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# The hydrogeology of the Oju/Obi area, eastern Nigeria: Adum West area data report

A M MacDonald and J Davies

Natural Environment Research Council

International Division
British Geological Survey
Keyworth
Nottingham
United Kingdom NG12 5GG

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J Davies and A M MacDonald

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Test pumping borehole BGS33 at Adum West.



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Keyworth, Nottingham NG12 5GG
☎ 0115-936 3100 Telex 378173 BGSKEY G
Fax 0115-936 3200

Murchison House, West Mains Road, Edinburgh, EH9 3LA
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☎ 01232-666595 Fax 01232-662835

Maclean Building, Crowmarsh Gifford, Wallingford, Oxfordshire OX10 8BB
☎ 01491-838800 Fax 01491-692345

*Parent Body*
Natural Environment Research Council
Polaris House, North Star Avenue, Swindon, Wiltshire SN2 1EU
☎ 01793-411500 Telex 444293 ENVRE G
Fax 01793-411501

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## PREFACE

Oju is a remote part of south-eastern Nigeria that suffers from severe water shortage during the annual dry season. From November to April, unprotected ponds, seepages and hollows are the primary source of domestic water. Unfortunately, these sources become less reliable towards the end of the dry season and many are contaminated. As a consequence, much of the population of Oju (300 000 approx.) is badly affected by a variety of water related illnesses, of which guinea worm and malaria are endemic; outbreaks of cholera, typhoid and dysentery are also common. In response, DFID have commissioned WaterAid to provide improved village level, year round water sources, primarily utilising the limited groundwater resources of the area.

Due to the complex hydrogeology, WaterAid have asked the British Geological Survey (BGS) to assist with the project. BGS are applying the results of TDR projects undertaken within other parts of the world to study these marginal groundwater resources.

The groundwater investigations by BGS started in September 1996. There are three main aims of the research: (1) to assess the potential of the Oju area for sustainable groundwater supplies; (2) to develop appropriate methods for siting wells or boreholes in the Oju environment; and (3) to recommend appropriate methods and designs for exploiting groundwater.

This report forms one of a series of data reports designed to complement the summary assessment of the hydrogeology of the Oju/Obi area and the Groundwater Development Map. The data presented were collected on five separate trips, August-September 1996, November-December 1996, February-March 1997, October-December 1997 and January-April 1998.

## EXECUTIVE SUMMARY

The groundwater development potential of the dolerite intrusions within the Awgu Shale was investigated at Adum West. EM34-3 and magnetic surveys along a 3 km traverse and three resistivity soundings were carried out during February and March 1998. Three boreholes were drilled and chip and core samples obtained were analysed and logged. All boreholes (BGS33, BGS34 and BGS35) were completed to production standard with screen and casing. All three boreholes were test pumped and water samples were obtained for hydrochemical analysis. The following conclusions can be made from the test site.

- The Awgu Shales are composed of soft mudstones with some siltstone and fine sandstone.
- Dolerite exists as thick intrusions, and comprises hard dark blue/green fine-medium grained basic igneous rock – it can be highly fractured, with much zeolite (mainly mesolite).
- Much groundwater was found within the fractured dolerite.
- Adjacent to the dolerite the shales were baked and turned light grey to white in colour; they did not contain much water.
- Pumping tests indicated high transmissivity values (20 – 60 $m^2/d$) from the dolerite – where the dolerite was found only at depth, the transmissivity was lower (4 $m^2/d$).
- The presence of dolerite at shallow depths was easily identified from geophysics: EM34-3 readings reduced from about 80 to 40 mmhos/m and the magnetometer recorded many magnetic anomalies.
- Only the resistivity sounding managed to identify the dolerite at 30 m depth in BGS34. Both the EM34-3 and magnetic surveys couldn't penetrate sufficiently to identify the dolerite.
- Water quality within the dolerite was good and within the WHO recommendations for drinking water.
- Although yields from the boreholes were high, the sustainability of the groundwater resources is not known – longer pumping tests and long term monitoring of water levels is required.

## 1. BACKGROUND INFORMATION

Adum West was chosen to test the groundwater development potential of dolerite intrusions within the Awgu Shale. A 3 km geophysics traverse was undertaken running north-south through Adum West Village in eastern Obi (see Figure 1). Within the Adum West area the Awgu Shale formation is primarily composed of dark grey black carbonaceous blocky shaley mudstones deposited within a shallow marine environment. The geological and aeromagnetic maps of the area indicated the presence of strong but discrete aeromagnetic anomalies within the Awgu Shale formation underlying the Adum West area, implying the presence of dolerite. A dolerite sill is known to crop out in the bank of the Obi River west of Adum West. There are very few wells in the area, most people obtaining water from seepages in the banks of the Obi river about 3 km to the west of the village. A borehole has been drilled to the south of Adum West for the use of the Elim health clinic.

Figure 2 and 3 show the available map data for the area and also the location of the geophysics traverse line and the test boreholes. Table 1 shows the appropriate maps and aerial photographs for Adum West. The topography is flat and the vegetation characterised by grassland with well spaced trees.

**Table 1. Available map information for Adum West.**

| Data type | Source |
|---|---|
| Aerial Photographs | Sheet 289, run 1, 100-103<br>Sheet 289, run 2, 41-45<br>Sheet 289, run 3, 16-19 |
| Topographic maps | 1:50,000 Sheet 289NE Ejekwe NE |
| Geology map | Ogoja Area, Map No. 73, Scale 1:250,000 |

## 2. GEOPHYSICS

Several geophysical surveys were carried out including EM34-3 and magnetic profiling along a three kilometre traverse between a culvert 2 km south of Adum West to a stream north of the village. Available maps (see Figure 2) indicated a high possibility of encountering dolerite intrusions within the Awgu Shale at Adum West. Table 2 gives a summary of the various traverses and soundings. Data are presented in Appendix 1.

The EM34-3 data indicates a change from high electrical conductivity (vertical coil ~ 80 mmhos/m) over the first 1.2 km, to lower readings (vertical coil ~ 40 mmhos/m) throughout the rest of the traverse (see Figure 4). Generally, vertical coil readings are higher than horizontal coil readings. The change in the conductivity measurements corresponds to an increase in anomalies recorded by the magnetometer. Two large anomalies at 0 m and 3000 m are due to culverts. A summary of the significant points of the geophysical surveys are given below:

1. Conductivity values are generally high: horizontal dipole readings range from 30 to 100 mmhos/m
2. Horizontal dipole measurements are higher than those taken with the vertical dipole
3. There is a marked reduction in conductivity at about 1.2 km
4. The section of the traverse with lower conductivity values corresponds to marked anomalies on the magnetic profile.
5. Where the conductivity values are high, there are no magnetic anomalies.

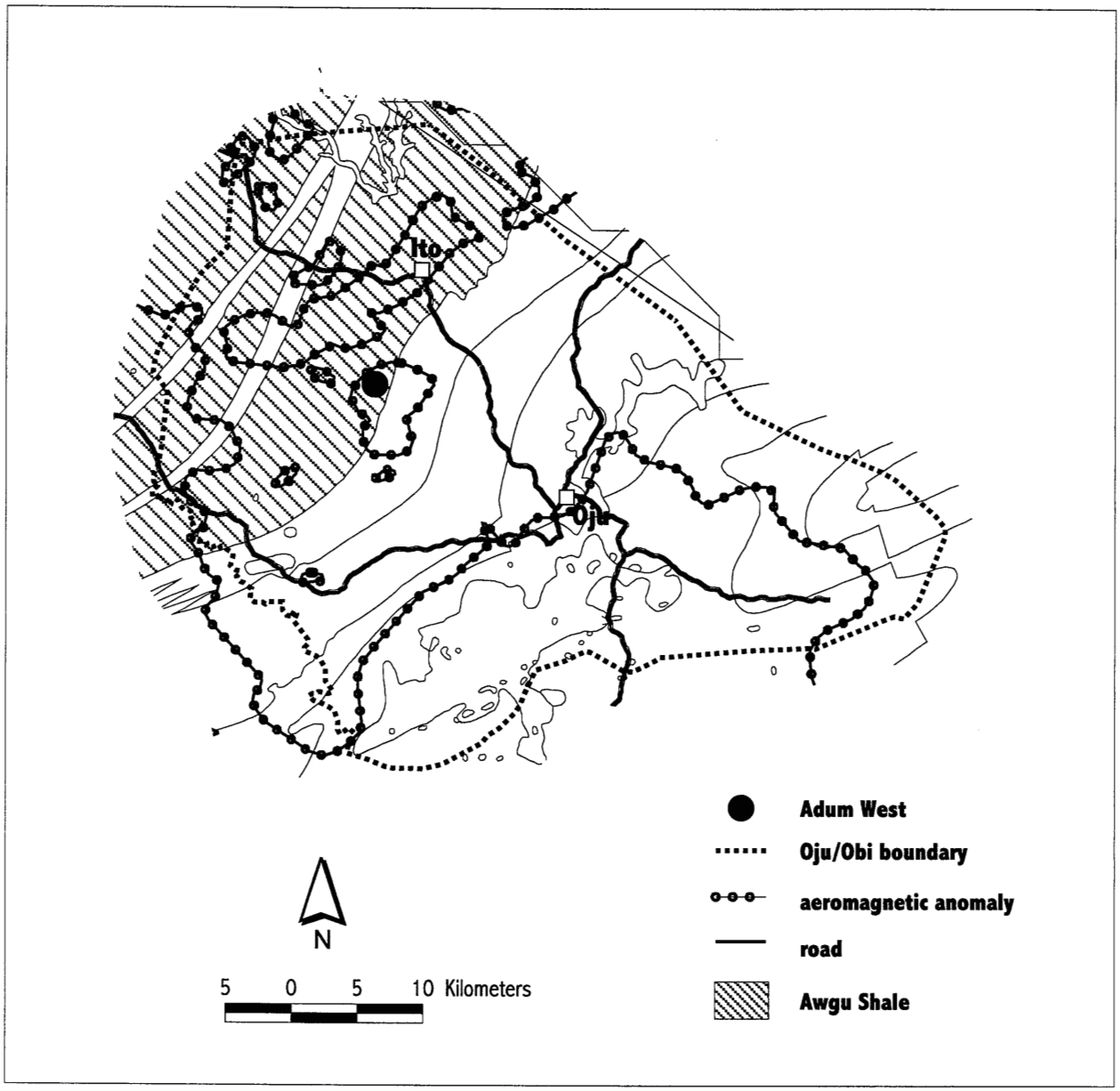



Figure 1. The location of Adum West village and the outcrop of the Awgu Shale.

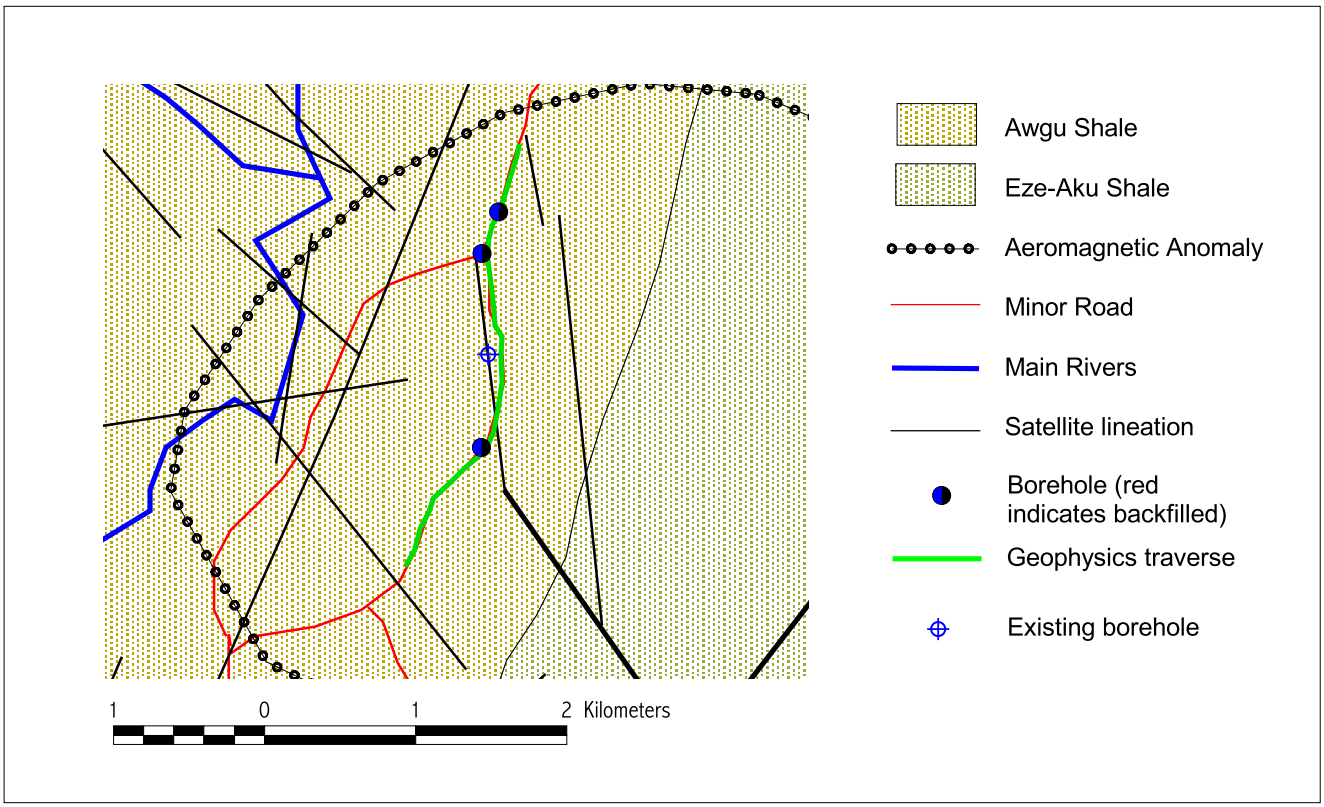



Figure 2. Available map information for Adum West, and location of boreholes and geophysical surveys.

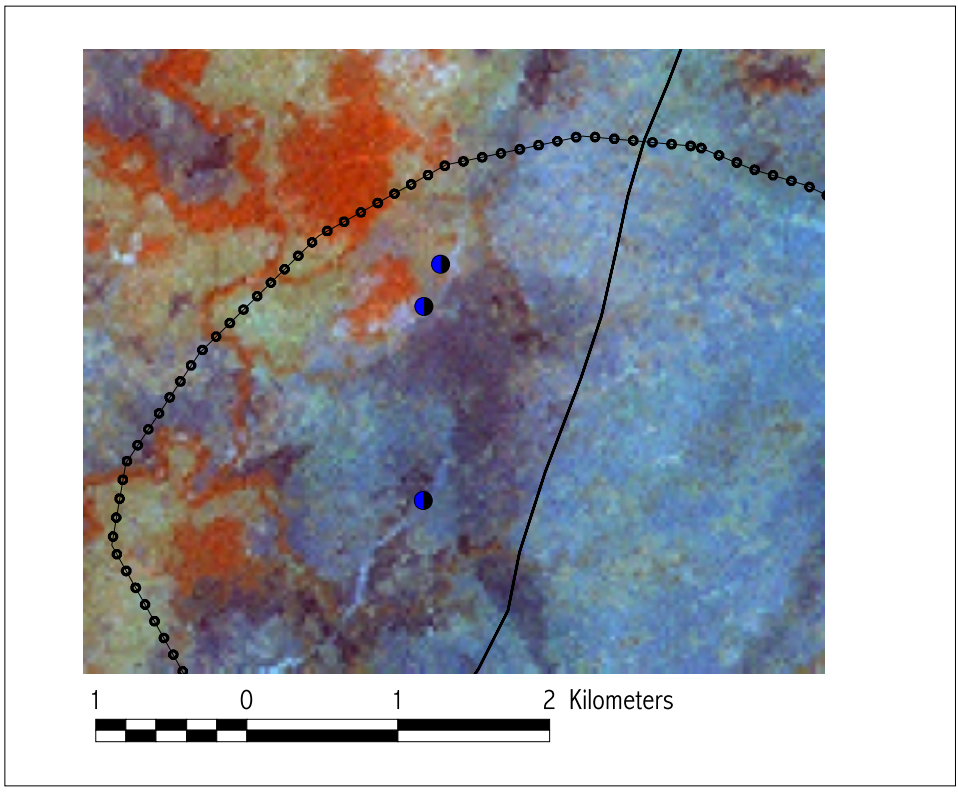



Figure 3. Satellite image for Adum West.

