure 5.7), there appears to be a shallow base-level, above which the groundwater can only rise for short periods. Such behaviour is entirely consistent with the existence of high permeability laterite in the upper 2-3 m.

To test changes in transmissivity throughout the year, eight boreholes that were originally tested in the dry season were retested during the rainy season (Table 5.2 and Figure 5.9). The three boreholes that showed the largest change in transmissivity (BGS1, BGS17 and BGS12) all had significant ferricrete between 0 and 3 m (see detailed logs in accompanying CD-ROM). This was particularly significant in BGS1 since the transmissivity of the underlying rocks was low. Once groundwater levels rose to saturate the lower part of the ferricrete, the yield of the borehole rose dramatically.

This has important implications for groundwater development in mudstone areas. First, pumping tests carried out in the wet season, when the ferricrete or ferruginous soil is saturated, will be misleading and optimistic. There are two sources of water to a well

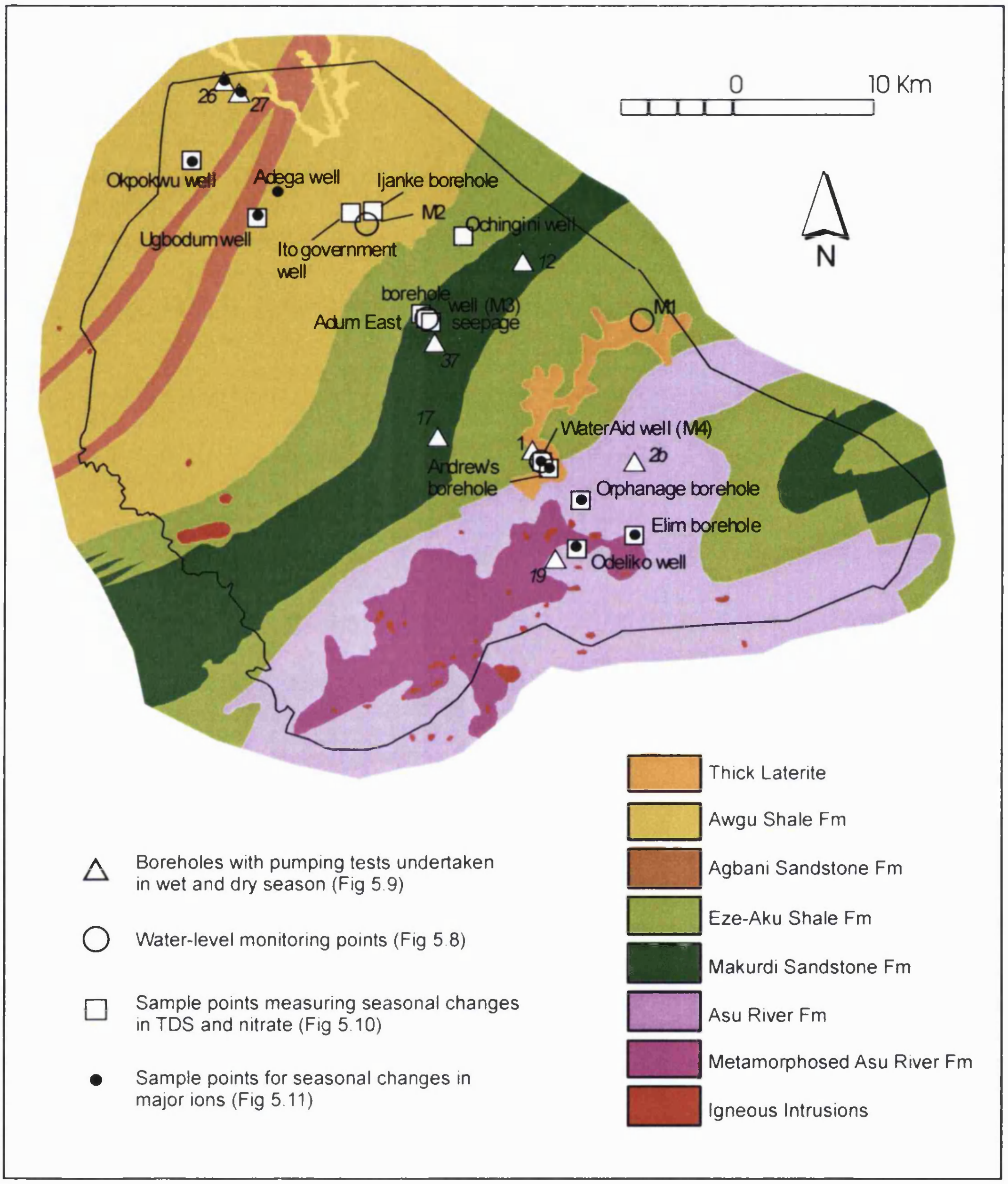


Figure 5.7 Location of sites for monitoring seasonal changes in transmissivity and chemistry in Oju and Obi.

or borehole: (1) shallow groundwater in the tropical soil during the wet and early dry season and (2) deeper groundwater from bedrock, where available. Boreholes or wells where the only source of water is from the thick soil will not be sustainable throughout the dry season. The second problem with this shallow permeable layer is that it can act as a conduit for contaminants, particularly in the wet season when saturated.

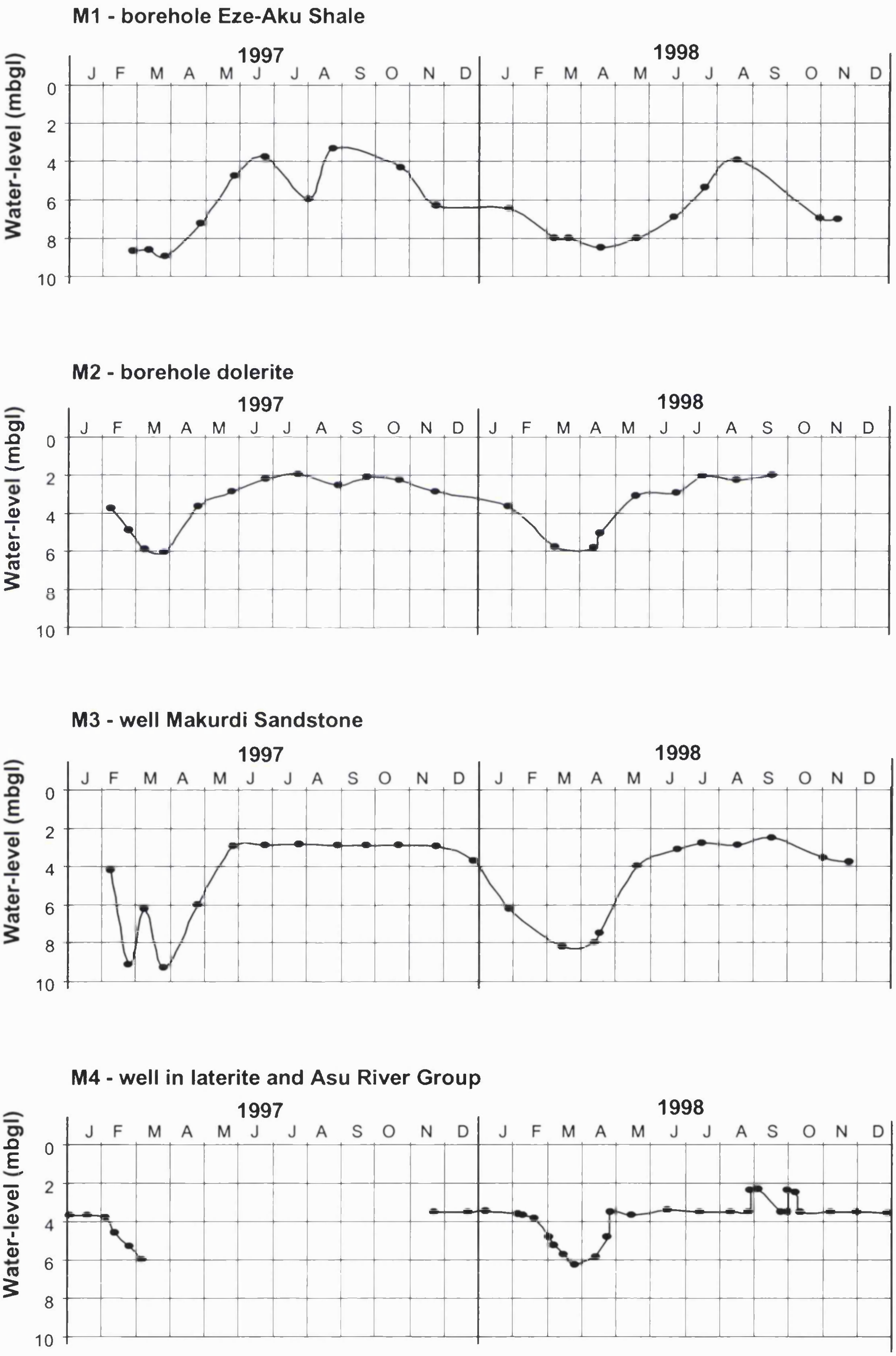


Figure 5.8 Groundwater level hydrographs for four different sources in Oju/Obi. The locations of the monitoring sites are shown in Figure 5.7

Table 5.2 Details of transmissivity measurements in both the wet and dry season at various sites throughout Oju/Obi. Locations in Figure 5.7.

Borehole	*Geological Formation*	*depth (m)*	*Dry season**			*Wet Season***		
			date	*rwl (m)*	*T (m^2d^{-1})*	*date*	*rwl (m)*	*T (m^2d^{-1})*
BGS19	mm Asu River	41.5	21/03/98	6.51	6	02/10/98	4.4	6.3
BGS2b	Asu River	19.5	28/03/98	7.32	3.5	02/10/98	2.73	4
BGS1	Asu River	12	07/04/98	3.25	0.27	10/10/98	2.97	1.3
BGS17	Lower Eze-Aku	29.5	26/03/98	6.77	1.7	03/10/98	1.98	5.3
BGS37	Makurdi Sandstone	18.5	27/03/98	5.83	0.6	12/10/98	3.65	1.1
BGS12	Makurdi Sandstone	15.7	13/03/98	5.54	1	13/10/98	2.8	2.5
BGS27	Awgu Shale	23.4	16/03/98	10.01	0.08	15/10/98	2.19	0.07
BGS26	Awgu Shale	23.4	16/03/98	14.71	0.02	15/10/98	1.86	0.27

*Transmissivity estimate from Table 3.4
**Transmissivity from 10 minute bailer test

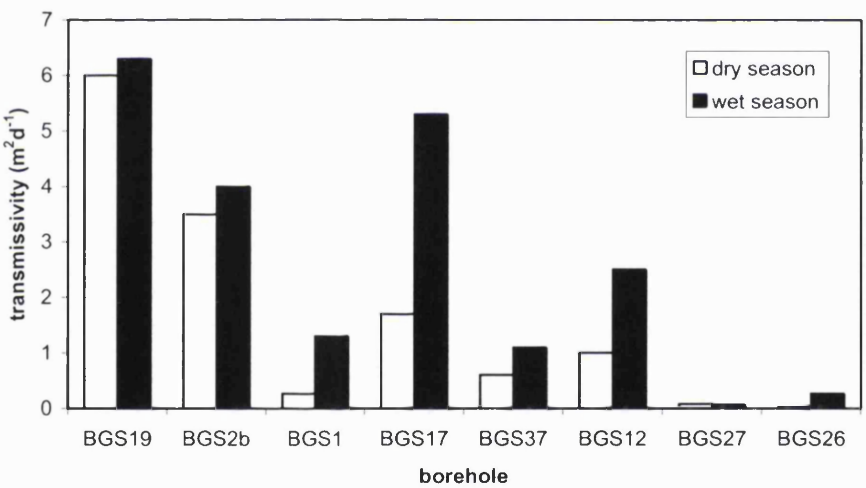


Figure 5.9 Transmissivity measured in both the wet and dry season at various sites throughout Oju/Obi. Details in Table 5.2, locations in Figure 5.7.

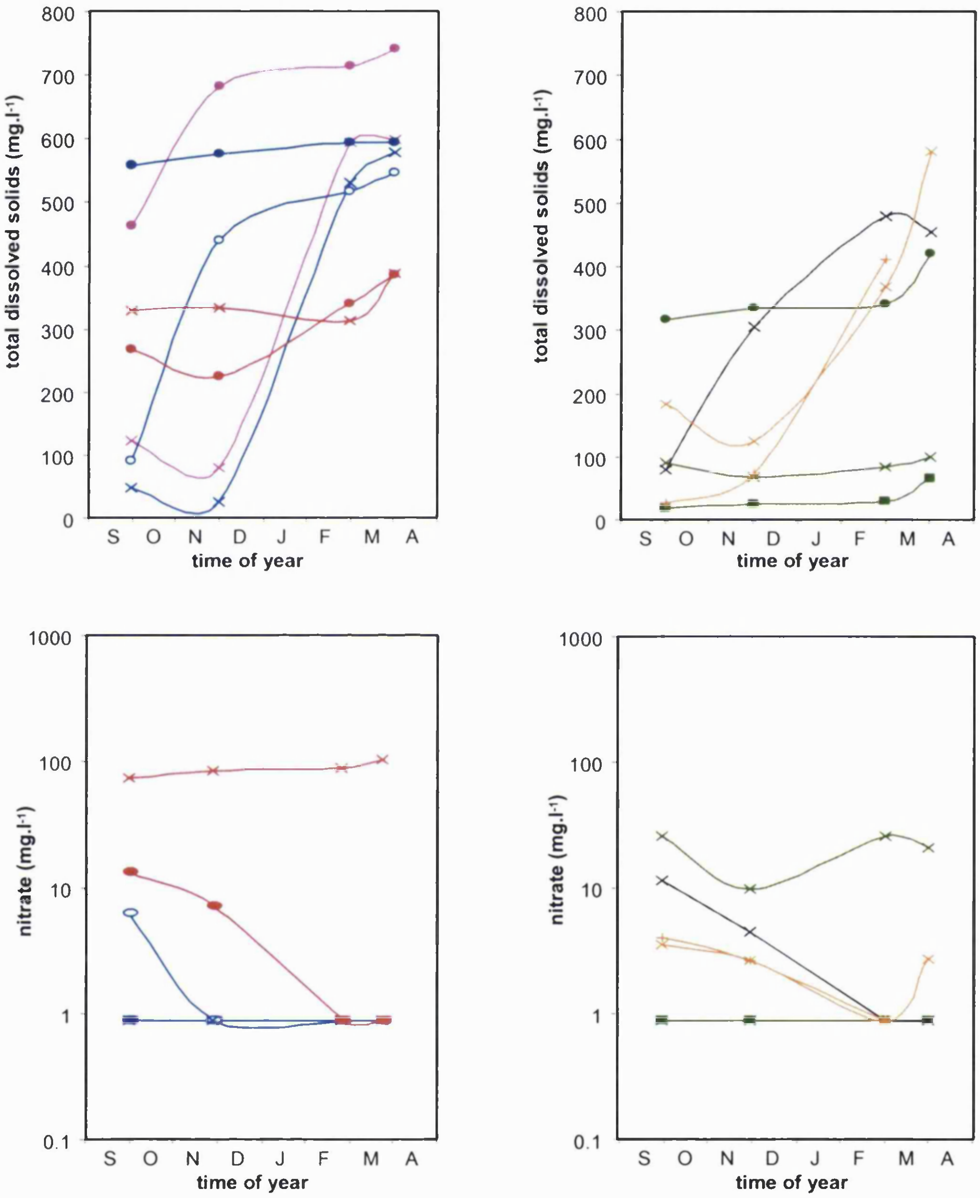
5.2.2 Water Chemistry

Thirteen sites were monitored for changes in water chemistry throughout the year. This was done to help identify changes in the contribution of shallow groundwater throughout the year and also detect any possible contamination. The locations of the sample sites are shown in Figure 5.7. All data are given in the Appendix.

Groundwater chemistry changes markedly throughout the year (Figure 5.10). In all rock types, the total dissolved solids (TDS) in the groundwater increases from wet season to dry season. The largest increases are observed in wells. One of the largest increases is in the Wateraid well where TDS rises from less than 50 mg.ℓ^{-1} in September to more than 500 mg.ℓ^{-1} in April. This observation is consistent with the transmissivity data discussed in the previous section. In the wet season the thick soil is saturated with recent rainfall which allows rapid recharge to the well of low TDS water. As the rains stop and the ferruginous soil dries out, the only water entering the well is groundwater from the base of the well. The shallow well only penetrates one or two small fractures, therefore the transmissivity is low, but the chemistry is typical of all groundwater measured throughout the Asu River Group. A similar pattern is observed in many of the wells and boreholes throughout Oju and Obi: recent recharge dominates the chemistry in the wet season with true groundwater being observed in the late dry season. Boreholes that have grouted out the shallow ferruginous soils show the least changes in TDS throughout the year (e.g. the Orphanage and Adum East boreholes). Here the true groundwater is pumped all year round.

Several sources have different behaviour to the trend described above. Adum East seepage shows very little change in TDS throughout the year. This source comprises a shallow dugout in a dambo on Makurdi Sandstone. The dugout does not penetrate deeper groundwater but is reliant solely on shallow soil water throughout the year; the yield declines to a handful of buckets a day (<100 litres) by April. The Ito Government well has high TDS throughout the year. This well is located in the centre of Ito – a busy market town. The consistently high TDS is a result of high levels of contamination.

Changes in nitrate concentrations throughout the year are also shown in Figure 5.10. Many of the sources show low nitrate concentrations throughout the year probably because they are far from possible contamination (at the time of sampling, 1997-1998, WaterAid had not started constructing latrines). Five sources, however show an inverted relationship with TDS: nitrate concentrations are high in the wet season and decline steadily as the dry season progresses. In the wet season, when the ferruginous soil is saturated contamination can flow rapidly from latrines to boreholes or wells. If the ferruginous soil is not cased out then the nitrate rich shallow groundwater can enter the borehole/well. Two wells (Ito government well and Adum East well) have high concentrations of nitrate throughout the year. Both these wells are located in market towns and groundwater is locally contaminated.



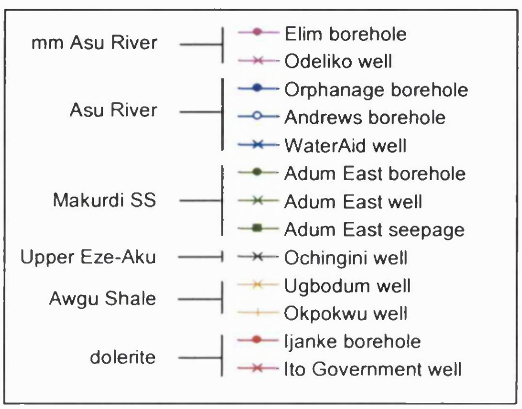


Figure 5.10. Changes in total dissolved solids and nitrate in 13 water sources throughout Oju and Obi. Data collected in 1997 and 1998.

As a result of this survey, further fieldwork was carried out in the wet season of 1999 by MacGillivray (1999) to study the impact that shallow groundwater had on the bacteriological quality of different sources. He measured faecal coliforms in 35 different water sources throughout Oju and Obi. The data demonstrated that traditional hand-dug wells which penetrate only the ferruginous soil have high coliform counts (>500 per 100 mℓ); boreholes that have been grouted to below the soil zone had zero coliforms whereas lined hand-dug wells and boreholes that were not lined throughout the entire soil zone had coliform counts between 50 and 500 counts per 100 ml.

Although seasonal changes in water chemistry are observed in each mudstone, the extent of these changes is dependent on the type of mudstone. Figure 5.11 shows hydrochemistry data for the illite mudstone, (Asu River Group) and the smectite mudstone (the Awgu Shale) plotted on a Piper diagram. Very little change in the chemical make up of groundwater is observed in the Asu River Group from the wet to the dry season, although the TDS increases markedly (see Figure 5.10). All the illite mudstone sources contained significant groundwater throughout the year, and towards the end of the dry season the water chemistry remains within the WHO drinking water guidelines. However a different pattern emerges in the low yielding smectite rich mudstone, the Awgu Shale. All of these sources were low yielding, with very little groundwater available towards the end of the dry season. As the dry season progresses and water within the shallow soil layers dries out, groundwater slowly seeps out of the smectite rich mudstone beneath. This contains much gypsum and the groundwater becomes sulphate dominated (see Figure 5.11).

5.3 Groundwater storage and recharge

Although low permeability is the main factor limiting groundwater availability in mudstones, groundwater storage and recharge can also be important, particularly if large quantities of groundwater are required. Neither groundwater storage or recharge are covered in detail within this thesis and few data were collected in relation to it. To give proper attention to either would be the subject of a new thesis. However, in this section I give some pointers towards the likely importance of storage and recharge in the context of rural water supply in sub-Saharan Africa. The few data available for Oju and Obi, both quantitative and qualitative, are also discussed.

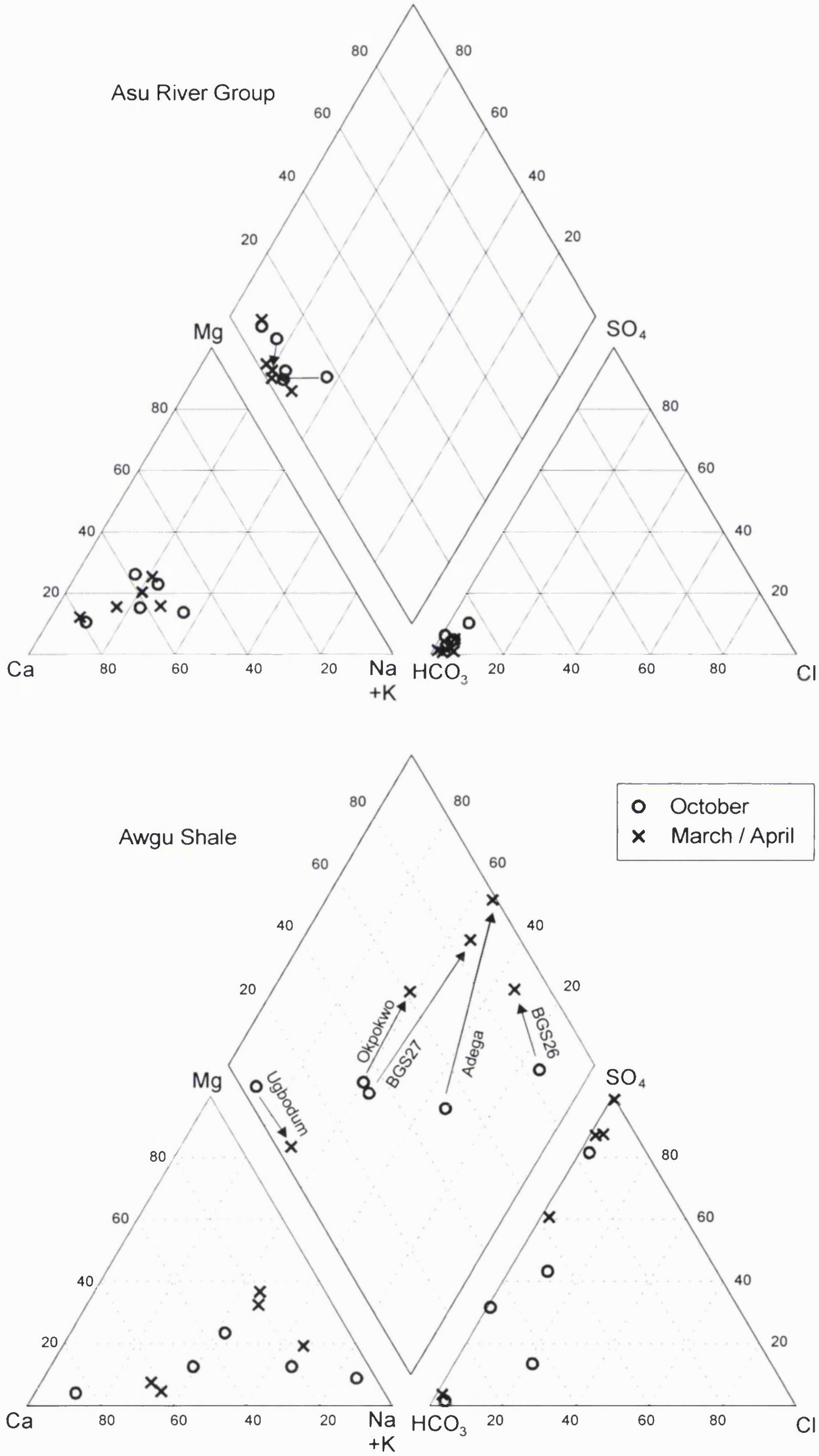


Figure 5.11. Seasonal changes in chemistry for the Asu River Group and Awgu Shale. Note that the chemical make up of groundwater in the Asu River Group changes little throughout the year, while groundwater in the Awgu shale alters considerably as the effect of rainwater reduces and sulphate rich water seeps from the low yielding mudstone.

The volume of water required to meet water demands in rural Africa is low. The WHO recommended daily usage is 25 litres per capita and most community water supplies are built around this volume. Many people make do with less if the source is more than a few hundred metres away (Kerr 1990). Community managed boreholes and wells generally serve 250 people. Greater numbers become difficult to manage (Davis *et al.* 1993). Therefore one source supplies on average 6.25 $m^3 \cdot d^{-1}$. Some simple calculations can show what recharge and storage is required to sustain such a supply.

1. Recharge: assuming 6.25 $m^3.d^{-1}$, then recharge of 12 mm per year would be sufficient if sources were spaced 500 m apart, or less than 3 mm per year if 1 km apart. Wright (1992) estimated that recharge of 1-3 mm per year would be sufficient to meet the needs of all of Africa's rural population, although this calculation did not take into account the clustering of people in villages.
2. Storage: assuming 6.25 $m^3.d^{-1}$ and a six month period with no active recharge then 1140 m^3 of water is required to be stored. This water could be stored in 3 m thick cylinder of rock radius 250 m with specific yield 0.002, or 0.0005 for radius 500 m. Note that the two measurements of the storage coefficient of the Asu River Group from pumping tests was 0.0005 (see Chapter 4).

For Oju and Obi potential recharge is high. Average rainfall is 1600 mm per year, and although evapotranspiration is more than 2000 mm per year (see Chapter 3), rainfall occurs as intense events. The rapid reaction of boreholes and wells to rainfall demonstrates that recharge can be rapid and high (Figure 5.8).

In an attempt to quantify potential recharge in Oju and Obi a chloride balance calculation was carried out. This is a rough method which assumes the chloride concentrations in groundwater are a result of chloride in rainwater (see Lerner *et al.* 1990, Edmunds & Gaye 1994). Chloride concentrations in rainwater were measured in each raingauge every month for one year (see Figure 3.4 for raingauge locations). Excluding outliers due to sampling errors, the average chloride concentration in rainfall was then calculated to be 0.8 $mg.\ell^{-1}$. Using this data the chloride balance was calculated for 80 sites, excluding those that showed evidence of contamination (e.g. elevated nitrate). Average potential recharge was calculated as 750 mm per year. However, much of this potential recharge cannot penetrate the aquifer since storage is low, hence the high groundwater levels during the wet season and the excessive runoff (Figure 3.5). Therefore in Oju and Obi, potential recharge is unlikely to be a problem, and the amount of groundwater entering the system is controlled by the storage in the aquifer.

Even in arid areas, the 3-12 mm of recharge per year required to sustain a community water supply is unlikely to be too great a problem. Studies in an area in the Sahel with average rainfall 280 mm per annum indicated active recharge of about 13 mm per annum (Edmunds & Gaye 1994). The distribution and intensity of rainfall, however, rather than total annual rainfall, is the controlling factor for recharge. Butterworth *et al.* (1999) estimated that rainfall of 100-140 mm in one week gave rise to widespread recharge of a shallow basement aquifer.

Estimating the storage capacity of the low permeability sediments is more problematic. Few measurements of storage coefficient were made during this study. As discussed in Chapter 3, a decision was taken early in the research to undertake widespread exploratory drilling and carry out single hole pumping tests rather than have extensive drilling and pumping tests at only a few locations. This method proved successful in helping to understand the controls on groundwater occurrence and the large variations in transmissivity, but at the cost of collecting rigorous data on groundwater storage. Clearly, the storage is not high. The cessation of riverflows in the dry season and rapid response of boreholes to recharge (see Figure 5.8) indicate low groundwater storage. However, groundwater storage in Oju and Obi has proved sufficient to sustain well sited wells and boreholes throughout the dry season. Collecting data on groundwater storage in mudstone environments should be the first steps in any further research. A monitoring network has been set up in Oju and Obi to help gather baseline data for such research in the future. However, in the absence of much useful data at the present time some suggestions are given here.

Measuring, or even defining the porosity of a mudstone is not trivial. Pearson (1999) for example, distinguished four types of porosity: physical, advective, diffusive and geochemical. Groundwater flow is governed by the advective porosity, i.e. the porosity that actually enables groundwater to move. For many mudstones, this porosity is governed by the volume of fractures, since flow within the matrix is too slow to respond to pumping. Black (1985) and Witherspoon *et al.* (1980) when reviewing specific storage of fissured porous rocks suggest that the cubic law was appropriate for estimating storage from transmissivity measurements. While a direct relation between storage coefficient and transmissivity can be valid in some high permeability fractured aquifers such as the Chalk (MacDonald & Allen *in press*) it may well seriously underestimate the fracture storage in low permeability aquifers. Any small restrictions or narrowings of fractures may well significantly reduce permeability, but will not affect the storage. In addition, small fractures are often highly important in providing storage but are not significant in providing flow to a well where flow is determined by major fractures. Finally, storage can be provided in fractures in all three dimensions while permeability is given by 2 dimensional flow only.

Studies in fractured aquifers show that fracture porosity can be high. The Chalk for example is believed to have a fracture porosity of around 0.01 (Price 1987), while the weathered crystalline basement is also believed to have a storage coefficient of 0.005 to 0.01 (Wright 1992, Macdonald *et al.* 1995; Singhal & Gupta 1999). In their review of the hydrogeology of UK mudstones, Tellam & Lloyd (1981) quote 0.001 to 0.0001 for the specific storage of mudstones, although it is unclear whether this includes a fractured element or solely a laboratory matrix estimate.

A study into the sustainability of groundwater sources in a crystalline basement aquifer in Zimbabwe demonstrated that permeability rather than groundwater storage was the main limiting factor on groundwater availability during drought (Macdonald *et al.* 1995). Changing to sources such as collector wells which maximise the seepage area allow access to more of the stored groundwater. Further modelling by MacDonald & Macdonald (1997) demonstrated that many wells and boreholes fail in the dry season or extended drought periods because of deep localised cones of depression around individual sources caused by low permeability and high demands rather than the dewatering of aquifers.

Recent work on the delayed drainage of recharge from the unsaturated zone suggests that storage can be enhanced by slow leakage from the unsaturated zone (Price *et al.* 2000). This could be an important mechanism in areas such as Oju and Obi with thick tropical soils. Highly fractured and weathered soils could provide significant storage throughout the dry season. This groundwater could slowly seep into the fracture zones that sub-crop at the base of the weathered zone throughout the year. The section above on seasonal changes in mudstones demonstrates that the permeability of the weathered zone is high. Significant iron staining is also observed on fracture surfaces in the weathered zone below about 4 m in most boreholes (see detailed logs in accompanying CD-ROM) therefore there should be little to limit the downward movement to fractures.

Clearly much more focused study is required of groundwater storage in low permeability aquifers such as crystalline basement and mudstones. However, the operational experience of rural water supply in crystalline basement aquifers suggests that permeability is generally much more limiting than storage, since the demands on the aquifers are so low. The long term monitoring of groundwater resources and sources in Oju and Obi will provide valuable information on the sustainability of such supplies.

5.4 Summary

The study of the hydrogeology of the Oju and Obi areas has provided an excellent opportunity to examine the hydrogeology of low permeability sediments in general. Two aspects are particularly important.

1. **Low-grade metamorphism** (Figure 5.12). The metamorphic model provides a major step towards understanding variations in transmissivity between different mudstone formations. Where mudstones have been buried and subjected to low – high anchizone grade metamorphism, illite clay dominates the clay mineralogy. Illite mudstones are stable and resistant to weathering. Any fractures at shallow depths within the mudstone will generally remain open. The brittleness of illite dominated mudstones ensures that they are easily fractured. Tectonic stresses, erosional unloading or even the reactivation of old hydrofractures may give rise to stresses that create the fractures. Mudstones that have not undergone late diagenesis, still have a high component of smectite clay. Because of its low negative charge, smectite clay has unique properties of water absorption and swelling - any fractures that might be generated within the smectite are quickly healed. Therefore, unaltered mudstones have little potential for groundwater. Mudstones that have been subjected to late diagenesis but not deep burial, comprise mixed layer illite/smectite clays. The ratio of smectite to illite is crucial within mixed layer I/S clays. Where illite dominates, fractures are likely to remain open and enhance the permeability of the mudstone. However, if diagenesis has not proceeded far, smectite will dominate the mixed layer I/S clays and secondary permeability will not develop.

