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LOW PERMEABILITY ROCKS IN SUB-SAHARAN AFRICA.

An assessment of the hydrogeology of the Afram Plains, Eastern Region, Ghana

Groundwater Systems and Water Quality Programme.

Internal Report CR/02/137N

BRITISH GEOLOGICAL SURVEY

INTERNAL REPORT CR/02/137N

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Key words

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Front cover

One of three low yielding boreholes drilled within 50 m of each other at Nyambekyere, Afram Plains, Ghana.

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Executive Summary

WaterAid, its partner NGOs and World Vision International are developing the limited groundwater resources of the Afram Plains area of Ghana for water supply to rural communities. Water supply borehole drilling success rates (yields > 30 l/min) in the underlying Voltaian sediments are poor, at 18-40%. The location of and data from about 370 boreholes drilled in the Afram Plains have been collated into a database to enable assessment of the hydrogeological development potential of four of the five geological units present.

Near-horizontally bedded Middle Voltaian Formation sandstones and conglomerates underlie most of the Afram Plains. These are underlain by older shales and mudstones that crop out in the southern part of the area. These ancient Lower Palaeozoic age sedimentary rocks have undergone prolonged weathering, diagenesis and low-grade metamorphism; the effects of tectonic activity being limited to folding along the eastern margin of the area. The sandstones and conglomerates are generally massive and poorly jointed, and groundwater flow occurs in thin weathered zones, coarser sediment layers and a few fracture zones.

Two British Geological Survey (BGS) hydrogeologists supervised the installation and testing of 4 deep exploration boreholes and six production boreholes during April-May 2001. The data gathered during this drilling programme are used with information from the database to assess the groundwater resources of the Afram Plains. The BGS hydrogeologists worked with Afram Plains Development Organisation (APDO) and Technic-Eau staff and Legon University MSc students during the drilling and testing programme. The relationship of rock out-crops to topographic features; the selection of drilling sites using geological, geomorphologic and geophysical criteria; the use of simple test pumping methods, using bailers and low capacity Whale pumps; and the collection of rock and water samples during drilling and test pumping, were demonstrated to and discussed with APDO, university and consultant staff. Borehole design was also discussed according to Community Water and Sanitation Division guidelines.

APDO and Technic-Eau staff appreciate the need to collect adequate data during borehole drilling, testing and subsequent community use. The APDO are accurately locating villages and boreholes using hand held Global Positioning Systems and 1:50 000 scale base maps provided by the project. The need for improved collection of hydrogeological and related data to improve understanding of the nature of the aquifers present and the groundwater resources they contain was successfully demonstrated to stakeholders. These data allow improved selection of drilling sites and appropriate water supply technologies.

Recently, a number of boreholes drilled into the feldspathic sandstone unit have failed to produce adequate quantities of water after several years of use. Due to a lack of understanding of groundwater occurrence in this formation, numerous replacement boreholes, sometimes up to three at a site, have been drilled adjacent to an original borehole. These have also failed after several years of use. This study seeks to explain the cause to these and other problems and suggest methods to enable NGOs operating in the Afram Plains to overcome them.

1 Introduction

1.1 BACKGROUND

The Afram Plains area is located in the Eastern Region of Ghana, in the Volta River basin between latitude 6°30' and 7°30'N and longitude 1°00'W and 0°15'E (Figure 1). The area is about 4 285 km^2 in extent and lies between lake water level at 76 m and 300 m above mean sea level, bounded to the north by the Obosum River, to the south and south-west by the Afram River and to the east by the Volta Lake (Figure 2). The main topographic feature is a north-east to south-west trending ridge 200-300 m high, composed of sandstone in the west and conglomerate in the east. Along this ridge valleys are generally narrow and incised to a depth of 60 m or more in the east, and broader and shallower in the west. South of the ridge soft shales underlie the flat lakeside plain.

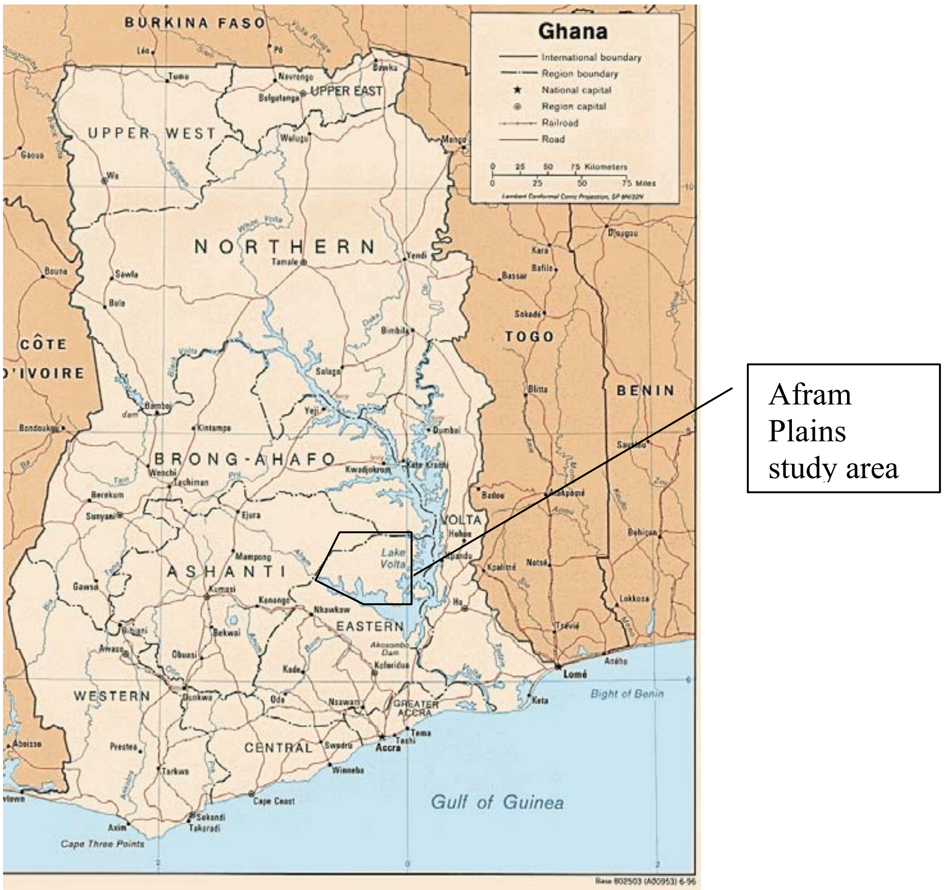

Figure 1 Afram Plains study area

Settlement of the Afram Plains area, originally designated a hunting area, began in 1930. During construction of the Akosombo Dam in the 1960s, the Volta River Authority drilled several boreholes for provision of water to main villages such as Donkorkrom and Forifori. The rural population of the Afram Plains increased rapidly during the following period. According to 1970 and 1984 census figures immigration of farmers, attracted by fertile soils and improving infrastructure, resulted in a 250% increase in population. By 1998 the Afram Plains Development Organisation (APDO) assessed the population to be 110 000. The APDO has accurately located 140 villages, using hand held global positioning systems (GPS), on the Afram Plains. The Afram Plains is divided into six administrative zones: Donkorkrom, Forifori, Kwasi Fante, Maame Krobo, Samanhyia, and Tease. Access to the Afram Plains is by ferry, across the

Afram River to Ekyiamanfurom and across the Volta Lake from Kpandu. An all-weather dirt road connects the two ferry points with the main centres of Tease and Donkorkrom, where hospitals, schools and telecommunication centres are found. Access to the western area is by poor feeder roads and bush tracks, often impassable during the wet season.

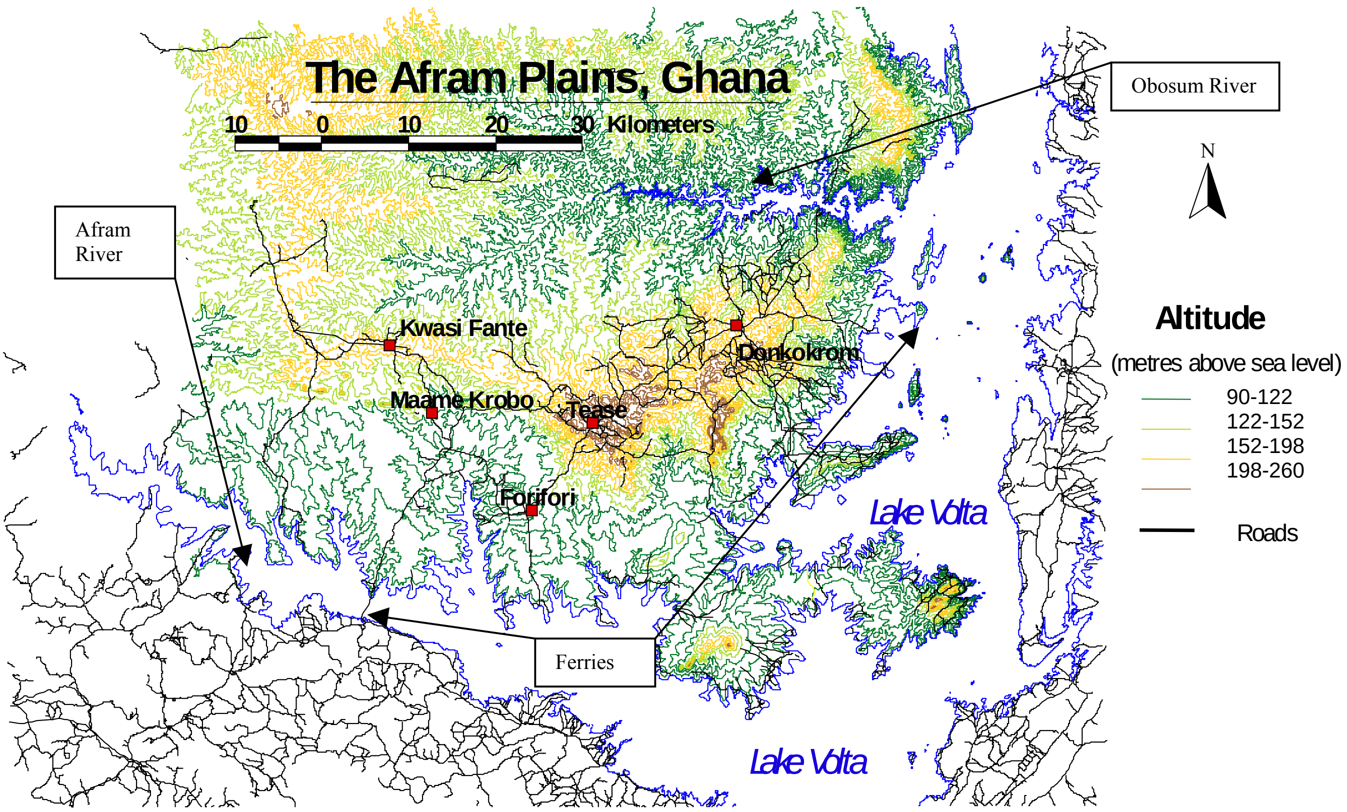

Figure 2 Contour map of the Afram Plains area showing the location of main villages.

The Afram Plains support typical savannah vegetation. The low-lying lakeside plain is covered by coarse tussock-grass with a few stunted trees. The better-drained ridge area supports dense bush with large trees that are being progressively cleared for agricultural use. Yams and charcoal are the main products exported from the area.

Late Precambrian to Ordovician age sandstones, conglomerates, siltstones and shales of the Upper Middle Voltaian Formation Obosum Beds, deposited within the southern Voltaian Basin, underlie the Afram Plains. Since deposition these sediments have been tectonically stable for the most part, only those sediments located along the eastern margin of the Voltaian Basin have been subjected to north-south striking folding. Away from this fold belt the sediments are reported to be flat lying with no igneous intrusions and few large faults. Thin well-drained sandy soils cap the sandstones and conglomerates of the east-west ridge. A thin ferricrete duricrust caps well-cemented feldspathic sandstones to the west. To the south the basal shales are overlain by fairly thick poorly drained black cotton clayey soils.

1.2 THE WATER SUPPLY PROBLEM IN THE AFRAM PLAINS

Before construction of the Akosombo Dam, village water supplies were obtained from the perennial Afram and Volta Rivers, seasonal flows and pools along ephemeral tributary streams and shallow water filled dugouts. Development of the groundwater resources of the Voltaian sediments of the area began in 1963-65 when the Geological Survey of Ghana and the Volta River Authority (VRA) drilled a series of test and production boreholes. During the late 1960s and early 1970s the Catholic Church funded the construction of 28 hand-dug wells to supply small villages. These were mainly located in valley sites to replace unprotected shallow dugout sources. Additional boreholes were installed by the VRA at Donkorkrom and Kaklakoklope (for Mimkyemfere) in 1983/84. UNICEF funded the drilling of a borehole for the secondary school at Donkorkrom in 1983. During 1984, Prakla Seismos drilled 47 boreholes at villages around Tease, Forifori and Donkorkrom for the German NGO MISEREOR. Of these, 19 boreholes were dry and 17 had yields greater than 30 ℓ min^{-1}.

During the 1990s, World Vision and APDO drilled more than 300 boreholes to meet the water supply needs of the expanding communities. A large proportion of the boreholes drilled were dry while other nominally successful boreholes show a progressive decline in yield, especially in the west. The borehole drilling programmes are listed in Table 1. Left click on the respective organisation name to obtain details of the drilling programme. Within the larger villages of Donkorkrom and Tease boreholes designed to supply the needs of up to 250 persons now supply many more. The resulting overuse causes frequent mechanical failure of pumps. Due to their short period of land tenure, communities have yet to develop coping strategies to manage the limited water available during dry periods. Since people have been attracted to the area by the groundwater supply, there are as yet no effective alternative sources when borehole yields fail after several years of use other than the drilling of replacement boreholes at already developed sites. Dry season water sources include boreholes, shallow wells, seasonal streams and lake water. Although the Volta Lake forms the eastern boundary of the area the underlying low permeability aquifer is the main source of water especially in the more remote western area.

Organisation	**Period**	**No. of Bhs**	**Wet Bhs**	**Dry Bhs**
Ghana Water and Sewerage Corporation (GWSC) for the Volta River Authority. Data from Bannerman 1990	1963-65	10	6	4
Prakla Seismos 1984 for MISEREOR (West German Catholic Charity). Data from Buckley 1986, Bannerman 1990	1984	47	28	19
World Vision International	1990-95	152	92	60
World Vision International	1999	30		
World Vision International	2000	36	?	?
WaterAid/APDO	1996	30	25	5
WaterAid/APDO	1997	20	10	10
WaterAid/APDO	1998	18	10	8
WaterAid/APDO	2000	28	17	11
WaterAid/APDO	2001	8	5	3
DANIDA exploration boreholes	2001	5	5	
Totals		384	198	120

Table 1 Water supply and investigation boreholes drilled in the Afram Plains

The groundwater resource is dependent upon rock mass permeability; a combination of primary intergranular and secondary fracture flow permeabilities. In the Afram Plains, diagenetic alteration of the Lower Palaeozoic age sediments has formed tight sandstones, well cemented with iron and manganese oxides and compacted by low grade burial metamorphism. Due to the tectonic stability of the area, the rocks appear to have been little affected by faulting and jointing, as determined from examination of outcrops and interpretation of landsat images and aerial photography. Only in the east of the area are north-south striking folds apparent. Development of secondary permeability within such a tight formation has mainly resulted from deep weathering within the present and former zones of water table fluctuation, related to local basin drainage base-flow levels and associated palaeo-climate systems. These are manifested by the development of pseudo-karst micro-fracture systems and weathering along discontinuities between dissimilar granular lithological layers. Long-term topographic stability is indicated by the presence of a thin ferricrete duricrust-capping layer that mantles much of the western half of the area. This surface layer appears to impede active recharge of wet-season rainwater to the underlying rock formations. These factors indicate that limited and difficult to define groundwater bearing targets are likely to be present for development. In the eastern half of the area where the duricrust is absent due to active surface erosion, rapid recharge of rainwater can occur.