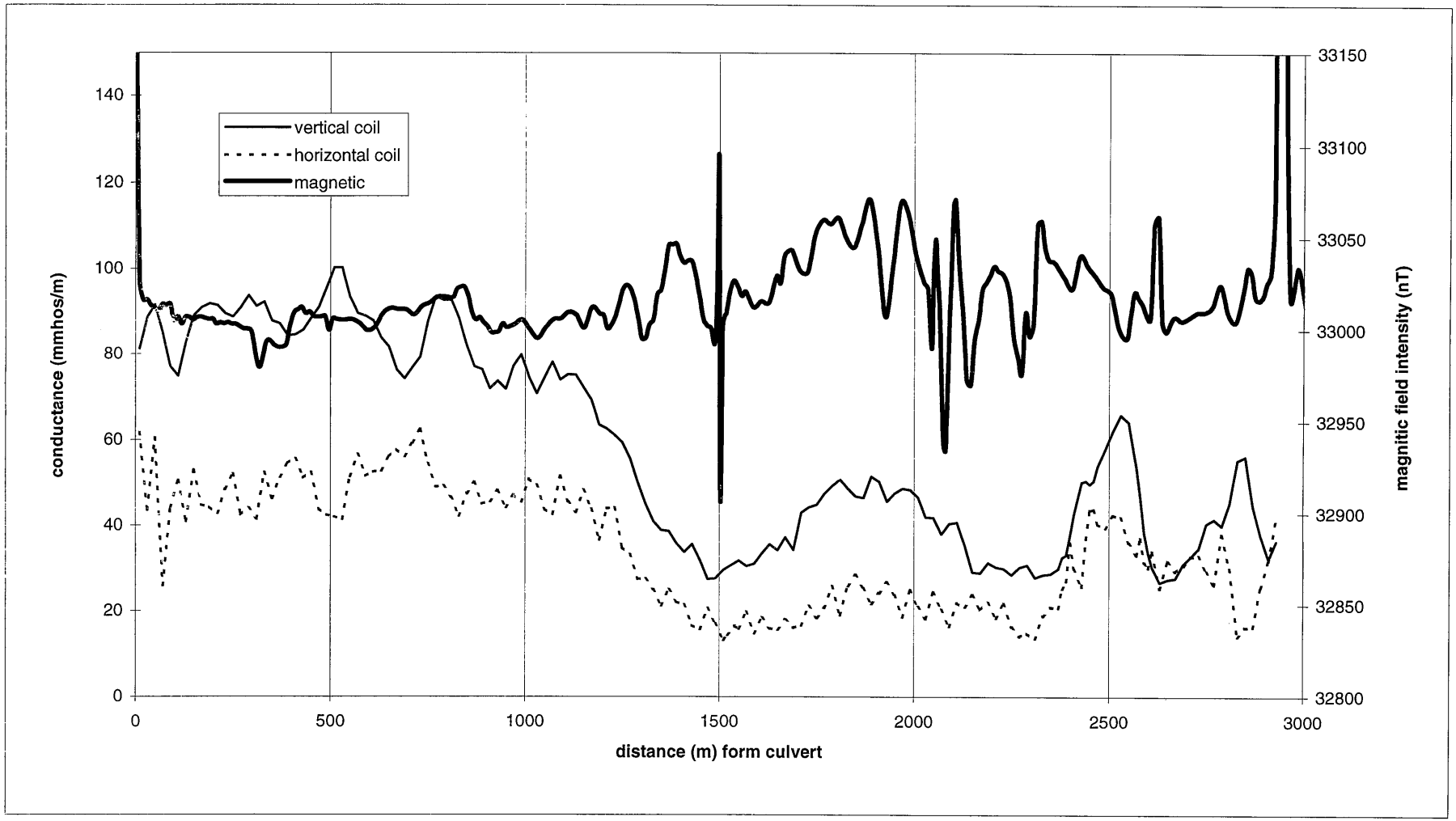



Figure 4 EM34-3 and magnetic field data for Adum West.

Three resistivity soundings were carried out along the traverse. They were located on type sections of the EM34-3 traverse. AW3 was located at 2200 m and indicated a resistive soil over a low resistivity clay layer followed by a moderate resistivity 50 – 100 ohm-m bedrock. AW4 was located at 980 m. This showed a resistive soil overlying a thick clay with a moderate resistive bedrock (190 ohm-m) at about 15 m. AW5 was located 2540 m along AW1and indicated a resistive soil overlying a 5 m clay layer with a highly resistive (2000 ohm-m) bedrock at 6 m depth.

Test boreholes were located on each of the resistivity survey sites:

- BGS 33: 2200 m along AW1 next to 'Assemblies of God' sign board
- BGS 34: 980 m along AW1
- BGS 35: 2540 m along AW 1 at C of S sign Board.

**Table 2. Main Geophysical Surveys carried out at Adum West (data in Annex 1)**

| Survey number | Co-ordinates start | Length | Average Spacing | Survey type | Description |
|---|---|---|---|---|---|
| AW1 | 6° 56.163'<br>8° 17.398' | 3 km | 20 m | EM34-3 (20 m) | From lopsided culvert north through Adum West village to culvert in valley. |
| AW2 | 6° 56.163'<br>8° 17.398' | 3 km | 20 m | Magnetic | As AW1 |
| AW3 | 6° 57.211'<br>8° 17.623' | | 0.5 – 64 m | Offset Wenner | On BGS33 2.2 km along AW1; poor electrode contact. |
| AW4 | 6° 56.521'<br>8° 17.665' | | 0.5 – 64 m | Offset Wenner | On BGS34 0.98 km along AW1; poor electrode contact |
| AW5 | 7° 57.367'<br>8° 17.727' | | 0.5 – 64 m | Offset Wenner | On BGS35 2.54 km along AW1; poor electrode contact |

## 3. DRILLING

Three boreholes were drilled at Adum West. The boreholes were drilled with tricone and hammer; core samples were taken where possible. Summary information on the boreholes is given in Table 3. More details on construction etc. are given in Annex 2.

**Table 3. Summary details of drilling. Full details given in Annex 2**

| Borehole ID | Location | Date completed | Total depth | Drilled diameter | Section cored | Water strike | Casing above gl | Comments |
|---|---|---|---|---|---|---|---|---|
| BGS33 | 6° 57.211'<br>8° 17.623' | 9/3/98 | 18.5 m | 165 mm | No core | 16.5 m (flowing) | 0.5 m | Much water |
| BGS34 | 6° 56.521'<br>8° 17.665' | 11/3/98 | 39.7 m | 165 mm | 20.5 – 23.0 m | 11.5, 32.5, (more) | 0.15 m | Majority of water from 32 m |
| BGS35 | 6° 57.367'<br>8° 17.727' | 12/3/98 | 21.5 m | 165 mm | 14.5-17.5 m | 12 (flowing)<br>19 (much) | 0.47 m | |

The following sections give a brief summary of the lithological logs. Full details are given in Annex3. Figure 5 shows a schematic of the borehole logs.

**Summary lithological log: BGS33**

| | |
|---|---|
| 0.0 - 1.5 | Soil/ferricrete horizon |
| 1.5 - 2.5 | Clayey very weathered horizon |
| 2.5 - 5.5 | Weathered silty mudstones |
| 5.5 - 8.0 | Weathered siltstones |
| 8.0 - 10.0 | Fairly weathered baked siltstones |
| 10.0 - 11.0 | Hard baked mudstones |
| 11.0 - 13.0 | Soft weathered dolerite |
| 13.0 - 15.0 | Dolerite |
| 15.0 - 18.5 | Soft fractured dolerite with zeolite |

**Summary lithological log: BGS34**

| | |
|---|---|
| 0.0 - 1.0 | Soil/ferricrete horizon |
| 1.0 - 3.0 | Clayey very weathered horizon |
| 3.0 - 6.5 | Weathered carbonaceous mudstones and siltstones |
| 6.5 - 10.0 | Fairly weathered shaley mudstone |
| 10.0 - 14.0 | Hard baked shaley mudstone |
| 14.0 - 17.0 | Carbonaceous shaley mudstones |
| 17.0 - 19.5 | Soft carbonaceous shaley mudstones |
| 19.5 - 20.5 | Carbonaceous shaley mudstones |
| 20.50 - 23.50 | Thinly bedded carbonaceous shaley mudstone with septarian nodules, pyrite and thin brown crystalline partings |
| 23.5 - 24.5 | Hard carbonaceous shaley mudstones |
| 24.5 - 26.5 | Carbonaceous shaley mudstones |
| 26.5 - 27.5 | Soft carbonaceous shaley mudstones |
| 27.5 - 29.0 | Harder carbonaceous shaley mudstones |
| 29.0 - 29.5 | Sandstone |
| 29.5 - 31.5 | Baked silty mudstone |
| 31.5 - 34.0 | Hard fine grained dolerite |
| 34.0 - 35.5 | Fractured dolerite with zeolite |
| 35.5 - 37.5 | Compact dolerite |
| 37.5 - 39.5 | Dolerite with zeolite |

**Summary lithological log: BGS35**

| | |
|---|---|
| 0.0 - 3.0 | Soil/ferricrete horizon |
| 3.0 - 4.5 | Clayey very weathered horizon |
| 4.5 - 7.0 | Very weathered clayey silts (from dolerite) |
| 7.0 - 12.0 | Very weathered dolerite with clay |
| 12.0 - 13.0 | Hard dolerite with xeolite |
| 13.0 - 14.5 | Soft very weathered dolerite |
| 14.80 - 15.20 | Weathered dolerite core-stone |
| 15.20 - 15.75 | Very weathered dolerite |
| 15.75 - 16.07 | Fairly weathered dolerite, some xeolite |
| 16.58 - 16.65 | Very weathered dolerite |
| 16.65 - 17.12 | Dolerite with much xeolite |
| 17.12 - 17.20 | Soft friable dolerite with zeolite vein |
| 17.20 - 21.5 | Hard dark green fine to medium grained dolerite |

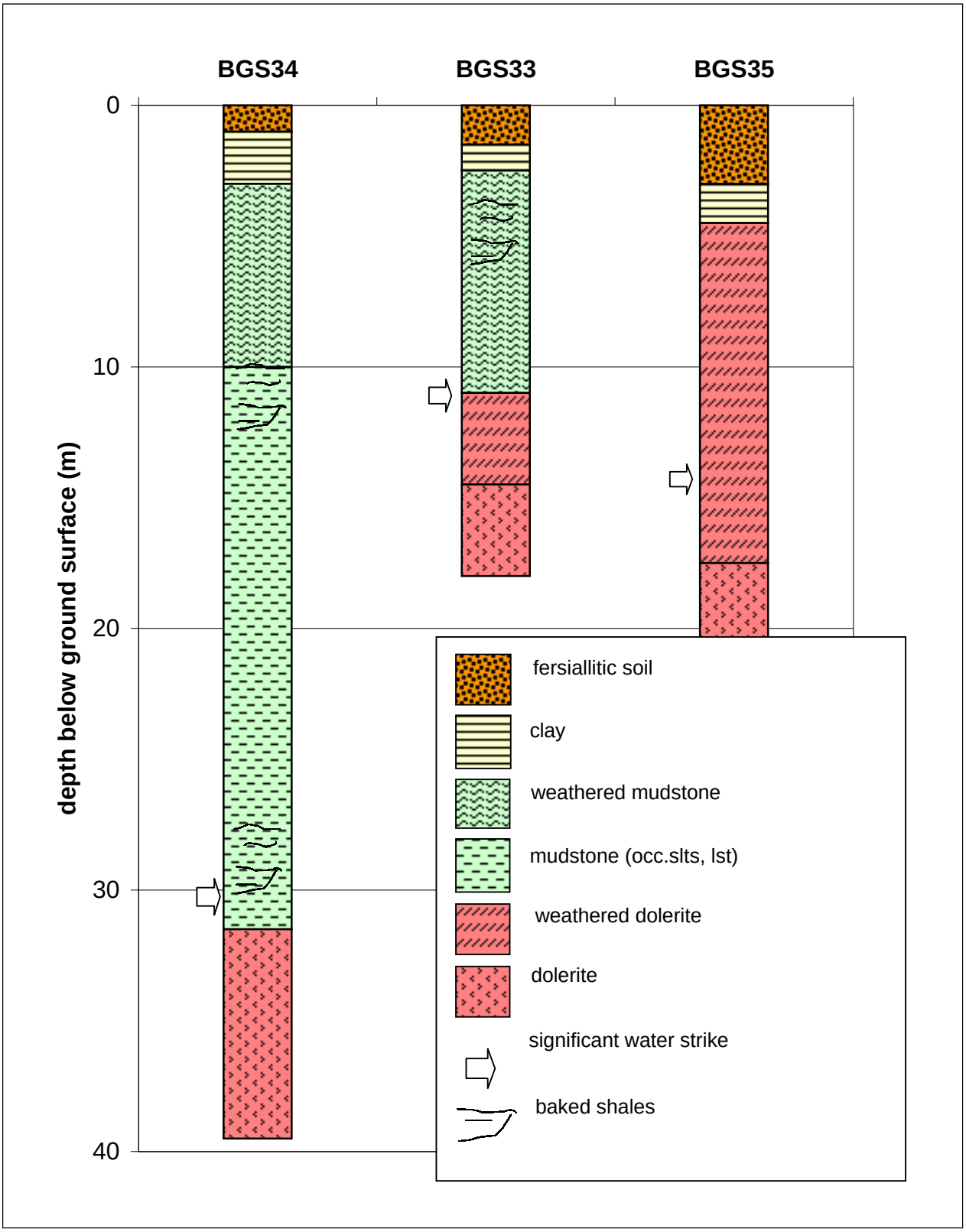



Figure 5. Simplified lithological logs for the Adum West Boreholes. (Horizontal axis not to scale).

## 4. TEST PUMPING

The three boreholes drilled at Adum West produced water at more than 1 l/sec by air-lift during drilling. Bailer tests were carried out on each borehole followed by longer tests using the Honda centrifugal and Grundfos electrical submersible pumps. Table 4 gives a summary of the test pumping; data and analyses are given in Annex 4.

**Table 4. Summary of pumping tests carried out at Adum West. (Annex 4 contains data and analysis).**

| Borehole and Test | Date | Casing height above ground | RWL (mbtc) | Length of test (mins) | P-rate (l/s) | Transmissivity ($m^2/d$) |
|---|---|---|---|---|---|---|
| BGS33 | | | | | | |
| Bailer test | 23/3/98 | 0.5 m | 3.54 | 8:50 | 0.35 | No analysis possible |
| Centrifugal | 11/3/98 | 0.5 m | 3.32 | 185 | 3.5 | Jacob: 61 |
| | | | | | | Theis Rec: 51 |
| BGS34 | | | | | | |
| Bailer test | 23/3/98 | 0.18 m | 4.659 | 9:39 | 0.3 | Barker: 8.7 |
| | | | | | | Theis Rec: 6.5 |
| Grundfos test | | | 4.43 | 51 | 1.1 | Jacob 4.3 |
| | 23/3/98 | 0.5 m | | | | Theis rec 3.8 |
| BGS35 | | | | | | |
| Bailer test | 23/3/98 | 0.5 m | 5.669 | 9:45 | 0.3 | Barker: 26 |
| | | | | | | Theis Rec: 28 |
| Grundfos test | 25/398 | 0.5 | 5.39 | 300 | 1.15 | Jacob: 22 |
| | | | | | | Theis rec: 23 |

Aquifer properties measured at each of the boreholes were good. The bailer tests were analysed using the Theis Recovery method (Kruseman and de Ridder 1990) and Barker's large diameter well method (Barker 1989). The longer pumping tests were analysed using standard drawdown and recovery methods (Kruseman and de Ridder 1990). The transmissivity of the rocks around Adum West is sufficiently high to support a hand pump. The best aquifer properties were from BGS33 and BGS35. These two boreholes penetrate dolerite at a shallow depth. The poorer aquifer properties encountered in BGS34 is probably because the dolerite is penetrated at 30 m and therefore is not within the weathered zone. The long term sustainability of the water supplies is not known. Longer term testing should be carried out in the area and water-levels in the vicinity monitored.

A water sample for hydrochemical analysis was taken from each of the boreholes. This was taken either during the pumping test or later using the Whale pump. Some field analysis was undertaken (see Table 5) and the samples were also analysed in the UK Annex 5 gives the chemistry data. All the samples conform to the WHO standards for drinking water.

**Table 5. Chemistry samples taken from Adum West.**

| ID No | Sample No | date | Conductivity (µS/cm@25°C) | TDS (mg/l) | pH | Temp (°C) | HCO3 titr (50ml 1.6M) | Comments |
|---|---|---|---|---|---|---|---|---|
| BGS33 | 213 | 12/3/98 | 509 | 207 | 6.95 | 25 | 141 | Taken after 1 hour pumping |
| BGS34 | 248 | 2/4/98 | 518 | 273 | 7.61 | 30 | 125 | pumped for 10 minutes with Whale Pump prior to sample |
| BGS35 | 249 | 2/4/98 | 546 | 275 | 7.67 | 29 | 147 | pumped for 10 minutes with Whale Pump prior to sample |

## 5. SUMMARY AND CONCLUSIONS

The groundwater potential of the dolerite area of Adum West was investigated. Various geophysical surveys were undertaken and a series of boreholes drilled and tested. The following work was undertaken in North Obi:

- 3 km of EM34-3 surveys
- 3 km magnetic profiling
- 13 resistivity VES
- 3 boreholes were drilled and approximately 3 m of core taken from two boreholes
- chip and core samples from each borehole were logged and analysed
- boreholes, BGS33, BGS34, BGS35 were screened and cased
- bailer tests and longer pumping tests were carried out on each screened borehole
- water samples were taken from each borehole for hydrochemical analysis.

The geophysical survey results correlated well with lithological data obtained from the drilling:

1. Conductivity values are generally high (horizontal dipole 30-100 ohm-m). This result correlates with the high percentage of smectite clay present within the thick soil profile.

2. Vertical dipole (horizontal coil) results were generally less than those from the horizontal dipole (vertical coil). This indicates that the conductivity reduces with depth, probably correlated with the amount of clay within the mudstone

3. High conductivity values (horizontal dipole: 80-100 mmhos/m) corresponded to the presence of unbaked Awgu Shale at shallow depths.

4. The marked reduction in conductivity (approximately 40 mmhos/m) and presence of magnetic anomalies from 1.2 to 3 km indicates the presence of shallow dolerite.

5. Neither the EM34 nor magnetic profiling identified the dolerite at depth in BGS34 – both survey techniques gave readings very similar to those found on the North Obi traverse (WC/98/52R). However, the resistivity sounding carried out at BGS34 gave a significantly different profile to those at North Obi. Interpretation of the data indicated a resistive layer at depth, which on drilling proved to be dolerite.

6. It was difficult to distinguish baked shales from dolerite using resistivity – both had a resistivity of about 100-2000 ohm-m.

Several conclusions can be made from the rock core and chip samples.

- The Awgu Shale generally comprises soft mudstones with some siltstone and fine sandstone

- The dolerite exists as thick intrusions, and comprises hard dark blue/green fine-medium grained basic rock.

- The dolerite can be highly fractured and contains many zeolites (mainly mesolite)

- At the surface, the dolerite weathers to form smectite clay.

- Most water was found within the fractured dolerite with much zeolite.

- The baked shales next to the dolerite are light grey to white in colour and do not contain much water.

