BRITISH GEOLOGICAL SURVEY
Natural Environment Research Council

TECHNICAL REPORT WD/98/9C
Hydrogeology Series

Technical Report WD/98/9C

The Sustainability of Partially Cased Boreholes with Particular Regard to Malawi

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This report was prepared for BDDCA,
Department for International Development

Bibliographic Reference

Robins N S 1998
The Sustainability of Partially Cased Boreholes with Particular Regard to Malawi
British Geological Survey Report WD/98/9C

 Keyworth, Nottinghamshire British Geological Survey 1998

BRITISH GEOLOGICAL SURVEY

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CLIENT	
DFIDCA, Department for International Development	CLIENT REPORT #
	BGS REPORT# WD/98/9C
	CLIENT CONTRACT REF
	BGS PROJECT CODE
	CLASSIFICATION Confidential

	SIGNATURE	DATE		SIGNATURE	DATE
PREPARED BY (Lead Author)	N S Robins	25/9/98	CO-AUTHOR		
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PEER REVIEWED BY	[signature]	22.9.98	CO-AUTHOR		
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CHECKED BY (Project Manager or deputy)			CO-AUTHOR		
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APPROVED BY (Project Director or senior staff)			CO-AUTHOR		
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APPROVED BY (Hydrogeology Group Manager)	[signature]	28/9/98	Assistant Director clearance (if required)		
Layout checked by	C. Sharratt	28/9/98			

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EXECUTIVE SUMMARY

The plateau areas of Malawi weather to form an upper zone called the regolith and a lower blocky and fractured zone of bedrock called the saprock. On the Escarpment the regolith is largely absent, and in the Shire Valley and Lake Chilwa Basin alluvial deposits are present. Boreholes drilled into the regolith and the alluvial deposits must be fully supported by casing and screen with appropriate formation stabilizer placed in the annulus between the casing and the drilled borehole wall. Boreholes drilled into the fractured bedrock may be completed as open-hole provided there are no soft and unstable horizons within these strata. It is advisable to drill 2 m into bedrock to establish firm ground before landing casing and cementing it to bedrock.

Use of light weight drilling rigs such as the Eureka Port-a-Rig equipped only with a 150 mm diameter drag bit and a 95 mm button bit does not allow penetration of the unweathered bedrock at full diameter which can later be cased. There is a risk when reducing to the smaller diameter to continue drilling with a button bit of penetrating further soft horizons which may later slough into the open-hole.

Adaptations to the Eureka Port-a-Rig allow it to drill into hard rock for a limited distance using an air flush button bit at 150 mm diameter. Given 2 m penetration of bedrock, hard ground can be proven (or otherwise) and 110 mm casing landed onto bedrock and cemented in. Reduction to 95 mm may then safely follow with open-hole completion.

Recommended guidelines for drilling and completing partially cased boreholes in Malawi are presented. These suggest that partial open-hole completion in unweathered bedrock is good practice provided that certain precautions are carried out to ascertain that no strata are left uncased which need supporting. It is recommended that partially cased borehole completion be continued in Malawi both on the grounds of cost, and improved well efficiency and hydraulic access to the aquifer.

1. BACKGROUND

The Malawi Ministry of Water Development (MWD) has standardised on 110 mm diameter fully cased boreholes for use in the rural environment. Partially cased boreholes have previously been installed in the region. The feasibility, practicability and sustainability of installing and operating partially cased boreholes in various geological settings needs clarification. In discussion with MWD it has been agreed that DFID fund a desk based evaluation of partially cased boreholes to increase knowledge of this technology within MWD and DFID.

This report reviews the feasibility and sustainability of partially cased boreholes with specific reference to Malawi. Data are drawn from experience in Malawi and in other similar geological and climatic conditions elsewhere in southern and eastern Africa.

2. OBJECTIVES

The broad objectives of this study are as follows:

- Review relevant documentation, data and literature to identify past experience of partially cased boreholes within the region.
- Review documentation on premature weathering, silting and collapse of partially cased boreholes and review comparative life-time costs of partially cased and fully cased boreholes.
- Review equipment, cost and community participation in intermediate rig technology.
- Review near-borehole hydraulics in terms of open-area of screen and design of partially cased boreholes.
- Make recommendations for optimum borehole design.

The report includes issues identified within the literature and by other key informants. The arguments for and against partially cased boreholes are presented along with recommendations on the use of partially cased boreholes in Malawi and outline guidelines for the use of open-hole completion.

3. HYDROGEOLOGICAL SETTING - MALAWI AND NEIGHBOURS

The crystalline basement rocks (gneiss and granulite with schists, quartzites and marbles) weather to form a low yielding but very extensive aquifer, typically 15 to 30 m thick. Water may occur in the granular weathering products, the saprolite, and in fractures within the bedrock. Transmissivity rarely exceeds 30 m^2d^{-1}, and permeability is low but variable: mostly in the range 0.05 to 1.50 m d^{-1}, exceptionally 5.0 m d^{-1} (Chilton and Foster, 1995). Storativity lies in the range 0.005 to 0.01; depth to water is normally less than 25 m, and the seasonal fluctuation in water level is typically between 1 m and 5 m. Dambos are low lying areas of groundwater discharge. On the escarpment area, the weathered material tends to be removed and groundwater occurs mainly in fractures within the unweathered rock.

The alluvial aquifers of the lake shore, the Shire Valley and the Lake Chilwa basin are Quaternary lacustrine and fluvial sediments. Clay layers may cause confined conditions to occur. Transmissivity values range from 100 to 300 m^2 d^{-1}, and storativity from 0.01 to 0.05. The depth to water in the lake shore areas may be less than 10 m, with seasonal variations of between 1 and 3 m. The depth to water increases away from the River Shire and the lake and may exceed 30 to 35 m in, for example, the Bwanje Valley, Rivi Rivi and the Upper Shire.

The distribution of rainfall in Malawi tends to reflect elevation. The plateau areas of the Central and Southern Regions receive a mean annual rainfall of between 400 and 1000 mm a^{-1} rising to 2000 mm a^{-1} in Northern Region. The Lower Shire Valley receives considerably less with rain-shadow effects resulting in less than 400 mm a^{-1}. However, the variability and reliability of the rain is considerable, both areally and temporally (it is in any case generally less than that in much of Zimbabwe). Potential evaporation is highest along the lake shore and the Shire Valley and decreases with increased elevation; the range is from 1100 to 1700 mm a^{-1}. Groundwater recharge estimates vary from 5 to 100 mm a^{-1} for the weathered Basement aquifers and from 3 to 80 mm a^{-1} for the alluvial aquifers (Smith-Carington and Chilton, 1983). Current groundwater abstraction from wells and boreholes is estimated to be less than an equivalent depth of 1 mm a^{-1} for rural areas and perhaps 2 to 3 mm a^{-1} for densely populated areas (Kafundu and Laisi, 1991).

4. HYDRAULIC AND ENGINEERING PROPERTIES OF THE BASEMENT AQUIFER

The Basement Aquifer is the weathered residual or regolith and shallow fractured bedrock (Figure 1). The upper part of the profile is the collapsed zone. This shows a marked lateral variation and may be sandy on interfluves and silty in valleys; there may be a stone line at the base. The saprolite derives from in situ weathering of the bedrock. It tends to be silty near the top and is increasingly granular and more permeable with depth. The saprock is the fractured bedrock, typically gneiss or granite or other hard indurated rock with little if any intergranular permeability.

The saprolite and collapsed zone, collectively the regolith, provide the main storage of groundwater for shallow wells and for deeper boreholes. The latter may draw groundwater from the fractured saprock although the storage is largely in the regolith.

The collapsed zone is typically sandy but may be clayey in valley bottoms; it includes laterites, calcretes, illuviated clays and stone layers. The upper part has a high infiltration capacity, but this decreases with the presence of clay material. *The collapsed zone is inherently unstable and boreholes and wells must be supported throughout this upper shallow zone.*

The saprolite derives from in situ weathering and may exhibit ghost structures from the original unweathered rock. This coarsens and becomes more granular towards the saprock. Wright (1992) describes four controls over the thickness and nature of the regolith:

- bedrock characteristics (chemistry, mineralogy, petrography and structure)
- climate (past and present)
- age of the land surface
- relief and other site factors.