1.3 THE PROJECT

In sub-Saharan Africa effective groundwater development often provides the best solution to rural community water supply problems. Where sufficient groundwater resources are available, traditional hand dug wells are constructed to exploit shallower groundwater and boreholes, constructed using more sophisticated technology, are used to exploit deeper groundwater. Both abstraction systems are reliable and easy to maintain at community level if appropriate training and mechanical support are provided AND sufficient renewable groundwater resources are present. Untreated groundwater is usually of good quality and safer for domestic use than traditional pond and stream surface water sources. Alternative water supplies, such as piped water from rivers or dams, or rainwater collection systems, can be considerably more expensive and difficult to manage, especially in areas prone to seasonal drought. However, in areas underlain by low permeability rocks with limited groundwater resources the above factors cannot be assured, as experienced in the Afram Plains. Groundwater use can help reduce health problems associated with unprotected surface water sources such as malaria, cholera and guinea worm, the last being periodically brought into the area by immigrants from affected areas in northern Ghana.

The British Geological Survey (BGS) has much experience in the investigation of the groundwater resources of geologically complex areas of rural sub Saharan Africa. The Department for International Development (DFID) funded a BGS 1996-99 study of the groundwater development potential of the Oju/Obi area of Nigeria. There, development was hampered by a lack of understanding of the geology and groundwater occurrence in the area as well as incorrect application of geophysical siting techniques by State level hydrogeologists. The project developed standard methods for locating and assessing groundwater resources, and the siting and testing of wells and boreholes, in areas underlain by low permeability rocks (Davies and MacDonald, 1999). Since 1998 a separate project (DFID KaR R7353) has built on the work done in Nigeria to investigate the groundwater resources of areas with low permeability geology in Zambia, Ethiopia, Ghana and Tanzania. This project has been informed by the problems faced by WaterAid when trying to develop groundwater sources during its rural water supply programmes. In 1999, short visits of 1 to 2 weeks were made to ongoing WaterAid projects in each of these countries to carry out rapid assessments of groundwater resource potential and make recommendations for groundwater development. In 2000-2001, longer visits of 6 weeks were made to the Tabora Region, Tanzania and the Afram Plains, Ghana, to carry out more detailed investigations and demonstrate the use of appropriate hydrogeological techniques for locating, assessing and developing groundwater resources.

This report describes the visit to the Afram Plains Region, Ghana by two BGS hydrogeologists during April-May 2001 (Appendix 1). This phase of the project coincided with borehole drilling undertaken as part of the ongoing WaterAid led village water supply and sanitation programme located in the Afram Plains. Techniques used for groundwater assessment and development in the field were demonstrated to staff from WaterAid, the Afram Plains Development Organization (APDO), the drilling/siting consultants Technic-Eau and students from the University of Ghana, Legon. The work included geophysical surveying and hydrogeological data acquisition at a series of exploration (drilled for DANIDA) and production boreholes (drilled for WaterAid and APDO), and water abstraction sites. The siting and drilling contractors, Technic-Eau, drilled 5 exploration and ten production boreholes during April-May 2001. Additional data were collected from previous drilling programmes. This report, with an accompanying groundwater resource map and database on a CD-ROM, is a practical example of an appropriate assessment and development programme for rural groundwater supply, presenting new hydrogeological data collected in the field and existing data collated from other sources. The raw data are held on the accompanying CD-ROM in updateable spreadsheets. The techniques used and initial results from the work were presented at a seminar in Tease to APDO staff and to WaterAid and DANIDA representatives in Accra in May 2001. The contents of this report and associated database were presented and discussed at a series of seminars held in Accra and Tease during March 2002 (Davies, 2002).

An associated manual designed for field use provides detailed practical instruction in the hydrogeological survey techniques applied in Ghana and described briefly in this report (MacDonald, Davies and Ó Dochartaigh, 2002). Hypertext links have been inserted in this summary report (in blue, underlined font) to link text with data files held on the CD-ROM. Readers who need to see more detail should (left) click on these links on-screen to access this information. The data files include diagrams, text and tables in Microsoft Word, charts and spreadsheets in Microsoft Excel, and photographs in JPEG formats based on the Windows 2000 operating system. Users of this report are encouraged to download these files and use them for report preparation, data entry and GIS inputs.

1.4 SUMMARY

The Afram Plains is a remote part of Ghana's Eastern Region with a population of approximately 110,000. There are severe water shortages during the 4 to 5 month dry season. The hydrogeology of the area is complex with widespread low permeability rocks. Although groundwater can be found in quantities that warrant the equipage of boreholes with hand pumps for village supply the groundwater resource and its sustainability is difficult to assess given the present database and level of knowledge. Communities that have become reliant upon groundwater as their main source of water during the dry season experience difficulty when groundwater yields diminish, often rapidly, after 2-3 years of use, necessitating the drilling of replacement boreholes.

2 BGS Investigation Framework

This section describes the BGS programme of work undertaken in Ghana and outlines the methods, processes and techniques used to investigate the groundwater potential of the Afram Plains. Details of the methods listed below are given in the associated manual (Macdonald, Davies and Ó Dochartaigh, 2001). The aim is to provide a flavour of the research without getting lost in detail. The data collected during new field studies and collected from other sources are summarised in section 2.9.

2.1 PRELIMINARY WORK

The organisations listed below are associated with groundwater development in the Afram Plains. Those visited by the BGS team are listed in Appendix 2. Left click on the name of an organisation for a brief description and contact details.

- Afram Plains Development Organisation
- Community Water Supply and Sanitation Division
- DANIDA
- Department for International Development, UK
- Geology Department, Legon University, Accra
- Geological Survey Department
- Land Survey Department
- Pronet
- Technic-Eau
- WaterAid
- Water Commission
- Water Resources Research Institute
- World Vision International
- Geomechanik

2.1.1 Literature Review

A desk study of maps, reports and data collected in Ghana and the UK was undertaken. The database produced provided information used to locate exploration-drilling sites and place the hydrogeology of the Afram Plains within a regional context. Left click on bibliography to access the annotated list of literature on the attached CD ROM. This material describes aspects of:

- The geology and hydrogeology of Ghana
- The geology and hydrogeology of low permeability rocks, such as compacted sediments and basement complex rocks and the nature of tropical soils
- The use of remotely sensed data and geophysical methods for locating structures likely to contain groundwater
- Background material on rainfall, rivers and other geographic aspects of south-eastern Ghana

1:50,000 scale topographic maps (in paper and digital formats) of the Afram Plains area produced in 1974 and older maps of the area prior to the construction of the Akosombo Dam were obtained from the Survey Department. Detailed geological maps of the Afram Plains are not available. A national geological map at 1:1,000,000 scale was obtained from the Geological Survey Department. Left click on maps to obtain a list of sheets obtained.

A cloud free digital Landsat TM satellite image (LANDSAT ETM 193-055, bands 1-4-8, visible, infra red and panchromatic), taken on 4 February 2000 was obtained for project use. This image is of hazy quality due to smoke from numerous bush fires at the time of photography. Left click on image to view the Landsat image.

2.1.2 Creating a base map

A base map of the Afram Plains area was created in ArcView GIS by using layered data derived from:

- Topographic contours from digital data
- Roads tracks and rivers from digital map data and Global Positioning System (GPS) data

- Geological boundaries from the national geological map
- Village locations determined in the field using a hand held GPS unit by APDO staff or derived from 1:50 000 scale topographic maps
- Borehole locations determined in the field using a hand held GPS unit or derived from report maps
- Hydrochemical sampling points determined in the field using a hand held GPS unit or derived from report maps

The digitised layers of information derived from maps, images and data sets of the Afram Plains area were combined using ArcView - a Geographical Information System (GIS) – to produce a series of maps of the Afram Plains. Left click on Afram Plains maps to view a series of maps produced in Microsoft Power Point format. These maps can be upgraded as additional data becomes available. GIS allows map data to be modified or analysed and permits maps to be updated cheaply or tailored to the needs of different users. However, since the use of ArcView requires specialist software, training and sufficient computer capacity its use should be undertaken by national institutions. Maps produced at 1:100 000 scale are accurate to about 200 m. A gazetteer of village names with GPS derived locations is being compiled by APDO for local use. Left click on gazetteer to view the village list.

2.1.3 Reconnaissance Surveys

An earlier visit made by a BGS hydrogeologist to the Afram Plains during February-March 2000 produced brief descriptions of the main rock units of the area seen at outcrop (Davies, 2000). In addition siting and drilling methods practiced by local contractors were observed and simple methods of data collection during borehole drilling and testing were demonstrated to APDO staff members in the field. Data held on borehole completion certificates from earlier drilling programmes undertaken by Geomechanik for WaterAid were collected.

2.2 PRODUCTION AND EXPLORATION BOREHOLE DRILL SITE SELECTION.

A community is required to undertake APDO-led water-hygiene awareness training before three provisional borehole-drilling sites are selected by an APDO team, in consultation with the community. During the 2001 drilling programme, a Technic-Eau geophysicist evaluated the proposed borehole-drilling sites at eight villages using electro-magnetic (EM34) and vertical electrical sounding (VES) geophysical surveys (Technic-Eau, 2002). Each community was required to cut access cutlines for survey purposes, normal to lineations indicated by vegetation and stream trends. Unfortunately, the geophysicist did not use aerial photography, topographic maps, Landsat image interpretation or GPS to accurately locate survey lines and drilling targets because he was concerned with the raw data being used by others.

BGS hydrogeologists located five sites for the drilling of DANIDA funded exploration boreholes, to investigate the hydrogeological potential of the main rock types crossed by the all weather road between Forifori and Donkorkrom. Each site was confirmed by APDO following consultations with the local community leaders to whom the purpose of the drilling exercise was explained.

Geomechanik (for APDO) and World Vision International (WVI) initially used geophysical survey methods to locate borehole-drilling sites. A wet borehole drilling success rate of 60% was achieved, at a minimum yield of 12 $\ell.min^{-1}$, prompting the location of further sites without time consuming geophysical surveys. With the aim of improving the drilling success rate, the Desert Research Institute (DRI) developed methods of initial site selection based on fracture lineaments interpreted from the analysis of remotely sensed Landsat TM imagery (Minor et al, 1995). The fracture lineaments were then located in the field using GPS and investigated using geophysical survey methods. The DRI claimed some increase in drilling success rate. However, both Geomechanik and World Vision teams continue to locate borehole-drilling sites using brief terrain surveys, based on topography and vegetation, of areas adjacent to target communities. Neither used topographic maps, aerial photography or GPS to locate village or borehole sites. The lack of accurate site location seriously limits the usefulness of data derived from survey and drilling programmes. Ideally site selection should be undertaken according to the methods listed below.

2.3 GEOLOGICAL SURVEYS

Simple geological surveys to identify the main rock types in an area can be undertaken using basic equipment. This includes 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. Digitally scanned photographs of rock chip samples, road cuttings and surface exposures examined by BGS hydrogeologists in the Afram Plains are stored on the accompanying CD-ROM.

2.4 GEOPHYSICAL SURVEY METHODS

In sub-Saharan Africa, two geophysical survey methods; frequency domain electromagnetic induction (EM34) (Plate 1); and vertical electrical resistivity sounding (VES) (Plate 2), are commonly used for siting boreholes by providing information for the identification of groundwater bearing targets in sub-Saharan Africa (McNeill, 1987). These methods are described in the manual and field sheets.

Plate 2 EM34 equipment in operation

Plate 1 ABEM Terrameter electrical resistivity equipment in operation

Although both survey methods are widely used for siting boreholes in crystalline basement areas in sub-Saharan Africa, methods for the interpretation of data derived from other rock formations are not well understood. The DRI advised WVI to use these methods to locate lineaments identified from Landsat TM images for location of borehole drilling sites. Only limited additional drilling rate success was achieved using this procedure in the Afram Plains.

The BGS team undertook 11 km of EM34 surveys at the first four DANIDA funded exploration borehole sites, using 10 m, 20 m and 40 m inter-coil separations; readings were made in both vertical and horizontal orientations (Table 2). The vertical coil readings gave information about the shallow weathered zone, while the horizontal coils penetrated deeper, being used to locate fracture zones. The survey results were correlated with the geological logs from the exploration boreholes. The results obtained are discussed in section 3.

Table 2 Summary of EM34 geophysical traverses conducted by BGS.

[Left click on village name for survey details and interpretation]

Village	Survey length	Date	Site Geology
Samanhyia	2.7 km	25/04/2001	Sandstones and conglomerates
Tease	3.0 km	26/04/2001	Sandstones and mudstones
Forifori	2.34 km	27/04/2001	Shales and fine-grained sandstones
Gazeri Camp	3.00 km	03/05/2001	Shales and fine-grained sandstones

A team from the University of Ghana, Legon undertook geophysical surveys using EM and resistivity equipment along the main road in the eastern Afram Plains, the results being presented in Banoeng-Yakubo and Armah (2001). EM34 and VES surveys of production borehole drilling sites were conducted by Technic-Eau (Technic-Eau 2001).

To date the application of geophysical surveying methods to groundwater studies in the Afram Plains has produced mixed results. In the western half of the area re-cemented sandstones up to 60 m thick form a low permeability homogeneous layer below an ancient weathered surface. Thin water bearing fracture or weathered zones beneath this layer cannot be detected using EM34 or VES equipment. In the eastern half of the area EM34 traversing can be used to differentiate between near surface sandstone, shale and conglomerate layers and location of vertical fracture zones. The resistivity (VES) method can be used to define these lithologies with depth and determine the approximate depth of weathering.

2.5 DRILLING PROGRAMME

The methods used to drill, construct and develop boreholes in low permeability rocks, and methods of data acquisition during drilling are described in the associated manual. Left click borehole drilling to access a synopsis of these methods.

Technic Eau were contracted to drill the production boreholes for APDO and the exploration boreholes for DANIDA during the 2001 field season. Each drilling site was accurately located using a GPS system. Borehole drilling is a dry season activity as access to drill sites remote from all weather roads becomes difficult with the onset of the rainy season. The drilling programme had two elements:

- *Exploration boreholes (DANIDA)* - Five deep (to 150 m) exploration boreholes were drilled by Technic-Eau for DANIDA. BGS hydrogeologists supervised the drilling of the first four of these boreholes and logged the rock chip samples obtained (Table 3).
- *Production boreholes (APDO/WaterAid)* – BGS hydrogeologists observed the drilling of six of the ten production boreholes installed by Technic-Eau. APDO regard boreholes yielding more than 7 l min^{-1} as successful (Table 4).

Table 3 Summary of DANIDA exploration borehole data

[Left click on Location name for detailed geological log and test pumping results]

Bh sites visited			Yield	Latitude (N)		Longitude (W)		
No	Location	Depth	ℓ.min^{-1}	Deg	Min	Deg	Min	Geology
1	Samanhyia	121.9 m	400	6	59.991	0	9.868	Conglomerate above grey fine sandstone
2	Tease APDO	152.4 m	130	6	56.121	0	14.997	Brown to grey fine sandstone
3	Forifori	104.4 m	>1500	6	50.175	0	19.236	Grey siltstone and shales
4	Gazeri Camp	152.4 m	133	6	45.537	0	19.022	Grey shale
5	Adufokrom	152 m	400	7	2.297	0	6.816	Sandstone and conglomerate

Table 4 Summary information from APDO/WaterAid production boreholes.

[Left click on borehole location for detailed geological log]

Bh sites visited			Yield	Latitude (N)		Longitude (W)		
No	Location	Depth	ℓ.min^{-1}	Deg	Min	Deg	Min	Geology
1	Nyambekyere S3-F1	54m	15.6	7	4.839	0	36.186	Orange brown and black sandstone
2	Nsareye F1-F1	41m	15	7	01.308	0	35.192	Orange brown and black sandstone
3	Bongkrom, P2	62m	Dry	6	58.298	0	34.422	Orange brown and black sandstone
4	Bonkrom P1	31m	15.6	6	58.333	0	34.548	Orange brown and black sandstone
5	Bonkrom F3	37.5m	140	6	57.953	0	34.087	Grey shale
6	Dartekrom	86.5m	Dry					Quartzitic sandstones
7	Tease APDO	54.9m	60					Dark brown sandstone
8	Isaac Akura	80.0m	Dry					Brown sandstones
9	Amankwak Tornu	61.70m	30					Grey shale
10	Somsei	80.0m	Dry					Brown sandstone

Technic-Eau mobilised two truck mounted drilling rigs with support vehicles to the Afram Plains.