The groundwater development potential of the dolerite at Adum West is very high. Tests indicate very high transmissivity values (20-60 $m^2/d$) in the two boreholes that encounter dolerite at a shallow depth. The majority of the water is flowing through the fractures within the dolerite. Although the transmissivity is high, the volume of water stored within the fractures may be quite low. Therefore the sustainability of groundwater supplies from this area should be monitored. Water quality from the dolerite is good and all samples were within the WHO recommended limits.

## REFERENCES

Barker J A, 1989. Programs to simulate and analyse pumping tests in large diameter wells. British geological Survey technical report WD/89/24.

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

Kruseman G P and de Ridder N A, 1990. Analysis and evaluation of pumping test data. IRLI publication 47, The Netherlands.

# Annex 1: Geophysics data

# Adum West

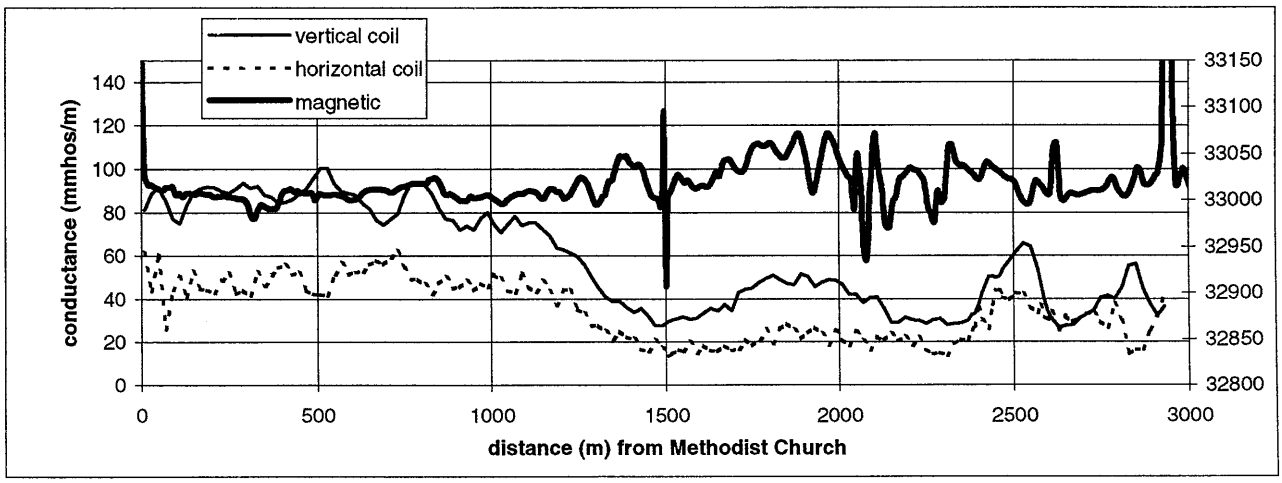
# AW1-2

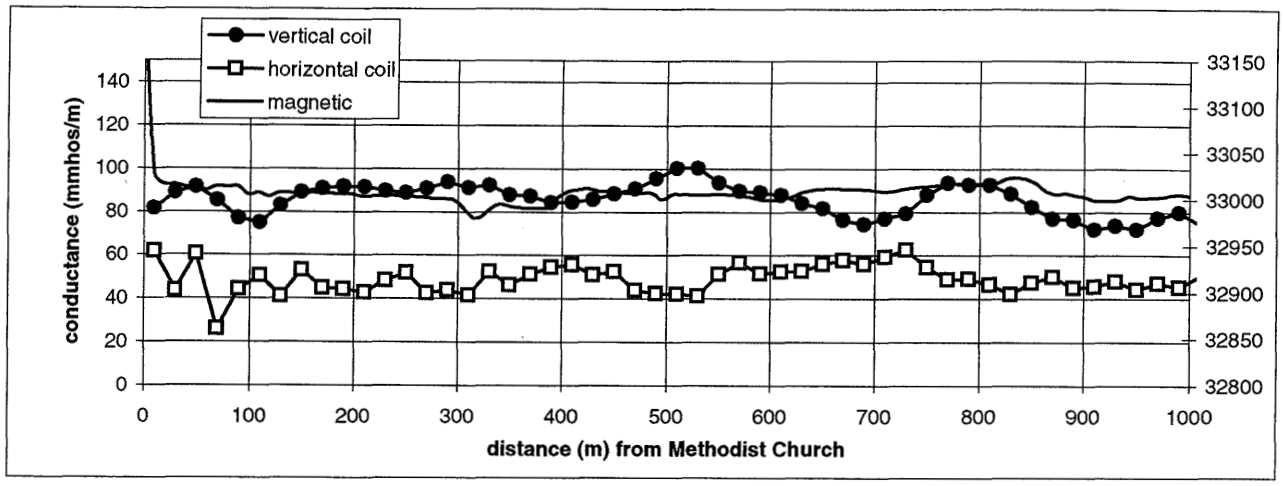
**GPS start:** 6 degs 56.163; 8 degs 17.398
**GPS finish**
**Date and time:** 25/02/98
**Survey:** AW1 From lopsided culvert throuh village to culvert Em34-3
AW2 magnetic as AW1

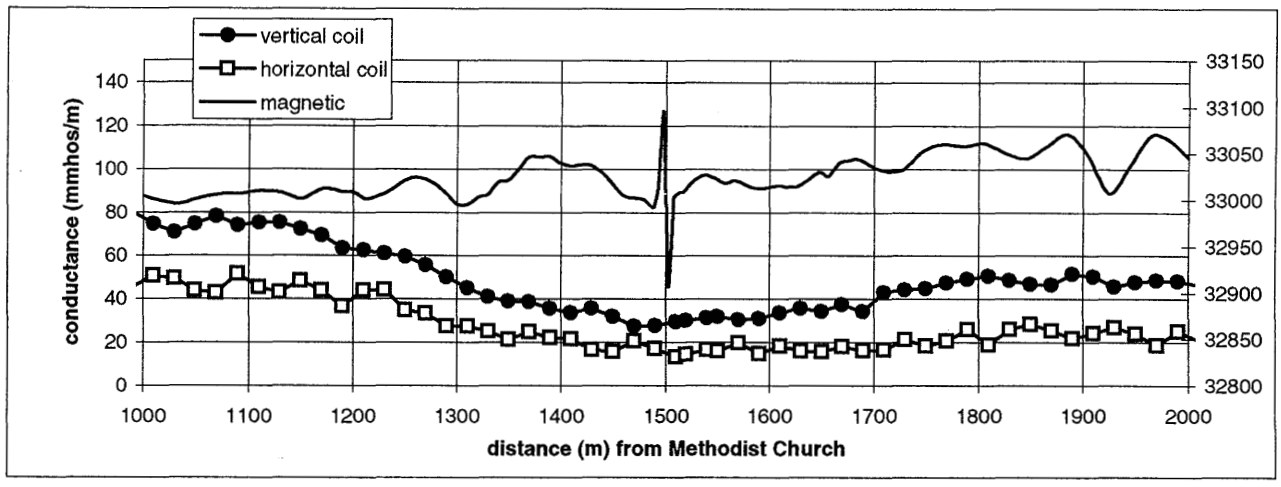
## AW 1:

| position (m) | strike (deg) |
|---|---|
| 0 | 24 |
| 60 | 30 |
| 140 | 19 |
| 280 | 30 |
| 380 | 46 |
| 440 | 52 |
| 540 | 60 |
| 760 | 45 |
| 880 | 36 |
| 1060 | 18 |
| 1180 | 10 |
| 1320 | 348 |
| 1840 | 350 |
| 2060 | 14 |
| 2180 | 16 |

| position (m) | comments |
|---|---|
| 0 | culvert - lopsided |
| 500 | anthill left |
| 535 | Agba tree |
| 730 | small path left |
| 850 | path |
| 1160 | road right |
| 1260 | farm path right |
| 1460 | path to Elim |
| 1680 | concrete culvert |
| 1940 | wooden culvert |
| 1980 | concrete culvert |
| 2180 | Mango tree |
| 2200 | sign board methodist church |
| 2250 | path left |
| 2405 | culvert |
| 2510 | C and S signboard |
| 2580 | end path to blue house |
| 2610 | x roads to houses |
| 2660 | path right to compounds |
| 2720 | down |
| 2925 | culvert |




vertical coil
horizontal coil
magnetic
conductance (mmhos/m)
0
20
40
60
80
100
120
140
32800
32850
32900
32950
33000
33050
33100
33150
0
100
200
300
400
500
600
700
800
900
1000
distance (m) from Methodist Church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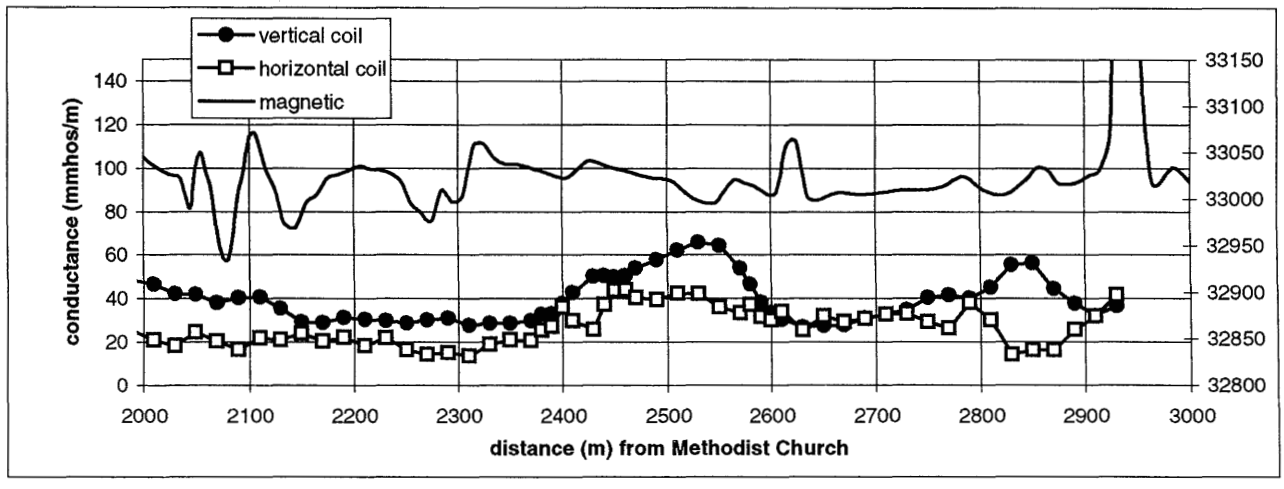
32850
32900
32950
33000
33050
33100
33150
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
2000
distance (m) from Methodist Church


vertical coil
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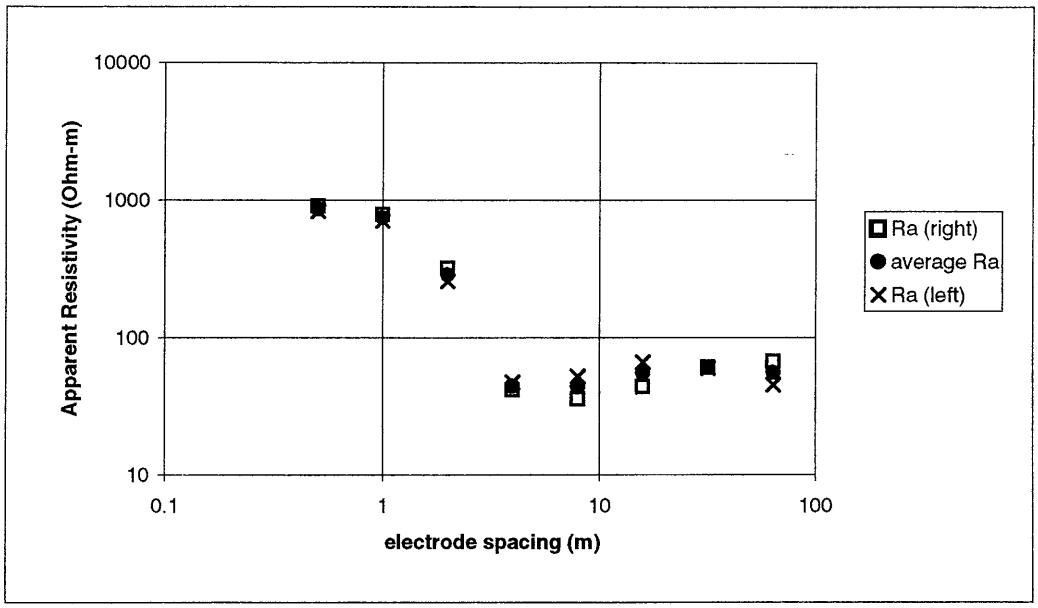
32950
33000
33050
33100
33150
2000
2100
2200
2300
2400
2500
2600
2700
2800
2900
3000
distance (m) from Methodist Church

# Adum West

# AW3

Resistivity Survey 1
Located at sign board - 2200 along AD1 poor electrode contact
Offset Wenner left to Egori
Strike 20 degs
03/03/98

| spacing (m) | left | right | Ra (left) | Ra (right) | average Ra |
|---|---|---|---|---|---|
| 0.5 | 264 | 286 | 828.96 | 898.04 | 863.5 |
| 1 | 111.7 | 125.1 | 701.476 | 785.628 | 743.552 |
| 2 | 20.4 | 25.2 | 256.224 | 316.512 | 286.368 |
| 4 | 1.876 | 1.647 | 47.12512 | 41.37264 | 44.24888 |
| 8 | 1.03 | 0.71 | 51.7472 | 35.6704 | 43.7088 |
| 16 | 0.65 | 0.432 | 65.312 | 43.40736 | 54.35968 |
| 32 | 0.297 | 0.3 | 59.68512 | 60.288 | 59.98656 |
| 64 | 0.112 | 0.164 | 45.01504 | 65.91488 | 55.46496 |



DATA SET: ADUM1

CLIENT: Wateraid
LOCATION: Oju, Benue State
COUNTY: Nigeria
PROJECT: Water and Sanitation
ELEVATION: 0.00
SOUNDING COORDINATES: X: 0.0000 Y: 0.0000

DATE: March 1998
SOUNDING: 1
AZIMUTH: 0
EQUIPMENT: BGS128

Offset Wenner Configuration

FITTING ERROR: 4.416 PERCENT

| L # | RESISTIVITY (ohm-m) | THICKNESS (meters) | ELEVATION (meters) | LONG. COND. (Siemens) | TRANS. RES. (Ohm-m^2) |
|---|---|---|---|---|---|
| | | | 0.0 | | |
| 1 | 981.2 | 1.06 | -1.06 | 0.00108 | 1043.6 |
| 2 | 5.45 | 0.871 | -1.93 | 0.159 | 4.75 |
| 3 | 95.48 | 9.43 | -11.37 | 0.0988 | 901.0 |
| 4 | 51.36 | | | | |

ALL PARAMETERS ARE FREE

PARAMETER BOUNDS FROM EQUIVALENCE ANALYSIS

| | LAYER | MINIMUM | BEST | MAXIMUM |
|---|---|---|---|---|
| RHO | 1 | 930.893 | 981.269 | 1045.859 |
| | 2 | 0.994 | 5.459 | 18.314 |
| | 3 | 67.616 | 95.485 | 112.513 |
| | 4 | 41.037 | 51.365 | 58.184 |
| THICK | 1 | 1.020 | 1.064 | 1.091 |
| | 2 | 0.146 | 0.871 | 3.107 |
| | 3 | 5.079 | 9.437 | 31.731 |
| DEPTH | 1 | 1.020 | 1.064 | 1.091 |
| | 2 | 1.223 | 1.935 | 4.160 |
| | 3 | 7.003 | 11.372 | 33.556 |

| No. | SPACING (m) | RHO-A (ohm-m) DATA | SYNTHETIC | DIFFERENCE (percent) |
|---|---|---|---|---|
| 1 | 0.500 | 863.5 | 925.7 | -7.21 |
| 2 | 1.00 | 743.5 | 708.1 | 4.76 |





| No. | SPACING (m) | RHO-A (ohm-m) DATA | SYNTHETIC | DIFFERENCE (percent) |
|---|---|---|---|---|
| 3 | 2.00 | 286.0 | 273.8 | 4.25 |
| 4 | 4.00 | 44.20 | 46.25 | -4.64 |
| 5 | 8.00 | 43.70 | 41.24 | 5.61 |
| 6 | 16.00 | 54.40 | 54.82 | -0.783 |
| 7 | 32.00 | 60.00 | 58.90 | 1.83 |
| 8 | 64.00 | 55.50 | 55.27 | 0.397 |

PARAMETER RESOLUTION MATRIX:
"F" INDICATES FIXED PARAMETER

| | P 1 | P 2 | P 3 | P 4 | T 1 | T 2 | T 3 |
|---|---|---|---|---|---|---|---|
| P 1 | 1.00 | | | | | | |
| P 2 | 0.00 | 0.51 | | | | | |
| P 3 | 0.00 | -0.01 | 0.92 | | | | |
| P 4 | 0.00 | 0.00 | -0.01 | 0.99 | | | |
| T 1 | 0.00 | 0.01 | 0.00 | 0.00 | 1.00 | | |
| T 2 | 0.00 | -0.48 | -0.05 | 0.00 | 0.00 | 0.49 | |
| T 3 | 0.00 | -0.03 | 0.20 | 0.07 | 0.01 | 0.07 | 0.30 |

