Clay, Conductivity, and Rural Water Supplies

A hydrogeological investigation

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Abstract

In regions where the underlying geology is comprised of few aquifers other sources of groundwater must be tapped into. Mudstones and clay-bearing rocks are traditionally thought of as being aquicludes. Mudstones and clay-bearing rocks, however, can contain groundwater in robust fracture networks. The main control as to whether or not these fractures will develop is the clay type. Smectite clay is poor at developing robust fracture networks, whereas illite clays can support them. EM34 surveying is a tool used by geophysicists which determines the conductivity of the subsurface. Borehole, EM34, and clay analysis data, taken by the British Geological Survey in a region of Nigeria, has been used to identify a relationship between clay type and measured conductivity. A strong, linear, positive correlation has been found between measured conductivity and smectite content in the rock. From this, rural groundwater potential has been inferred by counter-intuitively coming to the conclusion that areas of low conductivity are likely to hold groundwater in clay-bearing formations. The findings of the experimental data have been tested against theoretical models- the Bussian and Revil and Glover equations. The implications of this research within the WATSAN sector have been explored. Furthermore, information has been presented on the usefulness of this research in other sectors such as the nuclear industry, engineering applications, geohazards and remote sensing.

Executive Summary

It is acknowledged that in many water-stressed areas, particularly in Sub-Saharan Africa (SSA) and Southern Asia, sustainable rural water supplies will be key when it comes to meeting both present and future demands for clean and plentiful water. *WateraAid* estimates that 768 million people globally do not have access to safe water, *WaterAid*, (2013). This hydrogeologically orientated project focuses on how to improve successful siting of boreholes by using geophysics data to infer where groundwater is likely to be plentiful enough to sustain rural water supplies.

Hydrogeology of Africa and Mudstone Environments

The hydrogeology of SSA can be categorised into four main hydrogeological domains: crystalline basement rocks, volcanic rocks, consolidated sedimentary rocks, and unconsolidated sedimentary rocks. Each of these different types of formation has different porosities and permeabilities, resulting in groundwater being more abundant and accessible in some formations over others. Mudstones and clay-bearing formations are particularly poor aquifers. Clays have high porosities (spaces and voids for water to fill) but low permeabilities (the spaces and voids are not well interconnected). As such they are particularly poor for sustaining rural groundwater supplies. There are, however, two common ways in which these sorts of rocks can have acceptable transmissivities. The first of these is the presence of other subordinate lithologies (rock types) within the main clayey mudstone formation; for example, having a small sandstone unit within the surrounding clay. Secondly, is the presence of interconnected fracture networks which allow the groundwater to flow through the clayey mudstones freely, MacDonald et.al., (2005). It must be stressed that many demographic regions across the globe lie on top of clayey mudstone formations; therefore it is essential that any subordinate lithologies or fracture networks can be detected if successful siting of boreholes is to take place. In regions of water-scarcity these subordinate lithologies and fracture networks must be tapped into.

The clay type strongly determines whether or not fracture networks will exist. Smectite clays are soft, plastic weak, and can be easily deformed; consequently any fractures which are created within smectite clays will easily be squashed away by the pressure of the overlying rocks. Illite clays, on the other hand, are notably stronger and more resilient to deformation; therefore robust water-bearing fracture networks can exist in illite clays. Smectite turns into illite when it is exposed to heat and pressure- this reaction is irreversible. Exposure of rocks to heat and pressure is more commonly known as metamorphism. The transition of smectite to illite takes place just before metamorphism during a process of diagenesis.

A common way of resolving sub-surface features is by employing a geophysical surveying technique called EM34. EM34 is a type of conductivity surveying. Coils generate alternating magnetic fields which then induce alternating currents within the ground. Comparing the signal from the source coil and the signal from the receiver coil enables a value of conductivity of the ground to be determined. It is a type of geophysical surveying commonly used in developing countries as it is relatively cheap, simple to use, and easy to interpret the data.

The Problem

The problem which this dissertation is trying to solve can be summarised as:

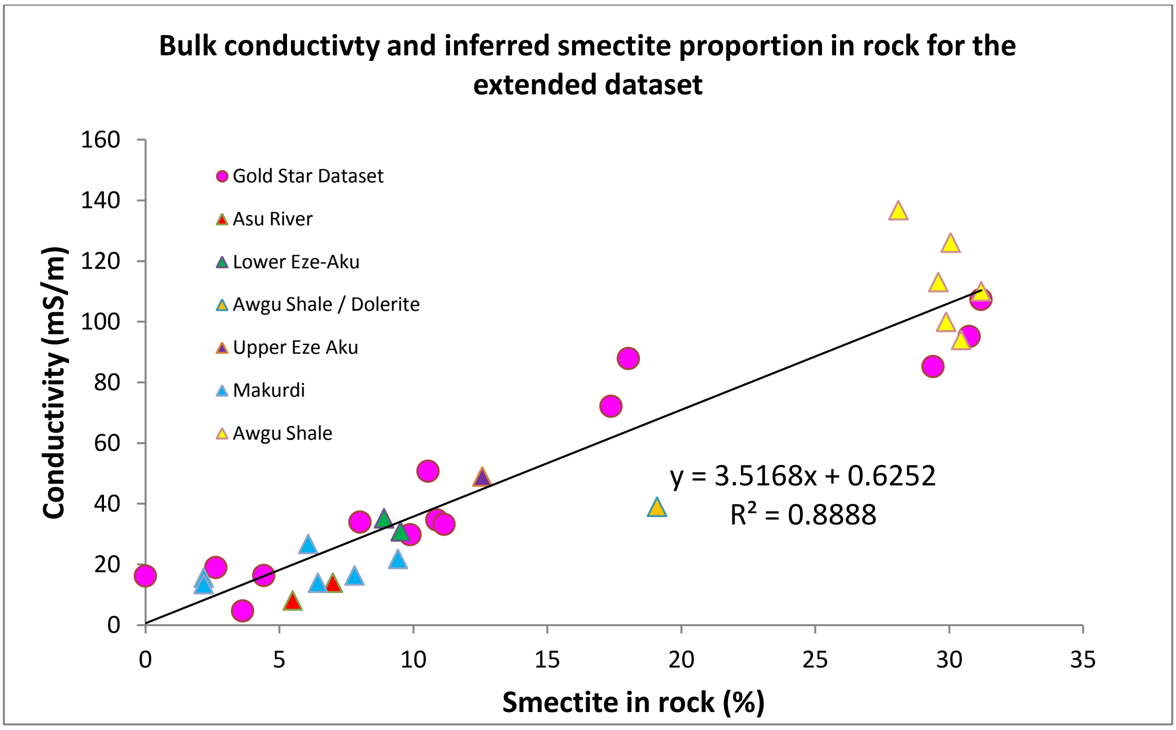
Can geophysical techniques, notably EM34 ground conductivity surveying, be used to distinguish between different types of clays in the ground?

Many scientists have postulated that such a relationship does exist and many have tried to quantify it. The first scientist who noted that a rock's measured conductivity is proportional to its physical properties was Archie, (1942) - he stated that a rock's conductivity is linked to its porosity and the conductivity of the pore water within (in most rocks the main conductors are the ions within the actual pore water – it is for this reason why high measured conductivity values imply groundwater abundance). Whilst this relationship has been used extensively by the hydrocarbon industry with huge success is does not work for clay-rich formations. The reason for this is because clay minerals/grains have a very high surface conductivity- this refers to currents which travel along grain surfaces. Surface conductivity is linked strongly to a property known as 'Cation Exchange Capacity' (CEC) which refers to how well positive ions can move along the surface of a mineral, Wilson, (1994). Because clays have such a strong CEC (due to them being highly negatively charged) they also have a high surface conductivity. With clays the effect of the surface conductivity often dwarfs the signal of the pore water conductivity, therefore both the surface and pore water conductivity must be taken into consideration.

Data Processing, Analysis and Interpretation

If a relationship between clay type and conductivity exists then it should be possible to determine different clay types in the ground by using EM34 data. Alan MacDonald of the British Geological Survey (BGS) has completed extensive EM34 surveying and detailed clay analysis of fifty boreholes in a water-stressed area in South-Eastern Nigeria. This large and comprehensive dataset was used to try to identify if a relationship between clay type and conductivity exists.

Out of the fifty boreholes drilled in the region seventeen of them underwent a process of clay mineralogy analysis at the BGS's laboratories in Keyworth, Nottingham. This enables one to use rock samples taken from different depths down boreholes to determine the amount and the type of clay present. This dataset was used to calculate the average smectite proportion in the rocks down-borehole. Each borehole was also sited on an area which had been surveyed by EM34 equipment. Consequently, every borehole has an associated measured bulk conductivity value. Knowing both this measured conductivity value and the amount of smectite present in each borehole it was possible to plot the two against one another. This dataset was referred to as the 'gold-star' dataset as each datum has both a value of measured conductance and a value of measured smectite proportion. For the other boreholes which had not undergone clay mineralogy analysis, estimations were made of the likely smectite proportion in the rocks by using lithological logs of the rock types down the boreholes and data from the gold-star boreholes. This lead to the creation of an extended dataset which could be used to determine a relationship between smectite content in the rock and measured conductivity. The figure below is the graph which represents the relationship.



The data-points are colour coded into the formations which they are part of across the region. As can be seen, a positive linear relationship does exist. A variance value of 0.89 represents a good fit to the data. The equation of the line suggests that a rock composed entirely of smectite would have a conductivity of 352 mS/m and a rock which has no smectite present whatsoever would have a conductivity of 0.63 mS/m. From the figure above, and by knowing the transmissivities of each of the boreholes in each of the different formations, the following new guiding principles have been developed for mudstone/clay-rich formations:

- Conductivities in the region of 0-40 mS/m are likely to suggest smectite proportions of 0-11%. It is therefore likely that such areas will be illite rich and have high transmissivities suitable for rural water supplies.
- Conductivities in the region of 40-90 mS/m are likely to suggest smectite proportions of 11-27%. Such areas will have moderate rural groundwater potential.
- Conductivities in the region of 90+ mS/m are likely to suggest smectite proportions >27%. Such areas will have poor rural groundwater potential.

Comparison with Theoretical Models

The next stage was to compare how the findings from this experimental data compared with what is predicted by theoretical mathematical models. Two mathematical models were tested: the Bussian, (1983) equation and the Revil and Glover, (1998) equation. Both of these were extensions of the aforementioned Archie's Law, but the difference is that these equations take into account surface conductivities. Investigation proved that the Bussian equation was mathematically impossible to solve for measured conductivity. The predicted measured conductivity could be calculated, however, using the Revil and Glover equation. For each of the boreholes in the gold-star dataset estimations were made as to what the values of certain parameters would be in the equation. Using the Revil and Glover equation proved to be unsuccessful. There was no correlation between what was predicted by the model and what was actually observed with the experimental data. Furthermore, the equation did not even yield any relationship between smectite content in the rock and the predicted measured conductivity.

Applications, Significance, and Suggestions

After realising and explaining the reasons why the models were inadequate focus was given to the significance of the findings of this research. Obviously, the main area where this research could have the most significant impact is in the WATSAN sector. Two other water stressed areas have been identified where the findings of this research could be used- the Karoo Basin, South Africa and the Voltaian Sediments, Ghana. Both areas are predominantly comprised of clay-rich mudstones, and both have significant abundances of both illite and smectite. Surveying these areas with EM34 and identifying the regions of low conductivity could signify illite dominated areas and thus good rural groundwater potential. Both of these areas are experiencing water scarcity, and with future demand only likely to increase it will be vitally important to find any water-bearing fracture networks which could be used to sustain rural water supplies by the means of handpumps. There are other sectors where this research can be applied. Engineering and geohazards are closely linked. Due to smectite's plastic and deformable nature it would not be prudent to lay solid foundations in smectite dominated areas, as they are likely to deform and slip. Illite dominated areas, on the other hand, would be safer to build on. Being able to distinguish between smectite and illite dominated areas using EM34 is a great advantage in this respect. Another hydrogeological application where the findings could be applied is the siting of a high-level nuclear waste repository. In a repository groundwater flow must be zero. Most dangerous radioactive particles are most mobile when in water. Illite's high potential for groundwater flow means that illite clays would not be a suitable place to site any repository. Smectite clays, on the other hand, would be particularly good at keeping out any water. Remote sensing data could also be used to map illite and smectite areas as satellites can distinguish between high and low values of cation exchange capacity on the earth's surface.

The proof that illite clays (which have good groundwater potential) have a low associated measured conductivity completely changes the way in which boreholes will now be sited in mudstone/clay-rich environments. Geophysicists and WATSAN professionals need to be looking for areas of LOW conductivity to signify groundwater potential – which goes completely against the guiding principle that areas of HIGH conductivity should signify good groundwater potential. This research will change the way in which new and existing conductivity data will be analysed in water-stressed mudstone environments hereon in.

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Glossary and Abbreviations

BGS - British Geological Survey

CEC - Cation Exchange Capacity

DFID - Department for International Development

HLW - High-Level Waste

SSA - Sub-Saharan Africa

VES - Vertical Electrical Sounding

WATSAN - Water and Sanitation

Cation - *An ion with a positive charge*

Diagenesis - *Changes to sedimentary rock caused by variations in temperature and pressure. The temperature and pressure changes must be significant enough to physically alter the rock but not so large as to create a new type of metamorphic rock. It often marks the earliest stages of metamorphism.*

Dyke - *A vertically orientated igneous intrusion*

Ion - *A charged particle. An element without a full outer-shell of electrons resulting in a net positive or negative charge.*

Lithological log - *A profile with depth, detailing downhole variations in geology (i.e. changes in rock and soil type). A graphical representation of the sub-surface geology of a particular site.*

Sill - *A horizontally orientated igneous intrusion*

Sub-strata - *The geological rock types and soils beneath the ground surface.*

A note on the Literature Review

For the purposes of clarity there is no single chapter dedicated to the literature review. Because of the broadness of the topic at hand it did make sense to have one extremely large literature review chapter when the information needed to be continuously referred to in other chapters. The largest literature review section, on clay and conductivity, can be found in Chapter 3. Smaller reviews of the literature have been presented in Chapter 1 for rural water supplies, Chapter 5 for mathematical works completed on describing a definitive link between clays and conductivities, and Chapter 7 for remote sensing applications. Furthermore, a wide range of literature has been consulted (over fifty references) and is presented throughout the entirety of the report, and this literature has been scrutinised throughout.

Chapter 1- Introduction to Clay, Conductivity, and Rural Water Supply

According to *WaterAid*'s most recent statistics 768 million people globally do not have access to safe water, *WaterAid*, (2013). Whilst this is an extraordinarily high figure of people (more than 1 in 10 of the world's population) it must be acknowledged that on the whole progress is being made. A driver of this is the Millennium Development Goals: targets implemented at the turn of the millennium, initiated by the UN, to eradicate extreme poverty by 2015. Many regions across the world have seen a decrease in the percentage of people without access to improved water supplies. Rapid population growth, however, means that whilst many percentages may look promising there are infact more people without access to improved water supplies in many regions. Figure 1.1 is taken from the Joint Monitoring Program for Water and Sanitation. It shows the distribution of access to different water sources across the globe. What is easy to appreciate is that the abundance of people without access to improved

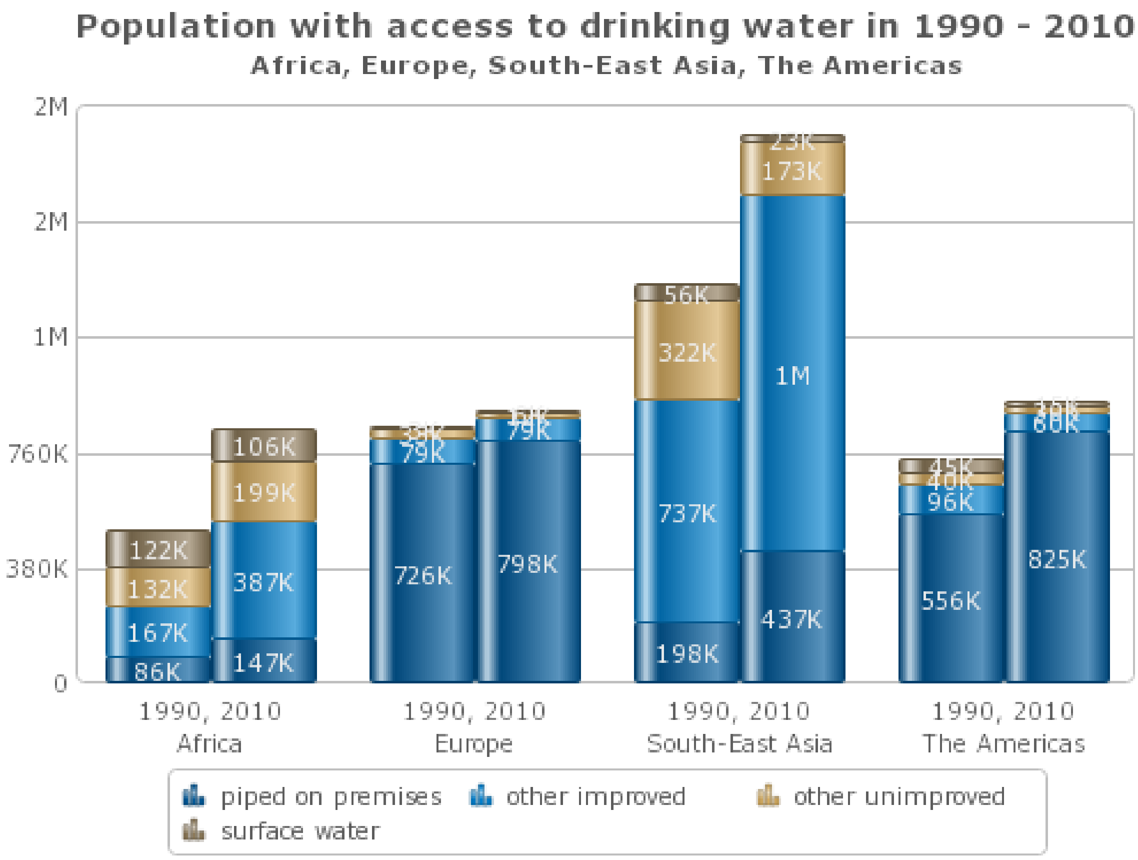


Figure 1.1: ***Distribution of access to different water sources globally from 1990-2010, JMP, (2013a)***

water sources is vastly greater in Africa and South-East Asia than in Europe and the Americas, as would be expected. Interestingly across Africa more people in 2010 do not have access to improved water sources compared to 1990 (notice the vast population increase though).

As would be expected, there are vast differences between urban and rural water supply. Whilst the previous statistics referred to both urban and rural, this dissertation is on rural water supply with a primary focus on Sub-Saharan Africa (SSA). Consequently, the rest of this document is focussed on rural water supplies.

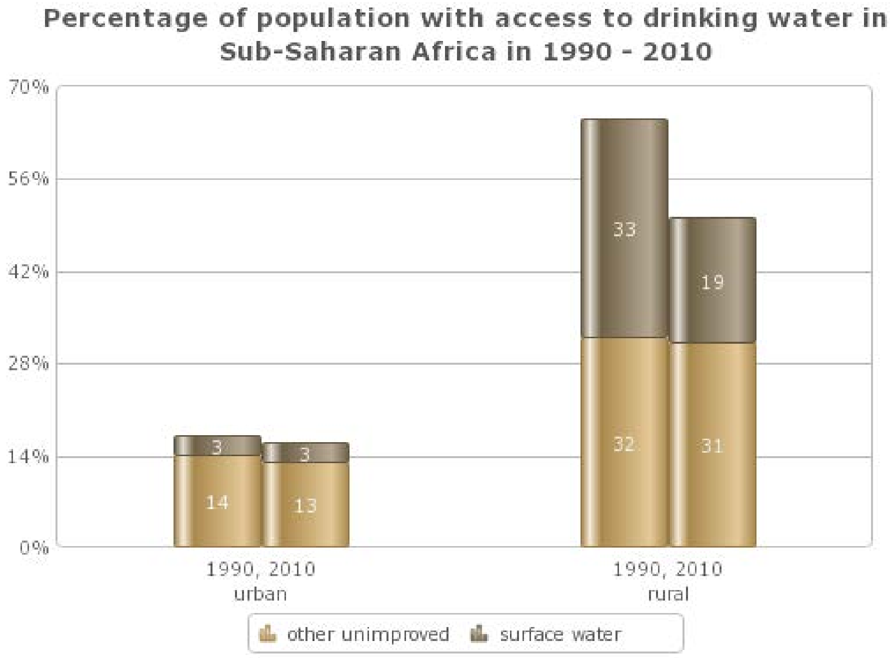


Figure 1.2: ***Percentage of people in SSA only with access to surface water and other unimproved supplies, JMP, (2013b)***

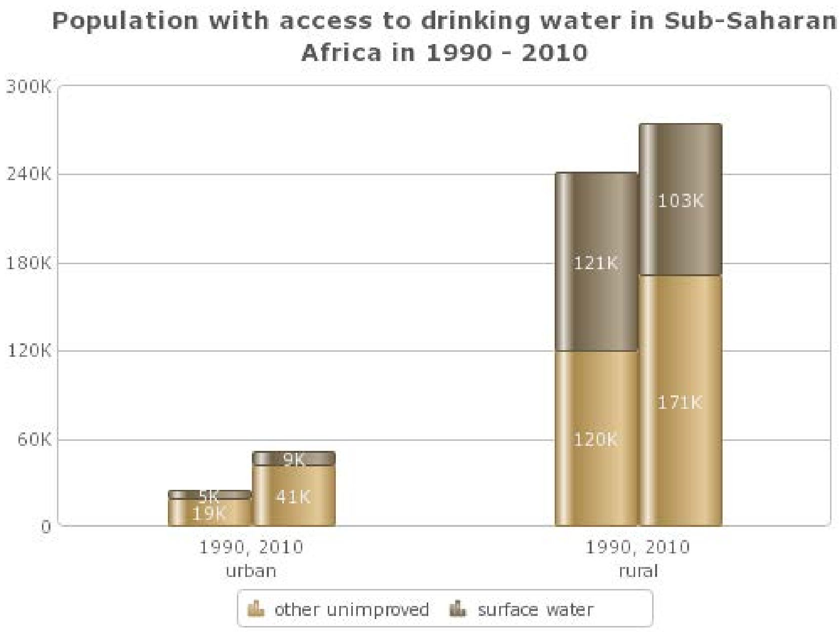


Figure 1.3: ***Population of SSA only with access to surface water and other unimproved supplies, JMP, (2013c)***

The Rural Water Supply Problem

Rural areas across SSA face many different, albeit no less challenging, water supply problems compared to that of urban water supplies.

Figure 1.2 shows the percentages of people without access to an improved water supply across SSA. Expressed as a percentage, there have been improvements across the region for both urban and rural areas in the last twenty years. What is immediately apparent about Figure 1.2, however, is the stark contrast between the rural and urban areas. In 2010 for example, 50% of the rural population were using unimproved water sources compared to only 16% of the urban population. The rural water supply problem becomes even more apparent when you view the same information expressed as a population (Figure 1.3), which shows that in 2010 274,000 people only had access to an unimproved water supply in the rural areas compared with only 50,000 in the urban areas (more than five times as many).

Nigeria: A Brief Case Study

With a population nearing 170 million, Nigeria is Africa's most populous country. It is widely acknowledged that at present Nigeria is unable to cope when it comes to delivering safe water supplies to its rapidly growing population and around 63.2 million people (approximately the population of the United Kingdom) do not have access to safe water; on top of this a further 3 million (66 million in total) have no choice as to what and where their preferred water supply is, *WaterAid Nigeria*, (2013).

Figure 1.4 shows rural drinking water trends specifically for Nigeria. Progress has been made by increasing the percentage of people of who have access to an improved water source and there has been a decrease in the percentage of people using surface water over the twenty-one year period. The percentage of people using unimproved water sources has remained constant which means when taking into consideration Nigeria's vast population growth a significantly higher number of people are using water from an unimproved source. What Figure 1.4 clearly shows is that Nigeria has a substantial way to go in improving water sources for its people- a trend common across many Sub-Saharan African countries.

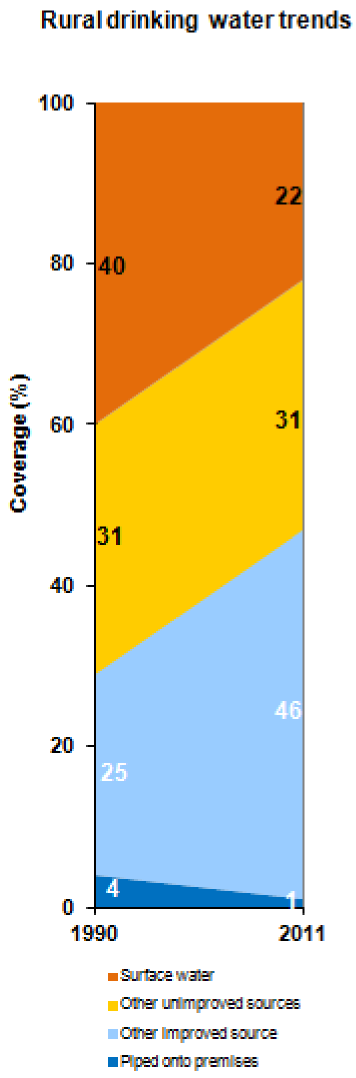


Figure 1.4: ***Rural drinking water trends across Nigeria, JMP, (2013d)***

This dissertation report uses data collected in a region called Oju and Obi, in Benue State, South-East Nigeria. Benue State has a population of nearly 5 million inhabitants. Its main industry is food production, signifying that vast quantities of water will be used for irrigation purposes, *Federal Republic of Nigeria*, (2013).

Groundwater: An Overview

Ask many people how water moves under the ground and they will think of great underground caverns and subterranean rivers. Whilst, admittedly, some groundwater does indeed flow in this way, the majority of it flows through pores in the rock matrix itself, along small joints and fractures, and occasionally along faults. It is difficult to estimate with any certainty how much groundwater there actually is. Furthermore, it is even more difficult to say how much of this groundwater is actually accessible. Price, (1996), delivers a sensible estimation of 54 million cubic kilometres of groundwater (around 7% of this is actually accessible) exists in the shallow crust beneath the earth’s surface.

Groundwater is often an excellent source of water to use in rural areas in SSA. During dry seasons, surface water flows often cease and therefore people need to look for other water sources. It is usually possible to find some traces of groundwater in the subsurface and providing the water table is not too deep it should be somewhat accessible. Another advantage is that groundwater is often plentiful during the dry season. Because it takes time for rainwater to trickle through the soil and into the rocks beneath, the groundwater peak often lags behind the rainfall peak (often by many months).

More often than not, aside from groundwater satisfying a quantity need, it also satisfies an excellent quality need. Groundwater is often of good quality because as the water percolates through the ground it becomes naturally filtered. Furthermore, due to the time it takes for this process to happen all pathogens die off. This results in water which poses no microbiological hazard (unless the groundwater has been extracted from very shallow depths). It is worth mentioning however, that groundwater can be very high in salt and metal concentrations, which over prolonged exposure can cause chronic illnesses.

African Hydrogeology

On a local level hydrogeological regimes will be varied and complex. The flow and abundance of groundwater will be controlled by many factors such as rainfall, recharge, porosity, permeability, faulting, fracturing, jointing, abstractions, mineral reactions, lithology/rock type, aquifer catchments, and topography. Fortunately, on a much larger scale (continent size) the hydrogeology is somewhat simpler to describe.

