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The groundwater potential of the Oju/Obi area, eastern Nigeria

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FINAL REPORT: THE GROUNDWATER POTENTIAL OF THE OJU/OBI AREA, EASTERN NIGERIA

J Davies and A M MacDonald

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Front cover illustration: Collecting water froma a borehole in Oju

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EXECUTIVE SUMMARY

Oju and Obi are two adjacent local government areas (LGAs) in a remote part of south-eastern Nigeria. During the annual dry season (November to April) both LGAs experience severe water shortage and families have to rely on unprotected ponds, seepages and hollows for their source of domestic water. Consequently, much of the population (approximately 300 000 people) is badly affected by various water related illnesses. The area is underlain by complex, low permeability, fine grained, sedimentary rocks of Cretaceous age, which have posed many problems for groundwater development in the area.

As part of a DFID funded rural water supply and sanitation project led by WaterAid, BGS have been investigating the groundwater potential of the Oju/Obi area and have demonstrated methods for siting and exploiting groundwater. The following work has been carried out by BGS:

- a literature review of the geology and hydrogeology of Benue area and of mudstones in general
- creation of a base map for the area using satellite images, published geology, aeromagnetic and topographic maps
- more than 75km of electro-magnetic conductivity (EM34) traversing, 40km of magnetic profiling and 40 resistivity depth soundings
- drilling and construction of 54 exploration boreholes
- analysis and logging of chip and core samples from each borehole
- 30 boreholes test pumped (of these exploration boreholes 13 can be fitted with hand pumps)
- 150 water samples taken for analysis.

The studies have shown that potential groundwater resources do exist within Oju/Obi. Standard geophysical techniques (EM34, resistivity and magnetic profiling) can be used to locate good sites for boreholes and wells throughout much of the area. There are three main targets for groundwater in Oju/Obi:

1. *Fracture zones within the Asu River Group and Lower Eze-Aku Shale Formation*: The Asu River Formation and Metamorphosed Asu River Formation both comprise hard splintery shales. Fractures within these rocks are common and generally remain open, regardless of their orientation. The Lower Eze-Aku Shale Formation, although softer, can contain open fractures. These tend to be more widely spaced than in the Asu River Group and are associated with faults.

2. *Sandstone and limestone layers within the Upper Eze-Aku Shale Formation, Makurdi Sandstone Formation and Agbani Sandstone Formation*: Sandstone is present, interlayered with thick shales, within the Upper Eze-Aku Shale and Makurdi Sandstone Formations. The sandstones are fine- to medium-grained and can be well cemented and consolidated. Intergranular permeability is low, but fractures are common from 10-15 m below ground surface. Hand dug wells constructed to 15 m depth could support up to 50 basins per day (1500 l/d) in the dry season. Thin limestones, where fractured, can provide sufficient water for a borehole and handpump.

The Agbani Sandstone Formation that is present within the Awgu Group, is a complex sandstone, with a low potential for groundwater. Potential for sustainable supplies is highest where the sandstone has been weathered along valleys.

3. *Dolerite intrusions within the Awgu Group*: In the north of the area underlain by Awgu Shale Formation there is little potential for groundwater. The mudstone is too soft for fractures to remain open, and sandstones and limestones are rare. The main targets for groundwater in this area are dolerite intrusions. The dolerite occurs both as sills and dykes and is often fractured. Where the dolerite is thick, high yields can be generally found. Where the dolerite is thin, the best targets are found in valleys where dolerites have intruded mudstone.

Throughout Oju/Obi targets for groundwater can usually be found within walking distance of most villages. The most severe groundwater supply problems are found within the area underlain by the Awgu Shale Formation mudstones. Here, the best targets for groundwater are dolerite intrusions, but these are often remote from villages. Alternatively, thin sandstones interbedded with Awgu Shale Formation mudstones could be developed where weathered, although yields from these sands are low. In some villages, where detailed geophysical surveys do not indicate dolerite or sandstone nearby, rainwater harvesting will need to be considered.

The groundwater development maps and guidelines, outlined in this report, should be used to help develop groundwater sources within the area. As more information is collected from drilling and hand dug wells, these guidelines should be upgraded. Simple data should be collected from all additional boreholes and wells drilled within the project area.

The local government WASU teams have been trained in many aspects of hydrogeology as part of a technique locally known as "geological triangulation". However, specialist skills such as geophysical surveys and borehole drilling are required to develop groundwater throughout much of the area. It is proposed that these skills would be best taught to and used by water engineers within WaterAid or BERWASSA. Nevertheless, the complexity of the area requires that these engineers be supported. This service could be best provided by BGS.

The information provided by BGS is directly applicable to over 150 villages and can easily be extrapolated to 100 additional villages. This would contribute to improving the quality of life of 200 000 people. However, the guidelines developed are not fully appropriate for the extreme east and west of Oju where geological conditions differ. Additional investigations are required to assist the 84 villages in these poorly accessible areas.

Although the BGS investigations have studied many of the problems of locating groundwater supplies they have not addressed the long-term reliability of groundwater abstraction. **The sustainability of groundwater abstraction is unknown**. The majority of the groundwater is abstracted from thin fractures that can store only a little groundwater. Long term monitoring of the groundwater resource and/or age determination is required to assess how the resource responds to pumping. The permeability of the laterite is also unknown; this could have an important bearing on the performance of latrines and the contamination of shallow wells.

The geology throughout much of Benue State, and the surrounding states in south-eastern Nigeria, is similar to Oju and Obi. Prior to this study little was known about developing groundwater in these low permeability sediments. At a project workshop, held with hydrogeologists from BERWASSA, UNICEF, Nigerian Geological Survey and Nsukka University, the difficulties encountered by staff working in such geologically complex areas were highlighted. They felt that the knowledge gained from this study and the exploratory techniques developed for use in Oju and Obi could be readily applied to other parts of Benue and the adjacent states.

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Acronyms and Abbreviations

BERWASSA	Benue Rural Water Supply and Sanitation Agency
BGS	British Geological Survey
DFID	Department for International Development
DFRRI	Directorate of Food, Roads and Rural Infrastructure
LGA	Local Government Area
Ma	Million years ago
NIGEP	Nigerian Guinea Worm Eradication Programme
RUSAFIYA	UNDP assisted Rural Water Supply and Sanitation project NIR/87/011
WASU	Water and Sanitation Unit (local government)

1. INTRODUCTION

1.1 Background

The Oju/Obi area is a remote part of Benue State in southeastern Nigeria (Figure 1). The area comprises two local government areas (LGAs) that were created in 1996 by dividing the existing Oju LGA into two. Obi LGA is in the north of the area, and Oju LGA in the south. Population estimates for the combined Oju/Obi area vary between 177 000 (1991 census) and 420 000 (RUSAFIYA Project census). For the purposes of this project an approximate population of 300 000 is used, most of whom belong to the Igede people (Morgan 1996).

The Oju/Obi area, about 2000km^2 in extent, can be divided into two main geographical areas: the Wokum Hills in the southwest and the central and northeastern low lying plains. The Wokum Hills trend NE-SW and reach a height of 550m asl. The plains range from 50 to 125m asl and are gently undulating. A north-south trending surface water divide crosses the area; to the east water flows into the Konshisha river and to the west into the river Obi. Both river systems flow to the south and form part of the Cross River Basin. Lateritic soils, supporting savannah woodland type vegetation, cover much of the area. The main crops grown are yams, cassava and rice. Sorghum, millet, maize, sesame seed, groundnuts and oranges are also cultivated.

Prior to the current project, village locations in Oju/Obi were imprecisely known. Only a small number were shown, with varying degrees of accuracy, on the 1:50 000 scale topographic maps of the area. During the project, the majority of known villages were visited and located accurately using a Global Positioning System (GPS). The village locations and names collected were used to compile the first accurate village location map and gazetteer of the Oju/Obi area (MacDonald and Davies 1998b). The distribution of villages within Oju and Obi is shown in Figure 2

The area is underlain by a thick sequence of Cretaceous age sedimentary rocks which form part of the Benue Trough. The sediments are mainly mudstones with occasional sandstones, siltstones and limestones. There are three main mudstone units in the area: the Asu River Group of shaley mudstones that have undergone low-grade metamorphism; the Eze-Aku Group shaley mudstones with siltstones and sandstones; and the Awgu Group very soft shaley mudstones. Dolerite intrusions are found throughout the area. A thick fersiallitic soil has developed over much of the area that can obscure the bedrock geology. The geology largely controls the availability of groundwater in the area and is therefore discussed in detail in the report.

1.2 The Water Supply Problem in Oju/Obi

The Oju/Obi area receives a mean annual rainfall of 1600mm, most of which falls between April and October, leaving five months without rain. During the wet season most rainfall runs off as rapid surface flow or percolates through shallow permeable soils to the rivers; flash floods commonly result. The laterite subsoils are rapidly recharged at the onset of the rains, water levels in wells and boreholes rise quickly in consequence. At the end of the rains, water within the laterite soils flows out of the system, either to streams and rivers or is abstracted by shallow wells.

During the dry season villagers become reliant on unprotected ponds (Plate 1), seepages and hollows as sources of domestic water. These sources tend to become polluted and unreliable as the dry season progresses; as local sources dry up, women and children are obliged to walk to more distant sources for water supplies. During this period, the population become increasingly prone to infection by a variety of water related illnesses during this period, of which guinea worm and dysentery are endemic; outbreaks of cholera and typhoid are also common. Within Oju/Obi, most of the cases of guinea worm occur in the northern area on the outcrop of the Awgu shales (Figure 3).

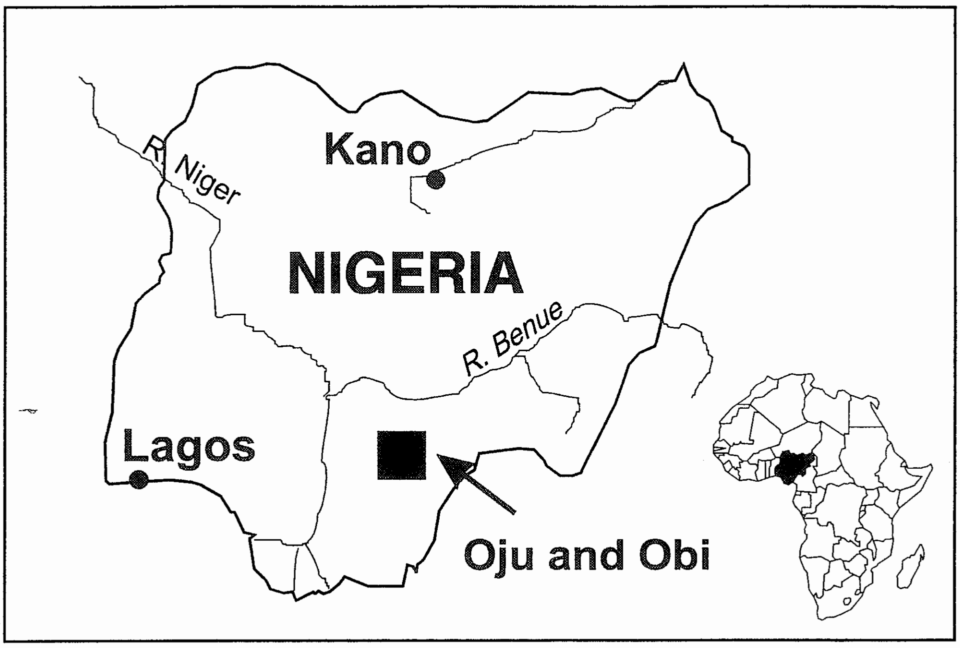


Figure 1 Location of Oju and Obi.

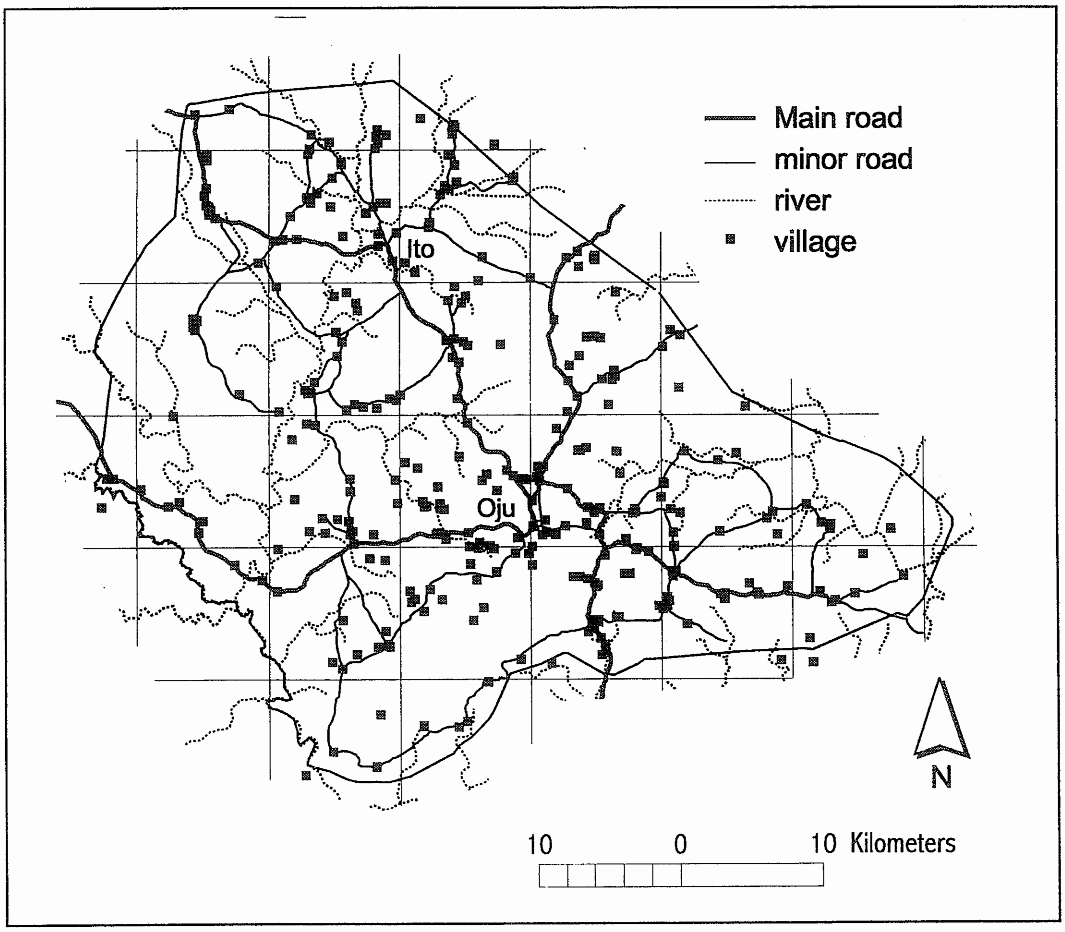


Figure 2 Map of the Oju and Obi area.

The seasonal dependence on various types of water sources is shown in Figure 4. During the rainy season most people rely on rainwater harvesting and streams for their water. As the rains stop and the streams dry up, ponds and seepages become more important. A brief description of the various dry season water sources is given below.

Stream Seepages (Plate 2). During the dry season, stream flows diminish and cease, leaving isolated pools that eventually dry up. Water is then obtained from shallow pits dug into thin and discontinuous river gravels that yield small quantities of water. As the dry season continues these gravels dry up, and additional pits are excavated further down stream. Studies of stream seepages show that most water is derived laterally from weathered rocks along stream banks.

Pond Seepages (Plate 3). Pond seepages are important water sources occurring within local depressions and along shallow valleys underlain by sandstones and siltstones. As the dry season proceeds, these ponds are cleaned out and deepened with decline of water level (Plate 4). Those that remain in use throughout the dry season often form sites of guinea worm infestation and mosquito breeding.

Shallow Hand Dug Wells (Plate 5). Unlined wells have been excavated in most communities in Oju/Obi. Although heavily used during the rainy season, many fail during the dry season. Most shallow wells are fed by inflow from shallow permeable layers within near surface laterites that dewater as the dry season progresses. All wells are heavily over-pumped, contributing to their seasonal failure. Unlined wells tend to collapse due to swelling clays in the near-surface weathered zone.

Boreholes (Plate 6). A number of boreholes had been drilled in the Oju/Obi area prior to the project. Most successful boreholes are located in the Oju area within hard and fractured Asu River Group rocks. Some boreholes supply large population groups (>1000) on a rotational basis during annual dry seasons. Unfortunately, borehole breakdowns are common. The main causes of failure are likely to be:

- erosion of pump leathers by fine sediments produced with pumped water;
- lack of appreciation of seasonal aquifer and well hydraulics; water levels fall to below pump level by late in the dry season (a misconception is that the pump is faulty);
- heavy pump usage can cause mechanical damage.

1.3 The Project

Experience gained from water projects world-wide shows that effective groundwater development often provides the best solution to rural community water supply problems. Hand dug wells exploiting shallower groundwater can be constructed and maintained by local communities. Deeper groundwaters are exploited using boreholes, constructed using higher technology, that can be reliable and easy to maintain. Alternative water supplies such as piping water from rivers or rainwater harvesting would be considerably more expensive in areas like Oju/Obi and more difficult to manage.

As a basis for improvement of water supply to the communities of Oju/Obi, the UK Department for International Development (DFID) funded a British Geological Survey (BGS) investigation of the groundwater resource development potential of the water bearing rock formations of the area. Prior to this study, little was known about the potential for groundwater in low permeability sediments, or methods for siting boreholes and wells. Such low permeability rocks underlie the Oju/Obi area. Past water supply projects in the area failed to find sufficient groundwater, due mainly to a lack of understanding of the complex geology present and incorrect application of geophysical siting techniques.

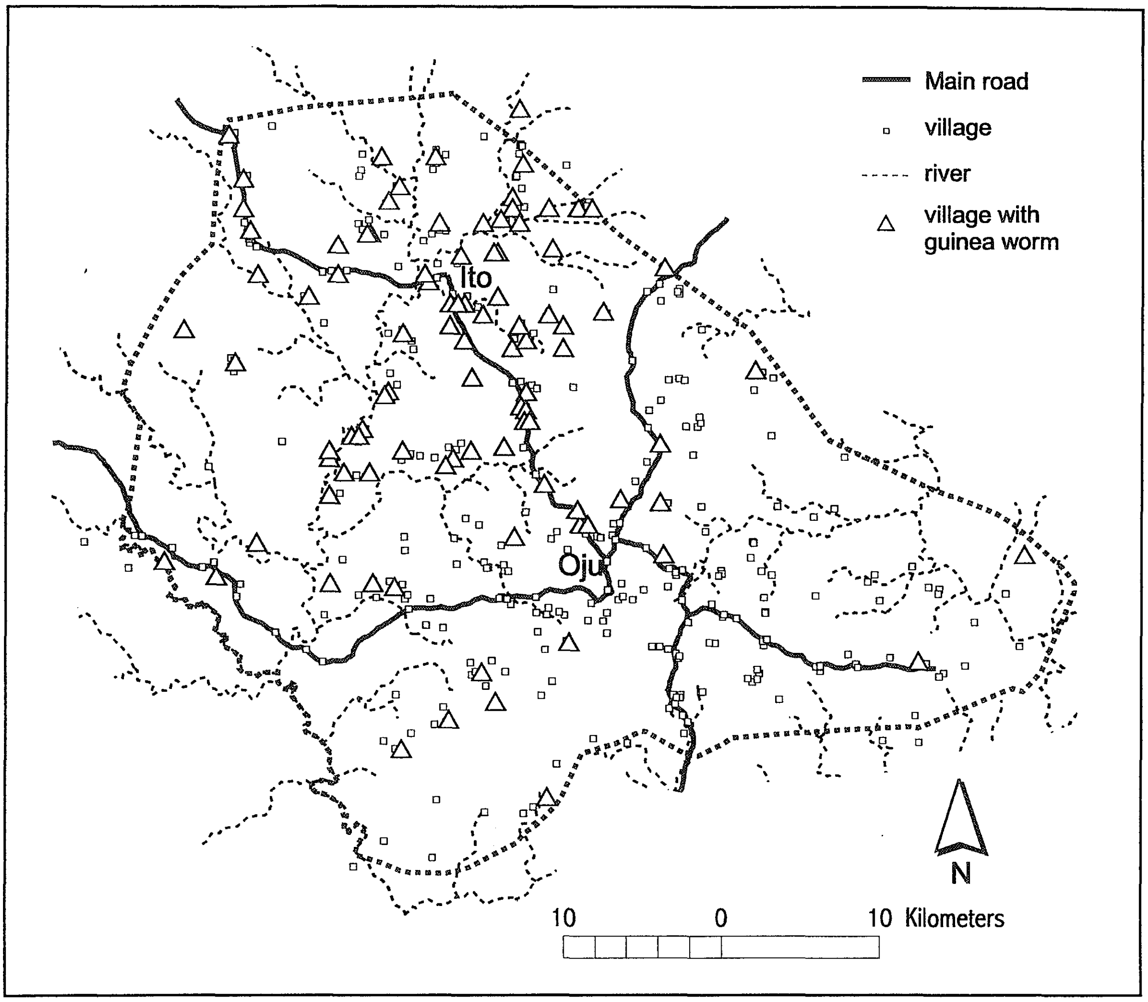


Figure 3 Villages with cases of guineau worm in 1991 (data from RUSAFIYA survey).

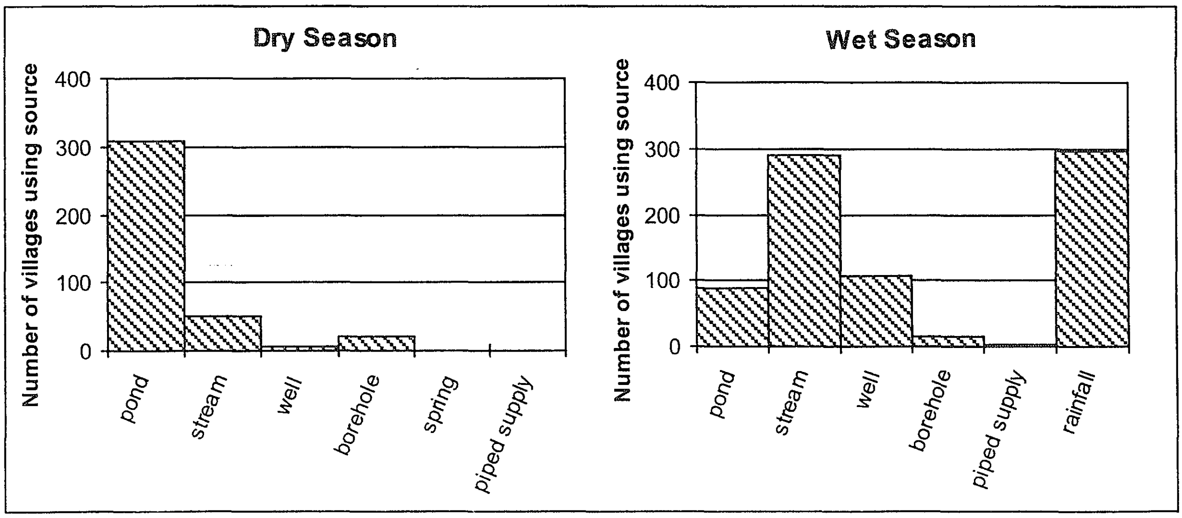


Figure 4 Wet and dry season water sources used in villages throughout Oju and Obi (original data from RUSAFIYA survey, 1991). Note that a village can have more than one source of water.

Plate 1. Children bathing in a pond in the Upper reaches of the River Obi.

Plate 2. A woman collecting water from a stream seepage near Odubwo.

Plate 3. A pond seepage used for drinking water and bathing near Adum West.

Plate 4. Taking water from a large dugout in a shallow valley at Adum East.

Plate 5. A dried up traditional shallow well.

Plate 6. A working borehole constructed during the project at Odubwo.

This report describes the results of hydrogeological investigations carried out in the Oju/Obi area by BGS during the period 1996 – 1999. The investigations had two main aims:

- To assess the hydrogeological development potential of aquifers underlying the Oju/Obi area.
- To develop standard methods for locating and assessing groundwater resources, and the siting and testing of wells and boreholes.

Information gathered and methods developed during this study are presented in a series of reports and maps (Appendix 1). WaterAid and local government staff have been trained to use the information and maps to help the local communities develop sustainable water supplies. Nigerian and locally based international hydrogeological organisations including BERWASSA, UNICEF and Universities are also benefiting from these studies.

This report provides a summary of both the methodology and results of the hydrogeological investigations.

1.4 Summary

Oju/Obi is a remote part of Eastern Nigeria with a population of approximately 300 000. There are severe water shortages during the 4-5 month dry season. The hydrogeology of the area is complex, and groundwater is difficult to find. Therefore during the dry season the majority of communities are reliant on stream and pond seepages to meet domestic water requirements. In an attempt to understand and quantify the available groundwater resources within the area, DFID commissioned BGS to carry out a hydrogeological review of the area and devise appropriate and effective methods for siting wells and boreholes assessing groundwater resources and how best these resources be developed. These results are being used by WaterAid, Local Government and BERWASSA staff to help local communities develop sustainable water supplies.

2. BGS INVESTIGATIONS

This section describes the various methods, processes and techniques used to investigate the groundwater potential of the Oju/Obi area. Rather than discuss each of the methods in detail, a brief summary is given with references to publications where the techniques are described more fully. In this manner, it is hoped to give a flavour of the research without getting lost in detail. The main findings and implications of the study are discussed in Section 3 and 4.

2.1 Preliminary Work

Literature Review

Detailed desk studies of maps, aerial photography, reports and digital remotely sensed data were carried out prior to fieldwork. The collated information provided a basis for locating exploratory drilling sites, while placing the hydrogeology of the Oju/Obi area within a regional context.

A review of literature collected in the UK and Nigeria was undertaken. The collected material are listed in an annotated bibliography (Davies and MacDonald, 1997). This material described aspects of:

- the geology and hydrogeology of the Benue Trough area of Nigeria
- the geology and hydrogeology of low permeability rocks, such as mudstones, and the nature of tropical soils
- the use of geophysical survey methods for locating structures likely to contain groundwater
- background material on rainfall, rivers and other geographic aspects of south-eastern Nigeria

Up-to-date maps and aerial photography of the Benue area and surrounding regions are not available. Available maps and aerial photographs were collected, with difficulty, from sources in Nigeria. These included:

- Topographic maps (at 1:100 000 and 1:50 000 scale)
- Geology maps (Nigerian Geological survey at 1:250 000 scale)
- Aeromagnetic anomaly maps (Nigerian Geological survey at 1:100 000 scale)
- Aerial photographs taken between 1959 and 1963 at a scale of 1:40 000

A cloud free digitised Landsat TM satellite image (LANDSAT TW 188-055, bands 4-5-7, red, green and blue), taken on the 17 January 1986, was obtained for project use. Interpreted data from these maps and images were used to produce a base map of the Oju/Obi area.

Creating a base map

The BGS remote-sensing group in Keyworth, Nottingham, digitised the maps, and registered them and the satellite image to the same projection. The satellite image was interpreted to identify roads, rivers and lineations. Lineations indicate possible fracture zones and geological boundaries. From the available information various layers of data were interpreted:

- topographic contours from topographic maps;
- roads, paths and rivers from the satellite image;
- geological boundaries from geological maps;
- large magnetic anomalies from the aeromagnetic maps;
- photo-lineations from aerial photographs and satellite imagery;
- accurate village locations from a rapid survey using a hand held global positioning system (GPS)
- Borehole locations using a GPS.

The various digitised elements of the maps, images and data sets of the Oju/Obi area were combined using ArcView® - a Geographical Information System (GIS) – to produce three maps (MacDonald and Davies, 1998b):

- groundwater development map (Figure 5);
- hydrogeology map;
- map showing the interpretation of aerial photograph and satellite imagery.

These maps were upgraded during the project as additional data became available. GIS allows map data to be easily modified or analysed and permits maps to be updated cheaply or tailored to the needs of different users. The maps produced at 1:100 000 scale are accurate to about 200m. A gazetteer of village names, GPS derived locations and approximate populations was compiled and is being used, in conjunction with the Groundwater Development Map, by WaterAid and the local government, for development programme planning.

Reconnaissance surveys

Surveys conducted prior to the test programme included a geological survey, during which rock samples of the major rock units present were obtained, to verify the geological map. Only a few good geological exposures were found north of the Wokum Hills Oju/Obi. In addition, the nature of typical wet and dry season water sources was noted together with location and reliability of available boreholes with details about drilling or construction. Data from earlier surveys, such as that conducted by the RUSAFIYA project, were analysed to provide background information.

2.2 Test Site Selection

BGS were required to investigate the groundwater development potential of each of the geological formations present in Oju/Obi by conducting surveys then drilling and testing boreholes at representative sites on each formation. The location of test sites was governed by community vulnerability, as defined by the WASU/WaterAid teams, and available access for the drilling rig. WaterAid and LGAs used indices of health and poverty to determine community vulnerability. Test sites were located at accessible vulnerable villages on each rock type.