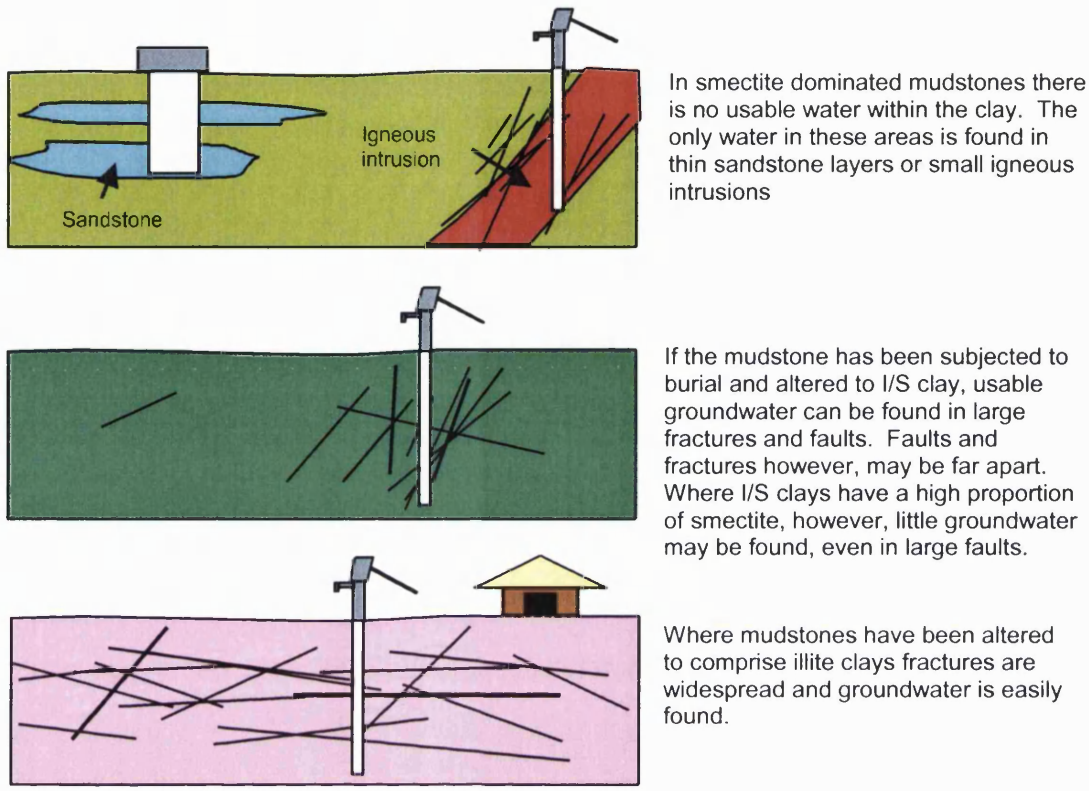


Figure 5.12 Schematic representation of the main factors affecting groundwater occurrence in low permeability sediments.

2. **The presence of other lithologies.** Dolerite intrusions within mudstones significantly increase the potential for groundwater, in contrast to studies in other rocks types which indicate the negative effect of dolerite on groundwater occurrence. Igneous intrusions within low permeability smectite rich mudstones are highly fractured and contain significant groundwater. This high degree of fracturing may have developed as a result of the high water content and the low permeability of the mudstones at the time of intrusion. The presence of even thin limestone or sandstone layers can improve the permeability sufficiently to sustain a borehole and handpump.

The seasonality of both the transmissivity and groundwater chemistry is also particularly marked in mudstone areas where thick tropical soils have developed. The transmissivity and yield of boreholes can increase four-fold during the wet season. The presence of a high permeability soil layer has important implications for the contamination and therefore construction of wells and boreholes. In the wet season the water chemistry is dominated by shallow water which can be high in nitrate and sewage derived bacteria. As this shallow layer dries out, only sources that penetrate deeper groundwater will be sustainable. Groundwater chemistry can change significantly and in low yielding smectite rich mudstones become excessively dominated by sulphate.

Few data have been collected within the present study to quantify groundwater storage and recharge. However, calculations suggest that less than 12 mm and possible only 3 mm of recharge are required each year to sustain rural water supply sources in sub-Saharan Africa, and a specific yield of approximately 0.001 should provide sufficient storage for a normal dry season. Operational experience from other low permeability fractured aquifers indicate that these figures are easily obtainable and that permeability is the main limiting factor for groundwater supply. A monitoring system has been installed in Oju and Obi to collect similar operational data for Oju and Obi. Few detailed studies of groundwater storage are available (particularly in an African context). Further research could be targeted to close this knowledge gap.

Chapter 6

A new bailer test for use in rural water supply projects

This chapter proposes an appropriate pumping test (a 'bailer test') for use in rural water supply projects in sub-Saharan Africa. The performance and analysis of the test are described in detail. Then the theoretical basis for the test is given and the limiting conditions. Data from the simple pumping test are then compared to more conventional methods for a sample of boreholes in the study area. Finally, analysis and interpretation of the test is further simplified for use as a rough 'rule of thumb' by field staff such as community health workers.

6.1 Introduction

The pumping test is one of the most important techniques available to the hydrogeologist. Properly carried out tests can give information ranging from the efficiency of the borehole to the aquifer properties of the rocks and the hydraulic influence of overlying strata. Pumping tests are carried out routinely in developed countries – mainly to "prove" the yield of a borehole before commissioning for supply. Also, the accumulation and analysis of such data can give important information on the regional variations in aquifer properties of different rocks. For example, in the United Kingdom the collation and analysis of over 30 years of pumping test data has allowed the publication of two major reviews of the aquifer properties of England and Wales (Allen *et al.* 1997; Jones *et al.* 2000). However, pumping tests are not routinely used in water supply programmes in sub-Saharan Africa since historically most financial resources are directed to borehole drilling – if a borehole strikes water it is generally assumed to be successful.

Routinely undertaking simple pumping tests on community boreholes could make a major contribution to rural water supply programmes in developing countries. Two emerging important issues facing the water sector in sub-Saharan Africa (SSA) could be addressed by undertaking pumping tests.

1. *The growing emphasis placed on the sustainability of boreholes and wells.* Many boreholes constructed during rural water-supply programmes fail within several years. Several factors are thought to contribute to borehole sustainability: hydrogeology, engineering, community ownership and cost recovery. Pumping tests can indicate if hydrogeological conditions may compromise sustainability.
2. *The decentralisation and privatisation of the drilling of rural water supply boreholes.* Following the lead given by the World Bank, the drilling of rural water supply boreholes is now often done by private contractors and managed by decentralised bodies. Information from pumping tests can be used as an independent check on the work of contractors who are under pressure to maximise profits.

6.2 The need for a simple test

At first sight it may appear unnecessary to develop a new pumping test field procedure and method of analysis when so many different methods already exist. Since the well equation was first applied to groundwater problems by Theis in 1935, a multitude of tests and analytical methods have been developed for use in different environments (Kruseman & deRidder 1990). Tests and equipment have become increasingly sophisticated as they try to capture the complexity of the groundwater environment. However, the needs of those involved in rural water supply projects in SSA, particularly those in low-permeability aquifers, are different to those in more developed countries. Personnel available to carry out tests often have little training or experience in hydrogeology; there are few resources for maintaining equipment or sophisticated analysis. A pumping test is required primarily to indicate whether a borehole will sustain a handpump, which generally have yields of between 0.1 and 0.3 $\ell.s^{-1}$. The test would act as an initial method of assessment, to discount boreholes that are obvious failures; borderline boreholes could be retested with a more accurate method.

Based on the needs and experience of the WaterAid staff and their partners in Oju and Obi, the following criteria that a pumping test would ideally meet were identified.

1. *Simple and rapid to carry out.* The test should be simple – not requiring sophisticated equipment or engineering prowess to conduct. Ideally, community members should be able to participate in the test. The test should be able to be completed within a few hours – the shorter the test, the more likely it will be performed.
2. *Cheap and robust equipment.* The equipment must be robust and where possible locally available and maintained. It must be easily transportable, such as in the back of a landrover or pickup truck.
3. *Appropriate level of information.* The test should be effective at indicating whether a borehole is likely to easily sustain a handpump. Additional information on aquifer properties, although useful for regional studies of hydrogeology, is of secondary importance.
4. *Effective.* The test must be effective for the low permeability environments found throughout much of sub-Saharan Africa (where transmissivities typically range over 0.1-10 $m^2.d^{-1}$).
5. *Easy to analyse.* The tests should not rely on elaborate methods of analysis requiring computers or complex manipulation of data.

These guidelines add to the complexity of choosing or developing a pumping test method. A short constant-rate pumping test analysed using 'Jacob' or 'Theis recovery' would give the information required to show if the borehole is successful. Drawdown and recovery is generally sufficiently slow to be measured easily using a manual water-level recorder. However, such a test would demand a low yielding electrical submersible pump to give the desired drawdown in a 0.1 - 10 $m^2.d^{-1}$ environment, compromising the requirement for cheap robust equipment and simplicity of use. The test would also have to be conducted for more than two hours for Theis recovery to be valid for a standard (6-inch) borehole in an aquifer with transmissivity of 1 $m^2.d^{-1}$ (Herbert 1990).

Slug tests are more promising in that they do not require complex pumping equipment and can be conducted rapidly (Butler 1997). The slug test is deceptively simple. The water-level in a borehole is changed instantaneously (either by the addition/removal of a solid object, or water) and the resulting recovery of the water-level to its original position recorded. Generally, only small head changes are involved due to the practicality of removing or adding volumes near instantaneously. Recording the recovery of the water-levels demands rapid and accurate measurements. This is best achieved by using a pressure transducer – a sensitive piece of equipment requiring frequent maintenance. Accurate measurement of the rapid changes in the water-level are troublesome to make manually using a water-level recorder. Effective analysis can also be complex – more so than for a standard constant-rate pumping test.

A compromise is required combining the speed and simplicity of the slug test, with the slow and easily measurable recovery of the constant-rate test. Such a test does not need to give precise information on aquifer properties, but only an indication of yield; where any doubts arise from the test a more complex and laborious test could be undertaken.

6.3 The bailer test

A simple test known as the 'bailer test' was developed during the project to meet the practical criteria of rural water supply programmes discussed above. The practical considerations of carrying out the test were given the highest priority. The test was based loosely on similar tests undertaken as part of site investigations – but rarely interpreted quantitatively (Brandon 1986). A similar field method in shallow auger holes has been used successfully by irrigation engineers for many years (Ritzema 1994) to estimate soil permeability – although analysis is empirical and based on evidence from narrow, shallow boreholes.

The test developed here comprises removing water from a borehole for 10 minutes using a bailer, and then monitoring the recovery of the water-levels for about 30 minutes. The equipment is cheap and low technology. The most sophisticated equipment is the water-level recorder – indispensable equipment for any groundwater studies. The test can be conducted successfully after minimal training and completed within an hour on most boreholes. Analysis of the data can be undertaken at three levels of complexity, varying from a quick 'rule of thumb' to a reliable estimate of the transmissivity of the aquifer using a computer programme.

The equipment required for carrying out the bailer test is shown in Figure 6.1. Each of the pieces of equipment is described below.

The *bailer* comprises a long cylindrical bucket that can easily fit down a borehole; it should contain 4 to 5 litres. It can easily be made from 3-inch steel pipe, which would allow about 4.4 litres from a one-metre length. Two bailers should be made to allow pumping to be carried out as fast as possible. A 20-m rope is attached to the top of the bucket.

A watch (preferably a *stopwatch*) is required to measure the time of pumping and recovery, as is a standard form to record data during the test.

The most sophisticated equipment required is the *water-level recorder*. This is common to all pumping test methods and is the only realistic and affordable method of measuring rapid changes in water-level. The device consists of a two-wire coaxial cable that has electrode separated by an airgap at the lower end. The circuit is completed when both electrodes enter the water and is indicated by a light or buzzer. The cable is graduated, so depth to water-level can be read directly from the cable. Realistically readings can be taken every 15-30 seconds, although experienced personnel can take readings more often.

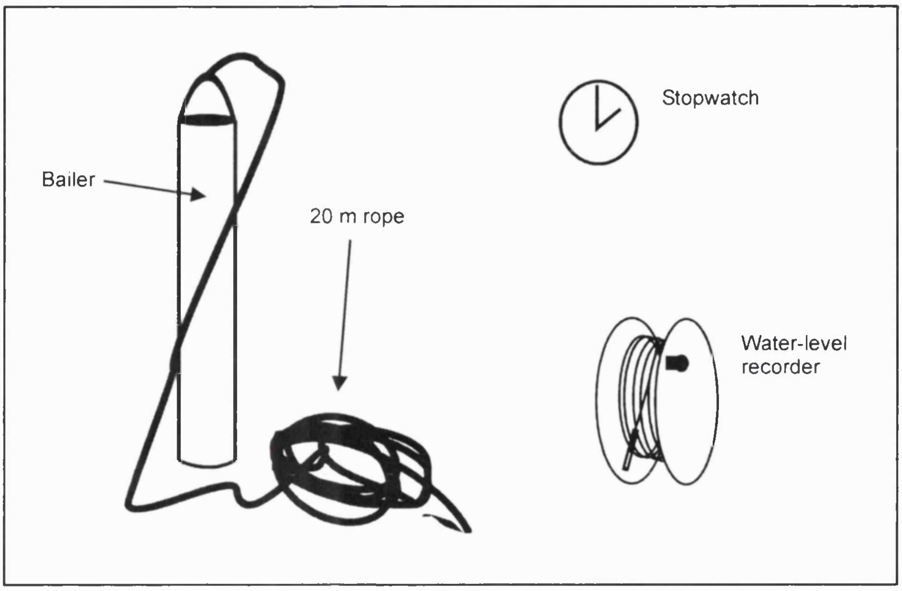


Figure 6.1 The equipment required for carrying out a bailer test.

The field procedure for carrying out a bailer test to indicate if a borehole can be equipped with a handpump is straightforward. The procedure is outlined below.

1. The rest water-table is measured in the borehole and the datum from where all readings to be taken chosen and recorded. The water-levels should be at rest prior to the test, therefore the test should not be conducted the same day as drilling or development of the borehole. However, if the test must be conducted while the water-levels are still recovering, a measured trend could be removed from the data.
2. Bailer A is lowered down the borehole; as the full bail is removed the stopwatch is started. This is repeated using a second bailer (B) as the water in Bailer A is emptied. This procedure continues for ten minutes, during which time 20-50 bails should have been abstracted, depending on the depth to water-levels. A good guideline figure to aim for is 40 bails in 10 minutes. Although an even pumping rate is not essential, the test will be more accurate if the rate of removal of the bails is fairly constant throughout the test. Since removing the bails becomes more onerous as the drawdown increases, bail removal should be paced during the first half of the test.
3. After ten minutes bailing, the stopwatch is reset and water-levels measured every 30 seconds for a further 30 minutes. A data form for recording and analysing data is given in Appendix 4.

6.4 Practical limitations

Before discussing the theoretical assumptions and limitations of the bailer test in the rest of this chapter, it is worth noting some practical considerations, particularly since this test has been designed for simplicity and practicality.

1. The test will only be appropriate where the water-table is shallow, ideally less than 10-15 m. Any deeper and it becomes difficult to remove bails at the rate required.
2. The test is designed for boreholes penetrating aquifers with transmissivity from 0.5 to 50 $m^2.d^{-1}$. In more permeable aquifers, the drawdown is too small and the recovery too fast to be accurately recorded. In aquifers with transmissivity less than 0.1 $m^2.d^{-1}$, recovery can be too slow to measure within 30 minutes. However, despite not being able to estimate transmissivity, the test will show whether the borehole can sustain a

hand pump by the very fact that drawdown is too small to be recorded or recovery too slow.

3. The test is designed for use in boreholes, not large-diameter-wells. Removing 40 bails in 10 minutes would not significantly alter the water-level within a large-diameter-well. Traditional large-diameter-well techniques and analysis would be more appropriate for use in large-diameter-wells (e.g. Barker & Herbert 1989; Mace 1999).

6.5 Analysis of the bailer test

Designing a simple quick and practical test method is only the first step towards developing a pumping test; success depends on the test being appropriately analysed and giving information relevant to the needs of the user. As a first step towards finding an appropriate analysis method several basic assumptions are made. The aquifer is assumed to be confined (or if unconfined, that the drawdown is less than about 10% of the aquifer thickness), homogeneous, isotropic and the abstraction rate constant over the duration of the test. Three main analysis types are possible: Theis Recovery analysis, slug test analysis using Hvorslev (1951), and large-diameter-well analysis (Papadopulos & Cooper 1967). These are discussed in turn below.

Krusemann & deRidder (1990) and Herbert (1990) suggest that Theis Recovery analysis is not appropriate when transmissivity is low and the diameter of a borehole finite. Through modelling, Herbert (1990) demonstrates that Theis Recovery will only give accurate estimates of aquifer properties if the time after the start of recovery is greater than $25\ r_c^2\ /\ T$, where r_c is the radius of the borehole casing and T is the transmissivity. For short tests in low permeability environments, water-levels would have fully recovered by the time Theis Recovery becomes valid.

Computer software, BGSPT,[1] has been used to demonstrate the errors arising from using Theis Recovery analysis when not strictly valid. Taking the average pumping rate, Q, of the bailer test as 25 $m^3.d^{-1}$, the period of pumping, t_p, as 10 minutes, the radius of the borehole, r_c, as 0.05 m, recovery curves were simulated for various transmissivity values (Figure 6.2). The normalised drawdown, $s\ /\ [Q\ /\ (4\pi T)]$, (where s is the drawdown

[1] BGSPT (Barker 1989; Barker & Macdonald 2000) numerically solves the generalised well function developed by Barker (1985) for large-diameter-wells in fractured aquifers and incorporates many other well functions as special cases.

in metres, Q the pumping rate in $m^3.d^{-1}$ and T the transmissivity in $m^2.d^{-1}$) is plotted to allow the errors arising from different transmissivity values to be directly compared (this however masks the absolute magnitude of the drawdown and hides the fact that for higher transmissivity values the drawdown may be too small to be measurable after about 30 minutes). It is obvious that for much of the transmissivity range that is relevant to mudstone (0.3-10 $m^2.d^{-1}$), the graphs do not conform to a straight line within a reasonable time frame and therefore Theis Recovery is not valid.

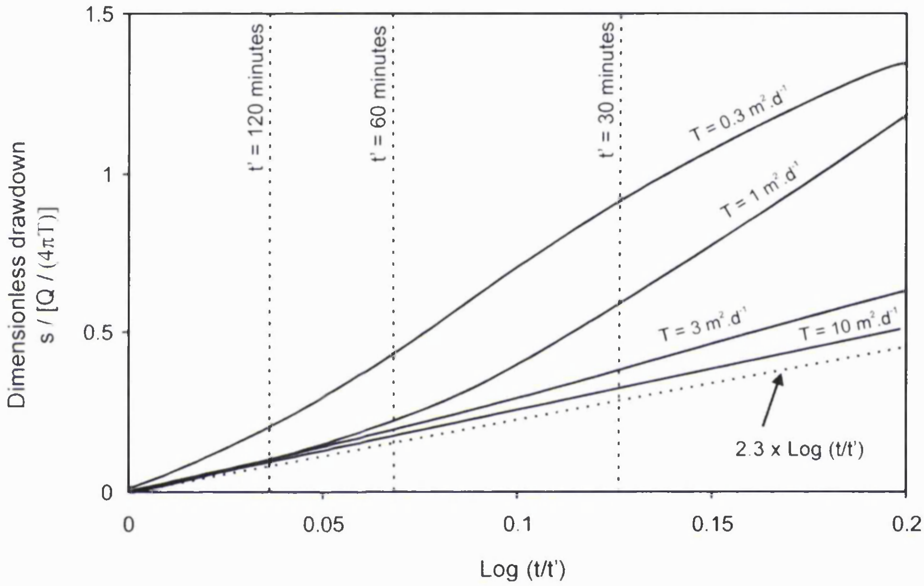


Figure 6.2 Theis recovery curves for the bailer test (see text for conditions) for various transmissivity values. The normalised drawdown, $s / [Q / (4\pi T)]$, is plotted to allow the errors arising from different transmissivity values to be directly compared; t is the time since the start of pumping, and t' the time since the pump was switched off and recovery began.

For slug test analysis to be appropriate, the flow of water into the borehole during pumping must be negligible, so that the head change can be considered instantaneous. Butler (1997) gives an excellent account of the slug test procedure and analysis. Mace (1999) used slug test analysis to calculate transmissivity from a series of wells when withdrawal of the "slug" was not instantaneous. He found that reasonable results (within 10%) could be gained if $(t_p\ T)/(4\ r^2) < 1$, where t_p is the duration of pumping and r is the radius of the borehole/well. Thus, in small diameter boreholes in low transmissivity aquifers, the non-instantaneous removal of slugs invalidates the use of slug test analysis (see Figure 6.3).

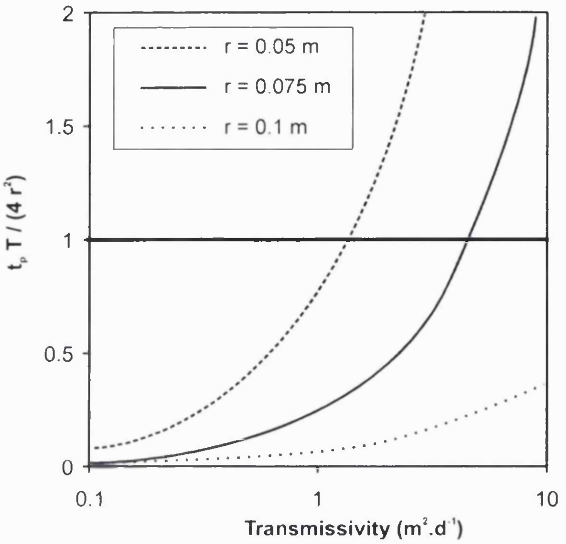


Figure 6.3 The validity of using Hvorslev slug test analysis to analyse bailer test data (Q = 25 m^3.d^{-1}; t_p = 10 minutes) for various values of borehole radii and transmissivity. Mace (1999) demonstrated slug test analysis was only appropriate if $(t_p T) / (4 r^2) < 1$.

The most promising technique for analysing bailer test data is large-diameter-well analysis. Based on Papadopulos & Cooper (1967), large-diameter-well analysis takes into consideration the storage within the borehole. It is most appropriate when the proportion of water taken from well storage during the test, λ, is less than 0.95 (Barker & Herbert 1989):

$$\lambda = \frac{\pi r^2 s_p}{Q t_p}$$

where r is the well/borehole radius; s_p, the drawdown at the end of pumping, Q the average pumping rate and t_p the period of pumping. Figure 6.4 shows the validity of the large-diameter-well analysis for standard borehole radii over the relevant range of transmissivity. It is apparent that large-diameter-well analysis is appropriate for the given pumping length and rate of the bailer test and over the radii and transmissivity values encountered in rural water supply programmes in Africa. Most large-diameter-well analyses also assume that pumping rate is constant, and that the borehole fully penetrates a homogeneous, isotropic confined aquifer. The importance of these assumptions is discussed later in the chapter.

In practice, large-diameter-well analysis can be conducted in a variety of ways: curve matching, nomograms and fitting data using a computer model. Where the technology is available, an easy method is BGSPT (Barker & Macdonald 2000). This evaluates the Papadopulos & Cooper solution using numerical Laplace transform inversion and achieves a fit to data by least squares through a series of iterations. Where computers are not readily available, curve matching or nomograms can be used. Curve matching (as given by Kruseman & deRidder (1990) for confined aquifers and Boulton & Streltsova (1976) for unconfined aquifers) is complex to undertake, requiring large families of types curves. The most appropriate analysis method for use where computers are not easily available is the nomogram method presented by Barker & Herbert (1989). The data required are: the drawdown at the end of pumping, the time for 25%, 50% and 75% recovery, borehole radius, pumping rate and length of pumping. These data are inserted into equations and nomograms used to estimate transmissivity and, with less certainty, storage coefficient.

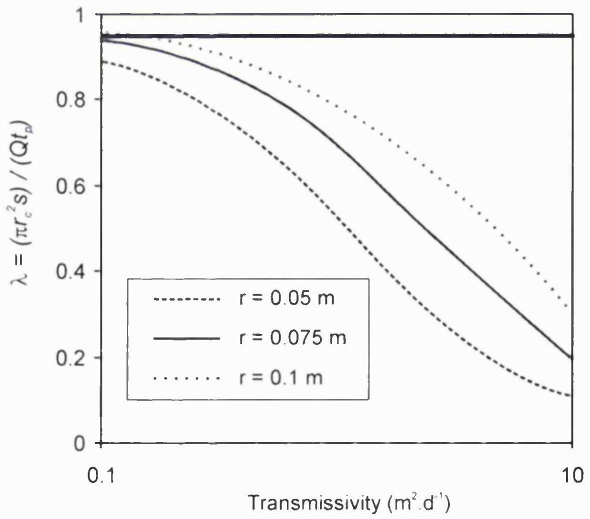


Figure 6.4 λ value $(\pi r^2 s) / (Qt_p)$ calculated for various values of transmissivity and borehole radius (using BGSPT) where Q = 25 $m^3.d^{-1}$ and t_p is 10 minutes. According to Barker & Herbert (1989), large-diameter-well analysis should be appropriate when λ is less than 0.95.

In summary, the most appropriate analysis for the short bailer test conducted on small diameter boreholes in low yielding aquifers is the large-diameter-well analysis developed by Papadupolos & Cooper (1967). The numerical analysis given by Barker & Macdonald (2000) and analysis using nomograms by Barker & Herbert (1989) allow accurate analysis and are presently the most simple available for large-diameter-well analysis. The assumptions of the analysis (borehole fully penetrating infinite, homogeneous isotropic aquifer, pumping rate constant) are not too restrictive. The sensitivity of the analysis to the most important of these assumptions is discussed in the next section.

6.6 Validity of test

6.6.1 Confined assumption

The bailer test has been primarily designed for a simple rapid test in low-yielding mudstone environments. Chapter 4 describes in detail the hydrogeological conditions found within the various mudstone environments found in the study area and Chapter 5 seeks to broaden this out to mudstones in general. Where available, groundwater is found within semi-confined fractures from 12 to 30 m below ground surface; rest water-levels often rise to about 5 m below ground surface. Since the bailer test is short and the drawdowns small, the aquifer conditions are unlikely to change significantly during the test. By far the majority of constant-rate tests undertaken in Oju and Obi show a linear response with drawdown against log(t) (see data on accompanying CD-ROM). This implies a 2-D radial response to pumping rather than any more complex interactions. Similar behaviour has been noted from aquifers within weathered crystalline basement (Wright 1992; Macdonald *et al.* 1995). Therefore the confined assumption should be valid in most cases over the length of the test.

However, even in unconfined situations, Papadupolos & Cooper (1967) large-diameter-well analysis can be valid if drawdowns within the aquifer are kept small to keep the flow in the aquifer approximately horizontal. Barker and Herbert (1989) suggest that drawdown in the borehole should be less than 10% of saturated aquifer thickness. As discussed in Chapter 5, delayed drainage and leakage can be an important form of groundwater storage within mudstone environments. However, the short time over which the bailer test is conducted (10 minutes) is unlikely to induce any vertical flow.

The effect of vertical flow (e.g. leaky conditions) on the estimation of transmissivity from the 10-minute bailer test was tested using BGSPT. Vertical and horizontal permeability were assumed to be the same (worst case scenario) for an aquifer with transmissity 1 $m^2.d^{-1}$ and storage coefficient of 0.001. The modelling predicted that the estimation of transmissivity would be affected by less than 1% by the presence of vertical flow. This prediction is reinforced by the lack of vertical flow observed in longer constant-rate tests in Oju and Obi (see data in accompanying CD-ROM). Therefore the 10-minute bailer test can be reliably used in unconfined and leaky conditions

6.6.2 Constant pumping rate

The most obvious assumption of the large-diameter-well analysis that the bailer test does not satisfy is the requirement for the pumping rate to be constant. In the bailer test, abstraction is by the removal of 40 bails of water over 10 minutes; the bails are not evenly spaced but can vary as personnel become tired and the drawdown increases. The effect of both these deviations (i.e. pulsed and reducing abstraction) from the ideal assumptions was explored by modelling using BGSPT.

Figure 6.5 shows the recovery from abstracting 174 litres in 10 minutes from 40 equal bails for a variety of transmissivity values. The recovery from abstracting the same quantity of water from constant rate pumping is shown for comparison. The recovery curves are practically identical. Re-analysing the simulated bailer data with large-diameter-well analysis assuming a constant pumping rate gives transmissivity values that

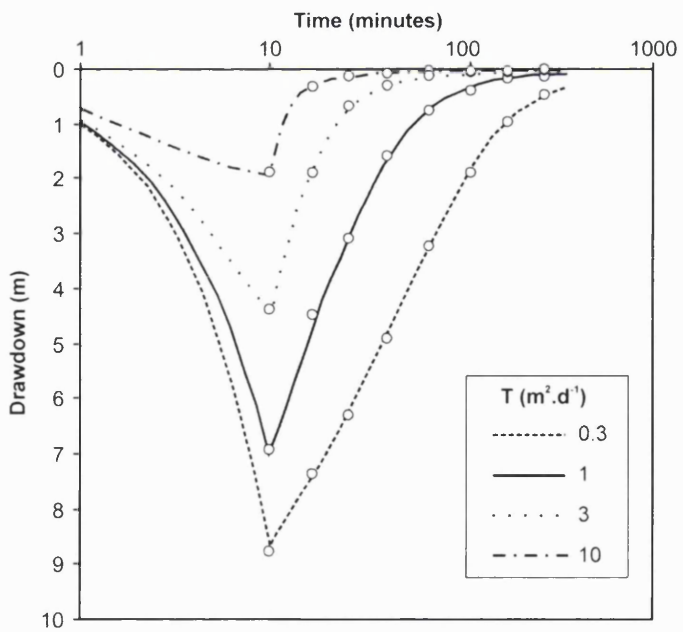


Figure 6.5 Drawdown from a constant rate pumping test (continuous lines) compared to a bailer test (circles) abstracting an equivalent volume of water in the same time. Drawdowns are modelled for a confined aquifer with S = 0.001 and borehole radius 0.075 m; 174 litres are abstracted over a 10 minute period.

are within 1% of the true transmissivity. Therefore abstracting using 40 bails, instead of a constant pumping rate has no significant effect on the analysis.

The impact of a changing pumping rate on large-diameter-well analysis is shown in Figure 6.6. Five scenarios are shown, each with an average pumping rate, Q, of 25 $m^3.d^{-1}$

1. constant pumping rate;
2. pumping rate reducing linearly from $1.5Q$ to $0.5Q$ in 40 steps;
3. pumping rate reducing linearly from $2Q$ to 0 in 40 steps;
4. $2Q$ for first half of test, 0 for second half;
5. 0 for first half of test, $2Q$ for second half.

Recovery data were simulated for the five scenarios for a borehole with radius of 0.075 m in a confined aquifer with storage coefficient 0.001 over a range of transmissivity values using BGSPT. The recovery data were then re-analysed with large-diameter-well analysis assuming a constant pumping rate.

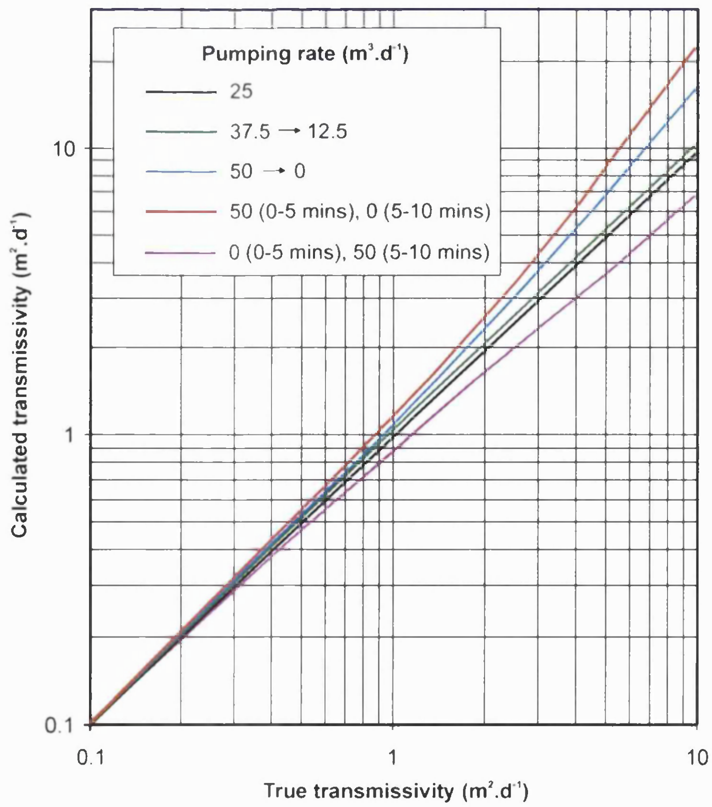


Figure 6.6. Transmissivity calculated from a bailer test (Q = 25 $m^3.d^{-1}$, t_p = 10 minutes) under various pumping regimes, plotted against true transmissivity. For transmissivity up to 10 $m^2.d^{-1}$ errors are less than 5% for changes in pumping rate up to 65%.