In the case of the continent of Africa, the hydrogeology and rocks beneath the surface can essentially be categorised into four main types. MacDonald and Davies, (2000), have

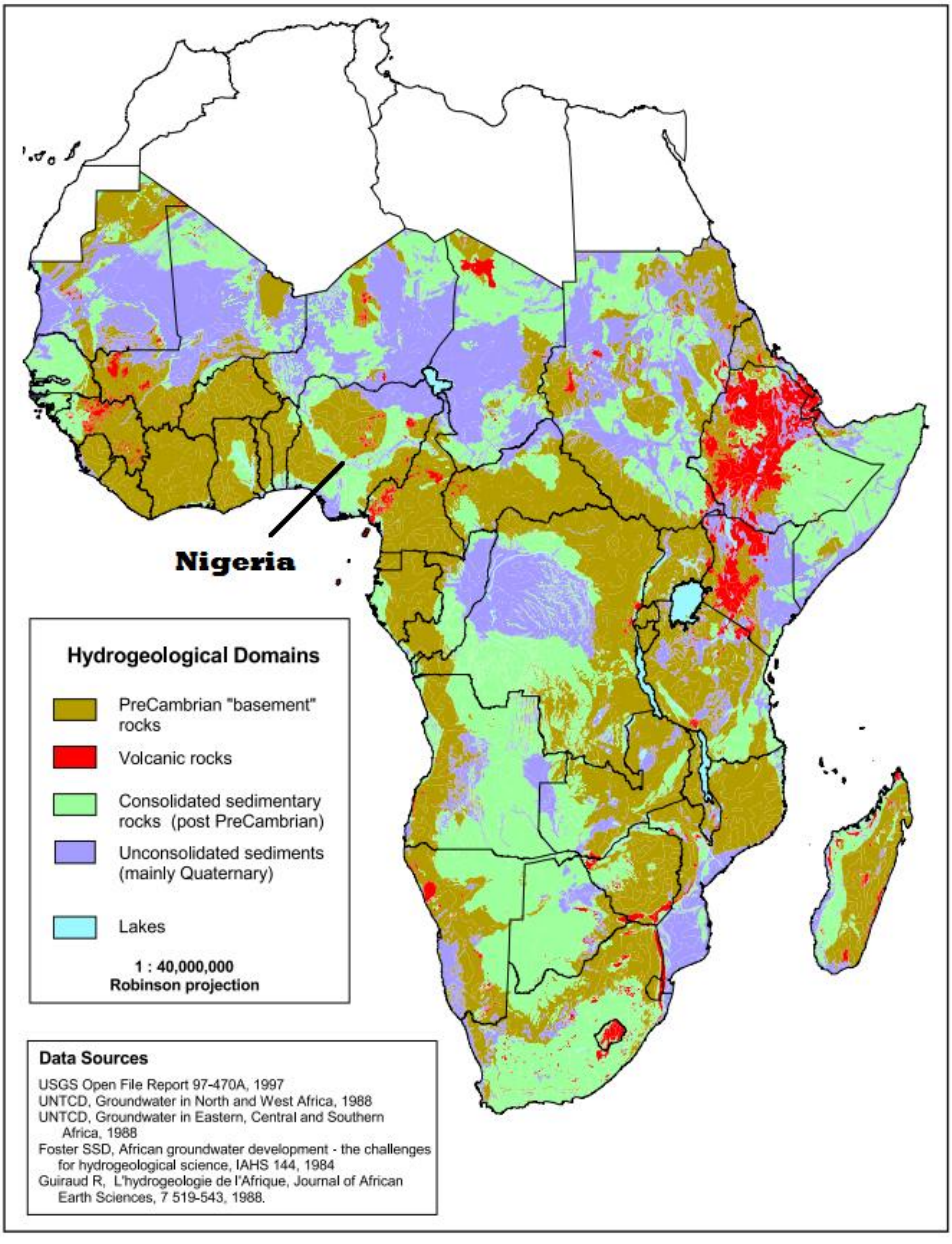


Figure 1.5: ***The hydrogeological domains of Sub-Saharan Africa. The position of Nigeria, the area of focus for this study is noted, MacDonald and Davies, (2000)***

described and mapped each of these four major rock types and the following has been adapted from their work.

The four main hydrogeological environments in Africa are as follows; each requires different means and methods of abstraction as the groundwater will appear at different depths and within different geological features:

1. ***Crystalline Basement Rocks***- These are the rocks which make up all of the earth's continents. They are igneous in their nature and have existed since the early beginnings of the earth. 220 million rural people in SSA live on them and they occupy 40% of the total land area. Groundwater potential is generally low, but sufficient quantities can often be found in fracture zones to sustain rural water supply needs.
2. ***Volcanic Rocks***- These rocks occupy 6% of the total landmass and 45 million people live on them. They lie, unsurprisingly, around the volcanous regions of SSA and are especially common on the drought stricken areas of the Horn of Africa- a region where the continent is literally trying to tear itself apart. Volcanic rocks are often extremely porous and permeable in nature because when they are solidifying gas bubbles out of them and leaves open many pathways and channels. Because of this, groundwater potential is high.
3. ***Consolidated Sedimentary Rocks***- Occupies 32% of the land area and 110 million people live on them. They consist of sandstones and limestones (good groundwater supply potential) and mudstones (poor groundwater supply potential. They account for two thirds of all sedimentary rocks in SSA).
4. ***Unconsolidated Sediments***- Occupies 22% of the land area and sustains a rural population of 60 million. These comprise of silt, sand and gravels often found in river beds and on deltas. During wet seasons they can yield good quantities of groundwater, however, because the groundwater is usually very shallow it can deplete during the dry season and can be of poor quality.

Figure 1.5 summarises the distribution of each of these rock formations described above on a map of SSA. Observation of Nigeria specifically shows that the main types of hydrogeological domain in the country are the Pre-Cambrian crystalline basement rocks and consolidated sedimentary rocks. The area under study for this research project, Oju and Obi, lies on consolidated sedimentary rock, most of which is made up of mudstone - the type of rock which has the poorest groundwater potential across the whole of Africa. Therefore, in order to try to improve the ability to access such small, but desperately needed, quantities of groundwater in such regions is a worthwhile endeavour.

A Geophysics Approach

Geophysics is a powerful tool which can be used to identify or infer the presence of groundwater in the subsurface. It essentially is a way of using various equipment to make measurements of the physical properties of the subsurface. Through not understanding how priceless geophysics data can be or by not knowing how to carry out surveying correctly, time and time again professionals in the WATSAN sector waste vast amounts of time, money and energy drilling holes in the ground which never have any chance of sustaining rural water supply.

EM34

EM34 is a type of non invasive surveying technique and is the type of surveying used in this dissertation report. It falls under the wider umbrella term of *Electromagnetic Surveying*: so named because it uses the phenomena of electromagnetic induction to "see" beneath the earth's surface.

Electromagnetism and Electromagnetic Induction

Electromagnetism was first described mathematically and comprehensively by the Scottish physicist James Clerk Maxwell. Electromagnetism is the study of electromagnetic waves and fields. These waves (of varying wavelength and frequency) are composed of both electric fields and magnetic fields which are orientated perpendicular to one another (Figure 1.6). Although Maxwell was the first scientist to be accredited with a full mathematical description of these waves, their existence had been known about for quite some time.

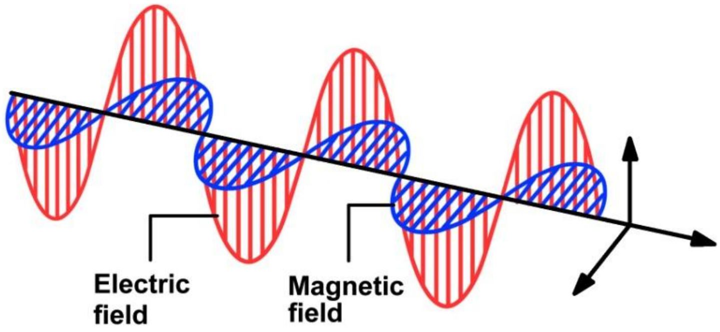


Figure 1.6: ***A schematic diagram representing the shape and orientation of an electromagnetic wave***

Michael Faraday famously noted the phenomena of electromagnetic induction (on which EM34 surveying is based). By placing two coils of wire close together, but not touching, he noticed that by passing a changed electrical current through the first wire an electrical current also flowed through the second wire. Although not fully understood at the time, Faraday had discovered the process of electromagnetic induction.

Electrical currents have electrical fields associated with them. Any charged particle (such as electrons or ions) has an electric field associated with it. This field technically extends for an infinite distance, but the force which another charged particle will experience when in the electrical field will quarter every time you double the distance separating the particles, so that electrical fields become negligible after relatively small distances. When you have a varying current (and thus a varying electric field) within a wire you create a varying magnetic field. This varying magnetic field extends throughout free space and then creates a voltage (and thus an electrical current) in a wire some distance away. This is the process of electromagnetic induction and is how EM34 works.

Conductivity

Conductivity refers to how well a particular material can facilitate the *movement of charge* (also known as *current*). Its inverse is referred to as resistivity, i.e. if a material has high conductivity it will have a low resistivity and vice versa. Materials which are good at conducting are known as conductors and those which are not are referred to as insulators. Even insulators will be able to conduct some electricity, albeit very weakly. There are many different mechanisms by which current can move throughout a material. In rocks, the two most common ways are through the bulk of the material (usually very weak) and through the pore water which exists in-between the individual particles (usually very strong).

In this report there will be three terms used throughout: conductivity, bulk

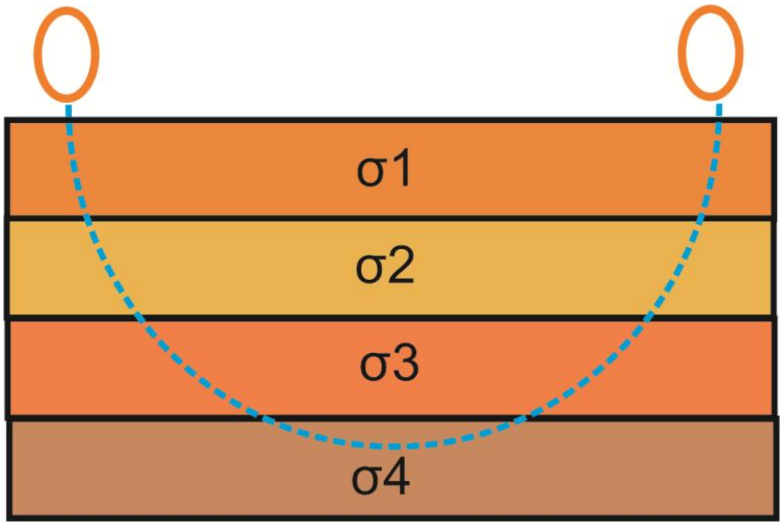


Figure 1.7: ***Schematic bulk conductivity of four layers within the earth. The ovals are the coils and the blue line represents the signal path.***

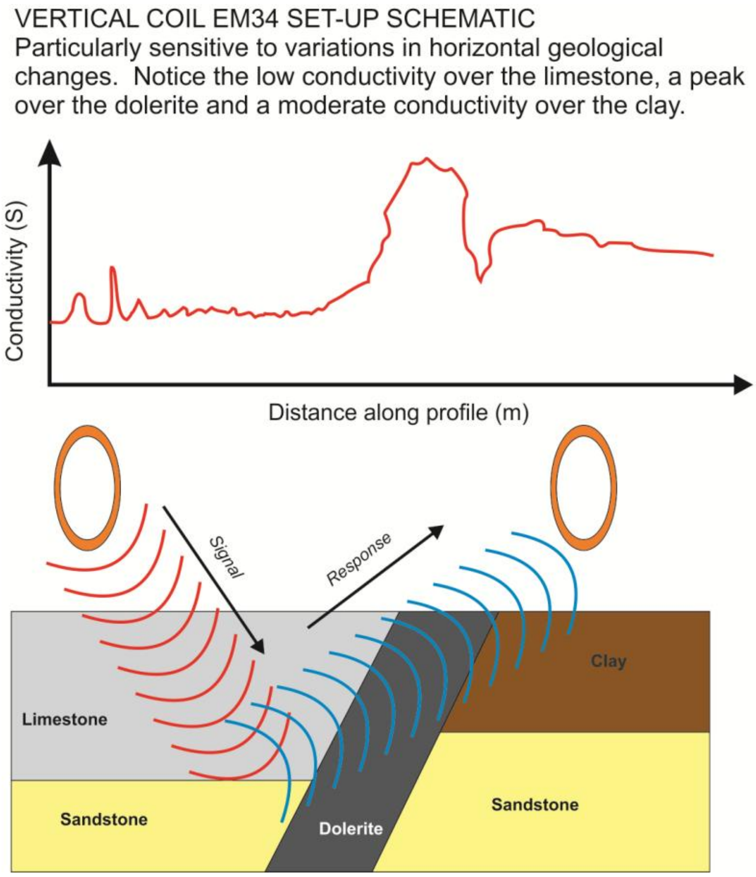


Figure 1.8: ***Vertical coil EM34 set-up. The bottom cross section represents the surveying taking place whilst the top graph corresponds to the signal response over each feature. Note the peak over the dolerite.***

conductivity, and measured conductivity. Technically these three terms have different meanings, but in this report the terms have been used interchangeably (as this is geological convention). Nevertheless, an appreciation should be given to what each of these terms actually mean. Conductivity (often referred to as actual or true conductivity) is the specific value of conductivity for one particular medium. Measured conductivity relates to what the instrumentation actually measures. Figure 1.7 illustrates the concept of bulk conductivity. Each of the four layers has its own conductivity (σ1, σ2, σ3, σ4). The instrument, however, does not display a value for each of these four layers. What it actually displays is a value of bulk conductivity which is a contribution of each of the conductivities from each layer. Throughout this report, unless specified otherwise, when one of these three terms is used it actually is referring to the bulk conductivity.

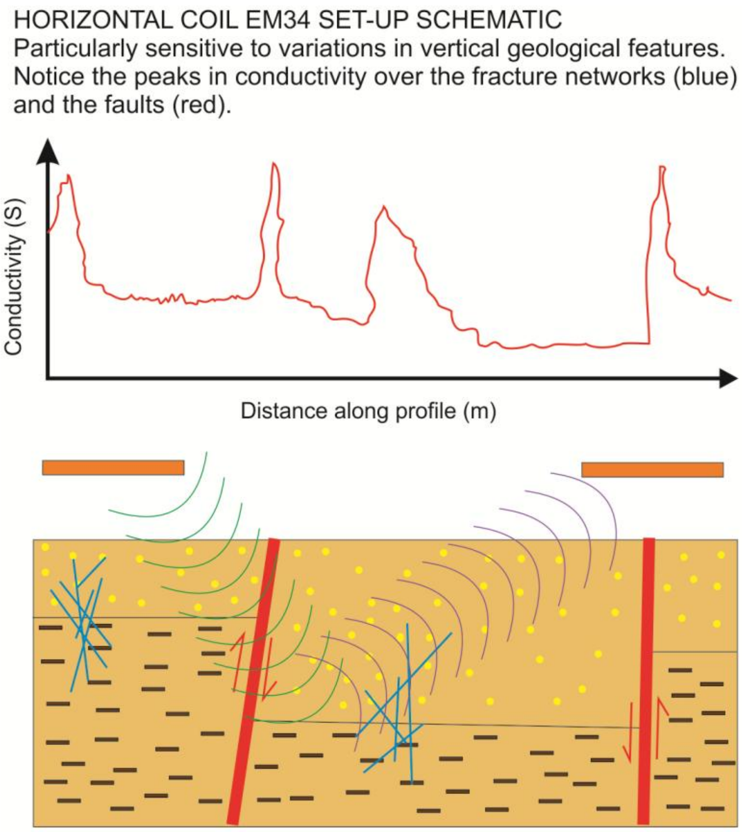


Figure 1.8: ***Horizontal coil EM34 set-up. The bottom cross section represents the surveying taking place whilst the top graph corresponds to the signal response over each feature. Red lines are faults, blue lines are fractures. The yellow dots and brown dashes represent different geological units.***

EM34 Surveying

EM34 surveying is a common form of surveying technique used in developing countries. The reason for this is because it is relatively cheap, easy to operate, and easy to interpret the data. Two coils are used, one is a transmitter and the other is a receiver. The transmitter emits a varying magnetic field, which then induces a varying electrical current beneath the ground. This varying electrical current then creates a varying magnetic field which is detected by the receiver coil. Figures 1.8 and 1.9 show how EM34 works by having a cross section of the geology and the signal response for both the vertical and horizontal coils. As can be seen, different coil orientations are sensitive to different features beneath the ground.

This report will now go on to explain the details, findings and interpretations, and discussion of the project in detail.

Chapter 2- *Background Study by the BGS*

This chapter provides a background for the reader concerning the work conducted by the British Geology Survey (*BGS*) in Oju and Obi, Benue State, Nigeria, upon which this dissertation is based. The information contained within this chapter is based upon the work of Dr Alan MacDonald and his team, and most of the information presented is sourced from his reports and also from person discussion.

DFID, WaterAid, and the BGS

The region of Oju commonly experiences severe drought issues in the dry season. During this season water is scarce, and the primary source of drinking and domestic water used to be unprotected ponds and seepages. Water related diseases, such as guinea worm, malaria, cholera, typhoid and dysentery were prevalent amongst the 300,000 strong population. *DFID* commissioned *WaterAid* to improve village level, domestic water supply by primarily exploiting groundwater. *WaterAid* drilled a borehole in the centre of the region but ironically it did not yield any significant amounts of water. The region has a complex hydrogeological profile and consequently *WaterAid* asked the *BGS* to provide assistance, and work began in September 1996, MacDonald and Davies, (1997); this same report discusses in detail the climate, river-flow, rainfall, and basic geology of the Oju area.

Geological Triangulation

To estimate the hydrogeological potential of the area the *BGS* employed a technique known as 'geological triangulation'. Geological triangulation essentially enables you to estimate the groundwater potential of a site by extracting information from three different sources prior to drilling. Figure 2.1 illustrates this technique and is

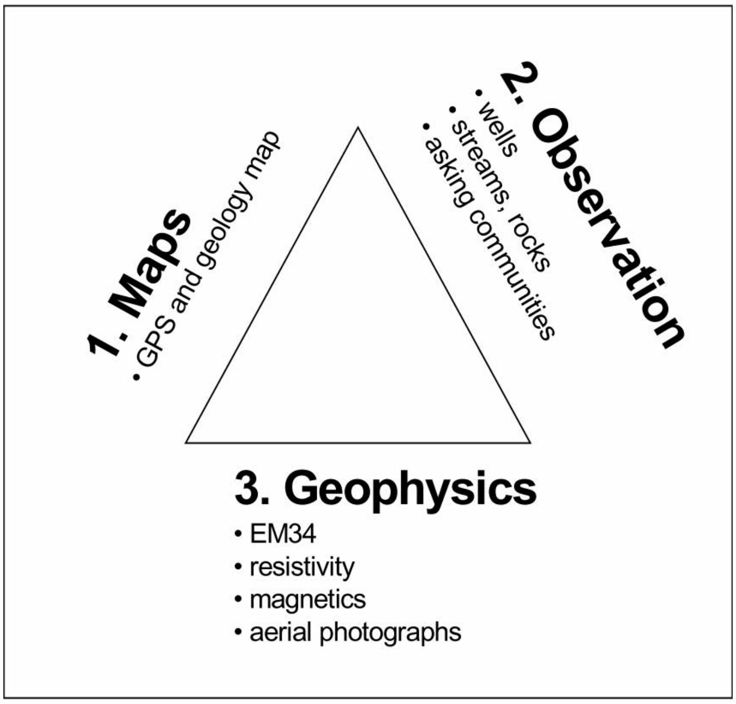


Figure 2.1: ***Geological Triangulation***

taken from MacDonald and Davies, (no date). Each of these three main sectors has their own merits but all should be treated with equal importance! Maps enable you to identify where the best places would be to conduct your geophysics. Hydrogeological maps will allow you to identify where potential major aquifers could lie and they narrow down the region where you would aim to conduct costly and time consuming geophysics. Geophysics is the only method which truly enables you to 'see' beneath the ground surface and try to spot groundwater within the underlying rocks. Observations, however, can be an invaluable tool. Local knowledge from communities in particular is often priceless and they can tell you where there is good river flow, the location of springs etc, which can all lead to increased success of finding rural groundwater supplies. Using these three sources in unison gives you your best shot at being able to find and exploit sustainable rural water supplies.

Observations and consultations with each community can be found in a series of village reports by the *BGS* (unpublished); they also contain information regarding what boreholes the *BGS* drilled in and around each village and the water quantity and quality which they delivered. The reader should contact Alan MacDonald of the *BGS* personally if they wish to read in more detail the findings of each of these reports, as they are not freely available in the public domain.

Geological Mapping

MacDonald and his team ensured that comprehensive geological mapping of Oju and Obi took place before conducting any geophysical surveying; they also mapped the precise locations of the villages with GPS coordinates - something which had not been done before (see MacDonald and Davies, (1998)). The maps which they produced are found in APPENDIX I. The various formations which make up Oju and Obi are presented in Table 2.1; this also includes the borehole numbers BGS(No.) which were drilled in the formation. The information in Table 2.1 is sourced from Davies and MacDonald, (1999).

Table 2.1: ***A summary of the geological formations across Oju and Obi***

Formation	Geology	Hydrogeology	Groundwater Potential	Boreholes BGS ( )
Metamorphosed Asu River	**Hard, splintery, slatey, mudstones. Sandstones, limestones, ash layers, dolerite, and gabbro are minor lithologies. Highly fractured.**	**Good aquifer. Rocks have low porosity and permeability but high degree of fracturing. Fractures are hard and remain open. Ash layers-best targets, fractured bedrock good.**	**HIGH Significant groundwater within fractures below 11m and in ash layers. Less groundwater where bedrock was less metamorphosed. Quality-good-within WHO guidelines.**	**19, 20, 21**
Asu River	**Hard splintery mudstones and**	**Groundwater occurs within widespread**	**HIGH Best targets are fracture**	

	laminated coarse siltstone to very fine sandstone. Often folded.	fracture systems at depths > 10-15m. Low porosity and permeability but fractures are hard and remain open.	zones 15-50m deep. Boreholes 40m deep are best. Long term sustainability difficult to tell. Quality-good.	1, 2, 2a
Lower Eze-Aku	Laminated mudstone with significant beds of siltstone, sandstone and limestone. Moderately hard.	Groundwater occurs within fractures and fault-zones. Fractures are not widespread. Sediment too soft for fractures to stay open. Only extensive faulting stays open.	MODERATE Boreholes must be located in highly fractured areas and to depths no greater than 30m. Quality-good.	14, 15, 16, 17, 18
Makurdi Sandstone	Fine-medium grained sandstone interbeded with mudstones, siltstones and limestones.	Groundwater in fractures at the base of weathered zone 8-15m deep. Sandstone has moderate porosity and a large range in permeability.	POOR-MODERATE Previously thought to be the best aquifer-incorrect. Weathered zone must be targeted. Quality within WHO limits.	4, 5, 6, 7, 8, 9, 10, 11, 12
Upper Eze-Aku	Shaley mudstones with interbeded thin sandstones and limestone bands.	Groundwater in thin (0.3m) limestone bands and sandstones. Limestones are fractured and laterally extensive.	POOR-MODERATE Soft mudstones=few fractures. Limited groundwater in sandstone. Most water in limestone fractures. Quality within WHO limits.	3, 3a, 13, 13a
Awgu Shale	Soft well bedded mudstones, thin (0.5m) interbeds of limestone and fine, moderately sorted, sandstones.	Mudstone too soft to contain open fractures. Usable water only found in sparse sandstone layers and dolerite intrusions.	POOR Very little water and the quality is low, well below WHO guidelines. Very low potential for development.	22, 23, 24, 25, 26, 27, 28, 29, 30, 31
Agbani Sandstone	Cross bedded sandstones with interbeded dark grey shaley mudstones.	Not well understood. Groundwater is in weathered zone where sandstone is finely grained. There may be groundwater in fractures in more competent sandstone.	POOR-MODERATE Wells can be located in the weathered sandstone and are likely to be more successful in valleys close to a source of recharge. Fractured weathered sandstone may be able to support a hand-pump. Mostly within WHO guidelines.	47, 48, 49, 50
Dolerite	Hard, medium grained, igneous rocks occurring as dykes and sills. Weathered and baked towards the edges.	Fractures within dolerite (most common towards the edges) where weathering has occurred are best possible targets. Main dolerite body contains little	MODERATE Best targets are within thick, fractured and coarse grained dolerite adjacent to valleys which are a good source of recharge. Quality is within WHO guidelines.	33, 34, 35

		groundwater.		
Laterite	**This is weathered material referred to as a regolith. Soils and clay rich zones.**	**Highly permeable rock and shallow groundwater does exist in top soils.**	**SEASONAL** **Water present in wet season but not in the dry. Vulnerable to contamination from pit latrines. Quality is below WHO guidelines.**	**None drilled**
Alluvium	**Very little present, river gravels.**	**Sufficient water for a hand dug well. Permeable material.**	**POOR** **Little groundwater storage available.**	**Cannot be drilled due to fine sediment infiltration.**

The reader is encouraged to refer to this table and the maps in the appendices whilst reading interpretation sections in the rest of the report.

Geophysical Surveying

Three different types of surveying were undertaken by the team to try to ascertain what the underlying geology was and also where groundwater was likely to be. The types of surveying undertaken were:

1. ***EM34 Conductivity Surveying*** - This was by far the most common and widespread type of survey undertaken. The details of how it works have already been presented in Chapter 1. It allows bulk conductivities of the ground to be measured. It is particularly good at being able to determine the likely geology beneath the surface, the location of fracture networks, and the presence of freely mobile groundwater.
2. ***Vertical Electrical Sounding (VES) Resistivity Surveying*** - This type of surveying pretty much measures the same thing as EM34, i.e. how electrical currents move within the earth. The difference is that resistivity is the inverse of conductivity. A *Wenner* array was used. This comprises of having four electrodes arranged equally spaced in a line. The outermost electrodes send the current through the earth, whilst the innermost electrodes measure the potential difference. Knowing the current and the potential difference, the equipment then displays a value of resistance, from which the resistivity can be calculated. Increasing the spacing of the electrodes allows currents to be transmitted to greater depths; therefore, keeping the midpoint the same but changing the electrode spacings enables you to 'see' deeper within the ground. This survey method is slower than EM34 and does not allow any lateral information to be gathered; consequently, it was only carried out in areas of particular interest in the EM34 profiles on sites for prospective boreholes.

3. ***Magnetic Profiling*** - Magnetic profiling enables you to measure how magnetised the ground is by using a piece of equipment called a magnetometer. It is a tricky type of surveying in that it cannot be completed at any time; during increased solar output magnetic storms can be created on earth and the signal from the changing earth's magnetic field can dwarf the signal response from the ground. It was mainly used to map the underlying geology, specifically to locate the dolerite as igneous intrusions contain an abundance of magnetised minerals. It is essentially useless for trying to locate groundwater as water is not magnetised. Profiles were generally created along the same traverses as the EM34 profiles.