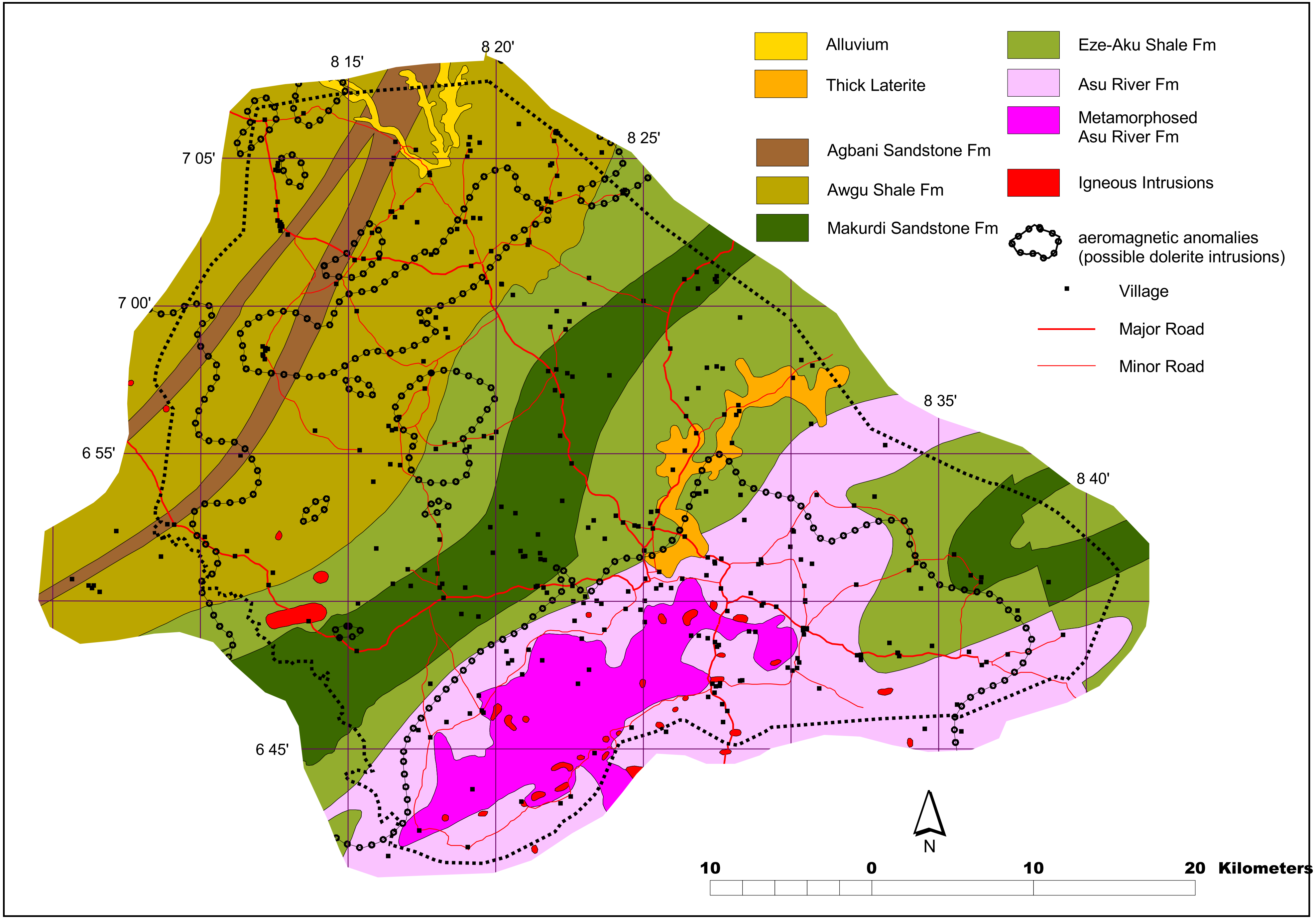


Figure 5. Simplified groundwater development map for Oju and Obi (taken from MacDonald and Davies 1998b).

After test site selection, the BGS team visited the community accompanied by a WASU member. The test programme was discussed with the community whose participation was requested. The village was accurately located using a GPS and maps. Village seasonal water sources and local geological exposures were examined. The geology map of the Oju/Obi area proved to be inaccurate in many respects therefore a reconnaissance geological field survey of each site was required to examine rock units present.

2.3 Geological Surveys

Simple geological surveys require use of basic inexpensive equipment; a hammer for collection of fresh samples, a hand lens to inspect samples, a GPS to locate villages and rock exposures, a compass-clinometer to determine dip and strike of rocks, and a camera to record rock exposures. The project used a digital camera to record images of rock cores, chip samples and sites on computer. Short, basic geological surveys were carried out at village sites prior to survey work to inspect the geological environment and validate the map data. A typical survey included:

- Discussions with local leaders about seasonal water sources and location of rock exposures
- Inspection of traditional wells and collection of rock samples.
- Inspection of nearby stream rock exposure sections.
- Inspection of seasonal water sources and other potential water development sites.

Local government staff have now been trained to undertake similar surveys as part of their rapid surveys of villages.

2.4 Geophysical Survey Methods

Geophysical techniques can be used to investigate the physical properties of rocks in an area without extensive drilling. If appropriate techniques are used and interpreted carefully, changes in geology or thickness of weathering can be mapped and faults identified. Geophysical techniques have been successfully used in basement areas to improve location for productive wells and boreholes (Dongen and Woodhouse 1994). They are largely untried in areas underlain by low permeability sediments such as Oju/Obi. On the few occasions when geophysics has been used, problems have arisen, largely because inappropriate techniques and methods of analysis were used or the geology was not clearly understood.

Three different geophysical survey methods were chosen to identify groundwater targets Oju/Obi:

1. frequency domain electromagnetic induction (using Geonics EM34-3 equipment);
2. vertical electrical resistivity sounding (VES) and
3. magnetic profiling (using a proton processor magnetometer).

Table 1 gives a summary of these techniques. Both EM34 and resistivity are established techniques for siting wells/boreholes in crystalline basement areas (e.g. Beeson and Jones 1988, Carruthers and Smith 1992). Their operation is well understood by most hydrogeologists working in sub-Saharan Africa, and equipment is generally widely available. Magnetic techniques are not used routinely in hydrogeological investigations. However, since dolerite intrusions form such an important part of the hydrogeology in the northern Oju it was thought appropriate to include the method.

During the project, 75km of EM34 surveys, 50km of magnetic profiling and 30 vertical electric soundings were undertaken. The surveys were correlated with the geological logs from boreholes to establish methods of interpreting geophysics in Oju and Obi.

Table 1. **Advantages and disadvantages of the three geophysical methods used in Oju/Obi.**

TECHNIQUE	MEASUREMENT OF	ADVANTAGES	DISADVANTAGES
EM34	Bulk ground electrical conductivity	Rapid surveying No direct contact to the ground Very simple operation	Requires two people operate Not enough detail
Resistivity	Ground resistivity	Much detail about one point Equipment robust and available	Slow. Not enough information about a wide area Electrodes must be hammered into the ground Poor at identifying lateral changes
Magnetic profiling	Earth's magnetic field	Good at identifying igneous rocks Rapid survey	Difficult operation Sensitive to noise (particularly metal)

EM34 (Plates 7 and 8)

The EM34 equipment is based on the principals of electromagnetic induction. The EM34 instrument creates a changing electromagnetic field by passing an alternating current through a tightly wound wire coil. The small currents induced in the ground by this alternating field produce a secondary field, which can be sensed, along with the primary field, by another coil. The operation and principals of the EM34 are fully explained by McNeill (1980a, 1980b 1983).

Three inter-coil spacings (10m, 20m and 40m) are used, each operating at a different frequency. The coils are orientated either vertically (horizontal dipoles) or horizontally (vertical dipoles); the different orientation changes the direction of the inducing field producing different depth responses. Barker et al (1992) reported the depth of penetration for the coil separations (10m, 20m and 40m) as 3.8m, 7.6m and 15.2m respectively for vertical coils and 8.7m 17.4m and 34.8m for horizontal coils. The EM34 measures the bulk conductivity of the ground measured in milli-mhos per metre (mmhos/m). Conductivity is the reciprocal of resistivity.

Factors affecting the electrical conductivity of the ground include porosity, presence and nature of pore fluid and clay content. Therefore, good geological control is needed for interpretation of survey results. The EM34 can also be used to identify dykes and fracture zones; horizontally aligned coils producing a characteristic negative anomaly over such features.

Plate 7. EM34 equipment used on the project.

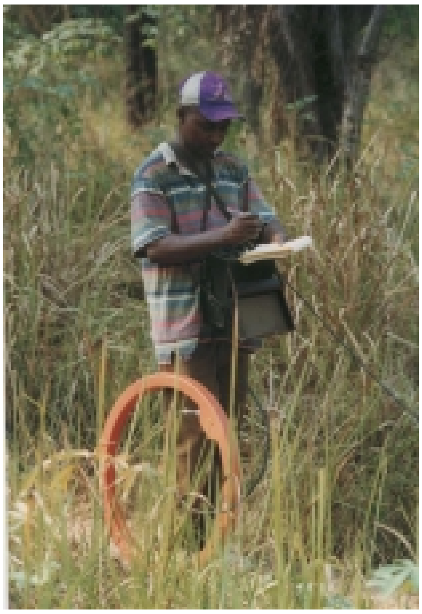


Plate 8. EM34 being used in the vertical orientation by BERWASSA staff.

Plate 9. The magnetometer in use in Obi.

Plate 10. Basic equipment required for a resistivity sounding.

Plate 11. Electrodes being watered to ensure good contact with the ground for a resistivity survey.

In Oju/Obi, EM34 surveys were generally undertaken using a 20m inter-coil separation; readings were made in both vertical and horizontal orientations. The vertical coil readings gave information about the shallow zone, while the horizontal coils penetrated deeper, being used to locate fracture zones. Measurements were usually taken at 20m intervals, the spacing being reduced to 10m or 5m to investigate specific anomalies.

Magnetic surveying (Plate 9)

Magnetic surveying involves measuring variations in intensity (and sometimes direction) of the earth's magnetic field. Variations in the magnetic field are complex and often localised, due to differences in the magnetic properties of rocks near to the surface. Metal objects such as steel roofs, bicycles and steel basins also give strong magnetic anomalies, making surveying within villages difficult. Magnetic susceptibility of rocks is determined solely by the amount of ferromagnetic minerals present. In general, sedimentary rocks have low magnetic susceptibility, and basic igneous rocks high magnetic susceptibility (Telford et al 1990). High contrast between the magnetic susceptibility of different rocks produces measurable anomalies in the local magnetic field. Hence, magnetic surveys are good for locating dolerite intrusions within mudstone in Oju/Obi.

Operation and principals of the proton precession magnetometer (PPM), used to identify magnetic anomalies, are explained in Breiner (1973) and Telford et al (1990). The PPM is easily portable and rapid to use, so that accurate surveys can be carried out quickly by one person. The instrument, accurate to about 0.1 nT, is carried on a long pole to minimise noise interference from ground surface or the operator and console. Magnetic surveys are carried out at the same time as EM34 surveys. The same intervals can be used by both techniques allowing direct comparison of results. The magnetometer was located 100m behind the EM34, to avoid any noise created by the other equipment. Measurements were usually made at 10m spacings, reduced to 1m over significant anomalies. No correction for the diurnal variation of the earth's magnetic field was made since the magnitude and wavelength the magnetic targets were easily distinguishable from the diurnal variation.

Resistivity methods (Plates 10 and 11)

Resistivity methods are commonly used for siting wells and boreholes in Africa. There are two main survey techniques: profiling and depth or vertical electrical sounding (VES). Profiling using resistivity is a slow method that has largely been superseded by EM34. VES produces a one-dimensional section at a spot location that distinguishes between geo-electrical layers. Methods combining profiling and VES are complex, requiring specialist equipment and interpretation. They are not usually appropriate for small rural water supply projects. In Oju/Obi VES were rapidly undertaken using the Offset Wenner electrode configuration, at intervals along EM34 surveys. This method minimises the effect of surface inhomogenities. Contact resistance between electrodes and ground surface is a problem in hot climates. Electrodes must be hammered in securely and water added to provide good contact with the ground. Further information on resistivity techniques is given in Milsom (1996).

2.5 Drilling Programme

54 exploration boreholes were drilled within Oju/Obi to assess the hydrogeological potential of the main geological formations. The boreholes were located at sites agreed with the local community using the results of geophysical surveys. Detailed geological and hydrogeological data were collected during the drilling of each borehole. Where sufficient groundwater was encountered the borehole was test pumped. WaterAid latterly fitted handpumps to boreholes with sufficient yields of good quality groundwater. Locations of exploration boreholes are shown in Figure 6 and details given in Table 2.

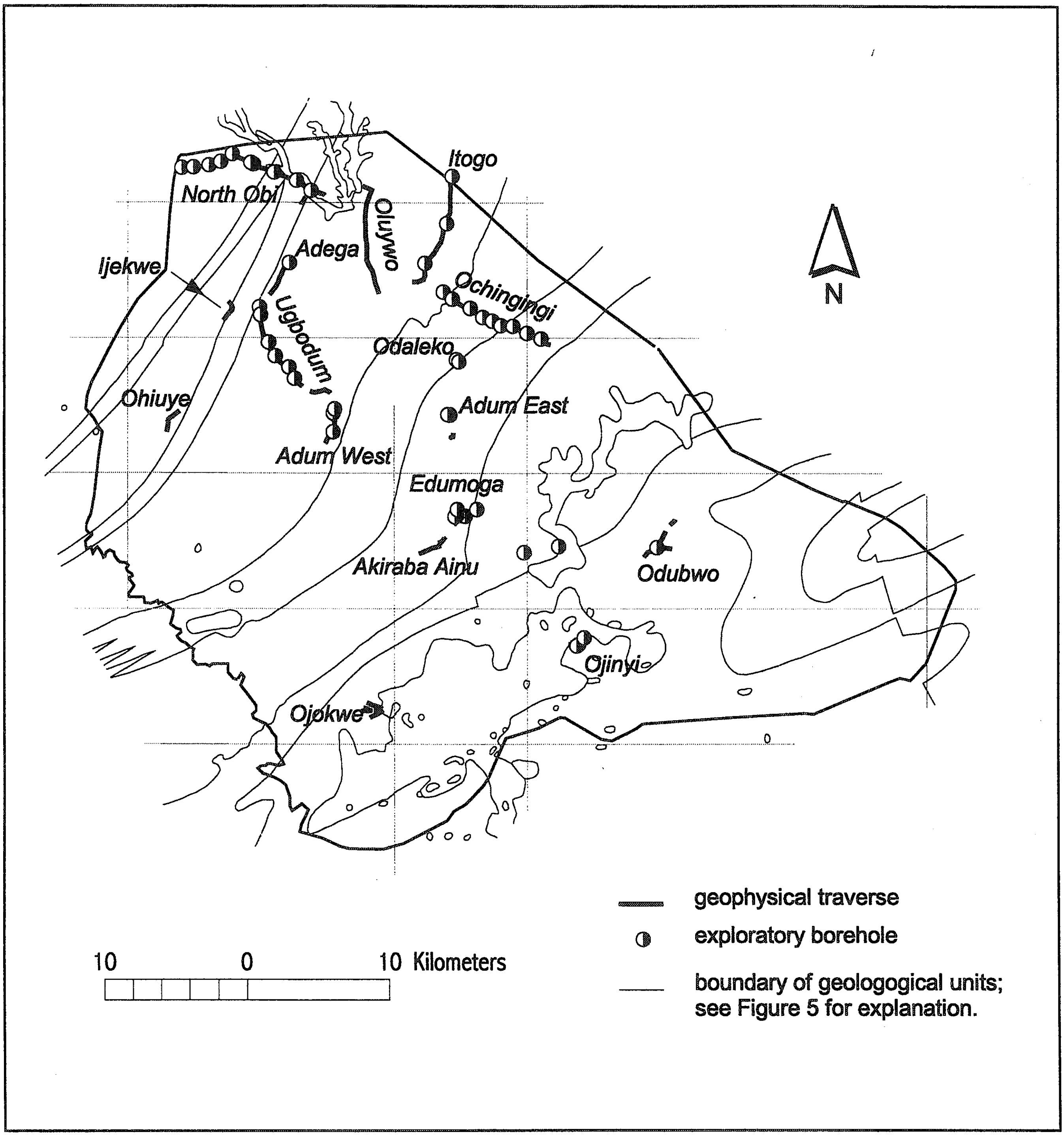


Figure 6 Location of exploratory boreholes and geophysics surveys.

Table 2 Summary information for exploratory boreholes

Bh ID	Location	Northing	Easting	Geological Formation	Date completed	Depth (m)	T (m^2/d)	status
BGS1	WaterAid	6 52.31	8 26.152	Asu River	17/11/97	12	0.27	screened
BGS2	Odubwo	6 52.27	8 29.87	Asu River	20/11/97	63.7	4	screened
BGS2A	Odubwo	6 52.27	8 29.87	Asu River	22/11/97	20.8		backfilled
BGS2B	Odubwo	6 52.27	8 29.87	Asu River	23/11/97	19.5	3.5	screened
BGS3	Odaleko	6 59.195	8 22.312	Upper Eze Aku	26/11/97	60.7		backfilled
BGS3A	Odaleko	6 59.195	8 22.312	Upper Eze Aku	29/11/97	16		backfilled
BGS4	Ochingini	7 01.700	8 21.822	Upper Eze Aku	01/12/97	12.7	0.7	screened
BGS5	Ochingini	7 01.441	8 22.166	Upper Eze Aku	02/12/97	23.4		backfilled
BGS6	Ochingini	7 01.091	8 22.847	Upper Eze Aku	03/12/97	19	18	screened
BGS7	Ochingini	7 00.754	8 23.313	Makurdi (sandstone)	04/12/97	16.5	0.1	screened
BGS8	Ochingini	7 00.615	8 23.666	Makurdi (limestone)	05/12/97	13.1	0.4	screened
BGS9	Ochingini	7 00.460	8 23.982	Makurdi (sandstone)	06/12/97	5.8		backfilled
BGS10	Ochingini	7 00.441	8 24.437	Makurdi (shales)	08/12/97	11.4	0.2	screened
BGS11	Ochingini	7 00.163	8 24.962	Makurdi (sandstone)	09/12/97	6.05		backfilled
BGS12	Ochingini	6 59.957	8 25.499	Makurdi (sandstone)	10/12/97	15.7	1	screened
BGS13	Odaleko	6 59.180	8 22.399	Makurdi (sandstone)	24/01/98	87.5	0.15	screened
BGS13A	Odaleko	6 59.180	8 22.399	Makurdi (sandstone)	27/01/98	8.3	0.07	screened
BGS14	Edumoga	6 53.418	8 22.655	Lower Eze Aku	28/01/98	27.4		backfilled
BGS15	Edumoga	6 53.651	8 23.095	Lower Eze Aku	30/01/98	29.5	1.6	screened
BGS16	Edumoga	6 53.433	8 22.342	Lower Eze Aku	04/02/98	29.5	2	screened
BGS17	Edumoga	6 53.393	8 22.257	Lower Eze Aku	05/02/98	29.5	1.7	screened
BGS18	Edumoga	6 53.655	8 22.352	Lower Eze Aku	07/02/98	53		backfilled
BGS19	Oyinyi	6 48.809	8 26.954	mm Asu River	10/02/98	41.5	6	screened
BGS20	Oyinyi	6 48.279	8 26.899	mm Asu River	12/02/98	41	27	screened
BGS21	Oyinyi	6 48.99	8 27.173	mm Asu River	13/02/98	38.5	3	screened
BGS22	North Obi	7 06.277	8 12.009	Awgu	19/02/98	23		backfilled
BGS23	North Obi	7 06.311	8 12.439	Awgu	20/02/98	23.5		backfilled
BGS24	North Obi	7 06.373	8 13.022	Awgu	21/02/98	23		backfilled
BGS25	North Obi	7 06.52	8 13.449	Awgu	24/02/98	21.3		backfilled
BGS26	North Obi	7 06.794	8 13.895	Awgu	25/02/98	23.4	0.02	screened
BGS27	North Obi	7 06.395	8 14.567	Awgu	26/02/98	23.35	0.08	screened
BGS28	North Obi	7 06.110	8 15.462	Awgu	27/02/98	23.4		backfilled
BGS29	North Obi	7 05.822	8 16.291	Awgu	03/03/98	23.6		backfilled
BGS30	North Obi	7 05.433	8 16.830	alluvium/Agbani ?	04/03/98	23.5	0.4	screened
BGS31	North Obi	7 06.395	8 14.567	Awgu	05/03/98	14.5		backfilled
BGS32	Adega	7 02.764	8 16.024	Awgu	06/03/98	32.5		backfilled
BGS33	Adum West	6 57.211	8 17.623	dolerite	09/03/98	18.5	51	screened
BGS34	Adum West	6 56.521	8 17.665	dolerite	11/03/98	39.5	4	screened
BGS35	Adum West	6 57.367	8 17.727	dolerite	12/03/98	21.5	23	screened
BGS36	Adum East	6 57.168	8 22.041	Makurdi (sandstone)	16/03/98	41.5	0.8	screened
BGS37	Adum East	6 57.168	8 22.041	Makurdi (sandstone)	18/03/98	18.5	0.6	screened
BGS38	Adum East	6 57.143	8 21.946	Makurdi (shales)	18/03/98	41.7		backfilled
BGS39	Elim	6 52.08	8 24.86	Asu River	23/01/99	40.5	2.5	screened
BGS40	Ugbodum	7 01.204	8 14.938	Agbani/dolerite	26/01/99	32.01	0.15	screened
BGS41	Ugbodum	6 59.809	8 15.229	Awgu	28/01/99	41.5	0.25	screened
BGS42	Ugbodum	6 59.345	8 15.499	Awgu/dolerite	29/01/99	32.05	0.8	screened
BGS43	Ugbodum	6 59.345	8 15.409	Awgu	30/01/99	31.86		backfilled
BGS44	Ugbodum	6 58.539	8 16.227	Awgu/dolerite	02/02/99	32	0.1	screened
BGS45	Ugbodum	6 59.345	8 15.499	Awgu dolerite	03/02/99	19.7	0.06	screened
BGS46	Ugbodum	7 0.842	8 14.993	dolerite	05/02/99	32.07	45	screened
BGS47	Itogo	7 04.287	8 22.162	Agbani/Awgu	06/02/99	31.69		backfilled
BGS48	Itogo	7 5.972	8 22.168	Agbani/Awgu	09/02/99	31.9	0.14	screened
BGS49	Itogo	7 5.972	8 22.168	Agbani/Awgu	09/02/99	10.5	0.04	screened
BGS50	Itogo	6 59.345	8 21.115	dolerite	10/02/99	31.75	2	screened

The Drilling Rig (Plates 12 and 13)

To ensure flexibility of drilling and sampling during investigation of the complex geology of the area the project procured a lightweight drilling rig, operated by an experienced driller. Appropriate drilling, geological sampling and test pumping methods were developed as the project proceeded.

The lightweight Dando GEOTEC-5 hydraulic top drive drilling rig, mounted on a 4x4 Bedford truck, has sufficient capacity to drill 6.5" diameter boreholes to 100m. The drilling system uses compressed air flush with tricone rock roller bits, drag bits, coring bits and a down the hole hammer, compressed air being supplied by a 600cfm 150psi Ingersoll Rand rotary screw type mobile compressor. The support vehicle is a 4x4 Bedford truck with a hydraulic crane.

Drilling and sampling methods (Plates 14, 15 and 16)

The boreholes were drilled using rotary airflush using drag bits or rock roller bits through the upper soft weathered horizons, and a down-the-hole hammer in hard rocks at depth. Generally, the last three metres of each borehole were cored. Parameters recorded during the drilling included:

Penetration logs. The time taken to drill 0.5m intervals were recorded and plotted; layers of hard and soft rocks were thereby identified.

Rock Chip samples. Rock chips produced during drilling using rotary air flush or down-the-hole hammer were collected at 0.5m intervals and geologically logged. Chip samples provided an accurate indication of rock type variation when collected during the drilling of specific 0.5m intervals; the borehole being blown clean prior to drilling of the sampled interval.

Core samples. Rock core sampling of sedimentary and softer igneous rocks was undertaken using tungsten carbide insert bits and airflush. Up to 3m of 3" diameter core was obtained from the bottom of most boreholes. A few boreholes were cored from the surface. These samples were stored in locally made hard wood boxes. The core samples provided a first indication of the non-weathered nature of rock formations and fracturing present. Cored samples of sandstones were tested for permeability and porosity.

Drilling Yield. Indication of borehole yield was obtained by monitoring water flow blown out of the borehole during drilling. The water is channelled away from the borehole, though a pipe into a bucket. The time taken to fill the bucket was measured to provide an indication of yield. Good yielding boreholes were constructed as production wells and developed by surging with air.

Analysis of rock samples (Plate 17)

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

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

Core samples were geologically logged by recording changes in colour, grain size, hardness and limestone content, sedimentary structures and joint/fracture systems. Each core run was washed and photographed to record the true nature of the rocks. Core samples, especially of soft mudstones, deteriorated quickly on exposure. Representative samples of core obtained for further analysis in the U.K. included:

Plate12. Project drilling rig at BGS18

Plate 13. Drilling support vehicle and compressor.

Plate 14. Drag bit used for soft overburden

Plate 15. Down the hole hammer used for hard rocks

Plate 16. Measuring the yield during drilling.

Plate 17. Chip samples from drilling collected and displayed in a core box for easy analysis.

- 48 lithological samples for mineralogical analysis (to assess intrinsic hydraulic properties and style of weathering)
- 15 sandstone samples for porosity/permeability determination;
- 12 limestone samples for palaeontological and lithological analysis;
- 104 samples for clay type analysis. The percentages of clay types present are indicative of degree of burial diagenesis experienced by a specific rock. The type of clay present can also be related to potential for collapse of near surface weathered zones in boreholes and hand-dug wells. The type of clay also affects the electrical properties of the rock measured by the geophysics.
- The macro and micro palaeontology of cored samples of the Awgu Shales are currently being investigated at Sheffield University.

2.6 Test Pumping

A variety of tests can be carried out on a completed borehole. These involve pumping the borehole for a length of time and measuring the change in water levels both during and after pumping. Interpretation of the results gives an estimate of the hydraulic properties of the rock, transmissivity and storage coefficient. These parameters are fundamental to hydrogeology and are used to estimate the sustainability of groundwater supplies from that rock type and to model the effectiveness of various well and borehole designs.

In Oju/Obi only a few high yielding boreholes could be test pumped using standard methods and equipment. Most project boreholes were low yielding and so were test pumped using new simple systems devised for application to low permeability rocks. Transmissivity values obtained from pumping tests carried out on the exploratory boreholes are shown on Table 2.

Bailer tests (Plate 18)

A simple, easy-to-use test system using a locally made bailer was developed to give a first approximation of the aquifer properties. This method is based on the slug test developed by Cooper et al (1967). The amount of water extracted during 10 minutes of bailing is recorded and the water level then measured until recovery to about 75% of the original level. Recovery of the water level is logarithmic, therefore measurement becomes less frequent as the borehole recovers. The resulting recovery curve is interpreted. When the yield of the borehole is very low, the slug test analysis from Barker (1994) is appropriate, but requires a computer to model the results. When the yield is higher, the Theis recovery method can be used (Kruseman and deRidder 1990). Information from the test is only applicable to the rocks immediately surrounding the borehole.

Whale pumps (Plates 19, 20 and 21)

A simple, low permeability, test-pumping system was designed around the 0.15l/s capacity Whale pump. The Whale pump is inexpensive and powered by a 12 volt car battery. The pump produces a steady output at a capacity similar to the yield of a hand pump. The hydraulic lift of a pump is limited to 6m, therefore, two or more need to be connected in series to make them practical for testing boreholes in Oju/Obi. The pumps were connected together with hosepipe and the yield measured accurately using a bucket and a stopwatch. The pump system is easy to use and maintain, and can be easily carried in a vehicle. When required, two sets of Whale pumps were installed in a borehole to produce a test yield of about 0.3l/s. Drawdown and recovery data from the Whale pump tests were analysed using standard test pumping analysis. Drawdown data were generally analysed using Jacob's straight-line method and recovery data using the Theis recovery method.

Plate 18. A bailer test being carried out at Edumoga.

Plate 19. Measuring water levels during a test at Ugbodum.

Plate 20. Recording the recovery rate after pumping has stopped.

Plate 21. A whale pump test at Ochingini.

Plate 22. Simple raingauge used by schools in Oju/Obi.

High yield testing methods

The low yielding exploratory boreholes could only be tested using Whale pumps. The few boreholes with yields greater than about 1l/sec were also tested using higher capacity pumps. Where water levels were shallow, a Honda centrifugal pump with a capacity of up to 4 l/s from a maximum pumped water level depth of 7m below ground surface, was used. Where the water level was deeper, a 1l/s capacity Grundfos electrical submersible pump was used. This is powered using a portable generator of at least 1.5kva capacity, and needs a high-pressure hose as a rising main. Unreliable generators and dirty fuel caused problems with this system. Fluctuations in pumping rate during a test can make the data difficult to analyse. The data produced by these methods are analysed using the techniques described for the Whale tests.