Small scale variation in the nature of the regolith suggests that the dominant controls are local. The divide between the regolith and the saprock may be quite sharp, but in other places it may be gradational. Regional variation also occurs so that the regolith is deeper beneath older erosional surfaces, for example it is deeper over much of Malawi than it is in many parts of Zimbabwe (Wright,

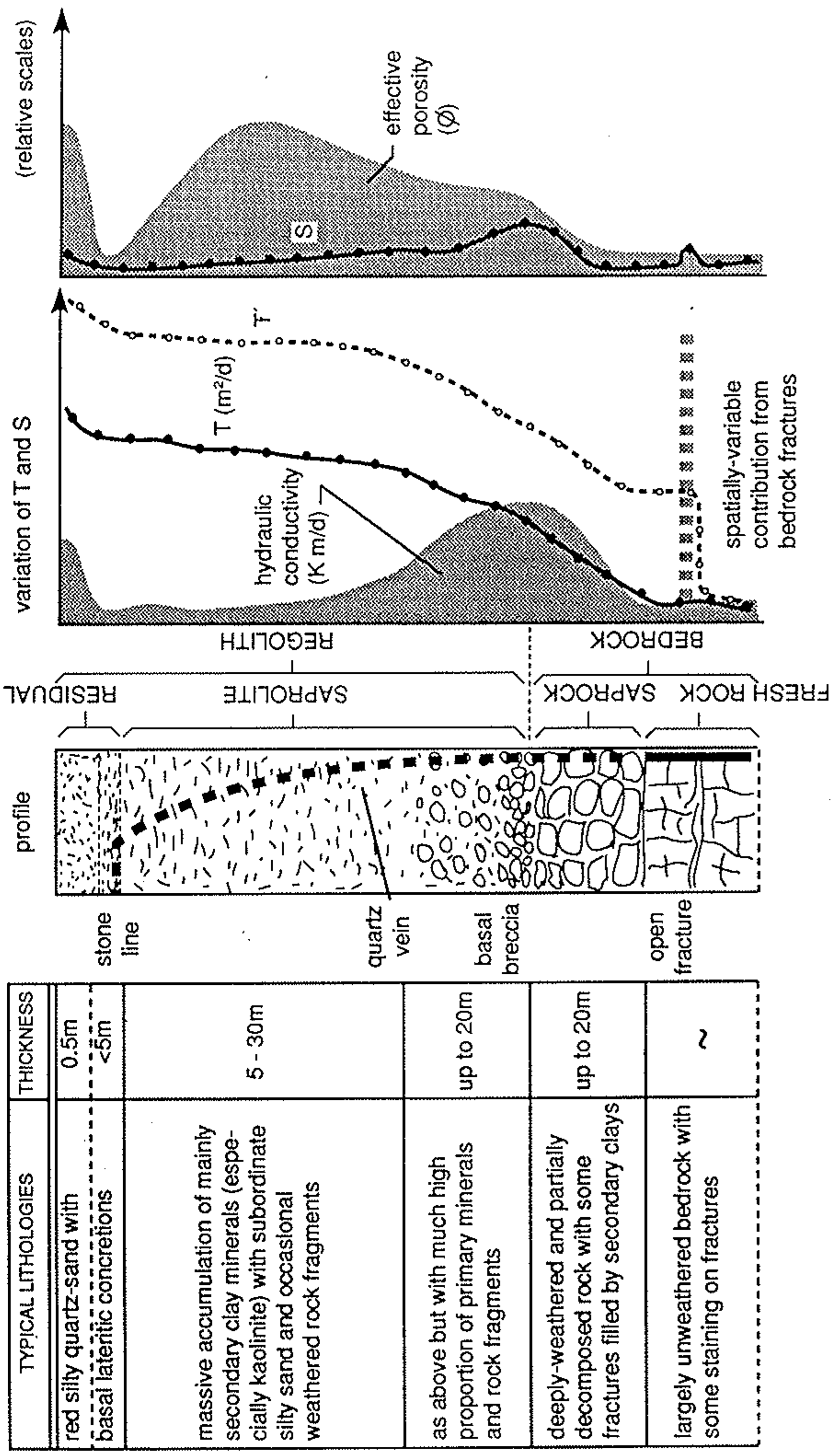

Figure 1. **Conceptual hydrogeological model of the weathered crystalline basement aquifer (after Chilton and Foster, 1995).**

1992). The permeability of the regolith in Malawi and Zimbabwe is generally less than 0.5 m d^{-1}, significantly lower than the ranges of higher permeability available in the saprock. Porosity in the regolith lies typically in the range 0.2 to 0.4, and reflects the presence of clay minerals, the original rock type and the aggressiveness of weathering. The thicker saturated zone in the regolith of the central plateau of Malawi lends itself to exploitation by shallow wells and boreholes within the saturated regolith alone; elsewhere, including most of Zimbabwe, it is necessary to drill into the saprock in order to draw on the groundwater stored above in the shallower regolith. In both cases typical sustainable yields may be 0.5 l s^{-1}, perhaps slightly greater in boreholes terminating in the regolith than in the saprock in the case of Malawi (McFarlane et al, 1992).

The physical strength of the regolith is also variable depending on the same factors that control permeability (Acworth, 1987). In general the upper section will be least able to stand unsupported, not least the clayey matrix of a dambo floor (McFarlane, 1992), whereas the more granular and blocky lower horizons may be self supporting. The fractured saprock is generally capable of standing open indefinitely, except in the event of a block falling across a borehole and preventing access below it.

5. ALLUVIAL AQUIFERS OF THE SHIRE VALLEY AND LAKE CHILWA BASIN

The alluvium in the Shire Valley and the Lake Chilwa Basin comprises Quaternary lacustrine and fluvial sediments with clay layers which create semi-confined conditions. Transmissivity is typically in the range 100 to 300 m^2 d^{-1}, and storativity between 0.01 and 0.05 (Kafundu and Laisi, 1991). Depths to water in the lake shore areas of Salima and Nkhotokota are generally less than 10 m, but increase to 30 m below ground level in higher elevation areas.

None of the alluvial strata are sufficiently consolidated for open-hole borehole completion. All boreholes in the alluvium must be fully lined with plain and slotted casing, and formation stabilizer or properly graded gravel pack placed behind the screened sections. A bottom cap should be used. These strata are readily drilled with a drag bit (except where lateritic horizons may occur) and use of lightweight drilling equipment is appropriate for the installation of fully lined 110 mm boreholes.

6. EVOLUTION OF THE BOREHOLE DESIGN

Although there are no hard and fast rules regarding borehole design, two factors are paramount. One is that the borehole must be capable of receiving water from the saturated formation at a rate that the aquifer can support, the second is that the borehole design should reflect the design life, perhaps twenty five years or more. The entry velocity of water passing into the borehole must be less than 0.03 m s^{-1} in order to prevent turbulent flow and high well loss (Driscoll, 1986). In addition the construction should afford some degree of sanitary protection at the well-head from surface runoff and other contaminants.

Until the early 1980s the usual completion design for Malawi boreholes involved hack-saw slotted mild steel casing and '12 mm down' crushed roadstone as a formation stabilizer. This combination of large slots (3-5 mm) and small open area (less than 5%) was used in all settings including the alluvium. It allowed fine material to enter the borehole with consequent damage to hand pumps and shortened borehole life due to silting up.

The preferred borehole design in Malawi evolved from a major hydrogeological investigation carried out in the early 1980s (Smith-Carington and Chilton, 1983; Grey et al, 1985). Cable tool rigs were used (now rotary and rotary percussion) to provide 200 mm drilled holes to depths of 20 to 30 m in

EMPIRICAL RULES TO BE OBSERVED FOR BOREHOLE DESIGN IN BASEMENT REGOLITH IN MALAWI (UNDP, 1982)

a) 110 mm Class 10 PVC screen should be installed from or just below the point at which water was first struck, but not above that, to the bottom of the hole (a 1 m blank casing sump can be used if available).

b) At least 9 m but not more than 15 m of screen should be installed.

c) If the depth from where the water was first struck in a confined aquifer to the bottom of the hole is more than 15 m some screen should be installed near the top of the aquifer and the remainder (totaling 15 m) at the bottom of the hole, with blank casing in between.

d) Screen should not be set at a depth of less than 3 m below the ground surface.

e) Three centralizers are required to be tied in the mid-point of each length of slotted pipe.

f) Plain 110 mm Class 10 PVC casing is installed in 3 m lengths from the uppermost slotted section to about 0.5 m above ground level. Any surplus pipe will be cut off.

g) A bottom cap is required, as is solvent cement and cleaning fluid.

h) Formation stabilizer is required.

the weathered zone. The preferred borehole completion was 110 mm diameter PVC casing and slotted pipe (screen) with an open area of 8% and an average slot width of 0.8 mm. A formation stabilizer surrounds the slotted pipe, usually '2 mm down' Lake Malawi beach sand. As the regolith is of low permeability the slotted pipe must be placed against the full length of saturated aquifer, from water strike to the bottom of the hole at the regolith/saprock junction. To this end a set of empirical rules were developed *for the regolith* (usually between 9 and 15 m in thickness) and incorporated into the UNDP sponsored Manual for Integrated Projects for Rural Groundwater Supplies (UNDP, 1982).