Figure 6.6 indicates that large-diameter-well analysis is relatively insensitive to moderate changes in pumping rate, particularly if the transmissivity is less than about 1 $m^2.d^{-1}$. If the pumping rate declines by up to 65% (scenario 2) then the error calculating transmissivity by assuming a constant (average) pumping rate is approximately 5% for true transmissivity as high as 10 $m^2.d^{-1}$. For scenario 3, where the pumping rate reduces to zero, the errors become significant at transmissivity values above 1 $m^2.d^{-1}$, 25% at 3 $m^2.d^{-1}$ and 65% at 10 $m^2.d^{-1}$. Scenarios 4 and 5 give two extremes: all the abstraction in one half of the test. Under these extreme scenarios, errors are below 15% for transmissivity less than 1 $m^2.d^{-1}$, but can rise to 40% for transmissivity of 3 $m^2.d^{-1}$ and over 100% at transmissivity above 10 $m^2.d^{-1}$.

Under normal circumstances, the pumping rate of the bailer test should not vary by more than 50% (i.e. reducing by half the number of bails in one minute). By reducing the number of bails abstracted during the first half of the test when water-levels are shallow and the operators fresh, an abstraction rate that does not vary by more than 50% is easily achievable. The bailer tests carried out in Nigeria usually had a pumping rate of about 5 bails a minute for the first half of the test, reducing to 3 bails a minute by the end of the test. This variation would cause an error of less than 5% in the measured transmissivity, assuming the average abstraction is accurately known (easily achieved by counting bails and timing the period of bailing).

6.6.3 Assumption that the aquifer is homogeneous

Most conventional pumping test analysis, such as Theis, Boulton and Jacob, assume homogeneity of the aquifer. Under most circumstances this assumption is violated – aquifers are rarely homogeneous. Allen *et al.* (1997) illustrated this for the U.K., showing that fracture flow was important for all major U.K. aquifers (Figure 6.7). Several publications, however, have illustrated that fractured aquifers can be adequately analysed using homogeneous techniques, provided the borehole penetrates a representative sample of the aquifer and the time taken for water to diffuse from the matrix to the borehole is short (e.g. Snow 1968; Barker 1993). Barker & Black (1983) and Black (1985) went a stage further and showed the errors introduced by using homogeneous analysis on dual-porosity media for slug tests. A similar approach is taken here for the bailer test.

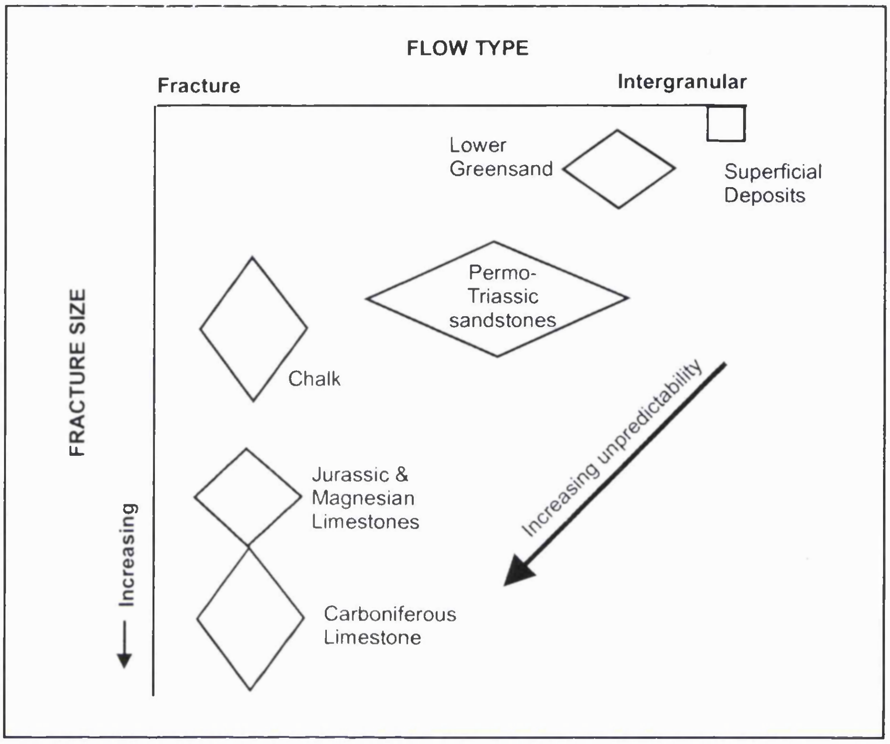


Figure 6.7. The importance of fracture flow for aquifers in England and Wales (from Allen *et al* 1997).

The nature of errors introduced into the analysis of the bailer test in dual-porosity conditions was tested using BGSPT for large-diameter-wells. Bailer tests in a series of dual-porosity scenarios were simulated and then analysed using homogeneous large-diameter-well analysis with a least squares fit. The deviations of calculated transmissivity from true transmissivity could then be observed.

As before, the conditions of the bailer test were, Q = 25 $m^3.d^{-1}$ for 10 minutes and the borehole had a radius of 0.075 m. The true transmissivity was taken as 1 $m^2.d^{-1}$ and groundwater flowed into the borehole only though fractures. Scenarios were modelled within a range of matrix permeability (10^{-14} - 10^{-10} $m.s^{-1}$), compressibility (10^{-10} - 10^{-8} $m^2.N^{-1}$) and block sizes (1-100 fractures per metre). For simplicity, the porosity of the matrix was kept at 0.3. These scenarios are indicative of various mudstones (see Chapter 2 and Chapter 5). The calculated transmissivity is plotted against the time of diffusion a cross a matrix block, $b^2\, S_s / K_m$, where b is the maximum distance to a fracture, S_s is the specific storage of the matrix and K_m is the hydraulic conductivity of the matrix. To give the worst case scenario, the specific storage of the fractures (S_f) was calculated from the transmissivity using the cubic law.

Figure 6.8 indicates that the error in calculating transmissivity increases with $b^2\ S_s\ /\ K_m$. When this time is less than 0.01 days, the error in T is negligible. By 0.1 days the calculated transmissivity is approximately 70% more than the true transmissivity. However regardless of conditions, the error does not significantly exceed 100%. The modelling was repeated for transmissivity of 10 $m^2.d^{-1}$ with similar results. Similar maximum errors were found by Black (1985) when studying the errors introduced to slug tests by using homogenous assumptions on dual-porosity media.

For many rocks the actual fracture storage is greater than that given by the cubic law (see Chapter 5). The modelling exercise was repeated with fracture storage of 0.0001. As before, for $b^2\ S_s\ /\ K_m$ less than 0.01 days the error is negligible. From 0.01 to 1 days the error is approximately 15% rising to a maximum of 40 % before declining to zero as $b^2\ S_s/\ K_m$ increases beyond 10 days (and therefore the matrix storage no longer influences the test). Where there is no matrix storage homogeneous analysis is entirely appropriate.

If the mudstone is consolidated, fractured or silty, $b^2\ S_s\ /\ K_m$ is likely to be less than 0.01 days. In softer compressible mudstones, where the specific storage is high and fractures are rare, $b^2\ S_s\ /\ K_m$ will generally be above 0.01 days. However, as was demonstrated in Chapter 5, these softer mudstones rarely have potential for groundwater supplies.

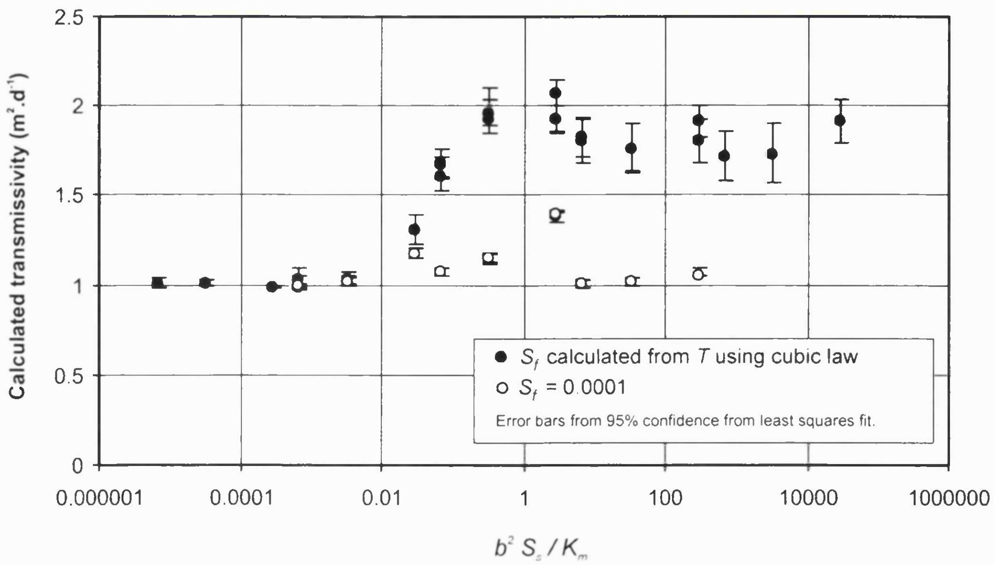


Figure 6.8 Transmissivity calculated using large-diameter-well analysis assuming homogeneous isotropic conditions for different dual-porosity scenarios each having transmissivity of 1 $m^2.d^{-1}$.

Therefore, strictly speaking the test should only be applied if the time of diffusion is less than 0.01 days. Such a condition is not unduly restrictive and for most fractured mudstones the condition is easily met. If this condition cannot be met, the error in calculating transmissivity is unlikely to exceed 100% and considerably less if fracture storage is greater than 0.0001. In a medium where transmissivity can vary by 4 or 5 orders of magnitude this error can be considered admissible.

6.7 Interpreting test results

Correctly undertaking the bailer test and appropriately analysing the data gives an estimate of transmissivity. How does this help the local rural water supply staff take a decision on the borehole? Two factors are important: understanding what portion of the aquifer this estimate refers to and also how it translates to drawdowns within the aquifer.

6.7.1 Radius of influence

Barker & Black (1983) estimated the range of influence of slug tests in fractured, porous media by calculating the distance at which negligible head change is experienced in the aquifer. Since the bailer test is longer than a slug test its radius of influence should be larger, and the radius given by Barker & Black (1983) can be treated as a minimum value. The maximum radius, r_{max} at which head changes are experienced in the aquifer in response to a slug test was estimated as:

$$r_{max} = \left[\frac{S}{r_e^2} + \frac{2n}{r_e}\left(\frac{S_s K_m}{T}\right)^{1/2} \tanh\left[\frac{d}{r_e}\left(\frac{S_s T}{K_m}\right)^{1/2}\right]\right]^{-1/2}$$

where S fracture storage coefficient

S_s specific storage of the rock matrix

T total transmissivity due to the fractures

K_m matrix hydraulic conductivity

d half the fracture separation

r_e effective casing radius of the boreholes

n number of fractures in the aquifer.

(Barker & Black (1983) demonstrated that this radius corresponds closely to where the head changes in the fractures are roughly 10% of the head change in the borehole). Using this formula for a mudstone environment demonstrates that the radius of influence can be greater than 100 m. For example, with transmissivity 1 $m^2.d^{-1}$, compressibility 10^{-8} $m^2.N^{-1}$, matrix hydraulic conductivity of 10^{-10} $m.s^{-1}$ and 10 fractures per metre, the radius of influence would be 150 m. However, this assumes theoretical conditions which will rarely be met in practice – in reality the radius will be much smaller.

In summary, the bailer test samples a significant element of the aquifer around the borehole. However, the effects of hydraulic barriers, or leakage from overlying deposits, will not be identified from the test. Only long-term tests (greater than 1 day) would reliably indicate this sort of behaviour.

6.7.2 What transmissivity values mean

On its own, knowing the transmissivity of an aquifer has little benefit to those responsible for making decisions about the water supply for villages. The knowledge has to be applied and translated into an estimate of how productive a borehole will be and whether it will sustain a handpump. By making some generalisations and carrying out simple modelling, a rough guide can be given to show the significance of transmissivity values. To model the significance of transmissivity values, various data are required: the average pumping rate, the maximum allowable drawdown, the rough borehole diameter, the length of the dry season and an estimate of the storage coefficient of the aquifer.

Average pumping rate. Most organisations involved in rural water supply suggest that community boreholes or wells should supply no more than 250 people. Twenty-five litres per day per person is a figure often used as a minimum – currently this is higher than used in much of sub-Saharan Africa. These two figures give an average daily abstraction of 6.25 $m^3.d^{-1}$. Assuming abstraction over a 12-hour period, this gives a pumping rate of 0.145 $\ell.s^{-1}$ for 12 hours a day.

Maximum allowable drawdown. Boreholes throughout rural Africa are often shallow, 30-50 m. Rest water-levels are generally less than 10 mbgl. With this in mind, a maximum permissible drawdown of 15 m is not unreasonable. This is the same value used by MacDonald & Macdonald (1997) in a study of borehole failure during drought in Africa. If this drawdown is exceeded, the pump may stop operating until water-levels recover. In many communities with low yielding boreholes, the pump is only used twice a day to give water-levels a chance to recover.

The length of the dry season. If the shallow aquifer is assumed to recharge during the wet season, then effective unsteady state aquifer behaviour (and groundwater depletion) starts at the end of the rains and continues until the rains start the next year. For much of Africa the dry season last for 6 months (180 days).

Borehole diameter. Several borehole diameters are used in rural water supply programmes: boreholes are often drilled at 6.25-inch and completed with 4 or 5-inch screen. More rarely, boreholes are drilled at 8-inch with 6-inch screen. If a gravel pack is used, then the effective diameter ($2r_e$) will be the screened diameter plus the pore space in the annulus. Changes in borehole diameter were found to affect drawdown by only a fraction of a metre after 180 days, therefore modelling was continued with a diameter of 5-inch (0.0625 m).

The storage coefficient. As discussed earlier, estimates of storage coefficient can vary significantly for mudstones. Modelling and discussions in Chapter 5 indicate that specific yield of 0.001 - 0.0001 are most likely for boreholes that contain sufficient water to test pump. Again Chapter 5 discusses how this may be an underestimate of the water stored in the rocks, since leakage from shallower layers may be highly significant for pumping over a matter of months. For basement rocks a long-term storage coefficient of 0.01 is thought reasonable (Wright 1992).

These criteria were modelled with large-diameter-well analysis using BGSPT. Pumping was taken as 0.145 $\ell.s^{-1}$ for 12 hours and 0 for 12 hours for a total of 180 days. The results of the modelling are shown in Figure 6.9. The drawdown does not have a high dependency on the storage coefficient. A transmissivity of 1 $m^2.d^{-1}$ would be

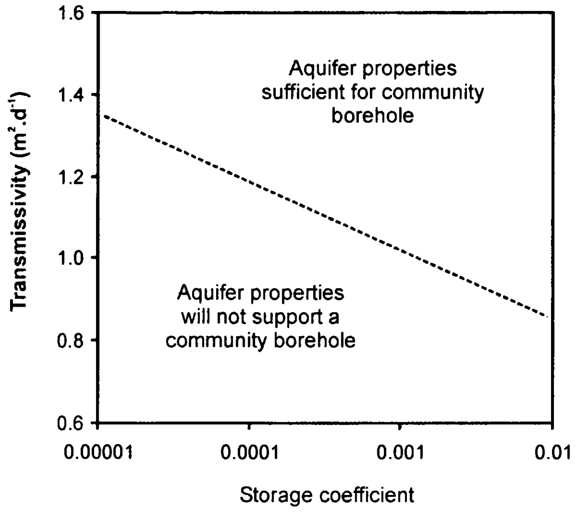


Figure 6.9 Aquifer properties required to sustain a community borehole for 250 people. Modelling was undertaken using BGSPT. (Yield of 0.145 $\ell.s^{-1}$, 12 hours a day for 6 months. Criteria for failure was drawdown of greater than 15 m).

adequate for a hand-pump serving 250 people if the storage coefficient is greater than 0.001. Where the storage is less, a slightly greater transmissivity (1.35 $m^2.d^{-1}$) would be required.

6.8 Data from Nigeria

The efficacy of the bailer test was examined using data from the study area in Nigeria. Fifteen boreholes were chosen covering a range of yields. Bailer tests were undertaken and analysed using BGSPT. Five-hour constant-rate tests were also carried out in the boreholes and the recovery data analysed with Theis Recovery (Kruseman & de Ridder 1990). The data are shown in Table 6.1 and plotted on Figure 6.10. Details of the tests are given on the accompanying CD-ROM..

The bailer test accurately determines transmissivity calculated from the five-hour test with a correlation r^2 of 0.9. Therefore, for these examples in Nigeria, the bailer test gave comparable data to that calculated from the much longer and more cumbersome constant rate recovery test. The bailer test gives slightly higher estimates of transmissivity than the longer rate test. These differences become more significant where the transmissivity is approximately 1 $m^2.d^{-1}$, the borderline for a sustainable borehole. In such borderline cases it is important to carry out more accurate and detailed tests than the bailer test.

Table 6.1 Estimates of transmissivity from constant rate tests and bailer tests carried out in the same boreholes under similar conditions.

Borehole	*Transmissivity* ($m^2.d^{-1}$)	
	C-rate test	*Bailer test*
2b	3.2	4.9
4	0.54	0.88
6	18.3	35
12	1.6	1.9
26	1.6	2
16	2.1	4.2
17	1.7	0.95
19	6.5	9.5
20	41	48
21	3	3.7
34	3.8	8.7
35	23	26
36	0.58	1.63
37	0.7	1.1
42	0.8	2.7

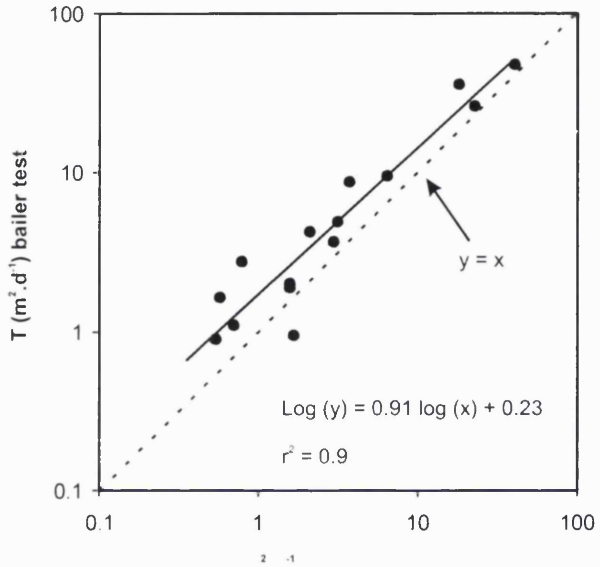


Figure 6.10 Comparison between transmissivity calculated from a bailer test and a longer constant rate test for a series of boreholes in Oju and Obi. Data are given in Table 6.1.

6.9 Further simplification

So far this chapter has described the development of the simple bailer test and shown its effectiveness. However, the analysis of the test is still a little more complex than desired, requiring either the use of nomograms (Barker & Herbert 1989) or a computer (BGSPT). By making several generalisations and undertaking a little more modelling it is possible to simplify the analysis. As described in the introduction to this chapter, the need for pumping tests in rural water supply boreholes in Africa is to answer the question "can this borehole sustain a handpump ?" A rule of thumb for the bailer test answers this question: yes, no or maybe.

Figure 6.9 shows transmissivity and storage values that produce an acceptable drawdown at the peak of the dry season for a borehole supplying 250 people. These aquifer properties can be used to simulate expected drawdown and recovery rates from a bailer test. If the maximum drawdown in a bailer test is significantly greater, and the recovery rate slower, than that simulated for these minimum aquifer properties, then it can be assumed that the borehole will not sustain a handpump. Conversely, if the maximum drawdown is significantly less, and the recovery more rapid, then the borehole will sustain a handpump.

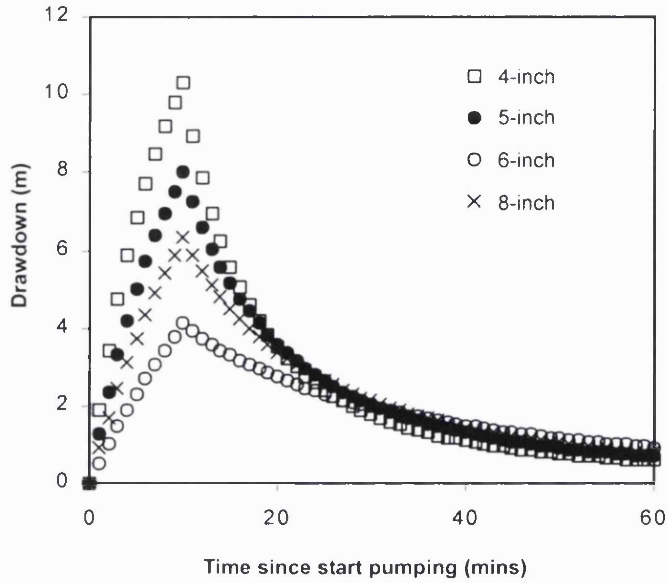


Figure 6.11 Drawdown and recovery for bailer test in boreholes with diameter 4 inch, 5 inch, 6 inch and 8 inch. $Q = 25$ m^3.d^{-1}; $t_p = 10$ minutes, $S = 0.001$ and $T = 0.85$ m^2.d^{-1}.

Using drawdown and recovery rates (rather than transmissivity) to give guidelines on borehole success adds another layer of uncertainty to the interpretation. Borehole radius and pumping rate also affect drawdown and recovery. Obviously the abstraction rate affects drawdown, but the effect of borehole radius is not so clear. The simulations in section 6.7.2 showed that borehole radius had a negligible impact on drawdown over 6 months. However, the influence of borehole storage causes the radius to have a much greater influence on drawdown and recovery for the short time period of the bailer test (Figure 6.11). Therefore to have effective guidelines for borehole success, the borehole radius and abstraction rate must be accounted for.

Drawdown and recovery curves were simulated for various borehole diameters and pumping rates with aquifer parameters which should be sufficient to sustain a handpump throughout a six month dry season. The length of the test was fixed as 10 minutes. Maximum drawdown, and the time for 25%, 50% and 75% recovery were recorded in Table 6.2. In all cases 25% recovery occurs very quickly and is not particularly diagnostic, particularly if water-level measurements are only taken every half minute. Maximum drawdown, 50% and 75% recovery, however, are easily measured within one hour and diagnostic of aquifer conditions.

Table 6.2 Maximum drawdown and recovery times (in minutes) for a 10-minute bailer test undertaken in various diameter boreholes at different pumping rates (simulated using BGSPT).

		$10\ m^3.d^{-1}$		$15\ m^3.d^{-1}$		$20\ m^3.d^{-1}$		$25\ m^3.d^{-1}$		$30\ m^3.d^{-1}$	
		high S*	*low** S*	*high* S*	*low** S*	*high* S*	*low** S*	*high* S*	*low** S*	*high* S*	*low** S*
4 inch	Max drawdown (m)	4.1	5.0	6.1	7.6	8.1	10.1	10.2	12.6	12.2	15.1
	25% recovery (mins)	2.2	2.8	2.2	2.8	2.2	2.8	2.2	2.8	2.2	2.8
	50% recovery (mins)	5.9	7.0	5.9	7.0	5.9	7.0	5.9	7.0	5.9	7.0
	75% recovery (mins)	14.4	15.1	14.4	15.1	14.4	15.1	14.4	15.1	14.4	15.1
5 inch	Max drawdown (m)	3.2	3.8	4.7	5.7	6.3	7.6	7.9	9.5	9.5	11.4
	25% recovery (mins)	3.1	4.1	3.1	4.1	3.1	4.1	3.1	4.1	3.1	4.1
	50% recovery (mins)	8.6	10.5	8.6	10.5	8.6	10.5	8.6	10.5	8.6	10.5
	75% recovery (mins)	20.9	12.8	20.9	12.8	20.9	12.8	20.9	12.8	20.9	12.8
6 inch	Max drawdown (m)	2.5	2.9	3.7	4.4	5.0	5.8	6.2	7.3	7.4	8.7
	25% recovery (mins)	4.2	5.8	4.2	5.8	4.2	5.8	4.2	5.8	4.2	5.8
	50% recovery (mins)	11.7	14.8	11.7	14.8	11.7	14.8	11.7	14.8	11.7	14.8
	75% recovery (mins)	28.3	32.2	28.3	32.2	28.3	32.2	28.3	32.2	28.3	32.2
8 inch	Max drawdown (m)	1.6	1.8	2.4	2.7	3.2	3.6	4.0	4.	4.82	5.5
	25% recovery (mins)	6.9	10.0	6.9	10.0	6.9	10.0	6.9	10.0	6.9	10.0
	50% recovery (mins)	19.2	25.6	19.2	25.6	19.2	25.6	19.2	25.6	19.2	25.6
	75% recovery (mins)	46.8	55.9	46.8	55.9	46.8	55.9	46.8	55.9	46.8	55.9

*high S is for aquifer parameters T = 0.85 $m^2.d^{-1}$ and S = 0.01

**low S is for aquifer parameters T = 1.35 $m^2.d^{-1}$ and S = 0.00001

Table 6.3 Guidelines for success of rural water supply boreholes using the 10-minute bailer test.

		$10\ m^3.d^{-1}$	$15\ m^3.d^{-1}$	$20\ m^3.d^{-1}$	$25\ m^3.d^{-1}$	$30\ m^3.d^{-1}$
	(Number of standard bails)*	(16)	(24)	(32)	(40)	(48)
4 inch	Max drawdown (m)	3.5	5.3	7.1	8.8	10.6
	time for 50% recovery (mins)	6	6	6	6	6
	time for 75% recovery (mins)	14	14	14	14	14
5 inch	Max drawdown (m)	2.9	4.3	5.7	7.1	8.5
	time for 50% recovery (mins)	9	9	9	9	9
	time for 75% recovery (mins)	21	21	21	21	21
6 inch	Max drawdown (m)	2.3	3.4	4.6	5.7	6.9
	time for 50% recovery (mins)	12	12	12	12	12
	time for 75% recovery (mins)	28	28	28	28	28
8 inch	Max drawdown (m)	1.5	2.3	3.1	3.8	4.6
	time for 50% recovery (mins)	19	19	19	19	19
	time for 75% recovery (mins)	46	47	47	47	47

*standard bailer is 4.4 litres (1-m long 3-inch pipe)

Certain rationalisations can be made to produce simpler guidelines. To minimise the chance of a borehole being wrongly diagnosed as successful, the most optimistic scenarios are taken for each pumping rate and diameter. Also, since the maximum drawdown is unlikely to be able to be taken at the exact time pumping stops, the drawdown after one minute recovery is taken. As the maximum drawdown can usually be taken within 30 seconds of the end of pumping this again makes diagnosis of success more cautious. Table 6.3 shows these simplified guidelines.Having all three measurements (maximum drawdown and time for 50% and 75% recovery) is a useful check against mistakes. If the borehole diameter has been underestimated then the test may indicate a 'pass' for drawdown, but 'failure' on recovery. If the diameter has been overestimated, then the test may indicate a 'failure' on drawdown, but 'pass' for recovery. In both cases such results would indicate that a longer test which is less susceptible to borehole diameter should be undertaken.

These criteria were tested against 24 bailer tests undertaken in Oju and Obi (Table 6.4). Transmissivity results from the longest and most appropriate tests carried out in each borehole are given for comparison (data from Table 3.5). The test accurately

Table 6.4 Bailer test results for Oju and Obi. Transmissivity estimates for the boreholes (by constant rate test, or numerical analysis of bailer test) are given for comparison (see Table 3.5)

B-hole	*diameter*	*p-rate* $m^3.d^{-1}$	*max dd* (m)	$t_{50\%}$	$t_{75\%}$	*bailer test scores* *max dd*	$t_{50\%}$	$t_{57\%}$	*overall*	*T* $m^2.d^{-1}$
BGS1	5 inch	26.352	7.1	33	63	fail	fail	fail	fail	0.27
BGS2b	6 inch	27.648	2.1	3.5	8.5	pass	pass	pass	pass	4.0
BGS4	6 inch	21.6	2.5	16	40	pass	fail	fail	retest	0.7
BGS6	6 inch	25.92	0.45	3	6	pass	pass	pass	pass	18.5
BGS12	6 inch	25.056	3.1	7.5	16	pass	pass	pass	pass	1.1
BGS13	6 inch	27.648	11	75	170	fail	fail	fail	fail	0.14
BGS15	6 inch	23.328	2.15	8.5	21	pass	pass	pass	pass	1.6
BGS16	6 inch	16.416	1.3	8	16	pass	pass	pass	pass	2.1
BGS17	6 inch	25.056	2.0	8	23	pass	pass	pass	pass	1.4
BGS19	6 inch	25.92	1.0	2.5	7	pass	pass	pass	pass	5.0
BGS20	6 inch	39.744	0.13	7		pass	pass	pass	pass	27
BGS21	6 inch	27.648	1.4	6	15	pass	pass	pass	pass	4.0
BGS26	6 inch	12.096	2.75	193	193	fail	fail	fail	fail	0.024
BGS27	6 inch	13.1328	4.0	93	215	fail	fail	fail	fail	0.08
BGS30	6 inch	26.784	4.7	63	113	pass	fail	fail	fail	0.36
BGS33	6 inch	30.24	0.02			pass			pass	51
BGS34	6 inch	25.92	0.86	2.5	10	pass	pass	pass	pass	6.5
BGS35	6 inch	25.92	0.35	2.5	12	pass	pass	pass	pass	23
BGS37	6 inch	19.872	2.8	5	17	pass	pass	pass	pass	0.70
BGS40	6 inch	11.232	9.0	38	93	fail	fail	fail	fail	0.15
BGS41	6 inch	19.872	4.1	51		pass	fail	fail	retest	0.25
BGS42	6 inch	25.056	3.6	8.5	15	pass	pass	pass	pass	0.80
BGS44	6 inch	24.192	6.5	26	45	fail	fail	fail	fail	0.10
BER2	5 inch	20.736	16.5			fail			fail	<0.01

identifies success or failure in all but two of the tests. These two borderline cases (BGS37 and BGS42) were assigned passes when a longer test indicated transmissivity of 0.8 $m^2.d^{-1}$, just below the pass rate. The longer tests showed breakaway drawdown and recovery curves indicated a reduction of transmissivity as the cone of depression extends. In both cases, numerical analysis of the bailer test gave transmissivity greater than 1 $m^2.d^{-1}$ (see Table 6.1). Unfortunately, breakaway curves will not be detected with such short tests, but as discussed above, it is better than undertaking no test at all. Currently, the bailer test is being used by WaterAid and local government staff in Nigeria to good effect. It is being carried out as a check against the claims of contract drillers that boreholes are successful. Community members are helping to carry out the test (see Figure 6.11).

6.10 Summary

1. A short bailer test (Section 6.3) has been designed around the practical requirements of rural water supply workers. The test requires simple equipment, and can be completed in one hour.
2. Since the test is short and permeability generally low, the data are best analysed using large-diameter-well analysis which allows for well storage. This can be done with numerical analysis (BGSPT), nomograms, or using simple guidelines outlined here.
3. "Pumping" using bails instead of constant rate has virtually no effect on analysis.
4. Declining yields during the test (due to deeper water-levels and pumpers' fatigue) only becomes significant if the pumping rate declines by more than 65% during the test.
5. The test is designed for confined or semi-confined conditions, which are generally met in mudstone or basement aquifers over the length of the test.
6. Dual-porosity aquifers (such as mudstones) have negligible effect on the calculation of transmissivity up to $b^2 S_s/K_m = 0.01$ days. At times greater than this the maximum error is 100%, which may be considered admissible given the large uncertainty and range in transmissivity.
7. For use in rural water supply programmes with boreholes of 4-8 inch diameter supplied with hand pumps, transmissivity of greater than 1 $m^2.d^{-1}$ indicates a successful borehole (0.85 $m^2.d^{-1}$ for S = 0.01; 1.35 $m^2.d^{-1}$ for S = 0.00001).

8. For a set of 15 boreholes in Nigeria bailer tests were found to predict similar transmissivity to five-hour constant rate test ($r^2 = 0.9$)
9. The test has been further simplified to indicate 'yes/no/maybe' for the borehole sustaining the yield of a hand-pump by measuring the maximum drawdown and time for 50% and 75% recovery.