# Adum West

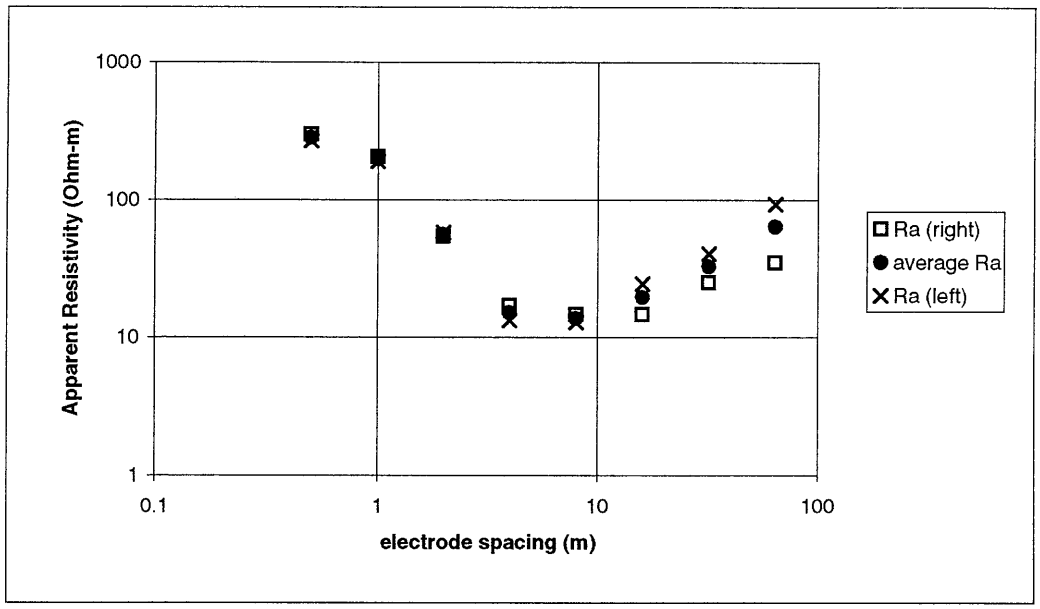
# AW4

Resistivity Survey 2
Located 980 along AD1
Offset Wenner
Strike 25 degs
03/03/98

right to Adum west

6 degs 56.601; 8 degs 17.617
poor electrode contact

| spacing (m) | left | right | Ra (left) | Ra (right) | average Ra |
|---|---|---|---|---|---|
| 0.5 | 85.5 | 95 | 268.47 | 298.3 | 283.385 |
| 1 | 30.3 | 32.6 | 190.284 | 204.728 | 197.506 |
| 2 | 4.61 | 4.31 | 57.9016 | 54.1336 | 56.0176 |
| 4 | 0.528 | 0.678 | 13.26336 | 17.03136 | 15.14736 |
| 8 | 0.256 | 0.29 | 12.86144 | 14.5696 | 13.71552 |
| 16 | 0.243 | 0.145 | 24.41664 | 14.5696 | 19.49312 |
| 32 | 0.201 | 0.124 | 40.39296 | 24.91904 | 32.656 |
| 64 | 0.229 | 0.087 | 92.03968 | 34.96704 | 63.50336 |



DATA SET: ADUM2

CLIENT: Wateraid
LOCATION: Oju, Benue State
COUNTY: Nigeria
PROJECT: Water and Sanitation
ELEVATION: 0.00
SOUNDING COORDINATES: X: 0.0000 Y: 0.0000

DATE: March 1998
SOUNDING: 2
AZIMUTH: 0
EQUIPMENT: BGS128

Offset Wenner Configuration

FITTING ERROR: 4.038 PERCENT

| L # | RESISTIVITY (ohm-m) | THICKNESS (meters) | ELEVATION (meters) | LONG. COND. (Siemens) | TRANS. RES. (Ohm-m^2) |
|---|---|---|---|---|---|
| | | | 0.0 | | |
| 1 | 324.2 | 0.818 | -0.818 | 0.00253 | 265.5 |
| 2 | 12.44 | 13.87 | -14.69 | 1.11 | 172.6 |
| 3 | 190.5 | | | | |

ALL PARAMETERS ARE FREE

PARAMETER BOUNDS FROM EQUIVALENCE ANALYSIS

| | LAYER | MINIMUM | BEST | MAXIMUM |
|---|---|---|---|---|
| RHO | 1 | 299.544 | 324.293 | 346.002 |
| | 2 | 11.415 | 12.445 | 12.948 |
| | 3 | 157.661 | 190.599 | 223.117 |
| THICK | 1 | 0.790 | 0.819 | 0.861 |
| | 2 | 11.503 | 13.873 | 15.117 |
| DEPTH | 1 | 0.790 | 0.819 | 0.861 |
| | 2 | 12.345 | 14.692 | 15.925 |

| No. | SPACING (m) | RHO-A (ohm-m) DATA | SYNTHETIC | DIFFERENCE (percent) |
|---|---|---|---|---|
| 1 | 0.500 | 283.0 | 290.7 | -2.74 |
| 2 | 1.00 | 197.5 | 189.8 | 3.88 |
| 3 | 2.00 | 56.00 | 56.77 | -1.38 |
| 4 | 4.00 | 15.15 | 15.19 | -0.319 |
| 5 | 8.00 | 13.70 | 14.09 | -2.90 |
| 6 | 16.00 | 19.50 | 19.37 | 0.615 |





| No. | SPACING (m) | RHO-A (ohm-m) DATA | SYNTHETIC | DIFFERENCE (percent) |
|---|---|---|---|---|
| 7 | 32.00 | 32.60 | 33.57 | -2.99 |
| 8 | 64.00 | 63.50 | 57.97 | 8.70 |

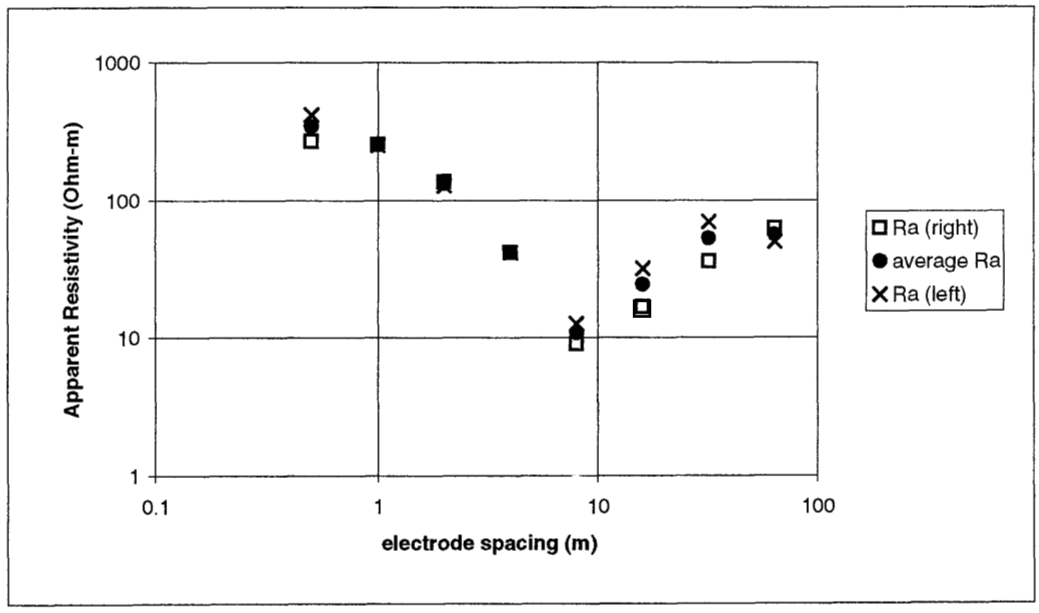
PARAMETER RESOLUTION MATRIX:
"F" INDICATES FIXED PARAMETER

| | | | | | |
|---|---|---|---|---|---|
| P 1 | 0.99 | | | | |
| P 2 | 0.00 | 0.99 | | | |
| P 3 | 0.00 | -0.01 | 0.84 | | |
| T 1 | 0.00 | 0.00 | 0.00 | 1.00 | |
| T 2 | 0.00 | -0.01 | -0.09 | 0.00 | 0.94 |
| | P 1 | P 2 | P 3 | T 1 | T 2 |

# Adum West AW5

Resistivity Survey 3 6 degs 57.427; 8 degs 17.752
Located 2540 m along AD1 poor electrode contact
Offset Wenner left to Assemblies of God
Strike 2 degs
17 degs

| spacing (m) | left | right | Ra (left) | Ra (right) | average Ra |
|---|---|---|---|---|---|
| 0.5 | 132.8 | 85.4 | 416.992 | 268.156 | 342.574 |
| 1 | 39.8 | 40.5 | 249.944 | 254.34 | 252.142 |
| 2 | 10.18 | 10.81 | 127.8608 | 135.7736 | 131.8172 |
| 4 | 1.65 | 1.65 | 41.448 | 41.448 | 41.448 |
| 8 | 0.25 | 0.179 | 12.56 | 8.99296 | 10.77648 |
| 16 | 0.314 | 0.166 | 31.55072 | 16.67968 | 24.1152 |
| 32 | 0.343 | 0.178 | 68.92928 | 35.77088 | 52.35008 |
| 64 | 0.123 | 0.155 | 49.43616 | 62.2976 | 55.86688 |



DATA SET: ADUM3

CLIENT: Wateraid
LOCATION: Oju, Benue State
COUNTY: Nigeria
PROJECT: Water and Sanitation
DATE: March 1998
SOUNDING: 3
AZIMUTH: 0
EQUIPMENT: BGS128
ELEVATION: 0.00
SOUNDING COORDINATES: X: 0.0000 Y: 0.0000

Offset Wenner Configuration

FITTING ERROR: 13.165 PERCENT

| L # | RESISTIVITY (ohm-m) | THICKNESS (meters) | ELEVATION (meters) | LONG. COND. (Siemens) | TRANS. RES. (Ohm-m^2) |
|---|---|---|---|---|---|
| | | | 0.0 | | |
| 1 | 305.7 | 1.50 | -1.50 | 0.00491 | 459.0 |
| 2 | 5.05 | 4.66 | -6.16 | 0.921 | 23.57 |
| 3 | 1706.3 | | | | |

ALL PARAMETERS ARE FREE

PARAMETER BOUNDS FROM EQUIVALENCE ANALYSIS

| | LAYER | MINIMUM | BEST | MAXIMUM |
|---|---|---|---|---|
| RHO | 1 | 264.007 | 305.727 | 352.965 |
| | 2 | 1.071 | 5.059 | 9.592 |
| | 3 | 212.298 | 1706.368 | 1780.816 |
| THICK | 1 | 1.364 | 1.502 | 1.654 |
| | 2 | 0.974 | 4.661 | 9.055 |
| DEPTH | 1 | 1.364 | 1.502 | 1.654 |
| | 2 | 2.629 | 6.162 | 10.500 |

| No. | SPACING (m) | RHO-A (ohm-m) DATA | SYNTHETIC | DIFFERENCE (percent) |
|---|---|---|---|---|
| 1 | 0.500 | 342.6 | 299.0 | 12.70 |
| 2 | 1.00 | 252.1 | 265.4 | -5.28 |
| 3 | 2.00 | 131.8 | 156.7 | -18.96 |
| 4 | 4.00 | 41.40 | 37.02 | 10.56 |
| 5 | 8.00 | 10.80 | 12.81 | -18.64 |
| 6 | 16.00 | 24.10 | 23.61 | 2.02 |





| No. | SPACING (m) | RHO-A (ohm-m) DATA | SYNTHETIC | DIFFERENCE (percent) |
|---|---|---|---|---|
| 7 | 32.00 | 52.35 | 46.57 | 11.03 |
| 8 | 64.00 | 55.87 | 90.75 | -62.44 |

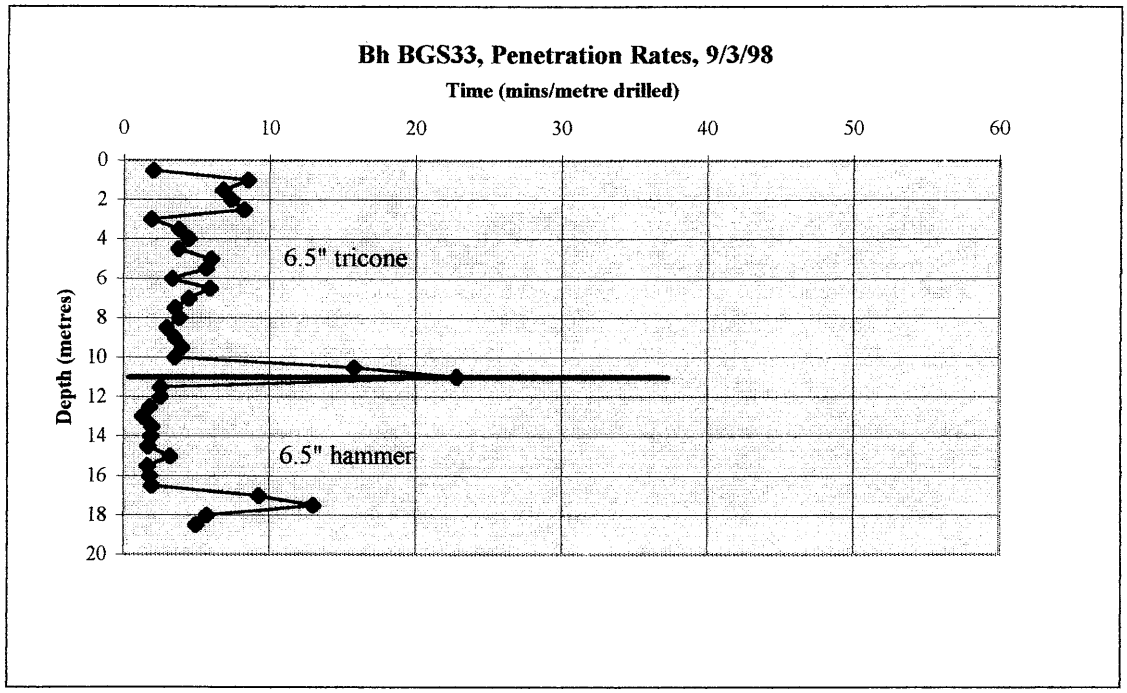
PARAMETER RESOLUTION MATRIX:
"F" INDICATES FIXED PARAMETER

| | P 1 | P 2 | P 3 | T 1 | T 2 |
|---|---|---|---|---|---|
| P 1 | 0.98 | | | | |
| P 2 | -0.01 | 0.55 | | | |
| P 3 | 0.00 | 0.00 | 0.03 | | |
| T 1 | 0.01 | 0.03 | 0.00 | 0.99 | |
| T 2 | -0.01 | -0.45 | -0.03 | 0.03 | 0.53 |

# Annex 2: Drilling and borehole construction data

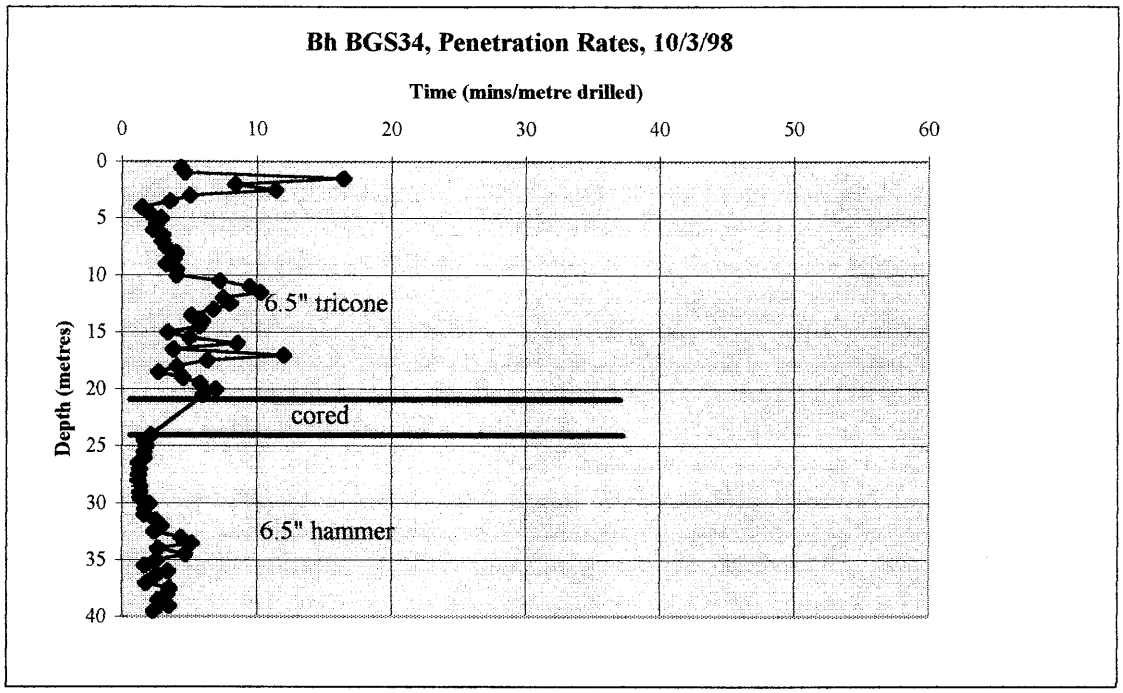
**Borehole BGS33**

| | |
|---|---|
| Borehole Drilling/Construction Details | |
| Date drilling started | 9/3/98 |
| Date drilling completed | 9/3/98 |
| 9/3/98 - Drilled with 6.5" tricone | 0.00 - 10.75m |
| 9/3/98 - Drilled with 6.5" hammer | 10.75 - 18.5m |
| Depths water struck | 10.5, 16.5 (flowing), 17.0 (much), 17.5 (much) |
| Depth of borehole on completion | 18.5mbgs |
| Borehole diameter | $6^1/_2$" |
| Casing erected in hole | 2x5.8mx125mm casing |
| | 3x2.9mx125mm screen |
| Original top of casing above ground level | 1.20m |
| Total length of casing/screen | 20.3m |
| Amount of casing removed | 0.70m |
| Top of casing above ground level | 0.50m |
| Rest water level below casing top | 2.86m |