Interestingly there does not appear to be much correlation between borehole performance and thickness of saturated saprolite in Malawi (Chilton and Foster, 1995) possibly because yields are consistently low and specific capacity (yield divided by drawdown) is relatively constant. More recently the use of light-weight drilling rigs has promoted a need to case the regolith but to leave the unweathered bedrock as open-hole. This is acceptable practice provided the casing is landed on firm rock and that there are no soft zones left uncased within the apparently 'hard rock'.

The need to case the weathered regolith and support it with formation stabilizer was reinforced by Clark (1985). Furthermore, a number of standard recognised manuals recommend borehole design which includes screen throughout the saturated regolith with casing landed onto or into fractured saprock with an open-hole (unlined) below to act as a sump (e.g. Clark, 1988; DWAF, 1997). The manuals do, however, vary in the recommended depth of bedrock that should first be penetrated before open-hole is acceptable, the South Africans, for example prefer three metres of firm rock in which to land the borehole casing, whereas others are happy to cement casing onto the upper surface of firm bedrock.

Experience to date suggests that open-hole completion in the fractured saprock is current practice and the best means of obtaining a good hydraulic contact with the formation water. Given that the geological conditions in Zimbabwe where the regolith is shallow, are slightly different to much of Malawi where the regolith is deeper, the consensus of technical literature based on experience in both countries is that the regolith should at all times be cased and supported (Figure 2). However, the sap rock should be left as open-hole only in the fractured zone.

In truth the required penetration depends on the nature of the rock head, be it a diffuse gradational boundary or a more sharp and sudden change. *The open-hole design is applicable in Malawi*, but at what depth below the saprock/regolith boundary it can be left unlined is difficult to define and varies regionally. As proof of hard bedrock is desirable before landing the casing it is suggested that an optimum penetration of the bedrock of 2 m is a viable target for Malawi. Drillers and hydrogeologists familiar with a given set of conditions are best able to prescribe the use of slotted liners.

7. NEAR-BOREHOLE ENVIRONMENT

A great deal of attention has been focussed on near-field hydraulics of production boreholes with regard to well efficiency and longevity. Needless to say, much of this work considers high yielding boreholes in highly permeable aquifers and assesses the entry velocity of groundwater into the borehole to ensure that the borehole design permits laminar rather than turbulent flow. Turbulent entry encourages the transport of fines into the borehole and this in turn leads to silting up and other damage. In the African basement context, yields to hand pumps are, by definition, small and entry velocities through slotted pipe and well screen are not likely to create problems. For this reason a formation stabilizer is used behind the slotted pipe rather than a hydraulically compatible gravel pack, the aim being only to retain the potentially unstable strata in position.

As the abstraction rates of rural water sources are generally small, the near field hydraulics are unlikely to create conditions in the aquifer which well promote significant physical erosion to destabilise the formation. Thus, if the saprolite stands up during drilling and throughout an aggressive cleaning programme (bailing and swabbing), it is unlikely that the relatively gentle action of a hand pump would create problems thereafter. However, there may be additional forces in action and these may lead to a gradual instability; they include chemical degradation of the strata which may be promoted by constant wetting overnight and exposure to oxygen by day when the water level is drawn down. The chemical degradation may be further exacerbated by microbial activity.

The nature of chemical degradation in the regolith adjacent to a village groundwater source depends largely on the geochemistry of the strata, the pH of the system and the rate at which dissolution products are removed (Acworth, 1987). Given the weak acid of normal rainfall, and the availability of hydrogen ions in normal soil water, calcium bearing minerals, such as for example anorthite, are particularly unstable as the calcium is readily replaced by hydrogen as follows:

$$CaAl_2Si_2O_8 + 2CO_2 + 3H_2O = Ca^{++} + 2HCO_3^- + Al_2Si_2O_5$$

This and other reactions, including similar degradation equations for forsterite and sodium feldspar, accelerated in time within the aggressive near field environment of an abstraction borehole, could provide opportunity for collapse of unsupported borehole walls at some future time. Prediction of timing and severity is well nigh impossible on a regional scale, although simulation studies could (at considerable expense) provide some insight on a local if not almost site specific basis. However, it is unlikely that chemical degradation could promote instability within the normal lifespan of a borehole.

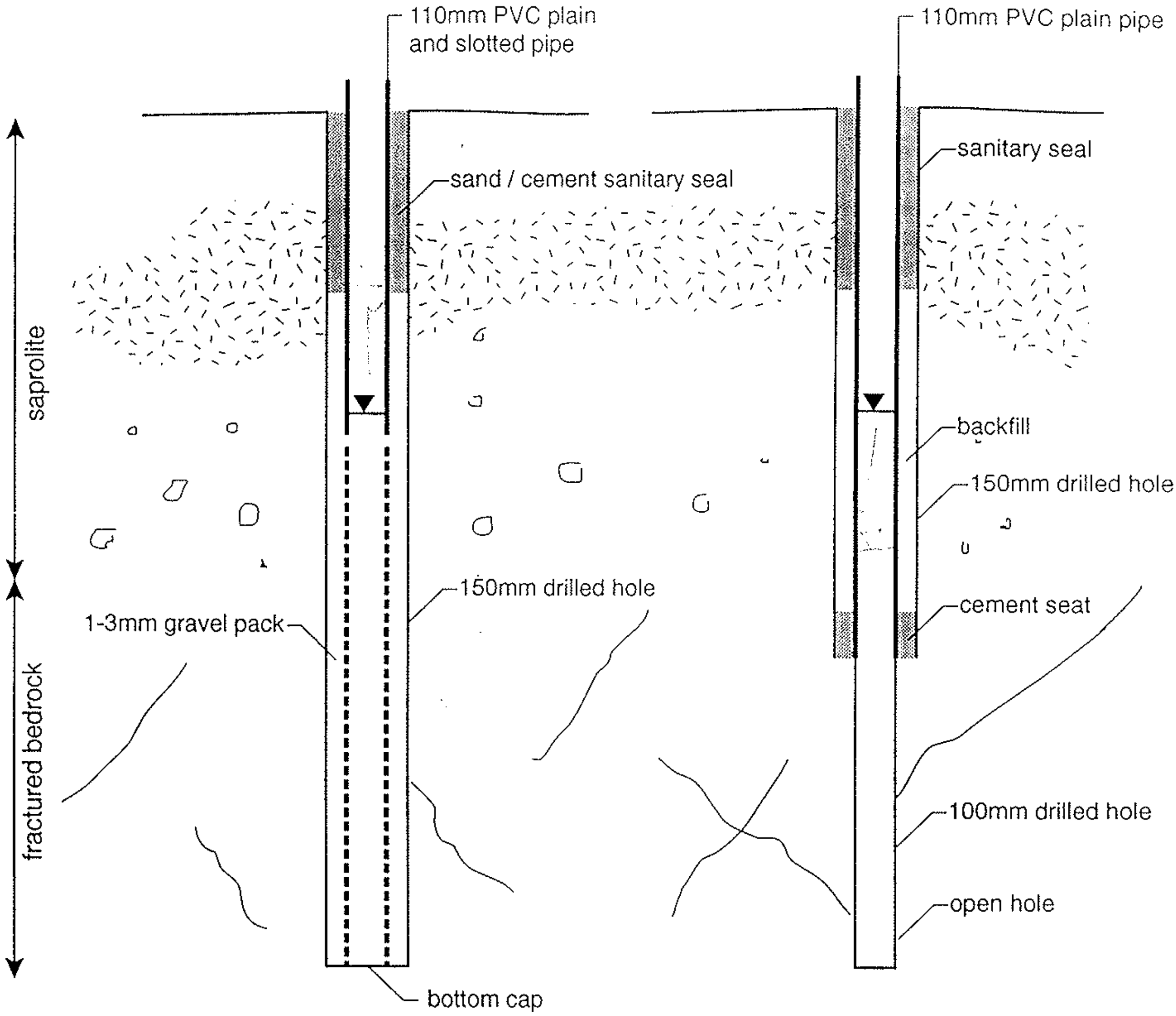

Figure 2. **Borehole design options.**

8. DRILLING TECHNIQUE OPTIONS

There are currently four levels of drilling technology available in Malawi. These are:

1) Cable-tool percussion drilling rigs, with limited opportunity for community participation, reasonable capital outlay, operating and maintenance costs.

2) Conventional rotary drilling machines, either fluid flush or air hammer, providing no community participation, high capital and operating costs, and associated problems with maintenance costs and availability of spare parts.