Figure 6.12 Community members carrying out a bailer test at Edumoga village, Oju.

In summary, the test is theoretically sound for low permeability environments, and could be widely applied for testing low yielding rural water supply boreholes in any geological unit. However, field trials of the bailer test in other environments and with other groups of water project staff throughout Africa should be undertaken to improve its practicality and demonstrate its usefulness.

Chapter 7

Simple geophysical methods for siting wells and boreholes in mudstones

The data presented in Chapter 4 showed that geophysical methods, and in particular electromagnetic profiling, could easily distinguish the various hydrogeological environments found within Oju and Obi. This chapter discusses in more detail the special considerations of using ground conductivity techniques (with Geonics EM34 equipment) in mudstone environments. Some of these responses are explained by clay mineralogy. Forward 3D electromagnetic simulations are also used to model the responses of fracture zones in mudstones. The use of magnetic methods for identifying dolerite intrusions is also considered in more detail in a section containing essentially the same information as MacDonald et al. (2001).

7.1 Introduction

Measurements of ground conductivity using frequency domain electromagnetics is a simple technique often overlooked by geophysicists in the northern developed world. Particularly in complex environments detailed techniques such as time domain EM or 2D and 3D resistivity tomography are used in preference to ground conductivity using EM34 equipment. Despite its limitations, however, ground conductivity has many advantages for use in sub-Saharan Africa (SSA). Although the reasons are discussed briefly in Chapter 3, the most important are repeated here.

1. Ground conductivity is a rapid technique, 5 to 10 km can be covered in one day using the EM34. In mudstone environments, targets for groundwater can be scarce, so widespread surveying is required. In Europe large areas such as these are usually surveyed by air (due to problems of access on the ground) with equipment similar to EM34. In Africa, aerial surveys are prohibitively expensive, and access on the ground is generally not a problem.
2. Ground conductivity techniques are simple. Conducting a survey with EM34 is uncomplicated compared to other geophysical methods. Engineers with limited education can be trained to collect useful information; this is particularly important in SSA where many water projects are managed by local government or small NGOs. The equipment is robust.
3. Ground conductivity equipment (particularly the EM34) is widespread in SSA. Due to the success of ground conductivity in locating borehole and well sites in crystalline basement, many water authorities and NGOs have EM34 equipment and personnel trained in their use. The cost is not prohibitive, £15-20k, when compared to the cost of drilling boreholes, £5-10k (Van Dongen & Woodhouse 1994).

7.2 Electrical conductivity of mudstones

Mapping subsurface geology by measuring the electrical conductivity of ground is an old technique dating back to the early 1900s with experiments by Conrad Schlumberger. There are several factors which contribute to the measured electrical conductivity of rocks:

- electrical conductivity of grains (this is generally negligible apart from some metal sulphides)
- porosity
- geometry of pore spaces
- presence and salinity of pore fluids
- electrical conductivity along grain surfaces (most significant in clays).

The first serious attempt to relate the physical properties of rocks to electrical conductivity was by Archie (1942). He established an empirical formula for clean, water saturated sands and sandstones which related the measured conductivity of the rock (σ_o) to the conductivity of the pore water (σ_w) and the porosity (ϕ):

$$\frac{\sigma_0}{\sigma_w} \approx \phi^m = \frac{1}{F} \tag{1}$$

F is known as the formation factor and m is an empirical constant. Subsequent experimental and theoretical analysis of granular rocks have shown the validity of equation (1), which has been widely used with excellent results (Sen *et al.* 1981). The constant m varies from 1.3 to 2.5 and is related to the shape of the grains – increasing as the grains become less spherical. For natural sands values of m have been found to vary from 1.4 to 1.6, and for more platy materials (such as shell fragments or kaolinite particles) approximately 1.85 (Jackson *et al.*1978; McNeill 1980a).

Archie's law, however, does not take into consideration electrical conductivity along grain surfaces and is therefore not applicable to formations containing clay. Clay particles are commonly negatively charged in solution and attract cations as a double layer on their surface. These ions are mobile and can provide important pathways for electrical currents. Since clay particles are so small, they have large surface areas per unit volume; for example illite clay can have a surface area of 50 $m^2.gm^{-1}$ and smectite, 700 - 800 $m^2.gm^{-1}$. Surface conductivity (σ_s) can be expressed as:

$$\sigma_s = \mu_i Q_v \tag{2}$$

where Q_v is the volume density of charges and μ_i is the average mobility of the ions. The mobility of ions can be less than 50 times that of free ions (Bussion 1983). The volume density of charges, Q_v, can be calculated from the Cation Exchange Capacity (CEC) of the clay. Using a volume density approach to calculating surface conductivity is necessarily a simplification; De Lima and Sharma (1990) and Bussian (1983) show its validity for several datasets. These datasets also illustrate a direct relation between surface conductivity and CEC such that $\sigma_s \cong 2.5 \times CEC$, where σ_s is in $mS.m^{-1}$, CEC is in mequivalents/100 grams dry clay, and the density of clay is assumed to be 2500 $kg.m^{-3}$.

Several models have been put forward to estimate the combined electrical conductivity of a rock from porosity, fluid conductivity and surface conductivity. Two of the most established are the Waxman & Smits (1968) model, and the Bussian (1983) model. The Waxman & Smits model is empirical, and because of its simplicity is one of the most widely used in the petroleum industry (Ruffet *et al.* 1995). There are problems with this model however, mainly because of the assumption that the clay exchange ions and pore water ions must follow the same path (Bussian 1983) and the dependence of ion mobility on the pore water conductivity (Ruffet *et al.*1995). The Bussian model allows for different paths of conduction through the rock and is based on the Bruggeman and Hanai equation rather than empirical data (Bussian 1983). For direct currents or low frequencies (such that permittivities are negligible):

$$\sigma_0 = \sigma_w \phi^m \left(\frac{1 - \frac{\sigma_s}{\sigma_w}}{1 - \frac{\sigma_s}{\sigma_0}} \right)^m \tag{3}$$

The equation reverts to Archie's equation when $\sigma_s \rightarrow 0$. Binomial expansion of the terms on the right hand side of the equation considerably simplifies the equation under the limiting conditions $\sigma_w >> \sigma_s$, *or* $\sigma_w << \sigma_s$ (de Lima & Sharma 1990). For $\sigma_w >> \sigma_s$

$$\sigma_o = \frac{1}{F}\left[\sigma_w + m(F-1)\sigma_s\right] \tag{4}$$

and for $\sigma_w << \sigma_s$

$$\sigma_o = \frac{f\sigma_w}{1 + n(f-1)\sigma_w/\sigma_s} \tag{5}$$

where $f = \phi^n$ and $n = m / (m - 1)$. These simplified equations can be used to estimate rock conductivity given ϕ, m, σ_w and an estimate of σ_s. For illite and smectite clays however (CEC values of 30 to 150 meq / 100 grams - see Chapter 2) with groundwater suitable for drinking (σ_w < 100 mS.m^{-1}) neither of these limiting conditions generally apply. Therefore, these simplified equations are only of use in mudstones if the water is brackish, or the clays have either very low or very high CEC (Figure 7.1).

Other models exist which claim to have a more realistic physical basis (e.g. Johnson & Sen 1988). However, for the current application, distinguishing different clay types in fresh water (σ_w < 100 mS.m^{-1}), it is the general form of these equations that is important rather than the details. Figure 7.1 shows the form of Equations 4 and 5. Changes in surface conductivity are at least as important as changes in fluid conductivity in the total measured conductivity. Where the porosity is low (such as a consolidated mudstone) most of the measured rock conductivity will be derived from the surface conductivity (de Lima & Sharma 1990). Only where the porosity and σ_w are high, will electrical conductivity of the pore fluid dominate.

There are few systematic field measurements of the electrical conductivity of different clays to prove the above theory. One study of unsaturated soils in Peurto Rico showed the conductivity of kaolinite rich soils to be 1-16 mS.m^{-1}, and smectite-rich soils from 170 - 270 mS.m^{-1}, although, the conductivity of the pore fluid is not given (Walker *et al.* 1973).

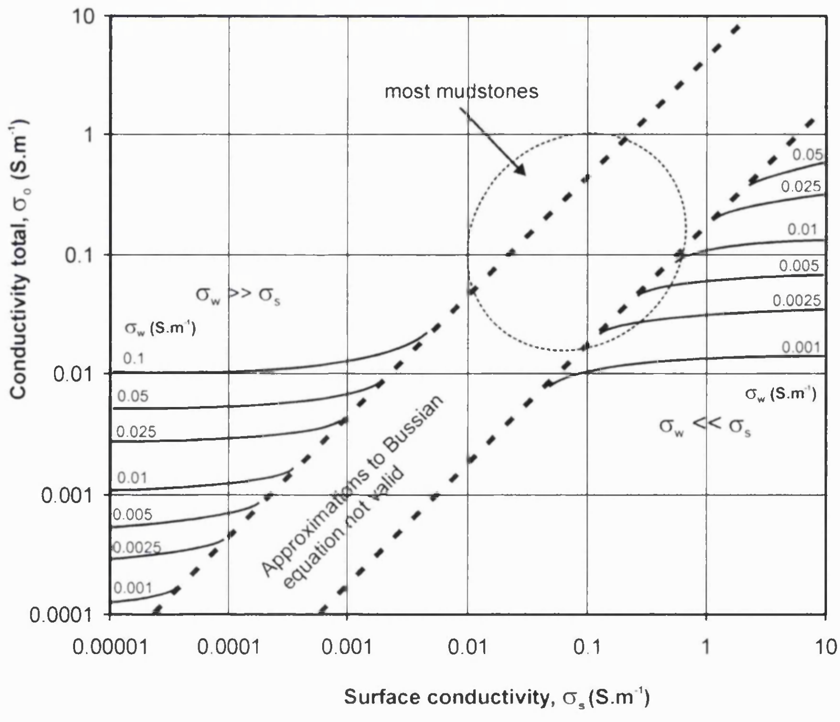


Figure 7.1 The form and validity of the approximations to the Bussian Equation (Equations 4 & 5) for different pore water and surface conductivity. Porosity is 0.3 and *m* 1.85. Note that the approximations are not valid for most mudstones.

In summary, the important factors to consider when measuring the electrical conductivity of mudstones are:

- the bulk conductivity of mudstones comprises a component from free electrolytes in the pore fluid of the rock and also from surface conductivity along ions loosely bound to clay surfaces;
- the cation exchange capacity of the clay (CEC) is proportional to surface conductivity; hence smectite has much higher surface conductivity than illite;
- electrical conductivity within pores is controlled by the porosity and the electrical conductivity of the pore fluid;
- in consolidated mudstones, where porosity is low, the bulk electrical conductivity is dominated by surface conductivity;
- only where porosity and electrical conductivity of pore waters are high will they contribute significantly to the measured bulk conductivity.

Hence, measuring the bulk electrical conductivity of consolidated mudstones, especially where the pore fluid conductivity does not vary much, should give a good indication of the dominant clay minerals present.

7.3 Performance of the EM34 instrument in a mudstone environment

Further information on the operation of the Geonics EM34 ground conductivity instrument is given in this section to help determine the effectiveness of the EM34 at detecting groundwater targets in a mudstone environment. The theory behind conductivity measurements at low induction numbers is described in McNeill (1980b); a summary of relevant information is given below. Diagrams and photographs of its operation are in Chapter 3.

Given certain constraints, the ratio of the quadrature component of the secondary magnetic field (produced by small currents induced in the ground by the primary field) to the primary field is directly related to the ground conductivity (σ). The apparent conductivity (σ_a) which the EM34 measures is then given by

$$\sigma_a \approx \frac{4}{\omega \mu_0 s^2}\left(\frac{H_S}{H_P}\right) \qquad (6)$$

where

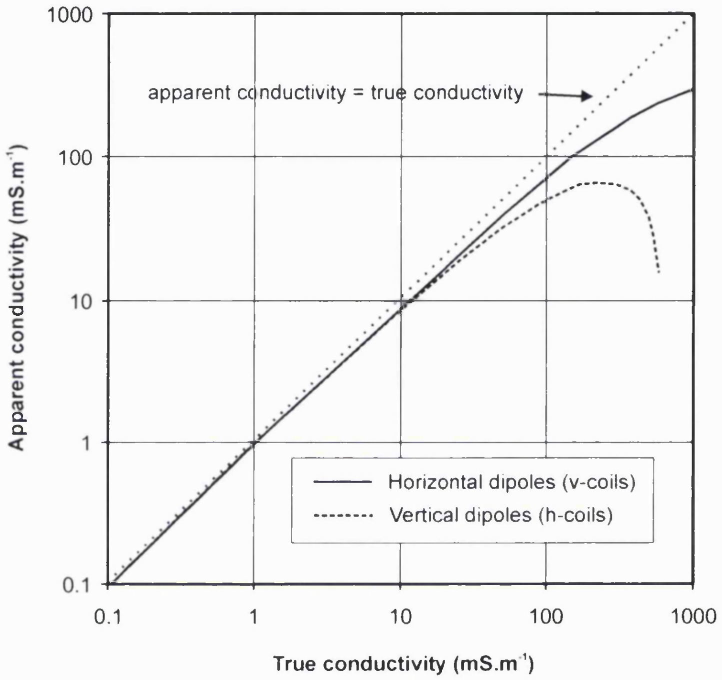
σ_a	=	apparent conductivity in $S.m^{-1}$ (SI equivalent $m^{-3}.kg^{-1}.s^3.A^2$)
H_S	=	quadrature component of the secondary magnetic field at the receiver coil (SI units $A.m^{-1}$)
H_P	=	primary magnetic field at the receiver coil $A.m^{-1}$ (SI units $A.m^{-1}$)
ω	=	$2\pi f$ where f is the frequency (SI units s^{-1})
μ_0	=	permeability of free space in Henry/m (SI equivalent $kg.m.s^{-2}.A^{-2}$)
s	=	the intercoil spacing (m)

This relation stays valid and the apparent conductivity a good estimate of ground conductivity provided that the coil separation is much smaller than the skin depth, z (the distance in which the signal is reduced to 37%, generally calculated by $z \approx 500\ (f\ \sigma_o)^{½}$ (Telford *et al.* 1990). Therefore to stay valid the following has to be satisfied

$$\sigma_o \ll \frac{2}{\omega \mu_0 s^2} \tag{7}$$

To examine the validity of the approximation, the discrepancy between apparent conductivity and actual ground conductivity has been calculated (Figure 7.2). When ground conductivity is low, as in basement rocks, both horizontal and vertical dipoles readings give a good estimate of ground conductivity. Difficulties arise however, when the ground conductivity is greater than about 50 $mS.m^{-1}$, as is the case of most mudstones. For example, for a true ground conductivity of 100 $mS.m^{-1}$, the EM34 will estimate apparent conductivity as 70 $mS.m^{-1}$ and 50 $mS.m^{-1}$ for the horizontal and vertical dipoles respectively. However, for the purpose of siting wells and boreholes, the actual conductivity measurements are not important, rather it is the presence of an approximately linear response over the range of conductivity values investigated. Figure 7.2 illustrates that a direct relation does exist for horizontal dipoles up to about 300 $mS.m^{-1}$. Thus, smectite, I/S and illite clays can be easily distinguished. However, a linear relation does not exist for the vertical dipole configuration much beyond 100 $mS.m^{-1}$. In fact the maximum reading of apparent conductivity with vertical dipoles is about 65 $mS.m^{-1}$, regardless of true electrical conductivity.

Therefore, for mudstones, differences in electrical conductivity should be mainly indicated by the horizontal dipoles. Vertical dipole information is useful for measuring the scattered currents produced by anomalies in the ground, such as fractures and faults, but not for estimating changes in electrical conductivity.



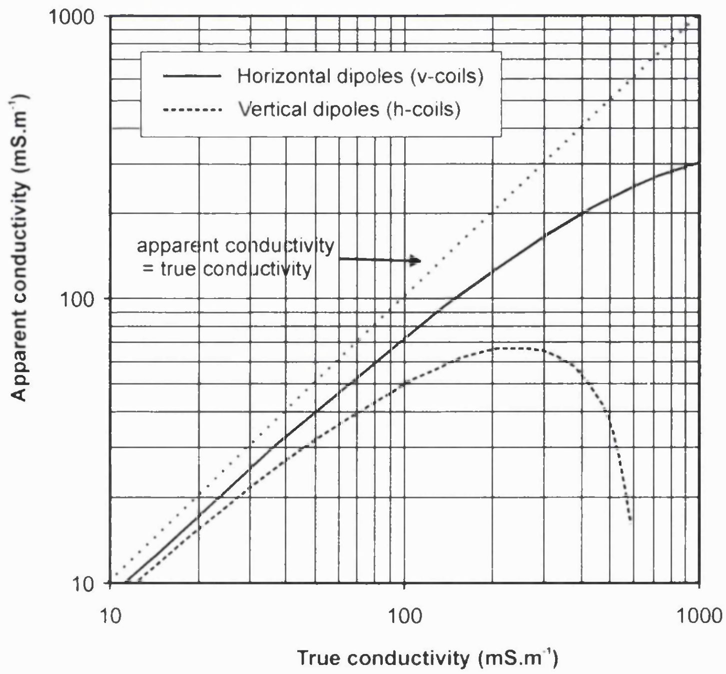


Figure 7.2 Apparent ground conductivity as measured by the EM34 instrument against true conductivity for 0.1 to 1000 mSm^{-1} and 10 to 1000 $mS.m^{-1}$ calculated using EMIGMA™ (2000).

Another important aspect of the EM34 instrument to discuss prior to the modelling of data from Oju and Obi is the relative response of the different dipole configurations. Simplified response functions have been constructed by McNeill (1980b) by considering the relative contribution to the secondary magnetic field from a thin layer, *dz*, at a normalised depth *z* (depth divided by the intercoil spacing) within a homogeneous half space. This response function $\phi(z)$ can be integrated to give the contribution to the secondary magnetic field (and thus apparent conductivity) from all material below a point *z*. This cumulative response is different for vertical and horizontal dipole configurations and given by:

$$R_V(z) = \int_z^{\infty} \phi_V(z)\, dz \qquad (8)$$

$$R_H(z) = \int_z^{\infty} \phi_H(z)\, dz \qquad (9)$$

Figure 7.3 shows the form of these two cumulative response functions for a homogeneous half space. Several points are worth noting.

- with horizontal dipoles the response is greatest at ground surface; 50% of the signal originates from above 0.4 x coil spacing;
- for vertical dipoles, the contribution from the ground surface is zero; 50% of the signal originates from above 0.9 x coil spacing; and
- The contribution of material at depths greater than twice the coil spacing is about 25% for vertical dipoles and 10% for horizontal dipoles.

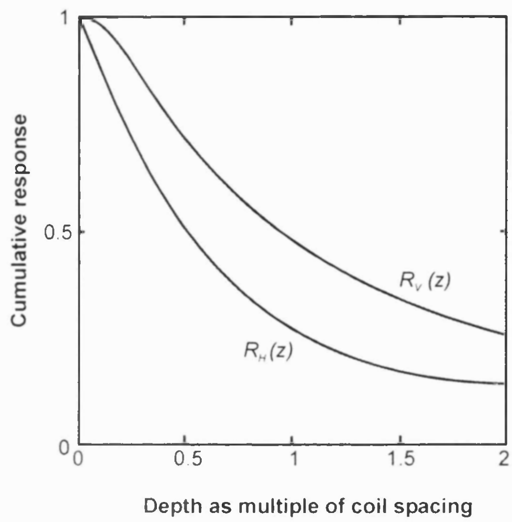


Figure 7.3 Cumulative response functions for the EM34. $R_v(z)$ is vertical dipole and $R_H(z)$, horizontal dipole (after McNeill 1980b).

7.4 Electrical conductivity of mudstones measured in Oju and Obi

The clay analyses performed on samples from boreholes throughout Oju and Obi provides a useful means for examining the relation between electrical conductivity and clay mineralogy in a field setting (data in Appendix). The EM34 with 20-m intercoil spacing was used to give an estimate of the bulk conductivity, since the depth of penetration is roughly equivalent to the depth over which information is available on clay mineralogy. The apparent electrical conductivity measured by the EM34 has been corrected to give an estimate of true electrical conductivity using Figure 7.2. Only boreholes that penetrated mudstone are included in the analysis.

Figure 7.4 demonstrates a relationship between clay mineralogy and electrical conductivity for representative boreholes in Oju and Obi. Mudstones where kaolinite and

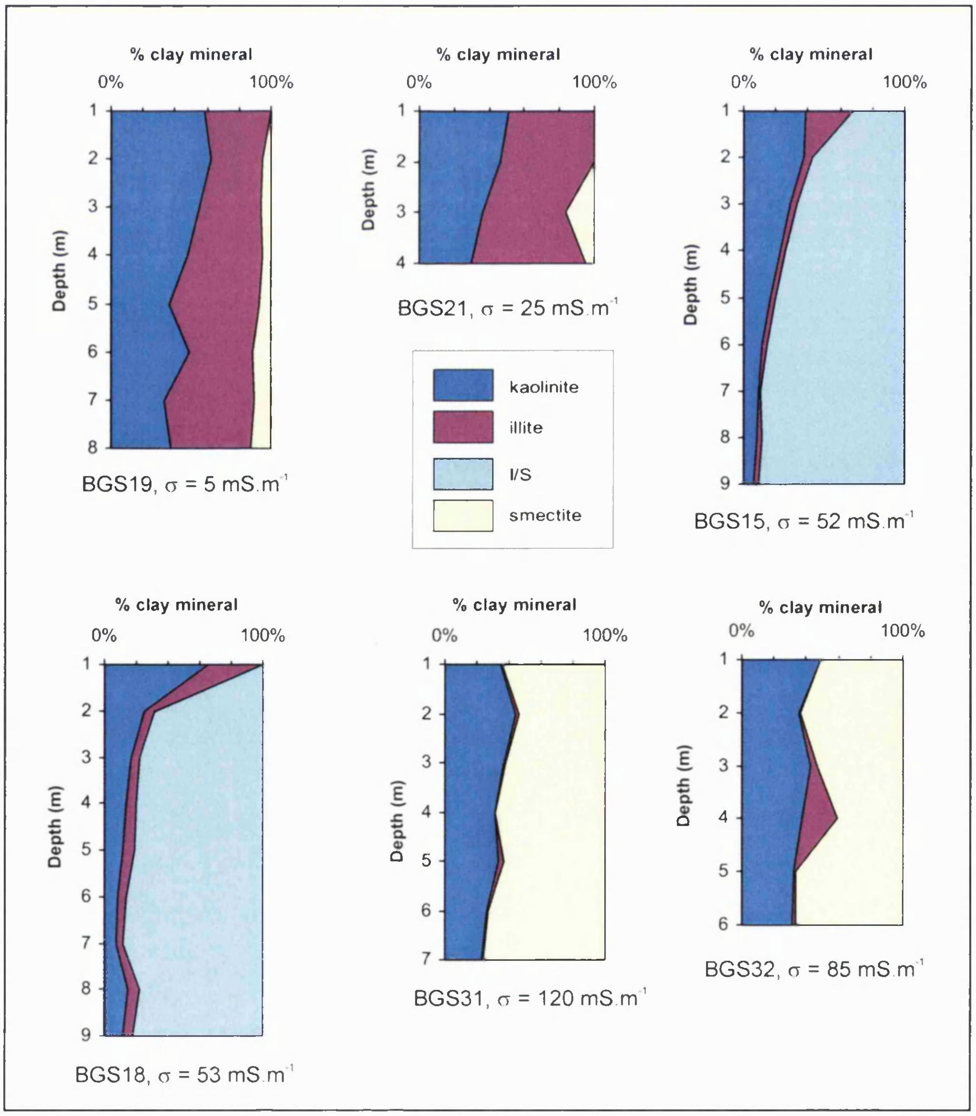


Figure 7.4 Clay profiles for representative boreholes in Oju and Obi. Ground conductivity was measured using the EM34 with 20-m horizontal dipoles.

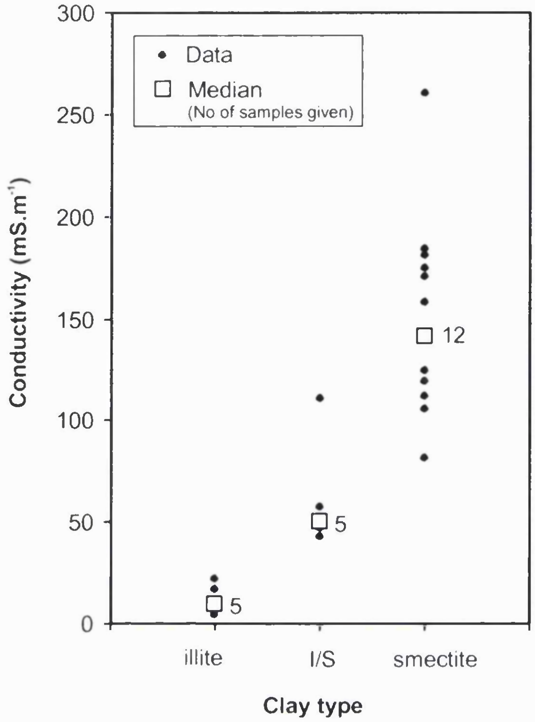


Figure 7.5 Measured electrical conductivity (using EM34, 20-m intercoil spacing, horizontal dipoles) against dominant clay type for mudstone boreholes in Oju and Obi.

illite clays dominate the profile have low conductivity. Mudstones where mixed layer illite/smectite or smectite clays dominate have considerably higher conductivity. To further examine this relation, the dominant clay mineral below the highly weathered zone was plotted against bulk ground conductivity for each mudstone borehole in Oju and Obi (Figure 7.5). Since the clay mineralogy in Oju and Obi is consistent within geological formations (see Chapter 5), electrical conductivity data are also included for boreholes where the clay mineralogy was not determined, but detailed lithological logs had identified the geology. The strong correlation between clay mineralogy and electrical conductivity is reinforced. Illite dominated mudstones have low conductivity; smectite dominated mudstones have high conductivity while mixed layer illite/smectite clays are intermediate.

Further analysis was undertaken on selected clay samples to quantify the relation between smectite and the measured bulk conductivity of the upper 15-20 m of the rock. Whole rock particle size analysis of representative samples from the mudstones indicate that silt and sand comprise 35-65% of the rock (mean 46%), although in the metamorphosed Asu River much of the phyllosilicates are larger than clay fraction (see Appendix 2). The proportion of illite and smectite in mixed layer I/S clays was also calculated using modelling (Table 7.1 and Appendix). From these data it was possible to estimate the average proportion of smectite in the mudstones for certain boreholes.

Figure 7.6 demonstrates a strong correlation between the presence of smectite and the bulk conductivity measured in the field using electromagnetic methods ($r^2 = 0.75$). No statistically significant correlation could be found with any factor, or combination of factors apart from smectite alone. The remaining variance, however, must be a consequence of variations in fluid conductivity, clay content, the presence of other clay minerals such as illite and kaolinite, and possibly aspects of non linearity in the relationship between total conductivity and surface conductivity. This non-linearity, and phenomena, such as interlayer ions and bound water may explain the higher variance at high smectite proportions.

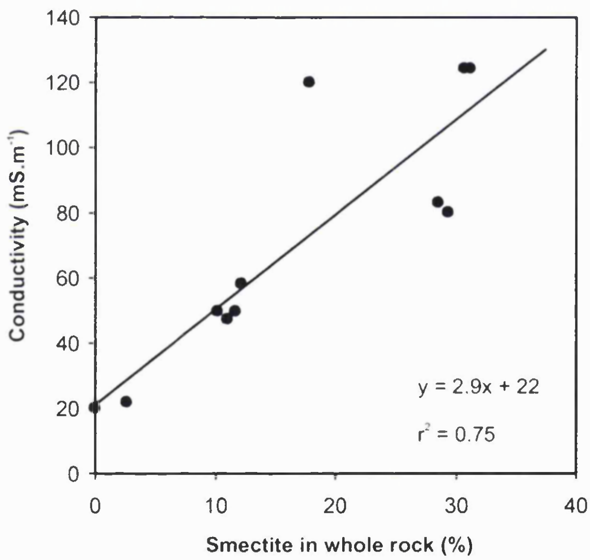


Figure 7.6 The bulk conductivity measured by EM34 in the field using electromagnetic methods against the smectite content of the whole rock (data in Table 7.1).

Despite the theoretical complexities, and the presence of the thick ferruginous soil over the mudstone, the data clearly show that the dominant control on the measured ground conductivity in the mudstones is the presence of smectite. Using simple extrapolation (and thus ignoring the non-linearity that may exist within the relationship) the data imply that a mudstone with 100% smectite content would have conductivity of 310 $mS.m^{-1}$. In Chapter 5, it was demonstrated that smectite content directly controlled the potential for groundwater in a mudstone. Therefore, being able to easily distinguish smectite-rich mudstones in the field, using such simple equipment such as EM34 is a major step towards improved siting of wells and boreholes in mudstone environments.

Table 7.1 The average clay mineralogy of samples from the weathered and unweathered zone from representative mudstone boreholes in Oju and Obi and the bulk conductivity measured using EM34.

	Formation	*Depth*	*No Samples*	*Kaolinite (%)*	*Illite (%)*	*Smectite (%)*	*I/S (%)*	*Illite[1] in I/S (%)*	*Smectite in whole rock[2] (%)*	*Bulk[3] conductivity* (m.Sm^{-1})
BGS2	Asu River	1 - 14	2	16	84				0	20
BGS3	Upper Eze-Aku	14.5	2	25	5		70	65	12.3	58
BGS4	Upper Eze-Aku	1.5 - 7.5	7	37	7.7		55.4	63	10.3	50
BGS6	Upper Eze-Aku	1.5 - 9.5	9	17.9	4.1		77.8	54	17.9	120
BGS15	Lower Eze-Aku	1.5 - 9.5	9	19.9	6.2		74	68	11.8	50
BGS18	Lower Eze-Aku	1.5 - 9.5	9	19.4	9.3		71.3	69	11.1	47
BGS21	mm Asu River	1.5 - 4.5	4	41	53.8	5.25			2.6	22
BGS27	Awgu Shale	14.5 - 9.5	2	35.5	3	61.5			30.8	124
BGS30	Awgu Shale	1.5 - 10.5	10	37.6	3.5	58.8			29.4	80
BGS31	Awgu Shale	1.8 - 5.3	8	35.9	1.8	62.4			31.2	124
BGS32	Awgu Shale	1.5 - 10.5	6	38	4.8	57.2			28.6	83

[1] Illite in I/S was calculated using modelling (see Appendix for details)
[2] Smectite in whole rock estimated by assuming the clay fraction comprises 50% of the sample. Particle size analysis of 5 samples indicated a mean of 46% and range 30 – 65% (see Appendix)
[3] Bulk conductivity measured using the EM34 with 20-m intercoil spaces (horizontal dipoles) and corrected from apparent resistivity.

7.5 3D modelling of EM34 response

Electromagnetic data are generally interpreted qualitatively. High readings are taken to indicate the presence of weathering in basement rocks (Beeson & Jones 1988), water in clean sands (Potts 1990) or clay in fluvioglacial deposits (MacDonald *et al.* 2000). Where vertical dipole measurements are higher than those measured using horizontal dipoles, the electrical conductivity is assumed to increase with depth and in crystalline basement rocks be interpreted as the presence of the water and weathering at depth. In many situations, where the geophysical responses of the geological conditions are well known, such an approach is sufficient. Variations of electrical conductivity in mudstones however, and in particular of groundwater targets within mudstones, are not well documented. Therefore, some modelling of variations in electromagnetic response is required to help interpret geophysical data.

On the rare occasions that ground conductivity data are analysed quantitatively, the data are usually inverted using a 1D model. One-dimensional models assume that the measured bulk conductivity at a point is attributed solely to a combination of horizontal layers with different electrical conductivity. This a very useful approach, but cannot account for the 2-3D responses from fracture zones which are so important for groundwater flow in mudstones. Analytical and empirical solutions have been presented for several simple 2-3D problems, such as a sub-vertical, thin conductive plate or sphere (e.g. Frischknecht *et al.* 1991). These are of little help when considering the types of targets present in a mudstone: low conductivity targets within high conductivity background, and highly complex fracture zones.

Recent advances in EM modelling software have enabled the 3D electromagnetic response in the earth to be modelled. Innovative software and the increased power of computers have allowed the complex integral solutions for electromagnetic scattering in a layered half space to be effectively modelled. The current market leader in this type of software is EMIGMA™, written by Petros Eikon Inc. in Canada. It is beyond the scope of this study to discuss the details of these approaches to modelling, in fact this particular area of geophysics is the subject of much detailed research and entire theses are devoted to it. The purpose of this study is to use existing modelling software to further examine the electromagnetic response of the groundwater targets found within the mudstone environments of Oju and Obi. Details of the algorithms used by Petros Eikon Inc. are given in Walker & West (1991), Habashy *et al.* (1993) and Petros Eikon (2000).