Siting Boreholes and Estimations of Transmissivities

Once all three components of the geological triangulation had taken place, the information gathered from these three sources was combined together to enable a decision to be made as to where would be the best place to site boreholes. Naturally, a site which may be perfect from a geological/geophysical perspective would not be well suited if it lay many kilometres away from a settlement.

Once a borehole had been sited and drilled, pumping tests were carried out on the boreholes to see if they could yield significant and sustainable amounts of groundwater. The type of test used to estimate transmissivities was what is known as a *Bailer* test. This is a simple method of removing water from boreholes from which the transmissivity can be estimated. This procedure was carried out on every borehole drilled, and a list of the transmissivities can be found in MacDonald, (1999). It is acknowledged that transmissivity values > $1m^2$/d are sufficient to sustain rural village water supplies (based on 250 people using 25L/d per borehole), MacDonald et.al, (2005). Out of the forty-three boreholes which underwent a Bailer test only seventeen (40%) had a transmissivity >$1m^2$/d. All of the boreholes in the *Metamorphosed Asu River, Dolerite* and *Asu River* formations had the required transmissivities. Around half of the boreholes in *Eze-Aku Shale* formations had the required transmissivities, most of which were in the *Lower Eze-Aku* formation. Only one borehole, out of five in total, met the criteria in the *Makurdi Sandstone* formation. None of the boreholes in the *Awgu Shale* formation met the criteria.

Clay Mineralogy Analysis

Whilst drilling was taking place the team took samples down representative boreholes. When back in the UK, clay mineralogy analysis was undertaken at the laboratories at the *BGS* Headquarters in Keyworth, Nottingham. The first task which was undertaken was to identify how much of each rock's constituent material was made up of clay particles; this was found to be approximately fifty percent in most cases. Furthermore, it allowed the team to identify what type of clay minerals were present and in what proportions: kaolinite, illite, and smectite most notably. Further details on the clay mineralogy data including relative proportions are present in greater deal in Chapter 4. Full tables are available in Appendix 2 of Macdonald, (1999).

Factors Controlling the Groundwater Abundance and Distribution Across Oju and Obi

It is hypothesised by MacDonald et.al., (2005), that transmissivity in the mudstone dominated region is primarily controlled by two main factors. The first one is low-grade metamorphism and the second is the presence of other smaller lithologies within the subsurface. These two factors are now discussed and the information presented is sourced from the same paper.

Diagenesis and Low-Grade Metamorphism

Diagenesis is an early form of metamorphism. It refers to physical changes which occur to sedimentary rocks due to changes in heat and pressure, but changes which are not so great as to create a new metamorphic rock. It is the early stage, and onset, of prograde metamorphism. The conversion of smectite → illite/smectite → illite→ muscovite is an example of an irreversible transformation from diagenesis to low-grade metamorphism, Merriman and Peacor, (1999).

The youngest formation across Oju and Obi is the *Awgu Shale Formation*. It has not undergone any significant burial (hence small/no increase in pressure and temperature) and has, therefore, an abundance of smectite dominated clays. The oldest formation, however, the *Asu River Group*, has undergone sufficient burial and folding and therefore is dominated by illite clays. Across Oju and Obi, travelling from NW to SE, there is a decreasing abundance of smectite matched by an increasing abundance of illite. Travelling in the same direction, there is also an increased groundwater potential suitable for sustainable rural water supplies. Therefore it is clear that as metamorphism, and thus illite, increases so does transmissivity.

Other lithologies within the subsurface

The other main suitable groundwater targets in the Oju/Obi area were the dykes and sills which were located primarily in the *Awgu Shales* formation. Dykes and sills are igneous intrusions. Igneous intrusions are rocks which have been thrust upwards through the crust towards the surface. Usually they are poor groundwater targets and they often act as barriers to groundwater flow, Bromley et.al, (1994). A good groundwater target in relation to the dykes and sills is the contact zone between the igneous intrusions and the surrounding rocks.

Figure 2.2 is a schematic diagram representing the various groundwater targets in the Oju/Obi area, taken from MacDonald et.al, (2005).

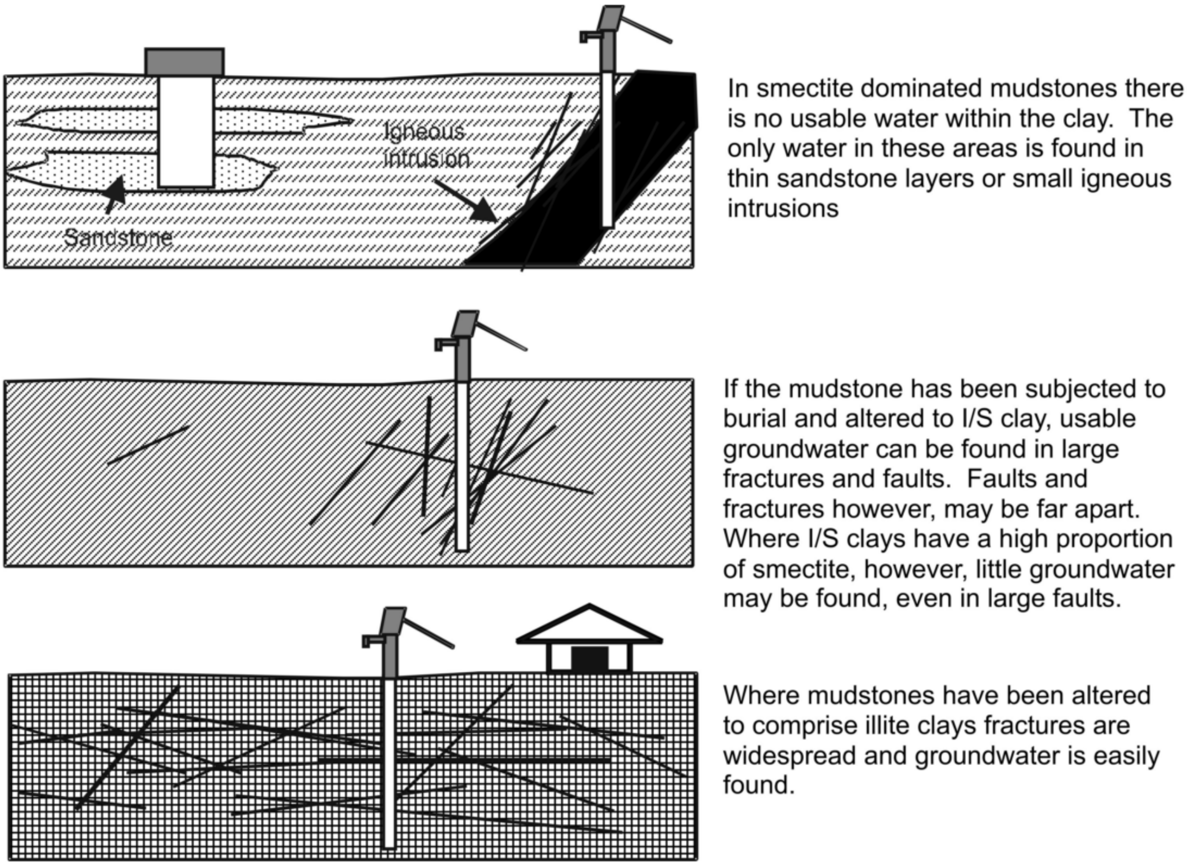


Figure 2.2: ***Groundwater targets in Oju and Obi***

Conclusions of the study

The project successfully identified the best areas in Oju/Obi where groundwater can be used as a sustainable rural water source. The general trend noticed was that the groundwater potential and transmissivities increase as you move from NW to SE with increasing illite content. Whilst it is acknowledged that subordinate lithologies within the mudstones can yield some groundwater supplies, groundwater potential is mainly controlled by the relative abundances of smectite and illite in the rocks - this determines whether or not suitable fracture networks can develop.

Once the boreholes were drilled, the ones with sufficient transmissivities were developed to provide the citizens of Oju and Obi with clean and sustainable domestic/drinking water. Whilst this relationship between smectite and illite abundance was noted by the team, it has not been pursued and investigated any further. It has been realised that being able to distinguish between smectite and illite in the subsurface by using non-invasive geophysical techniques would be a huge advantage in the hunt for locating rural groundwater supplies. Consequently, the data collected from this *BGS* project has been used in this dissertation to see if such a link can be made. Chapter 3 goes on to discuss in more detail the problem which this dissertation is addressing.

Chapter 3 - *The Problem*

Anything which furthers our understanding on groundwater and how to detect it will lead to increased success rates of drilling boreholes and wells and striking groundwater of sufficient quality and quantity to lead to sustainable rural water supplies. As such, furthering our understanding is a worthwhile endeavour, and consequently the author has chosen to dedicate his time for this research project to do just that.

The Problem in Question

This particular problem was brought to the author's attention by Dr Alan MacDonald, Principle Hydrogeologist of the *BGS* Edinburgh. Their work, which his team and he carried out, has already been discussed in the previous chapter to give the reader a flavour of the background and motivation of this project. In essence, the problem can be summarised in the following question:

Can geophysical techniques, notably EM34 ground conductivity surveying, be used to distinguish between different types of clay in the ground?

Upon first glance, the reader may question what this problem has to do with water supply. Put simply, in areas where there are extremely small amounts of groundwater to look for the groundwater directly using geophysical surveying techniques is difficult. Therefore, one must look at being able to identify clues in the underlying geology which suggests that groundwater may be present. Essentially, the clay type can indicate whether or not water will be present; therefore being able to distinguish between different clay types is a powerful tool when it comes to siting boreholes and wells.

Whilst there are many hundreds of different types of clay minerals present on earth there are four main ones which are common and are the focus of this study: kaolinite, smectite, smectite/illite (a transition phase), and illite. Smectite is soft, plastic, weak, and can be easily deformed. Illite, on the other hand, is notably stronger and more resilient to deformation. Smectite is essentially converted to illite through processes of diagenesis and early metamorphism. Fractures in smectite will soon be squashed away from the pressure of the overloading rocks/sediment. Fractures in illite, however, will not easily be squashed; they will maintain their shape and allow water to flow through with ease. In areas of unfavourable aquifer geology, i.e. areas which are dominated by a significant proportion of clay, being able to target these robust fractures in illite dominated rocks is key to being able to deliver sustainable rural water supplies.

It should be noted that clay is usually what is referred to as an *aquiclude* - a rock which does not yield significantly high amounts of water. Clay is very porous, meaning it has a lot of holes and gaps, both within and in-between mineral grains, which can hold water. The problem, however, is that it is not very permeable, meaning that these voids and pore spaces are not well interconnected meaning that water cannot flow. Knowing this fact, many areas around the world have been simply written-off as areas which cannot sustain rural groundwater supplies. In the most water-stressed regions of the world, such as SSA, water sources can be so few and far between that even the smallest supplies of groundwater must be tapped into. Therefore, being able to tap into fracture networks present in illite-clay rocks is essential to sustain people's livelihoods and general well-being.

Describing the Literature Review Thought Process

Once the problem had been identified the next step was to complete a literature review. Conducting a literature review allows the following points to be address:

- Is the problem a new topic which needs to be investigated? Has anyone already answered the problem?
- What information has already been written on the subject?
- With the information already out there, how reliable is this information? Does it need to be scrutinised? Does it make sense?
- The literature review will build up one's own knowledge and capacity to answer the problem.
- It enables the problem to be tweaked and tailored to answer something specific which has not been addressed in so much detail before.

Searching Strategy

To search for relevant information certain keywords had to be used in order to access this relevant information. Examples of relevant keywords and phrases are given.

KEYWORDS: **EM34, resistivity, geophysics, geophysical, surveying, surveys**, **electrical conductivity, electrical conductivity of rocks/clays/minerals**, **clay(s), smectite, illite**, **CEC (cation exchange capacity), surface conductivity, pore water (electrolyte) conductivity, double-layer,** **surface conductivity models, macroscopic, microscopic**, **Oju and Obi, African (hydro)geology.**

The above keywords and phrases have been grouped (using different colours) in order to distinguish topics which are similar and synonyms. Combinations of the above words were used to source suitable information.

Table 3.1 describes the various sources of information used to complete the literature review, the searching strategy, the justification of approach, and the quality controls.

Table 3.1: ***Searching strategy of the literature review***

Source of Information	***Search Strategy***	***Justification of Approach***	***Evaluation to ensure quality***
Library Catalogue	**Primarily using the advanced search and selected key databases. Inserting the keywords listed above in sensible combination.**	**Enables a wide range of databases to be searched and accessed. Different types of media can be found (i.e. journals, books, magazines etc…). High volume of results.**	**Peer reviewed journals accessed, and books have been published which have been reviewed, checked, and updated.**
Library Browsing	**The geology section on the ground floor of the Pilkington library enables browsing of book titles on the subject topic, enables discovery of key materials.**	**As the problem is quite specific the majority of the information needed can be sourced from the same section of the library. Enables you to pick up key materials which may have been missed when searching the library databases.**	**Peer reviewed journals accessed, and books have been published which have been reviewed, checked, and updated.**
WEDC Resources Centre Browsing	**Enables browsing of a range of materials specifically related to the WATSAN sector.**	**Context specific information available. Information often sorted into country-specific folders allowing relevant information to be found.**	**WEDC is a world leading institution with a reputable scientific appreciation. Resource centre manager has a phenomenal understanding of the literature and information in the centre.**
Journals	**Primarily accessed through Library Catalogue. Once key titles had been identified, i.e. "*Journal of Applied Geophysics"*, searching using the keywords above could be conducted on these journals websites.**	**Journals are going to be the primary material type to source information from. Often available in electronic format. Allows a snowballing effect- from one journal you may get three other references which you want to then go and find more information on.**	**Journals are peer reviewed, meaning that their quality is checked and authenticated by other leading academics in the field. Try to use journals as recent as possible to ensure information isn't outdated.**
Textbooks	**Mainly found from the Library Catalogue, also by library browsing. Reading the chapter list and index allows you to find the relevant information more**	**Textbooks contain a wide range of information on a very specific subject. Tend to give you a more general overview of the subject than journals**	**All books used were either from the Pilkington Library, WEDC resources centre, or books which I own based on recommendations from**

	quickly. Skimming certain chapters again can help you find more relevant information.	**which tend to be very case-study-specific.**	**academics in this field.**
PhD Thesis	**Thesis used was Dr Alan MacDonald's own research project personally sent to me by him. Searching not really required.**	**Subject specific case studies of the topic, knew that they contained relevant information.**	**Information within was deemed to be of a high enough standard for a PhD to be awarded. Same information repeated in many published articles.**
Personal Experience	**Searching not required.**	**Know that previous investigations are relevant to this problem statement.**	**Built up knowledge over many years on this subject.**
Private Discussions	**Discussion with supervisor Ian Smout and Alan MacDonald.**	**Allows a vast amount of information to be gathered and allows you to bounce ideas and thoughts off of others.**	**Both are experts in their respective fields and have personal experience of some of the problems discussed.**
Articles	**New Scientist, Science, and other articles were read. Individual articles were searched through the magazines' websites.**	**References within these articles were followed up and these have been referenced.**	**Quality is difficult to check, hence only used in this report if there were credible references attached to the articles which were further investigated to verify claims.**
Government Websites	**Websites BGS, and NERC Open Access were searched to find relevant information.**	**Governments conduct and pay for a vast amount of geological research. The data collected is often very useful and available in the public domain.**	**Government supported departments ran by leading academics in the field of geology/geophysics.**
Google/(Scholar)	**Keywords typed-in in a coherent and sensible order/combination, brings up some key journal articles.**	**Easy to use, good first step in scoping what information is already out there.**	**Information only included in report if it came from a reputable source, i.e. peer reviewed journal, government website etc…**

Literature Review of Clay and Conductivity

The first piece of information that has to be sourced, is how do rocks (and more importantly clays) actually conduct electrical currents? Appreciation of how rocks/clays conduct will enable us to determine whether or not they can be identified using electromagnetic surveying techniques. Kearey et.al, (2002), states that the conductivity of a particular specimen is dependent upon the chemical composition, size, shape and orientation of the grains. It is also strongly influenced by porosity and the abundance of fractures due to the main conductors in rocks being freely mobile ions. As early on as the 1940's, Archie, (1942), noted how the electrical conductivity of rocks can be related to its physical properties. The formula he created (see below) has been used as a firm foundation for all other subsequent relationships derived to match electrical conductivity to physical properties. It has been used with great success frequently by the hydrocarbon industry.

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

Archie's Law

Where…

σ_0 = measured conductivity of the rock
σ_w = conductivity of the pore water
φ = porosity
m= constant
F= formation factor

The problem with this rather simple formula is that it is only really dependent on the porosity and the ion abundance within the rock. In clays it is well known that the majority of currents pass along the actual grain surfaces, which Archie's Law does not take into consideration.

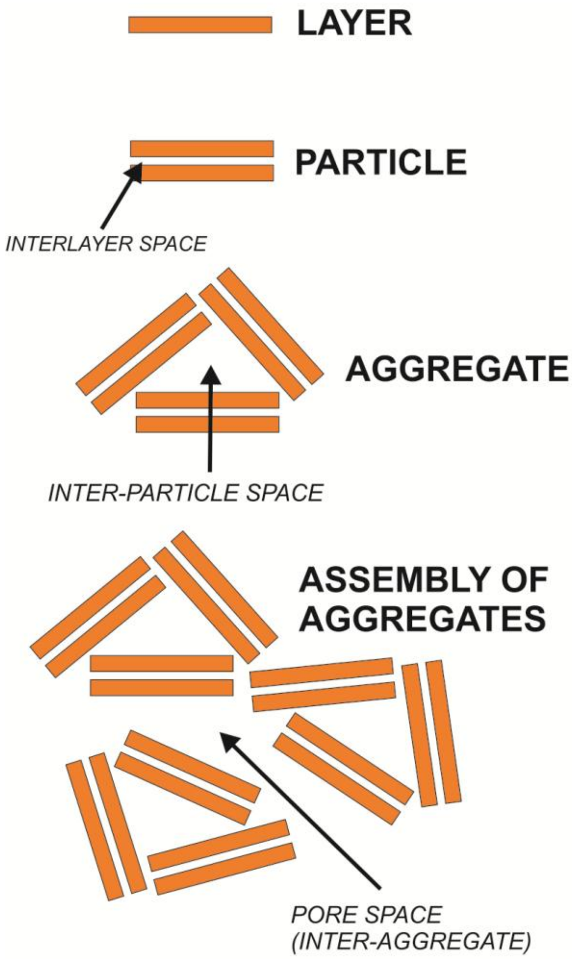


Figure 3.1: ***The microscopic structure of clays. Usually micro-metres in size.***

To understand what makes conductivity in clays unique we need to first understand the microscopic structure and properties of clays in general (and more specifically for this study, smectite and illite). Clays are often thought of as being plate-like in shape. Clay particles have incredibly large surface areas relative to their volume. Bergaya and Langaly, (2006), describe simply how clays are made up; Figure 3.1 has been adapted from their work. These assemblies of clay minerals are held together by electrostatic forces. Clay layers are highly charged and as a consequence, layers are attracted together to make particles, particles are attracted together to make aggregates etc…

It is because of these highly charged surface areas that a substantial amount of current travels along the surfaces in clayey materials, and the reason why simple formulas, such as Archie's Law, cannot be used.

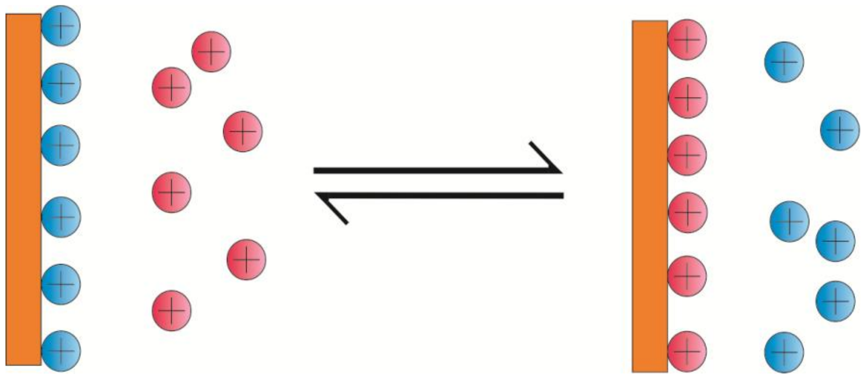


Figure 3.2: ***Cation Exchange Capacity (CEC). Notice the swapping movement of the blue and pink positive ions on the clay surface.***

What needs to be taken into consideration is a phenomenon known as *Cation Exchange Capacity* (CEC) - something particularly prevalent in clays. Wilson, (1994), defines CEC as:

The sum of exchangeable cations that a mineral can absorb, at a specific pH, i.e. a measurement of the negative charges carried by the mineral.

Put simply, this refers to how well positive ions (cations) can move along the surface of a clay mineral. **Clay surfaces are highly negatively charged**; consequently they attract positively charged ions to their surface. When a voltage is applied to the clay minerals, the cations which were stuck to the clay surface can be replaced by other cations which are in solution nearby. This swapping movement of charge creates a current which can be detected. Figure 3.2 is a diagram adapted from Bergaya et.al, (2006), to illustrate CEC.

The phenomenon of CEC indicates that there are numerous ways in which currents can travel through a rock body. Ruffet et.al, (1995), clearly states that it is impossible to estimate electrical conductivity from porosity alone; two different samples with the same value of porosity will not have the same electrical conductivity even if they both contain exactly the same pore fluid. They go on to state that when a fluid meets a boundary (i.e. the surface of a clay mineral) either an electrochemical reaction can take place or a double layer can be created (the double layer is an important concept which is described with more clarity by other authors). The theory of the electric double layer was first developed by Clavier et.al, (1977). de Lima and Sharma, (1990), state that the double layer corresponds to the layer of ions next to clay surfaces which will undergo CEC (Figure 3.2),plus a layer of ions within the pore-water sufficiently far away enough to not be influenced by the electrostatic pull of the clay surfaces. The freely mobile pore water is not influenced by the presence of the clay surface, as from a distance the electrostatic effects of the negatively charged clay surfaces and the surrounding positively charged cations nearby cancel one another out, resulting in zero net charge (Adamson, 1982). Figure 3.3 is a diagram representing the electric double layer.

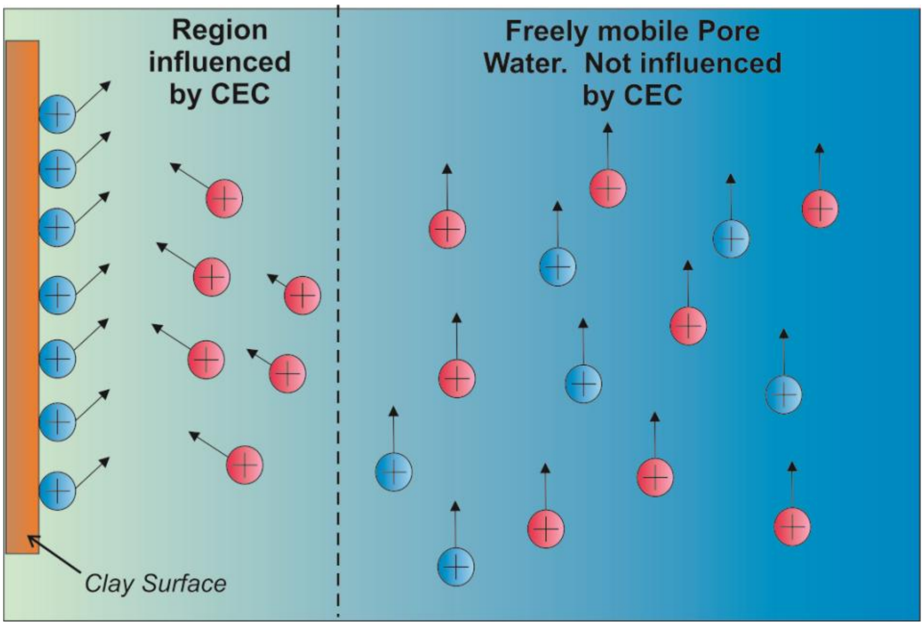


Figure 3.3: ***The electric double layer***

Tabbagh and Cosenza, (2007), state that the region in Figure 3.3 which is not affected by CEC, the freely mobile pore water, is known as the *Volume Conductivity* (sometimes referred to as the *pore water conductivity* or the *electrolyte conductivity*), and the region affected by CEC is known as the *Surface Conductivity*. In most rocks, such as sandstone and limestone, this surface conductivity is negligible, as most grains do not carry a significant amount of charge on their surfaces. With clays, however, the surface conductivity can often be many times greater than the volume conductivity. Consequently, it has to be taken into consideration.

As one would expect, there is a definite link between CEC values and surface conductivity (as surface conductivity happens due to CEC). CEC is measured in units called 'milli-equivalents per gram' (meq/g) and conductivity is given in units 'milli-mho's per metre' (mmhos/m) or 'milli-siemens per metre' (mS/m). It should be pointed out the siemen is the S.I unit of conductivity, however, the siemen and mho are exactly the same i.e. 1.0 mho = 1.0 S. Conductance is the inverse of resistance, so traditionally, for the unit of conductance, scientists just wrote the unit for resistance (the 'ohm') backwards. MacDonald, (1999), states that surface conductivity (σ_S) is directly proportional to the CEC and is described by the relationship $\sigma_S \cong 2.5 \times \text{CEC}$. Revil and Glover, (1998), give values of CEC as 0.04 meq/g for kaolinite, 0.22 meq/g for illite, and 1.5 meq/g for smectite. What this shows is that smectite has a significantly higher value of CEC than illite and kaolinite; therefore this will result in a greater value of surface conductivity, which means it should be possible to distinguish between these different types of clay using EM34 surveying methods.

What can be concluded by reading information presented by the aforementioned authors in this literature review is that the total conductivity is a combination of the surface conductivity plus the volumetric conductivity.

Many models have been put forward to incorporate the effects of the surface conductivity, and move on from the basic Archie's Law. Some of these proposed models will be discussed in more detail in Chapter 5. These models are essentially a mathematical description which links the total measured conductivity to the surface conductivity and the volume conductivity.

The information presented so far is a robust and complete discussion on how conductivity manifests itself on a microscopic scale. There is a vast amount of information published on this topic. Also, there is a vast amount of information out there on how to conduct EM34 surveying and the ability of EM34 to distinguish between different types of geology. What is harder to find, however, is any literature on the specific problem which this dissertation is trying to address: does this microscopic behaviour of conductance in clays manifest itself in macroscopic EM34 data? Can EM34 distinguish between smectite and illite in the subsurface?