3) The low technology hand driven drilling rig, the attraction of which is high community participation, small capital outlay and low operating and maintenance costs.

4) The small hand-portable power-driven drilling rig, providing some opportunity for community participation, reasonable capital and operating costs and straight forward maintenance.

Each of these techniques is constrained in some way. This may be the time taken to complete a borehole, lack of ownership through community involvement, or depth and diameter limitations. The cable-tool percussion drilling rig is the traditional work-horse for water borehole drilling throughout Africa, although now largely superseded by the rotary drilling machine. Its advantage is that it can cope with most drilling conditions, its disadvantage is a generally slow rate of penetration according to the hardness of the ground being drilled, and drilling into fractured bedrock could be as slow as 1 m day^{-1}. The conventional combination rotary fluid flush/air hammer rig is able to deal with nearly all geological conditions, and is an efficient and effective drilling technique. These rigs are operated both by Government and commercial contractors in Malawi.

Hand powered rigs include the Zimbabwe-built Vonder rig which has been successfully used to drill shallow rural community boreholes in Malawi. Penetration may be 2 m day^{-1} using four men to turn and weight the wing-bit at the end of the drilling cylinder, withdrawing the bit at intervals in order to empty the cuttings. Completion of a borehole up to 15 m deep requires between 2 to 3 weeks effort. Any hard rock or the occurrence of a boulder would prevent drilling even to 15 m.

The small hand-portable rig, such as the Eureka Port-a-Rig, offers tremendous advantages in terms of site access and running costs. Site access for this type of machine is limited only by the ability to tow a compressor to the drilling site. The Port-a-Rig offers the facility of a readily portable small rig with an integrated fluid flush tank with settling baffles for the chippings, plus combination facilities for down-hole air hammer. This allows a drag bit to be used in weathered material and alluvium and an air hammer in hard bedrock. Weight is applied to the bit by hand. This a most versatile piece of equipment and those that have used it speak most highly of its capability.

The Eureka Porta-Rig is capable of drilling and completing a 35 m deep borehole in two days. Maximum penetration in Malawi is 50 m in bedrock using the down-hole hammer and 35 m in alluvium using the drag bit. It is capable of drilling a 30 m deep borehole on 2 l diesel fuel. Furthermore the rotary drive engine, the fluid pump engine and the test pump engine are all interchangeable ensuring continuity of work should engine problems arise. Concern Universal currently have four trained crews and two Eureka Porta-Rigs, and a third is operated in Malawi, although not on a continuous basis, by Action Aid.

Estimates of average cost per borehole using the alternative available technologies were analysed at the start of the Malawi Community Schools Project. The economics of the Port-a-Rig type operation were convincing (Robins, 1996). Assuming a standard 35 m deep borehole, the Port-a-Rig average cost is £2 460 (K56 000 at 1996 exchange) with capital costs distributed amongst 100 boreholes. Hillyard and Mthunzi (1998) quote a lower figure which presumably excludes capital depreciation. Drilling contractors using air rotary rigs costed themselves at between K66 000 and K93 000 depending on the contractor, whereas the Ministry of Water Development estimated an average K60 000 per borehole. Interestingly the Vonder manual rig costs about the same per borehole as the Eureka Port-a-Rig although it could not produce a comparable 35 m deep borehole.

9. THE EUREKA PORT-A-RIG

The attraction of the Port-a-Rig lies in ease of operation, mobility, and economics (See Hillyard and Mthunzi (1998) Appendix 1). There are, however, a number of serious constraints, of which its lightness of construction and lack of power compared with conventional equipment is the key. The successes and constraints are highlighted by Hillyard and Mthunzi (1998), and only those that relate directly to the drilling and completion of rural community boreholes are highlighted below.

The rig drills to a diameter of 150 mm in the regolith using a drag bit and mud-flush to allow standard 110 mm diameter permanent casing to be installed (see example borehole reports, Appendix 2 - clearly not all geological conditions are suitable for the Eureka Port-a-Rig). The saprock has been drilled with compressed air to a diameter of 95 mm but this is too narrow to be effectively cased. There is a problem within the regolith to saprock interface area where unstable strata may be left unsupported, or where the narrow diameter bit is used to penetrate laterite layers and later encounters softer material below, which must also be left unsupported. The conventional fully cased and the partially uncased borehole is shown schematically in Figure 3. In actual fact, many conventional drilled boreholes are left open-hole in firm saprock, both in Malawi and more particularly throughout Zimbabwe.

Aware of the potential problems of borehole collapse at the base of the regolith, Concern Universal have started a programme of borehole monitoring using a down-hole CCTV system. To date no problems have been uncovered in completed partially cased boreholes. However, none have been commissioned for more than two years, and it is premature to conclude that longevity is assured.

In order to overcome the potential problem of partial casing, the rig manufacturers have produced an adaptation whereby a 150 mm diameter hole can be achieved into the unweathered bedrock using an air-hammer bit in a foam filled borehole. Trials of this system commenced in Malawi during late 1997, and if successful, will enable fully cased boreholes to be completed into the top of the saprock and completed as open-hole below (Figure 3). In addition a new up-graded rig has been designed, but not yet produced, which may be of considerable value for future NGO activities in Malawi.

10. OPTIMUM BOREHOLE DESIGN

Clear cut rules were laid down in 1982 for the construction of boreholes in the regolith (UNDP, 1992). These rules are acceptable to day and should be adhered to. However, there are no guidelines extant in Malawi relating to the use of open-hole borehole completion below the regolith in fractured bedrock, it being emphasised that the UNDP empirical rules were written only for the regolith. Hereby lies some confusion, with Government officials quoting advice from BGS hydrogeologists active in Malawi in the early 1980s that open-hole is unacceptable - open-hole *is* unacceptable in the weathered regolith, but it is standard completion practice in many areas in fractured bedrock in Africa and elsewhere.

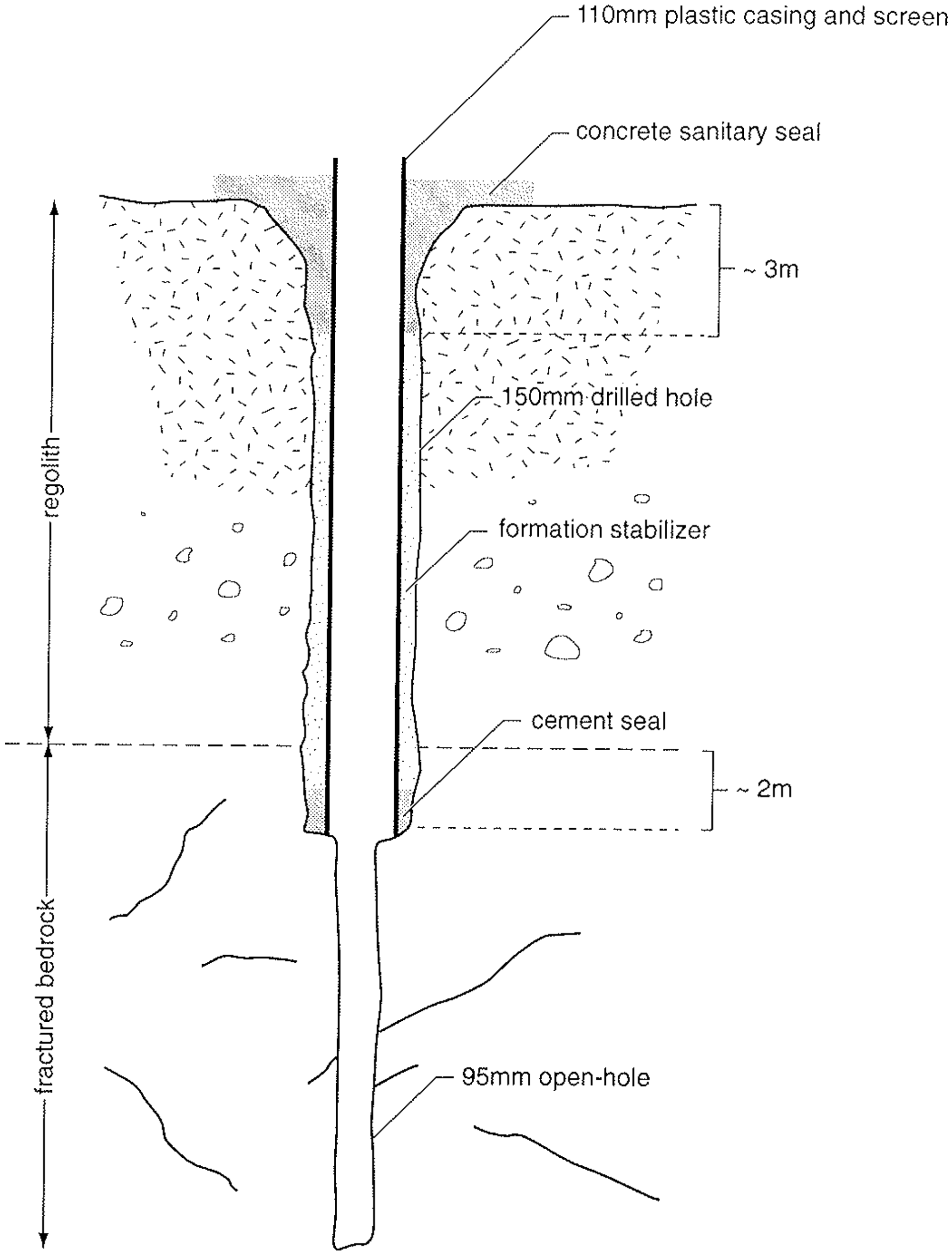

Figure 3. **Suggested borehole design using 150 mm drag bit, 150 mm hammer bit and 95 mm button bit with a light weight rig.**