Three-dimensional electromagnetic modelling has rarely, if ever, been applied to EM34 data. Modelling has focused on regional structures from airborne EM data (e.g. Peltoniemi *et al.* 1996) or EM methods which provide more detailed information than EM34 such as time domain EM (Groom *et al.* 1999). As discussed previously, despite its limitations, EM34 remains the most appropriate methods for use in SSA. The complexity of the targets and the scarcity of other examples of EM methods being used to characterise mudstones make 3D modelling an important and useful exercise.

7.6 Examples of EM response of groundwater targets in mudstone

In the remaining sections of this chapter, the EM response of the groundwater targets found within the mudstone environments of Oju and Obi are discussed. Examples of EM34 data are given along with lithological, mineralogical and hydrogeological data. Where appropriate, 3D modelling is used to explore possible mechanisms for providing observed EM responses.

7.6.1 Hard fractured mudstones – the case of the Asu River Group

The Asu River Group contains much groundwater. The mudstones comprise hard, consolidated illite clay, often fissile or splintery. They are intensely fractured, possibly as a result of hydrofracturing on deep burial (see Chapter 4 and 5). The mudstones are folded and faulted and are crossed by igneous (dolerite) intrusions. Close to the surface, the mudstones are weathered to kaolinite clay (see Appendix 2). Borehole logs and field observations indicate that the weathered zone can vary considerably in thickness, but is rarely greater than five metres. From the available information there appeared no correlation with fracturing and thickness of the weathered zone.

Figure 7.7 shows a typical section of EM34 data collected on the Asu River Group. The data are noisy, particularly vertical dipole data. Apparent conductivity varies from 5 $mS.m^{-1}$ to 25 $mS.m^{-1}$. Lower conductivity is measured with the shallow penetration, shorter intercoil spacing and higher frequencies. Groundwater has been found regardless of conductivity variations. The main attributes of the Asu River Group that can contribute to variations in electrical conductivity are:

Illite CEC. As detailed in Chapter 2 (Table 2.1), the CEC of illite is between 10 and 40 meq per 100 grams. Taking an average of about 25 meq per 100 gms, we can expect a bulk conductivity of approximately 30 $mS.m^{-1}$ for a mudstone with approximately 50% clay content. However, the Asu River Group has been subjected to deformation and folding. Consequently there are likely to be small variations in CEC and conductivity throughout the Asu River Group.

Weathered zone thickness. Kaolinite clay has low CEC (0 - 5 meq per 100 grams), and correspondingly low conductivity, for example 2 $mS.m^{-1}$. The high proportion of kaolinite clay in the weathered zone gives this layer a much lower conductivity than the unweathered mudstone. Variations in the relative proportions of the two clays, and the thickness of the kaolinite enriched zone will both affect measured bulk conductivity. Field studies in the Asu River Group indicate that the weathered zone varies considerably.

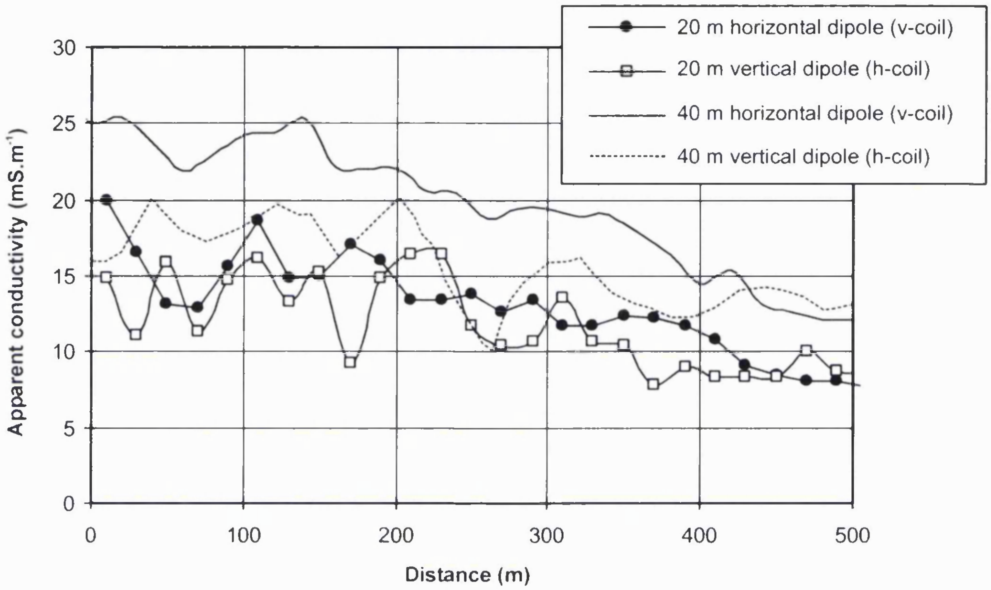


Figure 7.7 EM34 data for the Asu River Group (illite mudstone) at Odubwo (location is given in Chapter 3).

Presence of groundwater. Significant groundwater occurs in fractures from below 12 m. From core analysis, these fractures tend to have apertures of less than 1 mm and are well defined with little weathering and clay associated with them. Measurements of the electrical conductivity of groundwater within the fractures vary from 50 to 90 mS.m^{-1}.

Presence of interbedded quartzite and igneous intrusions. Within the Asu River Group, interbedded quartzite and igneous intrusions are common. At present it is unclear what effect they have on fracturing, but their impact on the electrical conductivity is more predictable. Electrical conductivity of unweathered igneous rocks and quartzite tend to be less than 5 mS.m^{-1} (see Telford *et al.* 1990).

The above factors have been combined into simple 3D models to illustrate how the observed EM34 response such as that shown in Figure 7.7 can be produced. Four models are shown in Figure 7.8. A simple three-layered model comprising soil, weathered zone and unweathered illite mudstone explains the general pattern of data. Large areas of low conductivity, especially with the 40-m coil separations, are best explained by changes in the CEC of the mudstone, or the presence of quartzite or igneous intrusions. The noise within the profiles can be accounted for by changes in the thickness of the weathered zone. The presence of fracturing at depths below 12 m has little impact on the measured bulk conductivity. The contrast in electrical conductivity between the groundwater filled fractures and the illite mudstone is small, the fractures occupy little of the rock area (possibly < 1% from estimates of storage in Chapter 5), and the mudstone is not significantly weathered around the fractures. Only where the fractures contain saline (undrinkable) water will their presence be detectable by EM34.

Therefore, EM34 measurements in the hard illite mudstone of the Asu River Group can be accounted for by variations in the thickness of the weathered zone, changes in CEC in the mudstone and the presence of quartzite or igneous intrusions within the mudstone. Fractures that contain groundwater cannot be identified using EM34. However, in these harder mudstones, drilling has shown that fractures are widespread and zones of fracturing do not need to be identified (Chapter 5). Therefore it is sufficient that EM34 can readily confirm that a site is underlain by an illite mudstone (by the low bulk conductivity) rather than illite/smectite or smectite-rich mudstone.

7.6.2 Moderately hard mudstones – the case of the Lower Eze-Aku Shale

The Lower Eze-Aku Shale contains groundwater in large faults or fracture zones. The mudstones are moderately consolidated and comprise illite/smectite clays with thin interbedded layers of silty-sandy clay. The top 4-5 m of mudstone has been weathered to kaolinite rich clay; information from the boreholes drilled into this formation shows that the weathered zone does not vary much in thickness. A 1-2 m thick ferricrete has developed. Groundwater is generally only found in large faults and fracture zones within this mudstone. These fracture zones show severe deformation of the mudstones, with large crush zones and significant weathering. Away from these fault zones there is no widespread fracturing.

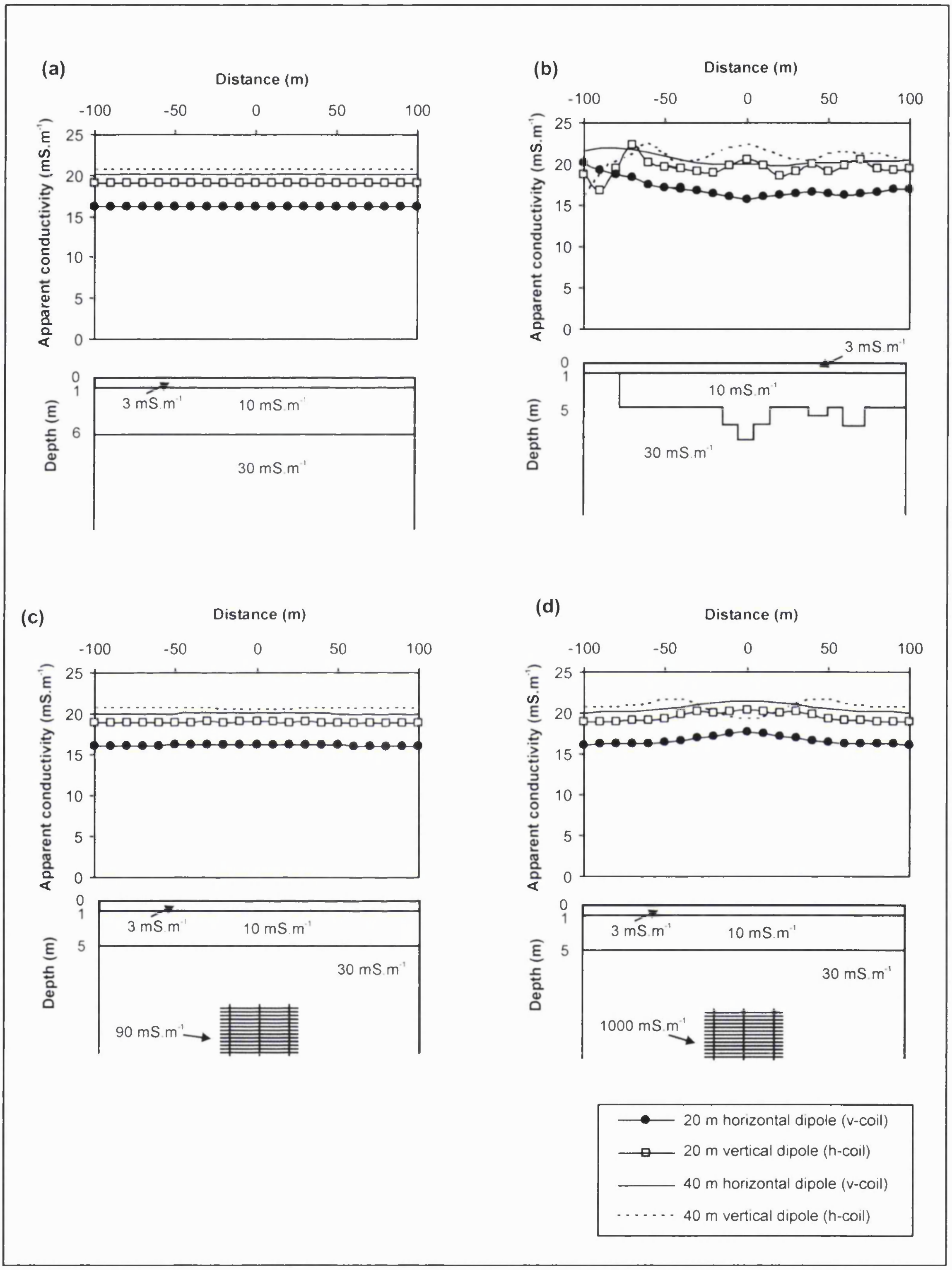


Figure 7.8 3-D modelling response (using EMIGMA™) of EM34 to various targets within a hard illite rich mudstone: (a) three horizontal layers; (b) three layers with variable thickness of the weathered zone; (c) three layers with fracture zone from 12-17 m (fractures 0.02 m thick and 50 x 50 m in extent); and (d) as (c) with fractures filled with brackish water.

Figure 7.9 shows typical EM34 data taken over the Lower Eze-Aku Shale. The data are fairly consistent, with the apparent electrical conductivity measured with 20-m coil separation being from 30-40 $mS.m^{-1}$. Data taken with 40-m coil separation generally give higher apparent conductivity (40-50 $mS.m^{-1}$). Superimposed on this general pattern are striking negative going anomalies and areas where the apparent conductivity varies considerably. The negative going anomaly is particularly unusual in that *both* the vertical and horizontal dipoles give striking anomalies. The main attributes of the Lower Eze-Aku Shale that can contribute to variations in electrical conductivity are discussed below.

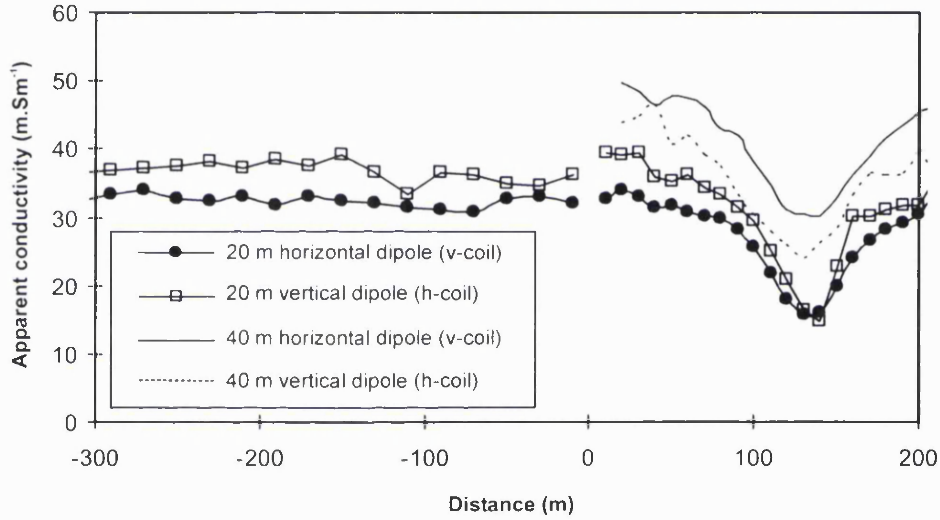


Figure 7.9 EM34 data for the Lower Eze-Aku Shale (I/S clay) at Edumoga. Location shown in Chapter 3; more data given in Chapter 4 and accompanying CD-ROM.

Clay mineralogy. The dominant clay type found in the Eze-Aku shale is I/S. The CEC of I/S depends on the proportions of illite and smectite within the I/S. A mixture of 30% smectite, 70% illite could give a CEC of about 50 meq per 100 grams. From this we could expect a bulk conductivity of about 60 $mS.m^{-1}$ (for 50% clay content). Slight increases in the proportions of smectite within the I/S clay, or the proportion of clay minerals within the mudstone, would have a significant effect on the measured bulk conductivity. The I/S ratio depends on the degree of low-grade metamorphism and is therefore likely to change regionally rather than locally.

Weathered zone thickness. As for most mudstones in tropical areas, the top few metres have been weathered to form kaolinite clay. The boreholes drilled into the Eze-Aku formation showed little variation in the thickness of this weathered zone, regardless of the presence of groundwater (see Chapter 4). As discussed above for illite rich mudstones, the kaolinite will provide low conductivity in the top few metres. At the study area, there was also a well formed low conductivity ferricrete layer.

Presence of significant groundwater. The electrical conductivity of groundwater measured in the Eze-Aku shales was approximately 60 $mS.m^{-1}$. This is the same as the conductivity calculated for the I/S clay and is therefore unlikely to be easily identified.

Fractures. Some large fracture zones have been identified within the Lower Eze-Aku shale – these are the targets for groundwater development. In low conductivity rocks such as basement, fracture zones are generally modelled as thin subvertical highly conductive zones, presumably from the presence of water and clays within the fractures (e.g. Carruthers & Smith 1992). Figure 7.10 shows the response of a typical model of vertical fault. Note that only the vertical dipoles give a negative anomaly, the horizontal dipole is virtually unaffected. In mudstones it is difficult to find a geological basis for faults comprising high conductivity vertical plates. In fact, it is more likely that the faults have *low* conductivity. The lithological logs from the test boreholes showed the mudstones were highly deformed within the fracture zones. It is probable that the degree of deformation and the flow of water within this zone will have significantly weathered the mudstones within the fault zone. This would most likely lead to alteration of I/S to low conductivity kaolinite. One of the few studies into the nature of faults in mudstones also found a fault zone within clay to have low conductivity (Hallam *et al.* 1992).

Several 3D models, reflecting the above characteristics, have been developed to recreate the bulk conductivity measurements shown in Figure 7.9. Background estimates of bulk conductivity can be easily reproduced by a simple 3-layer half space, representing ferricrete, kaolinite rich weathered zone and I/S rich bedrock (Figure 7.10). Small variations in the thickness of these layers could account for slight variations in measured bulk conductivity. However, the lithological logs and clay mineralogy analyses (Chapter 4) indicate that the thickness of these layers does not vary much, therefore it is unlikely that these could cause the sharp negative going anomalies, or the areas with 'noisy' measurements.

Since the electrical conductivity of the groundwater is similar to that of the I/S mudstones, it is unlikely that significant anomalies will arise from either the presence or absence of groundwater, provided a small amount of water is present to allow the surface conductivity of the clays. As discussed in Section 7.2, sufficient water is likely to be present within the clay to allow this. Also, changes in the ratio of illite to smectite in I/S are unlikely to occur at a local (i.e. village) scale and lithological analysis show little variation in sand content. Therefore the main reasons for significant anomalies within the Eze-Ake shale is the presence and nature of fractures.

Large fracture zones (10s of metres across) can be represented by a series of thin low conductivity plates, with the high conductivity volumes between the plates linked inductively with each other. The computer processing required to forward model scenarios involving several prisms linked inductively is considerable; therefore the true

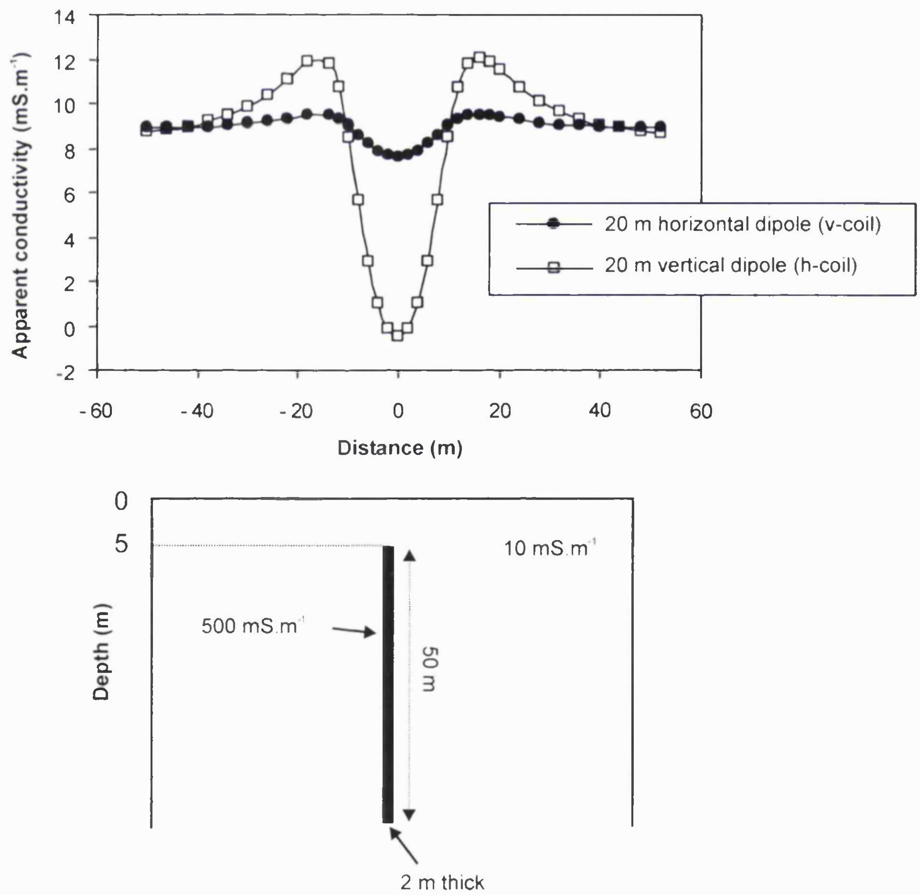


Figure 7.10 Bulk conductivity response of EM34 for a highly conductive vertical plate (50 x 50 x 2 m) in a low conductivity background modelled using EMIGMA™.

complexity of the fracture zone cannot be replicated. Instead, simplified scenarios must be constructed which reflect important aspects of fracture zones (Figure 7.11).

A wide asymmetric fracture zone can reproduce the large negative going anomaly seen in both the vertical and horizontal dipoles in Figure 7.9. Combinations of fractures with different symmetry and electrical conductivity (although all lower than the host rock) can also replicate the noisy section observed over a fracture zone in Chapter 4.

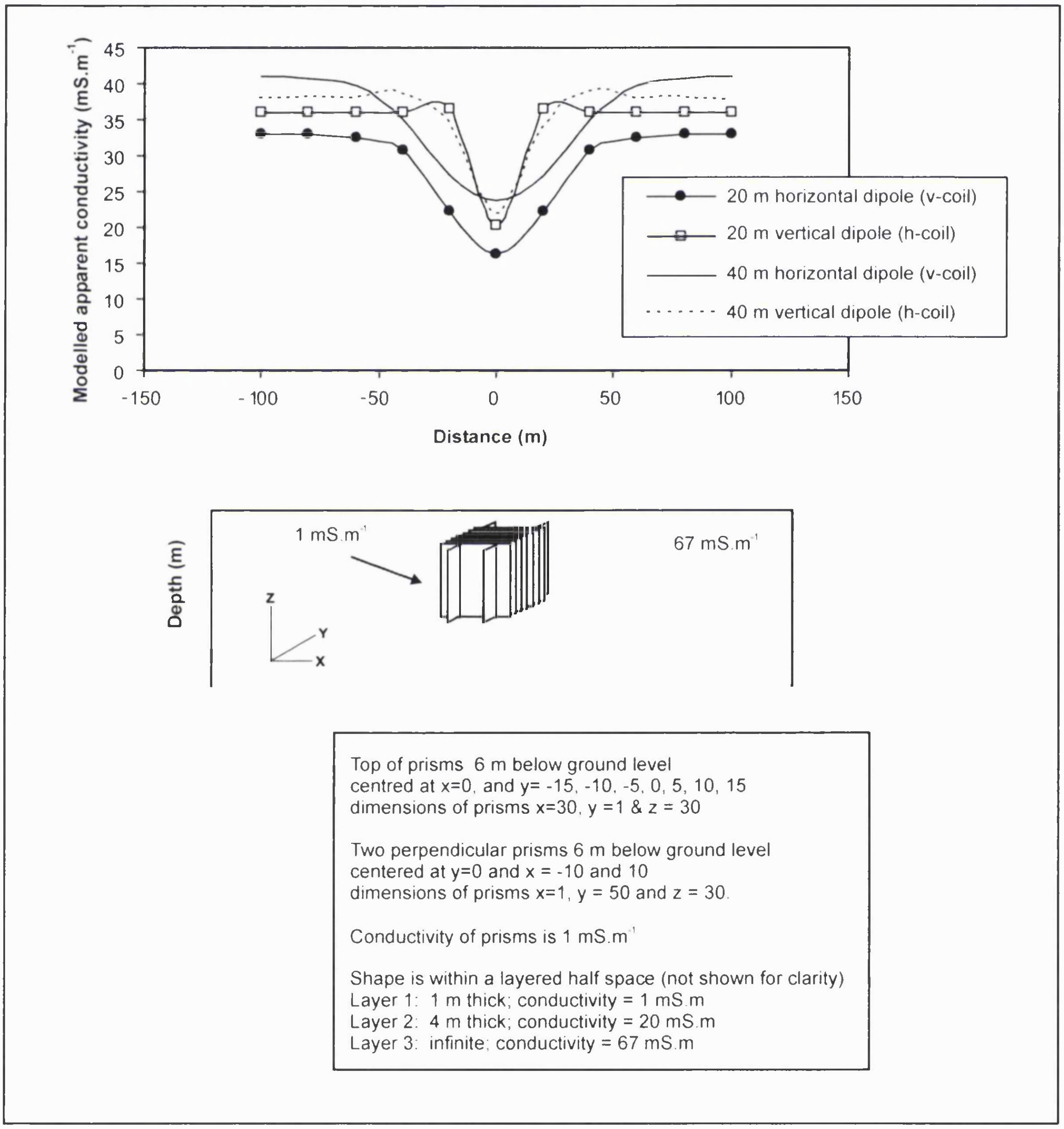


Figure 7.11 Model of a low conductivity fracture zone in a high conductivity background. Interaction between bodies is assumed to be inductive. Modelling undertaken with EMIGMA™.

7.6.3 Sandstone within mudstone

No usable groundwater was found within mudstone with a high proportion of smectite. In these areas, the best targets for sustainable groundwater supplies are within thin sandstone layers or dolerite intrusions. This section discusses locating sandstone within the mudstone, while the next section details finding dolerite. Two case examples of sandstone occurring in mudstone are given here: locating the thick Makurdi Sandstone layers in Odeleko Adiko, and finding the thin sandy layers in the weathered zone of the Awgu Shale.

The case of the Makurdi Sandstone at Odaleko Adiko

The Makurdi Sandstone contains groundwater within pore spaces. Small fractures at the base of the weathered zone increase permeability. These fractures have been found to be widespread, therefore locating individual fractures is not required, only making sure that wells are constructed within the sandstone (Chapter 4). The sandstone occurs in layers from several millimetres to tens of metres thick and is interbedded with illite/smectite mudstone. It is generally impossible to distinguish mudstone from sandstone by examining ground – help is required from drilling or geophysics.

The sandstone is relatively clean, with only small amounts of disseminated clay (see Chapter 4). Small proportions of illite and kaolinite clay can be present. The bulk conductivity of the sandstone can be calculated from Equation 4. Taking porosity as 25%, an illite content of 10%, electrical conductivity of the water as 40 $mS.m^{-1}$, and m as 1.5, the bulk conductivity is estimated as 15 $mS.m^{-1}$. The mudstone at Odaleko Adiko is composed of I/S with slightly higher smectite content than at Edumoga. Therefore a bulk conductivity of 70 $mS.m^{-1}$ is not unreasonable.

Figure 7.12 shows one of the EM34 traverses across Odaleko Village. The boundary between sandstone and mudstone is clearly identifiable. From 0 to 230 m the apparent conductivity measured with the 20-m intercoil spacing ranges from 10 to 15 $mS.m^{-1}$, indicating sandstone. A marked change occurs between 230 m and 300 m, then from 330 m to the end of the profile, the apparent conductivity is approximately 35 $mS.m^{-1}$ suggesting the presence of mudstone. Several profiles were undertaken to map the junction between sandstone and mudstone across the village (Figure 7.13). Two boreholes were drilled to confirm the interpretation: borehole 3 proved mudstone and

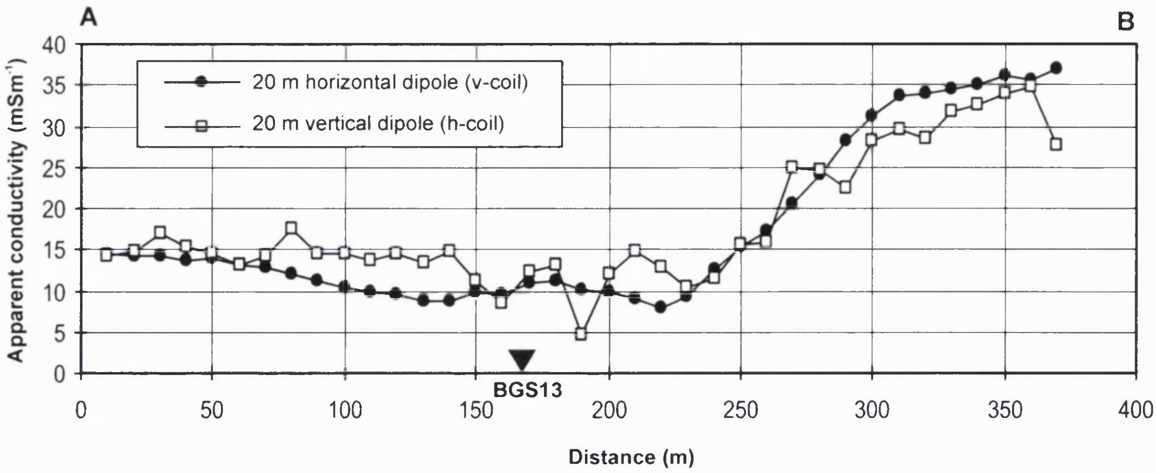


Figure 7.12 Apparent conductivity from EM34 at Odaleko Adiko (interlayerd sandstone and mudstone). Location of survey shown in Figure 7.13.

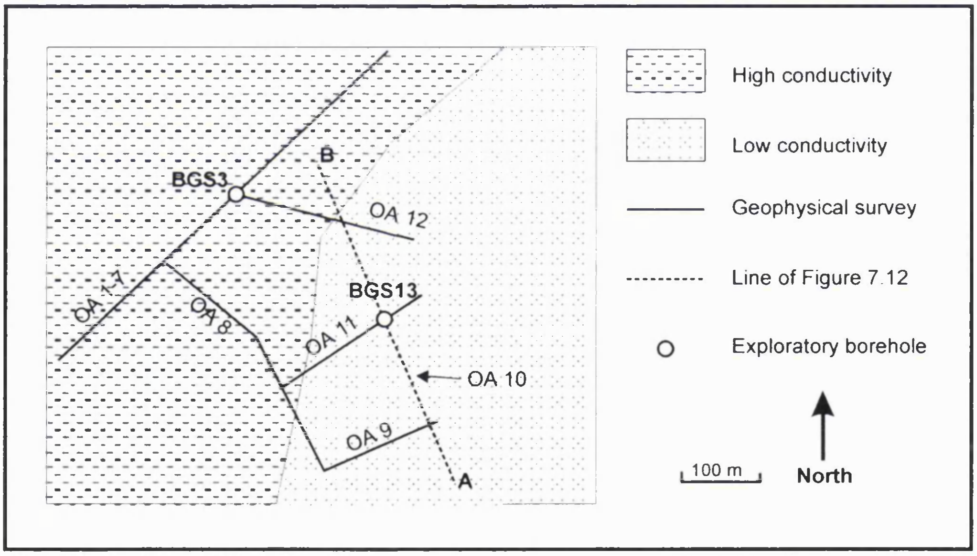


Figure 7.13 Approximate boundary between high conductivity (mudstone) and low conductivity (sandstone) at Odaleko Adiko.

borehole 13, sandstone. A community well constructed several metres from BGS 13 proved highly successful.

Sandy weathered zone within smectite mudstone

Sandy layers within (or overlying) the weathered zone of the smectite-rich Awgu Shale forms an important source of water. As discussed in Section 5, these sands are of uncertain origin and possibly the remains of sand dunes from a Saharan advance, or an accumulation of sands from millions of years of weathering of the shale. These sandy horizons are up to 10 m thick and often have a thin ferricrete layer at their base. Beneath this zone, weathered and unweathered smectite-rich mudstone is present. A small amount of groundwater, sufficient for a well providing 5-10 households can be found within the thin sands. In an environment with few alternative sources of clean water, this is an important resource.

The sands contain smectite and kaolinite clay (see Chapter 5), but in sufficiently small quantities to provide a large electrical conductivity contrast with the underlying mudstone. Figure 7.14 shows EM34 data for a profile crossing several areas of sand proved by drilling. Areas of low conductivity are easily identified and correspond to sand in the weathered zone proved by drilling. It is theoretically possible for factors other than the presence of sand within the weathered zone to give such a response, for example changes in clay mineralogy, but these are geologically unlikely. Simple 1D modelling has focused on reproducing these apparent conductivity measurements in two different ways: (1) variations in thickness of the shallow ferruginous soil (which would not give any water) and (2) the presence of sand in the weathered zone (which would be a target for development). Parameters for the modelling have been taken from resistivity surveys in the Awgu Shale (see data in accompanying CD-ROM).