Criteria for equipping borehole with hand pump

Exploratory boreholes that had sufficient water could be equipped with a hand pump and used by communities. Since the primary aim of exploratory programme in Oju and Obi was to assess the available groundwater resources throughout the entire area, and not just the higher yielding areas, only about a quarter of the exploratory boreholes had sufficient yields for a hand pump. The criteria used was based on modelling by MacDonald and Macdonald (1997). Assuming a viable storage of 0.001 – 0.01, then a transmissivity of greater than $1m^2/d$ should provide a viable water supply. Since the storage is largely unknown, and only estimated, monitoring is required to prove the long-term sustainability of these supplies. Boreholes with transmissivity values of 0.5 – $1m^2/d$ may sustain a hand pump, but would be liable to intermittent failure with heavy use.

2.7 Hydrochemistry

During the project, groundwater samples were obtained for hydrochemical analysis throughout Oju/Obi. Complex variations in groundwater chemistry were revealed, including areas where groundwater is not fit for human consumption. Hydrochemical variations can also be used to indicate the nature of groundwater flow in an aquifer. Samples were taken from borehole, wells and seepage sources during the 1997, 1998 and 1999 field visits. Water samples were also taken from each exploration borehole drilled that contained water. In addition, twelve sources have been routinely sampled to monitor seasonal hydrochemical changes.

Sample collection

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

Laboratory determinations

Groundwater samples have been submitted for analysis at BGS Wallingford. A comprehensive suite of inorganic major, minor and trace element concentrations were determined. Acidified filtered samples were analysed for major cations, SO_4 and selected trace elements by inductively coupled plasma optical emission spectrometry (ICP-OES). Cl, I, F, Br, NO_2-N and NH_4-N concentrations were determined by automated colorimetry. Of the elements determined Sc, Be, Y, Co, V, Cd, La, Cu, Zr, Cr, Ni, Mo and Pb were found to be absent or below detectable levels.

2.8 Monitoring

Monitoring of water levels and rainfall provides essential data for assessing the sustainability of groundwater systems. Average monthly rainfall data are needed to define seasonal rainfall patterns. Seasonal variations of groundwater levels also need to be determined and correlated with rainfall patterns. Annual fluctuations in the water table can indicate the nature of the aquifer. Likewise, long-term trends can indicate whether the resource is being over-exploited. Currently, rural water supply projects are encouraged to monitor health and poverty factors, but little emphasis is placed upon the monitoring of the state of the groundwater resource.

A network of ten wells and boreholes has been established where water levels are monitored each month. These include exploratory boreholes drilled by BGS, and existing hand dug wells and boreholes. The network includes boreholes close to pumping sources and also those in relatively natural conditions. An automatic water-level recorder has been fitted on the well in the WaterAid compound. This is measuring the effect of pumping on the hand dug well.

Seven rainfall monitoring stations were established, mainly at schools throughout Oju/Obi. Simple plastic rainfall gauges were used at the majority of the stations (Plate 22). These were generally located about 1m above the roof of the school to avoid vandalism and obtain a representative rainfall away from the shelter of buildings and trees. Measurements were made at these locations for two years. At two locations (St Joseph's School and the WaterAid office) standard metal rain gauges were installed. WaterAid aim to continue taking measurements at these two sites.

2.9 Summary

Various techniques have been used during the hydrogeological investigations in Oju/Obi. Below is a summary of the investigations:

1. Existing literature on the geology and hydrogeology of the Benue area and also about the hydrogeology and geology of mudstones in general were collated.
2. A base map was created for the area using published geology, aeromagnetic and topographic maps. A satellite image was interpreted to give the location of rivers, roads and lineations. Villages were located using a GPS.
3. Test sites were selected, for each geological formation, on the basis of community vulnerability indicators developed by WaterAid/WASU. The geology of these sites was confirmed using geological field mapping techniques.
4. Geophysical survey methods were used at each test site. EM34-3 was used to measure the bulk electrical conductivity, electrical resistivity soundings were carried out at borehole locations; magnetic profiling was used to identify the dolerite intrusions.
5. Several boreholes were drilled at each test site; the geophysics data and community's wishes governing their precise location. In total, 53 exploration boreholes at 11 test sites were drilled.
6. Penetration rates were measured and rock chip samples taken every 0.5m; core samples were generally taken from the last 3m of a borehole.
7. Rock chip and core samples were logged and photographed in the field; representative core samples were sent to the UK for further analysis.
8. Exploration boreholes that contained water were screened and cased and various pumping

tests carried out. A simple pump test method using bailers was developed; more conventional methods were also used.

9. Approximately 150 hydrochemistry samples were taken from existing sources and exploratory boreholes.

10. A simple groundwater and rainfall monitoring system was set up throughout the area.

3. THE HYDROGEOLOGY OF THE OJU/OBI AREA

3.1 Introduction

This section discusses the results of investigations in Oju and Obi. After an introduction to climate, hydrology and regional geology, a summary is given of the geology and hydrogeology of the groundwater units present in Oju/Obi. To help interpret and apply this information, a short summary of the groundwater potential of each unit is given. The section is best read in conjunction with the groundwater development and hydrogeology maps created for Oju/Obi (MacDonald and Davies 1998b).

3.2 Climate and Hydrology

The climate, and in particular the distribution of rainfall has an important bearing on the water supply problems in Oju and Obi. Rainfall data, collected at St Joseph's School, Ito, since 1988, indicate a mean annual rainfall of 1600mm. Average monthly data for the period 1988 to 1993 is shown in Figure 7. These data indicate that the wettest months are from May to October with two months, December and January, generally dry. The annual dry season lasts four to five months, but the start of the rains can be unreliable. For example, during 1988 rainfall began in June, whereas in 1990 rainfall occurred in March.

The closest meteorological index station to Oju/Obi is at Ogoja (N6° 39', E8° 42') where rainfall data recorded from 1931 to 1960 indicate a mean annual rainfall of 1800 mm (Tahal, 1982). At Ogoja there was an average of 96 rainy days per year with 7 rainy days during the November to April dry season. A summary of various meteorological parameters measured at index stations close to Oju/Obi is given in Table 3.

Seasonal variations in rainfall distribution across Oju/Obi were investigated using monthly data recorded at seven stations distributed throughout the area. Figure 8 shows that the pattern of rainfall changes across Oju and Obi. A distinct break in the wet season, locally known as the 'August break', is more distinct in the south of the area than in the north.

Rainfall events can be intense, occurring in downpours of 3-4 hours duration. Daily records from some of the project rainfall stations in Oju/Obi show rainfall of between 50-100mm in a 24-hour period. Similar daily rainfall figures (maximum of 152mm per day) have been recorded at Lokoja meteorological station (Hayward and Oguntoyinbo 1987). Swami (1970) estimated that 50-60% of Nigerian rainfall occurs in rainfall events with intensity greater than 25mm/hr, an intensity that can cause soil erosion.

The combination of climate, soil and geology produce distinctive hydrology in Oju/Obi. During the wet season, storm rainfall causes short-term flash floods – the result of rapid surface water runoff. Most of the rivers and streams are ephemeral, drying up soon after the rains stop. There are no river gauging stations within, or close to Oju/Obi, therefore all discussion of the river system is based on observations made by the project team during the 1996/97, 1997/98 and 1998/99 wet and dry seasons.

Oju/Obi lies within the northern part of the Cross River Basin, which drains south to the Gulf of Guinea. The two largest rivers are the Obi, to the west and the Konshisha to the east. These rivers tend to be entrenched with limited river gravel deposits. Aerial photographs show a change in the drainage pattern across the area. In areas underlain by the low permeability shales, the drainage density is very high and dendritic; on the outcrop of the Makurdi Sandstone Formation, the drainage density is lower.

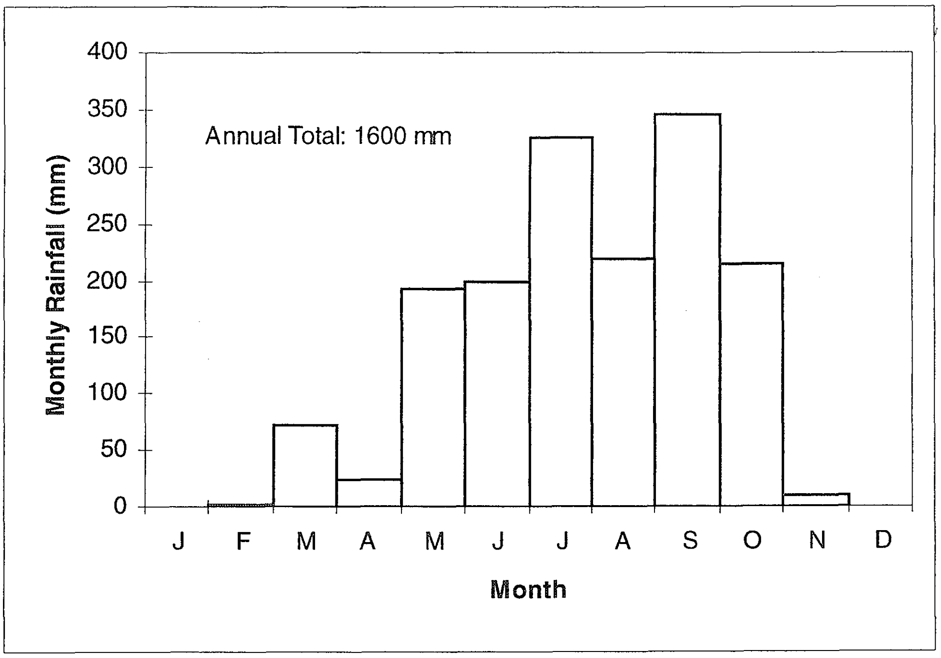


Figure 7 Average monthly rainfall data for St Joseph's School, 1988-1993.

Table 3. Average monthly estimates of various meteorological parameters from the nearest index stations to Oju/Obi.

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

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

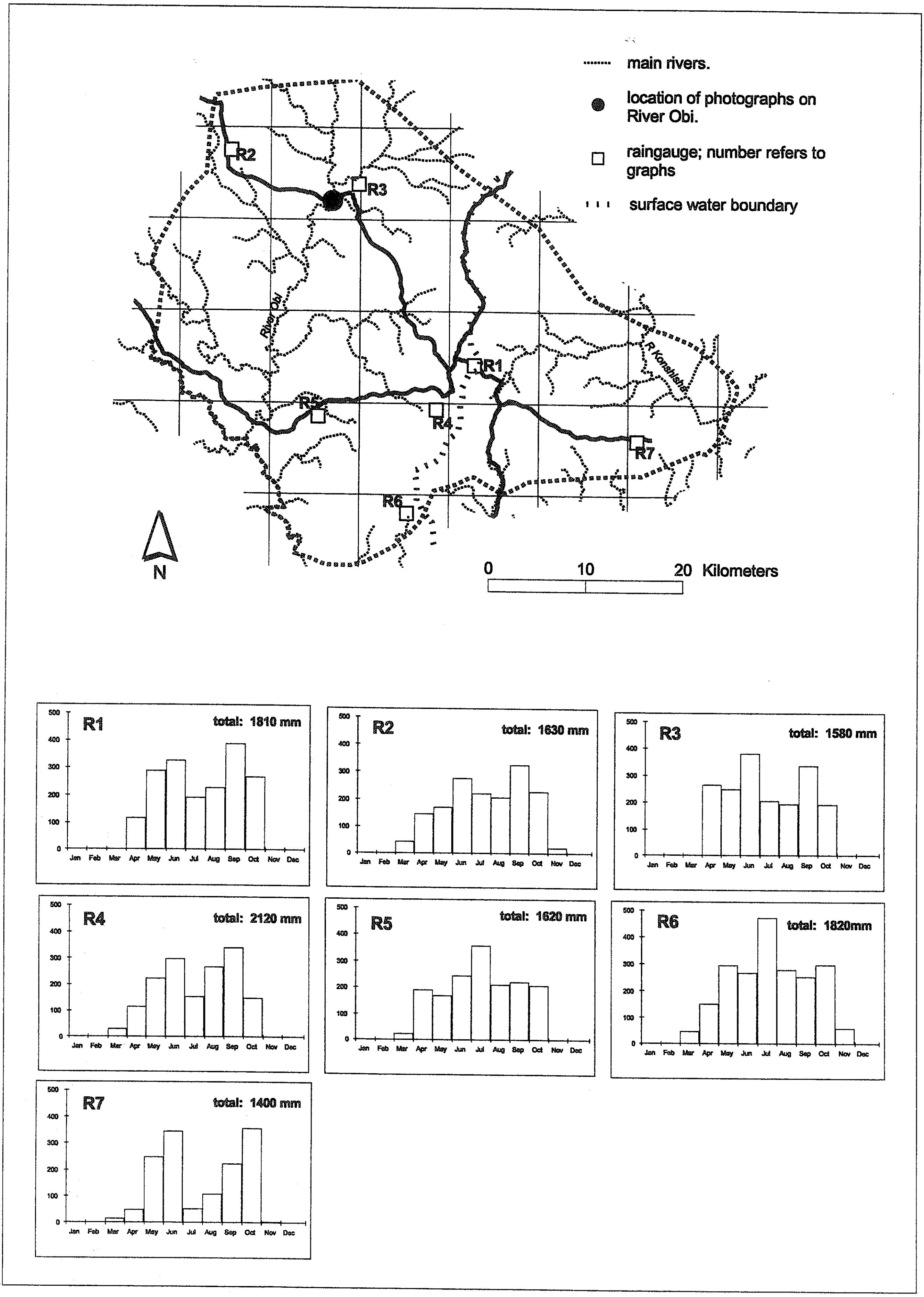


Figure 8 Recorded monthly rainfall for 1997/1998 across Oju and Obi.

Seasonal variations in river flow are illustrated using a series of photographs of the Obi River taken at different times of the year (Plate 23). During the wet season flow in the Obi River is substantial. Following intense rainfall, the level of the Obi River rises rapidly to cause widespread flooding. River flows are significantly reduced by the end of the rainy season. By February only isolated ponds are left in the upper reaches of the main river. The lower reaches of the Obi River are perennial and supply the piped water scheme to Oju town if functioning. All other rivers in the area are ephemeral. Most tributary streams dry up as the dry season progresses, occasionally leaving small ponds.

Natural groundwater fluctuations throughout the area are high, sometimes in excess of 5m. Continuous water level variations, recorded at the WaterAid office supply well, indicate the importance of groundwater flow through the near-surface permeable soil - the main source of recharge to most of the hand dug wells of the area. Water-level variations continue to be monitored monthly, to ensure that limited groundwater resources are not overexploited. Variations for the period 1997–1998 are shown on the hydrogeological map (MacDonald and Davies 1998).

Throughout the area - but more commonly on the Makurdi Sandstone Formation - river headwaters tend to form large shallow depressions. These features, generally lacking woodland, are marshy during the wet season but dry out during the dry season. These are similar to features observed in Central Africa, known as *dambos* (Goudie, 1996). Within Oju/Obi these features are often used for dry season water supply. Dambos store only direct rainfall or gain water from the surrounding interfluves. There is also doubt as to whether they contribute significantly to dry season stream flows.

3.3 Regional Geology

The Benue Trough is a major, elongated geological rift structure infilled with Cretaceous age fine-grained, low permeability sediments deposited within a series of basins (Figure 9). These were deposited in deep- to shallow-marine and deltaic to fluviatile environments – often during periods of active tectonism. Many of the sediments have undergone burial metamorphism, and have been folding and faulting to varying degrees. Igneous rocks (mainly dolerite) have been intruded into the sediments. The environment of deposition and also the subsequent history of the rocks have a significant bearing on the water-bearing capacities of these low permeability rocks.

Aspects of the geology of the lower and middle parts of the Benue Trough are described by Nwachukwu (1972), Petters (1978), Agagu and Adighije (1983), Ofoegbu (1985), Kogbe (1989), Nwajide (1990) and Ojoh (1990). Geological exploration of the Benue Trough was stimulated by the search for petroleum in the sedimentary rocks northeast of the Niger Delta. The results of exploratory work undertaken by the Shell/BP Oil Company and others provided the basis of the only published geological maps of the region, produced in 1957.

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

Along the southern side of the Middle Benue Trough in the Abakaliki area, a marked gravity high occurs, associated with volcanics of intermediate and basic composition. The presence of andesite suggests the presence of a former subduction zone beneath that area. Within the trough, compression folding began in the Senonian forming a series of long, narrow folds parallel to the axis of the basin forming anticlines more than 60km long. Ofoegbu and Odigi (1990) recognised that structural

Plate 23. A series of photographs showing the Obi River at various stages of the year: (1) after heavy rainfall; (2) at the end of the rains; and (3) towards the end of the dry season.

lineaments in the Benue Trough are dominantly N-S, NE-SW and NW-SE, often crossing one another forming a strong network of shearing fissures and fractures.

Crystalline basement rocks currently bound the Benue Trough; the Jos Plateau granites to the north and the Cameroon Basement Massif to the south. Cretaceous sediments and igneous rocks, ranging in age from Aptian to Campano-Maastrichtian, infill the trough. In some places the thickness of sediments can exceed 5000m. The distribution of these rocks within the lower and middle Benue Trough is shown (Figure 9). Lower Cretaceous sediments are presumed to unconformably overlie Precambrian basement rocks along the Benue Valley (Reyment, 1964). Ammonite faunas are used to subdivide the stratigraphy of these Cretaceous rocks (Reyment, 1956).

The lithologies and stratigraphical relationships of the sediments found in the Oju/Obi area are outlined in Table 4. Their distribution is shown in Figure 10 and a cross section in Figure 11. The depositional environment and regional geology of each of these units is discussed in more detail in the following sections.

Table 4. Stratigraphic sequence of the Oju/Obi area.

STAGE	GROUP	FORMATION	LITHOLOGY
Maastrichtian			Post Maastrichtian NW-SE trending folding and faulting
Campanian			
Santonian			NE-SW trending elongate folds and faulting
Coniacian	Awgu Group	Awgu Shale Formation	Shaley carbonaceous mudstones with thin shelly limestones and sandstones
		Agbani Sandstone Formation	Fine to medium sandstones with siltstones and mudstones Dolerite intrusions
Upper	Eze-Aku Group	Upper Eze-Aku Formation	Shaley mudstones and siltstone with thin sandstones and limestones
Turonian		Makurdi Sandstone Formation	Fine to coarse sandstones with siltstones
Lower		Lower Eze-Aku Formation	Shaley mudstones and siltstone with thin sandstones and limestones
Cenomanian			Hiatus/unconformity
Upper Albian	Asu River Group	Asu River Formation	Carbonaceous shaley mudstone, limestone, sandstone and siltstone
Lower		Metamorphosed Asu River Formation	Pyroclastics and intrusives with metamorphosed mudstone, shale and sandstone
Precambrian Basement			N-S trending faulting

Recent studies of rocks of similar age in other parts of the world have revealed information relevant to Oju and Obi.

- Clay mineralogy of the mudstone is related to the depositional history (Agumany and Enu, 1990) and/or the effects of burial diagenesis/metamorphism (Akande and Erdtmann, 1998);

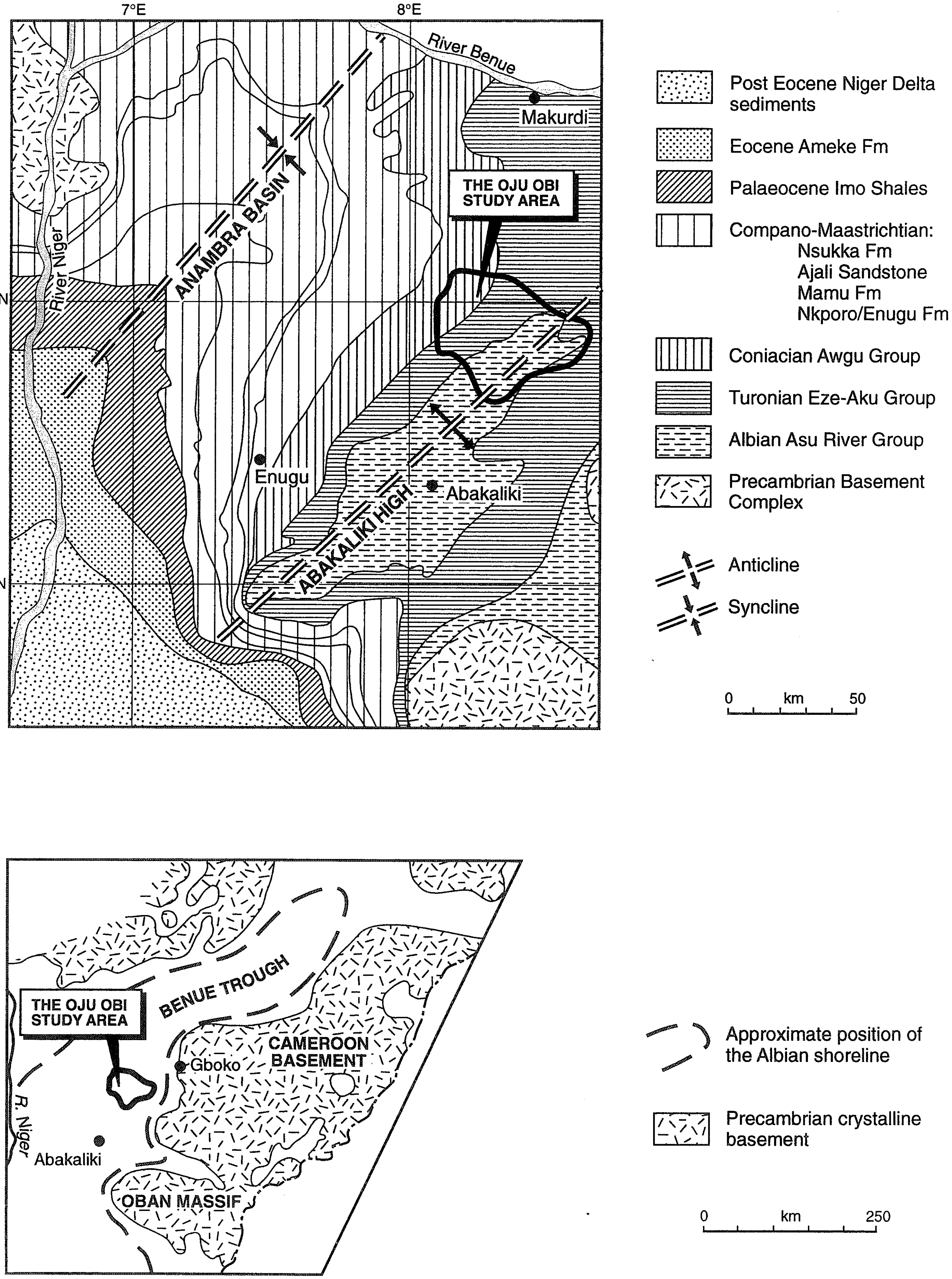


Figure 9 Geological map of southern Benue trough (insert map shows the approximate limit of the Albian Sea).

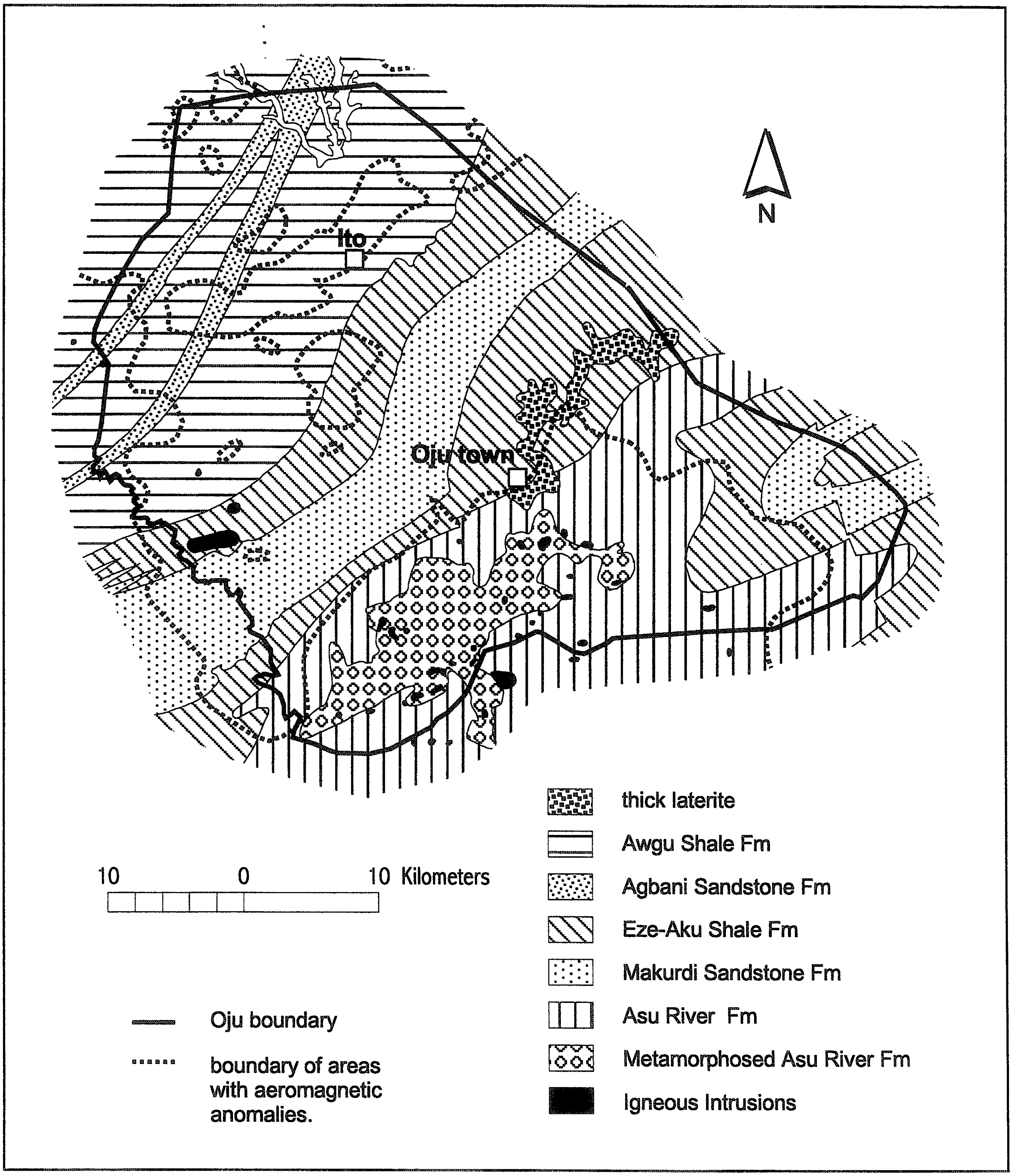


Figure 10 Geological map for the Oju/Obi area.

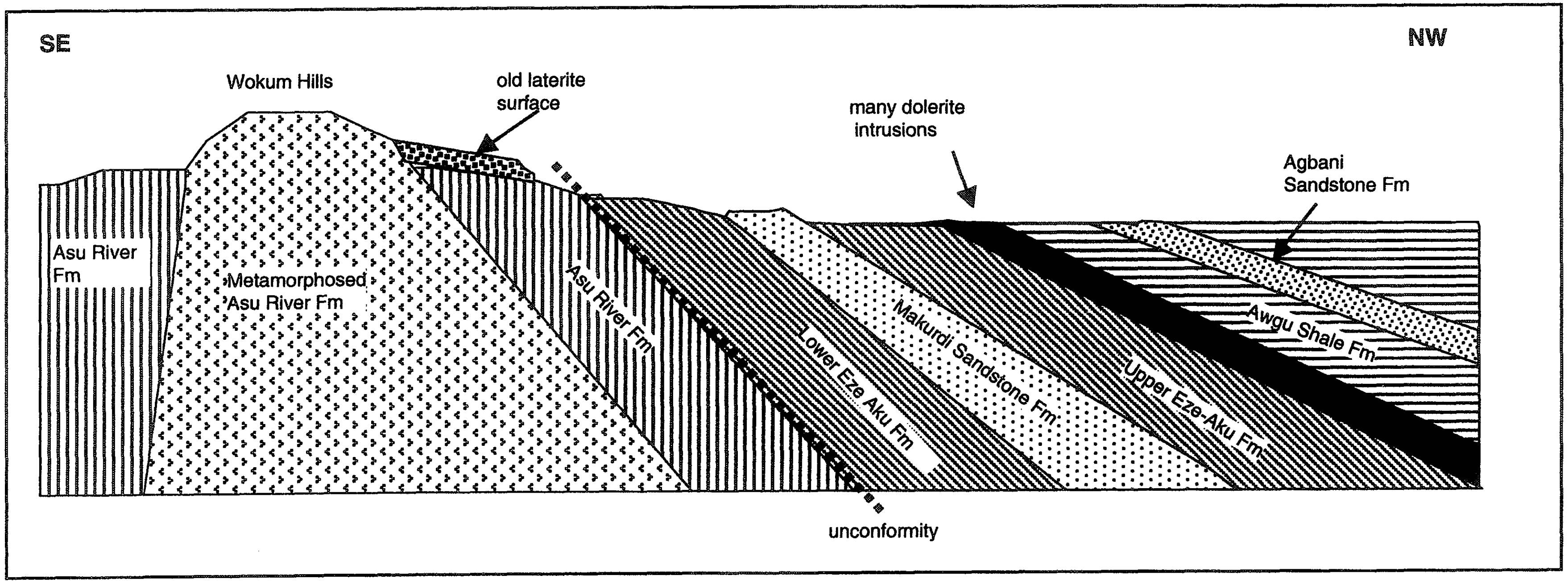


Figure 11 Schematic geological cross section through the Oju/Obi area.