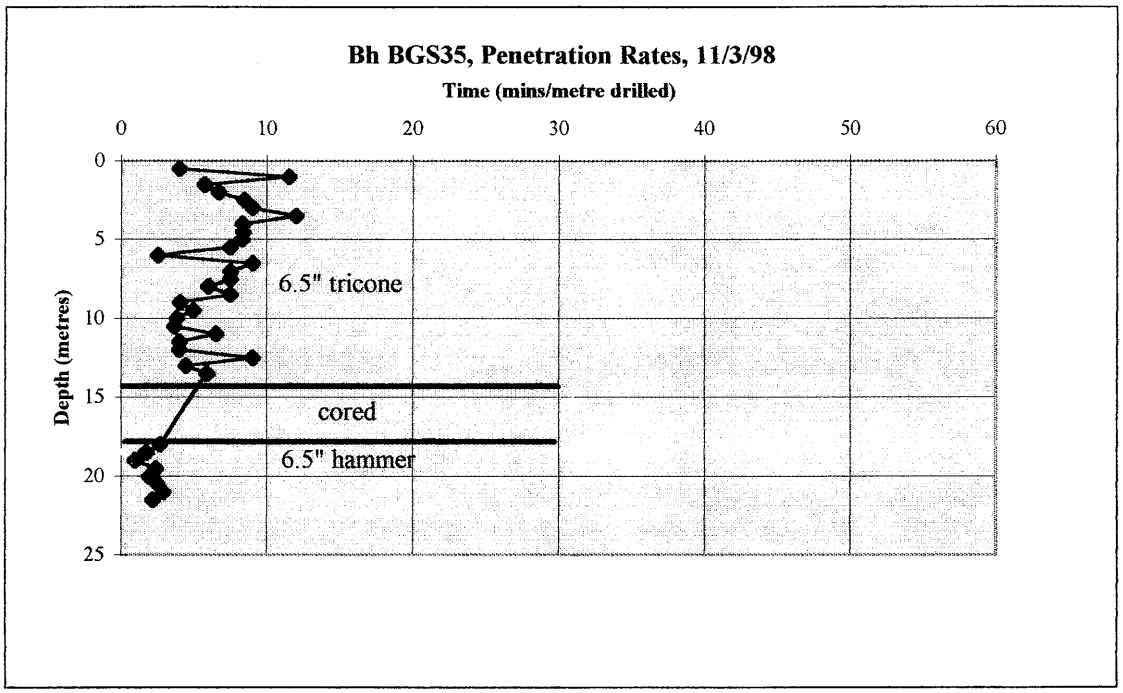
**Borehole BGS34**

| | |
|---|---|
| Borehole Drilling/Construction Details | |
| Date drilling started | 10/3/98 |
| Date drilling completed | 11/3/98 |
| 10/3/98 - Drillled with 6.5" tricone | 0.00 - 20.5m |
| 10/3/98 - Cored at 3" | 20.5 - 23.5m |
| 10/3/98 - Drilled with 6.5" hammer | 20.5 - 39.7m |
| Depths water struck | 11.0, 11.5 (flowing), 22.5 (more water), 32.5 more water), 33.5 (more water), 34.5 (more water) |
| Depth of borehole on completion | 39.7mbgs |
| Borehole diameter | $6^1/_2$" |
| Casing erected in hole | 1x2.9mx125mm casing<br>5x5.8mx125mm casing<br>3x2.9mx125mm screen |
| Original top of casing above ground level | 0.15m |
| Total length of casing/screen | 40.6m |
| Amount of casing removed | 0.00m |
| Rest water level below casing top | 4.39m |



**Borehole BGS35**

| Borehole Drilling/Construction Details | |
|---|---|
| Date drilling started | 11/3/98 |
| Date drilling completed | 12/3/98 |
| 11/3/98 - Drillled with 6.5" tricone | 0.00 - 14.5m |
| 12/3/98 - Cored at 3" | 14.5 - 17.5m |
| 12/3/98 - Drilled with 6.5" hammer | 17.5 - 21.5m |
| Depths water struck | 11.5, 12.0 (flowing), 19 (much water), 19.5 (much water), 20 (much water), 21 (much water), |
| Depth of borehole on completion | 21.5mbgs |
| Borehole diameter | $6^1/_2$" |
| Casing erected in hole | 1x2.9mx125mm casing<br>2x5.8mx125mm casing<br>3x2.9mx125mm screen |
| Original top of casing above ground level | 0.82m |
| Total length of casing/screen | 22.84m |
| Amount of casing removed | 0.35m |
| Top of casing above ground level | 0.47m |
| Rest water level below casing top | 6.25m |



# Annex 3: Lithological logs

# Lithological Log: BGS33

| | |
|---|---|
| **Soil/ferrecrete horizon** | |
| 0.0 - 0.5 | Orange, dark red, red purple and black nodular ferrecrete |
| 0.5 - 1.0 | Brown, dark red and black nodular ferrecrete with manganese oxide |
| 1.0 - 1.5 | Brown, dark red and black nodular ferrecrete with manganese oxide |
| **Clayey very weathered horizon** | |
| 1.5 - 2.0 | Brownish yellow (orange) 10YR6/6 and light grey 10YR7/1 mottled clay with light blue kaolin clay |
| 2.0 - 2.5 | Brown clay above soft weathered fine grained grey to light grey siltstone |
| **Weathered silty mudstones** | |
| 2.5 - 3.0 | Grey weathered blocky soft silty mudstone |
| 3.0 - 3.5 | Brownish grey siltstone weathered fawn in parts |
| 3.5 - 4.0 | Light grey blocky mudstone weathered yellow brown 10YR5/6 in parts |
| 4.0 - 4.5 | Very pale brown 10YR7/4 and light grey 10YR7/2 weathered blocky and shaley silty mudstones |
| 4.5 - 5.0 | Light grey 10YR7/2 blocky to shaley silty mudstones weathered brownish yellow 10YR6/8 in parts |
| 5.0 - 5.5 | Light brownish grey 10YR6/2 silty mudstones weathered yellow brown 10YR6/8 in parts |
| **Weathered siltstones** | |
| 5.5 - 6.0 | Pale brown 10YR6/3, yellow 10YR7/6 and light brownish grey 10YR6/2 mottled weathered siltstones |
| 6.0 - 6.5 | Pale brown 10YR6/3 to light brownish grey 10YR6/2 weathered siltstones |
| 6.5 - 7.0 | Pale brown 10YR6/3 to light brownish grey 10YR6/2 weathered siltstones with very weathered light grey 10YR6/1 and yellow 10YR7/8 partings |
| 7.0 - 7.5 | Light grey 10YR7/2 and brownish yellow 10YR6/6 weathered shaley siltstones |
| 7.5 - 8.0 | Light yellow brown 2.5Y6/4 with some dark red and light brownish grey weathered siltstones damp in parts |
| **Fairly weathered baked siltstones** | |
| 8.0 - 8.5 | Reddish grey 5YR5/2 and pinkish grey 7.5YR6/2 siltstones |
| 8.5 - 9.0 | Pinkish grey 5YR6/2 to pinkish grey 7.5YR6/3 siltstones |
| 9.0 - 9.5 | Bright yellow 7.5YR6/8 and light grey 7.5YR7/1 siltstones |
| 9.5 - 10.0 | Reddish yellow 7.5YR6/8 to reddish brown 2.5YR5/3 weathered siltstones with soft patches |
| **Hard baked mudstones** | |
| 10.0 - 10.5 | Very hard green black and red black baked mudstones and contact dolerite |
| 10.5 - 11.0 | Hard green black baked mudstones and fine grained dolerite |
| **Soft weathered dolerite** | |
| 11.0 - 11.5 | Dark green soft dolerite some brown weathered patches |
| 11.5 - 12.0 | Dark green soft dolerite some brown weathered patches |
| 12.0 - 12.5 | Dark green soft dolerite some brown weathered patches |
| 12.5 - 13.0 | Dark green dolerite some brown weathered patches |
| **Dolerite** | |
| 13.0 - 13.5 | Dark green dolerite |
| 13.5 - 14.0 | Dark green dolerite |
| 14.0 - 14.5 | Dark green fractured dolerite |
| 14.5 - 15.0 | Dark green hard fine grained dolerite |
| **Soft fractured dolerite with zeolite** | |
| 15.0 - 15.5 | Soft dark green dolerite with white zeolitic vein material |
| 15.5 - 16.0 | Soft dark green dolerite with some white zeolitic vein material |
| 16.0 - 16.5 | Fractured dark green dolerite with much white zeolitic vein material |
| 16.5 - 17.0 | Much broken dark green dolerite with much white zeolitic vein material |
| 17.0 - 17.5 | Much broken dark green dolerite with much white zeolitic and light green vein material |
| 17.5 - 18.0 | Less fractured dark green dolerite with much white zeolitic vein material, some $H_2S$ smell |
| 18.0 - 18.5 | Fairly fractured dark green dolerite with much white zeolitic vein material |

# Lithological Log: BGS34

| | |
|---|---|
| **Soil/ferrecrete horizon** | |
| 0.0 - 0.5 | Red 10R4/8, black and 7.5YR6/8 reddish brown nodular ferrecrete |
| 0.5 - 1.0 | Light blue grey, reddish yellow 7.5YR6/8 and brownish yellow 10YR6/8 clayey weathered mudstones with ferrecrete |
| **Clayey very weathered horizon** | |
| 1.0 - 1.5 | Mottled reddish yellow 7.5YR6/8,light blue grey and yellowish brown 10YR5/6 clay, above light olive brown 2.5Y5/6 to yellowish brown 10YR5/6 with light blue grey mottled caly, fairly damp |
| 1.5 - 2.0 | Grey 10YR5/1 weathered mudstone with olive yellow 2.5Y6/6 clays, some light blue grey 7/10B clay - kaolin |
| 2.0 - 2.5 | Light blue grey 7/10B kaolinitic clays with some orange partings with olive yellow 2.5Y6/6 clays |
| 2.5 - 3.0 | Light blue grey 7/10B clay with yellow 2.5Y7/6-6/6 clayey weathered mudstones |
| **Weathered carbonaceous mudstones and siltstones** | |
| 3.0 - 3.5 | Weathered black carbonaceous mudstones |
| 3.5 - 4.0 | Black to dark grey weathered carbonaceous mudstones |
| 4.0 - 4.5 | Weathered black carbonaceous mudstones |
| 4.5 - 5.0 | Weathered black to brown carbonaceous siltstone with soft damp orange partings |
| 5.0 - 5.5 | Weathered black carbonaeous silty mudstones with weathered orange partings |
| 5.5 - 6.0 | Black carbonaceous shaley mudstones, splintery, slightly weathered |
| 6.0 - 6.5 | Dark grey to black carbonaceous weathered shaley mudstones |
| **Fairly weathered shaley mudstone** | |
| 6.5 - 7.0 | Hard black shaley mudstones, some orange weathered partings |
| 7.0 - 7.5 | Very dark greyish brown 2.5Y3/2 shaley mudstones with reddish brown 5YR4/4 and dark grey partings |
| 7.5 - 8.0 | Dark olive grey 5Y3/2 to dark grey / black shaley carbonaceous mudstones |
| 8.0 - 8.5 | Dark olive grey to dark purple grey shaley mudstones, damp, some orange streaks and some mica |
| 8.5 - 9.0 | Dark purple grey interlayered with orange and dark red weathered shaley mustones |
| 9.0 - 9.5 | Dark grey/black shaley mudstones with yellow weathered bands |
| 9.5 - 10.0 | Dark olive green and black damp carbonaceous shaley mudstones |
| **Hard baked shaley mudstone** | |
| 10.0 - 10.5 | Black nonweatered shaley mudstones, hard below 10.2m |
| 10.5 - 11.0 | Hard black baked carbonaceous shales, some weathered orange bands and damp clayey patches |
| 11.0 - 11.5 | Hard black baked mudstones, some orange partings |
| 11.5 - 12.0 | Hard black baked mudstone |
| 12.0 - 12.5 | Hard black baked shaley mudstone |
| 12.5 - 13.0 | Fairly hard baked black shaley mudstone, splintery |
| 13.0 - 13.5 | Black splintery carbonaceous shaley splintery mudtones |
| 13.5 - 14.0 | Black slightly baked shaley mudstone |
| **Carbonaceous shaley mudstones** | |
| 14.0 - 14.5 | Black splintery carbonaceous shaley mudstones |
| 14.5 - 15.0 | Black to dark grey carbonaceous mudstones, some grey clay |
| 15.0 - 15.5 | Soft black carbonaceous shaley mudstone |
| 15.5 - 16.0 | Black shaley mudstone, hard band at 15.9m |
| 16.0 - 16.5 | Thinly bedded black shaley carbonaceous mudstone |
| 16.5 - 17.0 | Black carbonaceous shales with 5cm hard band below 16.6m |
| **Soft carbonaceous shaley mudstones** | |
| 17.0 - 17.5 | Black carbonaceous shaley mudstones with soft clayey partings, hard band at 17.3m |
| 17.5 - 18.0 | Soft black carbonaceous shaley mudstones |
| 18.0 - 18.5 | Black carbonaceous shaley mudstones |
| 18.5 - 19.0 | Soft black carbonaceous shaley mudstones |
| 19.0 - 19.5 | Soft black very carbonaceous shaley mudstones, hard band at 19.2m |
| **Carbonaceous shaley mudstones** | |
| 19.5 - 20.0 | Black carbonaceous shaley mudstones |
| 20.0 - 20.5 | Black carbonaceous shaley mudstones |

| | |
|---|---|
| **Thinly bedded carbonaceous shaley mudstone with thin brown crystalline partings** | |
| 20.50 - 21.20 | Black to dark grey thinly bedded carbonaceous shaley mudstone, brittle with interbedded silty nodular bands and thin white occasional sandstone bands |
| 21.20 - 22.10 | Black carbonaceous shaley mudstones thinly bedded, very brittle, bands of light brown evaporite? at 21.31, 21.45, 21.50-21.60 (some iron **pyrite**) and 21.82 (thick iron **pyrite** layer) |
| 22.10 - 22.35 | Interbedded black carbonaceous shaley mudstones with thinly bedded white to light grey sandstones, also some thin brown secondary deposits that also occur as halos around thick septarian nodular deposits at 22.26, 22.30 and 22.35m |
| 22.35 - 23.15 | Thinly bedded and brittle slatey black carbonaceous mudstones with thin interbedded light brown crystalline layers developed along joints, cleavage planes and around prominent large septarian nodular masses of black or grey cherty material as at 22.63-22.67, 22.81, 22.96-22.99 and 23.07m. Some slickenslide development with iron **pyrite** facings at 22.87-22.88m. |
| 23.15 - 23.50 | Brittle baked black carbonaeous shaley mudstones, fracture with light brown crystalline deposits along fracture and cleavage planes. Very thinly bedded and splintery, prominent septarian nodule development at 23.39m and 23.49m, latter is light grey and hard. |
| **Hard carbonaceous shaley mudstones** | |
| 23.5 - 24.0 | Hard baked black carbonaceous shaley mudstones |
| 24.0 - 24.5 | Hard baked black carbonaceous shaley mudstones |
| **Carbonaceous shaley mudstones** | |
| 24.5 - 25.0 | Black carbonaceous shaley mudstones |
| 25.0 - 25.5 | Black carbonaceous shaley mudstones |
| 25.5 - 26.0 | Black carbonaceous shaley mudstones |
| 26.0 - 26.5 | Black carbonaceous shaley mudstones |
| **Soft carbonaceous shaley mudstones** | |
| 26.5 - 27.0 | Soft dark grey carbonaceous shaley mudstones |
| 27.0 - 27.5 | Soft dark grey carbonaceous shaley mudstones |
| **Harder carbonaceous shaley mudstones** | |
| 27.5 - 28.0 | Harder dark grey carbonaceous shaley mudstones |
| 28.0 - 28.5 | Harder dark grey carbonaceous shaley mudstones |
| 28.5 - 29.0 | Harder dark grey carbonaceous shaley mudstones |
| **Sandstone** | |
| 29.0 - 29.5 | Grey sandstone |
| **Baked silty mudstone** | |
| 29.5 - 30.0 | Light grey baked silty mudstones |
| 30.0 - 30.5 | Light grey baked silty mudstones |
| 30.5 - 31.0 | Light grey baked silty mudstones |
| 31.0 - 31.5 | Hard light grey baked silty mudstones and dolerite margin |
| **Hard fine grained dolerite** | |
| 31.5 - 32.5 | Hard dark green/black fine grained dolerite |
| 32.5 - 33.0 | Green black fine grained dolerite |
| 33.0 - 33.5 | Harder light green dolerite |
| 33.5 - 34.0 | Hard light green dolerite |
| **Fractured dolerite with zeolite** | |
| 34.0 - 34.5 | Fractured black fine grained dolerite |
| 34.5 - 35.0 | Black green dolerite with white zeolite |
| 35.0 - 35.5 | Black green dolerite with white zeolite and light green chlorite |
| **Compact dolerite** | |
| 35.5 - 36.0 | More compact green dolerite with little white zeolite |
| 36.0 - 36.5 | Compact dark green dolerite |
| 36.5 - 37.0 | Dark green dolerite with some white zeolite |
| 37.0 - 37.5 | Compact dark green dolerite |
| **Dolerite with zeolite** | |
| 37.5 - 38.0 | Dark green dolerite some zeolite |
| 38.0 - 38.5 | Dark green dolerite some white zeolite |
| 38.5 - 39.0 | Dark green dolerite some white zeolite |
| 39.0 - 39.5 | Dark green coarse grained dolerite with white zeolite |