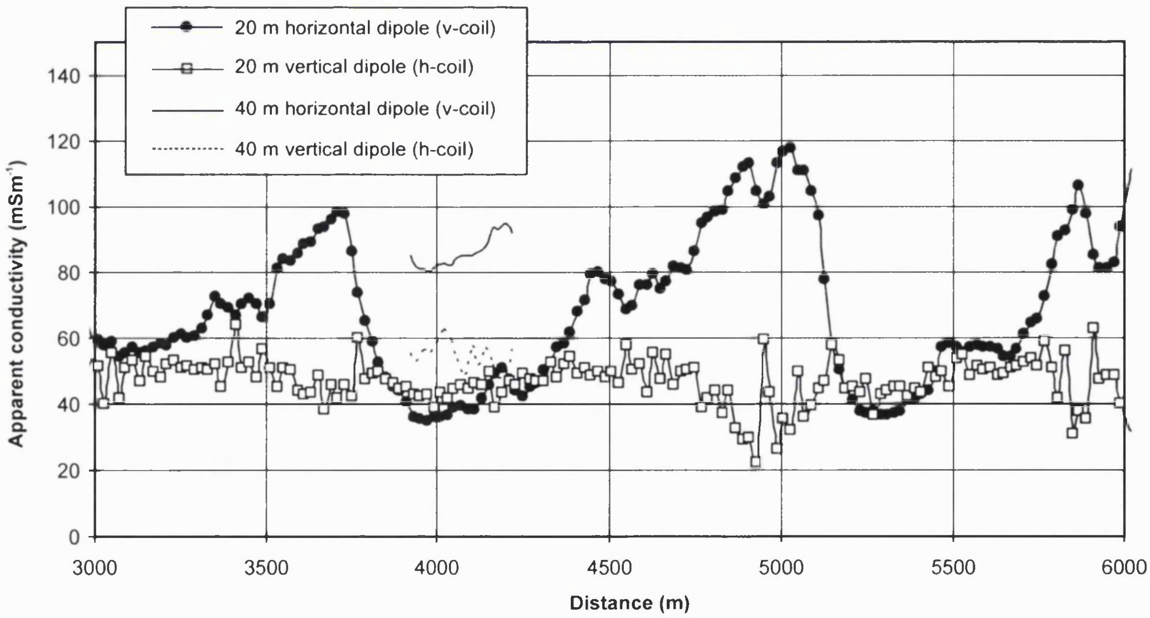


Figure 7.14 An EM34 survey over the Awgu Shales (smectite mudstone) at Itogo with thin sandy layers in the weathered zone.

The results of the modelling in Figure 7.15 indicate that variations in thickness of the soil layer of up to one metre cannot reproduce the anomalies found in the data. Simple models with a shallow sand layer from 4-8 m thick give apparent conductivity measurements in keeping with the measured data. Slight changes in clay content or water quality within the sand layer will produce subtly different anomalies, but the overall characteristics will remain the same.

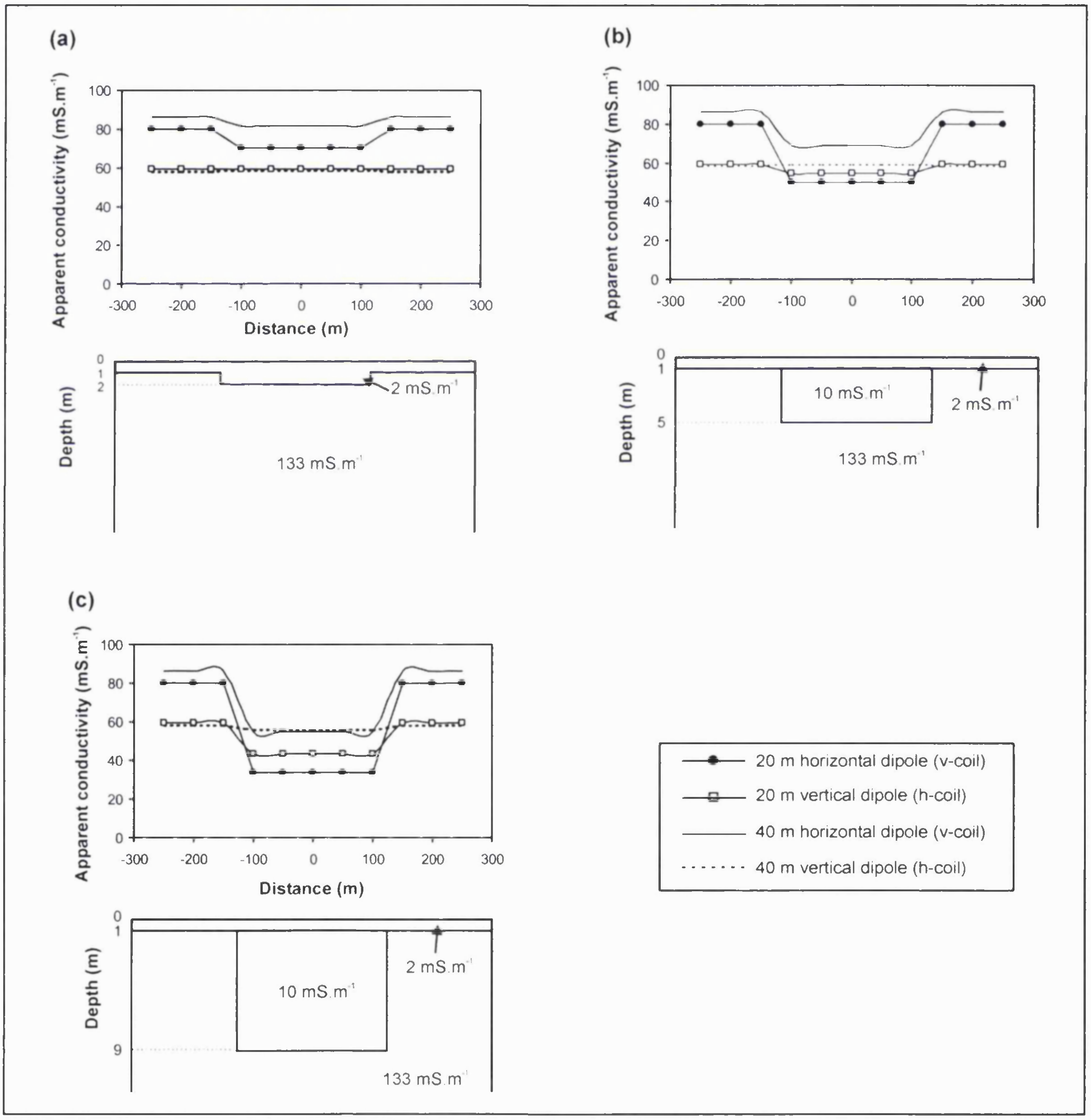


Figure 7.15 1-D modelling response of EM34 to variations in weathered zone of a soft smectite mudstone: (a) variations in the thickness of the soil; (b) response of a 4 m thick sand layer; and (c) the response of an 8-m thick sand layer.

7.6.4 Dolerite intrusions within mudstone

Dolerite sills and dykes form important aquifers in smectite-rich mudstone. The intrusions are often highly fractured and contain significant groundwater (see Chapter 5). Some groundwater is also found in the baked area around the intrusion. Since few other resources are available within these smectite-rich mudstones, reliably identifying intrusions is important. Aeromagnetic information can reveal the likelihood of the presence of dolerite in an area, but is insufficiently detailed to identify drilling sites. In Oju and Obi, there was seldom any surface expression of dolerite, apart from occasionally a change in soil type.

Figure 7.16 shows typical EM34 and magnetic data, taken in a smectite-rich mudstone with dolerite intrusions. The data reveal two characteristic geological environments which were proved by drilling (see Chapter 4): (1) relatively conductive country rocks (the soft Awgu shales) containing no significant shallow magnetic material, extending between 0 and 1200 m, and (2) much less conductive background, heavily intruded by magnetic material as shallow sills with occasional dyke-like bodies,

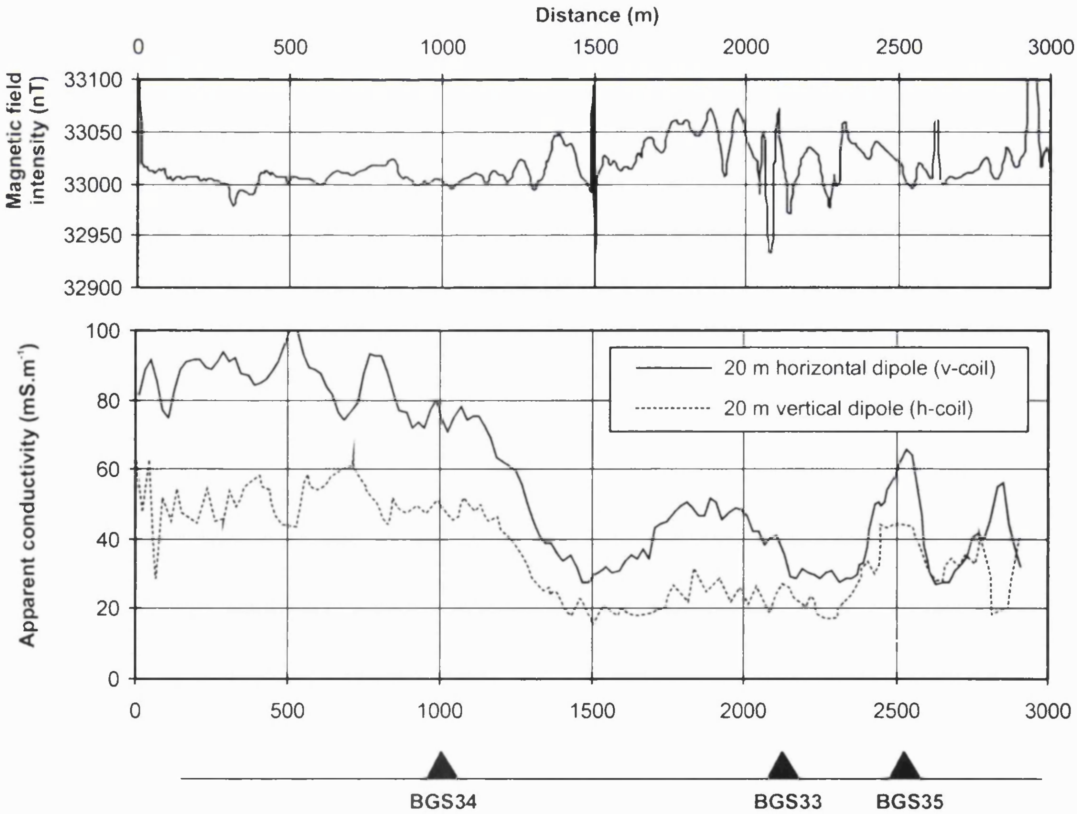


Figure 7.16 EM34 and magnetic data over a dolerite intrusion in the Awgu Shale (smectite mudstone).

extending between 1200 m and 3000 m. The important geophysical factors of the environment are given below.

1. Dolerite and mudstone have different magnetic susceptibility Telford *et al.* (1990).
2. Fresh dolerite has low electrical conductivity (less than 10 $mS.m^{-1}$), which contrasts with the smectite-rich mudstone (80-100 $mS.m^{-1}$).
3. Dolerite weathers to smectite, giving conductivity similar to the smectite-rich mudstone when totally weathered. However, weathering is generally only well developed at shallow depths. At several metres depth, the smectite content reduces substantially to provide a large contrast with mudstone.

The electrical conductivity characteristics described above can combine to produce different anomalies when dolerite is present. Generally, the low conductivity of the dolerite results in lower measured apparent conductivity measured with the EM34. If the dolerite is deep, however, this may not be identified by the EM34 with 20-m coil separations. Equipment with deeper penetration, such as the EM34 with 40-m coil separations, or electrical resistivity may identify reducing conductivity with depth of the intrusion. The reduced conductivity can be misinterpreted as sandstone.

The most unambiguous method of identifying dolerite is to use magnetic methods in tandem with EM. To illustrate the appropriateness of magnetic methods the data from Adum West were modelled using 1D software (MAGIX™). The results of the modelling are shown in Figure 7.17. The modelling indicated the broad sill underlying the area, dipping to the south, which is consistent with information from the boreholes. To the north (from 1300 m to 2600 m) the model illustrates that the sill is heavily intruded with dykes. The dykes and sill have susceptibility of 0.01 to 0.02 S.I. and exhibit remnant magnetisation.

7.7 Conclusions

This chapter has demonstrated that wells and boreholes in mudstone environments can be sited using simple geophysical methods. However, lithological variations in the mudstone need to be sufficiently understood to allow the appropriate interpretative methods to be applied. Once the lithology and hydrogeology of the mudstone is known, simple interpretative guidelines can be applied to large areas of similar geology. The study of lithological, hydrogeological and geophysical data from the diverse mudstone

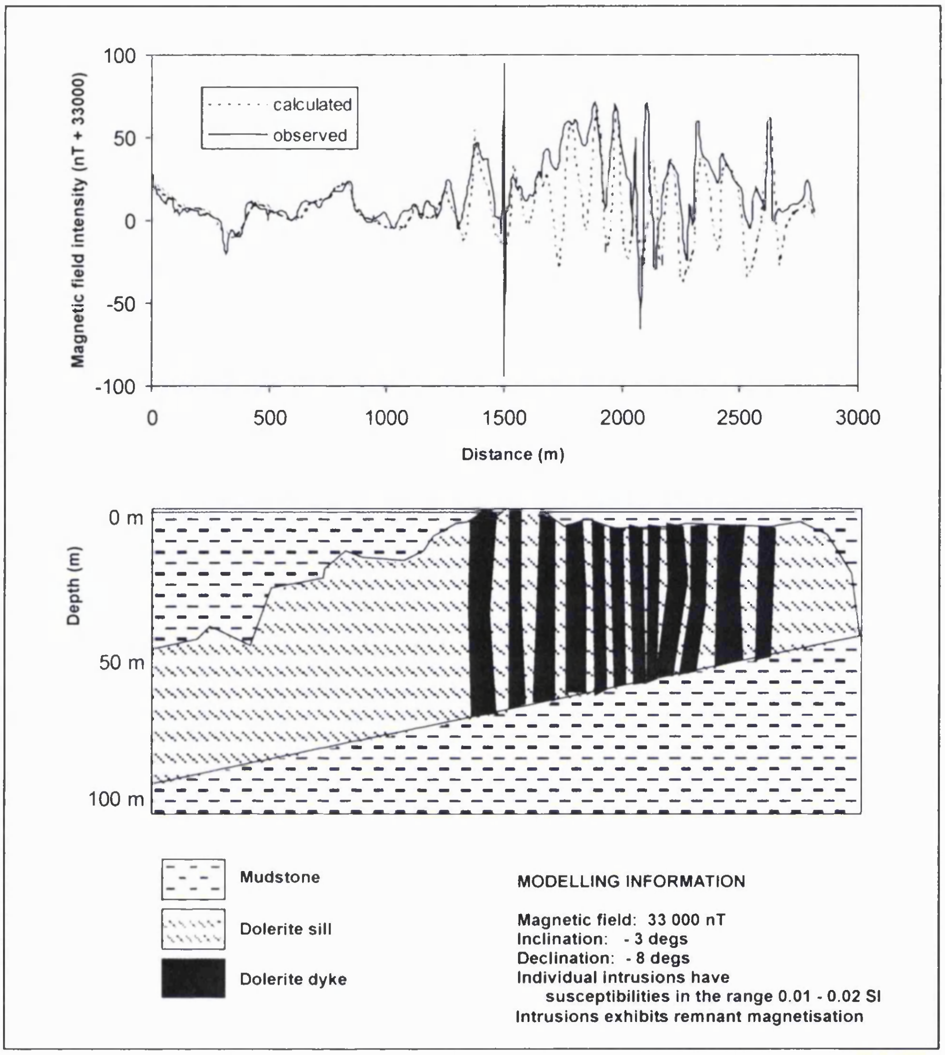


Figure 7.17 Modelled response of a series of dolerite dykes and sill within a mudstone.

environment of Oju and Obi has given insight to the use of applied geophysical methods in mudstones in general. 1D and 3D modelling has also been useful in broadening the application of the study. The main conclusions of the field and modelling study are given below.

1. Field data has shown a strong correlation between measured ground electrical conductivity and the mineralogy of the mudstone. Illite, I/S and smectite-rich mudstones can all be easily distinguished by measuring the ground conductivity. Further analysis has demonstrated that the dominant control on the measured field conductivity of the mudstones is the proportion of smectite within the rock.

2. In softer, I/S mudstones (such as the Lower Eze-Aku Shale Formation) large faults and fracture zones can be easily identified. Fracture zones have much lower

apparent conductivity than the surrounding undisturbed mudstones. Novel 3D modelling of combinations of interconnected plates of low conductivity, produce anomalies consistent with the data measured in Oju and Obi. Such conditions may arise from the formation of kaolinite clay on fracture surfaces within a fault zone as a result of deformation and increased water circulation. However, surface weathering is fairly homogeneous and does not produce large variations in ground conductivity.

3. Sandstone (such as the Makurdi Sandstone Formation) can be easily distinguished from I/S and smectite mudstone. However, sandstone is not easily distinguished from illite rich mudstones. Thin sandy layers within the weathered zone of smectite-rich mudstone can be identified using ground conductivity.

4. Dolerite intrusions within smectite mudstone (such as the Awgu Shale Formation) can be identified with a combination of ground conductivity and magnetic methods. Although unweathered dolerite has a low conductivity, it weathers to smectite, and can therefore be difficult to distinguish from mudstone using EM alone. Modelling of dolerite sills and dykes within mudstone indicates that variations in magnetic field are sufficiently large to be easily measured.

The study has highlighted the paucity of information regarding the electrical conductivity of mudstones, and in particular the characteristics of faults. Detailed study of fault zones would greatly add to the current knowledge. A series of faults could be studied in detail by drilling a series of exploration boreholes within the faults and undertaking mineralogical analysis, downhole geophysics and detailed electrical profiling.

Chapter 8

Conclusions and implications for water projects

This research is the first coherent study of mudstones as a source of groundwater for community water supply in rural Africa. The thesis has explored the question "Can groundwater within mudstone environments be exploited for rural water supply?" as outlined in Chapter 1. The research has been based on four objectives: How groundwater occurs; methods for finding groundwater; methods for testing boreholes; and the project management implications of the research. The conclusions of the first three objectives of the research are summarised in this Chapter. The project management implications arising from the research are then discussed.

8.1 Groundwater occurrence in mudstone environments

8.1.1 Conclusions

The research has demonstrated that sufficient groundwater to sustain boreholes with handpumps exists in mudstone environments (success is based on supplying 250 people with 25 litres per day). Two aspects are particularly important in controlling the availability of groundwater.

Low-grade metamorphism. Groundwater occurrence is clearly related to the degree of metamorphism the mudstones have undergone. Where mudstones have been subjected to low-high anchizone metamorphism, illite clays dominate the mudstone, and fractures at shallow depth within the mudstone tend to remain open and groundwater can be easily found. The general brittleness of illite dominated mudstone ensure that they are easily fractured. Where little metamorphism has occurred, and the mudstones are still dominated by smectite clays, fractures are easily healed, and the permeability is too low for boreholes or wells to be successful. In mudstones dominated by intermediate illite/smectite clays (present at the early-late diagenetic boundary) only large fractured zones contain groundwater. The ratio of smectite to illite determines whether these fractures remain open. This metamorphism model provides a major step towards understanding variations in transmissivity between different mudstone formations.

Presence of other lithologies. Dolerite intrusions within mudstones significantly increase the potential for groundwater, in contrast to studies in most other environments where dolerite intrusions are usually avoided. The research has demonstrated that igneous intrusions in low permeability, smectite-rich, mudstones are highly fractured, probably as a result of the high water content and low permeability of the mudstones at the time of intrusion. The presence of even thin limestone and sandstone layers at shallow depths can increase permeability sufficiently to sustain a borehole with a hand-pump.

The research has also highlighted the significance of the seasonality of transmissivity and groundwater chemistry in sub-tropical areas. Thick tropical soils can be highly permeable. During the rainy season borehole and wells constructed in low permeability rocks are dominated by groundwater from the tropical soil. As the rains stop and this shallow layer dries out, only wells and boreholes which penetrate deeper groundwater will be successful.

8.1.2 Further research

As this thesis is the first attempt to assess the potential of mudstones for rural water supply, there is much more work to be done.

1. The metamorphic model should be tested in other mudstone environments. This would require extensive clay mineralogy analysis and pumping tests.
2. Few data have been collected on groundwater storage. However, a groundwater-level monitoring system has been set up in Oju and Obi, which should provide long-term

data on sustainability. Long-term, controlled pumping tests could offer more information on groundwater storage. Groundwater residence times, which could be obtained from isotope studies, would also help assess sustainability.

3. Research of the mechanisms for the development of fractures at shallow depths within mudstones would be valuable. Particularly in assessing the likelihood of fracturing in the illite/smectite mudstones and in understanding the mechanisms which make the illite rich mudstones so fractured.

8.2 Finding groundwater in mudstones

8.2.1 Conclusions

The research in Oju/Obi has demonstrated that simple geophysical techniques can be used to identify targets for groundwater in a mudstone environment. Ground conductivity is particularly useful. Two findings of the research significantly add to the understanding of the EM response of mudstones.

1. The field data show a strong correlation between bulk ground conductivity and the clay mineralogy of the mudstone. Smectite, I/S and illite mudstones are all easily distinguished by their electrical conductivity. Further analysis has demonstrated that the proportion of smectite in the mudstone dominates the measured bulk ground conductivity, despite variations in clay content, fluid conductivity, thickness of soil and weathered zones. Therefore ground conductivity can be used to distinguish different types of mudstone, and thus the potential for groundwater.
2. Large faults within I/S mudstones (an important target for groundwater in the Oju/Obi area) can be easily identified using ground conductivity methods. Faults tend to have lower conductivity than the surrounding host rocks. Novel research using 3D EM modelling, EM34 surveys, and targeted exploratory drilling has demonstrated that faults within mudstones can produce complex EM anomalies. These can comprise negative-going anomalies with both vertical and horizontal dipoles and complex noisy profiles.

Other targets within mudstone areas, such as sandstone layers and dolerite intrusions can be easily identified using conventional ideas and survey methods.

8.2.2 Further research

The research has highlighted the paucity of information regarding the electrical conductivity of mudstones, particularly the characteristics of faults. Further research could follow the pattern below.

1. Laboratory analysis of the different clay minerals could be undertaken to understand further the relationship between electrical conductivity and clay mineralogy.
2. As models become increasingly sophisticated, research into the EM response of more realistic faults could be undertaken. This should be broadened from mudstones to include basement aquifers.
3. Detailed field studies of faults could be carried out, to help determine the EM characteristics of large faults in mudstones.

8.3 The bailer test

8.3.1 Conclusions

A new pumping test method has been designed around the practical requirements of those working in rural supply projects in SSA. The bailer test needs only simple equipment and can be completed in one hour. The test involves removing roughly 20-50 bails from a borehole over a 10-minute period and then measuring the recovery. The test is analysed using large-diameter-well analysis and is only appropriate for low yielding boreholes (transmissivity 0.1 – 10 m^2.d). Rigorous testing has shown the following:

- pumping using bails instead of at a constant rate has negligible effect on analysis;
- declining yields during the test (due to deeper water-levels and operators' fatigue) only becomes significant if the pumping rate declines by more than 65% during the test;
- the test is designed for confined or semi-confined conditions which are generally met in mudstone or basement aquifers over the period of the test, negligible vertical flow is induced if the transmissivity is low (approx. 1 m^2.d);
- dual-porosity aquifers have negligible effect on the estimation of transmissivity if the characteristic time for hydraulic diffusion, $b^2 S_s/K_m$, is less than 0.01 days. At times greater than this the maximum error is 100% (and more commonly < 40%) which may be admissible given the large uncertainty and range of transmissivity encountered in basement and mudstone aquifers;

- for a set of 15 boreholes in Oju/Obi, the bailer test was found to predict similar transmissivity to a five-hour constant rate test.

The test has been further simplified to indicate the likelihood of the borehole sustaining a handpump for 250 people, by measuring only the maximum drawdown and the time for 50% and 75% recovery. No complex interpretation is required, instead a table can be consulted for boreholes with diameters 4 - 8 inches. The guidelines could be easily modified for other requirements, such as boreholes supplying 100 people.

8.3.2 Further research

Although the bailer test has been trialed in Oju/Obi and the theoretical basis for it thoroughly investigated, more operational research is required to prove its long term efficacy and practicality. It is being used by staff on the WaterAid project in Oju/Obi and is soon to be made available to other WaterAid projects. Any further teething problems should be identified within the next few years. Ideally, duplicate pumping tests in different environments and diameters of boreholes should be undertaken.

The methods of research used to investigate the theoretical soundness of the test could be more widely applied. For example, the effects of dual porosity on standard pumping test analysis methods could be tested for longer constant rate tests or step tests. The effect of variations in pumping rates on calculated transmissivity could also be tested for more permeable aquifers and different pumping rates.

8.4 Implications of research

The conclusions from the research have implications for the design and execution of rural water supply and sanitation (RWSS) projects in areas underlain by mudstones. The implications have been split into three different levels: implications for programmes, projects and communities. Although this is a convenient way of dividing up the implications there is clearly overlap between the different levels.

8.4.1 Implications for RWSS programmes

RWSS programmes are often discussed at a country or regional level. Programmes will often include large areas which cover different hydrogeological environments. Pressures at this level are often to get value for money and to ensure that projects are targeted to most needy areas. The implications of the research in Oju and Obi for RWSS programmes are discussed below.

Mudstone areas should be a priority for poverty focused aid. Since conventional methods of finding groundwater in mudstone areas are generally unsuccessful, few people have safe water supplies in mudstone areas. This can be compounded (as it is in Obi) by the high incidence of guinea worm in the ponds often found in mudstone areas. These factors often combine so that people in mudstone areas have little access to clean water and have a high incidence of disease.

Groundwater does exist in mudstone areas, therefore they should not be written off. Large areas underlain by mudstone have been often written off as having no groundwater, often with little data or investigations to back this up (e.g the Cretaceous sediments of Nigeria prior to this study). The conclusions of the detailed research in Oju and Obi demonstrate that groundwater can exist in these difficult areas, but requires a different approach than for other, easier, areas.

Developing groundwater in mudstone areas may be expensive – but there are large benefits. Water supply projects in mudstone areas are likely to be more expensive than areas with more promising hydrogeology. Extra resources must be put into groundwater investigations, and for some areas more expensive solutions, such as rainwater harvesting may need to be considered. However, since access to water in mudstone areas is so poor, improvements in water supply in these areas have large benefits.

Putting money into research before making unilateral decisions can be money well spent. The cost of the investigations in Oju and Obi was in the region of £0.6 million. Conservative estimates of the cost of one borehole in West Africa suggest that this money could have been used to drill 100 boreholes (van Dongen & Woodhouse 1994). Alternatively, the money could have been used to pipe water several kilometres from one of the rivers. However, the research has formed a sound basis for water supply in Oju and Obi which should eventually lead to access to clean water for up to 300 000 people (over 1000 water sources).

8.4.2 Implications for RWSS projects

The research also has implications for the design and implementation of individual projects. Projects are often concerned with personnel, finance, the nuts and bolts of community participation and the timing of inputs.

Project teams in mudstone areas require significant hydrogeological and geophysical capabilities. Boreholes or wells in mudstone environments cannot be drilled anywhere, or with simple 'rules of thumb' transferred from other areas. Geophysical methods, such as ground conductivity and magnetic profiling must be routinely undertaken. The hydrogeology is complex, and may require different techniques for different areas. Therefore, adaptable hydrogeologists and geophysicists are a necessary part of any project team. The whole team must be aware of the hydrogeological constraints, however, so that the community development, engineering and hygiene aspects of the project can be considered from a sound hydrogeological base.

Mudstone areas demand a flexible and informed approach to water supply. Fixed approaches to borehole or well design are inappropriate. Some areas may require boreholes, other areas wells; some may require intensive geophysical surveys, in others boreholes may be sited anywhere. This flexible approach must run right through the project. Community development workers must have a mechanism for ascertaining the geology of a village, so that they can discuss with a community options that are appropriate to the local hydrogeological conditions.

Who pays the cost of failure? There are likely to be more failed boreholes in mudstone areas than in areas underlain by easier geology. In many projects, communities pay a contribution (money, or in kind) towards a well or a borehole. In difficult areas, it should be clear before the work is carried out who should pay the cost of failure, or provide the labour for an unsuccessful well. At the very least communities should be aware of the level of risk they are taking on.

Lead-time to assess the hydrogeology. If the hydrogeology has to be investigated then sufficient time must be given at the start of the project for the research to produce results that can be used by the project. Such investigations can be run in parallel with training of project staff.

8.4.3 Approach to communities

The peculiar hydrogeology of mudstone areas has implications for how projects should approach and work with individual communities. The relationship between community and project is fundamental to the development of successful water supplies. Below are some of the community issues that need to be addressed when working in a mudstone area.

The hydrogeology and hydrology of mudstone areas are often counterintuitive. Because of the low permeability of mudstone there is often an abundance of near-surface water during the rainy season (see Chapter 3). This results in shallow wells being full of water (mainly fed by surface water) and many ponds. When the rains stop, ponds and marshy areas are left which are often used by communities for water supply in the early dry season. If these are solely remnants of surface water they will not be good locations for boreholes or wells. Simple models may aid discussions with communities.

Communities must be prepared for failure and long walks to water sources. As discussed above, communities must be aware of the risks of failure when considering an improved water supply. Although this is good practice in all water projects, it is particularly important in mudstone areas. In some areas, improved water sources may only be found several kilometres from the village. Communities must be made fully aware that new sources may not be found close to the village centre. Multiple sources may also be needed within a community (wet season and dry season). If the goal of improved access to clean water is to be realised, the constraints and peculiarities of water supplies in mudstone must be effectively communicated to communities.

8.5 Epilogue

This research has demonstrated that groundwater can be found in mudstone areas, but its occurrence depends on subtle variations in geology. Locations for boreholes and wells can be found using simple geophysical methods (such as ground conductivity). Hopefully this first study of mudstones as aquifers, rather than receptacles of waste, will form the basis of further research that will eventually lead to improvements in the lives of up to 70 million people in sub-Saharan Africa. However, to help make these improvements, we as scientists have to learn to communicate effectively our science (and the implications of our science) to those who actually make decisions. That surely, is the most pressing task facing hydrogeologists today.

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Appendices

Appendix 1 summarises the BGS Technical Reports that contain the base data on which this thesis is based (all available from the BGS library). For completeness, digital copies of the reports are enclosed on a CD-ROM. Data not available in the BGS Technical Reports are recorded in Appendix 2 (clay mineralogy) and Appendix 3 (groundwater chemistry). A data recording sheet for the bailer test is given in Appendix 4.

Appendix 1: Summary of BGS Technical Reports of data on which the thesis is based

Much of the data on which the thesis is based has been collated in 11 BGS Technical Reports. One report has been written for each test site in Oju and Obi. The reports each follow the same format: a 10-15 page summary of the data and analysis for the test site, followed by an extensive appendix of all geophysical, lithilogical and test pumping data collected at the site. In the main body of the thesis, the reader has been referred to this Appendix or the accompanying CD-ROM for any data contained in these data reports. Several other (non-data) reports were produced during the lifetime of the project, these are referred to in the text by their bibliographic reference.

BGS Technical Reports are part of a recognised series of publications and are archived in the BGS Library at Keyworth (✆ 0115 936 3100). They are available to the public and shortly will be available online (www.bgs.ac.uk). However, for completeness a digital copy of all the data reports has been enclosed as a CD-ROM. The have been produced in pdf format using Acrobat 4.05; Acrobat Reader is enclosed on the CD-ROM.

Below is a summary of information contained in the BGS reports completed during the project.

Main Reports

MacDonald, A. M. & Davies, J. 2000. Communicating groundwater research the example of Oju and Obi, Nigeria. British Geological Survey Technical Report **WC/00/07**. 16pp	Discusses how the results of the research were communicated to various stakeholders. Also Summarises the rationale and results of the research in Oju and Obi and how the research process was informed by partners.
Davies, J. & MacDonald, A. M. 1999. Final Report: the groundwater potential of the Oju/Obi area, eastern Nigeria. British Geological Survey Technical Report **WC/99/32**. 97pp	This is the main project report. It summarises both the methods and results of the investigations in Oju and Obi. Guidelines are also given for the development of groundwater in the area.
MacDonald, A. M. & Davies, J. D. 1998. Groundwater development maps for Oju and Obi Local Government Areas, Eastern Nigeria. British Geological Survey Technical Report **WC/98/53** 5pp with annexes and 3 foldout maps.	Three 1:100 000 maps of Oju and Obi: groundwater development map; hydrogeology map and satellite and aerial photograph interpretation. A short accompanying report gives details of how the maps were constructed and a village gazetteer.

MacDonald, A. M. & Davies, J. 1997. The hydrogeology of the Oju Area, Eastern Nigeria: an initial assessment. British Geological Survey Technical Report **WC/97/54**. 47pp

The inception report for the project. Provides details of the groundwater problems in Oju and Obi, results of a survey of water points in the area illustrated with many photographs. A discussion of relevant literature is also given.

Data Reports

Davies, J. & MacDonald, A. M. 1999. The hydrogeology of the Oju/Obi area, eastern Nigeria: Ugbodum area data report. British Geological Survey Technical Report **WC/99/3R**.