DRAFT GUIDELINES FOR THE USE OF OPEN-HOLE BOREHOLE COMPLETION

- Open-hole completion should only be used when the driller and supervisor are satisfied that fractured bedrock has been encountered. Indicators include rate of penetration, relatively fresh appearance of chipping samples, inability to penetrate with a drag bit, and local experience of the depth of regolith and the nature of the regolith / saprock interface.

- Care must be taken to decide if firm bedrock has been reached rather than a hard band such as a laterite which may have soft rock beneath. The nature of the regolith/saprock boundary needs to be ascertained - is it a sharp divide, is there a stone layer present, is it a more gradational boundary? Drilling on through the hard contact to a minimum further depth of penetration of 3 m is recommended to ascertain that bedrock has been reached.

- Regolith casing must be landed on firm rock and cement sealed to that contact (Figure 4). This may be done at the top of the bedrock contact if the divide is sharp and clear or it may need penetration into the saprock until the driller and supervisor and convinced a firm footing has been achieved. Written and diagrammatic evidence for the decision to place casing to a specific depth should be recorded on the borehole completion report.

There are, however, two situations to beware particularly when a relatively light drilling rig is employed (see Hillyard and Mthunzi, 1998). The first is recognition of suitably hard and consolidated bedrock or saprock onto which to land the casing, and the second is the fear of a hardband such as a laterite overlying deeper soft rock which may slough into the borehole if left uncased (see Appendix 2). Use of the Port-a-Rig, whereby a drag bit can go no further on contacting hard rock, does not allow any penetration of hard rock in which to land the casing before continuing open-hole; the Port-a-Rig with combination air-hammer button bit will allow 2 m penetration to verify hard rock in which to land the casing.

There needs to be an element of trust in deciding where hard rock actually starts and where the casing should end. It is not possible for an NGO or the Government to supervise all borehole drilling and completion activities. However, the driller is familiar with the ground and with the equipment, and under normal conditions he is well placed to make the appropriate decision. It may be argued that not all drillers deserve such trust, particularly when they are under commercial pressure as a contractor. This is a weak argument provided the contractor is using a standard heavyweight drilling rig, because the margin for error in assessing rock head is far less using a rig which can drill equally well through regolith and bedrock without changing bits, bit weights or circulating fluids.

Bearing these difficulties in mind it is possible to create an optimum completion design for a borehole that penetrates both the regolith and the fractured bedrock. As in the UNDP guidelines the regolith needs to be fully cased and if necessary screened. The fractured bedrock may be left open-hole provided that there is no fear of collapse such as a block of material falling across the hole and severing access below. This is always a risk in open-hole completion, but the degree of risk must be outweighed against the cost saving and hydraulic benefit of open-hole completion. For the most part this falls in favour of the open-hole, and must do so also in Malawi wherever that risk is small.

Evidence with which to quantify risk in the Malawi basement is lacking. There are no records of collapsed open-hole boreholes, or of lost boreholes due to premature weathering and silting up of open-hole fractured rock completions. The down-hole CCTV now operated by Concern Universal to inspect new and existing partly cased boreholes will, in due course, help to evaluate the risk. In the mean time precedent must be taken from elsewhere: Zimbabwe does not experience premature failure of open-hole completion in crystalline basement (Norad/Interconsult, 1986).

A suggested design option for fractured bedrock is given in Figure 3. and draft guidelines for the use of open-hole completion are listed above. It is assumed that the regolith is in hydraulic contact with the fractures but that the majority of storage is within the regolith.

11. THE CASE FOR AND AGAINST OPEN-HOLE CONSTRUCTION

Fractured hard rock is completed with open-hole in many situations around the world. Experience to date in Malawi suggests that fractured hard rock open-hole completion is not putting borehole sustainability at any significant risk, on the contrary, it is likely to enhance the hydraulic contact between the borehole and the fractured rock and so improve well efficiency. The cost-savings of using lightweight rigs with casing and screen landed to supposed hard rock are significant and the economics of boreholes drilled and completed to this formula must outweigh the risks of occasional borehole loss due to collapse in undetected soft material situated below the casing bottom.

Evidence that open-hole completion in saprock is reducing borehole life expectancy is not forthcoming in Malawi. The overall picture is blurred for a number of reasons, not least poor standards of borehole design prior to the 1980s, and lack of elapsed time since the new narrow diameter boreholes have been commissioned with which to form a judgement. Calow et al (1997) reviewed causes of borehole failure and sited critical factors such as hilly and mountainous areas, shallow local aquifer, pump failure, falling groundwater levels and borehole silting up. However, this work highlighted the shortcomings of the Government run maintenance programme as the key to source failure. Failure due to silting up suggests either inadequate design with fine-grained material running through the screen sections or down the outside of the casing, or weathering of open-hole sections. It is unlikely that open-hole failure is significant, as the boreholes would otherwise be completely lost and need to be abandoned - reports are few of this occurrence.

The economic, access and community ownership attractions of small lightweight drilling rigs are compelling. The obvious downside is occasional borehole failure due to open-hole exposure of undetected soft ground. However, advances with this form of intermediate rig technology, including the use of the foam fluid button bit, help to reduce risk of the latter to an acceptable level. In addition, Eureka have plans to introduce further upgraded models in the intermediate technology field in due course, and NGOs operating in Malawi could usefully look towards this equipment as a means of overcoming any existing shortcomings.

The role of the Eureka Port-a-Rig in Malawi must, nevertheless, be assured once the present misunderstandings between Government, its advisors, and the NGO rig operators have been resolved. The Port-a-Rig has become a victim of its own success, it was after all only brought into the Malawi rural community water development field as a possible means of upgrading the Vonder manual rig low technology, and slow speed equipment. To this end the Port-a-Rig is undeniably successful as it returns a similar cost borehole with far greater safeguards with regard to borehole completion and longevity, takes a much shorter time to produce a deeper borehole, yet retains a valuable element of community participation.

In conclusion, partial open-hole completion in the Basement aquifer of Malawi is a viable and useful technique. However, it must be remembered that open-hole should only be used in the fractured bedrock or saprock, and that the key to successful completion is securing the casing through the regolith securely to the bedrock. The decision as to how far into bedrock the casing should penetrate depends on local factors and is best decided by the rig operator and the supervising hydrogeologist. The draft guidelines for open-hole completion (above) could usefully form the basis of a Government statement on this issue which has already attracted a degree of controversy in the water sector in Malawi.

ACKNOWLEDGEMENTS

Valuable discussion took place with a number of people who also assisted with the provision of data. Invaluable to the study were Theron Scott Robinson, PPI Consultants Limited, Lilongwe; David Hillyard, Concern Universal, and Peter Bell, Eureka. In addition, the personal experience of John Chilton, BGS, was pivotal to interpreting the recommended procedure established in Malawi in the 1980s.