# Lithological Log: BGS35

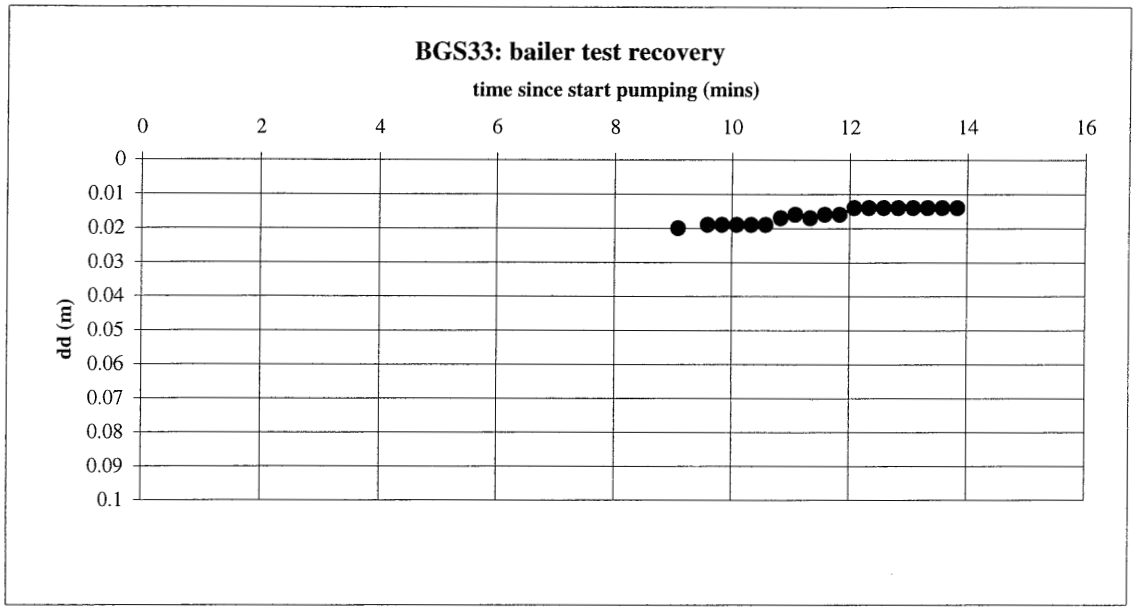
| | |
|---|---|
| **Soil/ferrecrete horizon** | |
| 0.0 - 0.5 | Light brown (7.5YR6/4) fine grained soil |
| 0.5 - 1.0 | Red 2.5YR4/8 and 2.5Y5/4 light yellowish brown mottled silty clays |
| 1.0 - 1.5 | 5YR4/6 yellowish red lateritic clay |
| 1.5 - 2.0 | Red 2.5YR4/8, dark red, brown and black nodular ferrecrete with 0.5" nodules |
| 2.0 - 2.5 | 10YR4/4 dark yellowish brown and 10YR6/8 brownish yellow matrix around mainly nodules of black manganese oxide |
| 2.5 - 3.0 | 10YR4/4 dark yellowish brown and 10YR5/6 yellowish brown clayey silts with some 2.5YR5/8 red to 2.5YR4/8 red nodular ferrecretes and black manganese oxide |
| **Clayey very weathered horizon** | |
| 3.0 - 3.5 | 5YR4/4reddish brown, 7.5YR6/4 brown and 10YR5/6 yellowish brown dampish clayey silts |
| 3.5 - 4.0 | 5YR4/4 reddish brown, 5YR4/6 yellowish red and 7.5YR5/6 strong brown mottled clayey silt, with some black manganese oxide nodules |
| 4.0 - 4.5 | 2.5Y5/6 light olive brown and 10YR5/4 yellowish brown with some 2.5YR5/6 red mottled damp clayey silts |
| **Very weathered clayey silts (from dolerite)** | |
| 4.5 - 5.0 | 2.5Y4/4 olive brown damp clayey silts |
| 5.0 - 5.5 | 2.5Y4/4 olive brown damp clayey silts |
| 5.5 - 6.0 | 2.5Y4/4 olive brown damp clayey silts - but few returns |
| 6.0 - 6.5 | 10YR4/4 dark yellowish brown to 2.5Y4/4 olive brown damp clayey silt |
| 6.5 - 7.0 | 10YR5/6 yellowish brown to 2.5Y4/4 olive brown damp clayey silt |
| **Very weathered dolerite with clay** | |
| 7.0 - 7.5 | 2.5Y5/4 light olive brown clayey silt (very weathered dolerite) |
| 7.5 - 8.0 | 2.5Y5/6 light olive brown clayey silt (very weathered dolerite) |
| 8.0 - 8.5 | 2.5Y5/4 light olive brown silty weathered dolerite |
| 8.5 - 9.0 | 2.5Y5/4 light olive brown silty weathered dolerite |
| 9.0 - 9.5 | 2.5Y4/4 olive brown weathered dolerite |
| 9.5 - 10.0 | 2.5Y4/3 olive brown and darker very weathered dolerite |
| 10.0 - 10.5 | Dark green - black and brown fairly weathered dolerite |
| 10.5 - 11.0 | Dark green brown weathered dolerite, some white calcite fragments |
| 11.0 - 11.5 | Very dark brown green/black fairly weathered dolerite, first water struck |
| 11.5 - 12.0 | Very dark brown green/black fairly weathered dolerite |
| **Hard dolerite with xeolite** | |
| 12.0 - 12.5 | Fresh hard blue black green dolerite |
| 12.5 - 13.0 | Black green dolerite with white vein material patches - zeolite? |
| **Soft very weathered dolerite** | |
| 13.0 - 13.5 | Very weathered brown and black dolerite, some clay? |
| 13.5 - 14.0 | Soft black and brown grannular weathered dolerite |
| 14.0 - 14.5 | Soft black and brown grannular weathered dolerite |
| **Weathered dolerite corestone** | |
| 14.80 - 15.20 | Granular weathered brown and white dolerite corestone, broken into competent slabs 2-4cm thick |
| **Very weathered dolerite** | |
| 15.20 - 15.35 | Very weathered brown clayey and sandy dolerite |
| 15.35 - 15.62 | Very weathered coarse grained brown and white dolerite corestone in slabs 6-12 cm thick |
| 15.62 - 15.75 | Very weathered soft clayey and sandy olive brown and white dolerite |
| **Fairly weathered dolerite, some xeolite** | |
| 15.75 - 16.07 | Competent fairly weathered brown with white specs medium grained dolerite with white veins of calcite and zeolite (radiating crystal groups of transparent mesolite), weathered upper portion of corestone |
| 16.07 - 16.58 | Hard blue green medium grained dolerite with weathered veins at 16.07,16.22 and 16.50m. Numerous radiating crystal groups of transparent mesolite on vein sides. |
| **Very weathered dolerite** | |
| 16.58 - 16.65 | Very weathered block of dolerite between corestones, olive brown with orange brown |

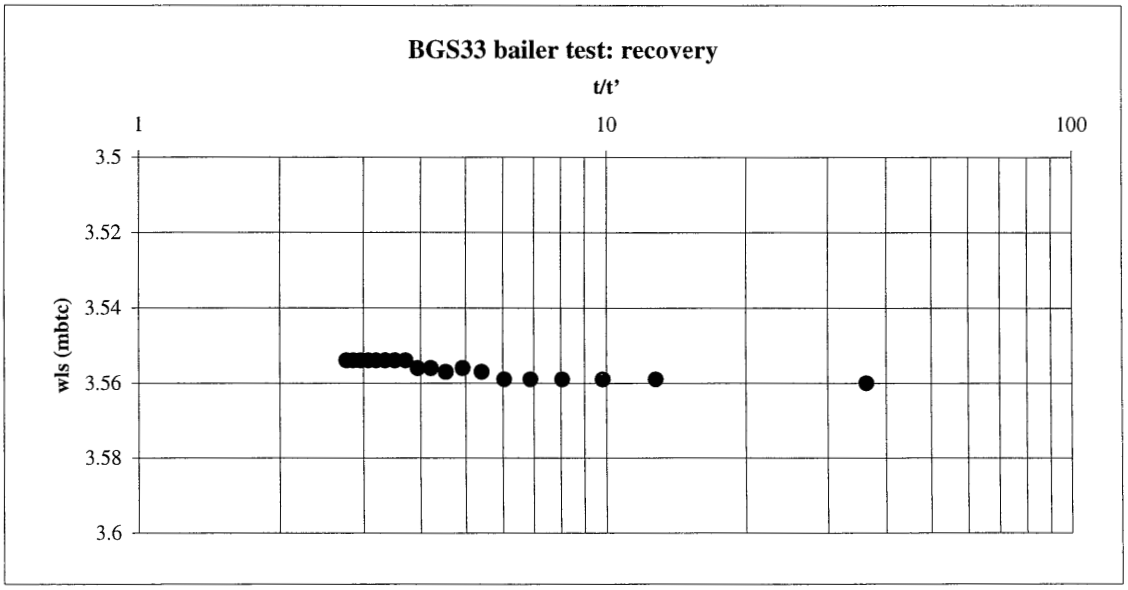
| | |
|---|---|
| | partings, many radiating crystal groups of transparent mesolite crystals along joint planes. |
| **Dolerite with much xeolite** | |
| 16.65 - 16.91 | Bluish green to brownish green medium grained dolerite with white veins at 16.75m and 16.85-16.88m Fairly hard and competent |
| 16.91 - 16.98 | Thick white vein of zeolite/calcite with soft friable dark olive green very weathered dolerite |
| 16.98 - 17.12 | Hard dark green fractured medium grained dolerite, vertical fractures with zeolite veining |
| **Soft friable dolerite with zeolite vein** | |
| 17.12 - 17.20 | Soft friable dark green dolerite with thick white zeolite vein |
| **Hard dark green fine to medium grained dolerite** | |
| 17.20 - 17.25 | Hard dark green black medium grained dolerite with coating of apple green chlorite?? on joint/fracture planes |
| 17.5 - 18.0 | Hard dark green dolerite |
| 18.0 - 18.5 | Dark green fine to medium grained dolerite with some white and green vein minerals |
| 18.5 - 19.0 | Dark green black fine to medium grained dolerite with white and green vein minerals |
| 19.0 - 19.5 | Dark green black fine to medium grained dolerite much white and green vein minerals |
| 19.5 - 20.0 | Dark green black fine to medium grained dolerite with much white and green vein minerals |
| 20.0 - 20.5 | Dark green black fine to medium grained dolerite with much white and green vein minerals |
| 20.5 - 21.0 | Dark green black fine to medium grained dolerite with much white and green vein minerals |
| 21.0 - 21.5 | Dark green black fine to medium grained dolerite with much white and green vein minerals |

# Annex 4: Pump test data

# BGS33: Bailer Test

rwl 3.54 m
height casing = 0.5 m agl
no bails 41
time 8:50 mins
prate = 0.35 l/s
23/03/98 no analysis possible

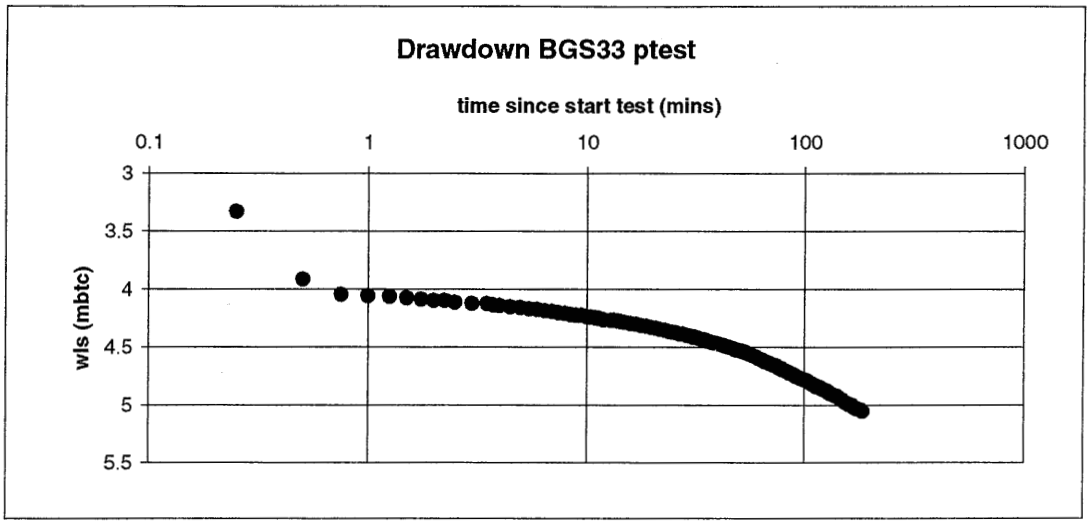


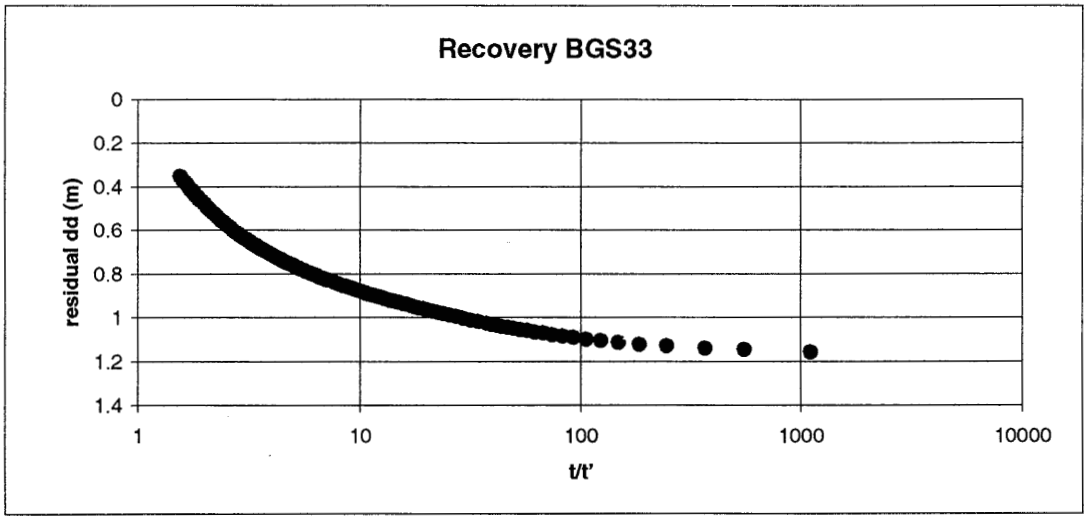



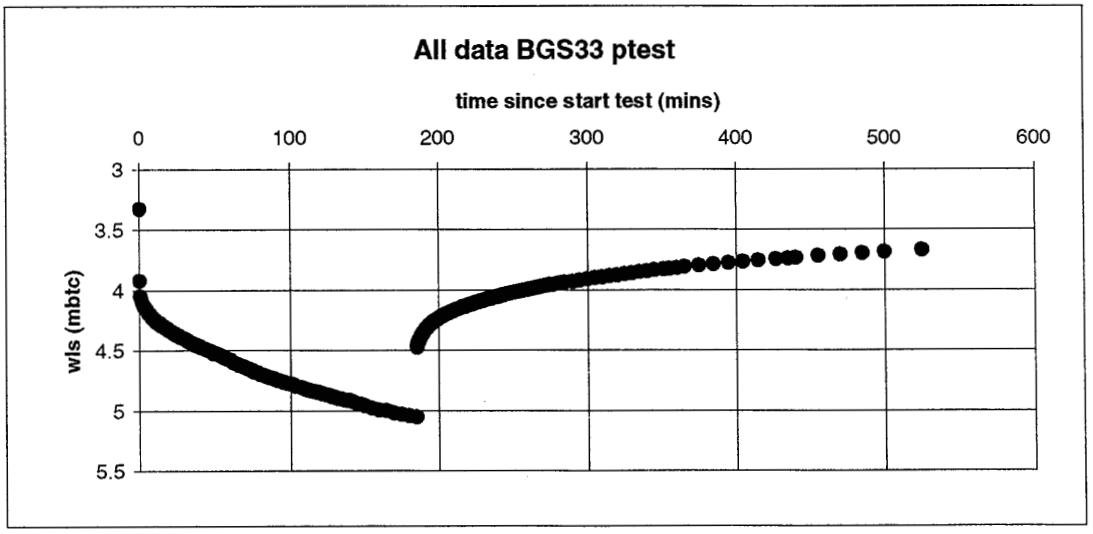
# BGS 33 - centrifugal pump

GPS: 6 dgs 57.226; 8 dgs 17.670
Casing 0.5 m agl
date: 11/03/98 00:00
using centrigal pump
rwl: 3.32 m btc
length of pumping = 185 mins
yield 3.5 l/s