To date, the author has been unable to find any literature relating to the ability to distinguish between smectite and illite using conductivity surveying techniques from ground level. It is not only rural water supply problems which have not been addressed, but also wider topics under the scientific/engineering umbrella. Really, the only documents where there does appear to be any information on the topic comes from Alan MacDonald of the *BGS* who suggested this particular problem at hand for investigation. MacDonald, (1999), noticed that the potential for sustainable rural water supplies in the Oju and Obi area is governed by the proportion of smectite and illite in the subsurface. Figure 3.4 is taken from this document and illustrates that preliminary investigation into this problem has taken place on a macroscopic/ground-surveying level. A clear distinction can be made between clay type and measured conductivity by referring to this diagram. This

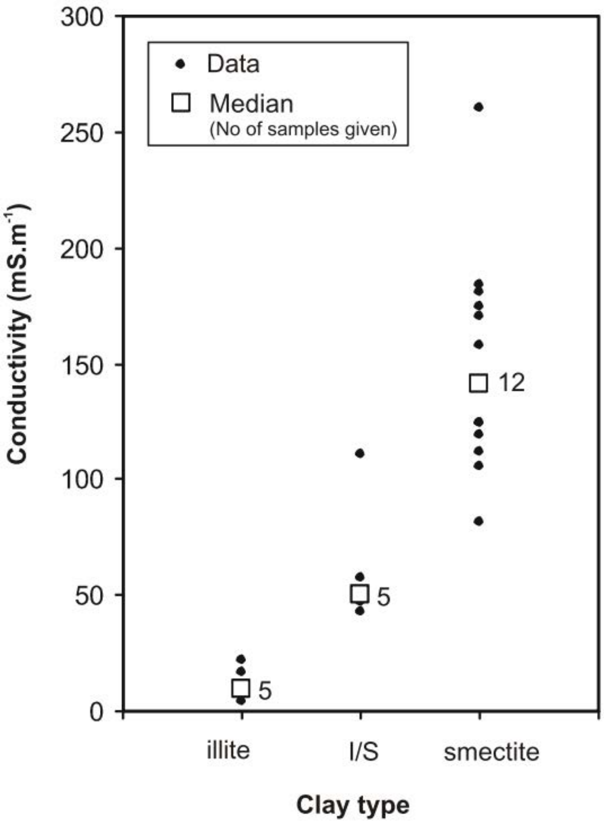


Figure 3.4: *Relationship between clay type and conductivity.*

document, and others by MacDonald, provides a good foundation for addressing the problem. Whilst MacDonald appreciates that rural water supply is partially governed by the smectite-illite ratio and that this ratio is mimicked in measured EM34 bulk conductivity data, he does not go on to explain the implications of these findings. Furthermore, only a few data-points have been included and there is no reference to the processing steps undertaken to plot these on Figure 3.4.

Critical Review of the Literature

The works by Kearey et.al, (2002), and Archie (1942), give clear and simple explanations as to how electrical currents pass through most rock types. They are good sources of literature to use for those who wish to understand more about conductivity surveying but do not have a geological background. Information is presented describing the different ways in which rocks conduct electricity. Attention is paid as to how this happens within the rocks and minerals themselves and a description is given as to how pore water conducts electricity with a particular emphasis on how porosity and permeability facilitate the conduction. For this particular problem at hand however, there is an over-simplification in their works, most notably that they do not take into account the surface conductivity in clays.

Ruffet et.al, (1995), provides an excellent overview of surface conductivities in rocks. They go on to explain some of the many ways in which people in the past have tried to create a link between clay type and conductivities on a microscopic scale. Summaries of the works of Bussian, Johnson and Sen, and Waxman and Smits (see Chapter 5) are presented. This paper essentially is a comprehensive review of the different equations which have been published so far to describe the influences of both surface conductivities and pore water conductivities on the measured conductivities. The paper provides an excellent overview of work already completed on a microscopic level but it does omit some key steps and equations which then have to be sourced from the original author's work. Alas, describing phenomena on a microscopic scale is something which all the authors seem to be very good at; the problem is that none of them go on to explicitly state how their findings can be scaled up for practical fieldwork use.

Revil and Glover, (1998), de Lima and Sharma, (1990), and Tabbagh and Cosenza (2007), present worthy information. Each of these authors have created new equations which attempt to try and describe the relationship between clay and conductivity, and other theoretical background information is presented which is useful (such as the appreciation of the link between CEC and surface conductivity, and the fact that in clays the surface conductivity often dwarfs the pore water conductivity on a microscopic scale). These three papers are, in essence, all trying to decipher the same thing: how does conductivity relate to clay-type on a mathematical level? As such they dispute each other's models and they are all presenting their own models which they think are more scientifically sound. The issue is, however, that these authors go into incredible amounts of detail which is not needed to address our particular problem. They focus heavily on the complicated mathematics which describes such physical phenomena, and they only contain snippets of information which is useful in helping us to understand our problem. The works by de Lima and Sharma, (1990) and Tabbagh and Cosenza, (2007) also have dramatic pitfalls in that they have forgotten to state what some of the terms in their equations actually mean! This is a catastrophic error because unless the reader is already very familiar with the topic it renders their whole work useless. Even more frustratingly, these two do not even clearly state which equation is the one which should be applied and as such they are very difficult papers to interpret. They may well have come up with some very useful ideas, but because of these mistakes their work has not been used anymore in this report.

The works of Revil and Glover, (1998), and other authors yet to be mentioned, will be discussed in Chapter 5 as they do present sound mathematical equations which could be used to see how well the dataset from Oju and Obi measured on a large scale compares to what is predicted by smaller-scale theoretical, mathematical models.

The only author who so far appears to have done any work on clays and conductivities on a field-scale level is MacDonald, (1999). MacDonald has used some of the information presented by the other authors already mentioned to hypothesise how the smectite to illite ratio is having an effect on his bulk conductivity measurements. MacDonald certainly appreciates that there is a link; however no effort is made to try and describe this link between clay type and conductivity by identifying a quantitative relationship between the two.

Justifications for investigating the proposed problem

What the literature review has shown is that there is a need for this investigation to be carried out. The justifications for why this is the case are as follows:

- Sufficient amounts of work have been completed to give a sound foundation from which this investigation can progress.
- Larger-scale investigations into this problem are few and far between, if not non-existent.
- There is too much of a microscopic focus. Whilst this is necessary, the findings of these investigations cannot be used for practical purposes.
- This problem has not been investigated before, meaning that the findings of this investigation will be fresh research and not just confirming the results of somebody else’s work.

- As an aspiring water professional with a geophysical/geological background, the author is well placed, and is passionate enough, to complete this research to a high standard.

Logical Framework

Before going on to discuss how the research was carried out in Chapter 4, it is wise to present a logical framework for the research project. This allows the author to plan successfully the steps needed to carry out the research and it allows the reader to see a unique summary of the research as a whole. The format of the framework is based on that of Sansom et.al, (2011). Table 3.2 is the logical framework.

Table 3.2: ***The Logical Framework***

CLAYS, CONDUCTIVITY, AND RURAL WATER SUPPLIES			
Objective Summary	**Objective Verifiable Indicators**	**Means of Verification**	**Important Assumptions**
Goals			
To increase the success rate of finding sustainable groundwater supplies in rural, water-stressed areas such as SSA.	The success rate of boreholes drilled in SSA which strike suitable groundwater increases.	Global statistics published by the UN, WaterAid etc show this to be the case.	The increased success rate can directly be attributed to the aim.
To be able to identify likely suitable locations of groundwater using remote sensing. (*Remote sensing is discussed in more detail in Chapter 7*).	It is proven that remote sensing data analysing soil/rock types can lead to identification of groundwater supplies.	Publications are produced in scientific journals using data from NASA, ESA etc.	It is actually possible to distinguish between illite and smectite from satellite data, and is there a link between remote sensing and EM34?
To reduce illness and disease by providing wholesome, clean and plentiful water supplies.	Child mortality rates decrease, age expectancy increases, decrease in water-borne diseases in areas where suitable groundwater has been found using smectite/conductivity relationship.	WHO and national statistics produced showing these trends.	These trends can be directly attributed to the aim. People actually read the dissertation and journal article and take the findings onboard.
Aim			
To find a relationship between smectite content and measured conductivity.	Completion of an MSc dissertation which passes. Publication of a journal article.	Papers accessible in WEDC resources centre and journal article available through online access.	Markers and peers deem the work to be of a satisfactory standard to award an MSc and to accept journal article for publication.
Outputs			
Chart comparing actual experimental results with	Calculations from theoretical models produced and used	Check final MSc dissertation and journal article.	Estimated values can be found for every required

theoretical models.	in chart against our own data.		parameter in each of the equations.
Graph of smectite vs conductivity for extended dataset.	Conductivity values calculated from EM34 graphs, smectite content taken from inferred clay mineralogy.	Check final MSc dissertation and journal article.	A relationship does exist, boreholes lie on EM34 profiles, conductivity values can be calculated, smectite content was able to be estimated.
Values of inferred smectite contents created for 33 boreholes.	Averaged smectite values calculated for each geological formation.	Excel document created.	Each type of rock from each formation already has a true smectite content in the gold-star dataset so that an average can be taken and used for the 33 boreholes.
Graph of smectite vs conductivity for Gold-Star dataset (see Chapter 4).	Conductivity values calculated from EM34 graphs, averaged smectite values taken from clay mineralogy data.	Check final MSc dissertation and journal article.	A relationship does exist, boreholes lie on EM34 profiles, conductivity values can be calculated.
Cross referenced list of surveys, boreholes and GPS positions.	Colour coded list created with data sourced from EM34 excel documents, and village reports.	Microsoft Word document created.	The boreholes lie directly over an EM34 profile for this output to be of any significant use.
Map Produced.	A0 map printed with surveys and boreholes plotted on.	Map printed and in use.	Digital map is of high enough resolution to enable clear printing.
Inputs			
Clay mineralogy data sourced.	Smectite % has been calculated downhole for selected boreholes to a reasonable depth.	Data can be tied to boreholes in the Oju and Obi area, found in Appendix document.	The relevant data is sent by the BGS.
Lithological Logs sourced.	Graphical representations including a key are sent in village reports.	Borehole information (in village reports) correlates with geological map.	The relevant data is sent by the BGS.
Localities sourced.	Each EM34 survey and each borehole has an assigned set of GPS coordinates.	Documents and spreadsheets contain measured localities.	The relevant data is sent by the BGS.
EM34 data sourced.	Graphs of conductivity vs distance are produced for each profile for both coils.	Excel documents containing data.	The relevant data is sent by the BGS.

Chapter 4 - *Methodology, Analysis, and Interpretation*

To investigate this particular problem, which this dissertation is addressing, the reader would not be far wrong in assuming that a substantial amount of fieldwork would have to be undertaken. However, the sheer enormity and quality of the data collected by the *BGS* is more than sufficient for the purposes of this study. After discussion with Alan MacDonald at the *BGS* it was realised that a desk based approach would work in answering this particular problem at hand. The main reasons for this are as follows:

1. Hundreds of kilometres of EM34 data had already been collected over a water-stressed region in SSA.
2. Extensive geological mapping had been undertaken in the region, enabling correlations to be drawn between EM34 data and the geology beneath the surface.
3. Over fifty boreholes had been drilled over the region, and data on water yield and water quality has been found for each.
4. Expensive, time-consuming, and detailed clay mineralogy analysis has already been completed on a selection from the fifty boreholes.
5. Initial interpretation of the data has already taken place.
6. This particular dataset was gathered with the primary aim of increasing the success rate of finding groundwater for sustainable rural supplies. Consequently, using this data as our dataset means that the methods which the author has applied to this region in Nigeria can be replicated with other datasets which have already been collected in water stressed areas.

Furthermore, the data collection mentioned above took much longer than the timescale allowed for completion of this MSc dissertation alone. Therefore, to have even tried to gather a dataset far less substantial than the one completed by the *BGS* would have taken too long and would have been far too expensive.

A desk based approach to the study has its advantages. First and foremost, it allows the author a lot more time to complete computational processing and analysis of the dataset; from this a more detailed relationship between smectite content and ground conductivity can be derived. Furthermore, the added time allows comparisons between this dataset and more theoretical mathematical models to be completed, strengthening the findings of the desk study.

Processing Steps

In order to distinguish a relationship between smectite content and ground conductivity a vast amount of processing steps had to be undertaken. After the dataset was sent by the *BGS* the first task was to identify what data had actually been gathered. Table 4.1 is a summary of the datasets received.

Table 4.1: ***Datasets received from the British Geological Survey***

Documents Received	***Format***	***Description***	***Quantity***
Geological Maps (MacDonald and Davies, 1998)	PDF	Maps of the geology and hydrogeology of Oju and Obi, Benue State, Nigeria, both qualitative and quantitative, GPS co-ordinates and scale given, groundwater levels, locations of rain gauges and boreholes given, water quality data given.	2
Geophysics Survey Data	Microsoft Excel Spreadsheet	EM34 conductivity, magnetic profiling and Wenner resistivity surveying data. Most files include multiple surveys. Files are named in terms of villages. GPS positions of the start of the surveys and bearings/strikes of the survey profiles are given.	41
Clay mineralogy data	PDF	Variations in clay proportions with Kaolinite, Illite, Illite/Smectite, and Smectite clays down a selection of boreholes; given as a percentage. Also total clay content within rock is given.	2
Clay vs Conductivity	Microsoft Excel Spreadsheet	Graphical representations of clay proportions down-borehole. Also includes straight line graph plots of a small number of data-points of smectite content in rock vs bulk conductivity.	2
Village Data Reports (not published)	Microsoft Word Document and PDF	Water quality data for the boreholes, qualitative information about each village, a summary concerning the surveys which took place in each village, the findings of the surveys, and the potential for sustainable rural groundwater water supplies inferred from local knowledge and pumping tests on *BGS* boreholes.	11
Main project report (Davies	Microsoft Word	A summary of most of the information above, plus diagrams of lithological logs down each of	1

and MacDonald, 1999)	Document and PDF	the boreholes drilled by the *BGS.*	
PhD Report (MacDonald, 1999)	PDF	Alan MacDonald's PhD report including more detailed diagrams and findings of the above information.	1

Table 4.1 will allow the reader to appreciate the vast amount of data which was collected by the *BGS* over the lifetime of their project. These sixty documents were each often hundreds of pages long if they were word documents, and often dozens of spreadsheets in size if they were excel documents. Naturally, the first stage in beginning the analysis of this project was to organise and cross-reference all of this data so that it could easily be sourced.

Listing and Cross Referencing the Data

The initial step was to create a list of all of the relevant data which would be needed to solve the problem in question. A numbered list of all of the different types of surveys/boreholes was created with GPS coordinates and page/sheet/document references. In total there were twenty eight relevant EM34 ground conductivity surveys, twenty three magnetic profiles, twenty seven VES (vertical electrical sounding) Wenner array resistivity surveys, and fifty boreholes. It was later noted that the VES and magnetic surveys were not strictly directly relevant to this particular problem at hand. This inventory of data collected was extremely useful in being able to identify what data was actually available within this dataset. The inventory can be found in APPENDIX II**.**

The Hydrogeological Map

Due to the difficulty of trying to interpret information in list-form, the next sensible stage was to print, in A0 size, the hydrogeological map of the area. With the aforementioned list, the surveys were colour coded (depending on the type of survey i.e. EM34, VES etc…), and also numbered. Using the grid coordinates of each of these surveys and boreholes, each was plotted on the printed-off map so that a clear visual representation of where each survey took place, and on what geology it took place on, could easily be seen. This had a vast advantage over trying to identify where surveys had taken place by just looking at a set of GPS grid coordinates alone, and it also aided in the interpretation of the information by having the data actually plotted on a hydrogeological map.

Correlating Boreholes and EM34 Surveys (Calculation of Bulk Conductivities)

It was postulated at the time that the majority of the boreholes which were drilled by the *BGS* should be located at precise points along the EM34 survey traverses. Further analysis of the data proved this to be the case, as the whole point of the *BGS* conducting these surveys would be to identify where the best position would be to drill their boreholes. It would make very little sense for them to site a borehole not directly above an area which they had surveyed. By referring to the annotated hydrogeological map of the area it was clear to see which boreholes appeared to be sited directly on, or very close to, EM34 surveys. Investigation of the relevant EM34 conductivity spreadsheets then enabled easy identification of the precise locations of the boreholes.

For each EM34 traverse, data was collected using both a horizontal coil and a vertical coil. The reader must note that the horizontal coil actually measures vertical dipoles (vertically orientated currents) within the sub-strata, and the vertical coil measures the horizontal dipoles. The horizontal coil is particularly sensitive at being able to measure vertically orientated fractures within the sub-surface, whilst the vertical coil is particularly sensitive to the horizontal layering of different rock types. As we are primarily concerned with the underlying geology, only the conductivity data from the vertical coil has been used in our analysis. Using the vertical coil also has an advantage in that fifty percent of the signal received originates from the top ten metres beneath the ground surface, a handy coincidence as we have detailed clay mineralogy analysis for the top ten metres of most boreholes; however, for the horizontal coil,

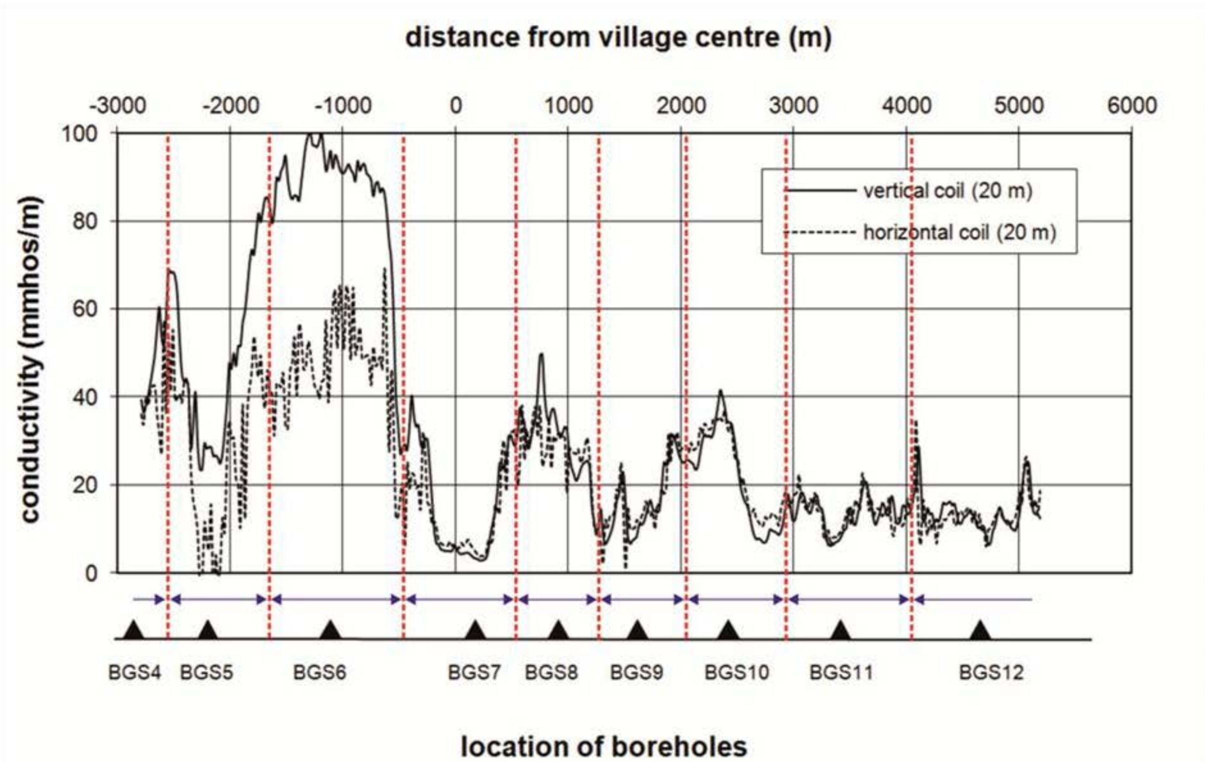


Figure 4.1: ***An example of the locations of boreholes along an EM34 traverse. The red dashed lines and purple arrows represent the boundaries of each borehole. For example, the boundaries of BGS5 go from -2532m to -1658m, therefore an arithmetic average of bulk conductivity was calculated from each conductivity measurement taken within this range.***

fifty percent of the signal originates from approximately the top twenty metres beneath the surface (much deeper than what we have data for, making it unsuitable), MacDonald, (1999).

The EM34 conductivity spreadsheets each had a plot of distance along the traverse against bulk conductivity. An example of this is given in Figure 4.1. At this point, knowing the position of the borehole along the traverse, it could have been quite easy to just read off a single value of bulk conductivity for the vertical coil. The issue with this, however, is if one of these readings is in fact an anomaly or an error in the data. Consequently, what was done was an arithmetic average of many of the bulk conductivities either side of the borehole to smooth out any anomalies.

After this had been completed each of the fifty boreholes had a single (averaged) bulk conductivity value associated with it.

Clay Mineralogy Analysis

As the boreholes were being drilled in the Oju and Obi area, geological samples were taken at various depths. The primary aim of this was to identify the different sequences of geology across the area to try and infer likely aquifer locations. A secondary by-product of this being completed was the ability to complete clay mineralogy analysis on some of the rock samples. The rock samples from seventeen, out of the fifty in total, boreholes underwent clay mineralogy sample analysis at the *BGS* headquarters in Keyworth, Nottingham. Clay mineralogy analysis basically allows you to determine how much clay there is in total in a given rock sample, and it also enables you to distinguish what *type* of clay is present within the sample. Essentially, there are four main types of clay found in the rocks from the Oju and Obi area: kaolinite, illite, illite/smectite (a stage in-between illite and smectite), and smectite. The seventeen boreholes which underwent detailed clay mineralogy analysis are here on in referred to as the '*Gold-star dataset*'; the reason being is that for these boreholes we have a value of bulk conductivity and we have a precise value of the smectite content within the rocks. It should be noted that smectite is being analysed instead of illite as it is easier to distinguish. Whilst we are interested in illite (as it has water bearing fractures) its CEC is very similar to kaolinite. Smectite's CEC is much larger (see Chapter 3). This is not too much of a problem however, because the process of geological triangulation (Chapter 2) should enable you to use other field observations to note that metamorphosed areas are present, thus suggesting illite is present over kaolinite.

Table 4.2 shows how the value of the average smectite content in the rock was calculated. By summing together the 'pure' smectite and the smectite in the illite/smectite mixed clay it is possible to ascertain a value of the total smectite proportion of the clay. For instance, at 1.5m depth the percentage of the clay which is smectite is actually 43.2%. Work undertaken at the *BGS* showed that in most cases fifty percent/half of the rock was clay in nature. Therefore, to get the smectite proportion of the *whole* rock (not just in the clay) the 'Smectite TOTAL' has to be halved again to get the percentage of smectite, which in this case is 21.6%. Doing this for all of the depths then allows you to calculate the average smectite proportion present down the borehole by simply taking an arithmetic average, in this case 17.38%; it is this value which can then be plotted graphically against the bulk conductivity (already calculated) to see whether there is a relationship between smectite content in the rock and bulk conductivity measured at the surface.

Table 4.2: *Calculation of smectite proportion in rock for borehole BGS 34. The red value is the average smectite content down the entire borehole*

Borehole	Mean depth (m)	Formation	Smectite	Smectite in Illite/ Smectite	Smectite TOTAL	Smectite in rock	Geology
34	1.5	Awgu Shales	0	43.2	43.2	**21.6**	Soil/Clay
34	2.5	Awgu Shales	0	47.04	47.04	**23.52**	Clay
34	3.5	Awgu Shales	0	36	36	**18**	Clay
34	4.5	Awgu Shales	0	28.2	28.2	**14.1**	Clay/ Weathered Mudstone
34	8.5	Awgu Shales	0	31.2	31.2	**15.6**	Weathered Mudstone
34	29.5	Awgu Shales	0	22.26	22.26	**11.13**	Mudstone
34	30.5	Awgu Shales	0	23.45	23.45	**11.725**	Mudstone
34	31.5	Awgu Shales	27	19.8	46.8	**23.4**	Mudstone
						17.38	

Smectite Content and Bulk Conductivity Relationship

For the gold-star dataset the above processing steps were completed to ensure that all boreholes had an associated measured bulk conductivity and an average smectite content. Figure 4.2 shows this relationship.

The observant reader will notice that in Figure 4.2 there are only fourteen data-points, whereas previously it was stated that seventeen boreholes underwent thorough clay mineralogy analysis. Data from three of the boreholes were not included for the following reasons:

- Boreholes BGS13 & BGS32 are not included as their precise location along one of the EM34 traverses is not known from the data provided. Consequently, no value of conductivity could be estimated.
- Borehole BGS35 penetrated dolerite. Dolerite is an igneous intrusion thrusted upwards from the underlying mantle into the earth's crust. It has a very different geology to the sedimentary rocks which make up the rocks of Oju and Obi. It does contain smectite but only due to weathering of the dolerite and the surrounding rocks. Unweathered parts should not contain smectite. Therefore, it does not fit well onto the graph and thus has been omitted.

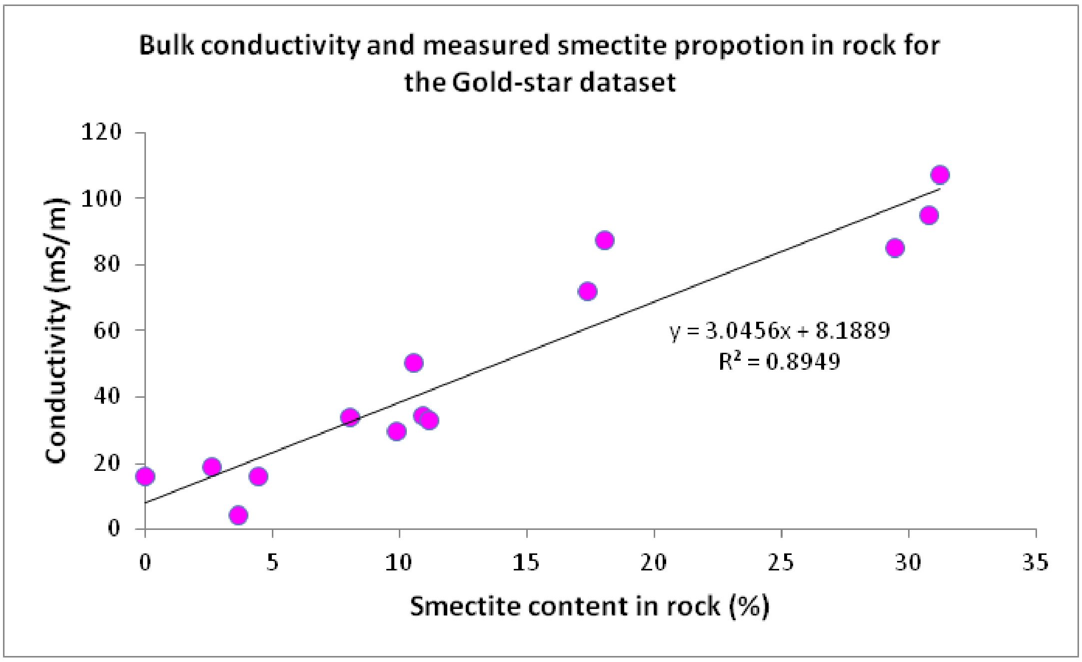


Figure 4.2: ***The relationship between smectite content and measured conductivity for the gold-star dataset***

Calculation of Clay Mineralogy for other Boreholes

Whilst the processing of the data, for the seventeen boreholes which had clay mineralogy data, was relatively straightforward, the approach to include the other thirty three boreholes without clay mineralogy data was more complicated. Whilst the method for working out the bulk conductivity attributed to each borehole was the same as what has already been described, estimations of smectite content in the rock was more tricky. Without having detailed clay mineralogy analysis for these boreholes, the smectite content in the rock would have to be estimated.

Fortunately, although these thirty three boreholes had not had clay mineralogy studies undertaken on them, they had still had rock samples taken down-borehole so that lithological logs could be created. This enabled estimations of smectite content to be made.