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GLOSSARY

aquifer: a rock formation which is sufficiently permeable to yield a usable quantity of water to a borehole, well or spring.

baseflow: the sustained flow of a stream, provided from stored sources (principally groundwater). The flow is unrelated to a specific rainfall event.

bedrock: the unweathered rock beneath the saprolite, regolith and/or alluvium.

confined aquifer: an aquifer overlain by less permeable strata in which groundwater is under pressure.

crystalline basement: non-sedimentary rocks which yield water from the regolith or aquifer weathered surface and fractures at depth.

drawdown; the difference between the rest water level (or piezometric head) and the water level caused by pumping a borehole.

evapotranspiration: water returned from plants to the atmosphere.

fissures / fractures: the preferential storage and transport of groundwater in fresh bedrock may best occur in dilated cracks or joints. Water may be fed to the fractures from the granular regolith above, provided that the saprolite is saturated.

formation stabilizer: rounded gravel (pea gravel) placed in the annulus between the borehole casing and the borehole wall to hold the formation in place.

gravel pack: rounded granular material (typically 1 to 3 mm in diameter) placed in the annulus behind slotted borehole casing or screen. It acts as a borehole stabiliser and as a means of promoting water flow into the borehole.

groundwater system: qualitative description of the flow of groundwater in an aquifer and how it is affected by the prevailing geology.

head: the height to which water rises above a set datum (often sea level) in a well or borehole.

hydraulic gradient: the prevailing inclination of the water table which provides the driving force to transmit groundwater through an aquifer.

igneous: rocks formed by solidification from a molten state; includes intrusive (eg granites) and extrusive rocks (eg lavas).

metamorphic: a rock derived from a pre-existing rock by mineralogical, chemical or structural change, the process being sufficiently complete to form a well defined new rock type.

permeability: the ability of a material (eg rock) to allow fluid to pass through it under the pressure of a hydraulic gradient.

porosity: the ratio of the volume of the voids in a rock to the total volume of the rock.

regolith: the weathering product that may be present over crystalline basement rocks. It may have a clay rich upper part which inhibits downward percolation of rainwater, and is generally granular, progressing to blocky with depth. It may be a few metres to a few tens of metres thick.

salinity: the concentration of salts and chemicals within water.

sanitary seal: a concrete seal placed at the well head between the borehole casing and the ground in order to prevent ingress of contaminated water from the ground surface draining down the outside of the borehole casing.

specific capacity: the yield of a borehole divided by the respective drawdown. For interborehole comparison the pumping elapsed time should always be the same (e.g. 240 minutes).

storativity: the volume of water that can be released from or taken into storage per unit surface area of the aquifer for each unit change of head.

transmissivity: a measure of the ability of an aquifer to transmit groundwater, being the product of aquifer thickness and aquifer hydraulic conductivity.

unconfined aquifer: an aquifer in which the saturated zone meets the unsaturated zone at the water table, the latter maintained at atmospheric pressure.

APPENDIX 1

Hillyard and Mthunzi (1998)
Introduction of low cost rotary drilling to Malawi - specifically the Eureka Port-a-Rig.

Introduction of Low Cost Rotary Drilling to Malawi - Specifically the Eureka Port-a-Rig
Agency: **Concern Universal**
Authors: **David Hillyard & Masauko Mthunzi**

1.0 Outline

From 1989 onwards, Concern Universal (Malawi) was involved in drilling boreholes through sub contracting, use of the Vonder rig (hand operated auger) and Shallow well construction. In 1995, Concern Universal began its investigations into the use of the Eureka Port-a-Rig. This was as a result of Concern Universal's own experience in the water sector in Malawi and a recognition of the high cost of engaging commercial contractors. The Water Department and UNICEF was also developing its programme plan of action for the period 1997-2001 and also recognised the need for alternative technologies and stated:-

"Given the present coverage and technologies available, Malawi urgently needs to find a means of accelerating it's population's access to clean water and adequate sanitation facilities. Investigations are necessary to find the technologies that are quickest and most cost effective for installing both water and sanitation facilities." And specifically:
"(I) To identify appropriate and low cost existing and new technologies in water and sanitation, such as alternative drilling methods."

Concern Universal experience in the sector concurred with the Water department/UNICEF. The Eureka Port-a-rig was identified as one such possible appropriate technology. The Port-a-rig is a rotary, diesel operated, compressed air/fluid flush rig that is assembled on site and is carried from site to site in a 4WD Pick-up truck.

As a result, Concern Universal approached the British Government for funding to pilot test the Eureka Port-a-Rig in Malawi. This proposal was supported and pilot testing of the rig began in November 1995 in Central Malawi with an initial 30 holes.

The test period was successful with a variety of geological conditions encountered requiring mud and air drilling. All of these holes remain within areas where Concern Universal are operating and a check of all pumps in April 1997 (on average 18 months after construction) found them working effectively. A further eight holes had their pumps removed for more detailed inspection and depth measurements.

Having initially tested the rig with good results, it was promoted as an appropriate drilling technology that could be used more widely. Therefore, operation of the rig continued and specifically on a Ministry of Education Primary Community Schools Project, since this project covered the whole country.

There are now three rigs in operation in Malawi, two by Concern Universal and one by Action Aid.

Construction Methodology Adopted with the Eureka Port-a-Rig

In fractured basement, holes are not fully cased (only the top unstable or weathered section is cased) and drilling at a smaller diameter of 95mm is undertaken, sufficient to allow installation of the Afridev and Malda handpumps. This is what contributes to the significant cost saving in borehole construction, since the Port-a-rig is a rotary diesel operated compressed air/fluid flush rig with the other associated running costs (although on a smaller scale and with a 12bar, 275cfm compressor), but of a much lower capital cost and drilling capacity. In any unstable or soft formations drilling occurs at 150mm to allow installation of 110mm PVC casing as per current Malawi standards (i.e. borehole construction standards set in the early 1980's with support from British Geological Survey). It is worth noting that drilling technology and construction methods since then have improved and hence current advice from British Geological Survey indicate that the methodology adopted for the Port-a-rig is sound.

Successes

- **Operation.** Drilling operations are entirely operated and managed by National staff after a six week training period. To date over 100 new boreholes drilled and operational.
- **Maintenance.** Effective operation and maintenance established and maintained.
- **Low Cost.** The nominal cost per hole using the Port-a-rig currently stands at approximately £1,200 or MK36,000. This is a very considerable saving over the use of commercial contractors, where total construction costs exceed MK100,000. The Port-a-rig can replace a good number of holes traditionally drilled by commercial contractors.
- **Effective Communication and Support.** Peter Ball of Eureka UK Ltd. has been efficient in the supply of spare parts and in providing ongoing technical support as drilling experience was developed.
- **Integration.** The Port-a-rig allows for a good deal of community participation in terms of its transport and erection on site as well as during the construction period. It is able to access those areas where communities live but cannot be reached by larger rigs.
- **Flexibility.** The rig can be flexibly operated by CU to take into account community aspects (e.g. waiting for community to mobilise, ensuring participation, delays for funerals). This ties in well with community based management and the need for maximum participation and ownership.
- **Complimentarity.** The rig is operated in conjunction with a number of Vonder rigs and use of commercial contractors. This allows most appropriate technology choice for differing circumstances.
- **Construction Methodology.** Low cost, alternative construction methodology re-introduced to Malawi which can be monitored for its appropriateness.
- **NGO "Friendly".** The rig and its operation has shown itself to be within the management capacity of a small NGO with relatively little prior direct experience of borehole drilling.
- **Drilling Rates.** Completion of drilling takes approximately two days, competitive with larger rigs. Further low cost technology at present in Malawi is in the form of the Vonder Rig, which has a limited application as far as geology is concerned and can take in excess of two weeks to complete a hole.
- **Rig Performance.** The rig exceeded its expected performance criteria, with many holes going beyond 35m in basement complexes.
- **Larger Diameter Drilling.** Current compressed air drilling in basement at 150mm diameter is proving effective against expectations.

Constraints

- **Acceptance.** Despite regular communication, government is not willing to accept any modification to borehole construction methodologies. This has necessitated the development of upgrades to the rig (see lessons learnt).
- **Drilling.** Limited to maximum depth of 50m with air and 36m with current mud pump (not a problem in Malawi as few boreholes exceed 45m and average depth is 35m). Cannot cope with complex or difficult geological/drilling conditions.
- **Construction Methodology.** Due to lightweight, mechanical nature of the rig, sometimes difficult to ensure fractured basement has been reached and there is therefore a danger of leaving unstable sections of the hole uncased.
- **Spares.** Many spares have to be supplied by Eureka UK Ltd. Despite efforts to source locally or in the region, these often turn out to be more expensive than Eureka supply. UK supply means it is necessary to carry a comprehensive spares stock to ensure rig is not held on stop awaiting spares.
- **Operation and Maintenance.** Despite the simple technology, Local NGO partners would probably still have difficulty in effectively running the rig. This is more a reflection of the relatively weak local NGO sector than complexity of operations.