- An Ingersolll Rand T4W drilling rig, mounted on a 6x6 truck, has a drilling capacity of 300 m at 6 inch (150 mm) diameter. The 825 cfm/350 psi compressor is truck mounted with the rig.
- An Ingersolll Rand TH60 drilling rig, mounted on a 6x4 truck chassis, has a drilling capacity of 200 m at 6 inch (150 mm) diameter. The 825 cfm/350 psi compressor is truck mounted with the rig (Plate 3).

- Two 6x4 International Harvester trucks were used as support vehicles carrying water and fuel tanks, casing, screen, temporary steel casing, drilling bits, gravel pack material and drilling rods.

Plate 3 The Ingersoll Rand TH60 drilling rig at the Samanhyia exploration borehole site.

2.5.1 Drilling and rock chip sampling methods

During drilling, the soft near-surface weathered rock was drilled with a $9^7/_8$ inch (250 mm) tricone rock roller bit. This formation was cased with temporary 8 inch (203 mm) diameter flush joint steel pipe. Hard rock formations were drilled using a high pressure down the hole hammer with a $6^1/_2$ inch (155 mm) diameter button bit. Water injection during drilling reduced rock dust production without hindering recognition of water strike zones. Production boreholes were usually drilled to 50 m, but were halted at shallower depth when the yield was sufficient, or deepened when still dry at 50 m. The dry boreholes were backfilled after drilling. Borehole drilling usually took two days at each site.

Parameters recorded during the drilling are described in the manual. Those recorded at boreholes drilled during the study included:

- *Penetration rate logs*. The times taken to drill 1 m intervals were recorded.
- *Rock Chip samples.* Rock chip samples were collected at 1 m intervals during drilling and stored on a cleared area adjacent to the rig. Washed rock chip samples were geologically logged by noting colour, grain size, relative hardness, and the presence of calcareous material. For some of the boreholes, representative chip samples, placed in sequence within a core-box, were photographed to record changes in colour and lithology with depth. Left click on Bongkrom F3 to view an example of a pseudo-core with detailed lithological description. Note the blocky fragments at the water struck level at 23.4m and the red discolouration of the water producing weathered zone at 23.4-30.5 m.

Samples that could not be geologically logged on site were bagged and stored at the APDO office for future analysis.

- ***Drilling Yield.*** The rates of flow of water blown to the surface during down-the-hole hammer drilling were measured to determine the first water strike level, subsequent water strike levels and borehole yield at the end of each drilled rod length. These determinations are noted within the detailed geological logs of the producing boreholes.

2.5.2 Borehole design, construction and development.

Boreholes were constructed using 5 inch (125 mm) ID flush joint PVC pipe with 1mm slot screen placed against water bearing zones. On withdrawal of the 8 inch steel temporary casing coarse-grained sand pack was placed in the borehole as a formation stabiliser. The borehole was cleaned and developed by surging with compressed air.

2.6 TEST PUMPING

In the Afram Plains each production and exploration boreholes was test pumped by Technic-Eau using a Grundfos electrical submersible pump to determine borehole specific capacity as well as aquifer transmissivity and storage coefficient. BGS project staff demonstrated alternative, simple, cost effective systems for the test pumping of low yielding boreholes in low permeability rocks. These systems and interpretation of the data collected are described in the manual.

- *Bailer tests* - Four bail tests were attempted to demonstrate the method to APDO staff and others. However realistic levels of drawdown could not be produced within the high yielding test boreholes.
- *Whale pumps* – The Whale Pump system was demonstrated to APDO staff during the 2000 visit at Bonkrom Bh GM69. There was insufficient time to repeat the demonstration during the 2001 study.

Plate 4 Grundfos electrical submersible pump

- *High yield testing methods* - Grundfos electrical submersible pumps (Plate 4) of various capacities were used by the contractor to test pump both the production and exploration boreholes. Production boreholes were pumped for three hours, water level draw-downs and discharge rates were recorded. The rate of water level recovery was monitored for two hours. These data were used to determine aquifer transmissivity and borehole specific capacity. The data produced were analysed using standard test pumping analyses. The results and interpretations of pumping tests for the exploratory boreholes can be accessed by left clicking with the mouse on the borehole location shown on Table 3. Similarly, the results and interpretations of pumping tests for the production boreholes drilled during 2001 can be accessed by left clicking with the mouse on the highlighted locations shown on Table 4.

2.7 HYDROCHEMISTRY

Water samples for hydrochemical analysis were obtained from 29 boreholes and wells during the 2001 visit. Hydrochemical variations can be used to indicate the nature of groundwater flow in an aquifer.

The current WHO guideline maximum values for inorganic chemicals in groundwater and comments on their occurrence in the Afram plains are shown in Table 5.

Parameter	Chemical symbol	WHO guideline maximum value (mg ℓ$^{-1}$)	Comments on occurrence in the Afram Plains
Chemicals of health significance			
Antimony	Sb	0.005 (P)	Not measured
Arsenic	As	0.01 (P)	Below detection level
Barium	Ba	0.7	Below detection level
Beryllium	Be	NAD	Below detection level
Boron	B	0.5 (P)	Problem in unfractured shale and sandstone formation
Cadmium	Cd	0.003	Below detection level
Chromium	Cr	0.05 (P)	Below detection level
Copper	Cu	2 (P)	Below detection level
Fluoride	F	1.5	One exceedance
Lead	Pb	0.01	Below detection level
Manganese	Mn	0.5 (P)	All below 4 mg ℓ$^{-1}$
Mercury	Hg	0.001	Not measured
Molybdenum	Mo	0.07	Not measured
Nickel	Ni	0.02 (P)	Below detection level
Nitrate	NO_3	50	All below 11 mg ℓ$^{-1}$, presence indicative of pollution
Selenium	Se	0.01	Not measured
Uranium	U	0.002 (P)	Not measured
Substances that may give rise to complaints by consumers			
Aluminium	Al	0.2	Few exceedances
Ammonia	NH_3	1.5	All below 0.4 mg ℓ$^{-1}$, presence indicative of pollution
Iron	Fe	0.3	Few exceedances
Potassium	K	10	All below 5 mg ℓ$^{-1}$
Sodium	Na	200	Problem in unfractured shale and sandstone formation
Zinc	Zn	3	Not a problem

Table 5 WHO guideline maximum values for inorganic chemicals in groundwater and comments on their occurrence in the Afram plains

2.7.1 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. Two filtered (by passing through a 0.45 µm membrane) acidified (with aristar grade concentrated nitric acid) and non-acidified 30 ml samples were obtained from each source. The GPS was used to locate accurately the co-ordinates of each sample site.

2.7.2 Laboratory determinations

Hydrochemical analyses of groundwater samples undertaken at BGS Wallingford determined a comprehensive suite of inorganic major, minor and trace element concentrations. Acidified filtered samples were analysed for major cations (Ca, Na, Mg, K), SO4 and selected trace elements by inductively coupled plasma optical emission spectrometry (ICP-OES). Cl, I, F, Br, NO_2-N, TON 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. Left click on BGS chemistry for results of analyses in tabular and trilinear diagram formats and a sample distribution map.

2.7.3 Isotope samples

Stable isotope analysis (δ^2H and $\delta^{18}O$) was carried out by mass spectrometry on twelve samples submitted to BGS Wallingford. The results of these determinations when plotted with the 100 determinations obtained from borehole, lake and rainwaters by the DRI plot close to the world meteoric water line. There is some evidence for the possible mixing of lake-derived waters with aquifer waters in the Forifori, Bonkrom and Donkorkrom areas. Left click on isotopes for full listings of analyses and plots of results.

Acheampong (1996) reports the results of detailed hydrochemical studies undertaken by the Desert Research Institute that include determination of inorganic constituents. Left click on DRI chemistry for a listing of analyses.

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 indicators, but little emphasis is placed upon the monitoring of the state of the groundwater resource.

Until very recently, there was no routine monitoring of water levels in the Afram Plains. Although plated-over access holes for dipper sondes have been cut in most World Vision installed India Mark II pumps, no water level data have been presented by WVI. DANIDA have fitted Diver type autographic water level recorders to the five exploration boreholes for detailed long term monitoring of water levels. Details of the Diver system and initial results obtained are presented in Davies (2002). Rainfall is monitored by the APDO at Donkorkrom and by the agricultural station at Forifori.

2.9 THE DATA

An understanding of hydrogeological conditions in the Afram Plains can only be obtained through analysis of relevant data. A number of drilling programmes and hydrogeological surveys have been undertaken in the area, as outlined above. These had in common a lack of accurate site location data. To make sense of these survey data, the current project collated them into a single Excel spreadsheet with village location data obtained using a GPS. These location data are the ‘glue’ that hold the other forms of data together and ensure the useful application of the interpreted information at all levels. Left click on Afram Plains data for the spreadsheet. APDO have been advised to field check all of these locations. Hydrogeological and related data were obtained from four sources:

1. Reports of drilling programmes undertaken by Geomechanik for WaterAid/APDO during 1996, 1997, 1998 and 2000. Left click on APDO borehole data for a full listing of boreholes, with details of construction, geological logs and water struck levels with yields. These reports contained the following data:
    - Location – usually only the village name with an occasional sketch map
    - Geology – usually a brief description of the main rock types encountered and thickness of the weathered zone

- Water strike levels and flow rates – first water strike, fracture zones and yields per zone are usually noted
- Borehole construction – drilled diameter, depths, screen and casing types, diameters and lengths
- Test pumping details – 3-step step-drawdown test followed by a short constant discharge and recovery test
- Hydrochemistry – bicarbonate ion concentrations were determined using a Hach type field kit

2. Tabulated drilling and hydrochemical data from various hydrogeological study reports (mostly WVI related). These reports contained the following:
   - Summary of geological knowledge – main geological units interpreted and approximate boundaries
   - Use of remotely sensed data – location of lineations – possible fracture zones
   - Use of geophysical methods
   - Hydrogeological data – some data per borehole with village name
   - Hydrochemical data - some data per borehole with village name
3. Detailed hydrogeological data from the DANIDA exploration boreholes, surveys conducted by BGS and production boreholes drilled and tested by Technic Eau. This data set included:
   - Detailed borehole logs with drill penetration data
   - Photo pseudo-core logs of some of the boreholes (Samanhyia and Tease)
   - Accurate GPS determined site locations
   - Detailed hydrochemical analyses
4. A set of 1:50,000 scale topographic maps and a hand held GPS were provided to the APDO and used to undertake a base line survey of sites in the Afram Plains. This survey is ongoing and has provided:
   - Village names – to remove ambiguities of sub-village names
   - Accurate village locations – lat/long data GPS derived
   - Borehole names and locations – Bhs located by lat/long and village name

These data were collated into a series of up-gradable Microsoft Excel spreadsheets that were interrogated to produce a series of information tables and borehole logs. These were produced in Microsoft Word format to form the basis of site-specific reports and Microsoft Excel spreadsheets for integration into GIS systems for the production of maps for further analysis and planning purposes. The basic outputs include:

- Bibliography
- Village gazetteer
- Geophysical survey data base (needs to be updated with data from Technic-Eau (2002)
- Composite borehole database
- Hydrochemical database

A standard set of data should be collected during each hydrogeological study or borehole-drilling programme. A checklist of basic survey elements, based upon the contents of existing data sets and BGS survey activities, includes the following:

Phase 1 – Base line survey

- Site locations
- Baseline survey
- Hydrogeological information

Phase 2 – Geophysical surveys

- Geophysical surveys
- Survey site locations

Phase 3 - Borehole drilling and construction

- Geological data
- Hydrogeological data
- Construction data
- Drill site locations

Phase 4 – Borehole test pumping

- Borehole development and test pumping data
- Water quality testing data

Phase 5 - Borehole completion

- Borehole completion details

Data collected to date are listed according to this checklist to indicate where data are still lacking. Left click on checklist for full listing.

2.10 SUMMARY

Techniques used by BGS during the hydrogeological investigations in the Afram Plains include:

1. Production of a bibliography of literature on the geology and hydrogeology of the Afram Plains.
2. Creation of a base map of the area using information from published geological and topographic maps. Villages were located in the field using a GPS and from 1:50 000 scale maps.
3. EM34 geophysical surveys were undertaken at four of the five exploration borehole sites.
4. Monitored the drilling of four of five exploration and six of ten production boreholes.
5. Penetration rates were measured and rock chip samples taken at 1 m intervals at monitored boreholes
6. Rock chip samples were geologically logged and photographed, as pseudocores
7. Demonstrated bail and Whale pump test-pumping at five borehole sites.
8. Obtained 29 groundwater samples for hydrochemical analysis from production and exploratory boreholes.
9. Compilation of a database of existing and project generated hydrogeological data.

3 The Hydrogeology of the Afram Plains

3.1 INTRODUCTION

This section discusses the results of the 2001 BGS investigations in the Afram Plains. The climate, hydrology and regional geology of the Afram Plains are briefly described. The results of hydro-geological and related studies of the lithological units identified in the Afram Plains are then described with summaries of their groundwater development potential. The section is best read in conjunction with the groundwater development map and table for the Afram Plains (Appendix 3).

3.2 CLIMATE AND HYDROLOGY

Water supply in the Afram Plains is dependent upon the seasonal rainfall distribution. Daily temperature and rainfall data are collected at the Forifori agricultural station but only an incomplete record is available at present. Earlier data include average monthly rainfall data collected at Donkorkrom before 1986 (Figure 3). These limited data show that the wettest period is April to October with December and January generally dry. The annual dry season lasts four to five months. Regional data indicate that the climate of the Afram Plains is warm to hot with temperatures reaching their peak in March just before the onset of the rainy season. Mean annual temperature is about 32˚C with a slightly cooler period from July to October. Rainfall is seasonal, the average annual rainfall of about 1200 mm falling almost entirely between April to October. During the November to March dry season the area is affected by dust laden hot Harmattan winds blowing south from the Sahara. The nearest meteorological index station to the Afram Plains is at Keta Krachi, 100 km to the north east, where monthly potential and actual evapotranspiration data are collected.

Surface drainage is mainly ephemeral; water from heavy storms drains away by sheet flow, resulting in short lived floods. No stream flow data are available. The courses of drainage channels radiating from the main east-west ridge appear to be eroded along fault and joint lines.

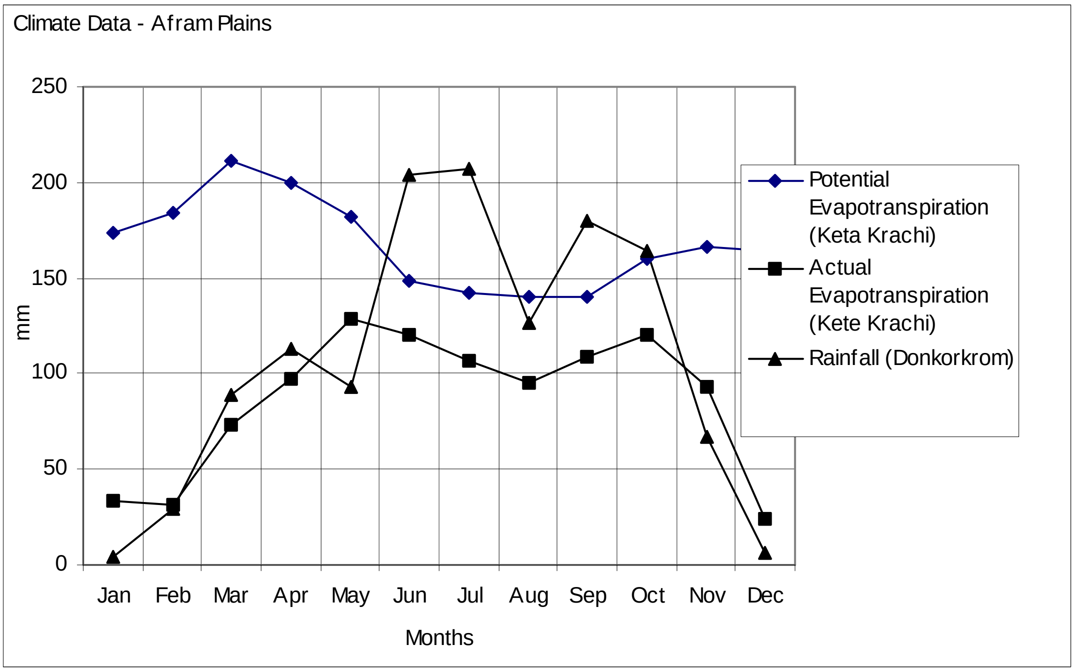

Figure 3 Afram Plains climatological data.