T from dd (jacob)= 61 $m^2/d$
T from recovery (Theis rec) = 51 $m^2/d$



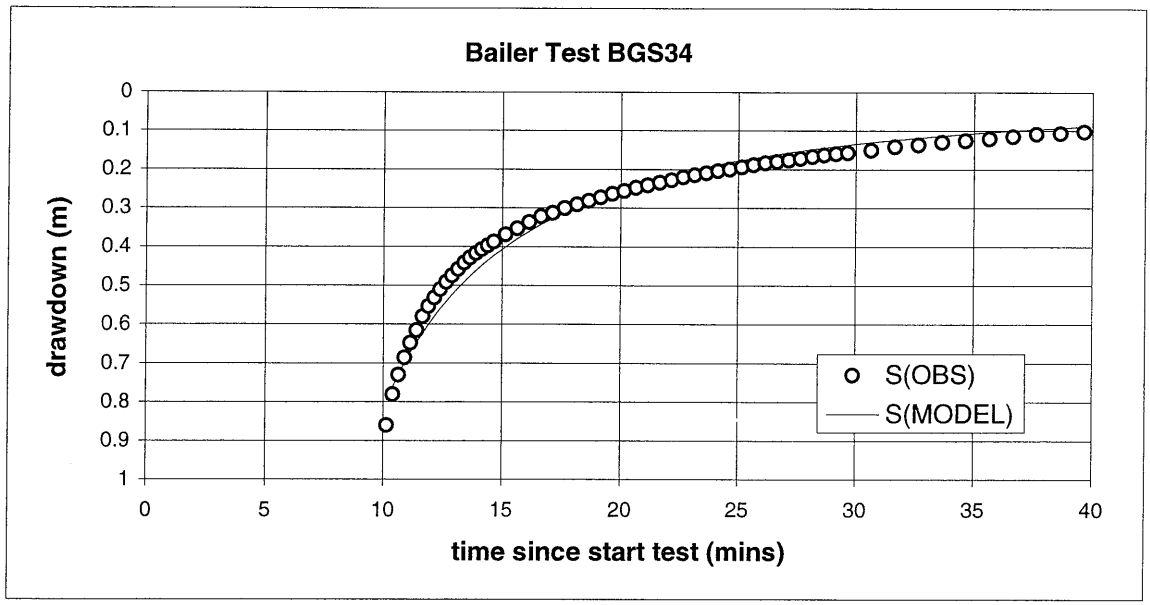



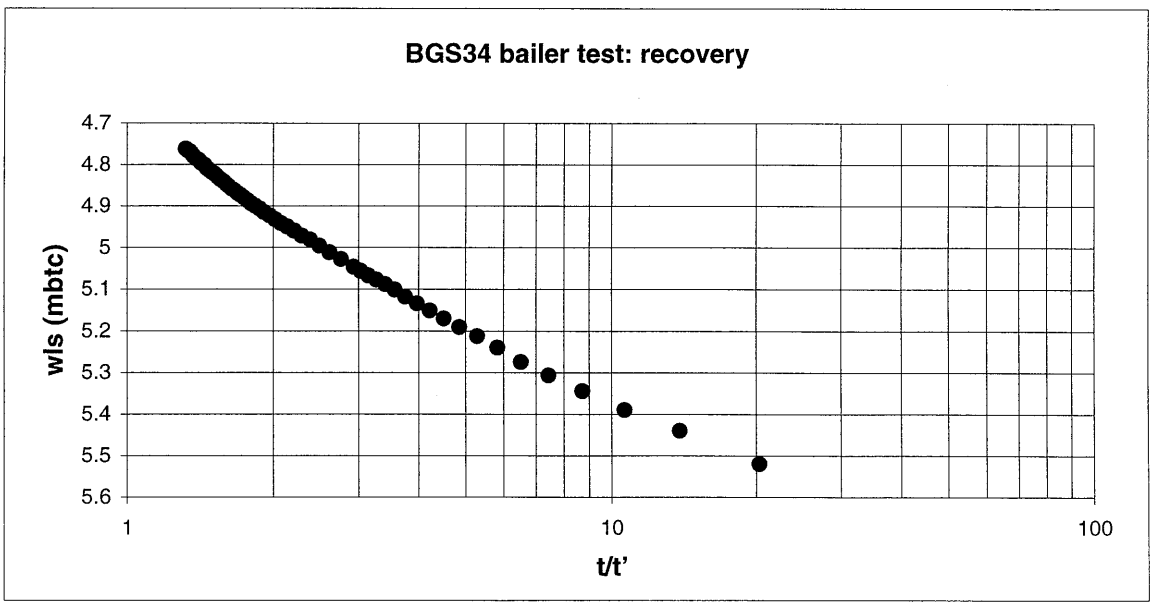
# BGS34 Bailer Test

rwl 4.659 m
height casing = 0.18 m agl
no bails 39
time 9:39 mins
prate = 0.3 l/s
23/03/98

**Barker**
T = 8.7 $m^2/d$
S = 0.04
R = 0.154 m

**Theis Recovery**
T = 6.5 $m^2/d$

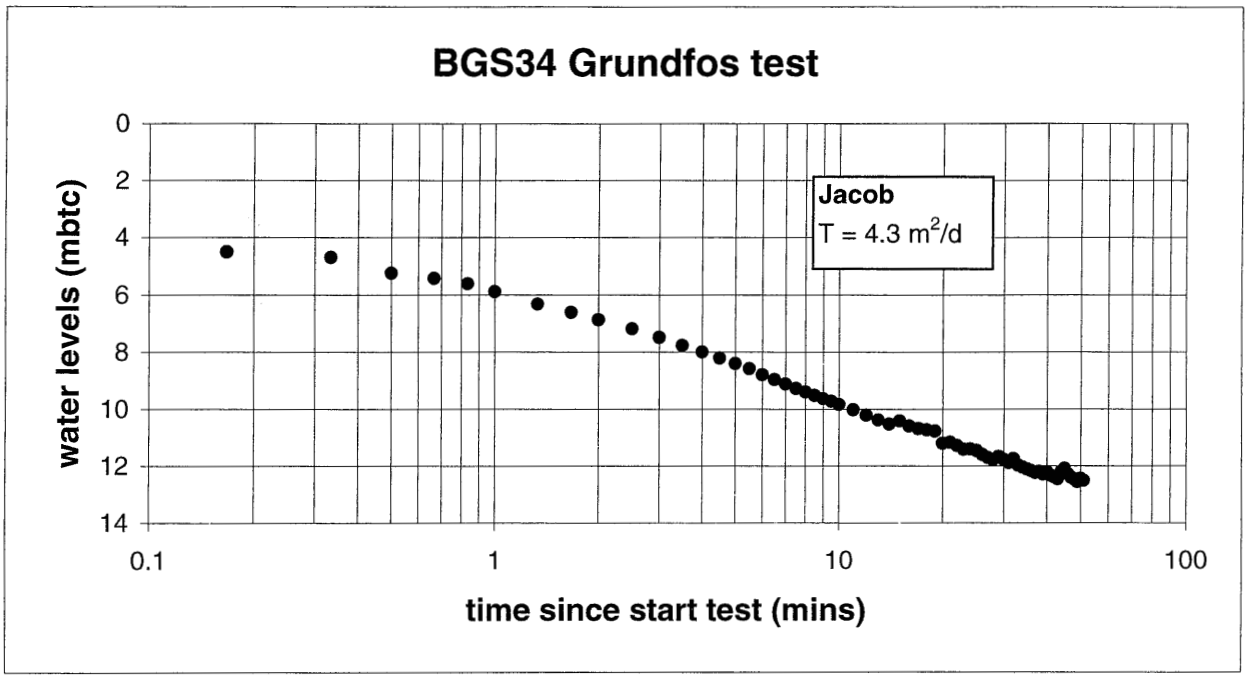


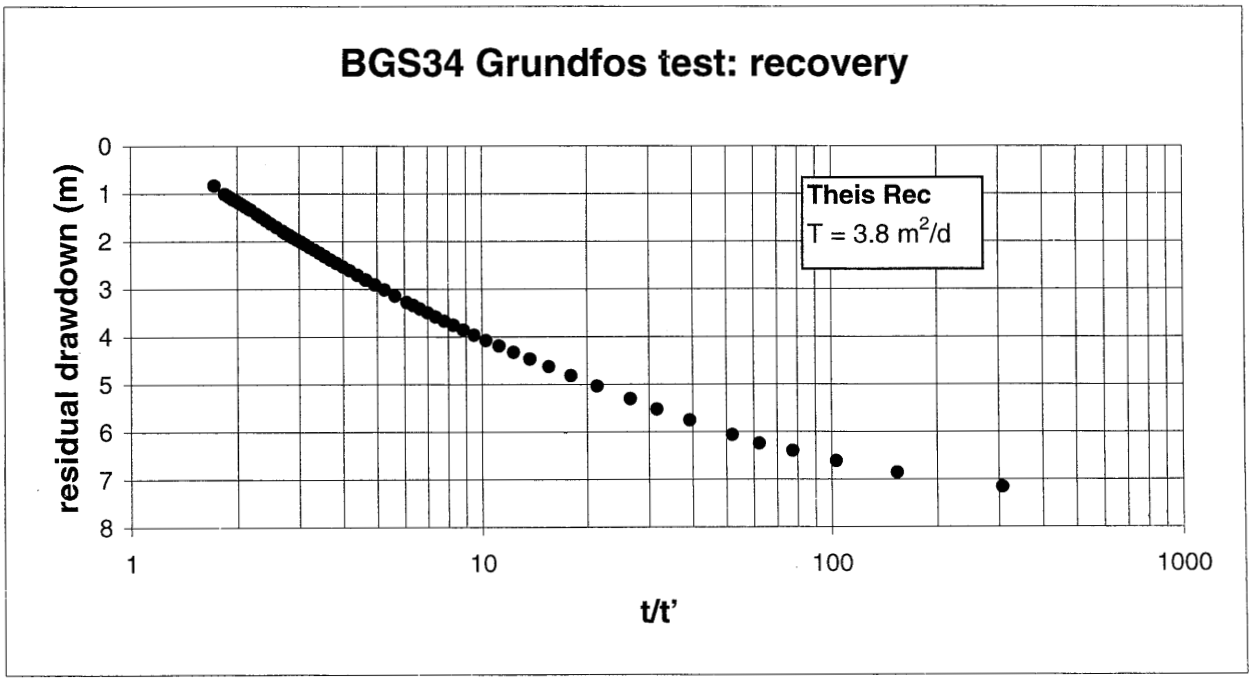



# BGS 34: grundfos test

rwl 4.43 m
height casing = 0.18 m agl
time 51 mins

prate =1.1 l/s = 95.04 $m^3/d$
23/03/98



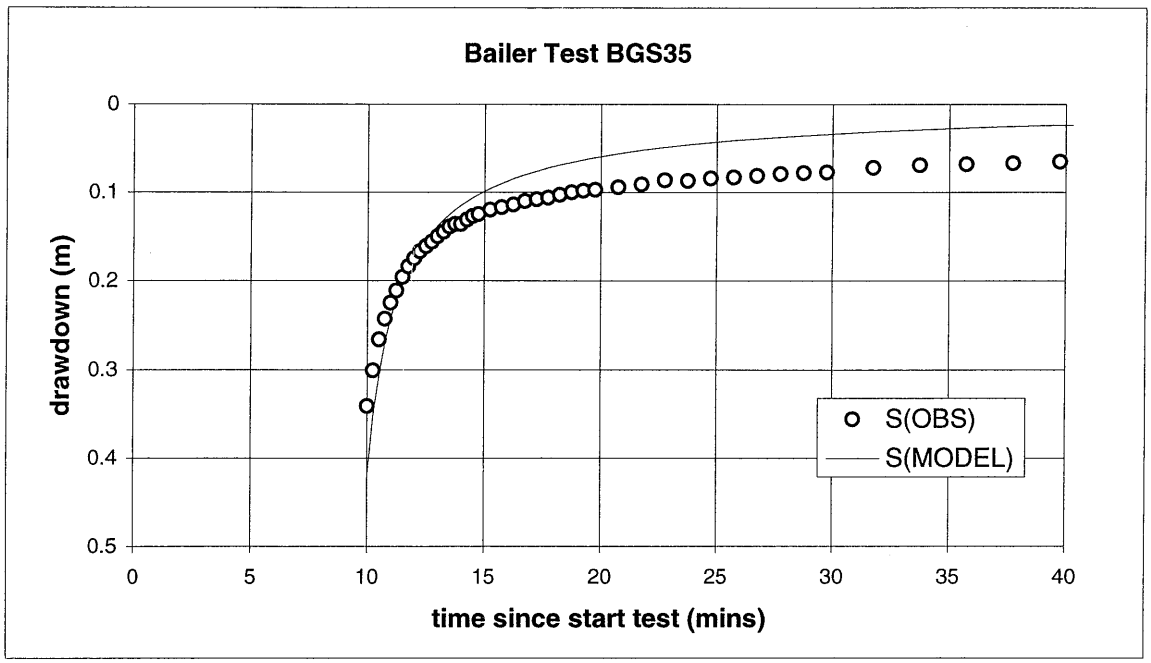



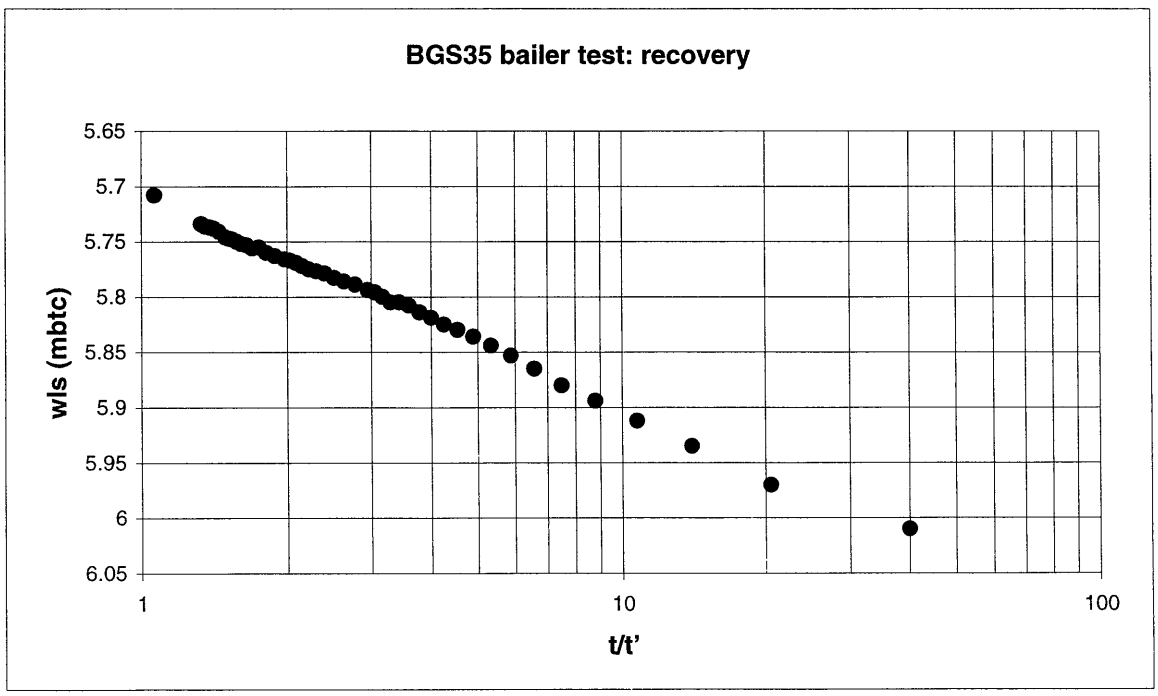
# BGS35 Bailer Test

rwl 5.669 m
height casing = 0.5 m agl
no bails 39
time 9:45 mins
prate = 0.3 l/s
23/03/98