- Deep burial of sediments may have produced distinct fractured horizons (Wang and Xie, 1998);

- Low grade regional metamorphism may have occurred due to both igneous intrusions and burial diagenesis (Frey and Robinson, 1999);

- Secondary gypsum deposits may occur within weathered shale layers (Tabakh et al, 1998)

- High concentrations of organic carbon in mudstones and associated formation of smectitic clays may have occurred due to the effects of global and regional volcanism (Schlanger and Jenkins, 1976 and Kerr 1998)

- Fracturing and zeolite formation within dolerite, may have occurred when dolerite is intruded into soft and saturated mudstones

- Sandstone deposition may have been enhanced by periods of acid rainfall (caused by regional and global volcanic eruptions) causing excessive erosion of adjacent landmasses (Kerr 1998).

These and other relevant ideas will be discussed here.

3.4 'Metamorphosed' Asu River Formation

Regional geology

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

Local geology (Plates 24 and 25)

The 'Metamorphosed' Asu River Formation occurs in southern Oju where it forms a distinct band of hills, the Wokum Hills, which rise to 550masl. The hydrogeological nature of this Formation was investigated at Oyinyi Iyechi in southern Oju. Three boreholes BGS19, BGS20 and BGS21 were drilled to about 40 m and rock chip and core samples analysed. Details of the exploratory programme are given in Davies and MacDonald (1998e); borehole logs are summarised in Figure 12.

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

Plate 24. Weathered interbedded slatey shales and pyroclastic rocks of the Metamorphosed Asu River Formation in the Wokum Hills.

Plate 25. Metamorphosed Asu River Formation from BGS20 at Oyinyi Iyechi. Note the fracture filled with calcite.

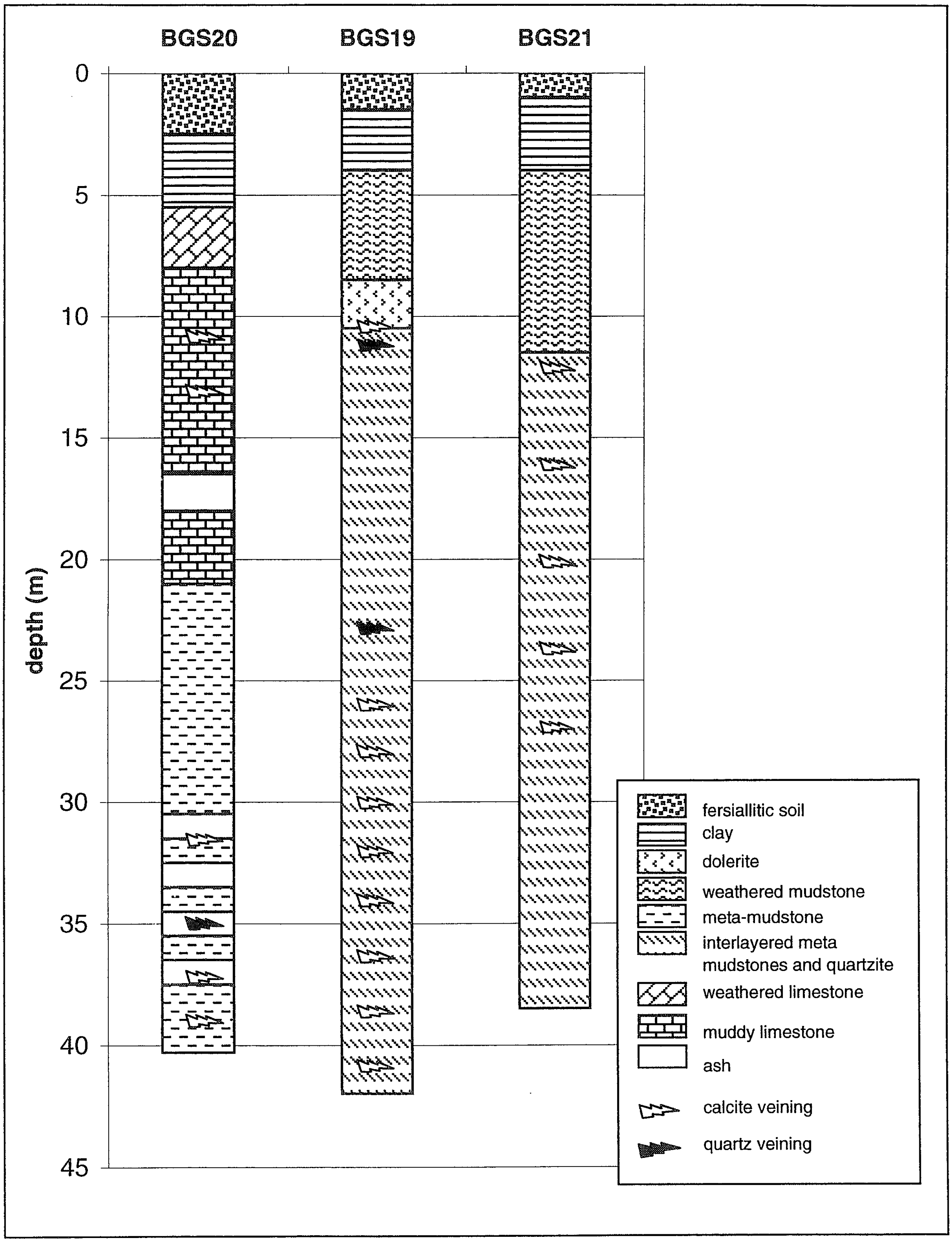


Figure 12 Lithological logs from exploration boreholes drilled into the metamorphosed Asu River Formation at Oyinyi Iyechi.

The rocks are highly fractured, and the fractures filled with pyrite, calcite and/or quartz. Fracturing may have occurred during burial by the process of hydrofracturing, (Wang and Xie, 1998) and been preserved by the effects of burial diagenesis. Alternatively, the fractures may have developed exclusively by weathering.

A thin fersiallitic soil has often developed over much of the 'Metamorphosed' Asu River Formation, underlain by a thin clayey layer. Ash, mudstones and igneous rocks often crop out, discoloured by recent weathering. The shales are mainly composed of kaolinite and illite clays although interbedded ash layers appear to have weathered to soft smectitic bentonite clay (Kemp et al, 1998). Exposures in streambeds and gullies show the rocks to be highly folded and well jointed.

Geophysical investigations

Several geophysical surveys were undertaken at Oyinyi Iyechi, including 3km of EM34-3 surveys, 1.5km of magnetic profiling and 3 resistivity VES (Davies and MacDonald 1998e). The investigation boreholes were sited on different forms of geophysical anomaly. A summary of the geophysical surveys and interpretation is given in Figure 13.

1. EM34 readings were generally low (0-30mmhos/m) reflecting harder, metamorphosed and igneous rocks with reduced clay content. Very low EM34-3 readings and intense magnetic anomalies were associated with igneous rocks at shallow depth. Higher EM34 readings were associated with shallow weathered mudstone. Very noisy readings with the horizontal coil at 200 m were associated with much fracturing.

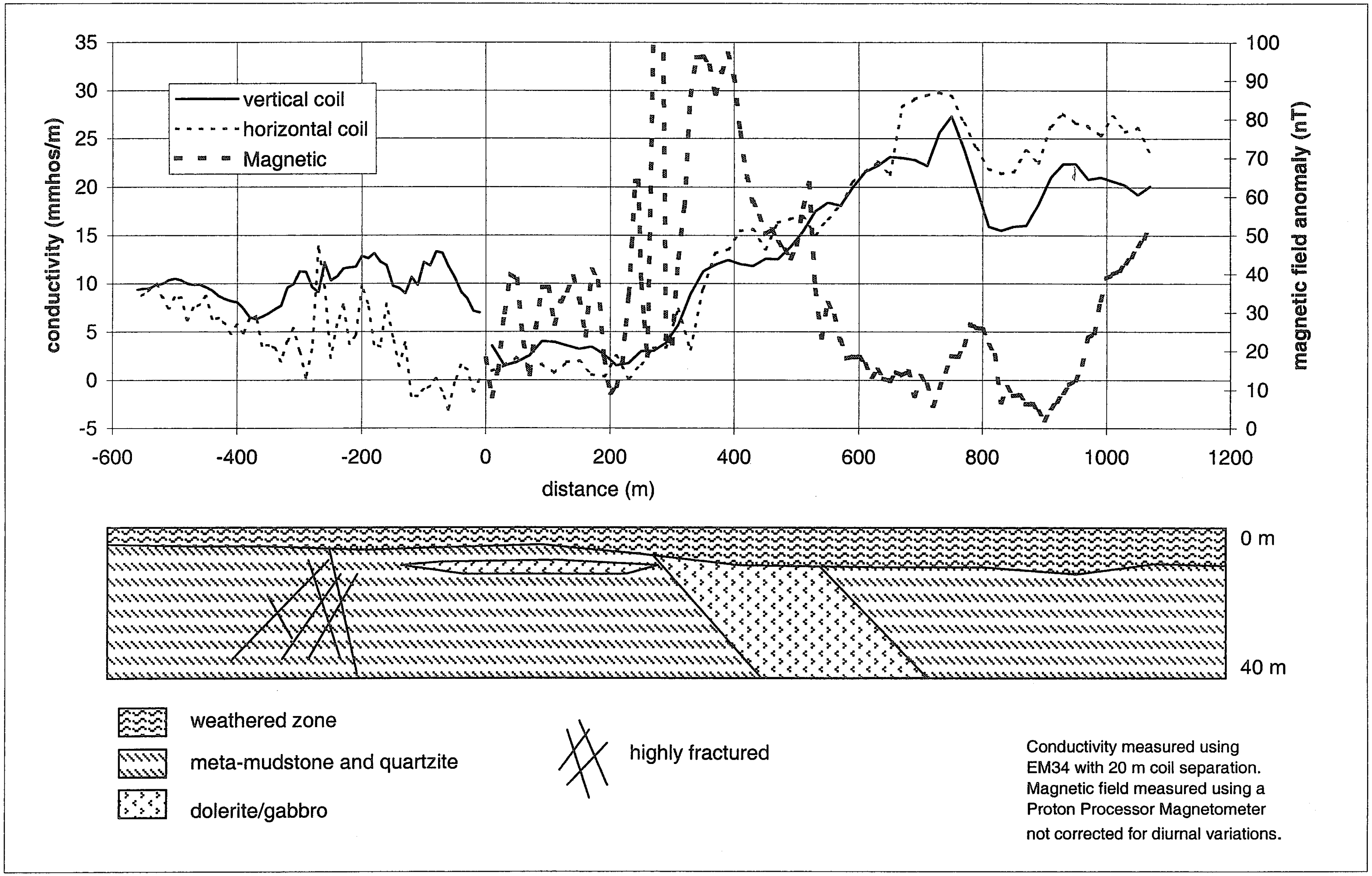
2. Resistivity soundings (VES) carried out at the three borehole sites produced distinctive profiles. At borehole BGS19, where conductance was low (<5mmhos/m), a bedrock of resistivity 900ohm-m was determined. Infinite resistivity was recorded at shallow depth where horizontal coil readings were very noisy at a site that produced much groundwater. Low resistivity bedrock (about 50ohm-m) was recorded where mudstone was present at shallow depths and the EM34-3 measurements were higher.

Understanding of the geophysical characteristics of the complex 'Metamorphosed Asu River Formation will be improved as additional data is obtained from future geophysical surveys and borehole drilling and logging. Investigations at Oyinyi indicate that igneous and highly metamorphosed rocks are characterised by low conductivity and high resistivity and igneous rocks are characterised by intense magnetic anomalies. Meanwhile weathered and non-metamorphosed mudstones give high conductivity (low resistivity) and no short wavelength magnetic anomalies. Fracture zones (or dyke swarms) give very noisy signals using EM34 with horizontal coils.

Hydrogeology

The 'Metamorphosed' Asu River Formation forms one of the best aquifers in Oju and Obi. The rocks have negligible intergranular permeability or porosity, but the high degree of fracturing make them good aquifers. The best targets for groundwater are probably blocky and highly fractured ash layers, although sufficient groundwater can probably be found wherever the bedrock is fractured. Since the rocks are hard, fractures tend to remain open, unlike the softer mudstones in the north.

The three exploratory boreholes at Oyinyi Iyechi (BGS19-21) yielded quantities of good quality groundwater from fractures and/or weathered ash layers at depths between 11m and 36m. Several pumping tests were undertaken in each borehole: transmissivity varied from 4 to 40m²/d. The borehole with the highest yield penetrated fractured ash layers, close to a river. The borehole that penetrated metamorphosed mudstones and sandstones had the lowest transmissivity, about 2 - 4m²/d. All three boreholes could sustain a hand pump. The limited drilling suggests boreholes penetrating ash layers will produce the highest yields; whereas those with increased mudstone content, especially



Conductivity measured using EM34 with 20 m coil separation. Magnetic field measured using a Proton Processor Magnetometer not corrected for diurnal variations.

Figure 13 EM34 and magnetic profiles for Oyinyi Iyechi with a simplified geological interpretation.

where less metamorphosed, will produce poorer yields. During a pumping test on BGS21, the main fracture zone at 21m was dewatered. It is therefore important to identify the depths of the main water producing fractures and ensure that pumping levels do not fall below these.

Recharge is an important component of the hydrogeology in the 'Metamorphosed Asu River Formation. Therefore in this hilly area with its incised valleys boreholes need to be located at the intersection of fracture zones and valleys towards the bottom of the hills.

Groundwater samples for hydrochemical analyses were obtained from a series of six boreholes, including boreholes BGS19-21, and a spring. Groundwater types present are $Ca(HCO_3)_2$ and $CaMg(HCO_3)_2$, all with TDS of less than 400mg/l. The quality of the groundwater is generally good and conforms to the WHO recommended guidelines.

General hydrogeological development potential

The groundwater development potential of the 'Metamorphosed' Asu River Formation is high. The rocks are highly fractured and significant groundwater occurs within the fractures. From the limited exploration at Oyiny Iyechi it appears that fractures below about 11m and weathered ash layers are the best targets for groundwater. The least groundwater was found where the mudstone had been less metamorphosed. All the boreholes drilled had sufficient yields for a hand pump. To maximise yields, boreholes should be located on significant fracture zones within the pyroclastic or highly metamorphosed areas close to streams or rivers. Geophysics is not essential to precisely locate boreholes, however, rapid EM34 and magnetic surveys may establish areas where the rocks are more metamorphosed or fractured.

The 'Metamorphosed' Asu River Formation slatey mudstones and pyroclastic rocks are generally too hard for excavation of hand dug wells; boreholes are more suitable for groundwater abstraction. These should be drilled to about 40m to penetrate as many fractures as possible.

3.5 Asu River Formation

Regional geology

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

Tightly folded, cross-bedded, laminated, convoluted and micro-brecciated sediments are present throughout the Asu River Formation. These deformation structures are indicative of sand hydro-plasticity, liquefaction, fluidisation and compaction related to pore water expulsion triggered by seismic activity within a tectonically active area.

Local geology (Plates 26 and 27)

The Asu River Formation occurs throughout much of central and southern Oju. The geological and hydrogeological nature of the non-metamorphosed younger Asu River Group sediments was investigated at two sites: Odubwo village (BGS2, 2a, 2b) and the WaterAid compound (BGS1). Detailed geological logs are presented in Davies and MacDonald (1998d), and are summarised in Figure 14.

Plate 26. Convoluted and folded Asu River Formation in a stream bed near Odubwo.

Plate 27. Water bearing fracture from BGS2a at 16 m depth. Note that the fracture is filled with calcite.

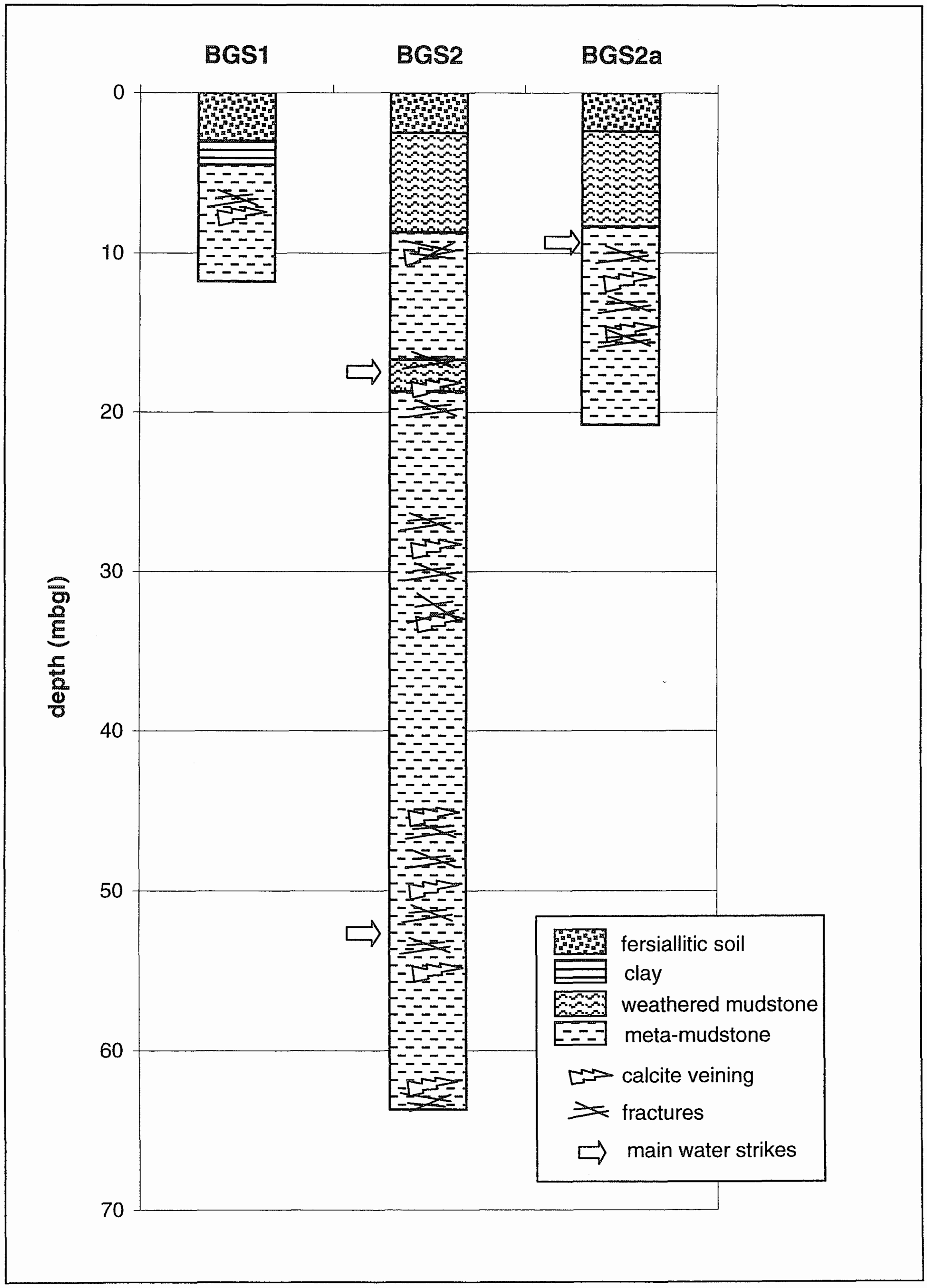


Figure 14 Lithological logs from exploration boreholes drilled into the Asu River Formation.

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

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

Geophysical investigations

The results of geophysical surveys undertaken at Odubwo and at the WaterAid office in Oju, including 7.5km of EM34-3 surveys, 3km of magnetic profiling and 2 resistivity VES, are presented in Davies and MacDonald (1998d). The investigation boreholes were drilled at sites selected using geophysical survey results.

1. The low EM34-3 conductivity readings of 5-30mmhos/m reflect the lithification of the mudstones due to burial diagenesis. Little high conductance clay occurs within the weathered zone (Figure 15).

2. Measured conductivity increased with longer inter-coil spacings (and therefore deeper penetration). However, with very deep penetration (40m coil oriented horizontally) conductivity reduced.

3. Resistivity vertical electrical soundings prove a resistive soil overlying a 10-20m thick moderately resistive (40-70ohm-m) layer that overlies more resistive bedrock. The low resistivity weathered zone is due to water filled fractures and clay content. A 20m thick low resistivity weathered layer explains variation in the measured conductivity with inter-coil spacing and coil orientation.

4. Magnetic profiling showed the presence of magnetic rocks at several locations, but due to the restraints of time these were not investigated.

There is insufficient data to produce guidelines for the location of borehole or well sites using geophysics alone in the Asu River Formation. Conductivity values tend to be low (<30mmhos/m), therefore EM34 can be used to indicate that a village is lying on the Asu River Formation as opposed to the Lower Eze-Aku Shale Formation (from the low readings). The presence of enhanced weathering and due to water filled fractures may be inferred from resistivity profiling (a middle layer of low resistivity) or maybe EM34 (slightly higher readings, especially with the 20m horizontal coil).

Hydrogeology

The groundwater development potential of the Asu River Formation is good. Groundwater occurs within apparently widespread fracture systems at depths greater than 10-15m. The Asu River Formation sediments underwent lithification due to burial diagenesis and so are moderately hard, fractures therefore tend to remain open. There is neither intergranular porosity nor permeability

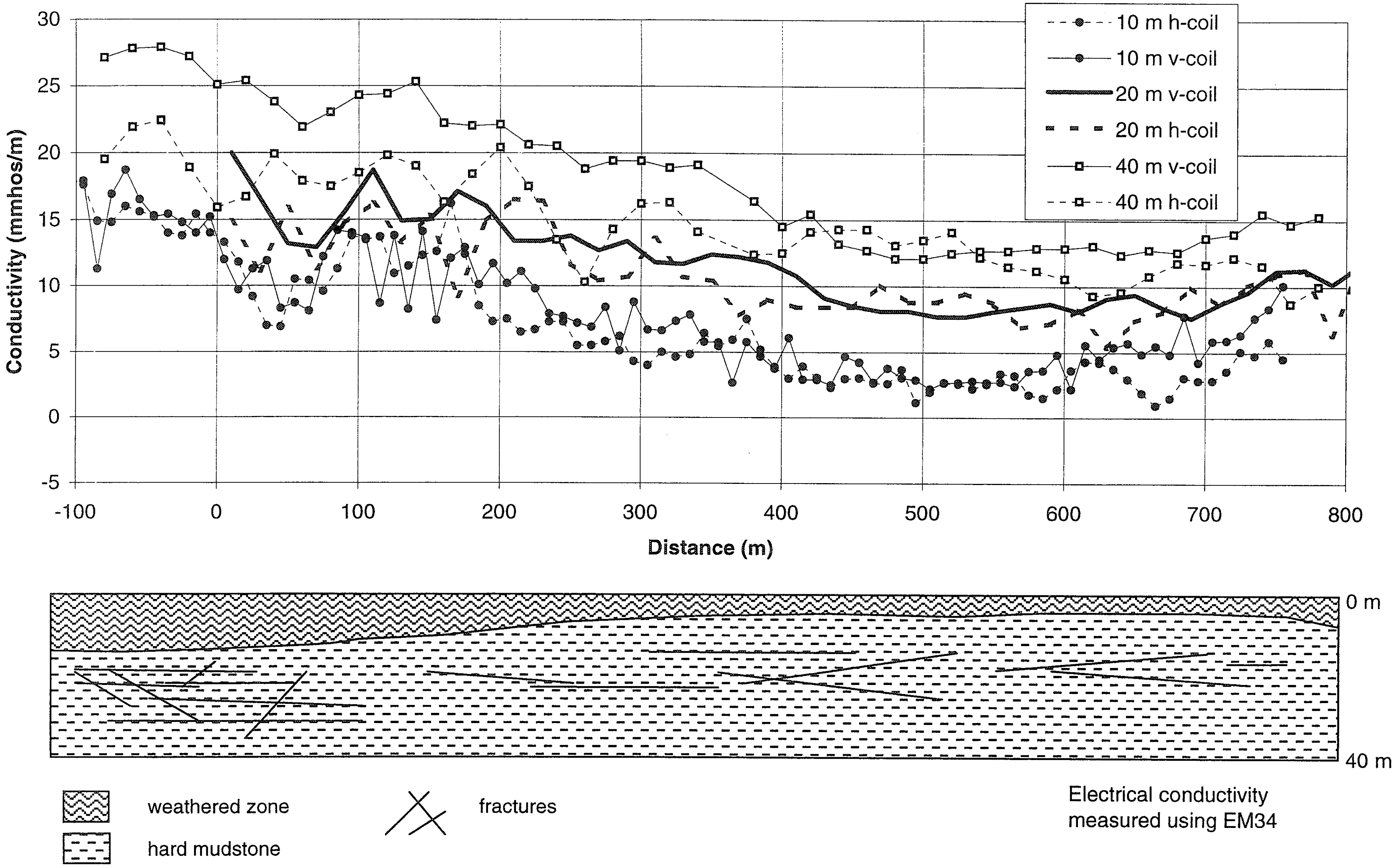


Figure 15 Geophysics surveys and suggested interpretation for the Asu River Formation at Odubwo.

within the mudstones. Therefore, shallow wells or boreholes that do not penetrate fracture zones have poor yields.

The two deep boreholes at Odubwo gave transmissivity values of about $4m^2/d$ – more than adequate for a handpump. Other boreholes drilled by DFRRI and BERWASSA in the Asu River Formation sediments have encountered a fracture zone between 15m and 25m depth and generally sustain a handpump. The 11m deep borehole drilled at the WaterAid compound gave a transmissivity of less than $0.3m^2/d$. This borehole was too shallow to penetrate the highly fractured zone. Water in this borehole (and the adjacent hand dug well) is derived from the thin fersiallitic soil horizon.

Two measurements of storage coefficient made at Odubwo gave values of 0.0005. The aquifer has low storage capacity, so is highly reliant on annual rainfall to recharge the aquifer. It is recommended that water levels close to abstraction boreholes be closely monitored for several dry seasons to establish whether over-pumping is depleting groundwater.

Groundwater quality in the Asu River Formation is generally good. Groundwater types present are $Ca(HCO_3)_2$, $CaMg(HCO_3)_2$ and $CaNaMg(HCO_3)_2$, all with TDS of <500mg/l, but with occasional high iron or sulphate. The sample analyses are all within the WHO recommended drinking water guidelines.

Summary of groundwater potential

The groundwater development potential of the Asu River Formation is high. The best targets for groundwater are fracture zones from 15 – 50m. These fractures appear to be widespread throughout the Asu River Formation rocks. Boreholes drilled to 40m are probably the best option for groundwater development, although dug well-cum-boreholes, or even hand dug wells if constructed sufficiently deep, could be sufficiently productive. The sustainability of water supplies from fractured aquifers is difficult to ascertain; therefore, long term monitoring of groundwater abstraction from boreholes and wells is advisable. Geophysical surveys are not essential for locating borehole sites; however EM34 and resistivity surveys may establish areas of enhanced fracturing.

3.6 Lower Eze-Aku Formation

Regional geology

The broadly folded Lower Eze-Aku Formation unconformably overlies the tightly folded older Asu River Group rocks. The junction of these formations is not observed at outcrop. The lower part of the Lower Eze-Aku Formation appears to be composed mainly of shaley to silty mudstones whereas the upper part of the sequence is sandier, composed of cycles of sedimentation as described below. Age determinations based on macro-palaeontological evidence indicate that this lithological change may indicate the location of a disconformity, the Cenomanian Hiatus. Alternatively Ojoh (1990) suggests, on the basis of micro-palaeontological evidence, that the sequence is continuous but attenuated. The junction may be coincident with an oceanic anoxic event during which marked species extinction occurred that was followed by transgression of a shallow marine sea.

The upper part of the Lower Eze-Aku Formation consists of cyclic deposits of cross-bedded quartz-cemented sandstones at base, bioturbated calcite-cemented sandy siltstones, and black carbonaceous shaley mudstones with thin bands of bioclastic limestone at top. The sandstone is typically cross-bedded, with vertical burrows and laminated grey shale partings, deposited within a quiet marine environment to be reworked by long-shore currents. The sandy siltstones are cross-laminated and bioturbated deposited within a delta front near shore environment. The black shaley mudstones are blocky to well laminated deposited beyond the delta front in quiet anaerobic anoxic bottom conditions. The limestone bands that alternate with shales are oyster beds up to 30 cm thick. Locally, towards the top of this formation these sediments grade into sandstones of the Makurdi Sandstone

Formation. The lowest part of this formation contains Turonian ammonites, while the top is early Coniacian.