3.3 REGIONAL GEOLOGY

The Afram Plains are located at the southern end of the large (>100 000 km^2) Voltaian Sedimentary Basin formed during the Precambrian to early Palaeozoic Pan-African Orogeny of 730-550 Ma. (Black and Liegeois 1993, Castaing et al 1993, Grant 1967 and 1969, and Shackleton 1976). The Voltaian Basin is interpreted as a foreland basin; with sediments of marine and terrestrial origin filling a flexural depression at the margin of the West African Craton (Ako and Wellman 1985). Junner and Hirst (1946), Saunders (1970), Annan-Yorke and Cudjoe (1971), Affaton et al (1980), Kesse (1988) and Anani (1999) describe the Voltaian basin sediments as fairly flat bedded sandstones, shales, pebble beds, mudstones, limestones and siltstones deposited unconformably upon older Precambrian rocks (Table 6). The molasse type sediment pile, that is estimated to be more than 4 km thick, resulted from erosion of mountain chain fold belts that occurred along the present Ghana-Togo border to the east. Deposition of sediments under marine, non-marine continental and glacial environments have been proposed, with coarse-grained tillite deposits at various levels. The Voltaian Formation Obosum Beds that underlie much of the southern Afram Plains have yet to be studied in detail.

Table 6 Stratigraphy of the southern Voltaian Basin according to Junner and Hirst (1946)

Age	**Formation**	**Division**		To view typical geological exposures left click on highlighted unit name or rock type	**Thickness (m)**
Lower Palaeozoic	Voltaian	Upper V3	V3b	UPPER SANDSTONE Massive, cross-bedded quartz sandstone containing in places beds of shales and mudstones	213 m
			V3a	THIN BEDDED SANDSTONE Thin bedded flaggy sandstone micaceous ferruginous or feldspathic clay galls and ripple marks common	121 m
		Middle V2	V2b	OBOSUM BEDS Red, Green, purple, mauve and chocolate arkose, mudstones, conglomerate and some limestones and quartz sandstones cross-bedding common in the sandy and pebbly beds.	152 m
			V2a	OTI BEDS Arkoses, conglomeratic grits, sandstones, mudstones, shales and limestones. Nodular structures common and yellow weathering typical	243 m
Infra-Cambrian		Lower V1		BASAL SANDSTONE Quartz-sandstone and pebbly grits, grits with ripple marks and galls	61 m
Upper Proterozoic	Buem	Buem		Shale, sandstone, arkose and lava	
	Togo	Togo		Quartzite, shale and phyllite	

Junner and Hirst (1946) suggested a thickness of 2600 feet (790 m) for the Voltaian sedimentary sequence, based upon outcrop mapping. Annan-Yorke and Cudjoe (1971) reported the results of

Russian drilling studies of the Voltaian Basin sediments to the north of the Afram Plains. There, the stratigraphic mapping of the 8,500 feet (2600 m) thick series of sediment proved difficult due to a lack of fossils and lateral facies changes. Present geological knowledge has been derived from rapid reconnaissance surveys, several deep exploration boreholes and a number of shallow groundwater boreholes. Annan-Yorke and Cudjoe (1971) assigned the brick red to chocolate brown cross-bedded sandstones, gravels and conglomerates that underlie much of the Afram Plains to the Tamale Red Bed Series (about 1300 ft (400 m) thick) and Sang conglomerate. In the Afram Plains, isolated outliers of horizontally dipping Upper Massive sandstones overlie the Tamale Red Beds.

The nature of some of the rock types present in the area was examined at a series of geological exposures. Only the weathered form of the harder formations appear at outcrop, the softer sandstones and shales being masked by tropical soils and thick scrub vegetation. In such an environment where access is difficult, a large proportion of information should be derived from analysis of rock chip samples during borehole drilling. Although more than 370 water supply boreholes have been drilled throughout the area detailed geological logs have been obtained from only 14 of these, all shallow boreholes located in the western part of the region. In recognition of this problem, DANIDA funded the drilling of five exploratory boreholes and associated geophysical surveys to investigate the geology of the eastern part of the Afram Plains area. A geological map of the Afram Plains area, based upon those in Bannerman (1990) and Minor et al (1995) forms the basis of the Afram Plains groundwater development map shown in Appendix 3. This map also shows the location of the five exploration boreholes drilled for DANIDA and the distribution of the main rock types.

The nature of the main rock formations seen at exposure and in borehole samples and their special relationships are shown in an illustrated sketch geological section through the area (Appendix 4). Only rocks of the Middle Voltaian upper V2 sequence crop out sporadically through a thin mantle of sands, clays and ferricretes within the area. Brief descriptions of the main geological elements have been compiled using field observations and detailed borehole logs. The depositional environment and regional geology of each of these units are discussed in more detail in the following sections.

3.4 REGIONAL HYDROGEOLOGY AND GROUNDWATER DEVELOPMENT

Gill (1969) produced an outline of the hydrogeology of Ghana including sediments of the Voltaian basin, more recently updated by Bannerman and Allison (1991). The Geological Survey Department undertook the first study of the hydrogeology of the Afram Plains area between 1963-65 for the Volta River Authority during the construction of the Akosombo Dam. In 1984 Prakla Seismos (now Geomechanik) drilled 47 water supply boreholes for MISEROR (a West German Catholic NGO) of which 19 were dry (Bannerman, 1990). Buckley (1986) studied the hydrogeology of the Tease - Donkorkrom area for WaterAid, including the use of geophysical surveying methods for borehole siting. The APDO, formed with WaterAid support in 1986, constructed 15 hand-dug wells during 1986-1992, six of which were successful. From 1992 APDO undertook pump and borehole maintenance, and community hygiene and sanitation training. Between 1990 and 1995 the Conrad Hilton Foundation funded drilling of 152 boreholes in the Afram Plains, 92 of which produced at least 10 ℓ min^{-1} (World Vision, 1995). During 1996-1998 WaterAid in association with DfID funded drilling and construction of 68 boreholes of which 23 were dry (Geomechanik, 1996, 1997 and 1998). The Desert Research Institute studied the application of remote sensing data to borehole siting in the area (Sander 1997 and Sander et al 1997). Acheampong (1996) surveyed groundwater quality of the area. The main groundwater types are $CaNa\text{-}ClSO_4$ in the Afram mudstones and $CaNaMg\text{-}HCO_3$ within the sandstones and conglomerates. MacDonald et al (1999) assessed the hydrogeology of the Afram Plains. Davies visited the area in 2000 and observed the drilling of a series of production boreholes from which were collected geological data.

The above studies indicate that limited quantities of groundwater occur in the Obosum sandstones and conglomerates. Moderate borehole success rates were achieved in the Donkorkrom area conglomerates. Within the less permeable massive sandstones in the western ridge area, remote from the Volta Lake, reduced groundwater resources occur. These compacted sandstones are well cemented with iron and manganese oxides and therefore have low intrinsic permeabilities. There are no data describing size or density of fracture zones, nor are there data describing geological processes such as facies of sediment deposition, structure, rates of burial or rates of denudation (Acheampong, 1999). Groundwater occurrence within the Afram Shales was investigated during the current project.

Results from the World Vision 1990-1995 programme indicate that:

- the average drilling depth was 55 m although dry boreholes have been drilled to 77 m
- borehole yields of 10-960 ℓ min^{-1} were determined. Water was struck at 1-41 m with static water levels of 1-20 m.
- the aquifers are semi-confined with low primary permeability and some secondary permeability along fracture zones.

Although World Vision and Geomechanik initially used geophysical surveys to locate borehole drilling sites, the hydrogeologists of both organisations latterly sited borehole drilling sites using geomorphologic and vegetation features alone. Neither aerial photography, Landsat imagery nor 1:50,000 scale topographic maps were used for site location, nor were GPS sets used to accurately locate the sites.

Acheampong (1999) determined transmissivities of 1-71.6 m^2 day^{-1} for sandstone aquifers using data from the test pumping of 28 boreholes by Prakla Seismos during 1984. Test pumping data produced by Geomechanik, during their 1996-98 programmes, were reassessed and the results are presented below.

Based on the conclusions of Bannerman and Acheampong, a five fold hydrogeological division of the rocks of the Afram Plains can be produced:

1. Massive conglomerate and sandstone
2. Quartzitic sandstone and conglomerate
3. Feldspathic sandstone, arkose, siltstone and mudstone
4. Unfractured shale and sandstone
5. Fractured shale and grey sandstone formation

Data are available for the first four of these lithological divisions and these are briefly described below. These descriptions are based primarily upon information obtained by BGS from geological and geophysical surveying, borehole logging and testing and hydrochemical surveys supplemented with information from analysis of earlier data held in the hydrogeological data base.

3.4.1 Massive conglomerate and sandstone

3.4.1.1 Local Geology

The north-eastern Afram Plains is underlain by massive coarse-grained conglomerates, sandstones and occasional shales. Inter-bedded reddened cross-bedded sandstones and conglomerates crop out as the northern section of the ridge with deeply incised eastward trending valleys occurring along apparent fault zones, as seen between the Obosum River ferry and Donkorkrom Town. Within the eastern fold belt, coarser conglomerates crop out adjacent to the new ferry point on Volta Lake north east of Donkorkrom. Shales underlie the low-lying area west of the new ferry point. The conglomerates, reported as tillites, are composed of rounded cobbles and gravels with a fine to coarse-grained sandstone matrix deposited as out-flow fans from a glaciated highland region to the east. These sediments are seen to fine to the west (Appendix 5, Sheet 2).

The unit was further investigated in exploratory boreholes drilled at Samanhyia and Adufokrum.

- At Samanhyia gravelly conglomerate (0-15 m) occurs above medium to fine sandstone dipping to the east. The conglomerate and gravelly coarse sandstones are very weathered to 24 m, with the base of the weathered zone at 54-62 m. A well-defined fracture zone, with white vein quartz, was found at 118-121 m. Small weathered zones were found at 82-86 m and 97-99 m with water flowing from coarser layers.
- At Adufokrum a summary log shows interbedded conglomerates and sandstones weathered to 8 m and fairly weathered to 99 m. The weathered zone at 96-99 m correlates with the present lake surface. Iron pyrite was found at 94-95 m and 140-142 m in conglomerate with greenish grey sandstone matrix. Mudstones occur between 96-99 m depth.

3.4.1.2 Geophysical Investigations

EM34 geophysical surveys were undertaken by BGS at Samanhyia (2.7 km) where formation conductivities of 0-55 mmhos m^{-1} were determined using 20 m and 40 m coil separations. Three traverses were undertaken, to the east, north and west of the road junction, on the eastern side of the village. Higher formation conductivities of 10-25 mmhos m^{-1} were determined over conglomeratic sandstones and lower formation conductivities of 5-10 mmhos m^{-1} were determined over sandstones. Negative departures indicative of faulting were determined using the vertical dipoles at 20 m and 40 m spacings. Within the village, west of the road junction, high formation conductivities of 20-55 mmhos m^{-1} were determined over conglomerates using the 20 m coil separation with sharp downward departures that could be indicative of faulting, but were probably due to anthropogenic effects (power cables and steel sheet roofs).

3.4.1.3 Hydrogeology

The massive conglomerates and sandstones of this unit appear to have negligible inter-granular permeability or porosity. Exploratory drilling at Samanhyia and Adufokrum produced groundwater only in weathered and fracture zones. At Samanhyia the first water strike at 24 m, the base of a weathered gravel layer, produced 42 ℓ min^{-1}. A small amount of water was seen at the base of the weathered zone at 54-62 m. Further small inflows occurred in weathered zones below 82 m (equates with the present day lake level at 85 mbgl). The main flow of > 400 ℓ min^{-1} (a rate large enough to halt drilling), came from a fracture zone at 118-121 m. Test pumping data, from this borehole and an adjacent observation borehole, produced transmissivities of 3 to 6 m^2 day^{-1} and storage coefficient of $9x10^{-4}$. This indicates a semi-confined first water production zone at 24 m. At Adufokrum the first water bearing fractures were recorded at 7.8 m (41 ℓ min^{-1}) at the base of the very weathered zone, progressively reduced to 18 ℓ min^{-1} by 43 m. The next water inflow occurred from weathered zones at 67-68 m (92 ℓ min^{-1}) and 76-77 m (200 ℓ min^{-1}) in weathered sandstone. Most water was produced from conglomeratic sandstones in a weathered /fractured zone at 113-114 m (400 ℓ min^{-1}) (equates with the base flow level of the Volta River system, below present day lake level at 99 mbgl). Test pumping data from this borehole produced transmissivities of 4-11 m^2 day^{-1}

The data-base of other hydrogeological data from this formation indicates that of the 114 boreholes drilled, 75 boreholes were wet and 39 boreholes were dry. Borehole yields of 6-900 ℓ.min^{-1} were obtained. Water levels in 21 boreholes were shallow at 0.13-18 mbgl. Data from 21 pumping tests produced transmissivities of 0.22-198 m^2 day^{-1} (of which 19 were less than 30 m^2 day^{-1}). Hydrochemical analyses suggest the presence of good quality water with SECs of 200-

805 µS cm^{2-1} from 34 records. BGS hydrochemical analyses from 12 sites (Appendix 6, Table 6/1), showed groundwaters of $Ca-HCO_3$, $CaNaMg-HCO_3$, $CaNa-HCO_3$, $NaHCO_3$ and NaCl types indicative of mixed recently recharged and old waters. There is some aluminium; waters range from acid to alkaline, and there is detectable NH_4-N, NO_2-N and NO_3-N in some Donkorkrom boreholes, indicative of possible effluent contamination.

3.4.1.4 GENERAL HYDROGEOLOGICAL DEVELOPMENT POTENTIAL

The groundwater development potential of the Massive Conglomerate and Sandstone Formation is moderate. The rocks are generally tight with groundwater occurring in weathered and fractured zones. Limited data from boreholes at Samanhyia and Adufokrum indicate that weathered zones, occurring at and above the former base flow levels of the Volta river system, and linear fracture zones form the best targets for groundwater. Drilling should at least be to the level of the present day lake surface. Borehole yields were generally sufficient for a hand pump. The mixed recent and old groundwaters of sodium bicarbonate to sodium chloride types are indicative of limited recharge. EM34 geophysical surveys can be used to differentiate between near surface conglomerate and sandstone horizons as well as locate fracture zones. Although water quality is generally good the presence of NH_4-N, NO_2-N and NO_3-N in waters from some village centre boreholes may be indicative of contamination by effluent.

3.4.2 Quartzitic Sandstone and Conglomerate

3.4.2.1 LOCAL GEOLOGY

The central, highest part of the Afram Plains is underlain by interbedded: cross bedded yellow white and greyish purple and red quartzitic medium-grained sandstones, fine-grained sandstones, siltstones and conglomerates. The harder quartzitic sandstones cap the northeast-southwest trending ridge in the Tease area (Appendix 5, Sheet 3). These sediments have been eroded to form distinct valleys and ridges; the quartzitic sandstones and harder gravelly conglomerates forming ridges and the softer fine sandstones and siltstones being eroded to form valleys. The geological nature of this unit was investigated in exploratory Bh 2 drilled at Tease where medium grained sandstones and some shales were found above hard fine grained sandstone to siltstone. These sediments were very weathered to 40 m and fairly weathered to 86 m.

3.4.2.2 GEOPHYSICAL INVESTIGATIONS

A 1 km EM34 geophysical traverse, centred at the Tease office of APDO and run along the northeast-southwest trending main road, with 10 m, 20 m and 40 m coil separations produced formation conductivities of 3-45 mmhos m^{-1}. Low formation conductivities (3-20 mmhos m^{-1}) were determined on fine-grained sandstones and siltstones and high formation conductivities (90-45 mmhos m^{-1}) were determined on conglomeratic sandstones. These formations dip to the east. Low conductivities determined at 10 m coil separation indicate dry near surface conditions. Higher conductivities, recorded using 20 m and 40 m vertical dipole coil separations over conglomerates appear to indicate the presence of some water at depth.