**Barker**
T = 26 $m^2/d$
S = 0.05
R = 0.092 m

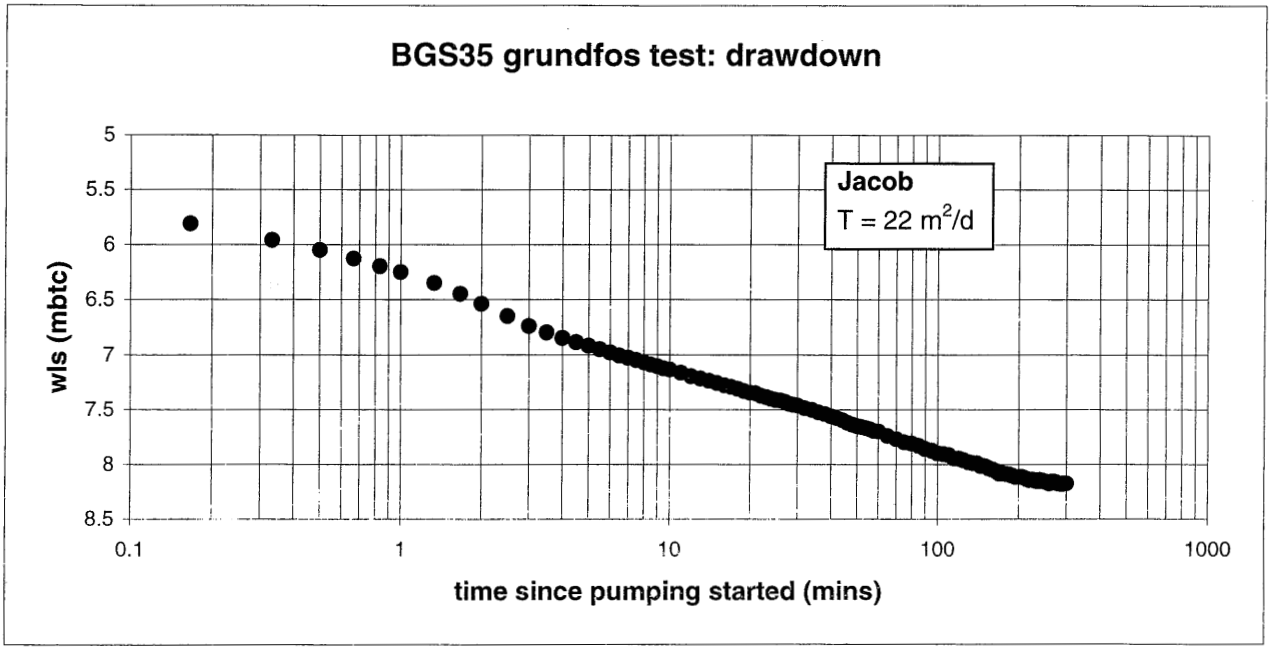
**Theis Recovery**
T = 28 $m^2/d$

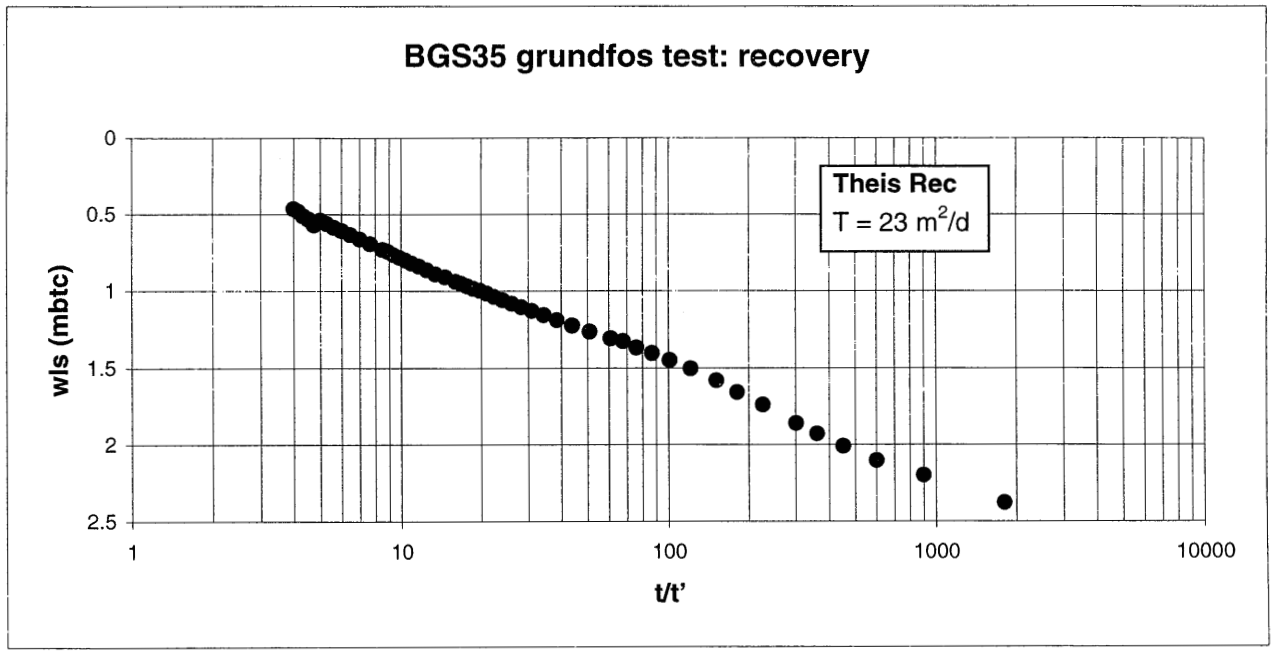


# BGS35: grundfos test

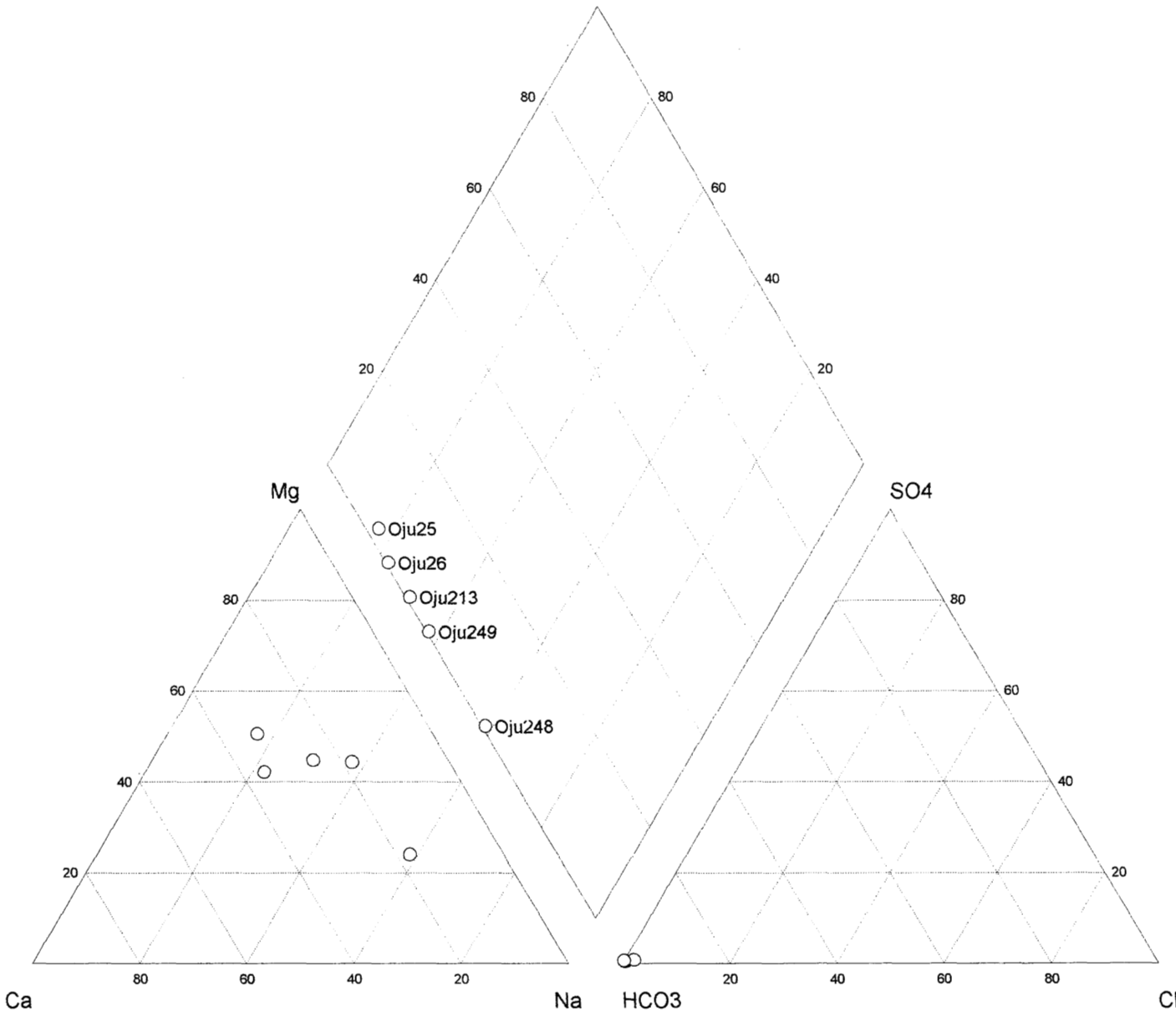
rwl 5.39 m
height casing = 0.5 m agl
time 300 mins
prate = 1.2 - 1.12 l/s = 99.4 $m^3/d$
25/03/98



# Annex 5: Water quality data

## Groundwater Chemistry - Adum West



| | |
|---|---|
| SampleID | : Oju25 |
| Location | : Obi |
| Site | : Adum West Pond |
| Sampling Date | : 27/02/97 |
| Geology | : Awgu Shale |
| Watertype | : Mg-Ca-HCO3 |

| | |
|---|---|
| Sum of Anions (meq/l) | : 3.70 |
| Sum of Cations (meq/l) | : 3.91 |
| Balance: | : 2.8% |

Total dissolved solids : 7.6 meq/l 290.7 mg/l

| Hardness | : meq/l | °f | °g | mg/l CaCO3 |
|---|---|---|---|---|
| Total hardness | : 3.1 | 15.51 | 8.68 | 155.1 |
| Permanent hardness | : 0.0 | 0.00 | 0.00 | 0.0 |
| Temporary hardness | : 3.1 | 15.51 | 8.68 | 155.1 |
| Alkalinity | : 3.59 | 17.95 | 10.05 | 179.5 |

(1 °f = 10 mg/l CaCO3/l 1 °g = 10 mg/l CaO)

Major ion composition

| | mg/l | mmol/l | meq/l | meq% |
|---|---|---|---|---|
| Na+ | 14.3 | 0.622 | 0.622 | 8.178 |
| K + | 3.2 | 0.082 | 0.082 | 1.078 |
| Ca++ | 24.4 | 0.609 | 1.218 | 16.014 |
| Mg++ | 22.9 | 0.942 | 1.884 | 24.77 |
| Cl- | 2.3 | 0.065 | 0.065 | 0.855 |
| SO4-- | 1.5 | 0.016 | 0.031 | 0.408 |
| HCO3- | 219.0 | 3.59 | 3.59 | 47.201 |

| Ratios | | | Comparison to Seawater | |
|---|---|---|---|---|
| | mg/l | mmol/l | mg/l | mmol/l |
| Ca/Mg | 1.066 | 0.646 | 0.319 | 0.194 |
| Ca/SO4 | 16.267 | 38.985 | 0.152 | 0.364 |
| Na/Cl | 6.217 | 9.588 | 0.556 | 0.858 |
| Cl/Br | 143.75 | 323.984 | 287.5 | 648.1 |

| Dissolved Minerals: | | mg/l | mmol/l |
|---|---|---|---|
| Halite (NaCl) | : | 0.107 | 0.0018 |
| Dolomite (CaMg(CO3)2): | | 173.422 | 0.942 |
| Anhydrite (CaSO4) | : | 2.127 | 0.016 |
| SiO2 as Quartz | : | 21.207 | 0.353 |
| or Feldspar (NaAlSi3O8): | | 92.606 | 0.353 |

| | |
|---|---|
| SampleID | : Oju26 |
| Location | : Obi |
| Site | : Adum West Clinic |
| Sampling Date | : 27/02/97 |
| Geology | : Awgu Shale |
| Watertype | : Mg-Ca-Na-HCO3 |

| | |
|---|---|
| Sum of Anions (meq/l) | : 4.97 |
| Sum of Cations (meq/l) | : 5.20 |
| Balance: | : 2.2% |

Total dissolved solids : 10.2 meq/l 393.7 mg/l

| Hardness | : meq/l | °f | °g | mg/l CaCO3 |
|---|---|---|---|---|
| Total hardness | : 3.96 | 19.79 | 11.08 | 197.9 |
| Permanent hardness | : 0.0 | 0.00 | 0.00 | 0.0 |
| Temporary hardness | : 3.96 | 19.79 | 11.08 | 197.9 |
| Alkalinity | : 4.92 | 24.59 | 13.77 | 245.9 |

(1 °f = 10 mg/l CaCO3/l 1 °g = 10 mg/l CaO)

Major ion composition

| | mg/l | mmol/l | meq/l | meq% |
|---|---|---|---|---|
| Na+ | 26.0 | 1.131 | 1.131 | 11.124 |
| K + | 2.2 | 0.056 | 0.056 | 0.551 |
| Ca++ | 36.3 | 0.906 | 1.811 | 17.812 |
| Mg++ | 26.1 | 1.074 | 2.147 | 21.116 |
| Cl- | 0.0 | 0.0 | 0.0 | 0.0 |
| SO4-- | 1.5 | 0.016 | 0.031 | 0.305 |
| HCO3- | 300.0 | 4.917 | 4.917 | 48.36 |

| Ratios | | | Comparison to Seawater | |
|---|---|---|---|---|
| | mg/l | mmol/l | mg/l | mmol/l |
| Ca/Mg | 1.391 | 0.844 | 0.319 | 0.194 |
| Ca/SO4 | 24.2 | 57.998 | 0.152 | 0.364 |
| Cl/Br | 0.0 | 0.0 | 287.5 | 648.1 |

| Dissolved Minerals: | mg/l | mmol/l |
|---|---|---|
| Halite (NaCl) : | 66.159 | 1.1309 |
| Dolomite (CaMg(CO3)2): | 197.656 | 1.074 |
| Anhydrite (CaSO4) : | 2.127 | 0.016 |
| SiO2 as Quartz : | 15.445 | 0.257 |
| or Feldspar (NaAlSi3O8): | 67.441 | 0.257 |

| | |
|---|---|
| SampleID | : Oju213 |
| Location | : Obi, Adum West |
| Site | : bgs33 |
| Sampling Date | : 12/03/98 |
| Geology | : Awgu Shale |
| Watertype | : Mg-Na-Ca-HCO3 |

| | |
|---|---|
| Sum of Anions (meq/l) | : 5.69 |
| Sum of Cations (meq/l) | : 6.04 |
| Balance: | : 3.0% |

Total dissolved solids : 11.7 meq/l 453.2 mg/l

| Hardness | : meq/l | °f | °g | mg/l CaCO3 |
|---|---|---|---|---|
| Total hardness | : 4.16 | 20.79 | 11.64 | 207.9 |
| Permanent hardness | : 0.0 | 0.00 | 0.00 | 0.0 |
| Temporary hardness | : 4.16 | 20.79 | 11.64 | 207.9 |
| Alkalinity | : 5.64 | 28.19 | 15.79 | 281.9 |

(1 °f = 10 mg/l CaCO3/l 1 °g = 10 mg/l CaO)

Major ion composition

| | mg/l | mmol/l | meq/l | meq% |
|---|---|---|---|---|
| Na+ | 41.2 | 1.792 | 1.792 | 15.276 |
| K + | 3.0 | 0.077 | 0.077 | 0.656 |
| Ca++ | 29.9 | 0.746 | 1.492 | 12.718 |
| Mg++ | 32.4 | 1.333 | 2.666 | 22.726 |
| Cl- | 0.8 | 0.023 | 0.023 | 0.196 |
| SO4-- | 1.3 | 0.014 | 0.027 | 0.23 |
| HCO3- | 344.0 | 5.639 | 5.639 | 48.069 |

| Ratios | | | Comparison to Seawater | |
|---|---|---|---|---|
| | mg/l | mmol/l | mg/l | mmol/l |
| Ca/Mg | 0.923 | 0.56 | 0.319 | 0.194 |
| Ca/SO4 | 23.0 | 55.122 | 0.152 | 0.364 |
| Na/Cl | 51.5 | 79.418 | 0.556 | 0.858 |

| Dissolved Minerals: | mg/l | mmol/l |
|---|---|---|
| Halite (NaCl) : | 0.037 | 0.0006 |
| Dolomite (CaMg(CO3)2): | 245.366 | 1.333 |
| Anhydrite (CaSO4) : | 1.843 | 0.014 |
| SiO2 as Quartz : | 22.514 | 0.375 |
| or Feldspar (NaAlSi3O8): | 98.31 | 0.375 |

SampleID : Oju248
Location : Obi
Site : BGS34
Sampling Date : 02/04/98
Geology : Awgu Shale
Watertype : Na-Mg-HCO3

Sum of Anions (meq/l) : 5.04
Sum of Cations (meq/l) : 5.31
Balance: : 2.7%

Total dissolved solids : 10.4 meq/l 413.5 mg/l

| Hardness | meq/l | °f | °g | mg/l CaCO3 |
|---|---|---|---|---|
| Total hardness | 2.15 | 10.73 | 6.01 | 107.3 |
| Permanent hardness | 0.0 | 0.00 | 0.00 | 0.0 |
| Temporary hardness | 2.15 | 10.73 | 6.01 | 107.3 |
| Alkalinity | 5.0 | 25.00 | 14.00 | 250.0 |

(1 °f = 10 mg/l CaCO3/l 1 °g = 10 mg/l CaO)

Major ion composition

| | mg/l | mmol/l | meq/l | meq% |
|---|---|---|---|---|
| Na+ | 69.5 | 3.023 | 3.023 | 29.195 |
| K + | 3.6 | 0.092 | 0.092 | 0.888 |
| Ca++ | 18.1 | 0.452 | 0.903 | 8.721 |
| Mg++ | 15.1 | 0.621 | 1.242 | 11.995 |
| Cl- | 0.4 | 0.011 | 0.011 | 0.106 |
| SO4-- | 1.4 | 0.015 | 0.029 | 0.28 |
| HCO3- | 305.0 | 4.999 | 4.999 | 48.278 |

| Ratios | | | Comparison to Seawater | |
|---|---|---|---|---|
| | mg/l | mmol/l | mg/l | mmol/l |
| Ca/Mg | 1.199 | 0.727 | 0.319 | 0.194 |
| Ca/SO4 | 12.929 | 30.985 | 0.152 | 0.364 |
| Na/Cl | 173.75 | 267.941 | 0.556 | 0.858 |

| Dissolved Minerals: | mg/l | mmol/l |
|---|---|---|
| Halite (NaCl) : | 0.019 | 0.0003 |
| Dolomite (CaMg(CO3)2): | 114.353 | 0.621 |
| Anhydrite (CaSO4) : | 1.985 | 0.015 |
| SiO2 as Quartz : | 12.755 | 0.212 |
| or Feldspar (NaAlSi3O8): | 55.698 | 0.213 |

SampleID : Oju249
Location : Obi
Site : BGS35
Sampling Date : 02/04/98
Geology : Awgu Shale
Watertype : Mg-Na-HCO3

Sum of Anions (meq/l) : 5.90
Sum of Cations (meq/l) : 6.23
Balance: : 2.7%

Total dissolved solids : 12.1 meq/l 471.7 mg/l

| Hardness | meq/l | °f | °g | mg/l CaCO3 |
|---|---|---|---|---|
| Total hardness | 3.81 | 19.07 | 10.68 | 190.7 |
| Permanent hardness | 0.0 | 0.00 | 0.00 | 0.0 |
| Temporary hardness | 3.81 | 19.07 | 10.68 | 190.7 |
| Alkalinity | 5.87 | 29.34 | 16.43 | 293.4 |

(1 °f = 10 mg/l CaCO3/l 1 °g = 10 mg/l CaO)

Major ion composition

| | mg/l | mmol/l | meq/l | meq% |
|---|---|---|---|---|
| Na+ | 52.6 | 2.288 | 2.288 | 18.856 |
| K + | 2.7 | 0.069 | 0.069 | 0.569 |
| Ca++ | 22.2 | 0.554 | 1.108 | 9.132 |
| Mg++ | 32.9 | 1.353 | 2.707 | 22.31 |
| Cl- | 0.4 | 0.011 | 0.011 | 0.091 |
| SO4-- | 1.2 | 0.012 | 0.025 | 0.206 |
| HCO3- | 358.0 | 5.868 | 5.868 | 48.361 |

| Ratios | | | Comparison to Seawater | |
|---|---|---|---|---|
| | mg/l | mmol/l | mg/l | mmol/l |
| Ca/Mg | 0.675 | 0.409 | 0.319 | 0.194 |
| Ca/SO4 | 18.5 | 44.337 | 0.152 | 0.364 |
| Na/Cl | 131.5 | 202.787 | 0.556 | 0.858 |

| Dissolved Minerals: | mg/l | mmol/l |
|---|---|---|
| Halite (NaCl) : | 0.019 | 0.0003 |
| Dolomite (CaMg(CO3)2): | 249.152 | 1.353 |
| Anhydrite (CaSO4) : | 1.702 | 0.012 |
| SiO2 as Quartz : | 22.744 | 0.379 |
| or Feldspar (NaAlSi3O8): | 99.316 | 0.379 |