Across the region it was postulated that the smectite proportion in a particular type of rock should not vary greatly provided all the rock samples were from the same formation, i.e. the smectite proportion in a sandstone rock from the Makurdi Sandstone formation should be similar to another sandstone rock many kilometres away, provided that sandstone too was part of the Makurdi Sandstone formation. The reason for this is because the underlying geology of a particular formation should be relatively uniform across the area and also, the whole formation across the area has undergone the same tectonic regimes resulting in the same variations in temperature and pressure applied to the rocks over time. Therefore, in the transition from smectite to illite (due to diagenesis and early metamorphism, which is essentially caused by changes in both heat and pressure) one would expect the same proportion of smectite to have converted to illite across the formation. Therefore, it is possible to use the values of smectite content from the seventeen boreholes which have undergone clay mineralogy analysis to infer the amount of smectite in other boreholes.

Table 4.3: ***Clay mineralogy analysis of boreholes in the Awgu Shales formation.***

Borehole	Depth (m)	Smectite in rock (%)	Geology
27	14.5	**30**	Limestone
27	19.5	**31.5**	Limestone
30	1.5	**19.5**	Soil
30	2.5	**26**	Clay
30	3.5	**31**	Clay
30	4.5	**26.5**	Clay/Fine Grained Sand
30	5.5	**27.5**	Fine Grained Sand
30	6.5	**33.5**	Fine Grained Sand
30	7.5	**31**	Weathered Sandstone
30	8.5	**37**	Weathered Sandstone
30	9.5	**30**	Weathered Sandstone
30	10.5	**32**	Mudstone
31	1.75	**19.5**	Soil
31	2.25	**32**	Soil
31	2.75	**27**	Soil/Clay
31	3.25	**31**	Clay
31	3.75	**34**	Clay
31	4.25	**31.5**	Clay
31	4.75	**36.5**	Clay
31	5.25	**38**	Clay
34	1.5	**21.6**	Soil/Clay
34	2.5	**23.52**	Clay
34	3.5	**18**	Clay
34	4.5	**14.1**	Mudstone
34	8.5	**15.6**	Mudstone
34	29.5	**11.13**	Mudstone
34	30.5	**11.725**	Mudstone
34	31.5	**23.4**	Mudstone

Table 4.3 represents the boreholes which have undergone clay mineralogy analysis in the Awgu shales formation; this was used to calculate the average values shown in Table 4.4. For example, using Table 4.4,

one can estimate that the amount of smectite in a mudstone rock, found anywhere in the Awgu Shales formation, would be 32%.

These tables were created for each of the six major formations concerned: namely *Upper Eze Aku, Lower Eze Aku, Makurdi Sandstone, Asu River, Dolerite, and Awgu Shales* (presented). It is these average tables, alongside lithological logs, which were used to estimate the average smectite content in the other thirty three boreholes which had not undergone the clay mineralogy analysis.

Using the lithological logs it was possible to measure how far down beneath the surface each of the different rock types extended for. Figure 4.3 is an example of one of these lithological logs for borehole BGS5 in the Upper Eze Aku formation. For the gold-star dataset, clay mineralogy data was usually given for every metre below the ground level, usually starting at 1.5m below ground level and finishing at 9.5m below ground level. To keep things consistent with the gold-star dataset, in the majority of cases, smectite content has been estimated for every metre below ground level starting at 1.5m and finishing at 9.5m. Table 4.5 shows the estimated smectite content for every metre below ground level down to 9.5m for borehole BGS5. The reader is encouraged to note the correlation

Table 4.4: *Average values of smectite content for each lithology in the Awgu Shales formation*

Averages	
Soil	**23.7**
Clay	**32.6**
Limestone	**30.8**
Fine grained sand	**30.5**
Weathered Sandstone	**32.7**
Mudstone	**32**

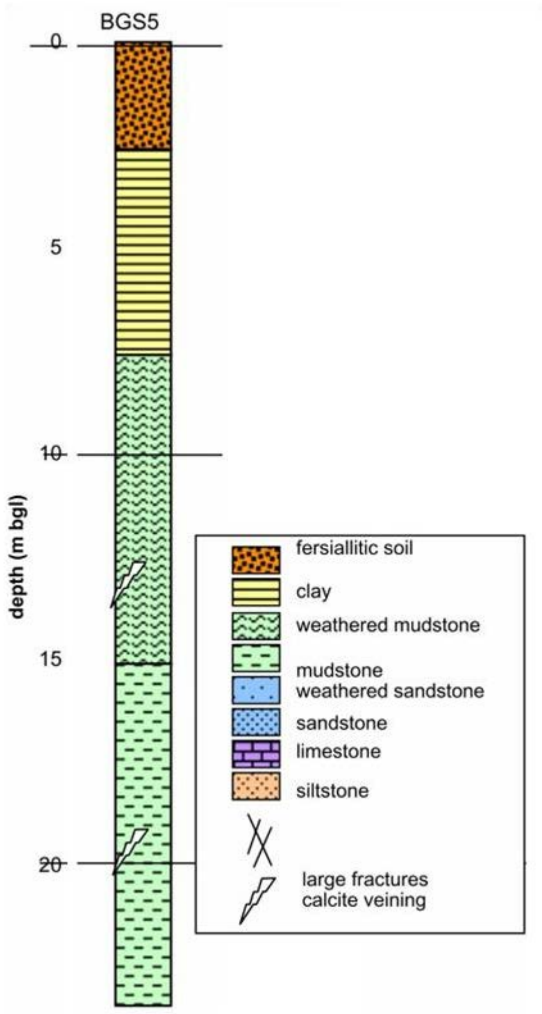


Figure 4.3*: Lithological log of borehole BGS5, 'mbgl' refers to 'metres below ground level*

between the lithological log and the table of estimated smectite content. The values in Table 4.5 were calculated from a table similar to that of Table 4.4, only for the Upper Eze Aku formation.

Table 4.5: ***Estimated smectite content for borehole BGS 5***

Depth (mbgl)	Geology	Smectite in Rock (%)
1.5	Soil	4.4
2.5	Soil	4.4
3.5	Clay	13.3
4.5	Clay	13.3
5.5	Clay	13.3
6.5	Clay	13.3
7.5	Clay	13.3
8.5	Weathered Mudstone	18.9
9.5	Weathered Mudstone	18.9
	Average	***12.6***

Once this was completed for all the remaining boreholes a dataset existed of the majority of the fifty boreholes. Each borehole had an average smectite content and an associated measured bulk conductivity. These points were then plotted alongside those from the gold-star dataset to create one master dataset of smectite content in rock (%) against bulk conductivity, thus, completing the processing of the data enabling an answer to the problem to be found.

Figure 4.4 is the graph of smectite content in rock (%) against bulk conductivity for the extended dataset.

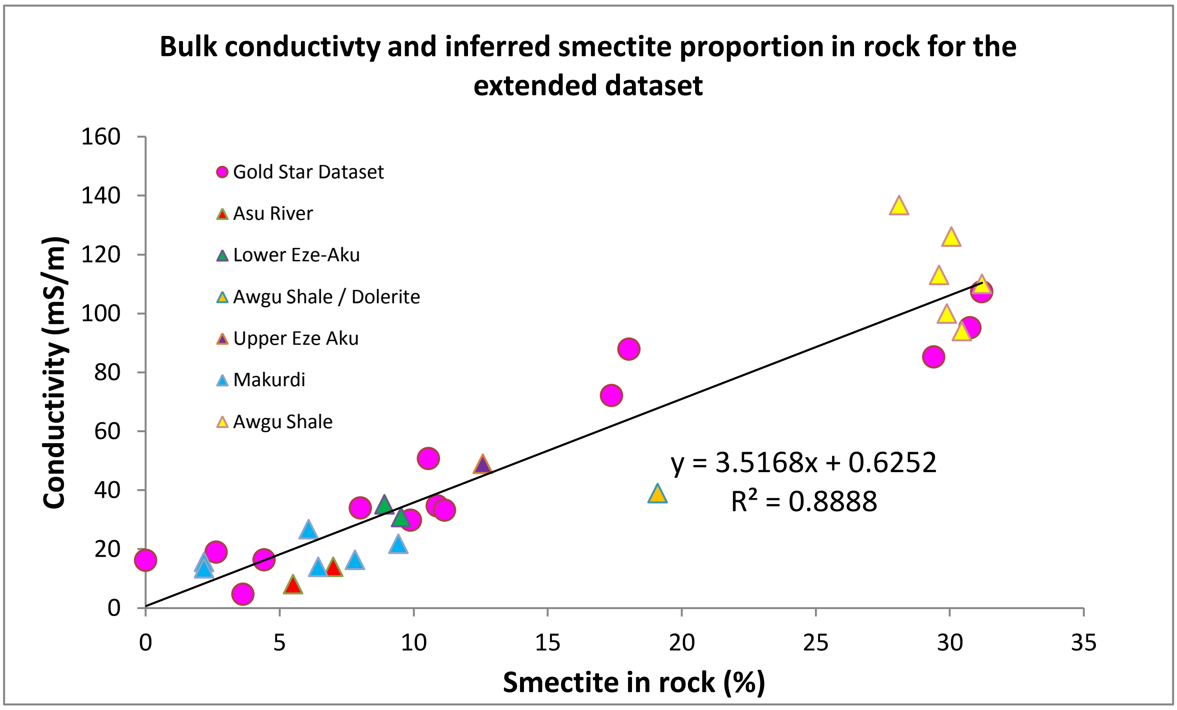


Figure 4.4: ***The relationship between smectite content and measured conductivity for the extended dataset***

Similarly to the gold-star dataset not all of the fifty boreholes have been included in this model. Primarily, there are three reasons for this:

1. The boreholes could not be sited at an exact locality along an EM34 profile, resulting in the inability to assign the borehole a scientifically sound conductivity value.
2. The boreholes contained a significant proportion of a specific type of rock which the gold-star boreholes did not contain. Therefore, it was impossible to tell what the smectite content would be in such a rock.
3. The boreholes contained a significant abundance of sandstone, which, unless it has been weathered significantly, should not contain any smectite.

Analysis and Interpretations of Findings

By referring to Figure 4.2 and Figure 4.4 it can clearly be stated that in both cases there is a clear linear relationship between smectite content in rock and measured bulk conductivity.

Gold-Star Dataset Analysis

The trendline for the gold-star data set has a good fit. A variance of 0.89 indicates a good fit to the data (1.0 represents a perfect fit, 0 represents no fit whatsoever). This indicates that there is a strong relationship between smectite content and measured bulk conductivity. Taking the equation of the line, it is possible to say from this relationship that a rock with absolutely no smectite in whatsoever would have a conductivity of 8.2 mS/m, whereas pure smectite should have a conductivity of 312.7 mS/m. The advantage of using this dataset over the extended one is that with this dataset none of the information has had to have been inferred. The smectite proportions in the rock have scientifically been precisely measured; therefore this data is much stronger at being able to clearly show a definite relationship than the extended dataset. Having said that, the downside of this dataset is that there are only fourteen data-points, certainly sufficient, but more would certainly be advantageous.

Extended Dataset Analysis

The advantage that this dataset has over the gold-star dataset is that there are far more data-points. The more data-points one has the more rigorous and strong their model is. The reader should always, however, appreciate the limitations this model has in that the smectite content has been estimated mathematically and it has not been specifically measured. The fit of the trendline is only marginally different to that of the gold-star dataset. The variance is almost exactly identical (0.89 to two decimal places), with the differences lying in the gradient and the y-intercept of the equation of this trendline. The gradient, at 3.52, is fractionally steeper than the gradient of the gold-star dataset (3.05) indicating that for every unit increase in smectite content there is a greater increase in conductivity. The y-intercept (the number which represents the conductivity of the ground when there is 0% smectite present) is also lower at 0.63 (mS/m).

In the extended dataset, there is one point which lies significantly out from the rest: the orange data-point (borehole *BGS33*) part of the Awgu Shale/Dolerite formation. Whilst it was feasible to infer values for smectite content of this rock, hence why it is included, the dolerite found at greater depths (below the 9.5m limit) of this borehole will be having a marked impact on the conductivity measurement taken at the ground surface. As a consequence, this data-point should not be taken at face value, on the contrary, there is an argument that because of the impact of the dolerite beneath the surface the reader may choose to ignore this data-point altogether.

Interpretations of the findings

The finding of a definite, positive, linear relationship between smectite content in the rock and measured conductivity allows for some rather interesting conclusions and interpretations to be drawn. The most striking thing which can be learnt from these findings is the way in which EM34 data needs to be interpreted in the future over geologically similar regions.

The key point is that this relationship shows that measured bulk conductivity *increases* with smectite content. Normally, when interpreting conductivity data, one usually would assume that any increase in measured conductivity should mask any increase in groundwater abundance. This is because, generally speaking, in most rocks, very little current actually travels along the grain surface or through the grain, and the majority of the current travels through the freely mobile ions in the pore water (often referred to as the 'electrolyte'). However, in the case of clays it well acknowledged that a substantial amount of current (often much more than what travels through the pore water) travels along the grain surface (see Chapter 3). The fact that a strong relationship exists between smectite content and measured conductivity signifies that smectite abundance is the main factor which affects measured conductivity, not the abundance of pore-water. What has also been previously discussed in this dissertation is the fact that groundwater availability for rural water supply increases with decreasing smectite content and increasing illite content due to fractures becoming more robust and staying open with increasing illite content. What this means is that people who assume that pore water is the main conductor in such water-stressed areas will be looking out for any increase in measured conductivity to signify increased water content. The relationship which has been proven in this dissertation, though, indicates that this approach would in fact be incorrect. Oddly, and counter-intuitively, in order to locate the best regions to site boreholes and wells for sustainable rural water supply, you need to look for the regions of low conductivity because these regions will indicate a region of high illite content and thus increased potential for rural groundwater supply. This fact unquestionably changes the way in which data should be analysed in these water-stressed areas of high clay content.

Whilst it must be noted that the above statements are well founded, this is only evidence of smectite being the main control on measured conductivity in horizontally orientated dipoles, as we have only analysed data taken by the vertical coil. If there is an abundance of vertically orientated, water-filled fractures (which would be resolved by the horizontal coil), the measured conductivity may be more strongly influenced by the groundwater, not the clay.

The y-intercepts on the graphs, which represent the conductivity value of the rock with zero smectite content, should not be zero or less. This is because all rocks should still conduct, even though it may be very slight. Fortunately, our y-intercept values prove this to be the case. These conductivity values could be attributed to currents passing through/along mineral grains or they could be attributed to currents in the pore water - if it exists.

Figure 4.5 is exactly the same as Figure 4.4 only the gold-star data-points have been grouped into their formations alongside the extended dataset data-points. The Asu River Group and Lower Eze-Aku formations all have low smectite values (<11%) and they also have low conductivity values. These formations are also the best for providing sustainable rural groundwater supplies as they have the highest transmissivities (see Chapter 2). On the other hand, the Awgu Shale formation (one of the worst for rural groundwater supplies) has a substantially higher proportion of smectite (>27%) and also higher conductivity values. The Upper Eze-Aku and Awgu Shale/ Dolerite formations have intermediate values of smectite and conductivity and they also have moderate groundwater potential. The Makurdi Sandstone formation does not quite fit the pattern – it has low smectite, low conductivity, but also poor groundwater potential. This can be explained by the fact that it is a sandstone formation, whereas the rest are mudstone formations. The relationship which the author has derived is predominantly for clayey mudstone formations.

Figure 4.5 can be used to derive the following general guidelines:

- **Conductivities in the region of 0-40 mS/m are likely to suggest smectite proportions of 0-11%. It is therefore likely that such areas will be illite rich and have high transmissivities suitable for rural water supplies.**
- **Conductivities in the region of 40-90 mS/m are likely to suggest smectite proportions of 11-27%. Such areas will have moderate rural groundwater potential.**
- **Conductivities in the region of 90+ mS/m are likely to suggest smectite proportions >27%. Such areas will have poor rural groundwater potential.**

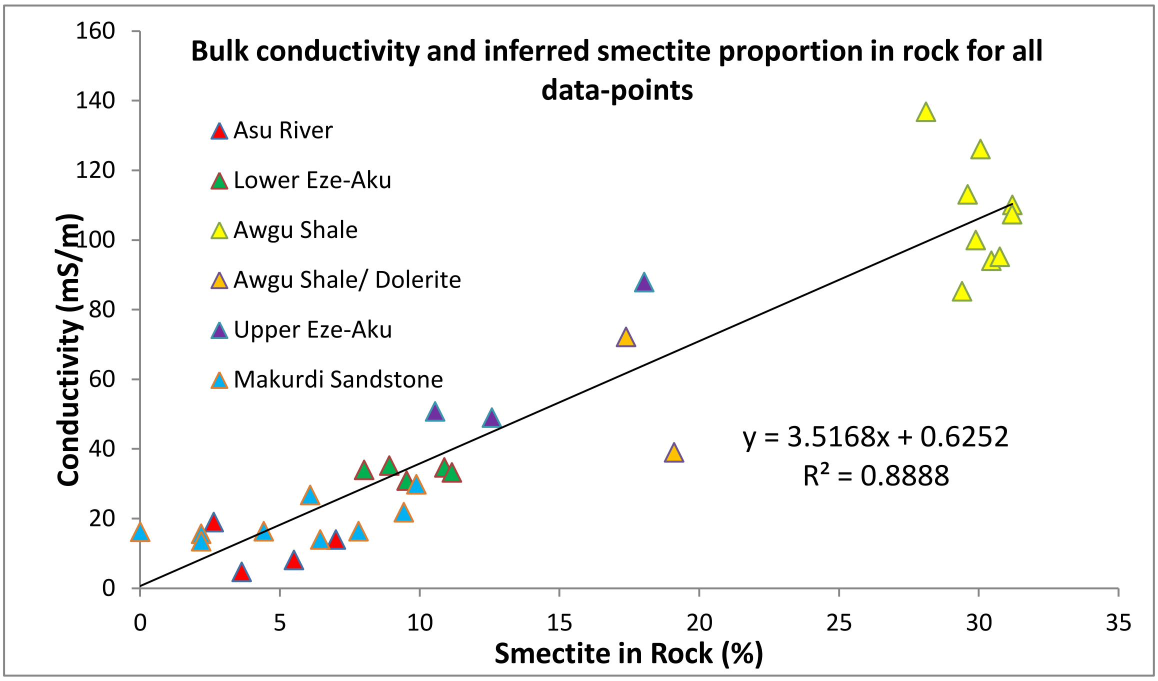


Figure 4.5: ***Grouped gold-star and extended datasets into formations***

One of the limitations of these datasets is that it is impossible to say how much of the bulk conductivity can be attributed to the smectite grains, how much can be attributed to other minerals, and how much can be attributed to the pore water. Although geochemical analysis was carried out on samples of groundwater taken from most of the boreholes, and the conductivity of the water itself was measured, it is still impossible to say how this attributed to the overall measured bulk conductivity without knowing how much of it there is in the ground and its position/depth. For example, borehole BGS26 in the Awgu Shales formation has a measured bulk conductivity of 113.11 mS/m; however the conductivity of the groundwater sample taken from this borehole was 1008 mS/m - a value much greater than the measured bulk conductivity. What this shows is that even though the actual conductivity of the groundwater is incredibly high, there is not enough of it within the subsurface for it to be the dominant control on the signal received by the EM34 equipment. Whilst this is a limitation, this is always the case with raw geophysics data: you cannot say for sure what is contributing to the signal; as such you have to make an intelligent guess. Models can be created, but without actually completing vast amounts of drilling to actually see what is in the earth it is impossible to say whether or not the models are correct and therefore they are just an educated guess. The relationship which has been proven with smectite content and conductivity will give people more confidence in their data, they will be able to make a better guess at interpreting their data, and it will increase their success rate of drilling and striking sustainable rural water supplies.

The significance of these findings in a broader context will be discussed in more detail in Chapter 6.

Chapter 5- *Comparison with Theoretical Models*

It is a prudent step to compare the results presented in Chapter 5 with theoretical and mathematical models. If the published theoretical and mathematical models carry any weight then the results which they predict should correlate with what is actually the case as proven by experimental data. Regardless of how sophisticated, well thought out, and complex a mathematical model may be if experimental data does not agree with it then the mathematical model is wrong. As previously mentioned in previous chapters, Archie's Law was the first ever relationship which correlated measured conductivity with a rock's physical properties. As is already mentioned, Archie's Law cannot be used for formations rich in clay minerals as it fails to take into consideration conductance originating from the surface of minerals. Since Archie's Law gained recognition in the 1940s, many other mathematical models have been created and tested to try and take into account the surface conductivities exerted by clay minerals.

Published Theoretical Models (A Short Literature Review)

Especially since the late 1970s, many models have been published which aim to relate the bulk conductivity of a rock to its physical properties. A good summary of the mathematical models of electrical conductivities in clay bearing formations is presented by Ruffet et.al., (1995). Listed below are some of the models which have been published on this topic; whilst each of them do have long and extensive mathematical derivations, they are not presented in this report (if the reader wishes to view the formulas then they can be sourced from the individual papers listed in the reference list):

1. **Waxman and Smits' model (1968) -** This model was the first to really take into account that in many rocks (especially those rich in clay) there are two different ways in which rocks can conduct electricity. Their model is based on three hypotheses:

- *The rock has two paths of conduction. One associated with the pore fluid and the other associated with the double layer (see Chapter 3) controlled by surface conductivity.*
- *The surface current and the pore water current propagate along the same paths in the rock.*
- *The double layer/surface conductivity is directly proportional to the pore water conductivity as the surface conductivity is controlled by the CEC which is related to the ions in the pore water.*

This model has been used extensively by the petroleum industry but its simplicity produced problems; notably the second bullet point has been proven to be incorrect, MacDonald, (1999).

2. **de Lima and Sharma's model (1990)** - This model is in essence an extension of the model hypothesised by Bussian (to be discussed later on in the chapter). It is specifically used for clay bearing rocks. What the authors try to do is model the surface conductivity as if it were a volume/pore water conductivity; therefore, it is possible to then attribute everything to a volumetric conductivity alone. They argue that having only one type of conductivity makes it easier to interpret data. The problem with their model is that it based on being able to measure the three dimensional shape of the grains within the rocks, as this dictates what path the currents will take. In reality, this is neither practical nor feasible to measure on a large scale.
3. **Johnson and Sen's model (1988)** - This model hypothesises that the current can be modelled by being solely the product of the effects created by cations and anions in a fluid. It simplifies for when pore water conductivity is much greater than the surface conductivity and vice versa. The issue with this model, however, is that for our investigation of investigating fresh groundwater the model does not simplify.

Whilst the above models certainly do have their uses, none of them are applicable for comparison of the data used in this study. Two other models have been identified as likely candidates for seeing how the experimental results from this study compare to mathematical theoretical models. Details of these, including the equations, are now presented.

The Bussian Model (1983)

The Bussian equation is a model put forward in the1980s. It allows for separate paths of conduction (surface and volume) throughout the rock body and it works for direct currents at low frequencies, MacDonald, (1999). The general form of the equation is as follows:

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

Where:

$\boldsymbol{\sigma_0}$= *measured bulk conductivity*

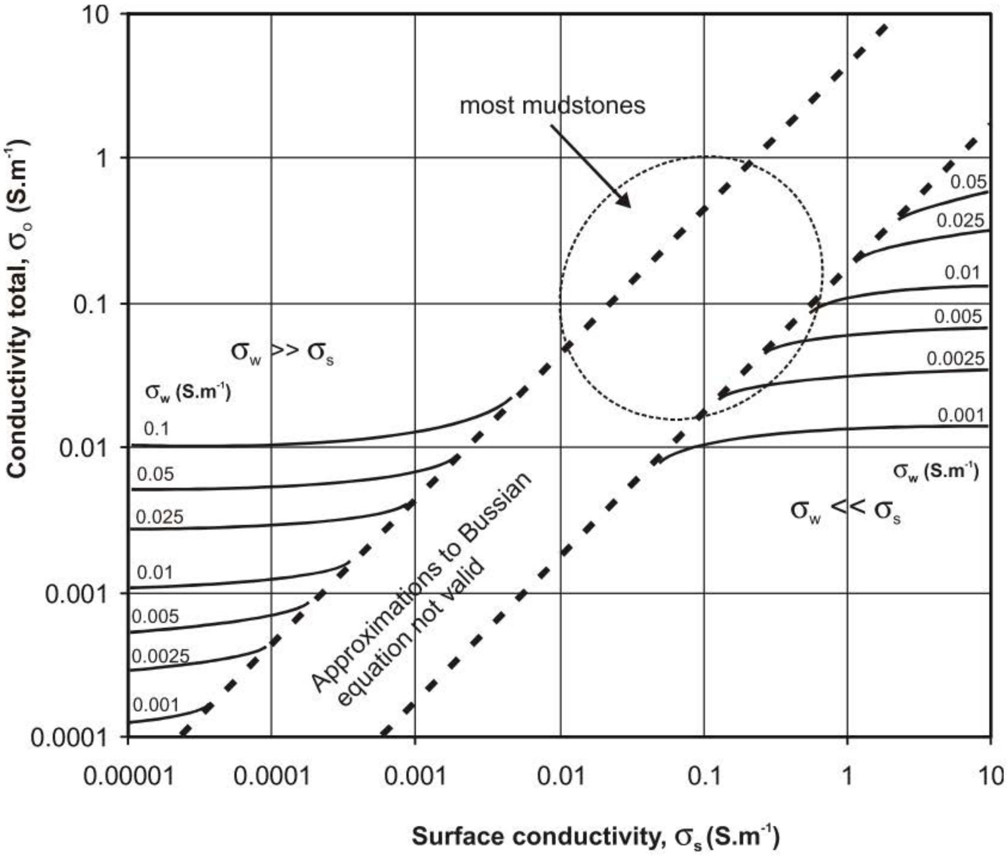
$\boldsymbol{\sigma_w}$= *conductivity of the pore water*

$\boldsymbol{\sigma_s}$= *surface conductivity*

$\boldsymbol{\varphi}$= *porosity*

m= *empirical constant*

This model also simplifies to two simpler forms when the pore water conductivity is much greater than the surface conductivity and vice versa (the simplified versions are not presented as they are not used). Figure 5.1 is taken from MacDonald, (1999), and is a representation of when the simplified Bussian equations are valid.



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.

Figure 5.1: ***Approximations when the Bussian simplified equations is valid***

Referring to Figure 5.1, one can notice that there are cases where the simplified Bussian equations are not valid, i.e. when the pore water conductivity and the surface conductivity are roughly similar. This is the case for the data used in this study, and our relationship suggests that in the region where Bussian's simplified equations are not valid, a linear relationship should exist between surface conductivity and measured conductivity. As such, with the dataset used in this investigation it is the general form of Bussian's equation which we are concerned with, not the simplified ones.

It would be of use to try and use Bussian's equation to predict what bulk conductivity should have been measured for our dataset. By knowing the smectite content in the rock samples, from the boreholes, the surface conductivity of the rocks can be calculated. Furthermore, chemical tests of the water were undertaken by the *BGS* for each borehole, therefore data exists for the conductivity of the pore water. Porosity can be estimated by knowing the relative proportions of clay, silt and sand in the rocks down each borehole, and *m*, the empirical constant, has a value of 1.85 for clay formations, MacDonald, (1999). What was interesting is that it does not appear as though anyone has ever used the general form of Bussian's equation in their analysis. This could be for one of three reasons:

1. Coincidence. No one has ever thought to apply Bussian's general form to their work.
2. All other studies have been cases where Bussian's general equation reduces to the two simplified formulas because one of the conductivities is much greater than the other.
3. It is mathematically impossible to yield an answer of measured bulk conductivity using the general form alone.