3.4.2.3 HYDROGEOLOGY

The Quartzitic Sandstone and Conglomerate have poor intergranular permeability and porosity. Exploratory drilling at Tease shows the presence of groundwater in green and orange-stained weathered and fractured zones. The first water strike at 45 m, in medium sandstone with gravel at the base of a very weathered zone produced water at 16 ℓ min^{-1}. Water inflow increased to 20 ℓ min^{-1} at 90-91 m and to 60 ℓ min^{-1} at 92 m within a calcite lined fracture. At another fracture at 106 m the rate of water flow increased yield to 92 ℓ min^{-1}. Water flow further increased to 130 ℓ min^{-1} from a possible weathered zone at 134-136 m. The borehole was completed at 154 m, at a depth several metres above lake surface level. Data obtained from the test pumping of this and an adjacent observation borehole produced transmissivities of 2-7 m^2 day^{-1} and storage of $8x10^{-4}$ reduced to $6x10^{-5}$ below the first inflow zone.

The database of other hydrogeological data from this formation indicates that of the 58 boreholes drilled, 19 were wet and 39 were dry. Borehole yields of 10-480 ℓ min^{-1} were obtained. Water levels were shallow at <10 mbgl. Data from 10 pumping tests showed transmissivities of 0.35-45.2 m^2 day^{-1}, and hydrochemical analyses suggest the presence of good to poor quality water with SECs of 318-610 µS cm^{2-1} from 14 records. BGS hydrochemical analyses from six sites (Appendix 6, Table 6/2) produced groundwaters of Ca-HCO_3, CaNaMg-HCO_3, CaNa-HCO_3 and $NaHCO_3$ type, indicative of mixed recently recharged and old waters. There is some aluminium; waters range from acid to alkaline, and there is detectable NH_4-N and NO_2-N in some Tease village boreholes that is indicative of possible effluent contamination.

3.4.2.4 General hydrogeological development potential

The groundwater development potential of the Quartzitic Sandstone and Conglomerate Formation is moderate. The rocks are generally tight with groundwater occurring in discoloured weathered and veined fractured zones. Limited data from boreholes at Tease indicate that weathered zones, occurring above the former base flow levels of the Volta river system, and linear fracture zones, form the best targets for groundwater. Drilling should approach the level of the present day lake surface. Borehole yields are generally sufficient for a hand pump. Groundwaters appear to be a mixture of recent calcium bicarbonate and older sodium bicarbonate types, indicative of limited present day recharge. EM34 geophysical surveys can be used to differentiate between near surface conglomerate, sandstone and siltstone horizons as well as to show the location of fracture zones.

3.4.3 Feldspathic sandstone, arkose, siltstone and mudstone

3.4.3.1 Local Geology

The western Afram Plains is underlain by cross-bedded dark greyish purple and red brown medium to fine-grained sandstones with interbedded thin gravel bands. These crop out as a series of inselbergs, as at Abotum hill near Bonkrom, and rock platforms and low ridges west and north of Mame Krobe. These massive sandstones are commonly re-cemented with manganese and ironoxides as a duricrust to 60 m depth. At outcrop, these are compact sandstones with few joints but with some pseudokarst weathering. A water worn scarp with a concave front marks the southern edge of this unit and duricrust development. This scarp feature strikes north-eastward to the Obosum River ferry-point where conglomeratic beds crop out. Fairly soft homogeneous medium to fine grained sandstones cemented with black manganese oxides were noted in production boreholes at Bonkrom, Nsareye, Nyamekyere and Issac. Soft weathered sandstones occur down to 11 to 30 m in these boreholes. Few quartz veins indicative of fractures were found. The re-cemented sandstone duricrust may be an old African laterised surface. (Appendix 5, Sheet 4)

3.4.3.2 Geophysical Investigations

Although EM34 and VES surveys were carried out by a Technic-Eau geophysicist in this area, the 60 m thick re-cemented weathered zone masks the presence of fracture zones. These methods cannot be used effectively to locate fracture and micro-weathered zones at greater depths.

3.4.3.3 Hydrogeology

The small yields in boreholes investigated in this area were obtained from green or orange discoloured weathered zones probably less than 1mm wide. Yields of 0.3 ℓ sec^{-1} were obtained at Bongkrom and Nsareye; with transmissivities of 0.2-22 m^2 day^{-1} obtained at Bonkrom (10-22 m^2 day^{-1}), Nsareye (0.5-1.3 m^2 day^{-1}), and Nyambekyere (0.2-0.6 m^2 day^{-1}). Borehole yields tend to decline after several years of use. Replacement boreholes, drilled adjacent to and sited upon the same lineaments as failed boreholes, often dry up after a year or so of operation. Although rainfall can be heavy (the area experiences temporary flooding) little rainwater recharges to the underlying aquifer through the low permeability re-cemented sandstones. This problem was studied at Oku to the west, in an area underlain by the same sandstone formation. The deepest boreholes have been drilled to 70 m, probably too shallow to intercept weathered zones associated with the base flow levels of the Volta River system.

The database of other hydrogeological data from this formation indicates that of the 96 boreholes drilled, 63 were wet and 33 were dry. Borehole yields of 10-960 ℓ min^{-1} were obtained. Water levels were shallow at 2-20 mbgl. Data from six pumping tests showed transmissivities of 0.18-56 m^2 day^{-1}. Hydrochemical analyses suggest the presence of good to poor quality water with SECs of 276-1360 µS cm^{2-1} from 15 records. BGS hydrochemical analyses from five sites (Appendix 6, Table 6/3) showed groundwaters of $NaHCO_3$ type, which supported by high silica levels, is indicative of old waters with little or no recharge to the system. There is some aluminium and iron in solution.

3.4.3.4 General hydrogeological development potential

The groundwater development potential of the Feldspathic Sandstone, Arkose, Siltstone and Mudstone Formation is moderate to low. These recemented sandstones are tight, with groundwater occurring in thin weathered zones. Investigations to date have been targeted at apparent fault lineations but these have in general proved to be low yielding. Limited data from boreholes at Nyambekyere, Issac, Nyasere and Bonkrom indicate that the weathered zones occur toward levels of base flow in the Volta River system. They form the best targets for groundwater but these have yet to be investigated in deep exploration boreholes. Recharge to the aquifer is stopped by the thick layer of recemented sandstone. Long term pumping of low yielding boreholes has resulted in the mining of groundwater. Geophysical surveys should not be used to site boreholes on this formation.

3.4.4 Unfractured shale and sandstone

3.4.4.1 Local Geology

The oldest sediments in the area are dark grey siltstones, fine grained sandstones and shales underlying the low lying areas between the lake shores and 137 m altitude in the southern Afram Plains. The geology of this unit was investigated in exploratory boreholes drilled at Gazeri Camp and Forifori and production boreholes at Bonkrom and Akura. Analysis of rock chip samples collected proved sequences of black, dark green grey and dark grey siltstones, shales and mudstones with thin fine grained and conglomeratic sandstones. Siltstones weathered to 10 m occur at Bonkrom. At Forifori hard shales underlie medium to fine grained sandstones and siltstones, weathered to 20 m. At Gazeri Camp hard shales weathered to 21 m were found. A thin fersiallitic soil capping this formation is a source of ferricrete for road construction. At Takoratwene this thin ferricrete overlies clays and red very weathered mudstones (Appendix 5, Sheet 5).

3.4.4.2 Geophysical investigations

EM34 geophysical surveys were run at Forifori (2.3 km) and Gazeri Camp (3 km). At Forifori low formation conductivities of 20-30 mmhos m^{-1} were determined using 20 m and 40 m coil separations. High formation conductance of 60-100 mmhos m^{-1} , determined using 40 m vertical dipoles indicate a geological boundary, while reduced formation conductance with 40 m vertical dipoles indicate a small fracture zone. At Gazeri Camp low formation conductance over weathered wetter siltstones and shales of 20-30 mmhos m^{-1} were determined using 10 and 20 m coil separations. Lower formation conductance of 10-20 mmhos m^{-1} were obtained using 40 m coil separations from less weathered drier and deeper shales and siltstones, with marked negative shifts determined using vertical dipoles indicating a fracture zone.

3.4.4.3 Hydrogeology

The Unfractured Shale and Sandstone Formation is the poorest aquifer in the Afram Plains. These fine-grained rocks have very low intergranular permeability or porosity. Recent drilling shows the presence of groundwater at depth in weathered zones associated with base flow levels of the Volta River system. Production boreholes at Bonkrom and Akura and exploratory boreholes at Forifori and Gazeri Camp yielded poor quality groundwater from weathered zones. At Bonkrom water was struck in a reddened weathered zone at 23.4-30.5 m in siltstones. Transmissivities of 34-90 m^2day^{-1} were obtained from pumping tests. At Forifori water was struck at 19 m at the base of the very weathered zone. A yield of 1200 ℓ min^{-1} was obtained at 25 m from a weathered conglomeratic layer. This level equates with that of the lake surface some 5 km to the west. The higher yield of water met at 103 m was enough to stop drilling. This weathered zone is at the base-flow level of the Volta River. Transmissivities of 56-109 m^2 day^{-1} and a storage coefficient of $8x10^{-3}$ were determined from test pumping. At Gazeri Camp water was struck at 13 m in weathered siltstones and shales. Further water was met below the very weathered zone at 25 m, at the lake surface level. More water was struck in a fracture at 74-79 m, at the base-flow level of the Volta River. No further water was met below this level. Transmissivities of 1-6 m^2 day^{-1} were determined from test pumping.

A small flow of water was obtained from calcite filled fracture zones discoloured by orange iron oxide in an ADPO borehole near a World Vision borehole at Alizimah. A pumping test to demonstrate the Whale pump system showed a drawdown of 0.24 m after 200 mins pumping at 0.094 ℓ sec^{-1}. The water level recovered to 12.196 m, 165 mins after pumping was halted. A transmissivity of 40 m^2day^{-1} was determined. Six water samples for hydrochemical analysis (Appendix 6, Table 6/4) were obtained from boreholes at Bonkrom, Takoratwene, Forifori and Gazeri Camp. $NaHCO_3$, NaCl-HCO_3 and NaCa-HCO_3Cl type waters, with SECs of 983-1851 µS cm^{2-1} were found. Moderate F concentrations of 1.2-1.38 mg $ℓ^{-1}$ were found at Gazeri Camp and Forifori. An Al concentration of 2.02 mg $ℓ^{-1}$ was found at Forifori. The quality of the groundwaters was poor.

The database of hydrogeological data from this formation indicates that of the 28 boreholes recorded 14 were wet on drilling and 14 dry. The latter boreholes had yields of 7-360 ℓ min^{-1}. Water levels were shallow at 2-10 mbgl. One pumping test showed a transmissivity of 63 m^2 day^{-1}. Hydrochemical analyses of samples from 3 boreholes suggest the presence of poor quality, old groundwaters with SEC of 790-2550 µS cm^{2-1}.

3.4.4.4 General hydrogeological development potential

The groundwater development potential of the Unfractured Shale and Sandstone Formation is moderate to low. The rocks are generally tight with some groundwater occurring in weathered zones. Limited data from boreholes at Forifori, Gazeri and Bonkrom indicate that weathered zones, occurring at and above former base flow levels of the Volta River system, form the best targets for groundwater. These levels need to be projected away from the Volta Valley to provide an indication of potential depths of drilling. Drilling should be to the level of the present day lake surface. Borehole yields are generally sufficient for a hand pump. Groundwaters appear to be old being sodium bicarbonate to sodium chloride in type, indicative of low present day recharge.

3.4.5 Summary

Data from earlier drilling programmes and those generated during the 2001 study were collated into a composite data base. This data base was interrogated to provide summary hydrogeological information for each of the geological units studied in the Afram Plains. The acquisition of a limited amount of more detailed data from a limited number of exploration boreholes can radically alter concepts of how groundwater exists in an area. The results gained here indicate that each of the geological units studied has a unique set of hydrogeological characteristics. In the absence of exploratory boreholes, the true nature of water bearing structures in these sedimentary rock formations can only be fully realised through careful acquisition of geological and related hydrogeological information during production borehole drilling. Such knowledge would enable the better targeted use of geophysics and analysis of remotely sensed, data thus reducing the costs involved with these survey elements and hopefully providing realistic expectations of borehole yields and groundwater resource sustainabilities.

4 Discussion, and Guidelines for Groundwater Development

Year round water supply is a major problem in the Afram Plains where groundwater development has followed a pattern typical of an area with seasonal rainfall, ephemeral drainage, and underlying low permeability rocks. Reconnaissance level geological and hydrogeological surveys were first undertaken with limited drilling more than thirty years ago. Limited borehole drilling was undertaken to supply water to communities resettled by the building of the Akosombo Dam. During the ‘World Water Decade’ (1980’s) NGOs were encouraged by international donors to provide village-level water supplies using groundwater as a way of providing aid directly to poor communities. In the Afram Plains, NGO-led water supply programmes funded the drilling of about 370 boreholes during 1984 - 2001. During these programmes the economic design and construction of boreholes, and borehole drilling ‘success rates,’ were emphasised. The typical hand pump equipped borehole was expected to supply 250 people with at least 20 litres per capita of water per day. To ensure this, a borehole should yield 30 ℓ min^{-1}, but in the Afram Plains the acceptable yield minimum is 12 ℓ min^{-1}, due to the low borehole yields generally obtained. Although many boreholes have been drilled, the geology of the area, how groundwater occurs within these rocks, and the nature of the water resource remain poorly understood. This problem has been worsened by the failure of apparently successful boreholes after 3-4 years of use. This project seeks to improve understanding of the groundwater resources of the area through better data acquisition during the drilling of successful and unsuccessful production boreholes and with limited targeted hydrogeological exploration of deeper aquifer systems.

The current emphasis on decentralised, demand-driven groundwater schemes, usually donor funded, has worsened this problem. Although the Water Commission and Water Research Institute are responsible for the collation of data from groundwater supply programmes neither have the finance nor the manpower necessary to carry out this function. Therefore, mistakes are repeated, and drilling success rates remain low. The integrated management of surface water, shallow groundwater, rainwater and deep aquifers is poor to non-existent. The conjunctive use of such water sources may be the only realistic solution for water supply in those parts of the Afram Plains where initially successful boreholes have dried up after several years of use, due to a lack of surface water recharge to aquifers. Unfortunately, in such areas communities that have been established for several years are now totally reliant upon groundwater as their sole source of dry season domestic water.

Given the nature of current and emerging problems associated with water supply on the Afram Plains, the BGS work brought to light several issues concerning groundwater exploration and development which deserve further discussion:

4.1 IMPORTANCE OF ACCURATE SITE LOCATION

Inexpensive GPS systems provide the most convenient and accurate means of locating boreholes, villages, rivers, roads and other data points. Accurately located (spatially referenced) data points can be easily plotted on a map for location by future workers, or included in a geographical information system (GIS) for planning purposes. In the past, groundwater studies, drilling programmes and development projects have relied on sometimes ambiguous place names to locate data points. Where these points cannot be accurately relocated the associated data cannot be used for planning purposes. Many of the borehole data available for the Afram Plains are located by place name alone. These data are difficult to geo-reference, hampering the production of accurate geological or groundwater maps. The APDO are using GPS sets provided by the project to accurately locate communities, social institutions and boreholes in the Afram Plains to enable better use of existing data.

4.2 GEOPHYSICS ON THE AFRAM PLAINS

Geophysical surveys using resistivity and EM methods have been used to locate borehole-drilling sites on the Afram Plains. Latterly these methods have been used to accurately locate ‘fracture’ lineations identified using the interpretation of remotely sensed Landsat TM and aerial photograph data. Although some improvement in borehole drilling success rate was claimed, these methods have to a certain extent fallen out of favour in the Afram Plains, being seen as relatively expensive and time consuming to use for little apparent benefit. In the western Afram Plains, the deep but very thin zones of weathering that are the main sources of groundwater there cannot be defined using geophysical surveys beneath the thick duricrust layer. However, in the eastern Afram Plains these methods can be used to differentiate between near surface shale, siltstone, sandstone and conglomerate bands as well as to delineate possible fault zones.