Local geology (Plates 28, 29 and 30)

The Lower Eze-Aku Formation occurs in a band across northern Oju, which broadens to the northeast. The Formation is also thought to crop-out in the west of Oju, test drilling has yet to be undertaken within this area. The geological and hydrogeological nature of the Lower Eze-Aku Formation was studied at Edumoga village. Five exploration boreholes, BGS14, BGS15 BGS16, BGS17 and BGS18 were drilled to depths of between 27m and 53m. Detailed geological logs are presented in Davies and MacDonald (1998a), and are summarised in Figure 16.

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

The upper mudstones are highly weathered with 3m of ferruginous soil, containing iron nodules and ferricrete, above 2–3m of plastic clay. Below the clay layer to about 12m the mudstone is soft and discoloured due to weathering. The shaley mudstones are composed of illite/smectite clays (Kemp et al, 1998). Significant fractures were found in three of the exploratory boreholes, each of which yielded useable quantities of groundwater. Core and chip samples indicated that the fractures occurred in fault zones with: (1) significant vein calcite, with gypsum/barytes; (2) slickenslides; and (3) fault breccia (BGS17 only). Many of the fracture surfaces were coated with iron oxides.

Typical cyclic deposits of interbedded shale and sandstone/limestone are found exposed in stream sections to the north of Edumoga and in the bed of the Konshisha River in the southeast of Oju/Obi area. Some of these rocks exhibit dips of 30° to 50° with NE trending strikes, on the limbs of elongate NE trending folds.

Geophysical investigations

Geophysical surveys undertaken at Edumoga included 4.7km of EM34 surveys, 0.3km of magnetic profiling and 4 resistivity VES (Davies and MacDonald 1998a). The five exploratory boreholes were sited on different forms of geophysical anomaly. A summary of the geophysical surveys and interpretation is given in Figure 17.

1. EM34 conductivity measurements were generally high (40-50mmhos/m) reflecting the moderately soft silty mudstone. Where conductivity values do not vary, the rock is generally non-fractured.

2. Distinct negative conductivity anomalies or sharp shifts in conductivity over a short distance are indicative of highly fractured rock. Three successful boreholes were located on EM34 anomalies consistent with fracture zones. Boreholes BGS16 and BGS17 were located on negative anomalies and borehole BGS15 was located where the horizontal coil recorded sharp fluctuations. Two unsuccessful boreholes, BGS14and BGS18, were drilled in areas of flat EM34 response, indicating little likelihood of fracturing.

3. Resistivity soundings (VES) produced consistent results at all five borehole sites, detecting the near surface resistive ferruginous soils and underlying conductive clays, above weathered to non weathered shales that become more resistive with depth. The VES resistivity surveys could not be used to identify vertical fracture zones.

Plate 28. Alternations of hard sandstone, limestone and shale within the Lower Eze Aku Formation at the Konshisha River.

Plate 29. Fossil burrows forming on the base of hard sandstone layers at Edumoga.

Plate 30. Core sample from BGS16, showing moderately soft mudstone and muddy sandstone.

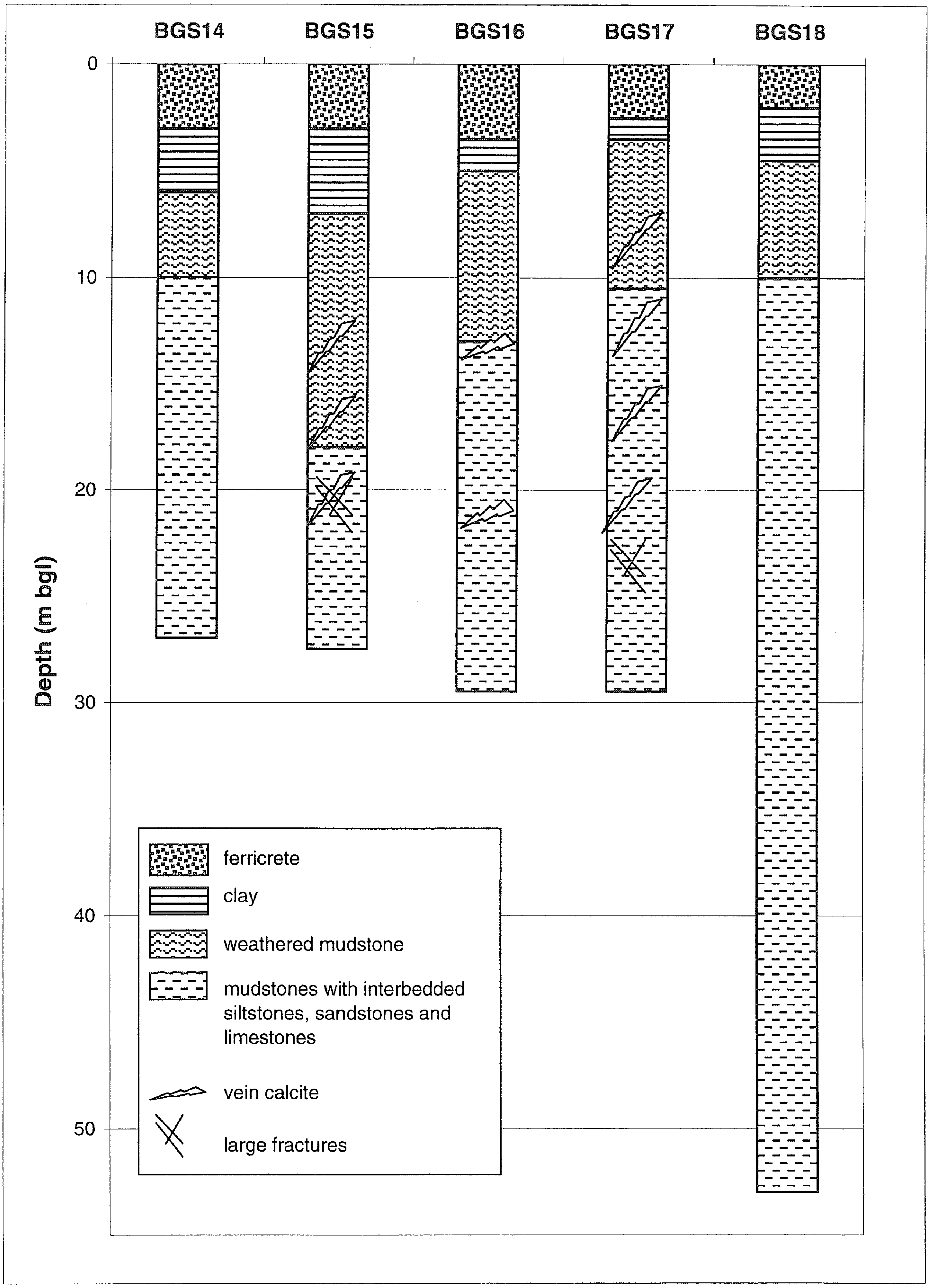
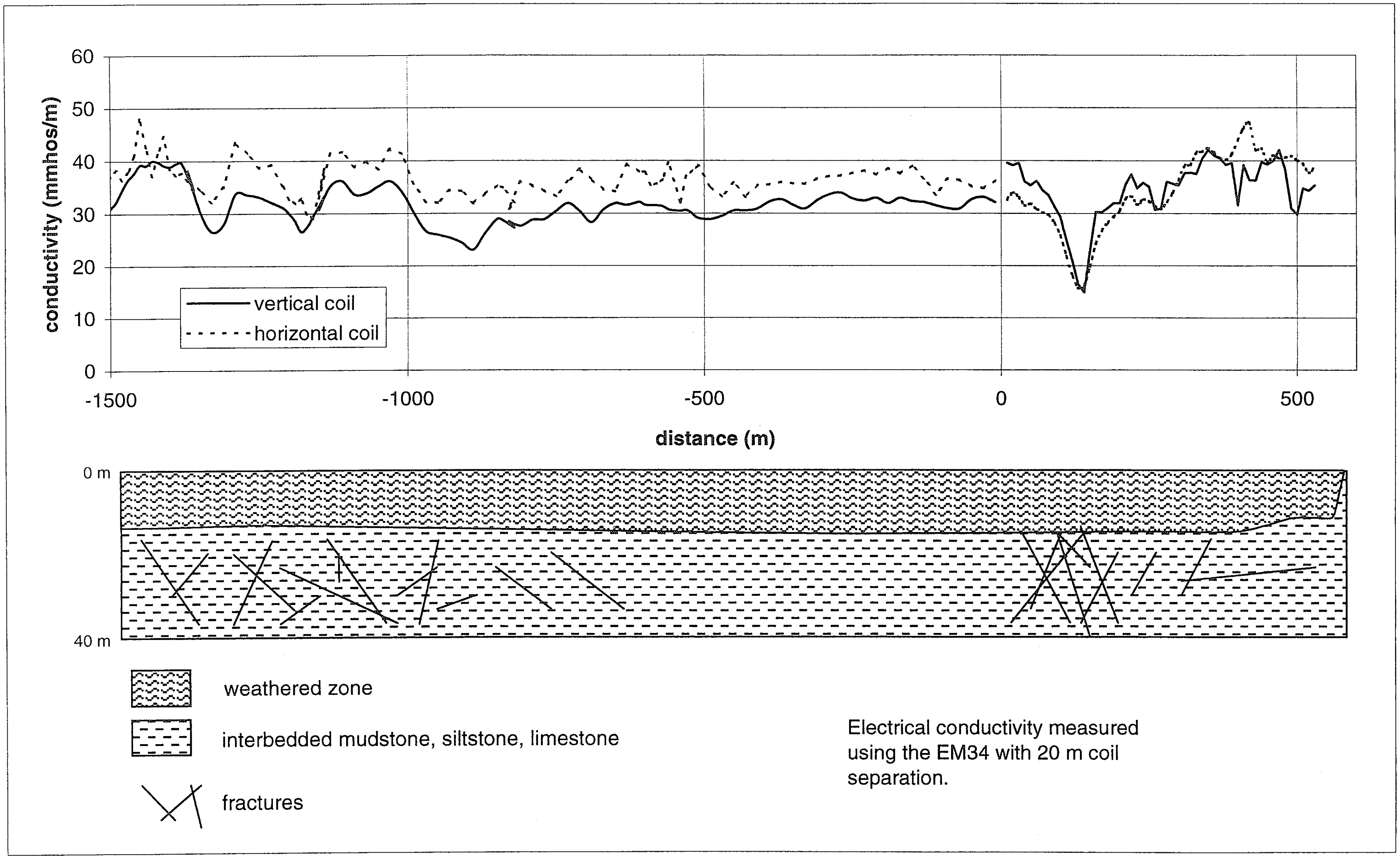


Figure 16 Lithological logs from the Lower Eze Aku Formation at Edumoga.



Electrical conductivity measured using the EM34 with 20 m coil separation.

Figure 17 Geophysical surveys and interpretation for the Lower Eze Aku Formation at Edumoga.

4. Magnetic profiling is of no use in this area, since there are no magnetic rocks present.

Fracture zones, the best targets for groundwater, can be identified using the EM34. Negative going anomalies, or fluctuating readings with the horizontal coil are indicative of fractures.

Hydrogeology

Groundwater occurs within fracture and fault zones in the Lower Eze-Aku Formation. However, unlike the Asu River Formation, fracture zones are unlikely to be widespread. The sediments are too soft for small fractures caused by weathering to remain open. Only where the sediments have been extensively faulted and fractured will significant groundwater exist. There is negligible intergranular porosity and permeability. Evidence of fracturing obtained from boreholes includes significant vein calcite, slickenslides, and iron oxide staining on fracture surfaces and fault breccia. Limited groundwater also occurs within the shallow laterite zone. Numerous shallow hand-dug wells exploit the water within the laterite but dry up shortly after the rains stop. Sustainable water supplies can only be gained from sources which tap fracture zones below 10m.

Of the five exploratory boreholes drilled, three (BGS15, BGS16 and BGS17) yielded quantities of good quality groundwater. Test pumping of these boreholes determined transmissivity values of 1-3m^2/d, sufficient for a hand pump. As with other fractured aquifers in the area, the long-term sustainability of these water sources is unknown. Water levels and abstraction rates need to be monitored for several dry seasons.

Groundwater samples for hydrochemical analyses were obtained from boreholes BGS15; BGS16 and BGS17 as well as a number of boreholes and hand dug wells within adjacent areas. The groundwater quality in the Lower Eze-Aku Formation sediments is generally good. Groundwater types present are $CaMg(HCO_3)_2$, $NaCa(HCO_3)_2$ and $NaCaMg(HCO_3)_2$, all with TDS of <600mg/l. Samples are within the WHO recommended drinking water guidelines.

Summary of groundwater potential

The groundwater development potential of the Lower Eze-Aku Formation is moderate. Boreholes should be located in highly fractured areas and completed to more than 30m. Extensive fracturing can be identified using the EM34. Negative anomalies or noisy horizontal coil profiles can indicate fracture zones. The Lower Eze-Aku Formation sediments are soft enough for excavation of hand dug wells. As with boreholes, hand dug wells need to be located on fracture zones and excavated to depths greater than 15m. Any groundwater sources developed should be monitored to determine the sustainability of water supplies from the aquifer.

3.7 Makurdi Sandstone Formation

Regional geology

The Makurdi Sandstone Formation forms part of the Turonian Eze-Aku Group. These sandstones underlie an elongate belt of more than 1000km^2 extent between Makurdi and central Benue State. In the type section at Makurdi they form a thick sequence of feldspathic sandstone interbedded with marine carbonaceous mudstone and limestone. Poorly sorted feldspathic sandstone rhythmically alternate with clay-silt layers. Several fining upward cycles of deposition have been recognised in the Makurdi Sandstone Formation. Away from Makurdi, the sandstones generally become thinner and finer grained.

Local geology (Plates 31, 32, 33, 34, 35 and 36)

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

The hydrogeological nature of the Makurdi Sandstone Formation was investigated at several locations in Oju and Obi. Six exploratory boreholes were drilled at Ochingini (BGS7, BGS8, BGS9, BGS10, BGS11 and BGS12); two at Odaleko Adiko (BGS13, BGS13a) and three at Anyoga Adum East (BGS36, BGS37 and BGS38). The detailed results of these investigations are given in MacDonald and Davies (1998a; 1998d) and Davies and MacDonald (1998c). Simplified geological logs of some of these boreholes are shown in Figure 18.

The studies showed that in Oju and Obi, the sandstone mostly comprises fine- to medium grained sandstone interbedded with mudstone and occasional thin limestone layers. The sandstone layers vary in thickness from several millimeters to several metres. Sandstone layers are commonly cross-bedded; load cast features and evidence of bioturbation are also present. Much feldspar is present within the sandstone, although quartz remains the dominant mineral; at Adum East the sandstones were muddy and silty and contained much mica. The sandstone is generally very hard and well cemented. Limestone layers, such as those noted at BGS8 are commonly shelly and muddy and contain vertical fractures.

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

Much detailed information from the Makurdi Sandstone Formation was obtained from an 83m deep borehole (BGS13)(Figure 20). Fining upwards sequences, 4m to 7m thick, of coarse- to fine-grained feldspathic sandstones capped by black carbonaceous mudstone were present. A 20m thick layer of soft, friable fairly homogeneous sandstone was penetrated from 60-80m which appears to have been deposited under deeper fluviatile conditions.

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

Plate 31. Cross bedding in weathered Makurdi Sandstone Formation.

Plate 32. Thickest unit in the Makurdi Sandstone Formation exposed in a road cutting at Adum East.

Plate 33. Very hard silcrete layer often found in the near surface weathered zone of the Makurdi Sandstone Formation.

Plate 34. Weathering and fracture at 16 m depth in the Makurdi Sandstone Formation (BGS7).

Plate 35. Alternations of sandstone and shale in the Makurdi Sandstone Formation (BGS12).

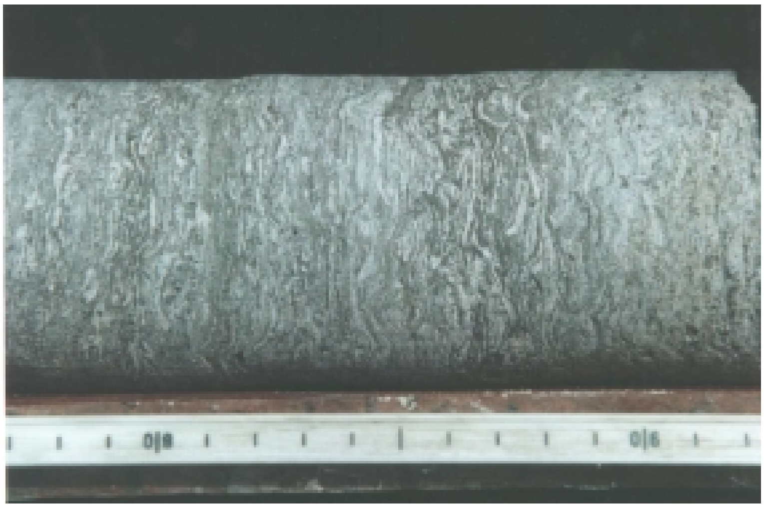


Plate 36. Shelly limestone layer from the Makurdi Sandstone Formation (BGS36).

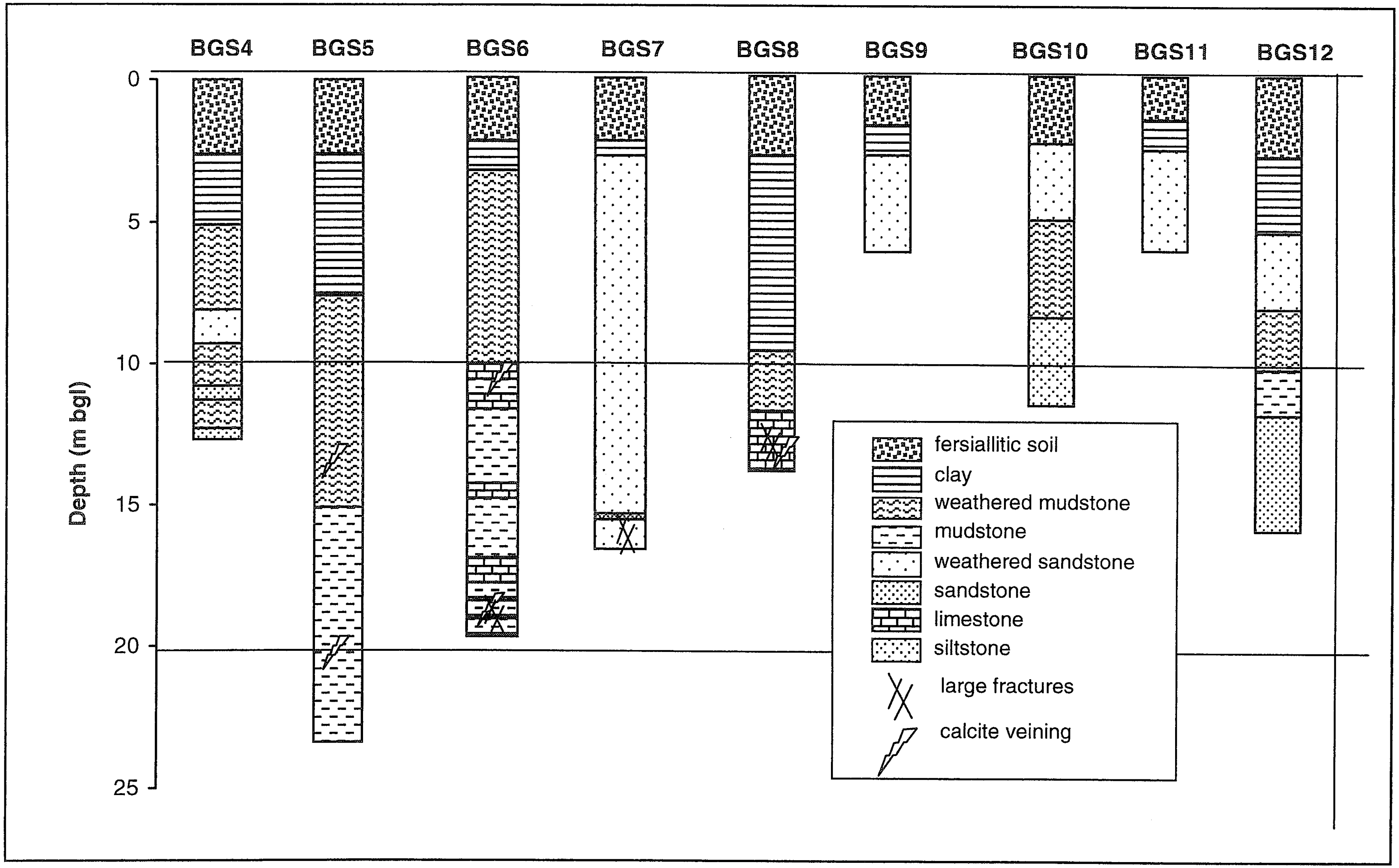


Figure 18. Lithological logs from exploration boreholes drilled into the Makurdi Sandstone and Upper Eze-Aku at Ochingini

Geophysical investigations

A series of geophysical surveys undertaken at Ochingini, Odaleko and Adum East included about 10km of EM34 surveys, 5km of magnetic profiling and 7 resistivity VES. These surveys have been correlated with lithological data obtained from exploratory boreholes. Typical EM34 signals from the different lithologies is shown in Figure 19.

1. When the underlying rocks are primarily sandstones the measured electrical conductivity using a 20m coil separation is between 10 and 20mmhos/m. Vertical and horizontal coil readings are similar.

2. Conductivity values in excess of 30mmhos/m were indicative of mainly mudstones. Measurements taken with the vertical coil are often greater than with the horizontal coil.

3. Limestone bands could not be distinguished using geophysical techniques.

4. None of the geophysical methods could be used to identify fracturing within the sandstones.

5. Magnetic profiling is of little use in the Makurdi Sandstone Formation since there is little difference in the magnetic properties of the various lithologies.

6. Resistivity surveys carried out over sandstone and mudstone showed similar profiles: resistive surface layer, conductive middle layer (about 5-10m thick) and resistive (>80ohm-m) bedrock. For the sandstones the middle layer had a resistivity of about 30 ohm-m; the mudstones had a resistivity of less than 10ohm-m. This difference is due to the amount and conductivity of the clays present in the weathered zone of the mudstones and sandstones.

Therefore, the quickest and easiest method for distinguishing sandstones from mudstones is EM34. Low conductivity values (< 20ohm-m) indicate sandstone present within the weathered horizon.

Hydrogeology

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

The sandstone has moderate porosity. Core samples taken from seven boreholes gave measurements of porosity varying from 9 to 34% (median value 16%). Sandstone porosity is enhanced within the weathered zone by leaching of feldspar crystals leading to the formation of intergranular voids. Unfortunately, these voids may not be well interconnected so that although porosity is high, permeability is often low. Measured permeability from the seven boreholes varied from less than 10^{-4}m/d to 0.7m/d (median 0.001m/d). These measurements indicate a large range in sandstone permeability; most of the samples had insufficient intergranular permeability to provide significant flow in the aquifer. Hence the need for fractures in the sandstone to increase the permeability and transport water sufficiently quickly to wells.

Eight pumping tests were carried out in the Makurdi Sandstone Formation. Transmissivity determinations ranged from 0.07m²/d to 1.5m²/d, with a median value of 0.4m²/d. Higher transmissivity values were found in those boreholes that penetrated sandstone to more than 12m. These determinations are much higher than the intergranular permeabilities suggest, indicating the importance of fractures. Poor yields were measured at BGS10 and BGS38, boreholes that penetrated

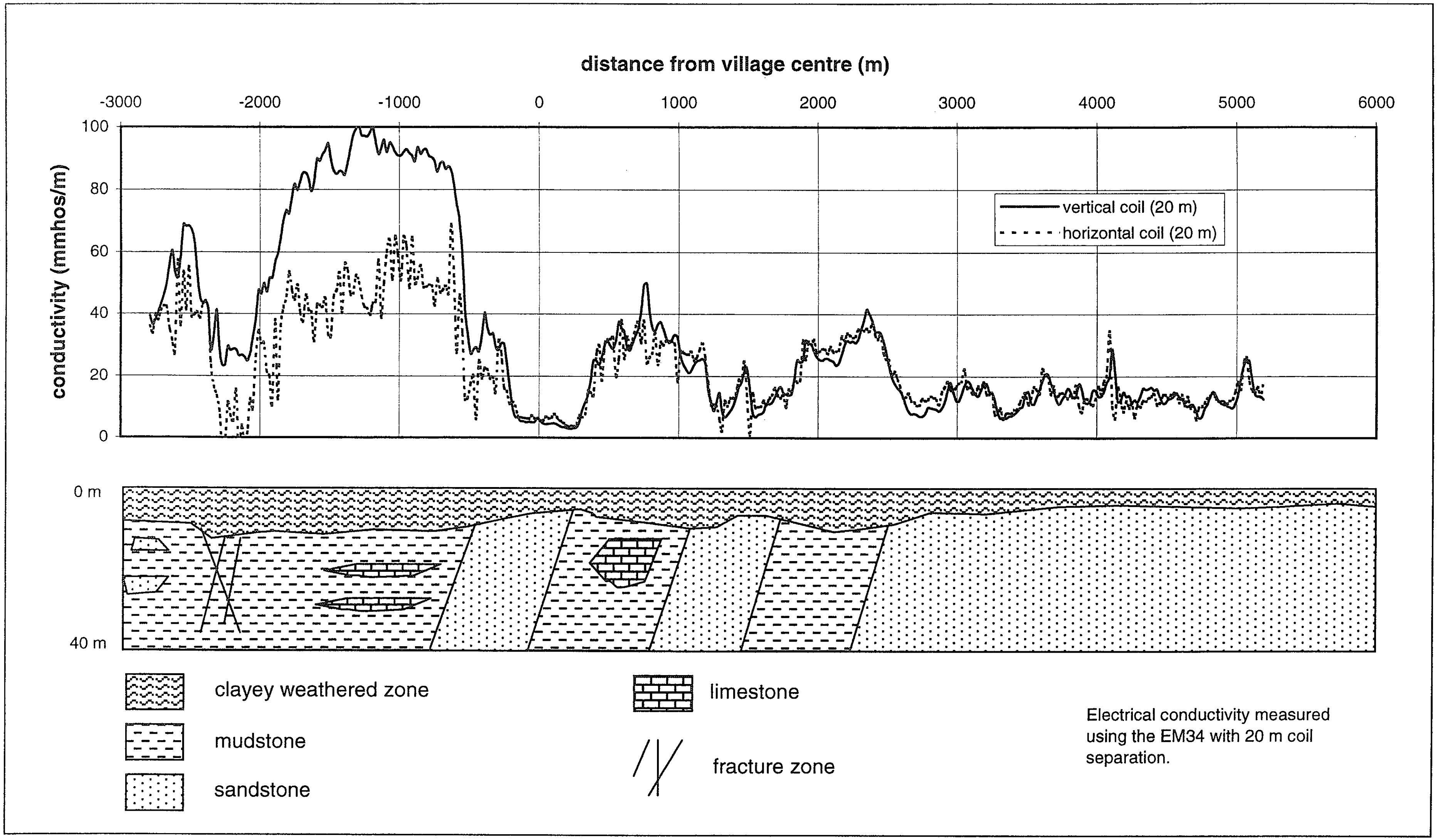


Figure 19 Geophysics surveys and schematic interpretation across the Makurdi Sandstone and Upper Eze Aku Formations at Ochingini. (Note that there is no geophysical expression of the limestone and also the the fracture zone at -2200 m did not contain water).

thick mudstone layers. A poor yield was also obtained from BGS7, due to fine sand clogging the borehole.

The groundwater quality in the Makurdi Sandstone Formation sediments is generally good. Shallow groundwater present is $CaMg(HCO_3)_2$, and $NaCaMg(HCO_3)_2$ type, with conductivity (SEC) of 100-300μS/cm. All samples taken are within the WHO recommended drinking water guidelines. However deep groundwater, as obtained from BGS13, can be saline with TDS >3000mg/l. Poorer quality water was also noted from fairly deep boreholes drilled at Adum East.

Summary of groundwater potential

The groundwater development potential of the Makurdi Sandstone Formation is poor to moderate. The best targets for groundwater are fractures at the base of the weathered zone (8-15m) within sandstone layers and possibly fractured limestone layers. EM34 can be readily used to distinguish the sandstones from the mudstone layers, but none of the geophysical methods could identify fractured sandstone zones. However, most of the exploratory boreholes drilled into sandstone units encountered fractures between 8 and 15m below ground surface, therefore such fractures are probably widespread. Groundwater quality was generally within WHO recommended limits. Deeper boreholes however encountered saline water.