Geophysical data, map information, pump test data, and drilling and lithological data for boreholes BGS40 – 46 at Ugbodum, Obi. This test site is located primarily on the Awgu Shale Formation and encounters small dolerite intrusions.

MacDonald, A. M. & Davies, J., 1999. The hydrogeology of the Oju/Obi area, eastern Nigeria: Itogo area data report. British Geological Survey Technical Report **WC/99/4R**.

Geophysical data, map information, pump test data, and drilling and lithological data for boreholes BGS47-50 along the Itogo traverse in Obi. Pump test data for two additional boreholes (Berwassa 1 and Berwassa 2) and results of the 8 km long EM traverse at Oluywo. This test site is located primarily on the Awgu Shale Formation but also encounters dolerite and thin shallow sand layers.

Davies, J. & MacDonald, A. M. 1998. The hydrogeology of the Oju/Obi area, eastern Nigeria: Odaleko Adiko area data report. British Geological Survey Technical Report **WC/98/65R.**

Geophysical data, map information, pump test data, and drilling and lithological data for boreholes BGS3, 3a, 13 and 13a at Odaleko Adiko in Obi. The test site is underlain by the Makurdi Sandstone Fm and Upper Eze-Aku Fm.

MacDonald, A. M. & Davies, J. 1998. The hydrogeology of the Oju/Obi area, eastern Nigeria: Adum West area data report. British Geological Survey Technical Report **WC/98/66R.**

Geophysical data, map information, pump test data, and drilling and lithological data for boreholes BGS33-35 at Adum West in Obi. The test site is underlain by Awgu Shale with large dolerite intrusions.

Davies, J. & MacDonald, A. M. 1998. The hydrogeology of the Oju/Obi area, eastern Nigeria: Odubwo area data report. British Geological Survey Technical Report **WC/98/67R.**

Geophysical data, map information, pump test data, and drilling and lithological data for boreholes BGS1, 2a and 2b at the WaterAid Office and Odubwo in Oju. This test site is underlain by the Asu River Formation.

MacDonald, A. M. & Davies, J., 1998. The hydrogeology of the Oju/Obi area, eastern Nigeria: Anyoga Eddi Adum East area data report. British Geological Survey Technical Report **WC/98/68R.**

Geophysical data, map information, pump test data, and drilling and lithological data for boreholes BGS36-39 at Adum East in Obi. This test site is underlain by the Makurdi Sandstone Formation.

Davies, J. & MacDonald, A. M. 1998. The hydrogeology of the Oju/Obi area, eastern Nigeria: Oyinyi Iyechi area data report. British Geological Survey Technical Report **WC/98/69R**.

Geophysical data, map information, pump test data, and drilling and lithological data for boreholes BGS19-21 at Oyinyi Iyechi in Oju. Thje test site is underlain by the metamorphosed Asu River Formation.

MacDonald, A. M. & Davies, J. 1998. The hydrogeology of the Oju/Obi area, eastern Nigeria: Adega, Ojokwe, Ohuije, Ijokwe and Akiraba Ainu areas data report. British Geological Survey Technical Report **WC/98/70R**.

Geophysical data, map information, pump test data, and drilling and lithological data for borehole BGS32 at Adega, Obi. The site is underlain by the Awgu Shale. Assorted geophysical data from various other investigations (which were not full test sites) are also given.

Davies, J. & MacDonald, A. M. 1998. The hydrogeology of the Oju/Obi area, eastern Nigeria: Edumoga area data report. British Geological Survey Technical Report **WC/98/50R.**

Geophysical data, map information, pump test data, and drilling and lithological data for boreholes BGS14-18 at Edumoga, Oju. The test site is underlain by the Lower Eze-Aku.

MacDonald, A. M. & Davies, J. D. 1998. The hydrogeology of the Oju/Obi area, eastern Nigeria: Ochingini area data report. British Geological Survey Technical Report **WC/98/51R**.

Geophysical data, map information, pump test data, and drilling and lithological data for boreholes BGS4-12 at Ochingini, Obi. This long traverse cuts across the Upper Eze-Aku and Makurdi Sandstone Formations.

Davies, J. & MacDonald, A. M., 1998. The hydrogeology of the Oju/Obi area, eastern Nigeria: North Obi traverse - data report. British Geological Survey Technical Report **WC/98/52R**.

Geophysical data, map information, pump test data, and drilling and lithological data for boreholes BGS22-31 from Ijegwu to Ameka in Northern Obi. The traverse cuts across the Awgu Shale.

Auxiliary Reports

MacDonald, A. M. 2001. Report on visit to a WaterAid project, Nigeria, to carry out workshops and assess geology of Benue State. British Geological Survey Internal Report, **IR/01/18**. 26pp.

Summarises the activities and conclusions of a short visit to the project to give additional geophysical training, carry out a desk study of the hydrogeology of Benue State and review ongoing drilling progress by WaterAid.

MacGillivray, S. D. 1999. Rural water supply pollution management in Nigeria, MSc Thesis, Dept of Civil and offshore Engineering, Heriot-Watt University, Edinburgh.

MSc Thesis supervised by Alan MacDonald investigating permeability of shallow soil layers and contamination of drinking water supplies through bypass flow in the soil zone.

Lott, G. K. 1998. Thin section petrography of thirty-five samples from boreholes in the Cretaceous succession of the Benue Trough, Nigeria. British Geological Survey Technical Report **WH/98/174C**.	Photographs of thin sections along with descriptions of the petrography of selected samples in Oju and Obi.
Lott, G. K. 1998. Thin section petrography of two limestone core samples from the Benue Trough in Nigeria. British Geological Survey Technical Report **WH/98/98R**	Photographs and descriptions of limestone cores from the Upper Eze-Aku.
Kemp, S. J., Hards, V. L. & Murphy, M. H. 1998. The clay mineralogy of shallow borehole sequences from the Benue Trough, Nigeria. British Geological Survey Technical Report **WG/98/41**.	Clay mineralogy data from representative boreholes in Oju and Obi. A complete dataset is given in Appendix 3.
Davies, J. & MacDonald, A. M. 1997. An annotated bibliography of the geology and hydrogeology of the Oju area, Nigeria. British Geological Survey Technical Report **WC/97/8**.	Initial bibliography for the project. Divided into geology, hydrogeology, geophysics, pumping tests etc.
Davies, J. 1994. Water supply and sanitation project, Oju and Katsina Ala LGAs, Benue State, Nigeria: hydrogeological input. British Geological Survey Technical Report **WD/94/38R**.	First BGS report on the area, commissioned by DFID. Describes the problems of Oju and Obi and a first guess at the hydrogeology. This report was used to design the project.

Appendix 2: Clay mineralogy data from selected boreholes in Oju and Obi

Clay mineralogical analysis

The clay minerals making up the clay fraction in the rock was determined for representative boreholes throughout Oju and Obi. For most of the boreholes it was possible to get samples every metre for the top ten metres. In all but a few cases chip samples were taken. X-Ray diffraction was used to determine clay mineralogy. Details of the laboratory procedure are given in Kemp *et al.* (1998). Clay minerals determined for each sample are shown in the table below.

Borehole	*mean depth (m)*	*Kaolinite (%)*	*Illite (%)*	*Smectite (%)*	*I/S (%)*	*Other (%)*
BGS2a	1.2	12	88			
	14.2		84			Chlorite 16%
BGS3a	14.5	25	5		70	
BGS4	1.5	82	18		0	
	2.5	76	24		0	
	3.5	39	4		58	
	4.5	24	2		74	
	5.5	11	1		88	
	6.5	15	3		82	
	7.5	12	2		86	
BGS6	1.5	38	5		57	
	2.5	25	4		71	
	3.5	19	3		77	
	4.5	14	4		82	
	5.5	14	4		82	
	6.5	16	4		80	
	7.5	13	3		83	
	8.5	9	4		87	
	9.5	13	6		81	
BGS7	1.5	86	14			
	2.5	82	18			
	3.5	64	36			
	4.5	52	48			
	5.5	45	55			
BGS8	1.5	84	16		0	
	2.5	89	11		0	
	3.5	66	8		29	
	4.5	29	6		65	
	5.5	25	5		71	
	6.5	21	2		77	
	7.5	33	5		62	

Borehole	mean depth (m)	Kaolinite (%)	Illite (%)	Smectite (%)	I/S (%)	Other (%)
	8.5	26	4		70	
BGS13	1.5	66	34			
	2.5	56	44			
	3.5	42	51	7		
	4.5	39	53	9		
BGS15	1.5	39	29		32	
	2.5	37	6		57	
	3.5	29	4		67	
	4.5	23	3		74	
	5.5	17	3		80	
	6.5	11	4		85	
	7.5	9	1		90	
	8.5	8	3		89	
	9.5	6	3		92	
BGS16	1.5	64	36			
	2.5	66	34			
	3.5	32	10		58	
	4.5	20	7		73	
	5.5	10	4		86	
	6.5	1	7		92	
	7.5	1	7		91	
	8.5	1	6		94	
	9.5	1	6		93	
BGS18	1.5	65	35			
	2.5	25	7		68	
	3.5	17	5		78	
	4.5	14	6		80	
	5.5	12	7		82	
	6.5	8	6		86	
	7.5	7	5		88	
	8.5	15	7		78	
	9.5	12	6		82	
BGS19	1.5	58	42			
	2.5	63	32	5		
	3.5	55	39	6		
	4.5	48	47	5		
	5.5	36	57	7		
	6.5	48	40	11		
	7.5	34	56	11		
	8.5	38	49	13		
BGS21	1.5	51	49			
	2.5	46	54			
	3.5	37	47	16		
	4.5	30	65	5		
BGS27	14.5	36	3	60		
	19.5	35	3	63		
BGS30	1.5	57	4	39		
	2.5	44	4	52		
	3.5	35	3	62		
	4.5	42	5	53		
	5.5	41	3	55		
	6.5	31	2	67		

Borehole	*mean depth (m)*	*Kaolinite (%)*	*Illite (%)*	*Smectite (%)*	*I/S (%)*	*Other (%)*
BGS30	7.5	34	4	62		
	8.5	23	3	74		
	9.5	37	3	60		
	10.5	32	4	64		
BGS31	1.75	56	5	39		
	2.25	35	1	64		
	2.75	44	2	54		
	3.25	37	1	62		
	3.75	32		68		
	4.25	34	3	63		
	4.75	26	1	73		
	5.25	23	1	76		
BGS32	1.5	49		51		
	2.5	35	1	64		
	3.5	43	4	53		
	4.5	38	21	41		
	5.5	32	1	67		
	10.5	31	2	67		
BGS34	1.5	3	1		96	
	2.5	2	2		96	
	3.5	5	5		90	
	4.5	4	2		94	
	8.5	1	21		78	
	29.5	31	16		53	
	30.5	32	1		67	
	31.5	13		27	60	
BGS35	1.5	79		21		
	2.5	37		63		
	3.5	27		73		
	4.5	8		92		
	5.5	4		96		
	6.5	1		99		
	7.5	0		100		
BGS36	1.5	44	56			
	3.5	16			84	
	5.5	9			91	

Proportion of illite in I/S clay

Some of the early findings of the research suggested that the proportion of smectite in the rocks was key to both the hydrogeology and the geophysical response. Consequently further analysis of some sample was required to help determine the proportion of illite in mixed layer I/S clays. Simon Kemp at BGS Keyworth undertook modelling of the X-Ray diffraction data to help determine this important data. Two approaches were undertaken: measuring delta (difference in 2theta between two peaks) and the position of the 002/003 peak. The results for various boreholes in Oju and Obi are given below.

Borehole	Mean depth (m)	%illite delta	%illite 002/003
BH4	3.5	63	70
	4.5	62	59
	5.5	66	61
	6.5	65	63
	7.5	60	59
BH6	1.5	53	54
	2.5	59	58
	3.5	56	58
	4.5	53	55
	5.5	50	50
	6.5	51	51
	7.5	42	42
	8.5	60	51
	9.5	64	65
BH8	3.5		53
	4.5	56	59
	5.5	49	47
	6.5	55	55
	7.5	69	66
	8.5	63	63
BH15	1.5		60
	2.5	65	63
	3.5	64	67
	4.5	67	68
	5.5	63	70
	6.5	70	74
	7.5	70	72
	8.5	71	71
	9.5	71	74

Borehole	Mean depth (m)	%illite delta	%illite 002/003
BH16	3.5		71
	4.5		75
	5.5		72
	6.5		79
	7.5	75	70
	8.5		80
	9.5	75	79
BH18	2.5	66	64
	3.5	67	67
	4.5	75	78
	5.5	67	70
	6.5	68	74
	7.5	67	67
	8.5	73	69
	9.5	68	66
BH34	1.5	53	55
	2.5	46	51
	3.5	53	60
	4.5	69	70
	8.5	56	60
	29.5	58	58
	30.5	63	65
	31.5	63	67
BH36	3.5	79	89
	5.5		81

Illite crystallinity

In order to assess the stage of metamorphism of the Asu River Formation and metamorphosed Asu River Formation, illite crystallinity was determined for several samples. Again the analysis was undertaken by Simon Kemp in BGS Keyworth from qualitative glycol scans.

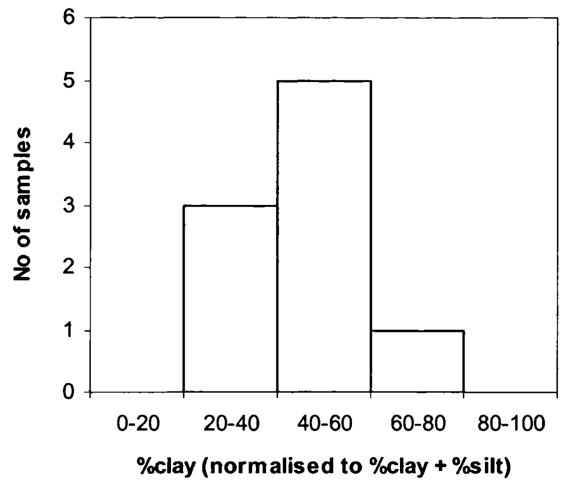
Borehole	Depth (m)	Illite Crystallinity
BGS19	1.5	0.27
	2.5	0.24
	3.5	0.27
	4.5	0.26
	5.5	0.21
	6.5	0.23
	7.5	0.28

Borehole	Depth (m)	Illite Crystallinity
	8.5	0.24
BGS21	1.5	0.39
	2.5	0.37
	3.5	0.31
	4.5	0.29
BGS2A	1.2	0.66
	17	0.49

Particle size analysis

Nine samples were analysed to for whole rock particle size analysis. Laboratory work was carried out by Simon Kemp at BGS Keyworth. Due to the expense of the analysis, only the deepest sample from each representative borehole was taken. The histogram shows the %clay in sample normalised to (%silt + %clay). This should minimise the problems of incomplete dispersion. The median clay content of the mudstones from this subset is approximately 50%.

BH	Depth	%sand >63 µm	%silt 2-63 µm	%clay <2 µm	Comments
BGS31	5-5.5 m	8.4	27.0	64.6	
BGS32	10-11 m	7.4	52.3	40.3	
BGS6	9-10 m	16.9	54.8	28.3	
BGS3	14.5 m	9.5	60.5	30.0	Incomplete dispersion
BGS18	9-10 m	72.5	13.2	14.3	Incomplete dispersion
BGS15	9-10 m	1.8	44.2	54.0	
BGS2	1.2 m	9.9	45.0	45.1	
BGS19	8-9 m	80.7	11.5	7.8	
BGS2	14-20 m	88.3	7.4	4.3	Incomplete dispersion



The histogram shows the %clay in sample normalised to (%silt + %clay). This should minimise the problems of incomplete dispersion. The median clay content of the mudstones from this subset is approximately 50%.

Appendix 3: Groundwater chemistry data

Location of groundwater sampling points

Site ID	Easting (decimal degrees)	Northing (decimal degrees)	name	source type
1	8.4397	6.8694	Andrews Borehole	borehole
2	8.4456	6.8645	Zion Hill	borehole
3	8.4513	6.8582	Professer	borehole
4	8.4597	6.8562	Anyitunkpo	borehole
5	8.4688	6.8561	Bethesda Hospital	borehole
6	8.4627	6.8462	Orphanage	borehole
7	8.4632	6.8489	Orphanage Staff	borehole
8	8.4819	6.8587	Anchimogbo-Iyeche	borehole
9	8.4618	6.8259	Ugbodo Igama	borehole
10	8.4882	6.8317	Adodo Anchim Uje	borehole
11	8.5115	6.8155	Otunche Anchin	borehole
12	8.5060	6.8043	Ohuhu Owo, seepage	seepage
13	8.5052	6.7997	Ohuhu Owo bh1	borehole
14	8.4948	6.7934	Ohuhu Owo bh2	borehole
15	8.4599	6.7909	Ameka Spring	spring
16	8.4625	6.7717	Adum Owo	pond
17	8.4591	6.8168	Odeliko dugouts	traditional well
18	8.2023	6.9729	Echuri	traditional well
19	8.2085	7.0590	Okpokwu	improved well
20	8.2130	7.0623	School Okpokwu	traditional well
21	8.2535	7.0276	Ugbodum well	traditional well
22	8.2546	7.0269	Ugbodum restraunt	improved well
23	8.3230	7.0250	Ito Government well	improved well
24	8.3133	7.0314	Ijanke, Rusafiya	borehole
25	8.2972	6.9606	Adum West pond	pond
26	8.2948	6.9476	Adum west clinic	borehole
27	8.2768	6.9298	Ikponyire	traditional well
28	8.4107	6.8742	Elim	borehole
29	8.4061	6.8855	Ega	borehole
30	8.3701	6.9394	Adum East "Dambo"	seepage
31	8.3629	6.9631	Adum East well	improved well
32	8.3620	6.9639	Adum East borehole	borehole
33	8.3672	6.9772	Adiko	seepage
34	8.4297	6.8878	College of Education	borehole
35	8.4474	6.8947	Obachita	borehole
36	8.4739	6.9429	Ebonda Spring	seepage
37	8.5008	6.9611	Ohuma Ukpa	borehole
38	8.4449	7.0174	Ukpute Ainu	borehole
39	8.3852	7.0158	Ochingini well	traditional well
40	8.3675	7.0799	Igbegi Itogo	traditional well
41	8.3660	7.0954	Iyaho Itogo	traditional well
42	8.3519	7.0365	Okwutungbe	traditional well
43	8.4234	6.8397	Anyuwogbu	borehole
44	8.3551	6.8531	Ikom Ainu	traditional well
45	8.3573	6.8462	Ihiokwu	borehole
46	8.2944	6.8300	Obussa town	improved well
47	8.2844	6.8230	Obussa west	seepage
48	8.3001	6.8751	Ohikpong	improved well
49	8.4768	6.8808	Bible College	borehole
50	8.4958	6.8237	Elim Vocational Centre	borehole

Site ID	Easting (decimal degrees)	Northing (decimal degrees)	name	source type
51	8.5378	6.8025	Ukpila Oboru	borehole
52	8.6204	6.8036	Obegede Oboru	borehole
53	8.6270	6.8029	Ida pond	seepage
54	8.6110	6.8390	Oye seepage	seepage
55	8.4359	6.8718	WaterAid Well	wateraid well
56	8.3293	7.0289	Fathers Well	improved well
57	8.3918	7.0854	St Antony's C5	improved well
58	8.3632	7.0623	St Michaels	improved well
59	8.2742	7.0871	Okpaga new well	wateraid well
60	8.2884	7.0884	Amaka Borehole	borehole
61	8.2887	7.0900	Amaka Well	traditional well
62	8.2849	7.0907	St Augustine C14	improved well
63	8.3162	7.0869	St Francis Well C15	improved well
64	8.3172	7.0832	NIGEP	traditional well
65	8.3808	7.0182	BGS6	borehole
66	8.3637	7.0283	BGS4	borehole
67	8.2937	6.9535	BGS33	borehole
68	8.4250	6.9993	BGS12	borehole
69	8.2428	7.1066	BGS27	borehole
70	8.2316	7.1132	BGS26	borehole
71	8.2660	7.0433	Adega well	traditional well
72	8.2805	7.0906	BGS30	borehole
73	8.4529	6.8165	BGS21	borehole
74	8.4483	6.8047	BGS20	borehole
75	8.3674	6.9528	BGS36	borehole
76	8.3733	6.9863	BGS13a	borehole
77	8.3849	6.8942	BGS15	borehole
78	8.3710	6.8899	BGS17	borehole
79	8.3724	6.8906	BGS16	borehole
80	8.3674	6.9528	BGS37	borehole
81	8.4978	6.8712	BGS2a	borehole
82	8.4073	7.0074	BGS10	borehole
83	8.3944	7.0103	BGS8	borehole
84	8.3886	7.0126	St Benedicts C10	improved well
85	8.3513	7.0396	St Catherines C2	improved well
86	8.3675	7.0799	St Johns C3	improved well
87	8.3657	7.0961	St Judes C4	improved well
88	8.3974	7.0637	St Bernards	improved well
89	8.2579	7.0302	Udegi	traditional well
90	8.3260	7.0324	St Josephs School	improved well
91	8.2944	6.9420	BGS34	borehole
92	8.2955	6.9561	BGS35	borehole
93	8.3733	6.9863	BGS13	borehole
94	8.4492	6.8135	BGS19	borehole
95	8.4978	6.8712	Odubwo BGS2	borehole

Groundwater chemistry data for widespread survey of Oju/Obi (mg.ℓ$^{-1}$)

Site ID	Chem ID	date sample	SEC	pH	T °C	Na	K	Ca	Mg	SO_4	Cl	HCO_3	NO_3-N	Si	Mn	Fe	Zn	Al	Pb	NH_4-N	F	Br	I	As
1	254	03-Apr-98	583	7.2	28	30	0.6	69	20	4	2.7	395	<0.5	20	0.68	0.9	0.02	<0.1	<0.2	0.03	0.1	0.006	0.001	<0.009
2	2	25-Feb-97	526	7.08	29	22.4	<0.5	74	12	1.8	0.56	305	<0.25	22	0.53	1.8	0.12	<0.1	<0.2	0.03	0.2	0.005	0.002	
3	3	25-Feb-97	855	6.87	30	40.2	0.6	117	25	12.3	1.13	512	<0.25	19	0.14	1.9	0.25	<0.1	<0.2	0.15	0.3	0.012	0.013	
4	4	25-Feb-97	559	6.92	29	20	<0.5	85	10	8.4	4.32	324	<0.25	29	0.78	1.7	0.35	<0.1	<0.2	<0.02	0.2	0.013	0.005	
5	5	25-Feb-97	834	6.85	30	35.3	1.1	127	17	14.1	1.99	541	<0.25	18	0.07	0.6	0.38	<0.1	<0.2	0.26	0.2	0.063	0.01	
6	255	03-Apr-98	660	7.17	28	47.8	1.2	79	14	12.7	3.3	412	<0.5	19	0.22	0.2	0.13	<0.1	<0.2	<0.01	0.3	0.012	0.006	<0.009
7	7	25-Feb-97	646	6.9	29	9.8	<0.5	119	12	7	1.13	441	<0.25	14	0.25	1.2	0.02	<0.1	<0.2	0.03	0.3	0.007	0.003	
8	8	26-Feb-97	792	6.89	29	18.1	0.6	139	16	3.6	1.14	500	<0.25	18	0.14	0.9	0.1	<0.1	<0.2	0.07	0.3	0.008	0.005	
9	9	26-Feb-97	598	6.96	29	16.8	0.6	98	11	9.4	0.57	370	<0.25	18	0.67	0.3	0.49	<0.1	<0.2	<0.02	0.3	0.007	0.004	
10	10	26-Feb-97	665	7.17	29	50.4	1.1	83	11	9.6	0.85	419	<0.25	13	0.13	0.6	0.04	<0.1	<0.2	0.16	0.4	0.009	0.015	
11	11	26-Feb-97	680	7.05	30	29.9	1.3	98	16	6.9	0.85	424	<0.25	18	0.16	0.3	0.04	<0.1	<0.2	0.11	0.2	0.009	0.008	
12	12	26-Feb-97	173	6.4	31	6.6	<0.5	16	8.5	1.9	0.57	107	<0.25	15	0.12	0.5	<0.02	<0.1	<0.2	<0.02	0.2	0.003	0.003	
13	13	26-Feb-97	620	6.93	30	19.9	<0.5	100	11	7.8	3.61	402	<0.25	23	0.67	1.6	1.33	<0.1	<0.2	<0.02	0.3	0.009	0.003	
14	14	26-Feb-97	662	7.1	29	17.3	0.5	108	16	3.9	0.57	410	<0.25	18	0.09	1.7	0.87	<0.1	<0.2	0.03	0.2	0.004	0.002	
15	15	26-Feb-97	204	7.2	30	6.2	<0.5	7.4	5.6	2.2	<0.3	73	<0.25	11	0.04	0.2	<0.02	0.1	<0.2	<0.02	0.2	0.002	0.002	
16	16	26-Feb-97	150.8	7.06	28	8.5	1.5	14	5.2	1.6	5.55	78	<0.25	6.6	0.08	0.1	<0.02	<0.1	<0.2	<0.02	0.1	0.012	0.006	
17	258	03-Apr-98	699	7.17	29	30.2	0.6	105	14	4.7	<0.4	424	<0.5	14	0.24	0.2	<0.02	<0.1	<0.2	0.06	0.4	0.007	0.016	<0.009
18	18	27-Feb-97	158	6.35	28	4.9	8.5	11	3.3	1.5	4.62	93	<0.25	8.1	0.73	8.4	6.26	<0.1	<0.2	0.28	0.1	0.016	0.01	
19	19	27-Feb-97	59	5.85	29	49.6	0.8	113	59	87.7	2.28	18	0.73	15	0.27	1.4	4.03	<0.1	<0.2	<0.02	0	0.004	0.002	
20	20	27-Feb-97	503	6.41	30	42.6	5.6	49	10	151	2.57	114	<0.25	30	0.58	2	0.04	<0.1	<0.2	1.24	0.2	0.024	0.033	
21	21	27-Feb-97	44.4	6.55	33	4.9	1.4	2.3	0.6	2.6	1.42	63	0.49	15	0.1	0.2	0.03	0.1	<0.2	0.04	0.1	0.009	0.004	
22	242	01-Apr-98	647	7.31	32	42.5	9	88	6.2	13.4	1.6	400	0.62	11	0.82	0.1	0.62	<0.1	<0.2	1.8	0.3	0.013	0.023	<0.009
23	243	01-Apr-98	561	7.18	30	13.7	0.9	50	22	9.1	54.2	90	23.2	44	0.02	0.1	0.09	<0.1	<0.2	0.01	0.2	0.068	0.004	<0.009
24	244	01-Apr-98	423	7.42	29	17.3	1.4	36	22	2	3	262	<0.5	38	0.04	0.2	<0.02	<0.1	<0.2	<0.01	0.1	0.01	0.003	<0.009
25	25	27-Feb-97	303	7.2	31	14.3	3.2	24	23	1.5	2.27	219	<0.25	28	2.02	0.4	<0.02	<0.1	<0.2	0.21	0.2	0.016	0.009	
26	26	27-Feb-97	396	7.36	32	26	2.2	36	26	1.5	<0.3	300	<0.25	20	0.08	0.4	0.42	<0.1	<0.2	<0.02	0.4	0.003	0.003	
27	27	27-Feb-97	20.8	5.38	30	1.5	0.7	1	0.3	1.5	<0.3	49	<0.25	7.6	0.05	0.2	0.05	0.1	<0.2	<0.02	0.1	0.002	0.001	

Site ID	Chem ID	date sample	SEC	pH	T °C	Na	K	Ca	Mg	SO_4	Cl	HCO_3	NO_3-N	Si	Mn	Fe	Zn	Al	Pb	NH_4-N	F	Br	I	As
28	28	01-Mar-97	720	7.43	31	43.5	0.8	87	35	5	1.13	568	<0.25	15	0.01	0.1	1.12	<0.1	<0.2	<0.02	0.1	0.011	0.004	
29	29	01-Mar-97	547	7.54	31	29.2	0.9	73	17	4.3	0.56	397	<0.25	14	0.1	0.2	0.07	<0.1	<0.2	0.09	0.2	0.005	0.002	
30	253	02-Apr-98	67.7	6.78	32	5.67	3.7	1.9	1	1.7	2.5	32.1	<0.5	11	0.02	0.2	<0.02	1	<0.2	1.96	0.1	0.009	0.002	<0.009
31	251	02-Apr-98	241	7.51	31	11	4.8	7.8	3.2	2.2	15.2	23	4.79	9.7	0.04	0.2	<0.02	0.3	<0.2	0.07	0.1	0.067	0.006	<0.009
32	252	02-Apr-98	464	7.42	30	40.9	1.6	31	22	4.5	0.7	291	<0.5	25	0.01	0.1	<0.02	<0.1	<0.2	0.01	0.2	0.007	0.011	<0.009
33	33	01-Mar-97	19.8	6.01	29	2	0.6	2	0.4	1.7	0.84	11	<0.25	3.5	0.06	0.8	0.03	0.2	<0.2	<0.02	0	0.009	0.003	
34	34	03-Mar-97	805	7.2	29	97.6	0.9	52	27	16.5	0.84	544	<0.25	15	0.02	0.3	0.17	<0.1	<0.2	0.22	0.3	0.009	0.011	
35	35	03-Mar-97	1027	7	28	48.6	0.6	112	59	87.4	25.8	619	<0.25	15	0.27	1.4	4.05	<0.1	<0.2	0.02	0.2	0.018	0.003	
36	36	03-Mar-97	43.6	6.1	28	2.5	1.2	3.1	1.7	2	1.12	22	<0.25	6.4	0.14	0.6	0.07	<0.1	<0.2	0.04	0.1	0.006	0.004	
37	37	03-Mar-97	478	7.02	29	31.4	0.8	80	11	4.5	0.84	356	<0.25	19	0.08	0.5	0.05	<0.1	<0.2	<0.02	0.1	0.004	0.002	
38	38	03-Mar-97	566	7.47	29	127	2.2	19	4.7	7.4	2.52	405	<0.25	7.4	0.3	0.1	1.02	<0.1	<0.2	<0.02	0.2	0.014	0.004	
39	230	31-Mar-98	545	7.14	29	20.6	3.2	50	33	6.8	1.7	312	<0.5	23	0.1	0.1	<0.02	<0.1	<0.2	0.09	0.4	0.012	0.007	<0.009
40	40	04-Mar-97	2070	8.99	29	360	39	101	27	1020	42.7	110	<0.25	11	0.24	0.2	<0.02	<0.1	<0.2	1.23	1.4	0.2	0.031	
41	41	04-Mar-97	2150	11.4	29	241	57	157	0.3	664	11	358	0.48	14	0	0.1	<0.02	0.1	<0.2	0.68	1.4	0.089	0.027	
42	42	04-Mar-97	91.7	6.11	30	8.9	2.5	3.5	3.8	4.9	8.09	27	0.48	8.7	0.24	0.3	0.03	<0.1	<0.2	0.03	0.4	0.024	0.007	
43	43	06-Mar-97	221	6.4	28	17.8	0.7	25	13	5.3	0.83	166	<0.25	24	1.11	2.2	0.06	<0.1	<0.2	<0.02	0.3	0.009	0.002	
44	44	06-Mar-97	570	7.42	28	63.3	7.3	41	4.1	4.8	33.8	268	<0.25	9.9	1.99	0.5	0.04	0.1	<0.2	11.7	0.9	0.075	0.125	
45	45	06-Mar-97	558	8.19	28	96.5	2	26	11	8.4	6.26	336	<0.25	5.4	0.03	0.2	0.1	<0.1	<0.2	<0.02	0.8	0.014	0.01	
46	46	06-Mar-97	1210	7.35	28	223	6.2	25	46	10.4	1.52	892	<0.25	13	0.2	0.5	<0.02	<0.1	<0.2	0.03	0.9	0.014	0.006	
47	47	06-Mar-97	24.7	5.85	28	4.3	0.9	1	0.5	1.8	0.83	12	<0.25	7	0.05	0.2	0.03	0.1	<0.2	0.02	0.1	0.002	0.003	
48	48	06-Mar-97	507	7	28	16.7	0.9	92	7.2	15.9	12.8	297	1.9	12	0.04	0.5	0.08	<0.1	<0.2	<0.02	0.3	0.014	0.004	
49	49	07-Mar-97	683	7	29	47.7	1.1	82	29	6.6	2.22	517	<0.25	17	0.17	1.3	0.11	<0.1	<0.2	0.34	0.2	0.008	0.003	
50	256	03-Apr-98	819	7.01	29	19.6	0.9	141	13	26.7	1.5	512	<0.5	17	0.41	3.4	0.06	<0.1	<0.2	<0.01	0.2	0.004	0.002	<0.009
51	51	07-Mar-97	590	7.05	29	21.7	1.7	102	11	7.1	8.05	371	<0.25	12	0.47	0.8	2.67	<0.1	<0.2	<0.02	0.4	0.012	0.005	
52	52	07-Mar-97	507	7.14	29	17	0.6	93	8.4	4.3	0.55	354	<0.25	24	0.09	0.8	0.18	<0.1	<0.2	<0.02	0.2	0.003	0.003	
53	53	07-Mar-97	556	6.67	27	13.7	<0.5	108	11	5.6	1.37	402	<0.25	7.7	0.21	2.1	0.03	<0.1	<0.2	0.07	0.2	0.007	0.007	
54	54	07-Mar-97	32.3	6.06	27	2.4	0.6	2.7	0.9	1.9	1.64	14	<0.25	5.5	0.2	1.3	0.03	0.3	<0.2	0.34	0.1	0.011	0.003	
55	260	07-Apr-98	616	7.51	29	32.8	2	78	21	3.3	<0.4	419	<0.5	17	0.18	2.2	0.04	<0.1	<0.2	0.03	0.1	0.006	0.004	<0.009
56	246	01-Apr-98	152.7	8.4	30	8.8	4.6	20	0.6	1.4	1.1	89.8	<0.5	20	0.02	3.6	<0.02	0.2	<0.2	0.01	0.1	0.007	0.002	<0.009