4.3 DATA GATHERED DURING BOREHOLE DRILLING

At little added expense much useful geological and hydrogeological data can be gathered during the drilling of a borehole. These data include:

- Geological data
- Penetration rate data
- Flow data
- Hydrogeological data

The results obtained from the exploration boreholes indicate that the rock types present in the Afram Plains are generally tight and fine-grained, with water being produced mainly from horizontal weathered pseudo karstic zones and along lithological boundaries rather than the odd near vertical fracture. In the western half of the area the presence of a thick (up to 60 m) duricrust weathered zone that inhibits recharge to underlying aquifer systems was recognised. These data are needed to better inform the conceptual model of the aquifer system thus enabling a better water supply.

4.4 TEST PUMPING

Pump test data from fractured aquifers are difficult to interpret since distinct changes between early and late time drawdown rates are often due to fracture dewatering. Interpretation of such data requires specific training and erroneous interpretations are often made, particularly if testing is carried out over short periods of time. Unfortunately, as in the Afram Plains, the test pumping of production boreholes is often done merely to satisfy contract conditions, without analysis of the pump test data being used to inform borehole completion. Simple pump tests give indications of the productiveness of the systems but the results obtained from 'fractured' aquifer systems with high secondary permeability zones can be difficult to reconcile. Fractured aquifer systems can initially give high yields, but when dewatered during extended periods of overpumping they can suddenly fail. The development of the bail test by BGS provides field personnel on the Afram Plains who are not trained in test pumping with a rapid simple procedure to decide in a general way whether or not to equip a low yielding borehole, without going through the standard pumping test. Such a test can be used to assess the rate of water level recovery of a low yielding borehole prior to well construction. If the rate is too slow to ensure an adequate supply then the borehole should be abandoned thereby saving the cost of well components. Conversely in areas where only very low yields are expected the results of a bail test can be used to identify boreholes that should be equipped rather than abandoned as apparently dry.

4.5 HYDROCHEMICAL SAMPLING

Hydrochemical sampling, apart from establishing initial inorganic groundwater quality, can provide information about recharge and contamination, and should be carried out as part of ongoing water quality monitoring on the Afram Plains. Water samples were taken during the BGS visit and analysed for major and minor ions, and some isotope samples were taken. There were few problems with inorganic water quality, but levels of ammonium and nitrate in some of the boreholes indicate possible anthropogenic contamination, as seen in central Donkorkrom and Tease. Water chemical types indicate that some groundwaters are relatively old, and may not be recharged at rates sufficient for sustainable abstraction. To provide initial indications of changes in water quality, the routine measurement of borehole water specific electrical conductance (SEC) would provide a useful guide. This field measurement can be quickly carried out by field staff with limited training. The results obtained could be used to roughly define areas or depths of different water quality that could provide information on aquifer recharge or dewatering.

4.6 INFORMAL MONITORING OF BOREHOLES

Certain boreholes on the Afram Plains have experienced declining yields and some have failed, after periods of abstraction lasting from a few months to a several years. These borehole failures are due to inadequate recharge of the water-producing fracture systems, resulting in the mining of the groundwater resources. It is thought that the zones of influence of even low yielding boreholes on the Afram Plains may be several kilometres in extent. The simple monitoring of borehole yields, undertaken by the borehole users, would provide a warning of this problem, and where boreholes are located by GPS, would enable areas prone to this problem to be defined. Water level monitoring and water conductivity measurements would provide very useful hydrogeological information that could be used to flesh out a "big picture" for the Afram Plains. Informal monitoring could also be used to identify construction problems such as pump failures. There is a tendency to regard the installation of a borehole as the only opportunity to collect information about the hydrogeology of an area, but much additional information, often the basis of resource sustainability judgements, could and should be obtained through ongoing informal borehole water supply monitoring.

The construction of a hydrogeological database, accurately referenced geographically, should be a priority for the region. This will inform future workers in the area, and help to improve drilling success rates. Such a database will serve to inform the expectations of development workers and communities. Growing from a good database should be the construction of a groundwater development map for the Afram Plains, which shows average yields for the various lithologies, likely depths to groundwater, modes of occurrence of the groundwater, and water quality information.

4.7 THE DATA BASE

Much information can be derived from the analysis of existing raw data (held in borehole completion certificates with geological logs, test pumping data and hydrochemical data) and tabulated analysed data (held in study reports). Unfortunately, borehole site locations are usually defined by village name alone. World Vision International hold their data within a GIS, for which boreholes and villages were accurately located using UTM coordinates determined in the field using GPS sets. Unfortunately, these data have not been made available to the project. Such data sets, privately held by consultants, are becoming more common in Africa. The basic requirements of a usable database are the accurate location of villages and estimations of their populations in the survey area. The APDO is currently undertaking such a base-line survey of villages and boreholes in the Afram Plains. For the purposes of the BGS study, those locations already available were combined with village coordinates obtained from 1:50,000 scale topographic maps to form a gazetteer of village locations. Other data with only village name were combined with the accurate village locations on a spreadsheet to form a composite database. This data set provides approximate lat/long coordinate locations for the bulk of the boreholes for which data exist. This data set was interrogated to produce various tables such as a listing of all pre 2001 production boreholes per village. This set has been divided to provide borehole data for each of the four geological units.

The data in the data base are held in a series of Excel spread sheets, designed for integration within a GIS such as ArcView, and Word documents designed to be included within short, community aimed, or larger reports. The database elements can be accessed directly on the CD or via hyperlinks from this report. The spreadsheets and documents can be copied onto a PC where they can be readily upgraded as additional data are obtained. In this way both the database and the accompanying report can be updated on a regular basis. Detailed data sets from the present BGS survey can be accessed by hyperlink from tables in the methods chapter.

4.8 GROUNDWATER DEVELOPMENT POTENTIAL MAP

Guidelines for development of the groundwater resources of the area have been formed using the results of hydrogeological studies carried out in the Afram Plains. Geology is the main factor controlling the presence or absence of groundwater, and therefore the guidelines are aimed towards understanding the geology of a site. As discussed in Chapter 3, the geology of the Afram Plains is poorly understood and complex in nature. The guidelines are not foolproof, but are the best that can be suggested given the present understanding of the area. As more information is collected from the drilling and testing of boreholes these guidelines can be updated.

Four phases in a groundwater development programme are considered: (1) identification of geological formations within which groundwater may exist in an area; (2) selection of suitable sites for borehole installation; (3) appropriate design and construction of boreholes, (4) appropriate monitoring of borehole water levels and abstraction rates.

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 the Afram Plains (Appendix 3). The groundwater potentials of these units are discussed in Chapter 3. The geological boundaries shown are gradational and fuzzy. Using a GPS a site can be approximately located on the map in the field. A first indication of the groundwater development potential of the underlying geological unit can then be obtained from the table on the reverse of the map. A more accurate assessment of the groundwater potential of a village requires additional information obtained from maps and aerial photography, an assessment of local geology and water sources with the community, and the use of geophysical survey equipment. On its own, each source of information may be misleading. However, taken together this can be a useful method of producing an initial assessment of groundwater potential.

4.9 CURRENT CONCEPTUAL MODEL OF THE AQUIFER

The occurrence of groundwater in the Afram Plains is also shown on a schematic hydrogeological cross section through the area (Appendix 4). The locations of the various geological units, with representative photographs of their outcrops, are shown together with the approximate lake and aquifer water levels. The main features of the conceptual model are as follows:

- Groundwater is thought to occur in discrete fracture systems or zones of weathering.
- The geological units have different hydrogeological characteristics but all are low yielding.
- In the west of the Afram Plains, the aquifer units may not be adequately recharged during successive wet seasons, leading to failure of boreholes with time. Old water is often present in the fracture systems.
- In areas where recharge of surface water occurs, rapid movement through near surface weathered zones and fracture systems can lead to rapid transport of contaminants into boreholes below sanitary seal zones, as seen in high ammonium and nitrate levels in central village borehole water sources on the Afram Plains.
- Water bearing weathered zones may be too deep and discrete to be determined using geophysical survey methods.
- Drilling deep boreholes to below the present day lake level may intercept fracture and weathered systems that can potentially be recharged by lake water. This process of recharge from the lake remains to be proved.

5 Conclusions

During the short project visit to Ghana, methods for the generation of high quality hydrogeological data from limited additional inputs to borehole drilling programmes were demonstrated. The collation of these and pre-existing data has produced a better understanding of the nature of the groundwater resources of the Afram Plains. The aquifer characteristics of low permeability Lower Palaeozoic sedimentary rocks that underlie the Afram Plains are complex. The permeability and porosity of these sedimentary rocks are dependent upon:

- geology - understanding the primary permeability, diagenesis (cementation and compaction reducing permeability) and tectonism (folding, fracturing and jointing producing secondary permeability). At present these factors are poorly understood.
- geomorphology – understanding the effects of long term weathering, with the formation of an ancient duricrust surface and recent weathering and regolith formation during the Late Quaternary period, related to erosion of the Volta valley and associated base-levels of water movement (producing zones of secondary permeability). The maximum depths of weathering due to these factors need to be defined.

- fracture patterns – the genesis of these linear features, located on Landsat images and aerial photographs needs to be understood. However the fracture zones reported in production boreholes drilled to depths less than 100 m are probably in reality horizontal weathered zones, rather than vertical fractures that will have been sealed by secondary cementation.

The combined use of remotely sensed data and geophysical surveys offers a powerful method for recognition of the nature of near surface stratified deposits and vertical fracture zones. However, they cannot be used to locate very thin (<0.1 mm) weathered zones at depth. The hydrogeologist can only recognise the presence and importance of these discrete zones of secondary permeability during borehole drilling and testing, when as much relevant data as possible should be collected. **All** boreholes are important sources of information, wet or dry. The assessment of groundwater occurrence is reliant upon point source data, therefore, data from previous drilling and testing programmes must be incorporated into area databases.

Low permeability rocks generally produce low yielding boreholes. Assessing groundwater potential of an aquifer is in part dependant upon the hydraulic parameters derived from initial test pumping and, more critically, the monitoring of borehole yields, water levels and water quality. The long-term sustainability of an aquifer unit is dependant upon recharge of surface water to the underlying aquifers. In the western Afram Plains, where little or no vertical recharge occurs through a duricrust layer, boreholes that pass through horizontal weathered inflow zones often run dry after a short period (2-3 years) of use. Conversely, in the eastern Afram Plains where the duricrust layer has been removed by erosion, rapid recharge of surface water can take place. Unfortunately, this can result in the contamination of water supply boreholes with effluent where they are located in village centres. The results of exploratory drilling indicate that where-as water quality generally declines with depth, borehole yields increase with depth, peaking at levels associated with the former base level of weathering of the Volta Valley. Possible direct recharge of lake-water into weathered zones below lake level should be evaluated. All future boreholes should be drilled to at least the level of the present lake surface.

NGO led projects form some of the largest groundwater development projects currently undertaken in Ghana and therefore form major potential sources of hydrogeological data. In addition, NGO water supply projects are often the first drilling programmes to be undertaken within remote rural areas, where hydrogeological conditions are little understood. The sustainability of such projects is dependent upon, among other things, data acquired during the drilling and testing of boreholes. Potentially, such data will be of great benefit to subsequent projects. However, acquisition of data, needed for determination of the potential resource or its long-term sustainability, is at times seen as a waste of capital resources and beyond the capabilities of NGOs. Therefore, relevant national institutions should be encouraged to participate in NGO-led water supply projects to ensure the acquisition of good quality data from the boreholes drilled. Government institutions such as the Geological Survey and CWSD should be involved with such projects, if only to update their own databases. The location of all boreholes and villages should be determined using GPS sets and recorded on baseline maps maintained by field staff at district offices. These location data are essential for borehole and other point source data entry into GIS systems at regional and national level, such as is being done at the Water Research Institute in co-operation with the newly constituted National Water Commission.

NGOs are expected to produce cost-effective boreholes of minimal dimensions. The borehole design adopted is based upon the smallest acceptable handpump. Data currently obtained during drilling is sufficient for borehole design, but rarely contributes improved understanding of the groundwater resource. Borehole completion designs should be amended to allow access of monitoring equipment.

Where success rates are low, NGOs should be able to call upon the assistance of local and international experts familiar with the local geology. These experts would need to take a more holistic approach to maximise data gathered during siting, drilling and monitoring programmes if a better understanding of local complex hydrogeological systems is to be achieved. Areas of local expertise include Legon University of Ghana (Landsat image and aerial photograph interpretation); Land Survey Department (digitised 1:50 000 maps); and the Geological Survey staff (mapping of rock exposures and logging of rock core and chip samples). Legon University and WRI hydrogeologists could undertake borehole test pumping and hydrochemical determinations. The CWSD could monitor and advise on borehole construction. APDO in co-operation with CWSD could monitor water levels, rainfall and borehole operation in association with community groups. These inputs could result in the collection of good quality data to be fed back into central and regional databases that could be used to inform optimum siting methods, drilling depths and potential resource development. These activities require funding channelled through the lead NGO. Without these activities little knowledge will be gained and the 'success rate' continue to be low. Some institutional capacity building is needed, including provision of transport, equipment, staff training and operational costs.

Analysis of future data sets should provide additional information on:

- Abstraction borehole densities
- Optimum borehole depths
- Optimum borehole design
- Risk of aquifer pollution
- Realistic minimum distances between abstraction boreholes and user communities
- Appropriate systems for borehole siting
- Realistic estimates of borehole yield and resource expectations by communities and planners

6 Recommendations

In 1946 Junner and Hirst observed that there was no systematic description of the geology of the Voltaian Basin of Ghana and that 'a thorough understanding of the geology and water-bearing properties of the rocks of the basin is essential in selecting sites for dams, wells and boreholes.' These two requisites remain to be fulfilled. The need for the second is essential to understand the sustainability of groundwater resources. However, for this geological perspective to be satisfied other factors need to be undertaken such as:

- Increased cooperation and a longer-term perspective need to be taken by stakeholders.
- The view amongst national institutions, consultants and international non-governmental organisations that data are confidential needs to be renegotiated.
- Work on a common database and a groundwater development map for the Afram Plains should proceed as a priority. The techniques used are transferable to other areas in Ghana
- The results of the DANIDA funded hydrogeological studies will inform development of deeper aquifers in the eastern Afram Plains. More work of a similar nature needs to be done on the Feldspathic Sandstone, Arkose, Siltstone and Mudstone aquifer in the west of the area.
- Conjunctive use of surface, rain and groundwaters needs to be explored, particularly in areas with unpromising groundwater development potential.
- The application of geophysical techniques needs to be better understood, and used more appropriately for borehole siting.

- APDO should establish a series of long-term borehole yield, water level and rainfall monitoring sites in association with community groups.
- The APDO will be the local repository for all data collected during this KAR project. The database that accompanies this report, especially the gazetteer of village locations, needs to be field checked and updated on a regular basis. The maintenance of the database will require the full co-operation of aid donors, including funding drilling programmes in the area.
- Representative core samples should be obtained in order to determine rock permeabilities and porosities and for lithological analysis. Cores from below 60 m depth should be obtained to determine if iron and manganese oxide cements are still present with depth and the effects of feldspar grain weathering upon rock permeability, in order to assess rates of water seepage to joints and weathered zones in the formation at depth.
- This report and accompanying database should be viewed as dynamic documents that can be added to on completion of subsequent drilling programmes to produce an updated statement of the hydrogeology of the Afram Plains.
- Further discussions need to be held with the district government authorities to ensure that the APDO continues to act as a repository for all hydrogeological data produced by future water supply projects conducted within the Afram Plains.

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WORLD HEALTH ORGANISATION guidelines

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Glossary

Aquifer - A rock formation that contains sufficient groundwater for water supply.

Borehole - A cylindrical hole, usually about 100 mm diameter and greater than 50 m deep constructed using a drilling rig for abstraction of groundwater from an aquifer.

Conglomerate – A clastic rock made from cemented pebbles, gravels and sands – can have a high potential for groundwater.

Geophysics - Techniques that measure the physical properties of rocks without the expense of drilling boreholes. In certain circumstances results from geophysics surveys can be used to predict the presence of groundwater.

Porosity - The ratio of void space in rock to the total rock volume - expressed as a percentage. Rocks with high porosity can store greater volumes of groundwater.

Permeability - Rate of groundwater flow through a cross section of aquifer. The ability of a rock to transmit water. Permeability is higher when there are interconnected fractures

Pumping test - A test that is conducted to determine aquifer (transmissivity and storage coefficient) or borehole (specific capacity) characteristics.