Hand dug wells are the best method to exploit groundwater from the Makurdi Sandstone Formation. Wells have a much larger seepage area than a borehole and therefore allow a greater chance of intersecting the small fractures at the base of the weathered zone; silt and sand can also be removed more easily from a well than a borehole. The exploratory boreholes and pumping tests indicate that if fractured sandstone is encountered, a well could supply from 1-5m^3/d (25-100 basins a day). To increase the supply to a village, laterals could be drilled into the sides of the well, or the well diameter increased. Alternatively more wells could be constructed within a village.

The Makurdi Sandstone Formation sediments are generally soft enough for excavation of hand dug wells but pneumatic drills may have to be used to excavate through very hard near surface silcretised zones. Wells should be reinforced through the clay layer, but are best left unlined in deeper, more competent rock. Although the majority of the groundwater is obtained from thin fractures, much of the groundwater is probably stored within pore spaces and seeps slowly into fractures to be transported to the wells. Long term monitoring will help to establish the sustainability of the groundwater resource within the Makurdi Sandstone Formation.

3.8 Upper Eze-Aku Formation

Regional geology

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

Local geology (Plates 37, 38 and 39)

The Upper Eze-Aku Formation occurs in southeastern Obi. The geological and hydrogeological nature of the Upper Eze-Aku Formation was investigated in two areas; west of Ochingini, and

Plate 37. Vertical fracture in a limestone bed within the Upper Eze Aku Formation.

Plate 38. Medium grained sandstone within the Upper Eze Aku Formation at BGS4.

Plate 39. Silty dark grey mudstones and fine grained sandstone in the Upper Eze Aku formation at BGS4.

Odaleko Adiko village. It may also have been intersected in one of the boreholes in Adum West. Detailed geological logs are given in MacDonald and Davies (1998a) and Davies and MacDonald (1998c). Summaries of the logs are given in Figure 20.

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

Typically the upper 10-15m of the Upper Eze-Aku Formation is highly weathered, to a red and fersiallitic to sandy soil. The soil layer overlies several meters of clayey laterite that is underlain by illite-smectite rich clay (Kemp et al, 1998).

Geophysical investigations

Approximately 6km of EM34 surveys, 4km of magnetic profiling and 2 resistivity VES have been undertaken to investigate the Upper Eze-Aku Formation. Typical geophysical signals are given in Figure 19 with an initial interpretation.

1. Generally the electrical conductivity of the rocks is high (> 40mmhos/m) which reflects the abundance of illite/smectite clays in the weathered zone. Lower conductivity (<40 mmhos/m) is associated with interbedded sandstone and mudstone, where kaolinite clay is dominant in the weathered zone.

2. The limestone layers are too thin to be detected using geophysical methods.

3. Negative going EM34 anomalies indicate fracture zones. However, fracture zones are probably not good targets for groundwater since fractures tend to close in soft mudstone.

4. Resistivity soundings at BGS3 showed a moderate resistive soil overlying 1-2m thick low resistivity (>15ohm-m) layer, followed by 40ohm-m bedrock, results that are consistent with the EM34 measurements.

The geophysical survey data from the Upper Eze-Aku Formation are complex. Sandy horizons can be identified from lower conductivity EM34 responses. Limestone bands, the main targets for groundwater development, cannot be located using geophysical methods.

Hydrogeology

Groundwater occurs within thin limestone and sandstone layers in the Upper Eze-Aku Formation. The limestone layers are often fractured and probably laterally extensive. The siltstones and mudstones may store groundwater, which slowly seeps into the limestone layers to be tapped by boreholes. Sandstones, where they occur, are similar to those of the Makurdi Sandstone Formation.

Analysis of core samples of sandstone from BGS4 gave porosity values of 26-34% and intergranular hydraulic conductivity of 0.004m/d. Pumping tests gave a transmissivity of 0.7m^2/d. These results suggest that the fractures within the sandstone provide most of the groundwater flow. Such aquifer properties are marginal for a borehole, but should be sufficient for a well. Pumping tests carried out

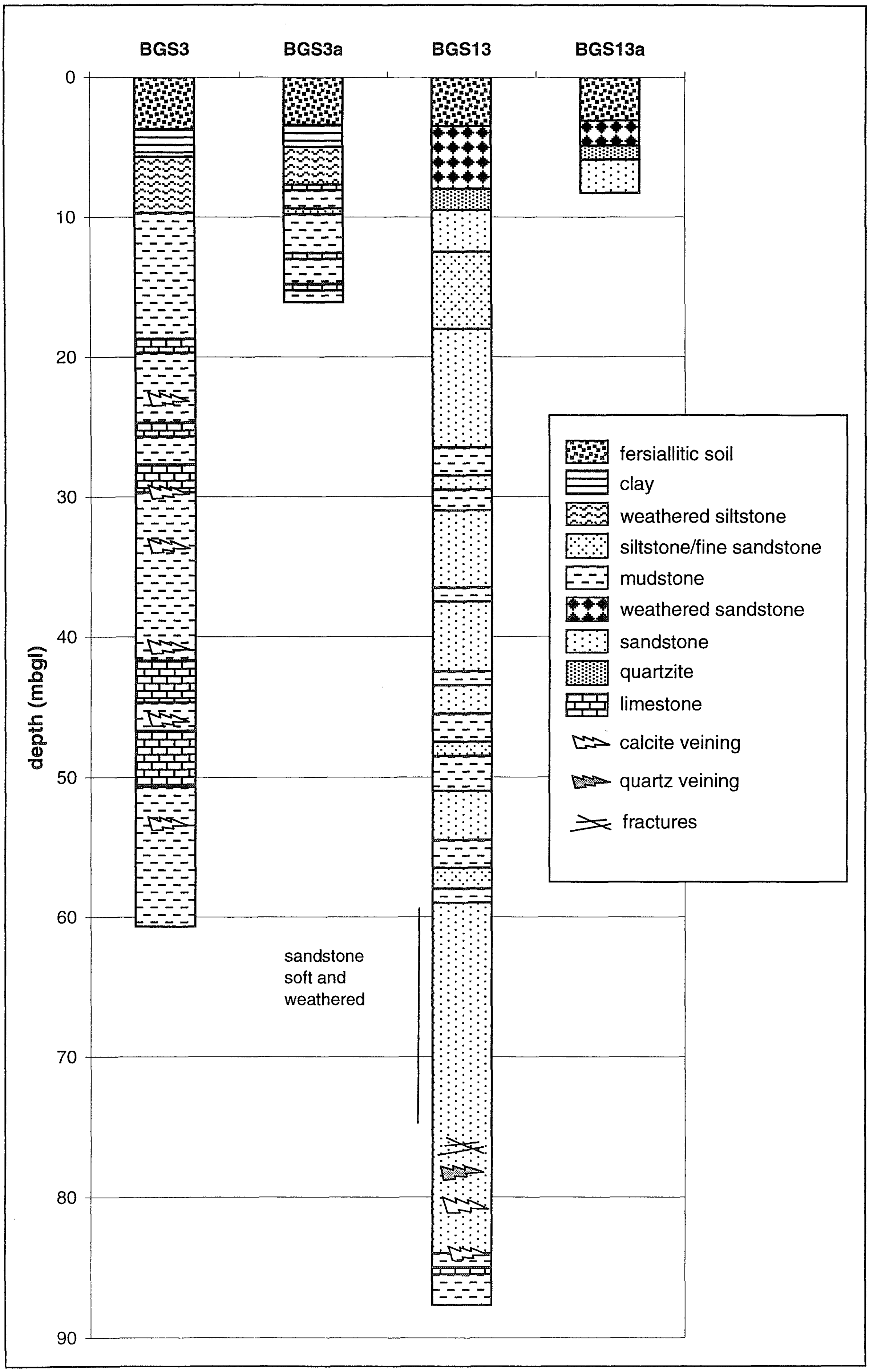


Figure 20 Lithological logs for exploration boreholes drilled into the Upper Eze-Aku and Makurdi Sandstone at Odaleko Adiko.

in fractured limestones at BGS6 gave high yields. Transmissivity values of 14m²/d were measured which is more than enough to sustain a handpump equipped borehole. However, boreholes (BGS3 BGS3a) drilled in the muddy limestones at Odaleko Adiko were abandoned and backfilled, yields obtained during drilling being very low. Only where limestone is competent and fractured can a good borehole yield be sustained.

Groundwater samples for hydrochemical analyses were obtained from boreholes BGS4 and BGS6 as well as a number of boreholes and hand dug wells within adjacent areas. The groundwater quality in the Upper Eze-Aku Formation is generally good. Groundwater types present are $CaMgNa(HCO_3)_2$, and $CaNaSO_4(HCO_3)_2$, all with TDS of <300mg/l. All samples are within the WHO recommended drinking water guidelines.

Summary of groundwater potential

The groundwater development potential of the Upper Eze-Aku Formation is poor to moderate. The Upper Eze-Aku Formation comprises soft shaley mudstones with thin fine-to medium-grained sandstones and thin limestone layers. Negligible groundwater is found within the soft mudstone. Limited groundwater is found within occasional sandstone layers, where the groundwater is best exploited with hand-dug wells. The sandstone layers can be found using the EM34: both the vertical and horizontal coils indicated conductances of less than 20ohm-m. Closer to the Awgu Group Shales, sandstones may be present where the conductivity of the two coils is similar and less than 40ohm-m.

The highest yields within the Upper Eze-Aku are found within thin fractured limestone layers. Unfortunately, the limestones are too thin to be located using geophysical methods. However, they probably only occur within mudstone environments (where EM34 conductivity is high) and are more common in the older deposits (close to the Makurdi sandstone Formation). Boreholes should be drilled to at least 40m depth to maximise the possibility of intersecting a freshwater bearing limestone band.

3.9 Awgu Shale Formation

Regional geology

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

The sandstones and dolerite intrusions found within the Awgu Shale Formation are discussed separately.

Local geology (Plates 40, 41 and 42)

The Awgu Shale Formation underlies much of Obi. The hydrogeological and geological nature of the formation was investigated at three locations: between Ijegwu and Ameka, Ugbodum and Itogo. These sites were also used to investigate the Agbani Sandstone Formation and the dolerite intrusions. Detailed geological logs are given in MacDonald and Davies (1998e, 1999) and Davies and MacDonald (1998b, 1999). A summary of the geological logs is given in Figure 21.

Plate 40. Weathered Awgu Shale Formation from hand dug well, note the gypsum crystals.

Plate 41. Base of weathered zone in the Awgu Shale formation showing development of red iron oxides and gypsum within carbonaceous mudstone.

Plate 42. Non-weathered Awgu Shale Formation from BGS31 - soft and highly carbonaceous mudstone.

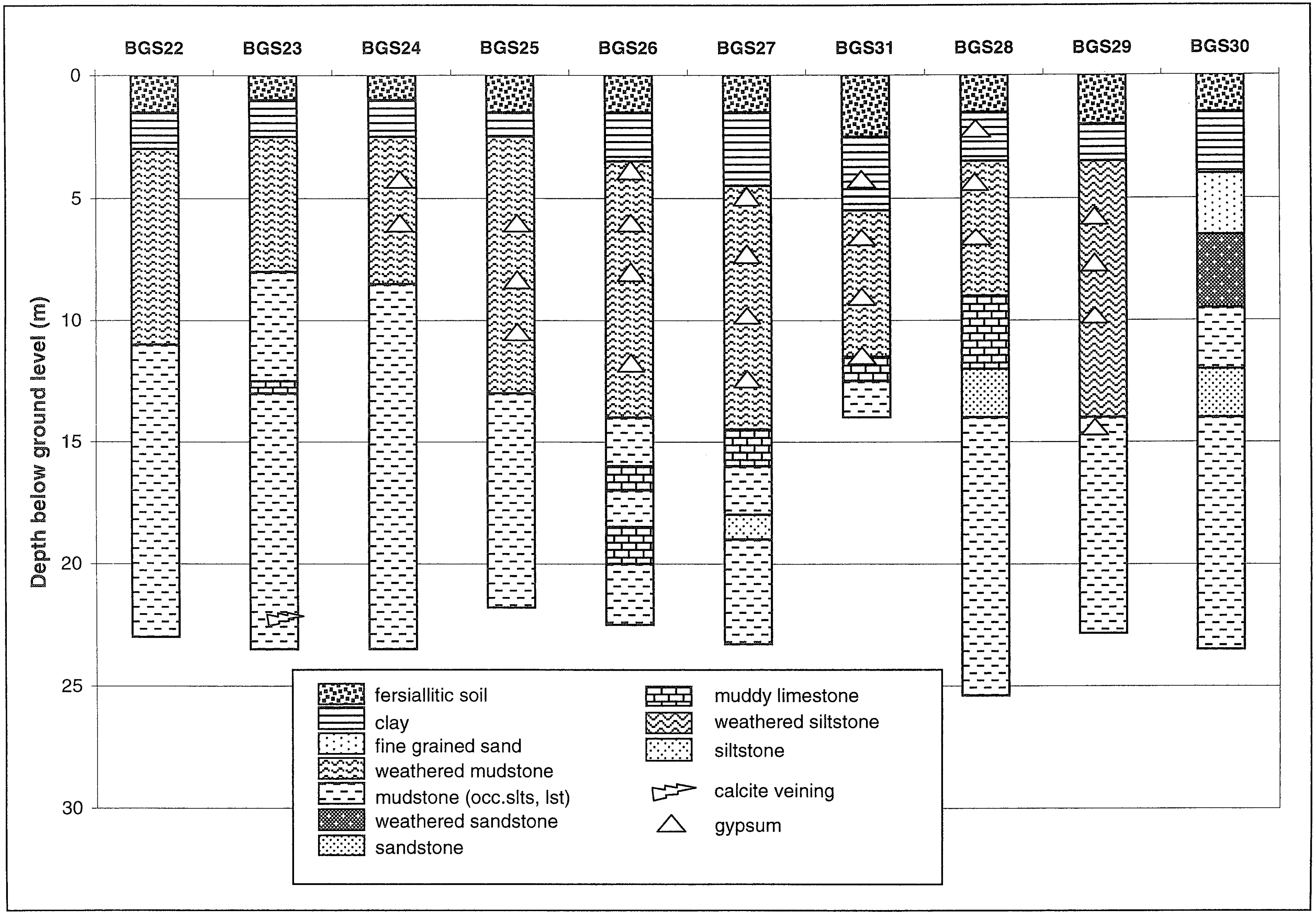


Figure 21 Lithological logs from exploration boreholes drilled into the Awgu Shale Formation along the North Obi traverse.

The Awgu Shale Formation consists of dark grey to black, soft, highly carbonaceous, well-bedded shaley mudstones, with thin (0.5m) interbeds of muddy shelly limestone and calcareous mudstone. There are also occasional layers of fine to medium moderately sorted sandstones referred to as the Agbani Sandstone Formation. These are discussed in Section 3.10.

The black shaley mudstones are very soft and contain much carbon. They are laminated and often break into thin layers when dry. In the upper part of the Awgu Shale Formation, some iron pyrite is found. In the lower part of the Awgu Shale formation (towards the southeast) the shaley mudstones are grey and less carbonaceous. Thin silt and limestone layers are common, but not hydrogeologically significant. At BGS26 a core of limestone obtained from 21.5m was composed of hard shelly limestone. This limestone was deposited as oyster-bank deposits in brackish-water without much current activity.

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

Geophysical investigations

25km of EM34 and magnetic surveying as well as 20 resistivity surveys were undertaken during investigations of the Awgu Shale Formation. An example of an EM34 survey and interpretation is given in Figure 22.

1. EM34 readings are very high (80-140mmhos/m). VES resistivity surveys show a corresponding low resistivity (<6ohm/m). Conductivity values are high due to the presence of saline water within the mudstone and the high smectite clay content of the weathered mudstone.

2. The large difference between the EM34 readings taken with the vertical coils and horizontal coils is probably due to the decrease in conductivity with depth. Such a decrease at depth may reflect less saline groundwater within the deeper mudstone.

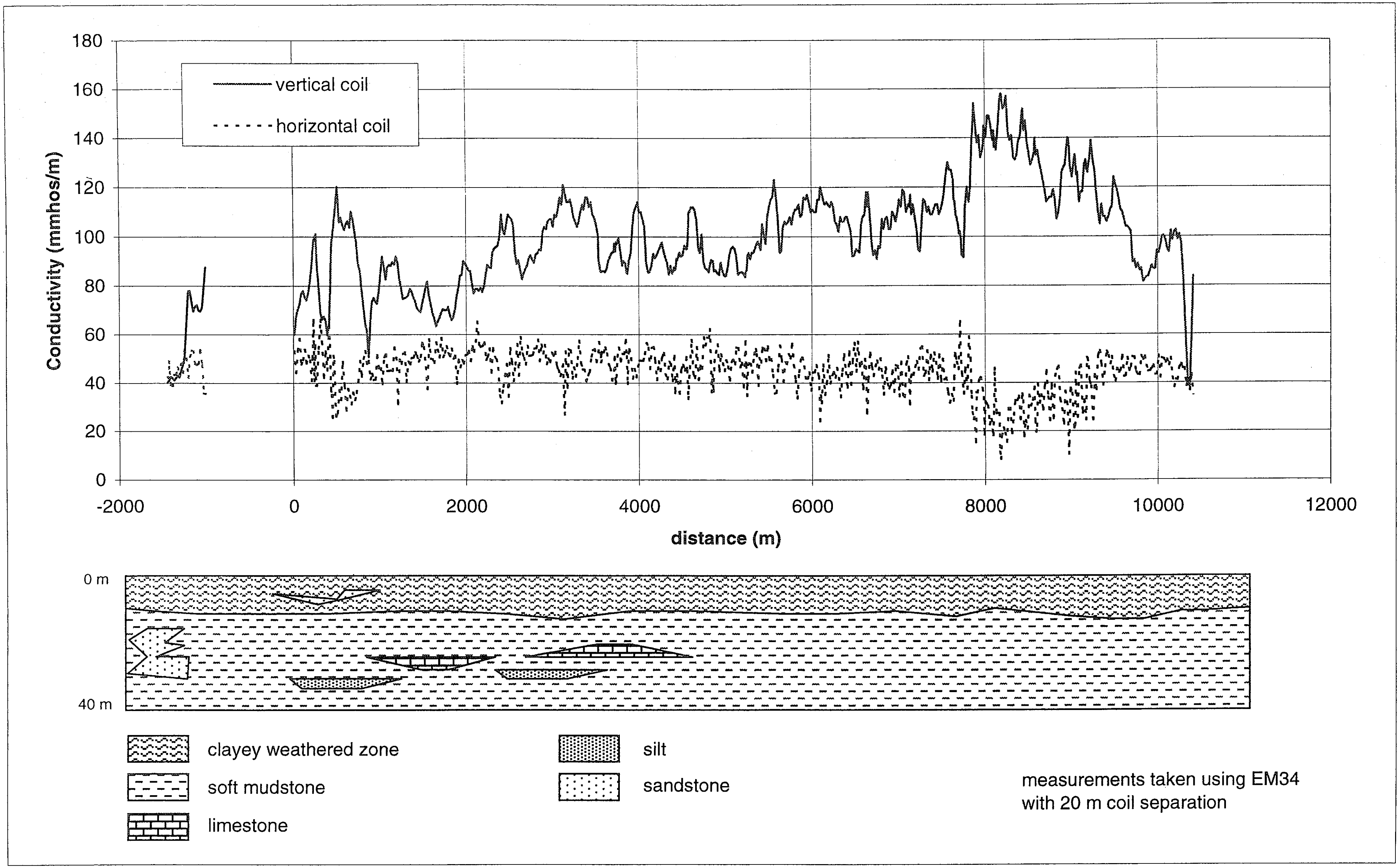
3. The resistivity surveys indicated a surface layer (usually several metres thick) of a few hundred ohm-metres followed by thick very low resistivity layer of about 6ohm-metres. In some of the traverses, the resistivity increased slightly at depth.

4. Sandstone layers and dolerite intrusions within the Awgu Shale Formation give distinct anomalies, as discussed in the following sections

Hydrogeology

Little usable groundwater exists within the Awgu Shale Formation. The mudstone is too soft to contain open fractures. Usable groundwater is only found within then sandstone layers and dolerite intrusions, as discussed in Section 3.10 and 3.11.

A little groundwater was found within thin limestone layers. Pumping tests carried out in two boreholes gave transmissivity values of 0.01-0.02m^2/d: too low for boreholes or wells. During the wet season groundwater is found within the shallow laterite layers. The laterite is fairly permeable and groundwater can flow through the layer to shallow wells and springs. However, shortly after the end of the rains, the laterite dries out.



measurements taken using EM34 with 20 m coil separation

Figure 22 EM34 survey and schematic interpretation across the northern Awgu Shales Formation (northern Obi traverse).

Groundwater quality in the Awgu Shale Formation sediments is generally poor. Within older sediments to the southeast groundwater types present include $CaNa(HCO_3)_2$, $NaCa(HCO_3)_2SO_4$ and $NaSO_4$ types, sometimes with TDS >2000mg/l. Only a few of these samples are within the WHO recommended drinking water guidelines. Within the younger Awgu Shale Formation sediments to the northwest, saline groundwater of $NaSO_4$ type occurred with TDS in excess of 3000mg/l. Some of the shallow hand dug wells that take water from the near surface laterite have both low pH and TDS but can contain high concentrations of dissolved metals. For example a sample obtained from a well in Adega had a pH of 4.3 and aluminum content of 11.2mg/l.

Summary of groundwater development potential

The Awgu Shale Formation comprises soft shaley mudstones, with very occasional silt, fine sand and muddy limestone. This formation has little potential for groundwater development. Even the small amount of groundwater obtained is of poor quality and not suitable for drinking. The poor quality is associated with gypsum in the weathered zone. Shallow wells, that tap the laterite and weathered zone, contain fresh water during the rains, but quickly dry out during the dry season. Small seepages from some of these shallow wells contain low pH groundwater with high concentrations of dissolved metals.

The only potential for groundwater development is from the Agbani Sandstone Formation and dolerite intrusions found within the Awgu Shale Formation.

3.10 Agbani Sandstone Formation

Regional geology

The Agbani Sandstone Formation occurs within the Awgu Shale Formation. The presence of cross-bedded sandstones, interbedded with the Awgu Shale Formation, suggests that the Agbani Sandstone Formation was deposited in a shallow marine shelf environment. In this section, the Agbani Sandstone Formation is taken to represent any significant sandstone layers within the Awgu Shale Formation.

Local geology (Plates 43, 44 and 45)

The Agbani Sandstone Formation occurs in north and west Obi. According to the geological map it occurs in two thin bands which cross Obi from northeast to southwest. However, from field observations sandstone often does not occur at the mapped locations. The geological and hydrogeological nature of sandy horizons within the Agbani Sandstone Formation was investigated in four areas; the eastern end of the Ijegwu to Ameka traverse, Itogo, Ugbodum and Echuri. Detailed geological logs are given in Davies and MacDonald (1998b, 1999) and MacDonald and Davies (1999). Several of these investigations found little evidence of sandstone occurrence. Logs of boreholes that penetrated sandstone within the Awgu Shale Formation are given in Figure 23.

Non-weathered cores of Agbani Sandstone Formation obtained from BGS40 show light grey, fine- to medium-grained, muddy, feldspathic sandstones with interbedded dark grey shaley mudstones. The sandstones are crudely cross-bedded and bioturbated. Drilling close to Ameka, at a site underlain by Agbani Sandstone Formation, gave fine-grained silty sandstones interbedded with much mudstone.

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

Plate 43. Very weathered Agbani Sandstone Fromation, alternating with shales; from stream bank near Echuri.

Plate 44. Weathered Agbani Sandstone Formation from hand dug well in Echuri.

Plate 45. Non weathered muddy fine grained Agbani Sandstone Formation from Ugbodum (BGS40)

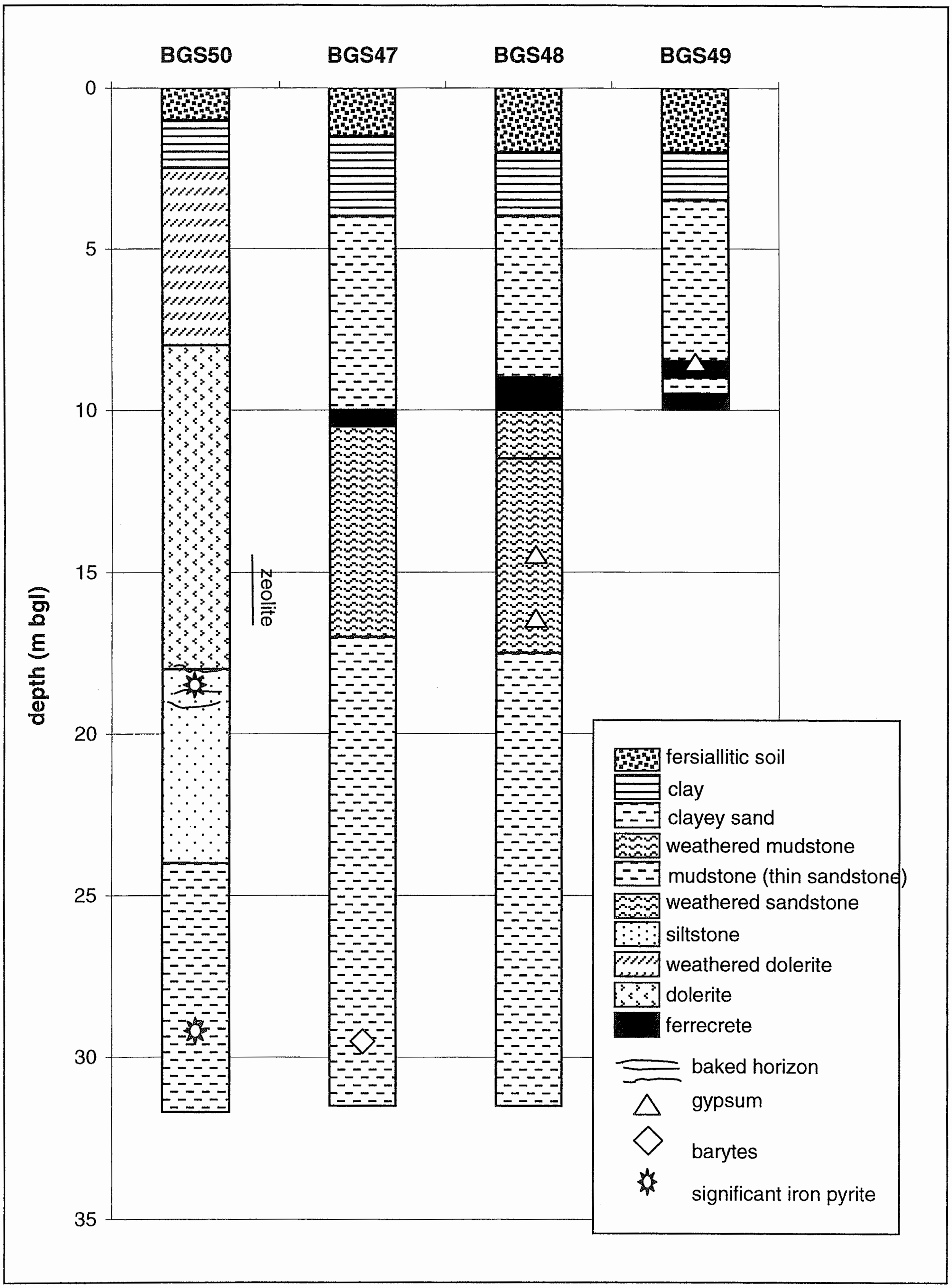


Figure 23 Lithological logs from exploratory boreholes that penetrated sandstone in the weathered zone of the Awgu Shale Formation (Itogo traverse).

Throughout various parts of the Awgu Shale Formation, the weathered zone is sandy, but the bedrock is mainly composed of mudstone. This feature was observed along the Itogo traverse and in a river valley close to Ameka. The sands are fine-grained, well rounded and often collapse during drilling. The sands are very clayey, with clay contents of 33% kaolinite and 67% smectite (Kemp et al, 1998). Along the Itogo traverse a pronounced gravelly laterite layer is present at the base of the sands (about 8-10m). These sands may be remnants of the weathered Agbani Sandstone Formation or are remnants of fossil sand dunes that covered the area during the Pleistocene (Nichol 1999).

Geophysical investigations

EM34-3 equipment can be used to distinguish between Awgu Shale and Agbani Sandstone Formations. A characteristic signal for the sandstone was produced in areas of known Agbani Sandstone Formation occurrence adjacent to wells at Udegi, Ameka and Echuri. At these locations both the horizontal- and vertical-coil conductivity values fall to about 30mmhos/m and do not vary much over the outcrop. Figure 24 shows typical geophysical responses from sandstones occurring within the Awgu Shale Formation.