Naturally, the next stage was to see if Bussian's general equation could be used to see how well the experimental results presented in Chapter 4 match up with a theoretical model.

By referring to the general Bussian equation, the observant reader will note that there is a problem in that the measured conductivity, σ_0, appears on both sides of the equation. This cannot be ratified by a simple rearrangement as on the right hand side of the equation the measured conductivity is to the power of *m*. Therefore, it is actually impossible to exactly rearrange the general Bussian formula to isolate σ_0. What can be done, by mathematical manipulation, is a good approximation can be derived. This is what the author has proceeded to do. The derivation of this is presented in APPENDIX III. In essence, it involves applying a first order linear binomial expansion of the general formula to yield a good approximation of σ_0. The solution is presented below:

$$\sigma_0 \approx \sigma_w \varphi^m \left(1 - \frac{\sigma_s}{\sigma_w}\right)^m + \; m\sigma_s$$

Once the equation is in a form where σ_0 is the subject, it should be possible to calculate values of bulk conductivity for each borehole. An attempt was made to calculate bulk conductivity for each borehole, however this turned out to be impossible. It was noted that values could only be calculated for the boreholes where the surface conductivity was less than the pore water conductivity. When it was the other way around, MATH ERROR, was displayed. Investigation showed the reason for this. When the surface conductivity was greater than the pore water conductivity the fraction term became >1. Therefore the bracketed term became a negative number. *m* was always 1.85 which can be written as 37/20. As this was the index, this essentially means that you have to take the 20th root of the term in the brackets and then raise it to the power of 37. Herein lies the issue. When the surface conductivity is greater than the pore water conductivity the term inside the bracket becomes negative. Unless you delve into the realm of imaginary numbers (not suitable for our problem) you cannot have the 20^{th} root of a negative number: it is a mathematical impossibility. Therefore, to try and compare our relationship to that predicted by Bussian would involve eliminating all boreholes where the surface conductivity was greater than the pore water conductivity (which was most of them as it is a clay dominated region). Consequently, whilst every effort was made to use the Bussian equation to model the data, it turned out that it was not feasible to do so for this particular problem.

The Revil and Glover Model (1998)

There was one more model in the published literature which looked promising - the model put forward by Revil and Glover. They acknowledge that the special geometry of clay particles has a defined and notable effect on the bulk conductivity measured on a macroscopic scale. The model is based on the general form of the Bussian equation. They stress the importance of there being both a surface conductivity and a pore water (referred to as fluid) conductivity. The equation which they have derived is as follows:

$$\sigma = \frac{\sigma_f}{F}\left[1 - t_{(+)}^f + F\varsigma + \frac{1}{2}\left(t_{(+)}^f - \varsigma\right)\left(1 - \frac{\varsigma}{t_{(+)}^f} + \sqrt{\left(1 - \frac{\varsigma}{t_{(+)}^f}\right)^2 + \frac{4F\varsigma}{t_{(+)}^f}}\right)\right]$$

Where:

$$F = \varphi^{-m}, \qquad \varsigma = \sigma_s/\sigma_f,$$

σ= *bulk electrical conductivity*

$\boldsymbol{\sigma_f}$= *pore fluid conductivity*

F= *formation factor*

m= *empirical constant*

φ= *porosity*

$\mathbf{t_{(+)}^f}$= *"Hittorf Number" (constant depending on the ions present)*

Upon first glance the equation looks complicated. Further inspection, however, will enable the reader to realise that although there are a significant number of terms in the equation, no complicated mathematics is actually taking place, just addition/subtraction, multiplication/division, and indices. Furthermore, unlike the general Bussian equation, the electrical bulk conductivity parameter is already isolated on the left hand side of the equation, meaning that it will be possible to solve the equation. For each borehole the pore fluid conductivity is known. For other parameters in the equation estimations will have to be made. These estimations are as follows:

- The porosities (φ) down the boreholes have not been identified. By knowing the rock type down-borehole porosity has been estimated by the chart given in WEDC, (2012), entitled '*Relationship between porosity, specific yield and specific retention'*.
- *m* is a constant value of 1.85 as explained by MacDonald, (1999).
- $t_{(+)}^{f}$ is a constant value of 0.38 as stated in Revil and Glover, (1998).

Calculation of the surface conductivity can be done by knowing the relative proportions of illite and smectite in the rocks. The surface conductivity can be calculated directly from the CEC. MacDonald, (1999), states that the surface conductivity (σ_s)= 2.5 x CEC x 100: where the multiplication by one hundred accounts for unit consistency. Revil and Glover, (1998) state that CEC values are 0.22 meq g^{-1} for illite and 1.5 meq g^{-1} for smectite. They also state that the total surface conductivity is just an average of the different surface conductivities created by smectite grains and illite grains. Therefore, as one would expect, different abundances/proportions of illite and smectite will yield different surface conductivities. At every depth down-borehole for which we had data, the surface conductivity was calculated using the above method. An arithmetic average was then taken to yield a specific value of surface conductivity for each borehole as a whole. Once this had been done, the calculated and estimated values for each of the parameters were inserted into the equation to yield a predicted bulk conductivity value for each borehole.

As previously noted in chapters beforehand, on average only fifty percent of the rock formation was made up of clay minerals. Revil and Glover's equation is only valid for clay formations. As only half of the formation can be estimated to be comprised of clay, it cannot be used for the other half of the formation. For the other half, Archie's Law has been used to estimate a value of predicted bulk conductivity (see Chapter 3 for the formula). Afterwards, a simple average of the two values of bulk conductivity was taken so that a predicted value of bulk conductivity could be generated for each borehole.

Figures 5.2 and 5.3 show the results of this modelling. Only the boreholes for the Gold-Star dataset have been used as accurate surface conductivities can be calculated by knowing the relative proportions of smectite and illite.

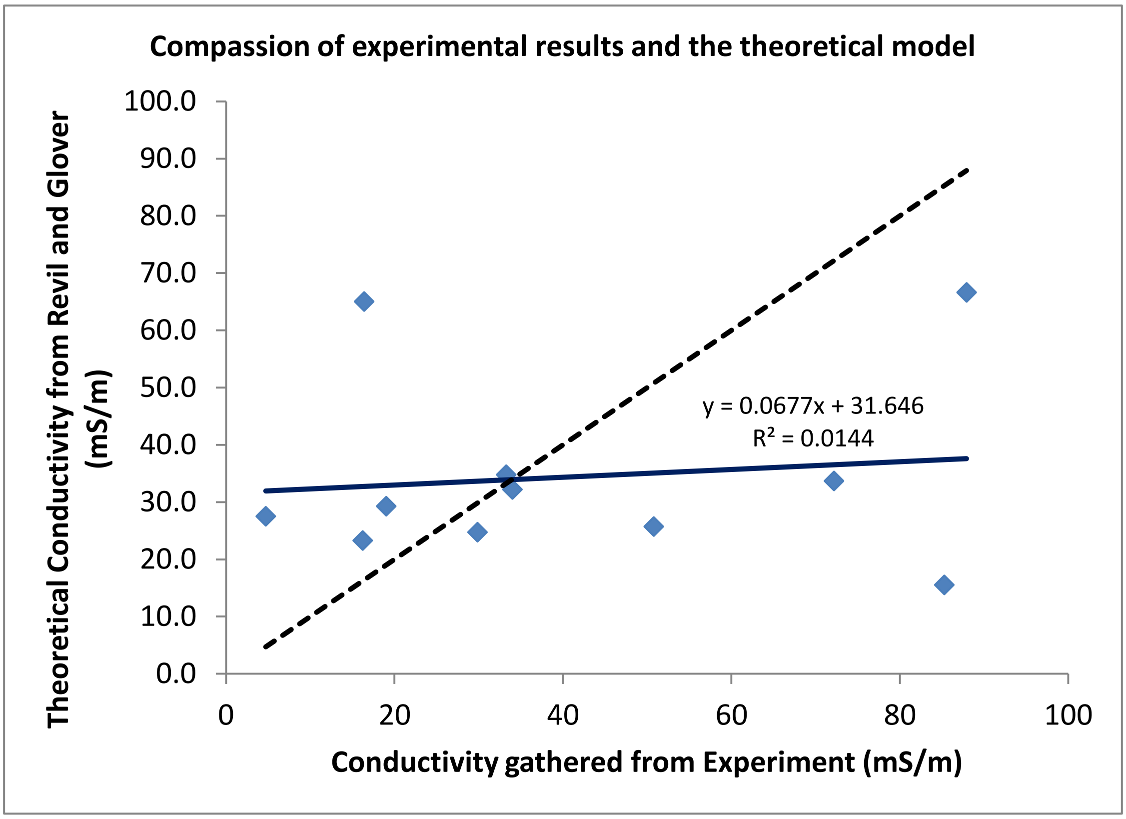


Figure 5.2: ***Comparison of conductivity values gathered from experiment and mathematical modelling.***

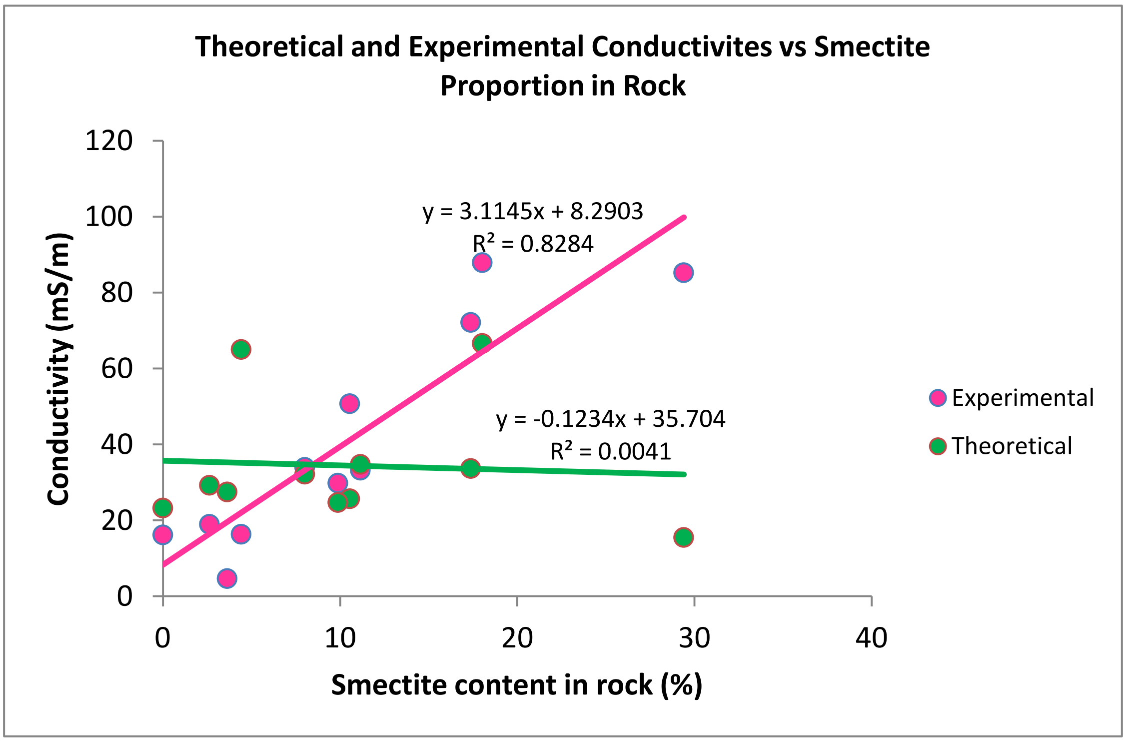


Figure 5.3: ***Smectite content in rock vs. both experimental and theoretical conductivities.***

Figure 5.2 compares the similarity between the conductivity values gathered from experiment and conductivity values predicted by Revil and Glover, (1998). The dashed line represents what one would expect if the mathematical model perfectly described what was actually measured in experimental data, i.e. the two values would be exactly the same for each borehole. What is actually found though (solid blue line) is that this is not the case. Although a straight line has been added, the variance of the solid blue line (0.0144) indicates that there is no relationship between what is measured by experiment and what is predicted by theory.

Figure 5.3 is a representation of the relationship between smectite content in the rocks and conductivity for both experimental and theoretical data. The pink line representing experimental data is merely a replica of that produced in Figure 4.2 and is simply there for comparison with the green line which represents what is predicted by the Revil and Glover model. Again, analysis of the variance shows that no relationship exists between smectite content in the rock and conductivity estimated by theoretical data.

What both of the figures show is that the model by Revil and Glover is poor at estimating what should be observed in the experimental data. The logic and reasoning behind their model is sound, but going from using equations which describe what is happening on a microscopic scale to what actually happens on a macroscopic scale is a big leap. Undoubtedly, their model has proven to work in experimental data taken in the laboratory, but the problem with conducting experiments in the laboratory is that everything is too controlled and precise, whereas in the field this just is not the case and is wishful thinking at best. The model perhaps works if your data has been collected in the field with the specific aim of addressing and quantifying the electrical behaviour of currents in clays. The problem is though, aside from aiding understanding, such field observations would have no real practical use. The dataset used in this dissertation has been gathered for a more practical aim, therefore parameters such as the porosity and the “Hitorff number” has had to have been estimated. Because geology in the field is so much more complex than in the laboratory the word ‘estimated’ in the previous sentence effectively translates to ‘an educated guess’. The problem with Revil and Glover’s mathematical model is that if you want to use it on a dataset which has a practical use you have to make many assumptions, and the more assumptions you make the more errors you introduce. This is why Revil and Glover’s model has failed to predict accurately what is observed in experimental data.

The reader should not be disheartened that the results gathered from experimentation in the field do not match up with what is predicted by theoretical models. On the contrary, there are a vast amount more variables in the field than in the laboratory, so being able to have derived a relationship from experimental data (as has been done in Chapter 4) is a worthy achievement. Scientific philosophy and protocol dictates that if mathematical theories do not match up with experimental data, then as long as the experiment has been carried out correctly, it is the theory and mathematical equations which are wrong and need work. What Chapter 5 has effectively proven is that there is much work which needs to be done to improve the theoretical models which describe electrical conductivity in clays on a macroscopic scale. Hopefully, the findings of this research will enable and encourage both theorists and experimentalists to pursue the subject further and stimulate more debate and research on the topic.

Chapter 6- *Significance and Applications of the Research*

As a relationship between smectite content and measured conductivity has been found there are broad and far-reaching implications and applications. It is not only the WATSAN sector which can benefit from the findings of this research project; as will be discussed in this chapter, the range spans from engineering to scientific study. Having said this, there is obviously potential for this work to be applied to the WATSAN sector and specific regions where this research could be applied are given.

Increased Success at Siting Boreholes and Wells

The data used for this investigation was taken from a project specifically aimed at increasing the success rate of siting boreholes and wells which can sustain acceptable yields for rural groundwater supply. Naturally, as a relationship has been found, this work can obviously be used and taken into consideration in other regions similar to Oju and Obi where there are no major aquifers and groundwater is scarce. As previously mentioned, EM34 is a favourable way of deciding where to site boreholes due to its simplicity of use and relative affordability - even for the poorest regions in developing countries in SSA and South Asia. The horizontal coil can be used to try and map/'see' fracture networks at depth, and the vertical coil can be used to support the data from the horizontal coil and make an assumption as to whether the sub-surface is dominated by smectite or illite clays, and thus, whether or not a particular area, at a particular depth, is a good target for striking an abundance of groundwater. The findings of this study significantly make the vertical coil data more useful and easier to interpret, resulting in less of a dependence on the data gathered solely from the horizontal coil.

Two regions are now presented which have similar hydrogeology patterns as Oju and Obi- where these findings can be applied.

The Karoo Basin Sediments - South Africa, Lesotho, & Swaziland

The Karoo sediments, which cover a vast proportion of the land area of South Africa (and other surrounding nations) date from the Carboniferous, Permian, and Triassic periods (approx~ 359-200Ma), *Encyclopaedia Britannica*. Its hydrogeology has been described particularly well by Goes, (2012), in a report for *Shell* in light of their recent application to drill for shale gas in the sediments. Goes has reported that there is both a shallow hydrogeological model and a deep hydrogeological model which can be applied to the region. Similarly to Oju and Obi, the shallow geology comprises of sediments, alluvium, dolerite intrusions and weathered zones. The deeper geology comprises mainly of shales and mudstones with some sandstones, lying on top of a granitic basement rock. Figure 6.1 is taken from Chevalier et.al., (2001) and shows a conceptual diagram of the hydrogeology in part of the shallow geology in the Karoo sediments. It should be noted that, similarly to Oju and Obi, the groundwater appears primarily in robust fracture networks, often next to the dolerite intrusions, with little groundwater appearing in the host sediments.

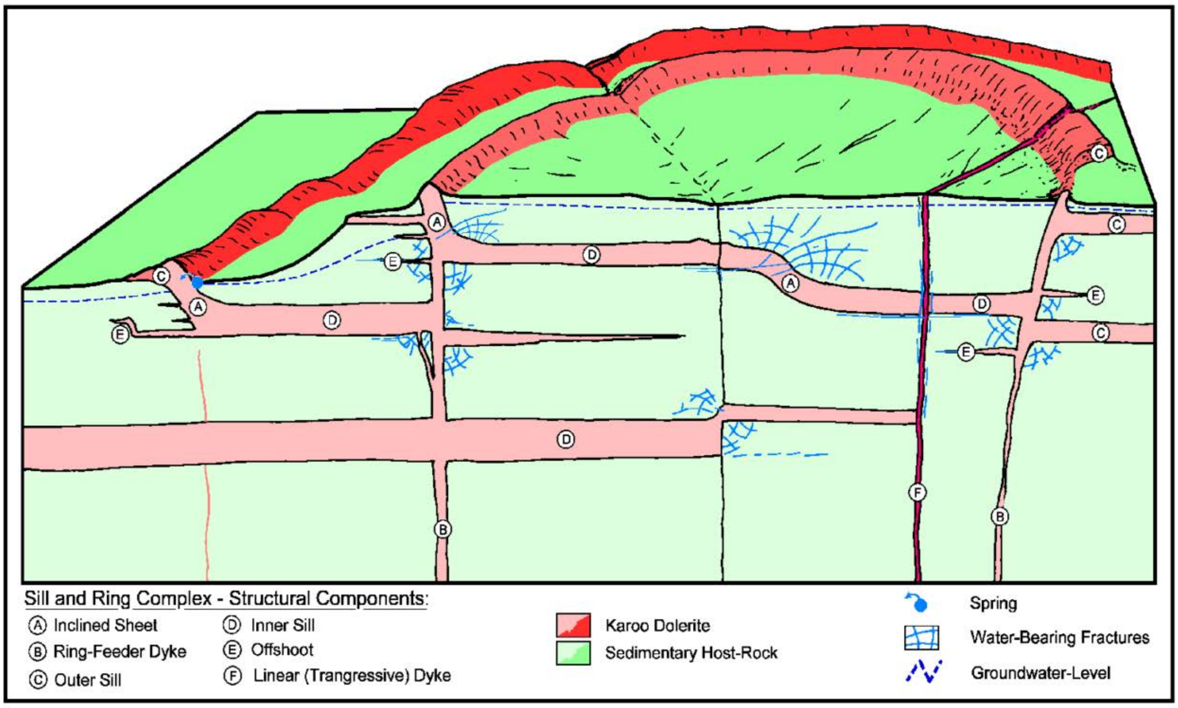


Figure 6.1: ***Schematic representation of the hydrogeology of the Karoo Sediments***

The Karoo sediments are known as a *Transboundary Aquifer* as they cross many international borders. Due to the scarcity of groundwater across the basin the management of this vital resource is complex and contentious. Davies et.al., (2012) classify the Karoo sediments as a "Troublesome" transboundary aquifer. "Troublesome", in this context, is defined as:

The most severe, warranting some form of international collaboration in monitoring and management, and appointments are needed now to avoid confrontation in the future should demographics, land, or climate, change.

Illite and smectite clays are prevalent across the Karoo Basin. Buhmann, (1992), used Karoo sediments, in-particular the illite and smectite clays within the sediments, as a geo-thermometer; minerals (such as illite) form at specific temperatures, therefore finding these minerals allows an indication of what temperature that specific area was at at some point in time. Buhmann also found that there was decreased water potential with increasing distance from the dolerite intrusions, because near the dolerite intrusions the heat has turned smectite into illite and form robust fractures, whereas further away the heat from the intrusion has not been significant enough to turn the smectite into illite. Figure 6.2 is taken from Buhmann, (1992), and is a geological map of the different groups across the Great Karoo Basin; it is good for highlighting the basin's spatial extent.

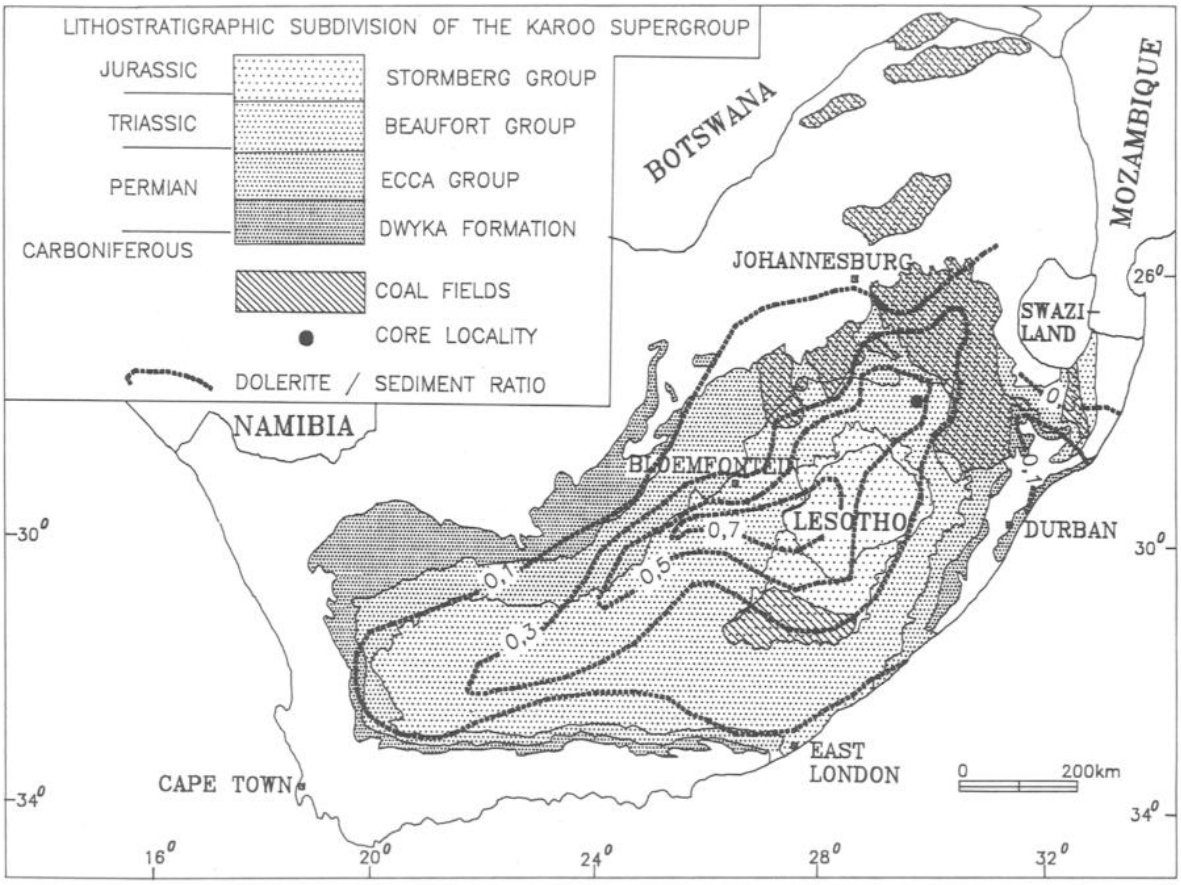


Figure 6.2: ***Geological map of the Karoo Basin***

The evidence which proves that groundwater is severely stressed in the region comes from the paper by Le Maitre et.al., (2009). They state that in the driest areas of the plateau rainfall is only 50-100mm per year. They go on to say that the water resources situation in Karoo (not just groundwater) is approaching a crisis. Table 6.1 is an extract from their paper showing the

Table 6.1: ***Water demand, past and future, in the Karoo Basin***

Sub-catchment	Net outcome for 2000					Scenario 2025	
	Availability	Local requirements	Transfers out	Total	Deficit	Base	High
J1	42	53	0	53	−11	−9	−10
J2	48	55	0	55	−7	−7	−12
J3	71	74	0	74	−3	−4	−12
J4, H8, H9	59	58	1	59	0	1	−1
K1-K6	55	98	0	98	−43	−60	−123
WMA	275	338	1	339	−64	−79	−158

differences in availability and requirements for actual data from 2000 and for forecasted predictions for 2025. What is clear is that for all catchments there is a water deficit. All values are given in $Mm^3\ yr^{-1}$.

Fortunately, the demand for domestic water in the region is quite low with the majority of the demand coming from irrigation practices.

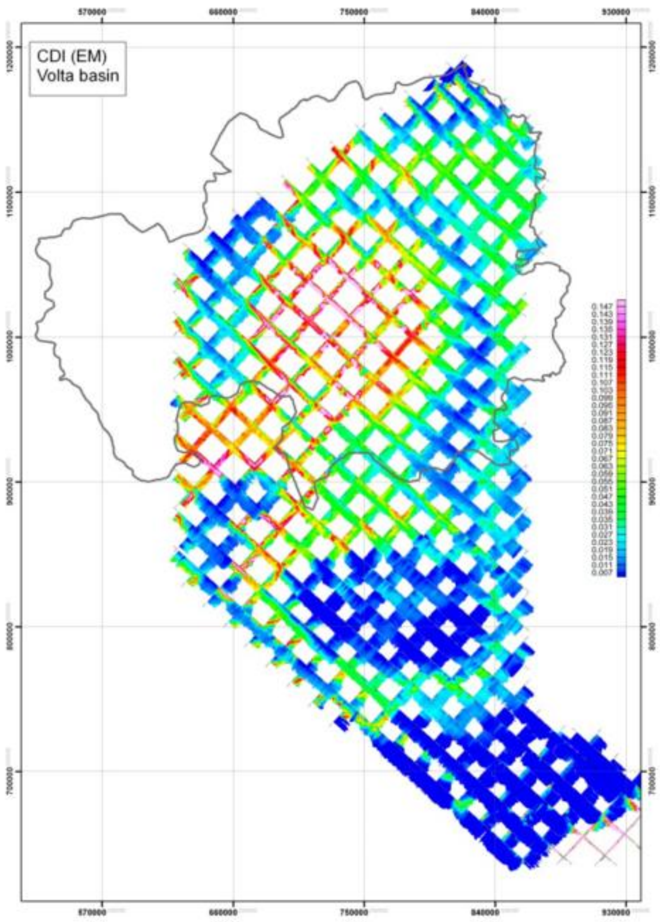
Many parallels can be drawn between this region and Oju & Obi in Nigeria. The hydrogeology is essentially the same - no major aquifers, a groundwater scarce region, the presence of illite and smectite, water filled fracture networks, dolerite intrusions, and increasing water potential towards the dolerite intrusions and subordinate lithologies. It is clear that anyone who in the future decides to undertake EM34 conductivity surveying within this region could use the findings presented in this report to infer the locations of smectite and illite dominated areas by analysing data from the vertical coil and assuming that high conductivities suggest smectite abundance and low conductivities suggest illite abundance. Taking the findings of this report into account could be the only way to dramatically increase drilling success rates and thus go a considerable way to meeting the likely future demand.