Sandstone - A rock that is made from cemented sand grains – usually has a high potential for groundwater.

Shallow well - A large diameter (usually greater than 1 m) hole, dug to less than 20 m depth to access groundwater.

Shale – Laminated mudstone– usually has a low potential for groundwater

Siltstones and mudstones - Fine-grained rocks made of mud and/or very fine-grained particles. Usually have a low potential for groundwater.

Success rate (borehole drilling) - Imprecise term, normally taken as the number of successful boreholes divided by the total number of boreholes drilled – expressed as a percentage. Different organisations have different measures for denoting a successful borehole.

Sustainable yield -

Weathered zone - A layer of rock beneath the soil zone that has been altered by physical breakdown or chemical decomposition.

Yield - The rate of water abstraction from a well or borehole, measured as m^3d^{-1}, $l\ min^{-1}$, $l\ sec^{-1}$.

Acronyms and Abbreviations

APDO	Afram Plains Development Organisation
BGS	British Geological Survey
BHC	British High Commission
CSIR	Centre for Scientific and Industrial Research
CWSD	Community Water and Sanitation Division
DANIDA	Danish International Development Assistance
DfID	Department for International Development
DRI	Desert Research Institute, Nevada
EM34	Frequency domain electromagnetic induction
GIS	Geographic Information System
GPS	Global Positioning System
KAR	Knowledge and Research
NGO	Non-governmental Organisation
VES	Vertical electrical resistivity sounding
WRI	Water Research Institute

Appendix 1 – Itinerary

7th April - Departed from London Heathrow at 08h45 on KL1002 to Amsterdam, arriving 11h05. Departed from Amsterdam at 14h35 on KL589. Arrived Accra at 19h45. Met Nick Burn, WaterAid representative for Western and Southern Africa.

8th April - Meeting with Gordon Mumbo, WaterAid country representative for Ghana at 11h00. Lunch with Nick Burn and Gordon Mumbo. Discussed WaterAid programmes in Africa.

9th April - Meeting with Kurt Klitten, DANIDA Water Sector Development Programme Coordinator, at the Danish Embassy at 09h00. Obtained World Vision report and VES data from university survey. Discussed work plan, and geophysical surveys and drilling done in the Afram Plains. Discussed visit to Oku. Obtained and cut steel pipe for bailers. Met Gordon Mumbo at WaterAid, discussed Oku visit. Met Mr Modoc, (APDO) at WaterAid where the local Compuserve connection did not to work. Met Nick Burn and discussed WaterAid policy and viability of BGS work to NGOs. Can Carlos understand and replicate what we show him? Entered VES data from Kurt Klitten into the computer.

10th April - To WaterAid where JD worked on VES data. Met Parkman manager from Nigeria, mapping project is still on. Photocopied World Vision report. JC to Survey office to obtain 1:50 000 maps of project area and collected bailers. Visited Mr Enoch Asare at Water Research Institute to discuss the project. Obtained distilled water and conc HNO_3, saw borehole logging equipment at WRI. Met Nick Burn and Gordon Mumbo to discuss BGS inputs to WaterAid projects in Ghana.

11th April - Left for Oku at 07h40, arrived at 16h00, met Father Patrick Lynch of Oku Catholic Mission. Discussed water supply and borehole yields in Oku. Visited bhs near mission. Heavy rain in the night.

12th April - Visited Oku area with Father Patrick to see bhs and dam sites. Discussed the recharge of aquifers with rainwater from rooftop catchments via bhs. Spoke to villagers about water problems. Discussed options with Father Lynch. Very heavy rain.

13th April Drove from Oku 45km to Ejura, recording GPS positions at 1km intervals, and bh locations. Lunch in Kumasi then to Accra.

14th April - JC ill. JD to Danish Embassy for discussion with Kurt Klitten. Oku results, no resistivity survey report from university, sent and received e-mails, met Dutch hydrogeologist Mr Peter van Dongen.

15th April - Analysis of VES data from Afram Plains, typed Oku GPS data into the laptop.

16th April - JC much better. JD to WaterAid. JD now ill.

17th April - Checked out of hotel, to WaterAid packed vehicle. Got 200m of rope, groceries and buckets Drove from Accra to Afram Plains. Caught the last ferry. Arrived at the Genesis guest house at 19:00hrs.

18th April - To the APDO office at Tease where met Alima, deputy to Modok. Collected air freighted equipment. Drove through Kwame Krobo to the Kwase Fante clinic where met Carlos. Met Technic Eau geophysicist Coomlan Abahounsignin siting boreholes at Nyambekyere using EM34 at 40m coil spacing, vertical dipole to get 60m penetration – below the weathered zone. No maps and no GPS. Left Carlos. At the Animal Research Station, Forifori, met technician collecting rainfall and temperature data. Drove to Kwamedwamenakurom on the lake from where located VES pegs at 1km intervals using GPS towards Donkorkrom. Collected equipment at Tease on to Donkorkrom. Charged EM34 batteries.

19th April - Checked EM34 equipment. To APDO Donkorkrom office. Power steering leaks repaired. Loaded equipment, met Alima at Samanhyia, drove to Tease and Forifori. Recorded GPS at 1km intervals along road to Nyambekyere. Met Carlos, took water samples from two wells, demonstrating use of equipment. Need permission of chiefs to site the 4 exploration boreholes. Back to Donlorkrom

20th April - Dropped off e-mail at APDO. Lack of diesel. Drove to Tease, met with Alima, Carlos and Augustine re exploration borehole locations. With Carlos visited sites at Forifori and 3km from lakeside. Collected GPS bh locations from Carlos at Tease. At APDO Donkorkrom received message to call Gordon who suggested I return to Accra and contact UK. Called the UK from post office at 19:30. Obtained diesel.

21st April - JD drove to Accra, via the second ferry. Typed borehole GPS locations onto the laptop. Decided to return to the Afram Plains for a week then to return to the UK. JC organised bailers, met Laurent Berube, of Hydro-Frac, re test pumping. To Nyamebetyere with Carlos and Gabriel to 1st bh site.

22nd April - JD in Accra. JC to Nyamebetyere with Laurent to see drilling. To Nsareye to locate the next bh with GPS.

23rd April - JD in Accra, contacted Dennis Peach. Contacted KLM to change flight. From Accra to Afram Plains via second ferry. JC to Nsareye, where bh completed. To Bonkrom where first of 3 bhs was being drilled. Met with the local chief. Logged rock chip samples from first exploration bh.

24th April - At Bonkrom 5th bh completed. Saw drilling rig and test pump unit. Water and chip samples from 5 bhs.

25th April - Put bh log for 5th bh onto computer. At Samanhyia did 3km EM34 survey. Put EM data onto computer.

26th April - JD logged chip samples for Bonkrom bhs P1, F1 and F3. Met Stephan Rodrigue, Ghana country director for Technic-Eau, JC to Tease, did 3km EM34 survey. Mini-cyclone hit Donkorkrom area. Logged chip samples for S3-F1 Nyambyekere bh. Test pump unit stuck at Bonkrom. Typed EM34 data onto laptop.

27th April - JD suffered bad dehydration at APDO Tease. Met Modok and was taken back to Genesis. Typed bh log data into laptop. JC did 2.5km EM34 survey at Forifori. Typed EM34 and test pumping data onto laptop. Met Sasha Belanger, hydrogeologist/project supervisor, Technic-Eau. The drilling rig had broken down.

28th April - Rig repaired and used to drill dry bh to 80m. JC to Tease, met drillers at Darte Krom to record site GPS. Began drilling ex bh 1 at Samanhyia with 2nd rig/T4. Drilled at 97/8" to 3.74m, cased with 8" plastic pipe, continued drilling at 6.5" DHD. Drilled to 96 samples (98m) by day end. Did bit on video camera for APDO. Main water struck at 63m, base of weathered zone. Put geological log onto laptop.

29th April - Completed Ex Bh 1at Samanhyia, problem at 114 sample, could not keep hammer free of cuttings due to back pressure and lack of non-return valve above hammer, hit more water at 114-117 samples, Q about 400 l/min, heavy rain, sited 2nd ex bh at APDO Tease, many scorpions. Discussed project with Modok.

30th April - JD to Accra . JC to Tease, drilling of 2nd ex bh started. Logged samples. Rig broke down. Copied drillers log, met Evans Amenu (MSc Hydrogeology student), discussed rig problems with Sasha.

1st May - JD in Accra at Danish Embassy. Sampled bhs in Donkokrom. Discussed geophysical data sharing and access in West Africa with Coomlan. Obtained data. Met Sasha and Technic-Eau mechanic.

2nd May - JD from Accra to Amsterdam/London. To Samanhyia for step test with Laurent. Sampled bhs from Forifori to Samanhyia. Copied geophysical data from Coomlan.

3rd May - To Gazeri Camp, did 3km EM survey. Visited lake area. Sampled bhs NE of Donkokrom.

4th May - To Nyamebetyere with Carlos, Evans and Amponsah for bail test on shallow b/h. Sampled bhs on return to Donkokrom. First (T60) rig returned from repairs in Togo.

5th May - Drilling 2nd ex bh at Tease. 1st bh to be water supply bh after good water strike. Logged bh.

6th May - Drilling 2nd ex bh at Tease, collected, logged and photographed samples. Rig (T60) broke down.

7th May - At Tease, rig to Togo. Did bail test at Samanhyia with Carlos and Augustine. Met with APDO water officers re bail and pump test analysis, demonstrated use of test sheets. Landrover broke down.

8th May - Landrover being repaired whole day. Collated data.

9th May - To Tease, no drilling rig. Sampled wells to NE of Donkokrom up to the main ferry point.

10th May - Meti Modoc to discuss progress. Bail test on shallow bh at Tease. Boxed chip samples collected so far.

11th May - Second rig (T4) returns to Tease, 2nd ex bh to 153m. Samples collected, photographed and logged. Sited 3rd ex bh started drilling at Forifori. Logged samples.

12th May - Finished bh at Forifori at 102m due to large water inflow. Sited and started drilling 4th ex bh at Gazeri Camp. Logged samples.

13th May - Drilling at Gazeri Camp, logged and collected samples. Sampled bh. Osmanu Munkailah, Hydrogeology MSc student, arrives.

14th May - Finished bh at Gazeri Camp to 152m, samples logged and photographed. Did bail test at Forifori with Carlos, and sampled the bh. Drove to Amankwa with Mr. Modoc to see old village water supply system and to discuss rehabilitation. Met with Evans and Osmanu to discuss the work so far.

15th May - Met Evans and Modoc, collated and boxed remaining samples. Checked and packed project equipment. Meeting at APDO Donkokrom with staff and other NGOs working in health and education in Afram Plains to discuss project. To village NE of Donkokrom with Modoc to see defunct village water supply system.

16th May - To Accra, left equipment at WaterAid and discussed its return to UK with staff there.

17th May - Met with Kurt Klitten at Danish Embassy to report progress. To WaterAid to organise equipment to be sent to the UK. Met Mr Ntau at WRI to return unused HNO_3 and report on work. To Danish Embassy to collect letter, then to Geological Survey to discuss work.

18th May - Purchased maps of Oku area from Survey department. Repairs made to WaterAid Landover. Telephoned Mr Desmond Woode at British High Commission to report on project. Finalised equipment to return to UK at WaterAid, and cleared it at airport.

19th May - Returned to UK on flight KL1001 at 21h20.

Appendix 2 - Contacts

Afram Plains Development Organisation, Donkorkrom and Tease.
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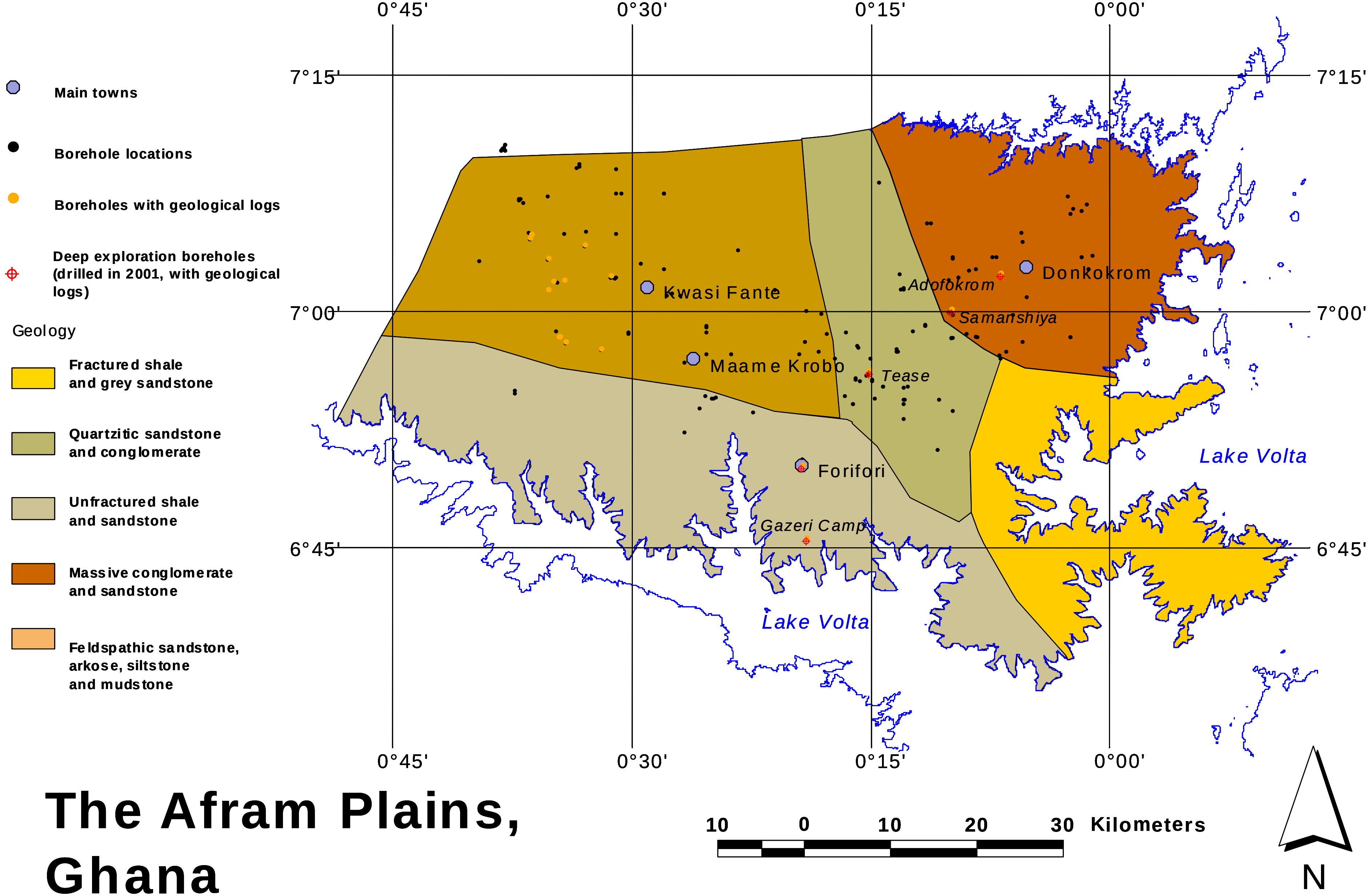
Desmond O Manful, dmanful@yahoo.com
Tel: 23321 403060 (home in Ghana) – currently on MSc course in Germany

Appendix 3 – Afram Plains Groundwater Development Map and Table



The Afram Plains, Ghana

British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL
WaterAid
DFID Department for International Development