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

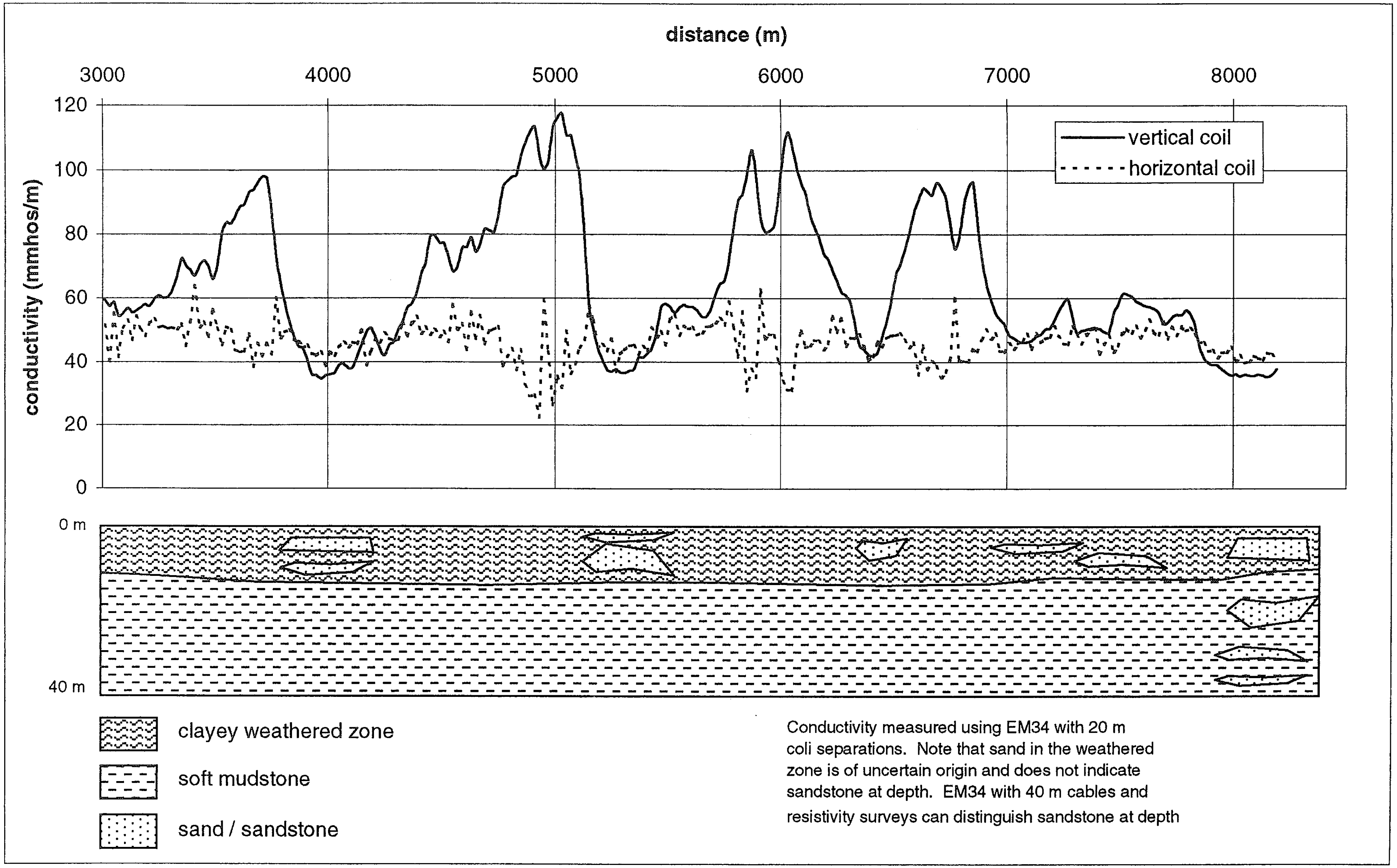
Therefore EM34 (using 20m intercoil separation) can distinguish sand within the weathered zone. Resistivity surveys (or EM34 with 40m coil separation) can be used to identify sandstone at depth.

Hydrogeology

Although little is yet understood of the hydrogeological nature of the Agbani Sandstone Formation, potentially it could form an important aquifer in north Obi. Groundwater occurs mostly within the weathered zone, where the sandstone has been weathered to fine sand. Groundwater may also exist in fractures within the more competent sandstone. Only one exploratory borehole penetrated the unweathered Agbani Sandstone Formation. This borehole collapsed during development and much fine sand entered through the screens. Therefore the transmissivity of $0.15m^2/d$ measured from the pumping test is probably an underestimate. Two existing boreholes penetrated the Agbani Sandstone Formation at Ameka and Oluywo. The local communities claim that, when working, these boreholes easily sustained a hand pump. They may have failed due to corrosion from brackish water or ingress of fine sands.

Several exploratory boreholes were drilled into weathered sandy layers. When test pumped these gave transmissivities of $0.05 - 0.36m^2/d$. Several of these boreholes obtained water from a thin ferricrete layer at about 10m depth. Within Obi, there are several groups of hand-dug wells that also obtain water from the sandy weathered zone, as at Adega, Oluywo and Itogo Iyaho. Many of these wells remain productive until March, while others are productive through the dry season. These wells are best located within the sandy weathered zone along a valley, close to a zone of recharge.

Groundwater samples for hydrochemical analyses were obtained from borehole BGS30 as well as a number of boreholes and hand-dug wells within adjacent areas. The groundwater quality in the Agbani Sandstone Formation sediments is generally good. Groundwater types present are $CaNa(HCO_3)_2$, and $CaNaSO_4(HCO_3)_2$, most with TDS of <100mg/l. Shallow groundwaters tend to have very low TDS (<50mg/l) and low pH, suggesting they are very young. Deeper boreholes and wells have high SO_4 content. Therefore, although samples are generally within the WHO recommended drinking water guidelines, the Aluminium and SO_4 content must be carefully monitored.



Conductivity measured using EM34 with 20 m coli separations. Note that sand in the weathered zone is of uncertain origin and does not indicate sandstone at depth. EM34 with 40 m cables and resistivity surveys can distinguish sandstone at depth

Figure 24 Typical geophysics surveys and schematic interpretation of sandstone in the Awgu Shale Formation. EM34 with 20 m cables can easily distinguish sand in the weathered zone; however sandstone at depth is more difficult to locate.

Summary of groundwater potential

The groundwater development potential of the Agbani Sandstone Formation is poor to moderate. The Agbani Sandstone Formation comprises fine- to medium-grained silty to muddy sandstones interbedded with thin limestone and mudstone layers. Wells can be located in the weathered sandstone, and are likely to be more successful in valleys close to a source of recharge. Wells are likely to sustain small yields, 30 – 50 basins per day in the dry season. It is possible that where the sandstone is present beneath the weathered zone it may be fractured and sustain a sufficiently high yield for a handpump.

Sandy weathered zones can be identified using the EM34. The electrical conductivity is low at 30ohm-m and the vertical and horizontal coils give similar readings. The unweathered Agbani Sandstone Formation at depth can be identified with the EM34 using the 40m intercoil spacing, or using resistivity equipment.

3.11 Dolerite

Regional geology

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

Local geology (Plates 46, 47 and 48)

Within the Oju/Obi area dolerite intrusions of various sizes appear to occur most frequently within the 'Metamorphosed' Asu River, Upper Eze-Aku and Lower Awgu Shale Formations. Dolerite bodies have been found to crop out at numerous locations within the central core of the Wokum Hills. However, hydrogeologically the presence of dolerite is most important within the Obi area, where the surrounding mudstones contain little groundwater. In Obi, dolerite crops-out in the Ito town and Adum West areas. Anomalies shown on the regional aeromognetic map can be used to locate dolerite intrusions. The hydrogeological nature of dolerite was investigated at three locations: Adum West, Ugbodum and Itogo (MacDonald and Davies 1998c, 1999; Davies and MacDonald 1999). Simplified geological logs of boreholes that encountered dolerite are shown in Figure 25.

The dolerites occur as hard dark blue/green fine- to medium-grained basic igneous rocks occurring as dykes and sills. These bodies have been intruded into mudstones, siltstones and sandstones of the Awgu Shale, Agbani Sandstone and Upper Eze-Aku Shale Formations. At Adum West and Ito thick dolerites have been intruded into mudstones. These dolerites are highly fractured with thick vuggy veins of crystalline zeolite (mainly mesolite) occurring along fracture zones. At Ugbodum the dolerite intrusions are thinner than those at Adum West. These dolerites are finer grained and less fractured, with poor zeolite formation especially where intruded into sandier sediments. A thin dolerite sill was also encountered near Okwutungbe. This dolerite was medium to fine grained and contained zeolite growths.

Sediments in contact with the dolerite intrusions have been baked. The mudstones become harder and change to a light grey/white colour. Little water was found within the baked horizons.

At the surface typical black/green clayey cracking soils develop, below which dolerite weathers to smectite clay (Kemp et al, 1998). Dolerite is easily identified at out crop in riverbeds, where it weathers to characteristic rounded hard dark grey rock masses with onion skin type weathering.

Plate 46. Weathered dolerite exposed in a river bed.

Plate 47. A thin dolerite sill near Adum west.

Plate 48. Dolerite core from BGS35 at Adum West. Note the white veins of zeolite associated with fracturing.

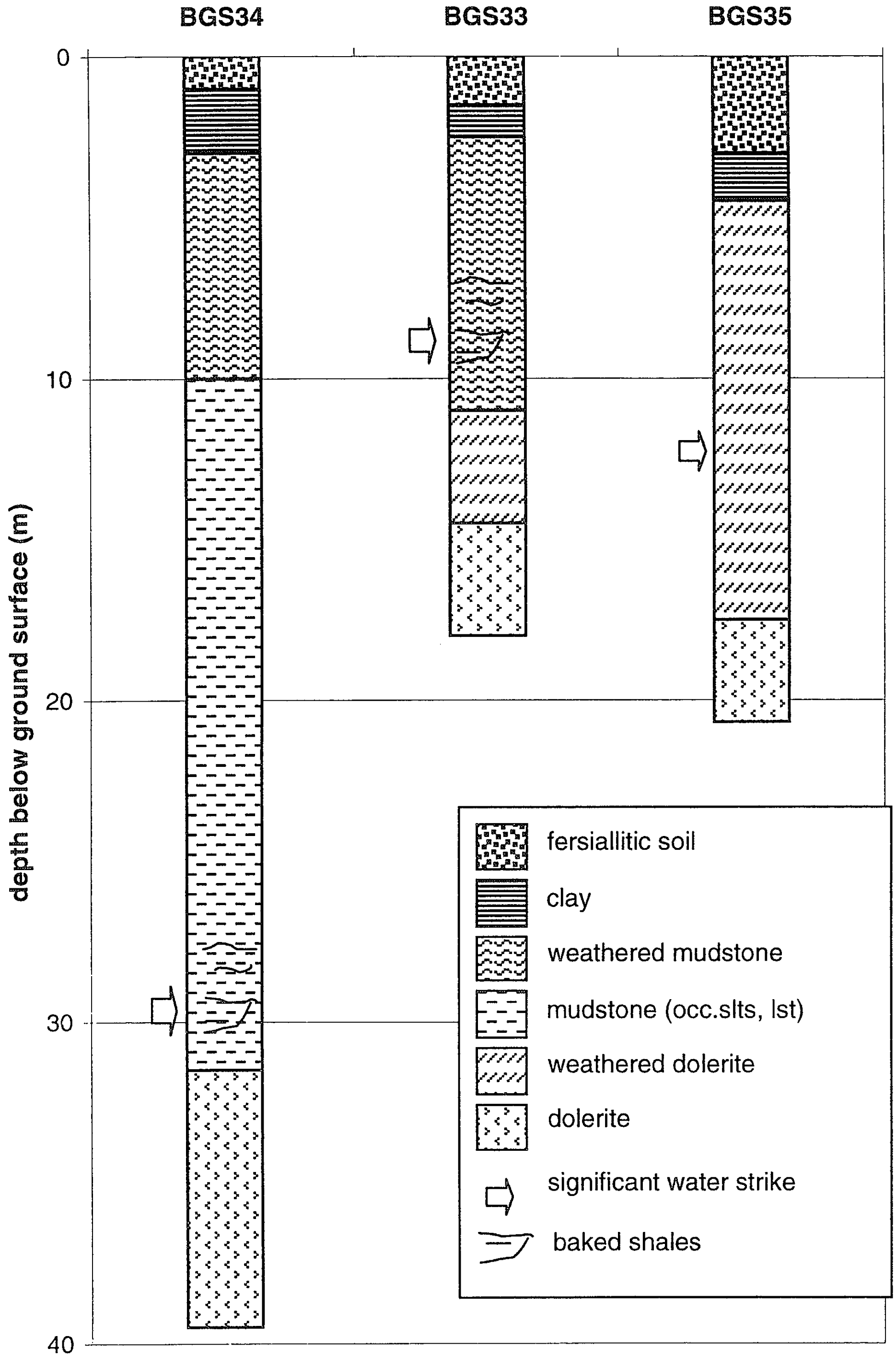


Figure 25 Lithological logs of exploratory boreholes that penetrated dolerite at Adum West.

Geophysical investigations

Various geophysical surveys have been undertaken to identify dolerite intrusions. The results of typical EM34 and magnetic surveys over a dolerite intrusion are shown in Figure 26. A summary of the main geophysical characteristics follows:

1. Where dolerite is close to the surface, a moderate EM34 conductivity is measured. The contrast with the high conductivities from the Awgu Shale Formation makes dolerite easily recognisable. Above dolerite, vertical coils with 20m intercoil spacing typical record about 40mmhos-m; whereas horizontal coils at the same spacing record about 20mmhos-m.

2. Large magnetic anomalies (100nT) are encountered where the dolerite lies close to the surface. The magnetic field often varies significantly within a few metres with no obvious reason (i.e. no steel roofs nor bicycles).

3. Where the dolerite occurs at depth (20 – 30m), the electrical conductivity measured using the 20m inter-coil spacing is high, reflecting the conductivity of the covering Awgu Shale Formation mudstones within the weathered zone. Subdued magnetic anomalies of 10 - 20nT are observed.

4. Resistivity surveys over dolerite produce different profiles to those undertaken over Awgu Shale Formation mudstones. Typically the smectite-rich black dolerite soil produces a low surface resistivity. The underlying less weathered dolerite gives resistivity values greater than 50ohm-m, in contrast to values of less than 10ohm-m typical for the Awgu Shale Formation mudstones. At depths greater than 20m, where the EM34 cannot easily distinguish dolerite, resistivity soundings can therefore be effective.

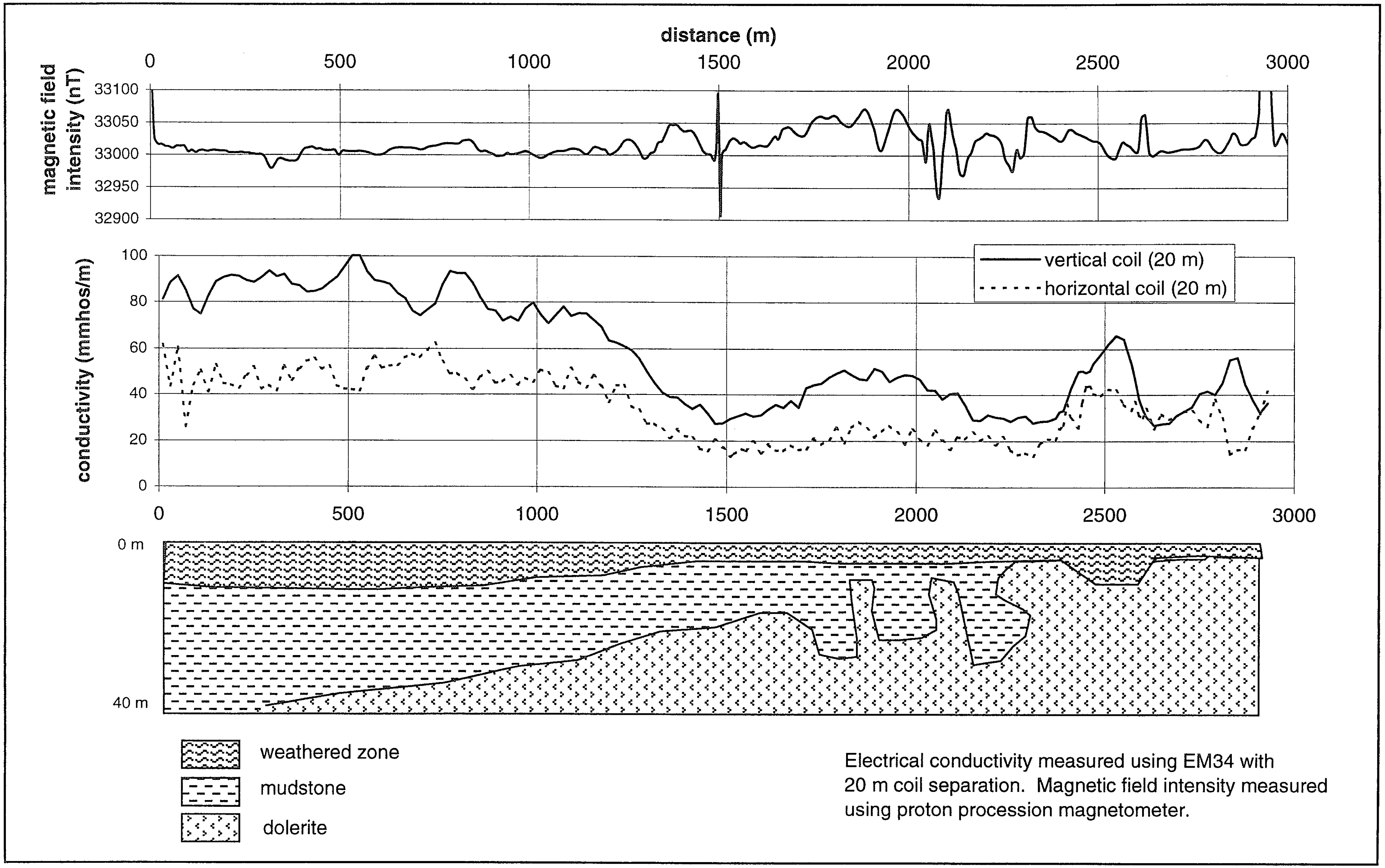
Hydrogeology

In Obi, groundwater occurs in fractures within dolerite, usually towards the edges of intrusions. Such fractures are often lined with vuggy zeolite growths with void spaces up to 10mm across. The widest fractures have been formed within dolerite that has been intruded into mudstone, rather than sandstone. The dolerite was probably intruded into wet and unconsolidated mudstones, the water would have been turned to steam which would have helped to form fractures close to the edge of the intrusions. Very little water was found within the baked shales or sandstones at the contact with the intrusions.

At Adum West the dolerite is highly fractured with much zeolite. Transmissivity values of 20 – 60m^2/d were calculated from pumping tests conducted on high yielding boreholes BGS33 and BGS35. Borehole BGS34, which encountered dolerite at 30m depth, produced a transmissivity of 5m^2/d when test pumped, sufficient to sustain a handpump.

At Ugbodum, thin dolerite intrusions were investigated. Dolerites intruded into sandstones produced transmissivity values of 0.15 – 0.3m^2/d and yields are too low to sustain a handpump at boreholes BGS40 and BGS44. A thin dolerite intruded into mudstone gave a transmissivity value of 0.7m^2/d and a yield that could marginally sustain a handpump at borehole BGS42.

Boreholes BGS46 and BGS50 encountered thicker dolerites in valley sites. When test pumped, transmissivity values of 2-30m^2/d were obtained at yields that could sustain a handpump. Valley sites are preferred for groundwater development, often being zones of groundwater discharge developed along fracture zones.



Electrical conductivity measured using EM34 with 20 m coil separation. Magnetic field intensity measured using proton procession magnetometer.

Figure 26 Geophysics surveys and geological interpretation for dolerite intrusions at Adum West.

The groundwater quality in the dolerite and baked sediments is generally good. Groundwater types present are $CaNa(HCO_3)_2$, and $CaNaMg(HCO_3)_2$, most with TDS of <300mg/l. Occasionally high iron is found, but samples tested were within the WHO recommended drinking water guidelines.

Summary of groundwater potential

The highest yielding boreholes in the Obi area have been installed within thick, fractured and coarse-grained dolerite located adjacent to valleys that form good sources of recharge. Most groundwater is obtained from zones of fractured and weathered dolerite near the edge of intrusions. These fractures are best developed where the dolerite intrusions are thick and have been intruded into unconsolidated muds. Thick dolerite intrusions are easily recognised using a combination of EM34, magnetic profiling and resistivity. Thinner intrusions have smaller magnetic anomalies. Deep intrusions have high electrical conductivity and subdued magnetic anomalies.

Groundwater in dolerite is best exploited using boreholes since the rocks can be very hard. Although high borehole yields can be obtained, the amount of groundwater stored within the dolerite may be low. It is therefore important to closely monitor the behaviour of boreholes drilled into dolerite.

3.12 Laterite

Regional geology

Fersiallitic soils (or laterites) form under the tropical climate of the region. These consist of a red iron rich soil, several metres thick, overlying a mottled clay horizon. The concentration of iron oxides in the upper zone is partly related to the iron content of the parent-rock. Clays washed downward accumulate to form the mottled clay horizon. Above, in the near surface zone remnant iron oxides accumulate as purple-red, iron-rich nodules of haematite and manganese oxide, that coalesce to form hard nodular and vuggy ferricrete bands with time.

Kaolinite is the predominant clay mineral within the mottled clay horizon. At depth within the weathered zone, smectite clays may form. The proportion of different clay types being dependent on the mineralogy of the underlying bedrock. Groundwater flows mainly within the iron crusts and at a reduced rate within the mottled clay horizons, redistributing iron, aluminium, and silica. Kaolinite clay has a tendency to concentrate in the deeper down-slope areas.

Local geology (Plates 49, 50 and 51)

A zone of weathered material (known as the "regolith") some 2 - 20 metres thick overlies the Cretaceous age sediments of the Oju/Obi area. The regolith generally comprises a red iron-rich fersiallitic soil, overlying a mottled clay horizon, followed by a clay rich zone containing weathered bedrock. The thickness and nature of the regolith depends on the physical and chemical composition of the underlying geology. Table 5 gives average thickness of the regolith layers developed upon the rock formations present in the project area.

From Table 5 several generalisations can be made. The fersiallitic soil is made up of 0-3m of red clayey soil with variable quantities of iron and manganese oxide nodules. Below the laterite are 2-4m of mottled clay, kaolinite clay predominates in the upper zone and smectite, illite or illite/smectite clays in the lower zone. Below the mottled clay layer occurs 5-15m of weathered bedrock, within which bedding features are preserved but the rock is soft, discoloured and clayey. Ancient, thick laterite layers occur around Oju town, forming an area of flat-topped high ground with a prominent escarpment along its northern edge.

Plate 49. Nodular laterite developed over swelling clays (illite/smectite) and kaolinite clays for the Lower Eze Aku Formation.

Plate 50. Sandy, nodular laterite developed on the Makurdi Sandstone Formation.

Plate 51. Ancient hard ferrecrete, overlying mottled kaolinite rich layer developed on the Lower Eze-Aku Formation.

Table 5. **Average thickness and composition of the weathered zone of the hydrogeological units in Oju/Obi.**

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

Geophysical investigations

Although not the subject of specific studies, the nature of the regolith has an important effect on the geophysical properties measured at the surface. In particular, the EM34 and resistivity response is dependent upon the composition of the clay horizon. As explained above, the composition of the clay is largely dependent on the bedrock geology.

Hydrogeology

The nature of the tropical soil cover present throughout Oju/Obi impacts upon the hydrogeology of the area. The shallow nodular zone can be highly permeable, particularly where the nodules have been bonded into a hard tubular and vuggy ferricrete. During the rainy season, water quickly flows through this permeable nodular zone to the rivers, causing flash flood conditions. Shallow hand-dug wells tap this water source, often supplying large amounts of water when the shallow zone is saturated. However, on cessation of the rains, the water table within the shallow laterite zone quickly declines, the volume of water available rapidly diminishes. Highly permeable ferricrete may pose a problem for latrine construction since rapid groundwater flow through laterite from latrines to wells will probably cause contamination of an well-utilised water resource.

The clay zone beneath the shallow laterite layer impedes the downward movement of groundwater, thus minimising direct recharge to the underlying bedrock aquifer However, rainfall may percolate very slowly through the clays providing some measure of recharge, as happens in the glacial clays in northern latitudes. The clay, when very close to the surface can often have an important impact on latrines. Waste cannot easily seep away through the clay, and expanding clays can often cause latrines to collapse.

Within the laterite, groundwater has little chemical content and is acidic. Since reservoir material is shallow and permeable, groundwater is vulnerable to contamination, especially within villages where contamination from latrines can move quickly through the laterite to shallow wells. High nitrate and ammonia levels were recorded in such a shallow aquifer/well environment at Ito town.

Summary of groundwater potential

The groundwater resources of the shallow nodular soil zones are seasonal. Such zones contain much water during the rainy season, but the resource quickly diminishes with the onset of the dry season. The water in this zone is vulnerable to contamination by effluent from pit latrines. Therefore wells and boreholes tapping deeper aquifers should be cased and cement grouted through the laterite zone. The clay type present within the near surface layers must be taken into account when constructing shallow structures such as hand dug wells, pit latrines and foundations for buildings and bridges. The clays present over much of the area are illite/smectite or smectite in form, clays that tend to contract and crack during the dry season then swell on wetting at the start of the wet season.

3.13 Alluvium and River Gravels

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

Alluvium can be located using geophysics and field observations. It occurs on flood plains along the main rivers. Since the sands have lower clay content than the weathered mudstone of the Awgu Shale Formation, their electrical conductivity measured by the EM34 is low.

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

Although not shown on the hydrogeology map, thin river gravels are present in many of the riverbeds. A study has been made of their potential to provide groundwater. Several sites were tested using a hand auger to measure the thickness and nature of the gravel (MacDonald and Davies 1997). The results of this survey show that:-

- The river gravel deposits of the major rivers are thin, intermittent and have little groundwater storage.

- Thin gravels (~1m) occur along small river valleys developed on the Asu River Group outcrop. Such gravels contain small amounts of groundwater early in the dry season that quickly diminish and dry out as the dry season progresses.

- More sustainable seepages found along riverbeds at the height of the dry season are usually fed by flow from the weathered rock zone along the valley sides.

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

Most of the significant river gravel deposits occur in Oju along valleys developed on the Asu River Group outcrop. Boreholes drilled into fractured Asu River Group rocks would provide much more reliable water sources.

3.14 Overview of the Groundwater Chemistry

The chemistry of groundwaters found in Oju/Obi is complex. This section provides an overview of groundwater chemistry in the context of drinking water. Approximately 150 groundwater samples have been taken from boreholes, wells and seepages throughout Oju/Obi. Analysis of these water samples has aided interpretation and understanding of groundwater flow within the aquifer units.

Several general statements can be made about the waters sampled:

- Waters from seepages tend to have low total dissolved solids (TDS) contents, indicating that the water is young and is probably derived from rainwater. Waters taken from shallow wells also tend to have low TDS contents. As the dry season progresses, TDS increases, indicating that the shallow laterite layers are drying out and there is increased contribution of deeper groundwater to flow.

- Borehole waters tend to have moderate TDS contents (about 500mg/l). The quality does not change much throughout the year since waters are abstracted from deeper sources unaffected by seasonal variations.

- Shallow groundwater from wells and seepages can be acidic. These waters tend to have a low TDS content and low pH, conditions under which heavy metals, such as aluminium, can be taken into solution. Higher nitrate and ammonia were observed in some shallow wells located within villages.

The different types of groundwater found within Oju/Obi are shown in Figure 27. The groundwater types have been divided into four groups, dependent upon geology. It should be noted that these groups are simplifications; variation of groundwater type may occur within a group.

Type 1. These groundwaters are found within the Asu River Formation, 'Metamorphosed' Asu River Formation and Lower Eze-Aku Formation. The quality of these waters does not change markedly from place to place; TDS is about 500mg/l and pH around 7. The groundwaters are calcium bicarbonate type. Occasionally the water smells of hydrogen sulphide. Dissolved iron concentrations are slightly high. This is not a risk to health, but can give the water a bitter taste. Moderate sulphate concentrations can also occur.