Site ID	Chem ID	date sample	SEC	pH	T °C	Na	K	Ca	Mg	SO_4	Cl	HCO_3	NO_3-N	Si	Mn	Fe	Zn	Al	Pb	NH_4-N	F	Br	I	As
57	235	31-Mar-98	985	6.59	29	102	7.1	91	20	96.6	1.1	485	<0.5	14	0.55	0.1	<0.02	<0.1	<0.2	<0.01	0.7	0.009	0.015	<0.009
58	203	30-Jan-98	166.4	9.15	30	14.2	11	11	0.5	11.8	1.5	59	2.61	3.3	0.01	0.1	<0.02	0.5	<0.2	<0.01	0.4	0.012	0.01	<0.009
59	240	01-Apr-98	4580	7.07	31	586	7.8	449	190	2520	14.3	622	<0.5	12	2.36	1.1	0.02	0.1	<0.2	0.86	0.5	0.045	0.025	<0.009
60	238	01-Apr-98	1308	7.3	31	141	10	93	38	313	16.1	393	2.08	8	0.17	1.4	0.19	<0.1	<0.2	0.53	0.3	0.02	0.032	<0.009
61	237	01-Apr-98	116	6.41	28	5.8	1.4	4.7	2	13	1.3	28	<0.5	8.7	0.24	2.2	<0.02	<0.1	<0.2	2.03	0.1	0.014	0.014	<0.009
62	239	01-Apr-98	312	7.2	29	10.5	6.3	46	1.9	16.1	1.1	164	<0.5	18	0.06	0.2	<0.02	0.1	<0.2	0.26	0.4	0.012	0.021	<0.009
63	247	02-Apr-98	208	7.25	29	6.2	3.5	30	1.8	2.9	1.7	114	<0.5	17	0.05	0.2	0.04	0.2	<0.2	<0.01	0.3	0.013	0.002	<0.009
64	210	05-Feb-98	1318	6.95	33	143	24	98	63	379	10.8	522	3.28	12	4.06	1.8	<0.02	<0.1	<0.2	0.06	0.3	0.035	0.037	<0.009
65	211	18-Feb-98	1225	6.74	28	97.2	2.8	142	32	367	2.9	373	<0.5	11	0.29	0.4	<0.02	0.1	<0.2	1.19	0.2	0.018	0.008	<0.009
66	212	21-Feb-98	410	7.2	28	21.6	1.9	32	16	2.1	1.3	232	0.73	33	1.56	0.1	<0.02	<0.1	<0.2	3.75	0.6	0.006	0.004	<0.009
67	213	12-Mar-98	509	6.95	29	41.2	3	30	32	1.3	0.8	344	<0.5	29	0.03	0.2	<0.02	<0.1	<0.2	0.87	0.3	0.004	0.004	<0.009
68	214	13-Mar-98	405	7.28	29	49.8	2.4	25	12	2.9	<0.4	252	<0.5	14	0.53	0.1	<0.02	<0.1	<0.2	<0.01	0.3	0.006	0.002	<0.009
69	215	17-Mar-98	7160	7.03	29	1150	11	426	433	4330	43.5	768	<0.5	9.2	0.5	0.2	0.05	0.1	<0.2	0.74	0.2	<0.05	0.041	<0.009
70	216	17-Mar-98	10080	7.38	30	1950	13	310	307	5290	231	624	<0.5	6.5	0.38	0.4	0.03	0.1	<0.2	2.07	0.4	<0.05	0.42	<0.009
71	217	17-Mar-98	2010	4.31	29	206	6.5	72	93	1030	2.5	0	<0.5	57	5.59	1.7	0.67	11	<0.2	0.97	0.6	0.022	0.021	<0.009
72	218	17-Mar-98	201	6.22	29	27.2	0.9	12	2.7	12.8	1.6	112	<0.5	21	0.38	3.6	0.29	0.4	<0.2	0.86	0.3	0.012	0.009	0.014
73	219	19-Mar-98	588	6.68	29	16.2	0.8	98	9.4	4.5	1.3	358	<0.5	18	0.4	0.1	<0.02	<0.1	<0.2	0.1	0.3	0.012	0.005	<0.009
74	220	19-Mar-98	699	7.07	28	34.8	0.9	107	14	13.1	3.2	410	<0.5	17	0.04	1.5	<0.02	<0.1	<0.2	0.28	0.2	0.011	0.008	<0.009
75	221	20-Mar-98	1510	7.55	29	360	4.3	22	17	8.5	15.9	1036	<0.5	11	0.06	0.6	<0.02	0.3	<0.2	1.01	1.6	0.058	0.01	<0.009
76	222	21-Mar-98	513	8.13	30	40.8	2.5	55	12	6.5	12	280	<0.5	24	0.34	0.1	<0.02	0.1	<0.2	0.72	0.2	0.049	0.006	<0.009
77	223	24-Mar-98	583	7	32	63.6	1	47	16	3.4	1	324	<0.5	15	0.23	0.1	<0.02	<0.1	<0.2	0.2	0.2	0.007	0.004	<0.009
78	224	25-Mar-98	1149	7.47	28	239	1	20	8.1	122	39.9	458	<0.5	8	0.07	0.1	<0.02	<0.1	<0.2	0.19	0.7	0.11	0.14	<0.009
79	225	26-Mar-98	558	7.15	28	74.6	0.8	37	13	12.2	2.9	302	<0.5	14	0.4	0.2	<0.02	<0.1	<0.2	0.42	0.2	0.013	0.009	<0.009
80	226	27-Mar-98	965	7.26	28	141	3.5	43	31	11.6	5	622	<0.5	16	0.17	0.1	<0.02	<0.1	<0.2	0.09	0.2	0.012	0.003	<0.009
81	227	28-Mar-98	905	6.93	29	54.1	1.2	115	25	18.5	1.4	563	<0.5	14	0.17	0.3	<0.02	<0.1	<0.2	0.48	0.3	0.019	0.024	<0.009
82	228	31-Mar-98	553	6.64	28	87.1	2.6	20	12	5.7	3.3	348	<0.5	7.8	1.49	2.4	0.02	0.1	<0.2	0.27	0.3	0.029	0.024	<0.009
83	229	31-Mar-98	399	7.09	29	6	0.5	79	1	1.4	0.7	217	<0.5	12	0.06	0.6	<0.02	0.1	<0.2	<0.01	0.3	0.003	0.002	<0.009
84	231	31-Mar-98	91	6.83	30	3.5	3.4	9.1	0.6	1.5	<0.4	43.4	<0.5	12	0.01	0.1	<0.02	<0.1	<0.2	0.5	0	0.009	0.001	<0.009
85	232	31-Mar-98	413	7.58	30	47.2	1.6	11	23	8.9	2	271	<0.5	13	0.13	0.1	<0.02	<0.1	<0.2	<0.01	0.8	0.008	0.003	<0.009

Site ID	Chem ID	date sample	SEC	pH	T °C	Na	K	Ca	Mg	SO_4	Cl	HCO_3	NO_3-N	Si	Mn	Fe	Zn	Al	Pb	NH_4-N	F	Br	I	As
86	233	31-Mar-98	948	7.32	29	164	26	23	1.8	274	10.5	134	5.93	7.3	0.03	0.2	<0.02	0.2	<0.2	<0.01	0.9	0.058	0.043	<0.009
87	234	31-Mar-98	410	7.15	29	55.6	24	18	0.6	53.5	2.4	141	2.76	6.4	0.02	0.1	<0.02	0.3	<0.2	<0.01	1	0.028	0.041	<0.009
88	236	31-Mar-98	313	6.79	29	19.5	1.6	24	13	7.2	1.3	176	0.72	10	1.65	0.2	<0.02	<0.1	<0.2	<0.01	0.6	0.008	0.004	<0.009
89	241	01-Apr-98	48.2	6.78	29	3.8	1	1.5	0.6	2.5	2.1	11.2	<0.5	10	0.06	0.2	<0.02	0.5	<0.2	0.48	0.1	0.006	0.002	<0.009
90	245	01-Apr-98	192.8	8.21	29	7.1	9.8	22	1.9	8.9	2.2	90.3	0.97	6.7	0.01	0.2	0.04	0.4	<0.2	0.61	0.5	0.011	0.013	<0.009
91	248	02-Apr-98	518	7.61	30	69.5	3.6	18	15	1.4	<0.4	305	<0.5	17	0.05	0.2	<0.02	<0.1	<0.2	0.08	0.2	0.004	0.003	<0.009
92	249	02-Apr-98	546	7.67	29	52.6	2.7	22	33	1.2	<0.4	358	<0.5	30	0.03	0.2	1.22	<0.1	<0.2	<0.01	0.4	0.004	0.005	<0.009
93	250	02-Apr-98	6470	7.44	30	1730	10	11	2.3	1.1	767	3199	<0.5	5.5	0.05	0.3	<0.02	0.1	<0.2	0.03	3.2	2.56	0.14	<0.009
94	257	03-Apr-98	532	6.93	29	15.2	1.5	81	10	7	3.3	319	<0.5	18	0.76	0.2	<0.02	<0.1	<0.2	<0.01	0.4	0.011	0.005	<0.009
95	259	03-Apr-98	915	7.05	29	74.2	1.2	96	27	21.7	0.7	607	<0.5	15	0.07	0.3	<0.02	<0.1	<0.2	0.28	0.4	0.02	0.032	<0.009

Data for seasonal groundwater quality survey of Oju/Obi (mg.ℓ$^{-1}$)

Chem ID	Site ID	Date	SEC	pH	T °C	Na	K	Mg	Ca	SO_4	Cl	HCO_3	NO_3-N	Si	Mn	Fe	Zn	Al	NH_4	F	Br	I	As
254	1	03/04/98	583	7.2	28	30	0.6	20	69.2	4	2.7	395	<0.5	19.6	0.682	0.9	<0.02	<0.1	0.03	0.14	0.006	0.0012	<0.009
1	1	25/02/97	592	7	29.6	28.5	0.5	19.3	68.7	4.8	1.84	368	<0.25	18.8	0.7	1.72	0.19	<0.1	0.03	0.17	0.0086	0.0019	
312	1	02/10/98	123.3	5.31	29.6	6.4	0.5	2.96	10.2	1.73	2.9	46.3	1.4	6.9	0.09	2.45	2.04	0.7	0.06	0.08	0.009	0.0013	
107	1	26/11/97	506	6.79	29.6	19.4	0.5	18.2	63.5	14.1	6.5	302	<0.2	10.2	0.833	2.08	0.03	<0.1	<0.01	0.17	0	0.001	
255	6	03/04/98	660	7.17	28	47.8	1.2	14.1	78.6	12.7	3.3	412	<0.5	18.8	0.222	0.2	0.13	<0.1	<0.01	0.29	0.012	0.0059	<0.009
308	6	02/10/98	644	6.54	28.7	36.3	0.87	14.4	90.6	15.2	4.1	373	<0.2	19.7	0.39	0.53	0.11	0.6	<0.01	0.25	0.017	0.0069	
6	6	25/02/97	644	7.05	28.9	45.6	0.9	13.8	80.6	13.1	2.86	414	<0.25	19.2	0.23	0.2	0.03	<0.1	<0.02	0.29	0.0131	0.0053	
108	6	26/11/97	603	7.11	29	37.2	1	13.6	88.5	14.2	3.7	397	<0.2	17.7	0.306	0.19	0.15	<0.1	<0.01	0.28	0	0.0032	
258	17	03/04/98	699	7.17	29	30.2	0.6	14	105	4.7	0.4	424	<0.5	13.6	0.243	0.2	<0.02	<0.1	0.06	0.39	0.007	0.0158	<0.009
311	17	02/10/98	141.5	6.4	28.5	4.6	0.5	2.89	19	1.15	0.4	82.9	<0.2	7.7	0.01	0.04	0.05	0.7	<0.01	0.12	0.007	0.0021	
17	17	26/02/97	619	7.12	32.4	24.8	1.4	14.5	94.7	3.3	2	434	<0.25	13.1	1.26	0.2	<0.02	<0.1	1.4	0.4	0.0131	0.0211	
110	17	26/11/97	95.8	7.76	28.1	4.7	0.5	2.6	9.71	1.2	0.4	50.7	<0.2	7	0.178	0.19	<0.02	0.2	<0.01	0.1	0	0.0065	
20	20	27/02/97	503	6.41	29.5	42.6	5.6	10.2	49.2	151	2.57	114	<0.25	30.1	0.579	2.04	0.04	<0.1	1.24	0.18	0.0241	0.0327	
101	20	26/11/97	89.2	6.86	28.8	2	0.7	0.7	12.8	1.7	1.2	41.2	0.6	7.6	0.028	0.11	<0.02	<0.1	<0.01	0.06	0	0.001	

Chem ID	Site ID	Date	SEC	pH	T °C	Na	K	Mg	Ca	SO_4	Cl	HCO_3	NO_3-N	Si	Mn	Fe	Zn	Al	NH_4	F	Br	I	As
301	20	29/09/98	39.4	5.73	29	2.7	0.53	0.52	3.24	1.03	1.2	5.12	0.9	7.1	0.01	0.04	0.04	0.8	<0.01	0.01	0.003	0.0006	
242	22	01/04/98	647	7.31	32	42.5	9	6.2	87.6	13.4	1.6	400	0.62	11.1	0.816	0.09	0.62	<0.1	1.8	0.27	0.013	0.0233	<0.009
22	22	27/02/97	382	7.28	31.3	34.8	7.3	3.2	56	10.4	0.85	241	<0.25	11.9	0.024	0.14	0.05	<0.1	0.04	0.17	0.0096	0.01	
100	22	26/11/97	190.4	7.27	27.9	3.2	1.3	0.9	29.4	1.3	0.9	75.6	0.6	8.3	0.005	0.16	0.12	0.5	<0.01	0.08	0	0.002	
302	22	29/09/98	213	6.37	29	5.3	1.51	1.19	36.7	1.5	1.2	120	0.8	11.5	0.003	0.06	0.05	0.7	<0.01	0.08	0.004	0.0015	
243	23	01/04/98	561	7.18	30	13.7	0.9	22.1	50.2	9.1	54.2	90	23.2	44.4	0.017	0.1	0.09	<0.1	<0.01	0.19	0.068	0.0039	<0.009
23	23	27/02/97	444	7	28.9	13.2	0.9	21.1	48.5	10	15.9	71	19.9	43.2	0.016	0.15	0.04	<0.1	0.03	0.14	0.112	0.0041	
102	23	26/11/97	484	7.14	28.4	12.3	0.8	19.8	45.4	8.3	48.9	68.3	19.1	43	0.008	0.11	0.08	<0.1	<0.01	0.18	0	0.0042	
304	23	29/09/98	478	6.26	28.9	16.3	0.99	18.4	48.2	8.43	47.8	68.3	16.7	44.3	0.003	0.04	0.2	0.6	<0.01	0.13	0.07	0.0043	
244	24	01/04/98	423	7.42	29	17.3	1.4	22.2	36	2	3	262	<0.5	38.1	0.038	0.23	<0.02	<0.1	<0.01	0.14	0.01	0.0029	<0.009
24	24	27/02/97	333	7.48	29.5	16.8	1.2	21.1	33.9	2.4	2.27	222	<0.25	37.3	0.039	0.17	0.08	<0.1	<0.02	0.13	0.0064	0.0039	
103	24	26/11/97	276	7.08	29.1	10.5	0.6	11.9	26	2.5	7.6	112	1.6	46	0.015	0.1	0.12	<0.1	<0.01	0.16	0	0.0042	
305	24	29/09/98	285	6.1	29.3	12	0.56	13.1	28.1	1.86	2.9	141	3	52.3	0.01	0.03	0.04	0.7	<0.01	0.14	0.015	0.0031	
253	30	02/04/98	67.7	6.78	32	5.67	3.7	1	1.88	1.7	2.5	32.1	<0.5	10.8	0.022	0.2	<0.02	1	1.96	0.06	0.009	0.0017	<0.009
318	30	12/10/98	18.4	5.65	26	2.5	0.5	0.36	1.46	0.63	0.4	5.1	<0.2	4.3	0.01	0.2	<0.02	0.7	<0.01	0.02	0.005	0.0015	
30	30	01/03/97	30.2	5.5	28.3	3.9	0.9	0.3	0.96	1.4	0.84	10	<0.25	9.3	0.016	0.21	0.03	0.3	<0.02	0.03	0.007	0.0022	
106	30	26/11/97	21.9	6.05	30.1	3.2	1	0.3	0.63	1.1	0.5	8	<0.2	7.9	0.024	0.15	<0.02	<0.1	<0.01	0.01	0	0.0022	
251	31	02/04/98	241	7.51	31	11	4.8	3.2	7.78	2.2	15.2	23	4.79	9.7	0.035	0.19	<0.02	0.3	0.07	0.11	0.067	0.0056	<0.009
306	31	29/09/98	155.1	5.33	30.2	12.1	7.53	2.49	7.45	5.06	14.6	9.5	5.8	5.2	0.01	0.03	<0.02	0.6	<0.01	0.02	0.023	0.0021	
31	31	01/03/97	164	6.4	29.4	10.4	5.1	2.6	6.21	2.9	14.1	9	5.87	6.2	0.02	0.15	<0.02	<0.1	<0.02	0.04	0.028	0.0047	
104	31	26/11/97	109.8	6.38	29.2	8.9	5.3	1.6	4.68	5.6	10.7	15.1	2.2	4.8	0.014	0.1	<0.02	<0.1	<0.01	0.04	0	0.0025	
252	32	02/04/98	464	7.42	30	40.9	1.6	21.5	31.2	4.5	0.7	291	<0.5	25.4	0.006	0.12	<0.02	<0.1	<0.01	0.24	0.007	0.0105	<0.009
307	32	29/09/98	350	7.26	31	20.9	1.42	18.8	30.8	2.79	0.4	207	<0.2	31.1	0.1	0.03	<0.02	0.6	<0.01	0.23	0.012	0.0144	
32	32	01/03/97	336	7.42	29.1	21.3	1.4	19.7	31.6	4.6	0.99	231	<0.25	27.3	0.007	0.17	<0.02	<0.1	<0.02	0.23	0.006	0.009	
105	32	26/11/97	364	7.32	29	22	1.5	18.8	30	3.8	0.5	229	<0.2	26.6	0.004	0.09	<0.02	<0.1	<0.01	0.22	0	0.0038	
230	39	31/03/98	545	7.14	29	20.6	3.2	32.5	49.7	6.8	1.7	312	<0.5	22.6	0.097	0.11	<0.02	<0.1	0.09	0.38	0.012	0.0072	<0.009
321	39	12/10/98	121	5.63	28	6.5	3.54	4.91	8.05	1.86	4.1	29.3	2.6	6	0.03	0.28	0.04	1.4	<0.01	0.08	0.014	0.0029	
39	39	04/03/97	485	7.23	27.8	20	3.8	30.3	47.1	7.6	1.67	344	<0.25	21.2	0.266	0.14	0.03	<0.1	<0.02	0.44	0.013	0.0059	
112	39	27/11/97	344	6.94	28	12.8	4.3	19.6	28.6	4.7	2.7	214	1	11.5	0.128	0.1	<0.02	<0.1	0.16	0.25	0	0.0055	

Chem ID	Site ID	Date	SEC	pH	T °C	Na	K	Mg	Ca	SO_4	Cl	HCO_3	NO_3-N	Si	Mn	Fe	Zn	Al	NH_4	F	Br	I	As
256	50	03/04/98	819	7.01	29	19.6	0.9	13.2	141	26.7	1.5	512	<0.5	17.1	0.406	3.36	0.06	<0.1	<0.01	0.2	0.004	0.0019	<0.009
50	50	07/03/97	736	6.86	29.2	18.8	0.9	14.4	144	28.7	1.38	483	<0.25	16.8	0.437	3.05	0.04	<0.1	<0.02	0.19	0.004	0.0017	
309	50	02/10/98	560	6.43	30	14.5	0.6	8.17	92.7	16.8	1.5	307	<0.2	13.4	0.27	4.98	0.09	0.6	<0.01	0.16	0.007	0.0018	
109	50	26/11/97	733	6.97	29.2	17.6	1	11.8	136	27.1	1	468	<0.2	14.5	0.329	1.17	0.22	<0.1	0.04	0.22	0	0.0017	
260	55	07/04/98	616	7.51	29	32.8	2	20.5	77.6	3.3	0.4	419	<0.5	17.1	0.183	2.17	0.04	<0.1	0.03	0.12	0.006	0.0037	<0.009
55	55	10/03/97	522	6.67	28.9	27.3	1.3	17.1	73.5	3.2	0.82	390	<0.25	14.5	0.127	0.32	0.66	<0.1	<0.02	0.18	0.007	0.0028	
317	55	10/10/98	63.9	4.84	28	2.6	0.5	0.76	8.3	0.76	0.4	24.1	<0.2	7.3	0.03	0.22	0.05	0.7	<0.01	0.04	0.002	0.001	
326	55	17/10/98	29.8	4.85	28.1	2.2	0.5	0.55	3.45	0.87	0.4	0.1	<0.2	5.4	0.02	0.06	0.03	0.7	<0.01	0.09	0.003	0.001	
111	55	26/11/97	27	5.9	28.5	1.7	0.5	0.4	2.44	1.1	0.4	10.5	<0.2	6.7	0.026	0.17	0.06	0.2	<0.01	0.02	0	0.0012	
201	56	30/01/98	116.9	8.88	30	4.4	3.9	0.3	18	3	3.5	66	<0.5	6.8	0.004	0.2	<0.02	0.5	<0.01	0.18	0.013	0.0065	<0.009
246	56	01/04/98	152.7	8.4	30	8.8	4.6	0.6	20.4	1.4	1.1	89.8	<0.5	19.6	0.018	3.55	<0.02	0.2	<0.01	0.08	0.007	0.0021	<0.009
202	57	30/01/98	773	7.45	29	84.7	7.8	16.1	76.7	82.5	2.2	383	<0.5	12.4	0.498	0.09	0.12	<0.1	<0.01	0.68	0.011	0.0088	<0.009
235	57	31/03/98	985	6.59	29	102	7.1	19.9	90.6	96.6	1.1	485	<0.5	14.1	0.554	0.11	<0.02	<0.1	<0.01	0.69	0.009	0.0147	<0.009
205	59	05/02/98	3910	7	28	557	9.9	173	454	2410	12.8	619	<0.5	12	2.53	0.97	0.92	<0.1	0.98	0.65	0.047	0.02	<0.009
240	59	01/04/98	4580	7.07	31	586	7.8	190	449	2520	14.3	622	<0.5	11.9	2.36	1.14	<0.02	<0.1	0.86	0.48	0.045	0.0253	<0.009
206	60	05/02/98	1170	7.2	31	188	9.2	15.5	67.3	288	22.3	346	0.58	4.4	0.372	4.01	0.13	<0.1	0.59	0.24	0.033	0.0071	<0.009
238	60	01/04/98	1308	7.3	31	141	10.3	37.5	93	313	16.1	393	2.08	8	0.167	1.39	0.19	<0.1	0.53	0.34	0.02	0.0322	<0.009
207	61	05/02/98	40.3	6.02	28	4.1	1.1	0.7	2.23	4.2	2.6	11.4	0.52	7.3	0.06	0.64	0.04	0.2	0.57	0.03	0.01	0.0136	<0.009
237	61	01/04/98	116	6.41	28	5.8	1.4	2	4.66	13	1.3	28	<0.5	8.7	0.238	2.24	<0.02	<0.1	2.03	0.07	0.014	0.0135	<0.009
208	62	05/02/98	204	6.76	29	6.8	7.6	1.2	32.1	5.5	0.6	131	<0.5	8.2	0.012	0.67	<0.02	<0.1	<0.01	0.15	0.004	0.005	<0.009
239	62	01/04/98	312	7.2	29	10.5	6.3	1.9	45.6	16.1	1.1	164	<0.5	17.6	0.064	0.17	<0.02	<0.1	0.26	0.38	0.012	0.0214	<0.009
209	63	05/02/98	79.1	6.23	29	3.7	2.7	1	7.73	1.7	2.7	30.9	1.51	10.3	0.061	0.18	0.12	0.3	0.05	0.06	0.012	0.0012	<0.009
247	63	02/04/98	208	7.25	29	6.2	3.5	1.8	29.7	2.9	1.7	114	<0.5	16.6	0.049	0.21	0.04	0.2	<0.01	0.26	0.013	0.0015	<0.009
212	66	21/02/98	410	7.2	28	21.6	1.9	16	31.7	2.1	1.3	232	0.73	33.3	1.56	0.12	<0.02	<0.1	3.75	0.63	0.006	0.0037	<0.009
320	66	12/10/98	15.76	4.67	29.2	1.8	0.5	0.3	1.32	0.67	0.4	2	<0.2	5.7	0.02	0.16	<0.02	1	<0.01	0.03	0.001	0.0007	
214	68	13/03/98	405	7.28	29	49.8	2.4	11.6	24.5	2.9	0.4	252	<0.5	14.3	0.525	0.1	<0.02	<0.1	<0.01	0.29	0.006	0.0022	<0.009
322	68	13/10/98	78.6	5.31	28.6	11.4	1.27	2.29	5.12	0.84	0.4	49.7	<0.2	11.8	0.15	0.08	<0.02	0.8	<0.01	0.07	0.001	0.001	
215	69	17/03/98	7160	7.03	29	1150	10.7	433	426	4330	43.5	768	<0.5	9.2	0.497	0.16	0.05	<0.1	0.74	0.2	0.05	0.0406	<0.009
325	69	15/10/98	145.8	6.14	29	13	0.64	4.05	9.9	27.9	0.4	71.2	<0.2	7	0.02	0.06	0.06	0.8	<0.01	0.02	0.002	0.001	

Chem ID	Site ID	Date	SEC	pH	T °C	Na	K	Mg	Ca	SO_4	Cl	HCO_3	NO_3-N	Si	Mn	Fe	Zn	Al	NH_4	F	Br	I	As
216	70	17/03/98	10080	7.38	30	1950	13.1	307	310	5290	230.9	624	<0.5	6.5	0.38	0.43	0.03	<0.1	2.07	0.36	0.05	0.42	<0.009
324	70	15/10/98	1155	6.65	29.3	220	2.69	11.7	13.3	429	2.9	100	<0.2	9.5	0.06	0.04	0.09	0.7	<0.01	0.38	0.013	0.0041	
217	71	17/03/98	2010	4.31	29	206	6.5	93.3	72.1	1030	2.5	0	<0.5	56.9	5.59	1.69	0.67	11.2	0.97	0.59	0.022	0.0211	<0.009
323	71	15/10/98	26.5	4.5	28.1	3.1	0.5	0.33	0.98	2.51	0.4	2.9	<0.2	5.3	0.01	0.05	0.04	0.8	<0.01	0.04	0.002	0.0006	
224	78	25/03/98	1149	7.47	28	239	1	8.1	20.3	122	39.9	458	<0.5	8	0.068	0.12	<0.02	<0.1	0.19	0.69	0.11	0.14	<0.009
315	78	03/10/98	255	5.8	27.8	28.1	2.43	1.79	3.93	12.2	8.6	36.6	<0.2	4.4	0.03	0.18	0.07	1	<0.01	0.13	0.034	0.0198	
316	78	03/10/98	653	6.55	28.7	135	2.63	5.52	13.7	62.1	28.9	300	<0.2	5.7	0.34	0.05	0.03	0.8	<0.01	0.44	0.101	0.1	
225	79	26/03/98	558	7.15	28	74.6	0.8	12.8	36.8	12.2	2.9	302	<0.5	14	0.399	0.18	<0.02	<0.1	0.42	0.19	0.013	0.0086	<0.009
314	79	03/10/98	41.1	4.79	27.8	4.2	0.5	0.79	2.33	0.5	4.7	2.4	<0.2	4.5	0.04	0.1	0.51	0.7	<0.01	0.03	0.011	0.0157	
226	80	27/03/98	965	7.26	28	141	3.5	31	43	11.6	5	622	<0.5	16.2	0.169	0.13	<0.02	<0.1	0.09	0.24	0.012	0.0032	<0.009
319	80	12/10/98	420	6.26	28.5	44	2.58	16.1	28.8	2.07	8	234	<0.2	12.8	0.3	0.09	<0.02	0.8	<0.01	0.13	0.003	0.0024	
257	94	03/04/98	532	6.93	29	15.2	1.5	10.4	80.6	7	3.3	319	<0.5	18	0.763	0.16	<0.02	<0.1	<0.01	0.4	0.011	0.0051	<0.009
310	94	02/10/98	633	6.57	29.3	22.7	2.12	11.7	96.4	9.93	2.5	344	<0.2	18	0.33	0.1	0.05	0.6	<0.01	0.33	0.008	0.0056	
259	95	03/04/98	915	7.05	29	74.2	1.2	27	95.9	21.7	0.7	607	<0.5	14.6	0.067	0.31	<0.02	<0.1	0.28	0.35	0.02	0.0317	<0.009
313	95	03/10/98	662	6.39	28.6	44.3	0.73	19.3	78.1	11	4.9	434	<0.2	12.7	0.12	0.22	0.46	0.6	0.35	0.28	0.019	0.0184	

Appendix 4: A data form for interpreting the bailer test

10 minute bailer test datasheet

Note: **always measure all waterlevels (including rest-water-level) from the same point**

Community:

Borehole Number:

Screen diameter:

Drilled diameter:

GPS:

rest water level:

Gravel Pack Yes / No

Number of bails:

period of pumping (mins):
(should be about 10 minutes)

time since pumping stopped	water-level	time since pumping stopped	water-level	time since pumping stopped	water-level	time since pumping stopped	water-level

Interpreting the 10 minute bailer test

To interpret the bailer test, follow the steps below

Pumping rate in m^3/d = $\dfrac{\text{volume of bailer (in } m^3\text{) x number of bails}}{\text{time of pumping in days}}$ ☐

Maximum drawdown

A = the earliest reading of water level after pumping stops ☐

B = the rest water level ☐

Maximum drawdown = A - B ☐

Time for 50% recovery (t_{50})

divide the maximum drawdown by 2 ☐

add the rest water level ☐

t_{50} is the time at which the water level recovers to the level above ☐
(from data overleaf)

Time for 75% recovery (t_{75})

divide the maximum drawdown by 4 ☐

add the rest water level ☐

t_{75} is the time at which the water level recovers to the level above ☐
(from data overleaf)

Estimate the effective diameter of the borehole.
If it is open hole then this will be the drilled diameter.

If the borehole is screened and gravel packed then the effective diameter will be somewhere between the screen diameter and the drilled diameter. (Generally closer to the screen diameter). ☐

Find the pumping rate and the diameter of the borehole in the table below.

The maximum drawdown, t_{50} and t_{75} for the test must all be **less** than that shown in the table.
If they are all much greater, then the borehole will have problems sustaining a handpump
If they are all much less than the table, then the borehole will sustain a handpump
If some are greater, and some are less then a proper pumping test must be carried out.

		10 m³/d	15 m³/d	20 m³/d	25m³/d	30 m³/d
4 inch	Max drawdown	3.5	5.3	7.1	8.8	10.6
	t50 (mins)	6	6	6	6	6
	t75 (mins)	14	14	14	14	14
5 inch	Max drawdown	2.9	4.3	5.7	7.1	8.5
	t50 (mins)	9	9	9	9	9
	t75 (mins)	21	21	21	21	21
6 inch	Max drawdown	2.3	3.4	4.6	5.7	6.9
	t50 (mins)	12	12	12	12	12
	t75 (mins)	28	28	28	28	28
8 inch	Max drawdown	1.5	2.3	3.1	3.8	4.6
	t50 (mins)	19	19	19	19	19
	t75 (mins)	46	46	46	46	46