Lessons Learnt and Learning

- **Operation and Management.** As with all drilling operations, good logistics support and efficient field management is essential for success. Project Field Engineer required on site frequently.
- **Borehole Monitoring Requirement.** Due to refusal of government to accept partially cased holes and lack of proper documentation of their performance in Malawi's geological conditions, it has been necessary to develop a monitoring programme and also upgrade the rig for the interim period. As a result, a Borehole Camera and VCR has been procured which will allow recording and viewing of boreholes constructed. Any indications that the boreholes are not performing and/or siting/collapsing will result in revision of the construction methodology or a reduction in terms of the areas of effective operation of the rig. This will allow for comprehensive testing and reporting.
- **Currently Proposed Upgrades to the Rig.** In light of current experience with the rig and also in response to some of the concerns raised by the Water Department with respect to construction methodology, Concern Universal with Eureka UK Ltd. has undertaken efforts to consider improvements to the rig in order to try to enhance its capacity and performance. Some of these are outlined below and constitute part of the ongoing testing of the technology and it's adaptation to the Malawi conditions. These upgrades will be developed within the context of the monitoring programme.

Rig Modifications/Upgrades

1. 150mm Compressed Air Button Bit combined with a High Pressure Foam Pump

The variable rock hardness found in some areas had resulted in the need to abandon some sites as a result of drilling with compressed air (at 95mm diameter) through hard laterite layers and less weathered basement into softer formations below, which subsequently collapse and cannot be cased.

Since the 150mm dragblade bits used with a mud flush does not have the capacity to penetrate these harder laterite layers or less weathered basement complexes, it was deemed necessary to try to establish a method of penetrating the harder formations at 150mm diameter through air drilling and use of button bits that would subsequently allow for casing at 110m.

In order to enable air drilling to be carried out without casing the top section of the hole (to prevent hole collapse and probable loss of the down-the-hole hammer), it was necessary to be able to inject stable foam into the hole while drilling with the button bits. The rig was equipped with a manual foam pump, which limited the potential for creating the stable foam required. Therefore, provision of a high pressure (100 bar) foam pump together with a 150mm button bit would allow drilling with compressed air and stable foam without fear of collapse of the hole. It would also increase the penetration capacity of the rig at larger diameter.

It was hoped that this additional capacity and facility on the rig would improve the application of the rig and ensure that all potentially unstable formations can be fully cased with 110mm PVC casing. This would reduce the number of sites that have to be abandoned due to drilling difficulties.

Field testing of this technique began in September 1997 and to date results have been very successful although only seven holes have been drilled so far and further testing is required.

2. Hydraulic Feed/Hoist to Drilling Operations

The manual operation of the hoist and light weight of rig limits the speed of drilling operations and also the available load applied to the dragblade bit during drilling operations. Therefore, addition of hydraulics to the rig would serve two functions:

a) Provide a feed weight during drilling therefore potentially increasing the penetration potential during mud/dragblade drilling.
b) Make drilling operations quicker and less labour intensive on the drill crew since the hydraulic hoist would be used to lift the drill stem from the hole - particularly relevant on the deeper holes.

3. New Drilling Rig - Upgraded/Up-sized Port-a-Rig

Eureka UK Ltd, having designed two appropriate technology drilling rigs (the "port-a-rig" and the larger "drill system"), is proposing to combine elements of both rigs in the design of a new intermediate rig which will be an up-sized port-a-rig costing approximately £12,000. The new rig would be fitted with hydraulics and deliver more power to drilling operations. Key improvements/differences to the port-a-rig would include:

- Trailer mounted rig as opposed to loading rig components onto a pick-up
- Hydraulic hoist/feed fitted as standard
- Larger drill mast, gearboxes, components etc.
- 11Hp engine versus the current 5Hp engine on the Port-a-rig.

It is expected that this rig would be able to demonstrate a clear improvement in performance and drilling capacity over the port-a-rig. It would also fit into the existing infrastructure of the project and Concern Universal. It would remain a low cost drilling option, with drilling parameters established during design but likely to be very appropriate to Malawi conditions.

- **Government.** High personnel turnover has resulted in a change in level of co-operation at Ministry level. There is limited commitment to develop appropriate drilling technologies and research capacity at the Ministry is weak. Government drilling programmes are donor funded and cost effectiveness is not a key issue. Possible strong lobby from commercial contractors against introduction of low cost alternatives.

APPENDIX 2

Sample Drilling Reports for the Eureka Port-a-Rig

The following examples of drilling reports from the Eureka Port-a-Rig equipped only with a drag bit come from the early part of the Malawi Community Schools Project. They illustrate the ground which the Eureka Port-a-Rig, so equipped, is capable of developing and the ground in which the rig is not properly suited.

Chaweta:	Alternating hard and soft rock required reduction to 95 mm diameter at 9 m so that casing could not be placed against deeper soft horizons.
Mulira:	(B-Hs 301 and 302) Hard rock at 3 m required reduction to 95 mm drilled diameter leaving lower soft formations unsupported in open-hole.
Mpsangwani:	As above.
Makali:	As above.
Thundu:	Hard and soft bands could be drilled to 150 mm diameter and casing and screen run to protect the soft formations.

APPENDIX 2.

EUREKA Port-A-Rig

DRILLER'S NAME: Dereck

LOCATION	HOLE NUMBER	DATE STARTED	DATE FINISHED
CHAWETA	RI 308	13-9-96	9-10-96

N. B. Make Sketch Map of Location Overleaf

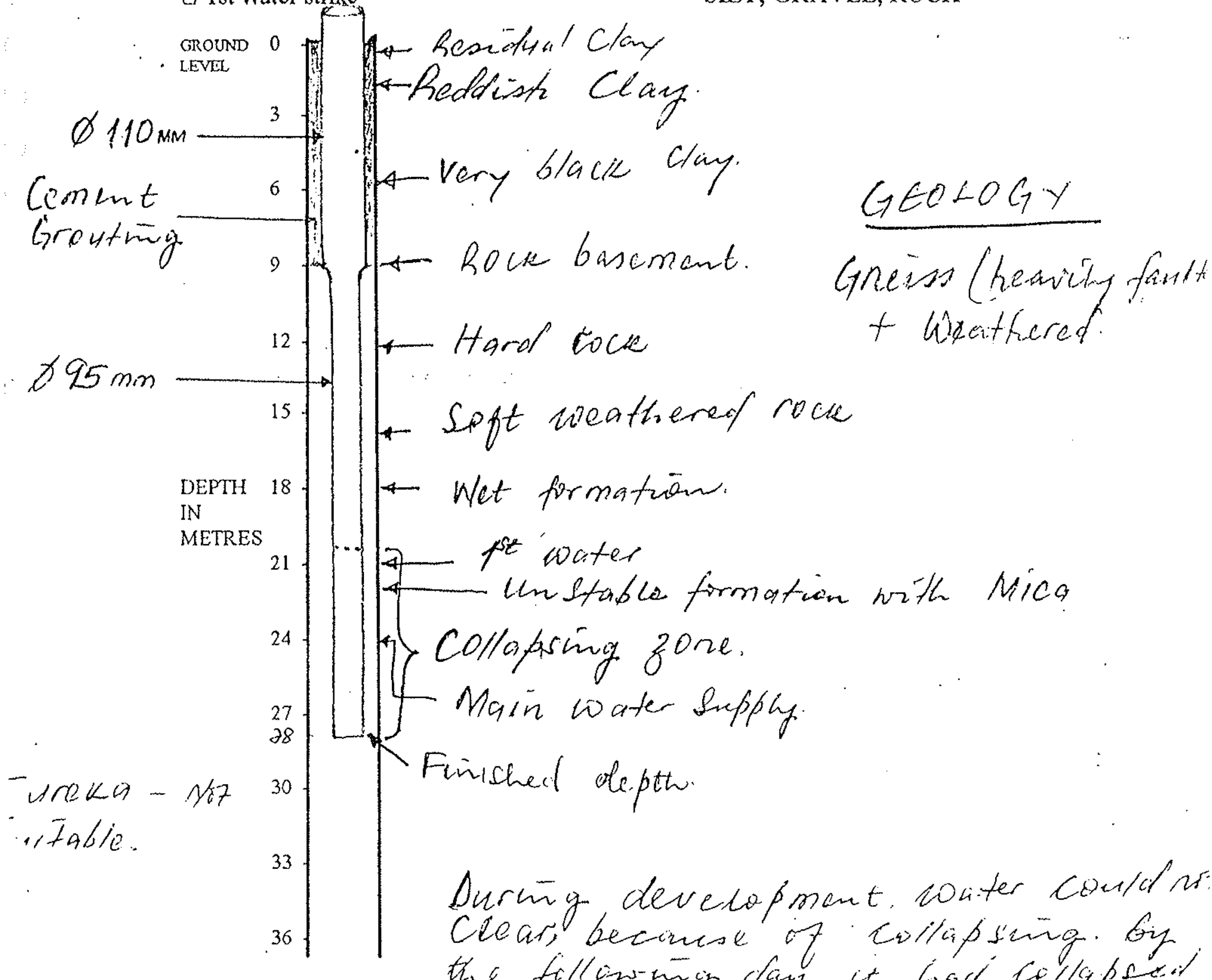
AIR OR ~~MUD~~ HOLE	AIR	meters
1st WATER STRUCK AT:	21	meters
WATER LEVEL RISES TO:	18	meters
FINISHED DEPTH OF HOLE:	28 - collapsed to 20	meters
DEPTH OF CASING (IF ANY):	9	meters

DESCRIPTION OF HOLE

1. Make special note of depths of:
- changes in soil type
- static water level
- 1st water strike

AND

2. Show soil types:
CLAY: WET/MOIST/DRY
SAND: FINE/MEDIUM/COARSE
SILT; GRAVEL; ROCK



Eureka - Not suitable.