The Voltaian Basin Sediments- Northern Ghana

Another region where the results of this project can be applied is in the water stressed region of Northern Ghana. Compared to the Karoo Basin, there is comparably little information on the hydrogeology of this particular area. It is speculated that the reason why far more investigations have been gathered on the Karoo Basin is because of *Shell*'s interest in the shale gas there. It is unlikely the South African government would grant drilling rights to *Shell* before substantial fieldwork and mapping of the hydrogeology of the area had been completed.

There are only really two major reports describing the hydrogeology of this region in question, both of which have been compiled by the *BGS*. The report by O Dochartaigh et.al., (2011a), describes how the BGS was commissioned to investigate low drilling success rates encountered by UNICEF's IWASH programme in Northern Ghana. The rocks in the region form low-very low productivity aquifers with only minimal sustainable groundwater supplies available. It is noted that the best target for groundwater is fracture networks within the sandstone, with the mudstone having very little potential to yield any significant amounts of groundwater. The mudstones are poorly fractured (suggesting mainly smectite dominated clays). The findings of the *BGS* team showed that, as is often the case, geophysical surveying is not being carried out correctly and it is not being used to its full potential. It was found that the IWASH project did not use geophysics enough hence the poor siting of their boreholes. This is a massive problem in the WATSAN sector. Airborne geophysics has taken place over the region and a groundwater potential map has been produced**.** Figure 6.3 is this map; the pink regions in the centre represent the best target for groundwater supply.

A vast and comprehensive description of the hydrogeology of the area is given by O Dochartaigh et.al., (2011b). To summarise, the best groundwater targets are the fractures within the sandstone; the most important zone of groundwater flow is 30-70m beneath ground level; and there is very little/no groundwater flow beneath 100m depth.



The colour range represents blue: lowest conductivity to pink: highest conductivity. Lower conductivities indicate sandstone; higher conductivities indicate mudstone

Figure 6.3: ***Airborne geophysics data of ground conductivity, Northern Ghana***

The *BGS* have not published any information regarding the clay mineralogy of the area; therefore it is not known what proportion of the mudstone is smectite and what proportion is illite. To solve this, EM34 data could be collected across the mudstones in the region and areas of high conductivity could be inferred as being smectite and areas of low conductivity as being illite. This would be beneficial as the two previous aforementioned reports state that the mudstone is a poor target for the groundwater, however, if the mudstones are illite dominated then robust fracture networks may exist and boreholes/wells could be sited to provide plentiful, sustainable, and wholesome rural water supplies.

The above two regions are areas in SSA where our findings could be put to good use to increase success rates of striking groundwater in rural water stressed areas. It is easy to see how the findings of this project can impact other water stressed areas as this dataset came from a water stressed area; parallels can easily made and the significance can obviously be appreciated. Whilst WATSAN is perhaps the area where this research has its most profound significance, there are many other areas where the findings of this report have substantial emphasis. These other fields of study are now discussed.

Identifying a Suitable Site for a High-Level Nuclear Waste Repository

Whilst this topic does not fall under rural water supply it does fall under the umbrella of water and environmental management and hydrogeology. One of the most crucial, important and exciting topics in the field of engineering and environmental geology is where to site a repository for highly radioactive nuclear waste. Highly radioactive nuclear waste originates mainly from the decommissioning of nuclear sites, highly active and long lived waste products from fuelling reactions, and also from other sites where radioactive isotopes are used - such as hospitals. High-Level Waste (HLW) is particularly problematic as it will remain highly radioactive for thousands to millions of years. Safe disposal of it requires not only consideration of the health impacts for our generation but also the subsequent generations after our own. Currently no disposal mechanism exists for the UK's HLW and it is currently all in storage in warehouses. This poses a problem as it is not a long term solution and it is a good target for any terrorist threat. Many suggestions have been put forward as to how to deal with the UK's HLW, McKinley, (1992), summarises them well. Some examples of these are as follows:

- **Send it to the sun** - *The sun offers permanent disposal as it is effectively a large nuclear reactor itself. The downside is that rocket launch is risky; explosion of the rocket would distribute vast quantities of lethal radioactive isotopes into the atmosphere.*
- **Indefinite storage** - *One option is to just leave the HLW in warehouses. This is not really suitable though for reasons already mentioned.*
- **Transmutation** - *Once considered the best option by many; transmutation involves turning long lived radioactive isotopes into different, shorter-lived, and less dangerous, radioactive isotopes. The problem with this idea though is that it involves significant handling of the waste - something which is best avoided.*
- **Bury it in the arctic ice caps** - *The heat produced by the radiation would melt the ice and the waste would slowly sink deep beneath the ice caps and freeze over. There are risks with climate change and it breaks international law.*
- **Dump it in the sea** - *The waste product is off of land in the middle of the ocean. Breaks the international marine dumping laws.*
- **Place it in subduction zones** - *A subduction zone is an area where one tectonic plate is being thrust beneath another deep into the earth's mantle. Placing waste here would push the waste deep beneath the crust. The issue is that it would take thousands to millions of years for disposal.*
- **Encapsulation in a very deep borehole** - *Drilling a deep borehole would allow you to place the waste in the bottom of it. The heat from the radiation would melt the*

surrounding rocks. After a few thousands of years when the activity has reduced the rock would then cool and solidify around the waste thus trapping it within rock. Difficulty arises with the technical aspects of drilling such a deep borehole.

All of the above suggestions have been seriously considered as a means of disposal. Whilst nothing has officially been approved yet, the most likely means of disposal will be none of the above, but burial in the ground in a nuclear waste repository. A nuclear waste repository must meet the following criteria:

1. **It must be sited in an area of low tectonic activity** - *Areas which are prone to high tectonic activity are hotspots for earthquake activity. Earthquakes could rupture the HLW repository and cause radioactive isotopes to enter the environment.*
2. **It must be sited in a hydrogeologically suitable formation** - *Radioactive isotopes entering water allow the easiest and most rapid passage of movement throughout underlying rock formations. It is essential that no water enters the repository. Although waste will be encapsulated in barrels these will degrade over time and not form a sturdy barrier. Therefore, a rock formation made of clay and minerals such as anhydrite is needed to form a geological barrier to water flow.*
3. **It must be sited in a geologically 'boring' area** - *It is critical that the HLW is not placed in an area of geological commercial interest. Putting it near to oil and gas fields or rich mineral deposits will only encourage future generations to mine the area. Stumbling across the repository could have lethal consequences for future miners and the nearby communities.*

What the reader should be able to appreciate is that the nuclear waste repository needs to be sited in a 'Goldilocks zone', i.e. everything must be just right. Such spots are incredibly difficult to locate and any information which leads to easier identification of potentially suitable areas will be incredibly useful. The findings of this research project will help to identify a site for HLW repositories.

The second criterion (in the list above) makes a sweeping generalisation that clay formations are a good place to site HLW repositories. However, what this research and the findings of many other scientists have shown is that illite clays allow significant groundwater flow. Therefore, it is clear to see that one would not want to site one's HLW repository in an illite dominated area, nor would one want to site it in a smectite dominated area which is going to be exposed to heat and pressure in the future thus facilitating the diagenetic transition of turning smectite into illite. Pusch and Karnland, (1994), have studied how this transition of smectite to illite will impact on HLW repositories; they state that when smectite turns into illite it releases trapper interlayer water into the pore water spaces, further adding to groundwater flow in the formation. Based on the likely geology of any suitable HLW repository site, they even put a time limit on when this transition is likely to happen of several tens of thousands of years. More work specifically related to smectite, illite and HLW repositories, showing that this is a significant area of research, is the work by Hokmark et.al., (1997). They state that any HLW repository is likely to include a clay buffer (clay will be added around the storage facility in-between the barrels and the surrounding host rock) and they model how smectite will turn into illite under these circumstances.

The research conducted for this area has explicitly shown that it is possible to distinguish between illite and smectite dominated areas in the subsurface by taking surface conductivity measurements. There is no reason why the findings of this research cannot be used in the search of a suitable site for a HLW repository. Both time and money can be saved by reducing the amount of boreholes and cores which will need to be drilled and gathered by narrowing down the search area by identifying illite dominated areas in the subsurface using ground conductivity data. Areas with high conductivities will suggest the presence of smectite and therefore would be good areas to site HLW repositories. When the conductivity begins to significantly drop, this would suggest illite/smectite and illite dominated regions which would not be suitable due to the increased likelihood of increased fracture networks promoting substantial fluid flow into and out of the repository. For this application, by some extension, measured conductivity could be seen as being inversely proportional to the degree of risk to public health and the environment.

Engineering Applications

One other area where the findings of this research could have implications is in the sector of civil engineering and construction. Generally, engineers try to avoid building on clay as it is often weak, plastic, and shears easily. Illite, being more robust and stronger, could perhaps support some foundations if it is not overwhelmingly domineering. It is hypothesised that it certainly would not be wise building on any smectite dominated formation due to its plastic and deformable nature. Whilst the author would indeed like to bring civil engineering and construction aspects into this report, it falls beyond the realm of this dissertation. Its importance and appreciation is stressed, however no more is presented on the matter. Again, the ability to use conductivity data to distinguish between different clay types in the subsurface will have significant implications in this sector.

The above categories have provided a flavour as to which other sectors the findings of this research could be applied to. Remote sensing is another area where this could be useful, however this is discussed in more detail in the next chapter. What this chapter has provided the reader with is an understanding of how this research is not just relevant to one particular region, in one particular country, in one particular sector, but its significance can be appreciated across many different sectors globally.

Chapter 7- *The Next Steps*

Presented in this report thus far has been a summary of work which has already been completed many years ago by the *BGS* and the steps taken by the author to process the data and turn it into something meaningful which has wider implications. The significance of the research has already been presented in the previous chapter. With conclusions having been drawn for the information presented in the subsequent chapters the next stage is to assess what are the next steps? Where do we go from here? How can the research be furthered both in the WATSAN sector and in other sectors? This chapter will highlight some suggested next steps and suggestions for further study. Also, a summary of the research as a whole will be presented and closing remarks will be made.

Suggestions for Further Study

Applications with Remote Sensing Data

The reason why this application is presented in this chapter and not in the previous one is because it is not directly linked to the outcomes of this investigation. Linked to rural water supply, but not exclusively dedicated to it, are the applications of this research which could be applied to remote sensing data. There are, however, strong ties between the data which can be collected by geophysical conductivity surveying methods and the data which can be collected by remote sensing.

Figure 7.1: *LANDSAT data taken over Greater London, UK*

For the readers who are not familiar with the topic, remote sensing refers to the domain of scientific information which can be collected remotely, most often referring to data collected by satellite. LANDSAT is perhaps the most famous example - it is a satellite system which emits electromagnetic radiation towards the earth and measures the degree of phase difference and interference in the reflected wave back to the satellite. Figure 7.1 is an example of remote sensing data taken over London, United Kingdom, UCL, (2013). This can tell us vast amounts of information about the nature of the ground surface and can also provide strong clues as to the nature of the media making up the subsurface.

Naturally, the question should be asked as to whether or not remote sensing can successfully come to the same conclusions about the nature of the subsurface as is drawn from our EM34 data used in this project. There are advantages to this because geophysical surveying is a slow and expensive process to undertake; if the same information can be gathered via remote sensing satellites then what usually takes months and many thousands of dollars to complete could be completed in a matter of seconds and more often than not the data is free to obtain.

Short Literature Review on Remote Sensing Applications

Whilst it is beyond the scope of this research to actually process any remote sensing data, an effort has been made to determine whether or not there is a strong possibility that remote sensing can distinguish between smectite and illite clays on the surface and the subsurface.

Before going on to mention how remote sensing can be used to detect likely areas of groundwater potential by mapping clay type it is worth mentioning that satellites are able to detect groundwater via observing gravitational changes. Large scale gravity observations to monitor groundwater changes have been undertaken, most notably by NASA with their GRACE mission. GRACE measures the changes in orbit between two satellites depending upon variations in gravity. Certain changes have been attributed to changing groundwater levels. These have been particularly useful in measuring country-wide groundwater variations, most notably in California, Texas, and India (*NASA, 2012*).

Kariuki et.al., (2003), used spectral data gathered by remote sensing satellites to estimate the CEC of the ground (from which the clay type can be inferred). They noted that the spectral range of 1300-2500nm was particularly good at being able to determine the CEC of the soil on the surface. Other scientists have gone further by stating that remote sensing can directly distinguish between smectite and illite.

Dogan, (2009), used remote sensing data to map distributions of illite and smectite in the Kelkit River Basin in Turkey. Dogan realised that clay minerals are essential for productive agriculture and therefore being able to rapidly distinguish between clay minerals and other minerals is a substantial advantage in terms of both cost saving and time. Dogan states that clay minerals are particularly susceptible to identification in the LANDSAT bands 5 and 7.

Van der Meer, (1999), presents a well-rounded comprehensive description on the uses of remote sensing to identify clay mineralogy on the earth's surface. Van der Meer highlights the particular importance of being able to identify how clays swell. It is noted that swelling clays pose a substantial geological hazard. When water is absorbed in-between clay plates they become further separated; this destabilises the mineral structure and can present vast civil engineering problems. Clays can swell up to 150% of their original size. It is noted that illite has a lower swelling potential than smectite, therefore if one can measure the swell then one can infer the clay type. It is noted that the swell could be measured by a system known as

InSAR which measures the changes in elevation of the earth's surface. The problem with this method, however, is that it is a temporal measurement, i.e. you need to take data over time to see if the clay has swelled. Furthermore, just because a clay can swell does not necessarily mean that it will, especially in water stressed regions such as Oju and Obi. Perhaps a more logical approach in the context which we are focussing on would be to try and directly measure the swell by analysing the reflectance properties of smectite and illite: something which Van der Meer also suggests.

Kariuki et.al., (2004), present some of the advantages and disadvantages of using remote sensing data to determine smectite or illite content. It is stated that recently the resolution of the data has increased and therefore it is possible to identify the major mineral present in every pixel of the image. Problems, however, include vegetation and free water cover which mask any mineralogy beneath, and there are also problems when you have mixed clays in the same area.

It is clear from the literature on this subject that it is possible to distinguish between different clay types on the surface. What is also apparent is that remote sensing does not give a good analysis of what can be found at depth, as it is primarily a tool which analyses reflectance - which can only be used on exposed surfaces. Whilst many have focussed on the implications of such research on civil engineering and more notably geohazards, there is no information directly related to the aims of this research. This shows that there is work which could be done by using remote sensing data over the Oju and Obi area and using the findings of this research as something to compare it to.

Stronger Theoretical and Experimental Agreement

Chapter 5 proved that the agreement between theoretical predictions and experimental evidence is at best inconclusive and at worst wrong. The issue is not that the models are completely incorrect, more that they are based on laboratory measurements where specific parameters can be identified; the field is a lot more variable and some of the parameters cannot be measured but must be estimated from other information. As of yet, no one has come up with a link which successfully describes how the microscopic behaviour of clays manifests itself on a macroscopic level. The macroscopic level, however, is the most important: especially in terms of locating suitable groundwater targets for rural water supply.

The results from this research show that the link between clay type and measured bulk conductivity is linear when measured on a field-scale. As indicated in Chapter 5, however, this may only be the case for when the surface conductivities and pore water conductivities are similar. It is clear that further work on the theoretical side must be undertaken to enable successful linear modelling of what is observed in the field.

A Comprehensive Survey of Water Supply in Oju and Obi Fifteen Years On

Personal conversation with Alan MacDonald of the *BGS* has provided some insight into how the boreholes and wells constructed by the *BGS* are operating fifteen years on. MacDonald states that to his knowledge the boreholes and wells are still, on the whole, operating successfully and are still delivering clean, wholesome and sustainable water supplies in the rural areas. He does indicate, however, that no comprehensive follow-up of the region has been undertaken by the *BGS* to specifically quantify how well each of the boreholes/wells is functioning. Naturally, some sort of region-wide survey would be prudent to conduct. It would allow geological assessment of the 'aquifers', technical assessment of the hand-pumps and wells, and the population's satisfaction could be measured by means of a sociological survey. This would enable us to categorically state whether or not the findings of this research would be applicable and useful in the long-term. If by some geological process (such as weathering or precipitation) the fractures in illite become blocked/filled over a very short period of time (in geological terms) then illite fractures might not be the best targets for long-term, sustainable rural water supplies. Whilst this is unlikely, it is possible.

Caution would have to be applied to the region-wide survey. If the boreholes and wells are not yielding sufficient quantities of water, this may not be down to 'aquifer' degradation, insufficient recharge, or water table draw-down; more often than not, these problems tend to be more technical in nature with boreholes and hand-pumps not functioning as well due to wear and tear of parts and overuse. These problems stem from more management related issues and are arguably often more difficult to solve. If this turned out to be the case, drilling of more boreholes would be pointless and a waste of money and resources.

Application of the Findings to Other Water Stressed Regions

Chapter 6 went into detail about where the findings of this research could be applied. From a WATSAN perspective this is unquestionably the greatest use of this research. This research will be of little use where there are an abundance of aquifers with substantial recharge. This research will be of use in geologically unfavourable areas - where there is little aquifer potential and poor recharge. In such areas, more so in areas which have a high population like Oju and Obi, every drop of useable, accessible groundwater must be extracted to serve the population (within sustainable limits, of course). Regions which have been written-off as aquicludes can now be reinvestigated by knowing that illite fractures can produce sustainable groundwater supplies, and that illite can be distinguished from smectite by using EM34 conductivity surveying as a linear relationship between clay type and conductivity has been proven to exist.

If listened to, and acted upon, this research could vastly improve borehole siting success rates. This would not only allow the best groundwater targets to be identified - by using the horizontal coil to look for fracture networks and the vertical coil to tell you whether they are likely to be illite or smectite based - but it would also save vast amounts of time, effort, and crucially money. Many of the most water stressed regions in the world are often also some of the poorest, and therefore any money which can be saved on siting boreholes can be put to better use- such as lowering water tariffs and drilling more successful boreholes.

Summary of the Findings

In the previous chapters a robust description of the problem has been presented and explained. Furthermore, solutions to the problem in question have been found and the significance of the work has been described.

Chapter 1 provided a flavour of what the project was all about. Broader issues of African hydrogeology, rural water supply, and geophysical surveying were presented. Chapter 2 very much focussed on the birth of this project by describing in detail the work undertaken by the *BGS* and where the data came from.

Once the problem had been clearly identified the literature review of clay and conductivity enabled an appreciation to be gathered on the work which had already been published on the topic. It became apparent that no one before had conducted any research to try and establish a link between clay type and measured bulk conductivity on a macroscopic scale. This justified the research being undertaken. The logical framework enabled a plan to be created of the steps which needed to be completed whilst keeping in mind the overall goals which wanted to be achieved.

The long and arduous process of sorting and processing the data was described step by step in Chapter 4. Once values for conductivity and smectite content had been calculated/estimated for the boreholes, the data points were able to be plotted onto graphs. Both the gold-star and extended datasets yielded strong linear relationships with smectite content of the subsurface being directly proportional to the measured bulk conductivity, measured by the EM34 apparatus. This demonstrated that the conductance signal received by the apparatus came mainly from the surface conductivity of the clays, not from the conductivity of the freely mobile groundwater. Illite clays have the largest potential for creating robust fracture networks- good groundwater targets- however due to its low CEC it produced a comparatively small conductivity signal. **This led to the groundbreaking conclusion that in such water-stressed clay dominated areas, geologists and geophysicists need to be looking for areas of *low* conductivity to have the best chance of finding groundwater. This fact is revolutionary as it goes completely against all other previous guiding principles which stated that areas of *high* conductivity signify groundwater flow in the subsurface.** The last two sentences are written in bold to highlight their importance as the take-home message from this research project. The implications of not knowing this counter-intuitive fact, which this research has shown to be true, is proven by people in the Oju and Obi region thinking that the Makurdi Sandstone formation was the best aquifer when in fact it was one of the worst! As ever, what this research has shown is that things in geology, geophysics and earth science are rarely so black and white as they may seem.

Who knows how many regions across the developing world have been surveyed and ruled out as being clay aquifers with low conductivity, when really surveyors have actually stumbled upon good illite fracture networks which make a good groundwater target? The beauty of this research is that so long as the data for such regions still exist, further surveying need not take place at the cost of both time and expense. Merely all that needs to be done is to look at the data with a new eye, focussing on areas of low conductivity in the vertical coil signals and using the horizontal coil signals to see whether robust fractures may be present.

As highlighted previously, the current models which try to describe the relationship between clay and conductivity are inadequate. Either they focus too heavily on microscopic parameters and thus they are not practical for using with field data (Revil and Glover's model), or they are likely to work with field data but only work when either the surface conductivity or pore water conductivity is much greater than the other (Bussian's model) which often, as in the case of Oju and Obi, is not the case. The experimental data used in this research suggests the relationship on a field-scale level is linear with increased smectite content resulting in increased measured bulk conductivity.

Finally, the significance of the research and the suggestions for further study has been discussed. As well as the obvious applications to the WATSAN sector, information on high level nuclear waste repositories, engineering, geohazards and remote sensing have all been mentioned. The findings of this research can be applied to many other sectors, making it a worthwhile topic of study.

Closing Remarks

The past four months of research have enabled me to pursue my interest in hydrogeology and rural water supply. I believe that the findings of this research could have significant and far-reaching applications, especially in the WATSAN sector. Naturally, for the work to receive wider recognition the findings must be summarised in journal format and published. I have discussed this both with Ian Smout of *WEDC, Loughborough University*, and Alan MacDonald of the *BGS*. Hopefully, someone with similar interests will be able to take this research further and enable it to become useful in a practical way- a way which addresses some of the goals mentioned in the logical framework in Chapter 3. This MSc dissertation has inspired me to continue working in the field of research by undertaking a PhD in hydrogeology at the

University of Birmingham. This research has focussed heavily on finding groundwater in regions where it is incredibly scarce, and as such I finish this dissertation with a quotation by Antoine de Saint-Exupéry, a twentieth century, French writer, which summarises this research and the topic of hydrogeology well:

"What makes the desert beautiful is that somewhere it hides a well."

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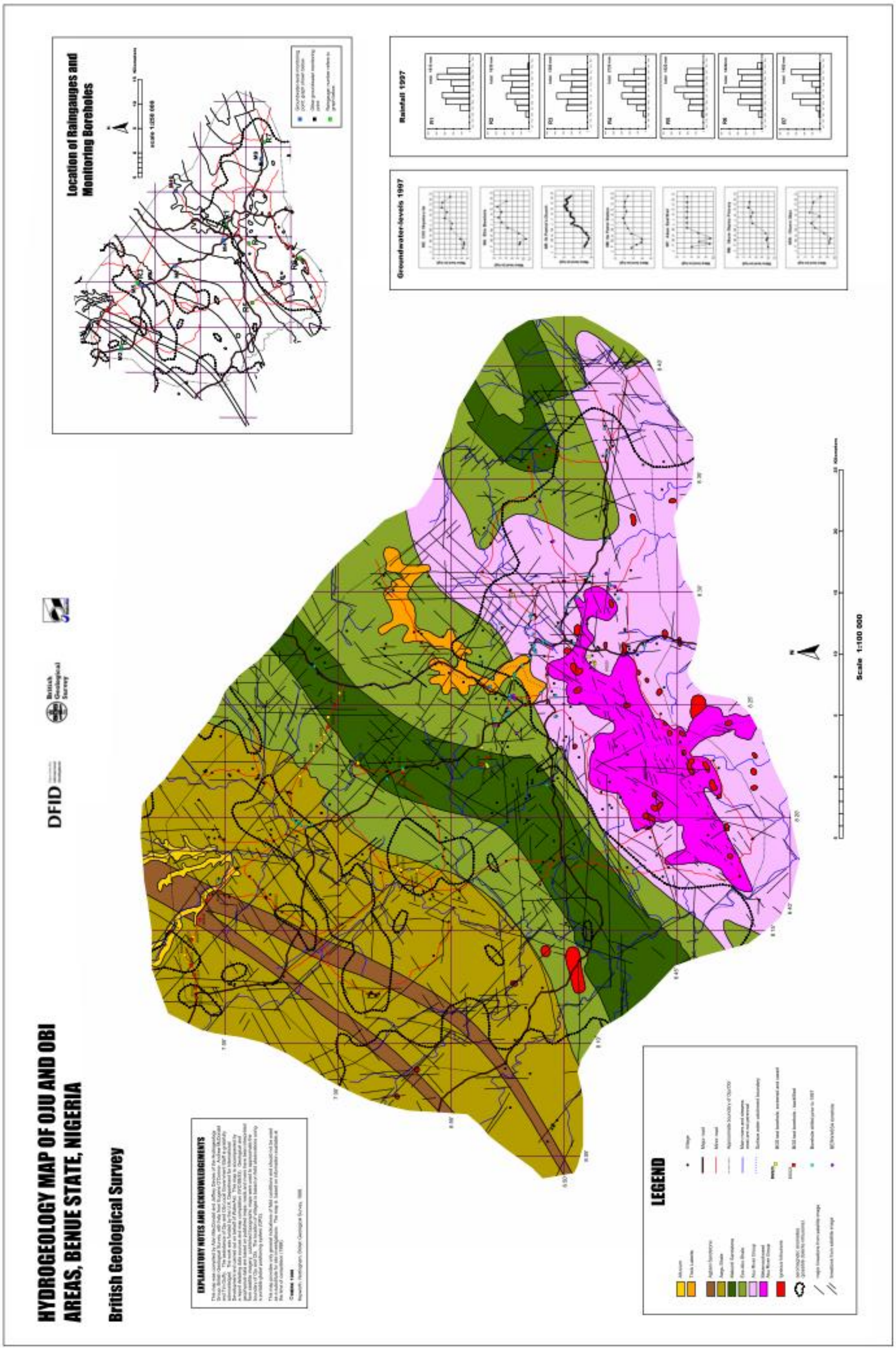
APPENDICES

Appendix I – Hydrogeology Maps



LEGEND

- Alluvium
- Thick Laterite
- Agbani Sandstone
- Awgu Shale
- Makurdi Sandstone
- Eze-Aku Shale
- Asu River Group
- Metamorphosed Asu River Group
- Igneous Intrusions
- aeromagnetic anomalies (possible dolerite intrusions)
- major lineations from satellite image
- lineations from satellite image

- Village
- Major road
- Minor road
- Approximate boundary of Oju/Obi
- Main rivers and streams most are not perennial
- Surface water catchment boundary
- BGS23 — BGS test borehole, screened and cased
- BGS23 — BGS test borehole - backfilled
- Borehole drilled prior to 1997
- BERWASSA borehole

EXPLANATORY NOTES AND ACKNOWLEDGEMENTS

This map was compiled by Alan MacDonald and Jeffrey Davies of the Hydrogeology Group, British Geological Survey, with help from Eugene O'Connor, Andrew McDonald and Tim Duffy. The assistance of Oju and Obi Local Government Staff is gratefully acknowledged. The work was funded by the U.K. Department for International Development and carried out on behalf of WaterAid. This map is accompanied by a report detailing data sources and map compilation (WC/98/53). Geological and geophysical data are based on published maps; roads and rivers have been interpreted from satellite imagery; published topographic maps were used to approximate the boundary of Oju and Obi. The location of villages is based on field observations using a portable global positioning system (GPS).