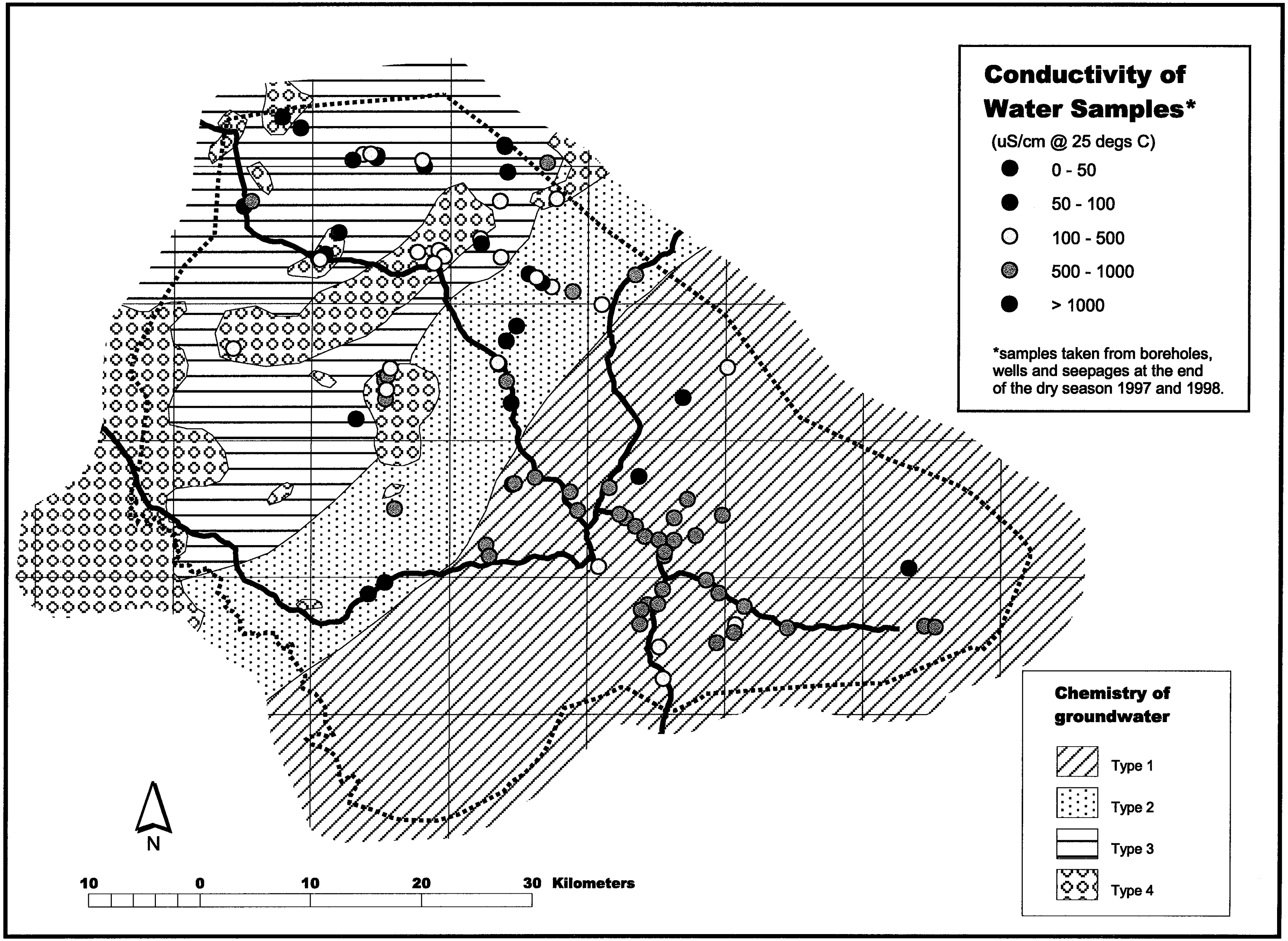


Figure 27 Groundwater chemistry of Oju and Obi. See text for description of groundwater type.

Type 2. These groundwaters are found within sandstones of the Makurdi Sandstone and Upper Eze-Aku Formations. TDS is generally less than 300mg/l. The waters are calcium/sodium bicarbonate type and have good taste. Very shallow waters, from wells and seepages, have low TDS contents (<50mg/l) and low pH (~6). Waters from sources deeper than 50m, can have higher salinities. Waters found within limestone layers are similar to Type 1.

Type 3. Waters found within the Awgu Shale Formation are of poor quality. TDS contents in waters obtained from below the weathered zone can be greater than 3000mg/l. These waters are of calcium sulphate type, with high concentrations of sulphate. Highly alkaline (pH >10) waters are found in some areas and acidic waters (pH ~4.5) in others. The acidic waters can contain unacceptable amounts of dissolved metals. Waters in shallow wells during the wet season are often recently recharged rainwaters of good quality. Good quality water occurs in the sandstone units such as those of the Agbani Sandstone Formation.

Type 4. Good quality mainly calcium/sodium bicarbonate type waters occur within dolerite intrusions mainly within the Awgu Shale Formation area. TDS contents are less than 400mg/l and pH about 7. Although only two areas are marked on the map, other areas may also exist.

Throughout the whole of the Oju/Obi area, natural iodide levels are low. Although salt is iodized throughout Nigeria, this is not always used in rural villages. Low iodide levels can give rise to an increased incidence of goitre and cretinism, which are common in Oju/Obi. Benue State was highlighted by UNICEF as have one of the highest incidences of goitre in Nigeria (UNICEF 1998). Fluoride concentrations throughout Oju/Obi are within the WHO limit and are not a concern for health. Arsenic concentrations throughout Oju and Obi are low. The high sulphate levels given in the Type 3 waters could give rise to chronic diarrhea. Another concern to the long-term health of inhabitants is the low pH waters found near to Adega. Low pH waters allow many toxic metals to stay in solution in the groundwater and be absorbed by the body. Aluminum levels were unacceptably high in these waters.

3.15 Summary

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

1. *Fracture zones within the Asu River Group and Lower Eze-Aku Shale Formation*: The Asu River Formation and 'Metamorphosed' Asu River Formation both comprise hard splintery shales. Fractures within these rocks are common and generally remain open, regardless of their orientation. Much horizontal fracturing is associated with the base of the weathered zone as described for the crystalline basement (Wright 1992) but may also be associated with hydrofracturing during formation consolidation during burial. The Lower Eze-Aku Shale Formation, although softer, may contain open fractures. These tend to be more widely spaced than in the Asu River Group and are associated with faults.

2. *Sandstone and limestone layers within the Upper Eze-Aku Shale Formation, Makurdi Sandstone Formation and Agbani Sandstone Formation*: Sandstone is present within the Upper Eze-Aku Shale, Makurdi Sandstone and Agbani Sandstone Formations. The sandstones are interlayered with thick shaley mudstones. The location of sandstone units from field observation alone is difficult due to the thick soil cover and flat topography. Geophysics, however, can be used to distinguish between sandstones and mudstones. The sandstones are fine- to medium-grained and sometimes silicified. Intergranular permeability is low, but fractures are common between 10-15m depth. Hand dug wells constructed to 15m may supply up to 50 basins per day during the dry season. Thin limestones (0.3m), where fractured, can provide sufficient water for a hand-pump-equipped borehole. The Agbani

Sandstone Formation out crop has yet to be accurately located. Yields from the Agbani Sandstone Formation are variable.

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

Throughout Oju/Obi targets for groundwater development can usually be found within walking distance of most villages. The main problem area is that underlain by the water deficient Awgu Shale Formation.

4. GUIDELINES FOR GROUNDWATER DEVELOPMENT

From the detailed hydrogeological investigations carried out in Oju/Obi, it is possible to form guidelines for developing the groundwater resources of the area. Geology is the primary factor controlling the presence or absence of groundwater, therefore the guidelines are geared towards understanding the geology of a site. As discussed in Section 3, the hydrogeology of Oju/Obi is highly variable and complex, therefore the guidelines are not foolproof, but are the best that can be suggested given the present understanding of the area. If more information is collected from the construction of wells and boreholes guidelines can be revised and updated. These guidelines should be used in conjunction with the groundwater development map of the area (MacDonald and Davies 1998b).

Three phases are considered: (1) identification of geological formations within which groundwater may exist in an area; (2) selection of suitable sites for borehole/well installation; and (3) appropriate design and constructing of boreholes/wells.

4.1 Identifying the Groundwater Potential of an Area

When planning a groundwater assessment programme it is important to know which areas are likely to contain groundwater. The groundwater development map shows the extent of the various hydrogeological units present in Oju/Obi. The groundwater potential of these units (as determined from the targeted exploration drilling) is discussed in detail in Section 3. However, as the geology is complex, and the map only based on reconnaissance geological data, the simple geological boundaries shown can be inaccurate and fuzzy. Therefore, it is possible that a village shown on the map to lie on one particular geological formation may in reality be located differently. For a more accurate assessment of the groundwater potential of a village, other factors should be considered in addition to the map information. A system known as *geological triangulation* has been developed to combine various factors to produce a reasonable assessment of groundwater potential.

Information about the groundwater potential of a village can be gained by combining data drawn from three different sources: maps, observation and geophysics (Figure 28). On its own, each source of information can be misleading. However, taken together this can be a useful method of producing an initial assessment groundwater potential. Notes from a workshop explaining geological triangulation in more detail are given in Appendix 2.

Maps. Villages must be located accurately before plotting on the groundwater development map. The latitude and longitude of each village is determined using a global positioning system (GPS) (Plate 52). Once located, the map provides an indication of the basic geology including the presence of dolerite intrusions and satellite lineations at the village site.

Observation. The local geology must be examined with care and discussed with the local community. The lithological nature of the rocks and any structural features should be noted. Local wet and dry season sources of water need to be visited, as should any locations that the community considers as possible groundwater sources. Rock samples need to be collected from local rock exposures (Plate 53); and rock spoil from shallow wells examined. This geological information should be used to up-date the scanty map information.

Geophysics. Geophysical surveys can then be undertaken at sites based upon geological observations made within the village. The type of geophysical survey depends on the rock types present. The survey results should support the observation data, confirming the type of rock present. The survey results can then be collated with observed data to identify targets for borehole and/or well installation (see next section).

Table 6. Guidelines for siting wells and boreholes throughout Oju and Obi.

Hydrogeological Unit	Description of rocks	Groundwater potential	Groundwater Targets	Survey Methods	Interpretation	Comments
Metamorphosed Asu River Formation	Very hard splintery shales with pyroclastic rocks.	High	Fractures at the base of the weatherd zone	EM34 Magnetic	EM34: Low values mean more pyroclastic rocks and harder shales Magnetic: anomalies indicate the presence of pyroclastic rocks or intrusions	From the testing, groundwater has been found in all types of geophysical anomalies. Therefore careful borehole siting probably not necessary. Preferred locations where much fracturing and close to a source of recharge
Asu River Formation	Hard splintery shales and quartzites, limestones	High	Fractures from about 12 – 25m depth	EM34 Resistivity	EM34: low values indicate harder rocks, high values (15-20 mmhs/m) may indicate deeper weathering Resistivity: low resistivity at depth may indicate fractures.	Boreholes can probably be sited anywhere, but best on fracture zones and near to sources of recharge.
Lower Eze-Aku Formation	Slightly lithofied mudstone with siltstone, fine sandstone and limestone layers.	Moderate	Widely spaced fracture zones	EM34	Sharp negative anomalies or large variations over short distances indicate fracture zones.	Test sites have shown that boreholes must be sited on fracture zones. Note that near the southern edge of the outcrop it may be more akin to the Asu River Group
Makurdi Sandstone Formation	Interbedded fine-medium grained well cemented mudstone, and sandstone.	Moderate	Softer and fractured sandstones Thin limestone layers	EM34	Low conductivity values (<20 mmhos/m) indicate sandstone. Limestones cannot be identified using geophysics	Sandstones are better targets when fractured. Geophysics cannot identify fractures, but fractures probably widespread.
Upper Eze-Aku Formation	Mudstone with interbedded sandstone and limestone	Moderate/Low	Sandstone Thin limestone layers	EM34	Low conductivity values (<20 mmhos/m) indicate sandstone. Limestones cannot be identified using geophysics	In the exploration boreholes, fractured mudstone was too soft to contain water. Limestone is more common close to the Makurdi Sandstone.
Awgu Shale Formation	Soft mudstone with occasional siltstone and muddly limestone	Low	Agbani Sandstone and dolerite (see below)	EM34	Awgu Shale generally has very high conductivity values	No reliable groundwater of good quality was found within the Awgu Shales
Agbani Sandstone Formation	Soft medium grained sandstone	Moderate/Low	Sandstone	EM34 Resistivity	Horizontal and vertical coil conductivity values are equal and fairly low (~ 30 mmhos/m). Low conductivity at depth may imply sandstone beneath the weathered zone.	The location of the Agbani Sandstone is uncertain and often far from that marked on the map. Sands often in weathered zone but not at depth. EM34 (40m coils) and resistivity survey can be used to indicate sandstone at depth.
Dolerite Intrusions	Very hard, fine-medium grained basic igneous sills and dykes	High/Moderate	Fractures within the dolerite	EM34 Magnetic	EM34: Low readings (< 30 mmhos/m) within the Awgu Shale Magnetic profiling: Any anomalies (not associated with metal objects) indicate the presence of dolerite	Dolerite is mainly found in the aeromagnetic anomaly areas marked on the map. If dolerite is deep (30 m). Thick shallow intrusions (many anomalies) have better potential than thin intrusions.

Table 7. Guidelines for developing groundwater within Oju and Obi.

Hydrogeological Unit	Groundwater Targets	Technology	Advisable Depth	Reasons for technology	Comments
Metamorphosed Asu River Formation	Fractures at the base of the weathered zone	boreholes	40 m	Rocks can be very hard; yield from fractures and soft pyroclastic rocks are generally sufficient for a hand pump.	
Asu River Formation	Fractures from about 12 – 25m depth	boreholes	40 m	Rocks are hard, but yield generally high	Alternatives: Hand dug wells if sufficiently deep (> 15 m) could be dug with pneumatic drill. Dug-cum borehole, combining a deep borehole with shallow reservoir could be appropriate.
Lower Eze-Aku Formation	Widely spaced fracture zones	boreholes	40 m	Targets can be far apart and fractures deep	Hand dug wells could be suitable if sufficiently deep, however, probability of dry borehole/well may be high. Dug-cum-boreholes as above may work.
Makurdi Sandstone Formation	Softer sandstone and fractured sandstones	Well	15 – 20 m	Groundwater can be shallow; permeability low therefore large reservoir capacity required	Wells have to dug through shallow hard sandstone layers to try and intersect softer sandstone or fractures. Some wells may supply less than 50 basins per day in the dry season.
	Thin limestone layers	Boreholes	40 m	As Upper Eze-Aku	
Upper Eze-Aku Formation	Sandstone	Well	15 – 20 m	As for Makurdi Sandstone	
	Thin limestone layers	Borehole	40 m	Thin limestone cannot be found with geophysics, greatest chance of encountering limestone layer is by drilling deep.	Drilling to find the limestones is hit or miss.
Awgu Shale Formation	Agbani Sandstone and dolerite (see below)	Rainwater Harvesting		Reliable groundwater has not been found within the Shales	Groundwater may be found within Agbani Sandstone or dolerite
Agbani Sandstone Formation	Sandstone	Well	15 m	Shallow groundwater exists in the sandstone	Wells may supply less than 30 basins per day in the dry season. Wells may collapse due to fine sand in the weathered zone. Best yields encountered in valleys close to source of recharge.
Dolerite Intrusions	Fractures within the dolerite and surrounding baked shales	Borehole	40 m	Rocks can be very hard, yield is from fractures	The depth of the borehole depends on the depth of the dolerite. Sufficient water bearing fractures should be intersected. Where dolerite intrusions thin – the best targets are in valleys.

In Oju and Obi, the WASU teams can carry out the first two parts of the geological triangulation. The geophysics techniques, however, are best undertaken by qualified engineers either from WaterAid or the State drilling organisation.

4.2 Hydrogeological Criteria for Selecting Sites for Boreholes or Wells

Well and borehole construction sites have to be located carefully. Geophysical surveys are carried out to locate small widespread aquifer targets. Such surveys make use of standard equipment that is commonly available throughout Nigeria: EM34-3 equipment for conductivity profiling and resistivity equipment for soundings. The only geophysics equipment that is recommended for use in Oju/Obi not in regular use in water supply projects is the magnetometer. However, with training, this equipment can be easily used. The magnetometer can be used to identify dolerite within the Awgu Shale Formation.

Table 6 gives a summary of the most appropriate survey methods for the various hydrogeological environments. Note that the EM34 is by far the most important survey tool. Resistivity sounding is generally of limited use, because it tests only a small area of the ground. As more data accrues from the siting and construction of wells and boreholes in Oju/Obi so the guidelines can be improved and refined. Geological data are required to calibrate all geophysical methods.

4.3 Choosing an Appropriate Design of Well or Borehole

There is no single technological solution for water supply problems in Oju/Obi. In some areas boreholes are the best solution, in others hand dug wells. The best technology for overcoming the hydrogeological difficulties however, may not be the most appropriate. For example, even boreholes lined with screens and gravel packs may fail to overcome the problems of running sand. Table 7 gives a summary of the most appropriate water supply option for the various rock units. Several guidelines are universally applicable:

- The tops of both wells and boreholes should be sealed through the upper soil layers, to stop contamination leaking through the soil into the well or borehole.
- Wells should be lined through the soil clay layers with reinforced concrete to prevent well collapse due to swelling clays.
- Wells and boreholes should be sufficiently deep. Water-bearing horizons are frequently found between 12 and 25m depth. Boreholes should be drilled through this zone to about 40m. Wells should be constructed to penetrate through the weathered zone into the unweathered bedrock, usually to depths greater than 15m.
- A borehole/well should be sited up gradient of and at least 50m from latrines to avoid contamination. The permeabilities of laterites have yet to be determined.

Dug well-cum-boreholes should be considered in Oju/Obi. The benefits of deep hand-dug wells over shallow boreholes are clear: hand dug wells have large reservoir capacities and community maintenance is straightforward. However, many areas require boreholes to penetrate fractures at depth. A dug well-cum-borehole combines the benefits of hand-dug wells and boreholes. After a borehole has been drilled and proved the existence of sub-artesian groundwater a dug well can be constructed around the borehole top. The resultant construction receives water flowing up the borehole into the hand dug well section that forms a large capacity reservoir. Water can be obtained either by bucket of through use of a hand pump.

In the sandstone areas, hand dug wells yield from 0.5 to 3m^3 of water a day. This yield is normally insufficient to supply the target population of 250. A higher ratio of wells to population needs to be

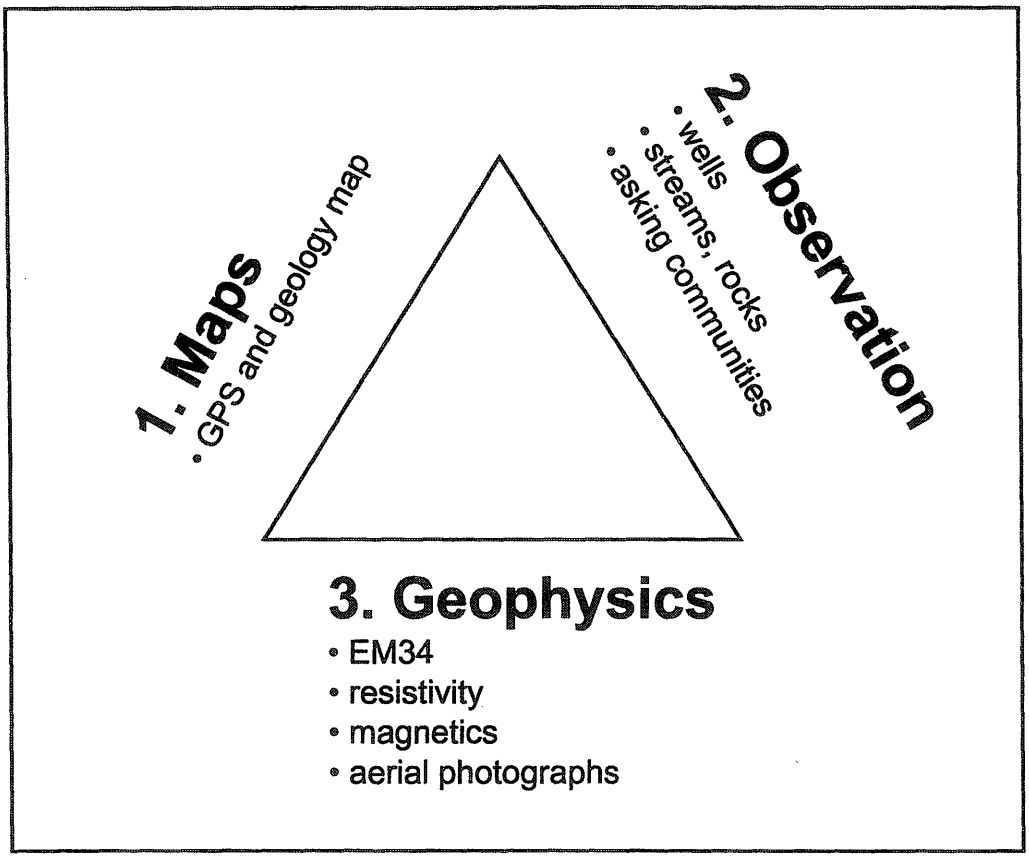


Figure 28 The geological triangulation used to site wells and boreholes at villages in Oju and Obi.

Plate 52. Amina from Obi WASU using the GPS to locate a village.

Plate 53. Aja from Oju WASU examining a rock sample as part of the "triangulation" procedure.

Plate 54. Obi WASU staff using the groundwater development map.

considered. Alternatively, higher yielding collector well systems could be constructed. Such systems employ laterals drilled into the side of hand dug wells to significantly increase the seepage area of the well allowing quicker recovery after pumping. However, collector wells are expensive and require specialised drilling equipment. Additional research into use of cheaper and more flexible equipment for the drilling of laterals is required.

5. CONCLUSIONS AND RECOMMENDATIONS

The sediments in the Benue Trough are complex and highly variable. Some have been lithified and metamorphosed, others are soft and unconsolidated. However, despite the complexity and high variability the following statements are true for Oju/Obi:

- Developable groundwater resources exist in most parts of Oju/Obi
- Targets for groundwater development include (1) fractures within the harder metamorphosed Asu River group mudstones in the south of the area; (2) fractured sandstones such as those of the Makurdi Sandstone and Agbani Sandstone Formations; (3) fracture zones within siltstone/mudstone/limestone complexes of the Eze-Aku Group; and (4) dolerite intrusions and adjacent baked zones, mainly in the north of the area.
- The Awgu Shale Formation area in Obi has negligible potential for groundwater development
- Both hand dug wells and boreholes are required to best exploit the groundwater resources of Oju and Obi.
- The geology of an area must be known prior to drilling or digging wells - the geological triangulation method can be used to help predict the geology.
- In most of Oju/Obi standard geophysical techniques should be used to locate potential groundwater targets, using newly developed methods of interpretation. EM34-3 has proved the most useful technique.

Although the WASU teams can undertake much of the work of locating potential groundwater targets and constructing wells (Plate 54), specialised expertise is required in interpreting geophysical surveys and drilling boreholes. The WaterAid Engineer and BERWASSA have received training in geophysics, however, further training and technical support are likely to be required due to the complexity of the area.

BGS studies have concentrated on a north-south traverse through the central part of the Oju/Obi area. The results of these studies can be applied to most of the rock units found in the area. The studies were not exhaustive and several areas require testing to provide a more complete picture of the groundwater potential of Oju/Obi. Figure 29 shows the present degree of uncertainty of hydrogeological knowledge. The guidelines developed in this document are most appropriate for the inner zone of confidence, but could probably be extrapolated to the second zone without a large reduction of success. The inner zone contains 154 villages (approximate population: 130 000) and the combined inner and second zone, 256 villages (approximate population: 220 000). This leaves 84 villages (approximately 75 000) where the guidelines may not be applicable. However, although the number of villages outside the scope of the guidelines are relatively few, they may command a higher priority since they are far from good roads and on the margins of the local government areas.

The following knowledge gaps remain within Oju and Obi:

- The sustainability of groundwater supplies from the Oju/Obi area. Long term monitoring of groundwater levels and borehole/well yields throughout the area; long term pumping tests or groundwater age determination could help to estimate sustainability.
- The groundwater development potential of the eastern quarter of Oju, where the Asu River Group is less metamorphosed and potentially contains less groundwater, has yet to be assessed.

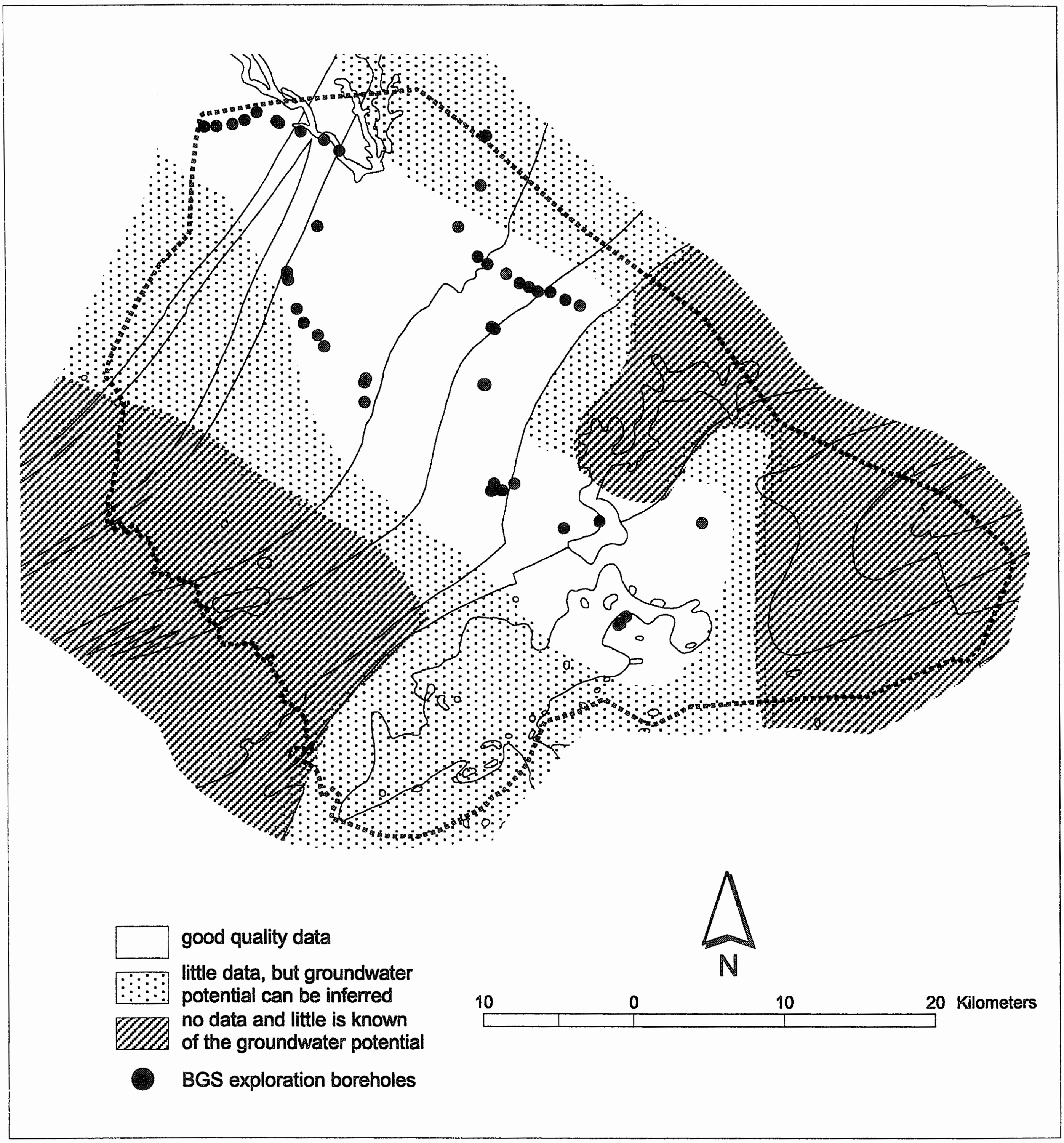


Figure 29 Uncertainty of hydrogeological information for Oju and Obi.

- The far west of Oju where the Makurdi Sandstone probably becomes finer grained and therefore has a lower potential for groundwater development.
- The high permeability of the shallow laterite layers and thus potential of contamination of wells with effluent from pit latrines via the laterite layers.
- Since the yields from many of the hand dug wells may be low, research into low technology methods for constructing laterals in the wells and upgrading them to collector wells would be appropriate.

The Awgu Shale Formation mudstones in Obi remain the most difficult formation from which to obtain groundwater. The only possibilities for groundwater in these areas are from dolerite intrusions or thin sandy horizons within the weathered zone. Dolerite can give high yields, but may be located far from villages. The thin sandy horizons appear common (especially in Itogo) but contain little groundwater – possibly only enough for 10-30 basins per day (300-900 l/day).

This study provides the first detailed insight into the complex hydrogeological and geological environments present in Oju and Obi. As production drilling and well digging is undertaken, much additional information on the groundwater potential of the area could be gained by collecting relevant data (e.g. chip samples, transmissivity from bailer tests, geophysics surveys). As these data become available, the guidelines and maps can easily be updated, as the project continues, further enhancing the chance of developing successful water sources.

The geology underlying much of Benue State, and adjacent states in south-eastern Nigeria, is similar to that of Oju and Obi. Prior to this study little was known about groundwater development in low permeability sediments in this region of Nigeria. At a project workshop, held with hydrogeologists from BERWASSA, UNICEF, Nigerian Geological Survey and Nsukka University, the difficulties encountered by staff working in such geologically complex areas were highlighted. They felt that the knowledge gained from this study and the exploratory techniques developed for use in Oju and Obi could be readily be applied to other parts Benue and the adjacent states.

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APPENDIX 1

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