	Description of rock/ hydrogeology unit	Groundwater targets	Ground-water potential	Groundwater quality	Field techniques	Technology	Comments
Obosum Beds –Upper Voltaian System	Massive conglomerate and sandstone.	Weathered zones and fracture zones Success rate ~66% wet 38% ≥ 30 l/min	**	Good. Presence of NO_3.N and NH_4 indicates of pollution in heavily used village centre Bhs.	Weathered conglomerate gravel often visible at surface: **EM34** – used to locate fractures and sandstones/conglomerate near surface. **VES** - depth of weathering	Boreholes 60-100 m.	Good recharge, best sites located in valleys, boreholes should be drilled to below present day lake level. May be able to induce flow from the lake along fracture zones. Problems with pollution with Bhs in villages.
	Quartzitic sandstone and conglomerate.	Weathered zones and fracture zones Success rate ~67% wet 40% ≥ 30 l/min	**	Good	Quartzitic sands often visible at surface.. **EM34** – used to locate fractures and sandstones/conglomerate near surface. **VES** - depth of weathering	Boreholes 100-150m.	Moderate recharge, best sites located in valleys, boreholes should be drilled to below present day lake level. May be able to induce flow from the lake along fracture zones. Problems with pollution with Bhs in villages.
	Feldspathic sandstone, arkose, siltstone and mudstone.	Weathered zones and fracture zones Success rate ~66% wet 39% ≥ 30 l/min	*/**	Good.	Weathered purple brown sandstone platform surface beneath thin ferricrete. Difficult to identify fractures with **EM34,** sandstones have been recemented to 60m. **VES** - depth of weathering	Boreholes 100-150m	Very poor recharge potential due to recemented layer down to ~60m. Deep holes may intercept weathered zones. Remoteness precludes direct recharge from lake along fractures. Fractures poorly defined.
	Unfractured shale and grey sandstone	Weathered zones and fracture zones Success rate ~50% wet 14% ≥ 30 l/min	*	Poor to saline.	Low lying low altitude lake side areas. **EM34** – moderate to high conductivities, used to locate fracture zones **VES** - depth of weathering	Boreholes – 50-100 m.	Poor to moderate recharge to tight formation except where conglomeratic bands area present. boreholes should be drilled to below present day lake level.
	Fractured shale and sandstone	Weathered zones and fracture zones Success rate Unknown due to lack of data	*?	Poor to saline?	Low lying low altitude lake side areas. **EM34** – moderate to high conductivities, used to locate fracture zones **VES** - depth of weathering	Boreholes – 50-100 m	Unknown

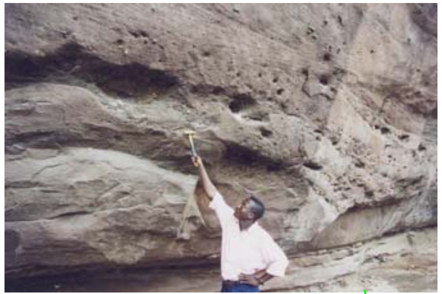
KEY	**Groundwater potential:** *** Low** **** Moderate** ***** High**	**Note:** Groundwater Potential is an overall function of groundwater storage, groundwater yield and groundwater residence time (length of time groundwater remains in the unit, i.e. rate of groundwater throughflow). It indicates both the available yields and the length of time these are available for: i.e. high, moderate or low yields, available only during the wet season & immediately afterwards, or year-round. See Comments column for more detail.	EM34 conductivity response: High > 50 mmhos/m Moderate 20 – 50 mmhos/m Low < 20 mmhos/m	Yield: High > 1 l/s Moderate ~ 0.5 l/s Low < 0.2 l/s

Note: *Where groundwater residence times are long, groundwater availability is likely to be less vulnerable to variations in seasonal rainfall – e.g. one year of drought. Where few data are available locally, the interpretations given here are preliminary, and should be updated as new data are provided by continuing groundwater development work.*

GROUNDWATER POTENTIAL IN THE AFRAM PLAINS AREA, EASTERN REGION, GHANA

For any site of interest in the area, use the map overleaf to identify the rock units in which groundwater may be found at that site. Use the table to see an overview of the groundwater potential of these rock units, including any water quality indicators, and an indication of field techniques which can be used to increase the likelihood of finding a suitable groundwater supply.

Appendix 4 – An Illustrated Geological Cross-section Through the Afram Plains, Ghana Showing the Main Rock Types and Their Distribution

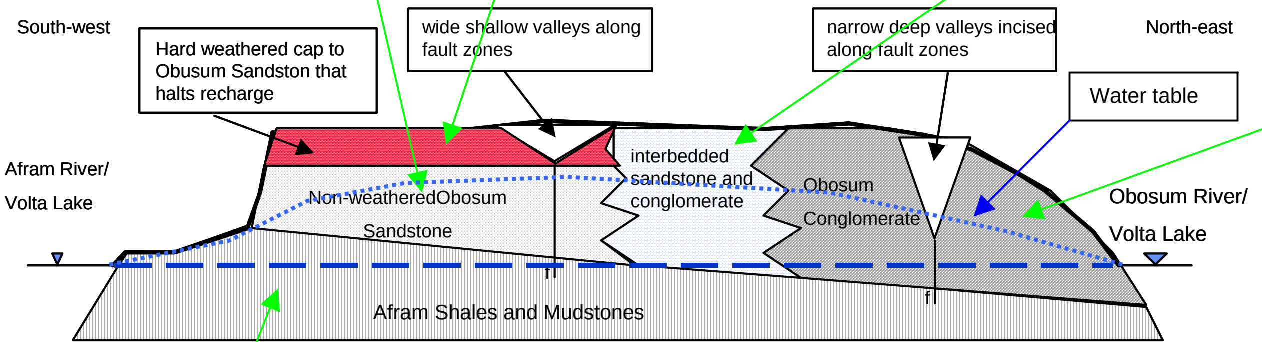


Obosum Sandstone

Weathered Obosum Sandstone platform

Obosum Quartzite

Sketch Geological Cross-section Through the Afram Plains Area



Fresh Obosum Conglomerate

Weathered Afram Shales

An Illustrated Geological Cross-section Through the Afram Plains, Ghana Showing the Main Rock Types and Their Distribution

Appendix 5 – Illustrations of the Voltaian Rock Formations Present in the Afram Plains and Adjacent Areas (Sheets 1-5).

SHEET 1 - LOWER VOLTAIAN FORMATION - BASAL SANDSTONES

Sandstone escarpment at Nkawkaw

North facing sandstone escarpment above the ferry point

Ripple bedded sandstones on road to the ferry point.

Road down the north facing sandstone escarpment to the ferry

SHEET 2 - MIDDLE VOLTAIAN FORMATION – OBOSUM BEDS. MASSIVE CONGLOMERATE AND SANDSTONE AT AMANKWA NEW FERRY SITE

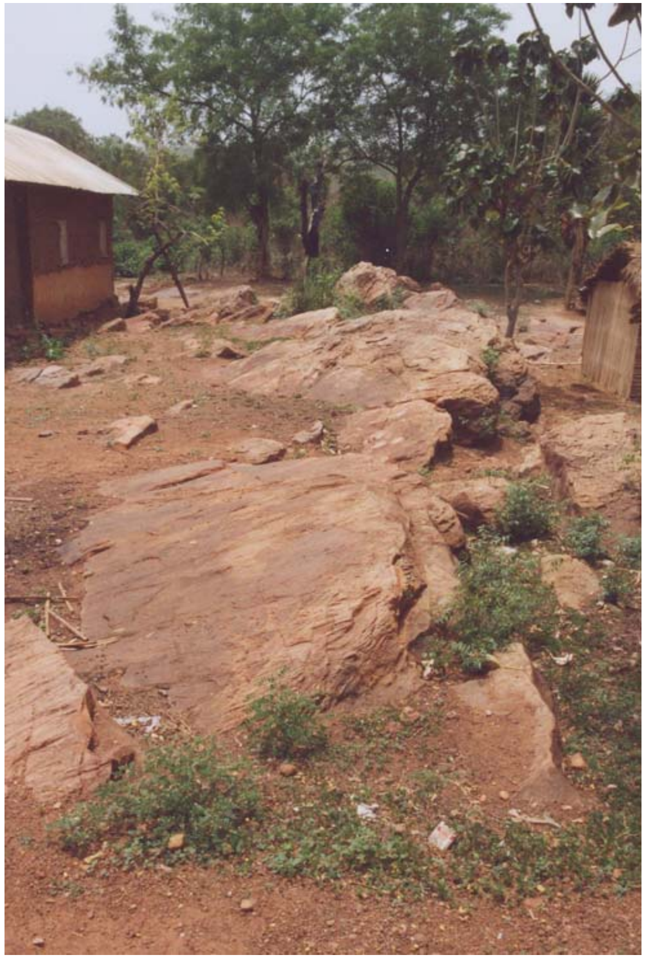
Exfoliated weathered conglomerate and sandstone

Eroded conglomerates showing subrounded to subangular pebble and gravel clasts in sandstone matrix, tillite formation?

Weathered interbedded ill-sorted sandy pebble and gravel deposits with wedges of silty to coarse grained sandstone.

Exfoliated blocks of conglomerate have slid down the weathered rock face to rest upon an accumulated weathered orange clayey ferricrete deposit at right.

SHEET 3 - MIDDLE VOLTAIAN FORMATION - OBOSUM BEDS QUARTZITIC SANDSTONE - AFRAM PLAINS



Quartzitic sandstone dipping to the west at Odumase

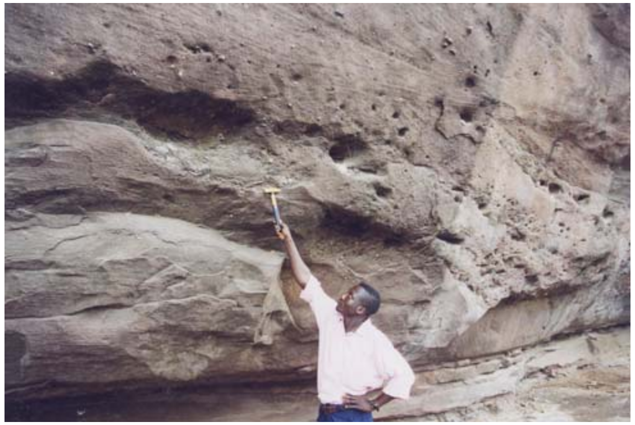
Cross bedded quartzite at Tease

Cross bedded sandstone at Odomase

SHEET 4 - MIDDLE VOLTAIAN FORMATION – OBOSUM BEDS. FELDSPATHIC SANDSTONES – AFRAM PLAINS

Weathered sandstone duricrust pavement west of Maame Krobo

Gravelly Obosum Sandstone west of Maame Krobo



Cross-bedded pseudo-karstic weathered sandstones
at Abotum Hill, Bonkrom

Weathered gravel and feldspathic sandstone

SHEET 5 - MIDDLE VOLTAIAN FORMATION – OTI BEDS, AFRAM SHALES

Afram Mudstone as excavated from a hand dug well at Takarotwene

Weathered Afram shales south of Ejura on the road to Kumasi.

Rock chip samples of grey-black silty mudstone from Borehole No 5 at Bonkrom

Appendix 6 – Summary Geological Formation Groundwater Hydrochemistries.

TABLE 6/1 - MASSIVE CONGLOMERATE AND SANDSTONE HYDROCHEMISTRY

Rock unit	**Massive conglomerate and sandstone**			
No of samples		**12**		
	Min	Max	Average	Comments
Temp deg C	26.8	30	27.8	
SEC	252	1133	621	
PH	5.89	7.94	6.59	
Major ions mg ℓ^{-1}				
Na	21	210	62.2	
K	1	4.6	2.97	
Ca	17.3	67	47.5	
Mg	5	32	19	
HCO_3	71	339	247.5	
SO_4	1.9	20.4	7.4	
Cl	10	264	61.8	
Minor Ions mg ℓ^{-1}				
Al	0.01	0.06	0.03	4 above detection limit
As				all below detection limit
B	0.2	0.8		2 above detection limit
Ba	0.055	0.69	0.21	
Be				all below detection limit
Br	0.05	3.6	0.45	
Cu	0.008	0.016		2 above detection limit
F	0.21	0.539	0.42	
Fe	0.006	0.121		5 above detection limit
I	0.02	0.177	0.085	
Mn	0.002	0.161	0.05	
NH_4-N	0.02	0.377	0.13	5 above detection limit
NO_2-N	0.006	4.24	0.91	5 above detection limit
NO_3-N	0.4	10.8	5.96	7 above detection limit
P	0.1	0.3	0.18	8 above detection limit
Si	11.9	57	33.7	
Sr	0.25	1.84	0.88	
Zn	0.01	0.06	0.02	

TABLE 6/2 - QUARTZITIC SANDSTONE AND CONGLOMERATE HYDROCHEMISTRY

Rock unit	**Quartzitic sandstone and conglomerate**			
No of samples		**6**		
	Min	Max	Average	Comments
Temp deg C	26.3	27.7	26.9	
SEC	126	486	358.5	
PH	5.78	8.37	6.9	
Major ions mg ℓ^{-1}				
Na	9.1	87.3	43.7	
K	0.8	3	1.4	
Ca	4.8	44.7	28.3	
Mg	0.94	14.1	8.1	
HCO_3	70.7	242.8	198	
SO_4	0.6	14.3	4.5	
Cl	0.7	22.3	6.3	
Minor Ions mg ℓ^{-1}				
Al	0.01	0.8	0.21	
As				all below detection limit
B	0.1	1.3	0.57	
Ba	0.01	0.44	0.23	
Be				all below detection limit
Br	0.01	0.07	0.04	
Cu				all below detection limit
F	0.2	1.38	0.5	
Fe	0.02	1.06	0.27	
I	0.008	0.056	0.03	
Mn	0.005	0.324	0.14	
NH_4-N	0.078	0.325	0.2	2 above detection limit
NO_2-N	0.003	0.006	0.005	2 above detection limit
NO_3-N				all below detection limit
P	0.1	0.1	0.1	1 above detection limit
Si	11.3	42	27.07	
Sr	0.112	0.553	0.36	
Zn	0.007	0.015	0.01	

TABLE 6/3 - FELDSPATHIC SANDSTONE, ARKOSE, SILTSTONE AND MUDSTONE HYDROCHEMISTRY

Rock unit	**Feldspathic sandstone, arkose, siltstone and mudstone**			
No of samples	**5**			
	Min	Max	Average	Comments
Temp deg C	26.6	27.5	27.2	
SEC	367	639	531	
PH	6.35	7.13	6.78	
Major ions mg ℓ^{-1}				
Na	28.5	96.2	61.9	
K	1.1	2.4	1.6	
Ca	32.7	56.6	44.4	
Mg	10.6	19.7	15.7	
HCO_3	229	378	298.2	
SO_4	2.3	4.6	4.3	
Cl	6	42	20.8	
Minor Ions mg ℓ^{-1}				
Al	0.01	0.12	0.05	
As				all below detection limit
B				all below detection limit
Ba	0.04	0.67	0.2	
Be				all below detection limit
Br	0.04	0.12	0.08	
Cu	0.013	0.013	0.013	2 above detection limit
F	0.2	0.26	0.24	
Fe	0.01	0.05	0.02	3 above detection limit
I	0.04	0.09	0.06	
Mn	0.02	0.17	0.1	
NH_4-N				all below detection limit
NO_2-N				all below detection limit
NO_3-N				all below detection limit
P	0.2	0.2	0.2	2 above detection limit
Si	22.9	55.7	36.46	
Sr	0.36	1.55	1.01	
Zn	0.03	0.73	0.16	

TABLE 6/4 - UNFRACTURED SHALE AND SANDSTONE HYDROCHEMISTRY

Rock unit	**Unfractured shale and sandstone**			
No of samples		**6**		
	Min	Max	Average	Comments
Temp deg C	27.3	29	27.8	
SEC	983	1856	1443	
PH	7.49	8.01	7.53	
Major ions mg ℓ^{-1}				
Na	149	444	293	
K	2.1	10	4.2	
Ca	19.7	60.3	58.6	
Mg	2.29	36.1	14.5	
HCO_3	465	584	535.4	
SO_4	9.9	92.6	46	
Cl	47.5	431	199	
Minor Ions mg ℓ^{-1}				
Al	2.02	2.02	0.54	3 above detection limit
As	0	0	0	all below detection limit
B	0.2	1.9	0.83	
Ba	0.148	0.559	0.27	
Be	0	0	0	all below detection limit
Br	0.33	2.08	0.877	
F	0.56	2.47	1.1	
Fe	0.01	0.77	0.153	
I	0.11	0.58	0.23	
Mn	0.03	0.12	0.06	
NH_4-N	0.12	0.21	0.162	
NO_2-N	0.01	0.01	0.01	1 above detection limit
NO_3-N	0	0	0	all below detection limit
Si	7.14	19.6	12.5	
Sr	0.42	2.38	1.1	
Zn	0.01	0.114	0.03	