This map provides only general indications of field conditions and should not be used as a substitute for site investigations. The map is based on information available at the time of compilation (1998).

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Appendix II – Inventory of Data

EM CONDUCTIVITY (GREEN DOTS)

1. **ADWTEM_1**- *Sheet 1, Sheet 2, Figures (Sheet 3),* ***(6 degs 58.05, 8 degs 18.022)***
2. **Ijekwe**- *Sheet 1, Figures (Sheet 2),* **IJKWEM_1**- *Sheet 1 Village Ijekwe, Figures (Sheet 2),* ***(7 degs 01.371, 8 degs 13.629).***
3. **OHYEEM_1**- *Sheet 1 Village Ohuiye, Sheet 2, Figures (Sheet 3),* ***(6 degs 56.944, 8 degs 11.46)***
4. **OCHING**- *Sheet 1: Village Ochinyini, Sheet 2, Sheet 3, 1-2 (Sheet 4,) 3-4 (Sheet 5), diagram (Sheet 6),* ***(7 degs 00.873, 8 degs 23.284)***
5. **ODBOEM_1**- *Sheet 1 Village Odubwo, Sheet 2, Figures (Sheet 3), OD1/2/3/4/7/8* ***(START 6 degs 52.27, 8 degs 29.87, FINISH 6 degs 87392, 8 degs 50473)***
6. **ODBOEM_1**- *OD5/6,* **ODBOEM_2**- *Sheet 1, Village Odubwo, Sheet 2,* ***(START 6 degs 53.091, 8 degs 30.405)***
7. **ODBOEM_3**- *9, 10, 11 (Sheet 1)* ***(START 6 52.201 8 29.847, FINISH '6 52.388 8 29.963).***
8. **ODBOEM_3**- *12, 13 (Sheet 2),* ***(START '6 52.388 8 29.963, FINISH 6 52.63 8 30.06).***
9. **ODBOEM_3**- *14, 15 (Sheet 3),* ***(START 6 52.768 8 30.161, FINISH 6 52.876 8 30.212).***
10. **Wataid**- *WA 1 (Sheet 1),* ***(Lat 6 degs 52.310 North, 8 degs 26.152' East).***
11. **EMOJOK1**- *Village Ojekwe, Sheet 2: Traverse 1* ***(START 6.7718 8.3249, FINISH 6.7744 8.3164).***
12. **EMOJOK1-***Sheet 3: Traverse 2* ***(START 6.7696 8.325, FINISH 6.7668 8.3171).***
13. **EMOJOK1-***Sheet 4: Traverse 3* ***(START 6.7702 8.3183, FINISH 6.7711 8.3125).***
14. **EMOJOK1-***Sheet 5: Traverse 4, Sheet 9: Traverse 6, Sheet 10: Traverse 7* ***(START 6.7711 8.3125).***
15. **EMOJOK1-***Sheet 6: Traverse 3/4 anisotropy test section. Sheet 8: Traverse 5* ***(START 6.77227 8.3252).***
16. **Adega-** *adega AD1 (Sheet 1),* ***(7 degs 02.869, 8 degs 16.253).***
17. **AdumWest**- *AW1 (Sheet 1), (Sheet 3), Sheet 4,* ***(6 degs 56.163, 8 degs 17.398)***
18. **AKIRIBA-** *1-7 (Sheet 1): Village Akiraba-ainu* ***(6 degs 52.400, 8 degs 21.743)***
19. **AMAKA**- *AM1 (Sheet 1): Village Amaka-Ijegwu, graphs (Sheet 2),* ***(7 degs 05.409, 8 degs 17.040).***
20. **AMAKA**-*AM2 (Sheet 4),* ***(7 degs 05.476; 8 degs 16.790).***
21. **ANYOGA**- *AE1 (Sheet 1): Village Anyoga Eddi Adum East,* ***(6 degs 57.18; 8 degs 22.130).***
22. **ANYOGA**-*AE3-5 (Sheet 3):* ***(6 degs 56.477' 8 degs 22.223).***
23. **EDUMAG-** Village Edumoga, Conductivity ***(6 degs 53.406; 8 degs 22.422)***
24. **ITOGO**- Village Itogo, EM34 conductivity ***(START 7 degs 02.059; 8 degs 21.011', FINISH 7 degs 06.025; 8 degs 22.168')***
25. **ODADEM-** Village Odaleko Adiko, EM34 conductivity ***(6 degs 59.195 8 degs 22.312)***
26. **OLUYO-** Village Oluywo, EM34 ***(7 degs 01.728' 8 degs 19.364)***
27. **OYINYI**- Village Oyinyi Lyeche, EM34 conductivity ***(6 degs 48.811; 8 degs 26.930)***

28. **Ugbodum**- Village Ugbodum, EM34 conductivity ***('6 degs 58.248'   8 degs 18.084')*** **ACTUALLY THE SAME AS 1!!!**

MAGNETICS (BLUE DOTS)

1. **ADWTEM_1**- *Sheet 1, Figures (Sheet 3), **(6 degs 58.05, 8 degs 18.022)***
2. **ADWTMG_1**: *Sheet1 **(6 degs 55.949, 8 degs 17.13)***
3. **Ijekwe**- *Sheet 1, Figures (Sheet 2),* **IJKWEM_1**- *Sheet 1 Village Ijekwe, Figures (Sheet 2),* **IJKWMG_1**- *Sheet 1, **(7 degs 01.371, 8 degs 13.629).***
4. **OHYEEM_1**- *Sheet 1: Village Ohuiye , Sheet 2, Figures (Sheet 3), **(6 degs 56.944, 8 degs 11.46)***
5. **OHYEMG_1**- *Sheet 1, Sheet 2, **(6 degs 56.9454, 8 degs 11.46)***
6. **OCHING**- *Village Ochinyini, 1-2 (Sheet 4), 3-4 (Sheet 5), **(7 degs 00.873, 8 degs 23.284)***
7. **OCHYMG_1**- *Sheet 1, Sheet 3, **(7 degs 00.873, 8 degs 23.284).*** **SAME AS 6!**
8. **OCHYMG_1**- *Sheet 2, **(START 7 degs 00.439, 8 degs 24.053, FINISH 6 degs 59.818, 8 degs 25.878)***
9. **ODBOEM_1**- *Figures (Sheet 3), **(OD1/2/3/4/7/8 START 6 degs 52.27, 8 degs 29.87)***
10. **ODBOEM_1**- *Figures (Sheet 3), **(OD5/6 START 6 degs 53.091, 8 degs 30.405)***
11. **ODBOMG_1**- *Sheet 1, Sheet 2, **(6 degs 52.27, 8 degs 29.87).*** **SAME AS 9!**
12. **ODBOMG_2**- *Sheet 1, **(8 degs 30.405, 6 degs 53.091)***
13. **ODBOMG_2**- *Sheet 2 **(8 degs 29.87, 6 degs 52.27)*** **SAME AS 9!**
14. **OJKWMG_1**- *Sheet 1, **(6 degs 46.305, 8 degs 19.494)**.*
15. **OJKWMG_1**- *Sheet 3, **(6 degs 49.175, 8 degs 19.502).***
16. **OJKWMG_2**- *Sheet 1, Sheet 2, **(8 degs 19.095, 6 degs 46.210)***
17. **OJKWMG_2**- *Sheet 3 **(8 degs 180955, 6 degs 46.314)**.*
18. **OJKWMG_2**- *Sheet 4, Sheet 5 **(8 degs 18.747, 6 degs 46.268).***
19. **AKIRIBA-** *1-7 (Sheet 1): Village Akiraba-ainu **(6 degs 52.400, 8 degs 21.743)***
20. **AMAKA-** *magnetics (Sheet 3) **(7 degs 05.409, 8 degs 17.040)***
21. **OLUYO-** Village Oluywo ***(7 degs 01.728' 8 degs 19.364)***
22. **OYINYI-** Village Oyinyi Lyeche ***(6 degs 48.811; 8 degs 26.930),***
23. **Ugbodum-** Village Ugbodum ***('6 degs 58.248'   8 degs 18.084')***

VES RESISTIVITY (YELLOW DOTS)

1. **ADWERS_1**- *Sheet 1, Sheet 2 **(6 degs 58.060, 8 degs 17.976)***
2. **OCHING**- *VES (Sheet 7): 3 res surveys, Survey 1 **(7 degs 0.754, 8 degs 23.313)***
3. **OCHING**- *Survey 2 **(7 degs 00.615, 8 degs 23.666)***
4. **OCHING**- *Survey 3 **(6 degs 59.958, 8 degs 25.499)***
5. **OCHYRS_1**- *Sheet 1 **(7 degs 00.735, 8 degs 23.323).***
6. **OCHYRS_1**- *Sheet 2 **(7 degs 00.652, 8 degs 23.641)***
7. **ODBOEM_3**- *VES (Sheet 5), **(START 6 52.768   8   30.161, FINISH 6 52.876   8 30.212).***
8. **Wataid**- *VES 1 (Sheet 2), **(Lat 6 degs 52.310 North, 8 degs 26.152' East).***
9. **OJKWRS_1**- *Sheet 1, Sheet 2, **(6 degs 46.336, 8 degs 19.512)***
10. **Adega-** *adega VES (Sheet 2), **(7 degs 02.869, 8 degs 16.253)***
11. **AdumWest-** *VES (Sheet 2), **(6 degs 56.163, 8 degs 17.398)***
12. **AKIRIBA-** *Village Akiraba-ainu, VES (Sheet 2), **(6 degs 52.400, 8 degs 21.743)***

13. **AMAKA**- *VES (Sheet 6), **(7 degs 06.142; 8 degs 15.497)***
14. **ANYOGA-** *ves (Sheet 2), **(6 degs 57.18; 8 degs 22.130)***
15. **EDUMAG-** VES ***(6 degs 53.418; 8 degs 22.655)***
16. **EDUMAG-** VES ***(6 degs 53.433; 8 degs 22.342)***
17. **EDUMAG-** VES ***(6 degs 53.433; 8 degs 22.342)*** **SAME AS 16!**
18. **ITOGO-** Village Itogo, VES ***(7 degs 04.287' 8 degs 22.162)***
19. **ITOGO-** Village Itogo, ***(7 degs 02.743; 8 degs 21.116)***
20. **ODADEM-** Village Odaleko Adiko, VES ***(6 degs 59.214; 8 degs 22.361)***
21. **ODADEM-** Village Odaleko Adiko, VES ***(6 degs 59.180; 8 degs 22.399)***
22. **Boreholes-** ***BGS40***,
23. **Boreholes-*BGS41***, ***(6 degs 58.157, 8 degs 16.702)***
24. **Boreholes-*BGS42***,
25. **Boreholes-*BGS43***, ***(6 degs 58.853, 8 degs 15.960)***
26. **Boreholes-*BGS44***, ***(6 degs 58.539, 8 degs 16.227)***
27. **Boreholes-*BGS46*** ***(7 degs 0.842, 8 degs 14.993)***

Appendix III – Bussian Equation Derivation

BUSSIAN DERIVATION

$$\sigma_o = \sigma_w \phi^m \left(\frac{1 - \frac{\sigma_s}{\sigma_w}}{1 - \frac{\sigma_s}{\sigma_o}} \right)^m \quad \leftarrow \text{General Bussian Equation.}$$

$$\Rightarrow \sigma_o = \sigma_w \phi^m \frac{\left(1 - \frac{\sigma_s}{\sigma_w}\right)^m}{\left(1 - \frac{\sigma_s}{\sigma_o}\right)^m}$$

$$\Rightarrow \sigma_o \left(1 - \frac{\sigma_s}{\sigma_o}\right)^m = \sigma_w \phi^m \left(1 - \frac{\sigma_s}{\sigma_w}\right)^m$$

$$\Rightarrow \sigma_o \left(1 - \frac{m\sigma_s}{\sigma_o}\right) \approx \sigma_w \phi^m \left(1 - \frac{\sigma_s}{\sigma_w}\right)^m \quad \leftarrow \text{1st order linear binomial expansion}$$

$$\Rightarrow \sigma_o - m\sigma_s \approx \sigma_w \phi^m \left(1 - \frac{\sigma_s}{\sigma_w}\right)^m$$

$$\Rightarrow \sigma_o \approx \sigma_w \phi^m \left(1 - \frac{\sigma_s}{\sigma_w}\right)^m + m\sigma_s$$

Appendix IV – Excel Spreadsheets

Clay Mineralogy

Borehole	Mean depth	Formation	Kaolinite	Illite	Smectite	Illitie/Smectite	Illite %	Smectie %	Smectite	Smectite TOTAL	Smectite in Rock	Geology
4	1.5	Upper Eze Akue	82	18	0	0	0	0	0	0	**0**	Soil
4	2.5	Upper Eze Akue	76	24	0	0	0	0	0	0	**0**	Soil
4	3.5	Upper Eze Akue	39	4	0	58	70	30	17.4	17.4	**8.7**	Clay
4	4.5	Upper Eze Akue	24	2	0	74	59	41	30.34	30.34	**15.17**	Clay
4	5.5	Upper Eze Akue	11	1	0	88	61	39	34.32	34.32	**17.16**	Clay- Weathered Mudstone
4	6.5	Upper Eze Akue	15	3	0	82	63	37	30.34	30.34	**15.17**	Weathered Mudstone
4	7.5	Upper Eze Akue	12	2	0	86	59	41	35.26	35.26	**17.63**	Weathered Mudstone
6	1.5	Upper Eze Aku	38	5	0	57	54	46	26.22	26.22	**13.11**	Soil
6	2.5	Upper Eze Aku	25	4	0	71	58	42	29.82	29.82	**14.91**	Soil/Clay
6	3.5	Upper Eze Aku	19	3	0	77	58	42	32.34	32.34	**16.17**	Clay
6	4.5	Upper Eze Aku	14	4	0	82	55	45	36.9	36.9	**18.45**	Weathered Mudstone
6	5.5	Upper Eze Aku	14	4	0	82	50	50	41	41	**20.5**	Weathered Mudstone
6	6.5	Upper Eze Aku	16	4	0	80	51	49	39.2	39.2	**19.6**	Weathered Mudstone
6	7.5	Upper Eze Aku	13	3	0	83	42	58	48.14	48.14	**24.07**	Weathered Mudstone
6	8.5	Upper Eze Aku	9	4	0	87	51	49	42.63	42.63	**21.315**	Weathered Mudstone
6	9.5	Upper Eze Aku	13	6	0	81	65	35	28.35	28.35	**14.175**	Weathered Mudstone
7	1.5	Makurdi Sandstone	86	14	0	0						
7	2.5	Makurdi Sandstone	82	18	0	0						
7	3.5	Makurdi Sandstone	64	36	0	0						
7	4.5	Makurdi Sandstone	52	48	0	0						
7	5.5	Makurdi Sandstone	45	55	0	0						
8	1.5	Makurdi Sandstone	84	16	0	0	0	0	0	0	**0**	Soil
8	2.5	Makurdi Sandstone	89	11	0	0	0	0	0	0	**0**	Soil
8	3.5	Makurdi Sandstone	66	8	0	26	53	47	12.22	12.22	**6.11**	Clay
8	4.5	Makurdi Sandstone	29	6	0	65	59	41	26.65	26.65	**13.325**	Clay
8	5.5	Makurdi Sandstone	25	5	0	71	47	53	37.63	37.63	**18.815**	Clay
8	6.5	Makurdi Sandstone	21	2	0	77	55	45	34.65	34.65	**17.325**	Clay
8	7.5	Makurdi Sandstone	33	5	0	62	66	34	21.08	21.08	**10.54**	Clay
8	8.5	Makurdi Sandstone	26	4	0	70	63	37	25.9	25.9	**12.95**	Clay

Borehole	Mean depth	Formation	Kaolinite	Illite	Smectite	Illitie/Smectite	Illite %	Smectie %	Smectite	Smectite TOTAL	Smectite in Rock	Geology
13	1.5	Makurdi Sandstone	66	34	0	0			0	0	**0**	Soil
13	2.5	Makurdi Sandstone	56	44	0	0			0	0	**0**	Soil
13	3.5	Makurdi Sandstone	42	51	7	0			0	7	**3.5**	Clay
13	4.5	Makurdi Sandstone	39	53	9	0			0	9	**4.5**	Clay
15	1.5	Lower Eze Aku	39	29	0	32	60	40	12.8	12.8	**6.4**	Ferricrete
15	2.5	Lower Eze Aku	37	6	0	57	63	37	21.09	21.09	**10.545**	Ferricrete
15	3.5	Lower Eze Aku	29	4	0	67	67	33	22.11	22.11	**11.055**	Ferricrete/Clay
15	4.5	Lower Eze Aku	23	3	0	74	68	32	23.68	23.68	**11.84**	Clay
15	5.5	Lower Eze Aku	17	3	0	80	70	30	24	24	**12**	Clay
15	6.5	Lower Eze Aku	11	4	0	85	74	26	22.1	22.1	**11.05**	Clay
15	7.5	Lower Eze Aku	9	1	0	90	72	28	25.2	25.2	**12.6**	Clay/Weathered Mudstone
15	8.5	Lower Eze Aku	8	3	0	89	71	29	25.81	25.81	**12.905**	Weathered Mudstone
15	9.5	Lower Eze Aku	6	3	0	92	74	26	23.92	23.92	**11.96**	Weathered Mudstone
16	1.5	Lower Eze Aku	64	36	0	0	0	0	0	0	**0**	Ferricrete
16	2.5	Lower Eze Aku	66	34	0	0	0		0	0	**0**	Ferricrete
16	3.5	Lower Eze Aku	32	10	0	58	71	29	16.82	16.82	**8.41**	Ferricrete
16	4.5	Lower Eze Aku	20	7	0	73	75	25	18.25	18.25	**9.125**	Clay
16	5.5	Lower Eze Aku	10	4	0	86	72	28	24.08	24.08	**12.04**	Clay/Weathered Mudstone
16	6.5	Lower Eze Aku	1	7	0	92	79	21	19.32	19.32	**9.66**	Weathered Mudstone
16	7.5	Lower Eze Aku	1	7	0	91	70	30	27.3	27.3	**13.65**	Weathered Mudstone
16	8.5	Lower Eze Aku	1	6	0	94	80	20	18.8	18.8	**9.4**	Weathered Mudstone
16	9.5	Lower Eze Aku	1	6	0	93	79	21	19.53	19.53	**9.765**	Weathered Mudstone
18	1.5	Lower Eze Aku	65	35	0	0	0	0	0	0	**0**	Ferricrete
18	2.5	Lower Eze Aku	25	7	0	68	64	36	24.48	24.48	**12.24**	Ferricrete
18	3.5	Lower Eze Aku	17	5	0	78	67	33	25.74	25.74	**12.87**	Clay
18	4.5	Lower Eze Aku	14	6	0	80	78	22	17.6	17.6	**8.8**	Clay
18	5.5	Lower Eze Aku	12	7	0	82	70	30	24.6	24.6	**12.3**	Weathered Mudstone
18	6.5	Lower Eze Aku	8	6	0	86	74	26	22.36	22.36	**11.18**	Weathered Mudstone
18	7.5	Lower Eze Aku	7	5	0	88	67	33	29.04	29.04	**14.52**	Weathered Mudstone
18	8.5	Lower Eze Aku	15	7	0	78	69	31	24.18	24.18	**12.09**	Weathered Mudstone
18	9.5	Lower Eze Aku	12	6	0	82	66	34	27.88	27.88	**13.94**	Weathered Mudstone

Borehole	Mean depth	Formation	Kaolinite	Illite	Smectite	Illitie/Smectite	Illite %	Smectie %	Smectite	Smectite TOTAL	Smectite in Rock	Geology
19	1.5	Asu River	58	42	0	0			0	0	**0**	Soil
19	2.5	Asu River	63	32	5	0			0	5	**2.5**	Clay
19	3.5	Asu River	55	39	6	0			0	6	**3**	Clay
19	4.5	Asu River	48	47	5	0			0	5	**2.5**	Weathered Mudstone
19	5.5	Asu River	36	57	7	0			0	7	**3.5**	Weathered Mudstone
19	6.5	Asu River	48	40	11	0			0	11	**5.5**	Weathered Mudstone
19	7.5	Asu River	34	56	11	0			0	11	**5.5**	Weathered Mudstone
19	8.5	Asu River	38	49	13	0			0	13	**6.5**	Dolerite
21	1.5	Asu River	51	49	0	0			0	0	**0**	Soil
21	2.5	Asu River	46	54	0	0			0	0	**0**	Soil/Clay
21	3.5	Asu River	37	47	16	0			0	16	**8**	Clay
21	4.5	Asu River	30	65	5	0			0	5	**2.5**	Weathered Mudstone
27	14.5	Awgu Shales	36	3	60	0			0	60	**30**	Limestone
27	19.5	Awgu Shales	35	3	63	0			0	63	**31.5**	Limestone
30	1.5	Awgu Shales	57	4	39	0			0	39	**19.5**	Soil
30	2.5	Awgu Shales	44	4	52	0			0	52	**26**	Clay
30	3.5	Awgu Shales	35	3	62	0			0	62	**31**	Clay
30	4.5	Awgu Shales	42	5	53	0			0	53	**26.5**	Clay/Fine Grained Sand
30	5.5	Awgu Shales	41	3	55	0			0	55	**27.5**	Fine Grained Sand
30	6.5	Awgu Shales	31	2	67	0			0	67	**33.5**	Fine Grained Sand
30	7.5	Awgu Shales	34	4	62	0			0	62	**31**	Weathered Sandstone
30	8.5	Awgu Shales	23	3	74	0			0	74	**37**	Weathered Sandstone
30	9.5	Awgu Shales	37	3	60	0			0	60	**30**	Weathered Sandstone
30	10.5	Awgu Shales	32	4	64	0			0	64	**32**	Mudstone

Borehole	Mean depth	Formation	Kaolinite	Illite	Smectite	Illitie/Smectite	Illite %	Smectie %	Smectite	Smectite TOTAL	Smectite in Rock	Geology
31	1.75	Awgu Shales	56	5	39	0			0	39	**19.5**	Soil
31	2.25	Awgu Shales	35	1	64	0			0	64	**32**	Soil
31	2.75	Awgu Shales	44	2	54	0			0	54	**27**	Soil/Clay
31	3.25	Awgu Shales	37	1	62	0			0	62	**31**	Clay
31	3.75	Awgu Shales	32	0	68	0			0	68	**34**	Clay
31	4.25	Awgu Shales	34	3	63	0			0	63	**31.5**	Clay
31	4.75	Awgu Shales	26	1	73	0			0	73	**36.5**	Clay
31	5.25	Awgu Shales	23	1	76	0			0	76	**38**	Clay
32	1.5	Awgu Shales	49	0	51	0			0	51	**25.5**	
32	2.5	Awgu Shales	35	1	64	0			0	64	**32**	
32	3.5	Awgu Shales	43	4	53	0			0	53	**26.5**	
32	4.5	Awgu Shales	38	21	41	0			0	41	**20.5**	
32	5.5	Awgu Shales	32	1	67	0			0	67	**33.5**	
32	10.5	Awgu Shales	31	2	67	0			0	67	**33.5**	
34	1.5	Awgu Shales	3	1	0	96	55	45	43.2	43.2	**21.6**	Soil/Clay
34	2.5	Awgu Shales	2	2	0	96	51	49	47.04	47.04	**23.52**	Clay
34	3.5	Awgu Shales	5	5	0	90	60	40	36	36	**18**	Clay
34	4.5	Awgu Shales	4	2	0	94	70	30	28.2	28.2	**14.1**	Clay/Weathered Mudstone
34	8.5	Awgu Shales	1	21	0	78	60	40	31.2	31.2	**15.6**	Weathered Mudstone
34	29.5	Awgu Shales	31	16	0	53	58	42	22.26	22.26	**11.13**	Mudstone
34	30.5	Awgu Shales	32	1	0	67	65	35	23.45	23.45	**11.725**	Mudstone
34	31.5	Awgu Shales	13	0	27	60	67	33	19.8	46.8	**23.4**	Mudstone
35	1.5	Dolerite	79	0	21	0				21	**10.5**	Soil
35	2.5	Dolerite	37	0	63	0				63	**31.5**	Soil
35	3.5	Dolerite	27	0	73	0				73	**36.5**	Clay
35	4.5	Dolerite	8	0	92	0				92	**46**	Clay
35	5.5	Dolerite	4	0	96	0				96	**48**	Weathered Dolerite
35	6.5	Dolerite	1	0	99	0				99	**49.5**	Weathered Dolerite
35	7.5	Dolerite	0	0	100	0				100	**50**	Weathered Dolerite
36	1.5	Makurdi Sandstone	44	56	0	0	0	0	0	0	**0**	Soil
36	3.5	Makurdi Sandstone	16	0	0	84	89	11	9.24	9.24	**4.62**	Clay
36	5.5	Makurdi Sandstone	9	0	0	91	81	19	17.29	17.29	**8.645**	Weathered Sandtone

Smectite and Conductivity Table

Borehole	Conductivity	Smectite	Formation
19	4.71	3.63	Metamorphosed Asu River
21	19.01	2.63	Metamorphosed Asu River
1	8.13	5.5	Asu River
2	14	7	Asu River
17	35.23	8.91	Lower Eze Aku
18	34.7	10.88	Lower Eze Aku
15	33.26	11.15	Lower Eze Aku
16	34	8.01	Lower Eze Aku
14	30.92	9.53	Lower Eze Aku
22	110.08	31.2	Awgu Shale
28	100	29.89	Awgu Shale
26	113.11	29.6	Awgu Shale
25	136.83	28.11	Awgu Shale
24	126.13	30.06	Awgu Shale
23	94.05	30.45	Awgu Shale
27	95.19	30.75	Awgu Shale
30	85.28	29.4	Awgu Shale
31	107.42	31.19	Awgu Shale
34	72.18	17.38	Awgu Shale/ Dolerite
33	39.03	19.1	Awgu Shale/ Dolerite
4	50.78	10.55	Upper Eze Aku
6	87.93	18.03	Upper Eze Aku
5	49.01	12.58	Upper Eze Aku
9	15.65	2.18	Makurdi Sandstone
10	21.84	9.43	Makurdi Sandstone
11	13.52	2.18	Makurdi Sandstone
12	14	6.44	Makurdi Sandstone
37	16.39	7.81	Makurdi Sandstone
38	26.78	6.08	Makurdi Sandstone
7	16.22	0	Makurdi Sandstone
8	29.85	9.88	Makurdi Sandstone
36	16.39	4.42	Makurdi Sandstone

Groundwater quality - Conductivity of Pore Water

Borehole	Conductivity mS/m
2	45.7
4	41
6	122.5
7	54.5
8	39.9
10	55.3
12	40.5
13	647
15	58.3
16	55.8
17	114.9
19	53.2
20	69.9
21	58.8
26	1008
27	716
30	20.1
33	50.9
34	51.8
35	54.6
36	151
37	96.5
39	52.1
40	61.4
41	250
42	56.3
44	41.7
46	31.6
48	499
50	55.8
13a	51.3
2b	45.4

<u>Revil and Glover, and Experimental Conductivities</u>

Borehole	Conductivity Experiment	Conductivity Model
4	50.78	25.73613536
6	87.93	66.64516053
7	16.22	23.2937653
8	29.85	24.74699515
15	33.26	34.7944315
16	34	32.21320374
19	4.71	27.52932686
21	19.01	29.28767706
30	85.28	15.54247124
34	72.18	33.70223931
36	16.39	65.05015707
27	95.19	284.2676322