During development water could n[ot] clear, because of collapsing. By the following day it had collapsed to 20 m.

DRILLER'S NAME:

LOCATION	HOLE NUMBER	DATE STARTED	DATE FINISHED
MULIYA	BJ 301	18-9-96	4-10-96

CZ. DISTRICT

N. B. Make Sketch Map of Location Overleaf GRID REF: 405535 - 153503

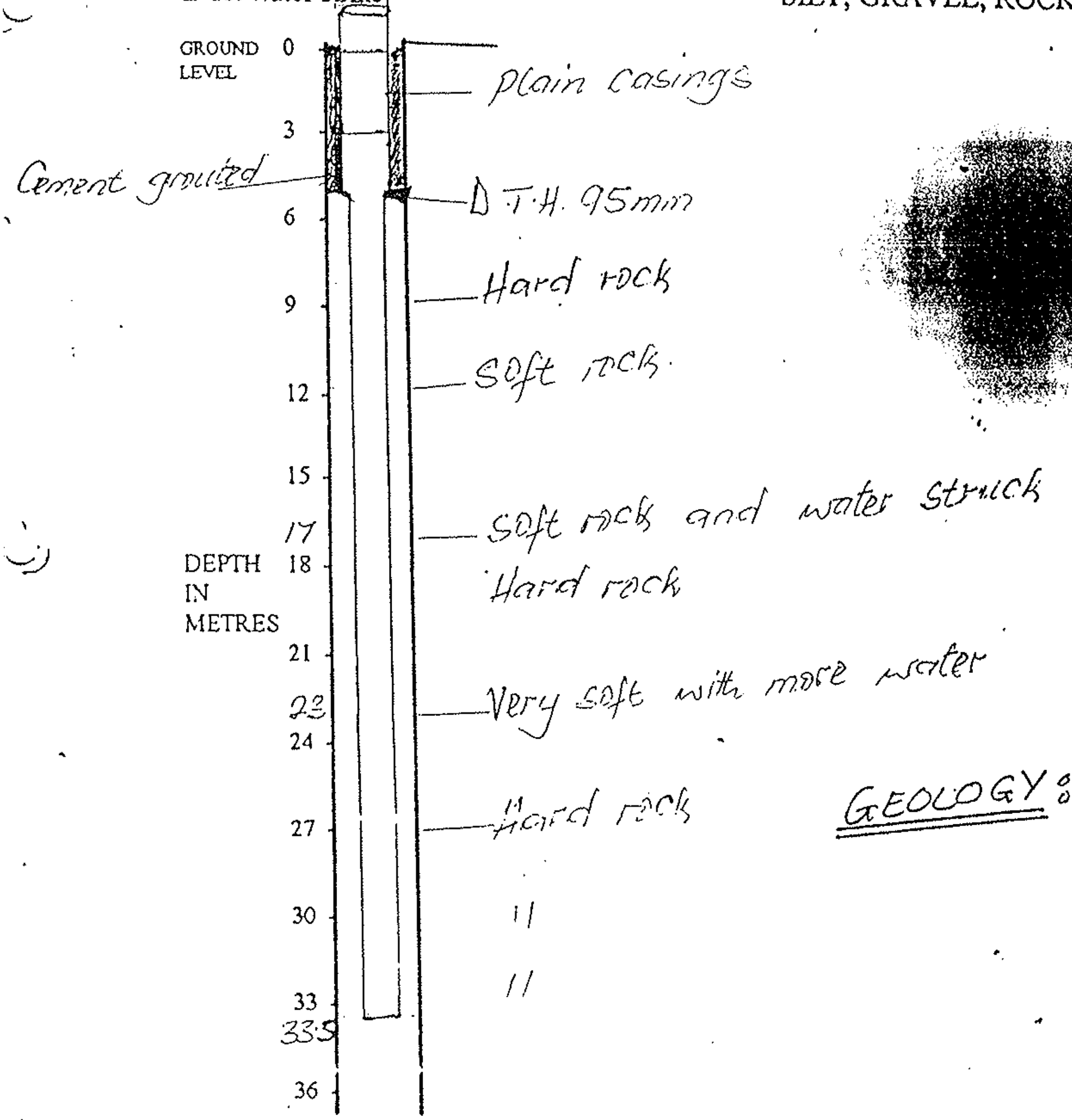
AIR OR MUD HOLE	AIR	meters
1st WATER STRUCK AT:	17	meters
WATER LEVEL RISES TO:	2.5	meters
FINISHED DEPTH OF HOLE:	33.5	meters
DEPTH OF CASING (IF ANY):	5.5	meters

DESCRIPTION OF HOLE

1. Make special note of depths of:
- ☐ changes in soil type
- ☐ static water level
- ☐ 1st water strike

AND

2. Show soil types:
CLAY: WET/MOIST/DRY
SAND: FINE/MEDIUM/COARSE
SILT; GRAVEL; ROCK



EUREKA Port-A-Rig

DRILLER'S NAME: *Abdul*

LOCATION	HOLE NUMBER	DATE STARTED	DATE FINISHED
MULIRA	RJ 302	1-10-96	2-10-96

N. B. Make Sketch Map of Location Overleaf

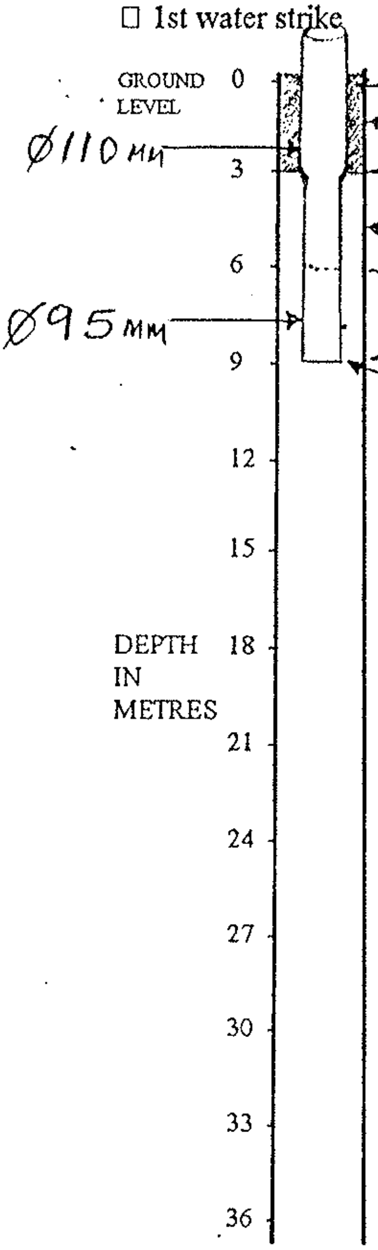
AIR OR ~~MUD~~ HOLE	AIR meters
1st WATER STRUCK AT:	5.4 meters
WATER LEVEL RISES TO:	3 meters
FINISHED DEPTH OF HOLE:	9 collapsed to 6. meters
DEPTH OF CASING (IF ANY):	3 meters

DESCRIPTION OF HOLE

1. Make special note of depths of:
- ☐ changes in soil type
- ☐ static water level
- ☐ 1st water strike

AND

2. Show soil types:
CLAY: WET/MOIST/DRY
SAND: FINE/MEDIUM/COARSE
SILT; GRAVEL; ROCK



GEOLOGY

Charnokitic gneiss - Overlain by residual soils.

This hole was abandoned at 9m because of collapsing. Within 1hr it had collapsed to 6m.

Eureka Technology is limited in this case.

DRILLER'S NAME:

LOCATION	HOLE NUMBER	DATE STARTED	DATE FINISHED
MASANGWANI PHALOMBE DISTRICT	BJ 305	8-10-96	9-10-96

N. B. Make Sketch Map of Location Overleaf GRID REF: 703693 – 153581

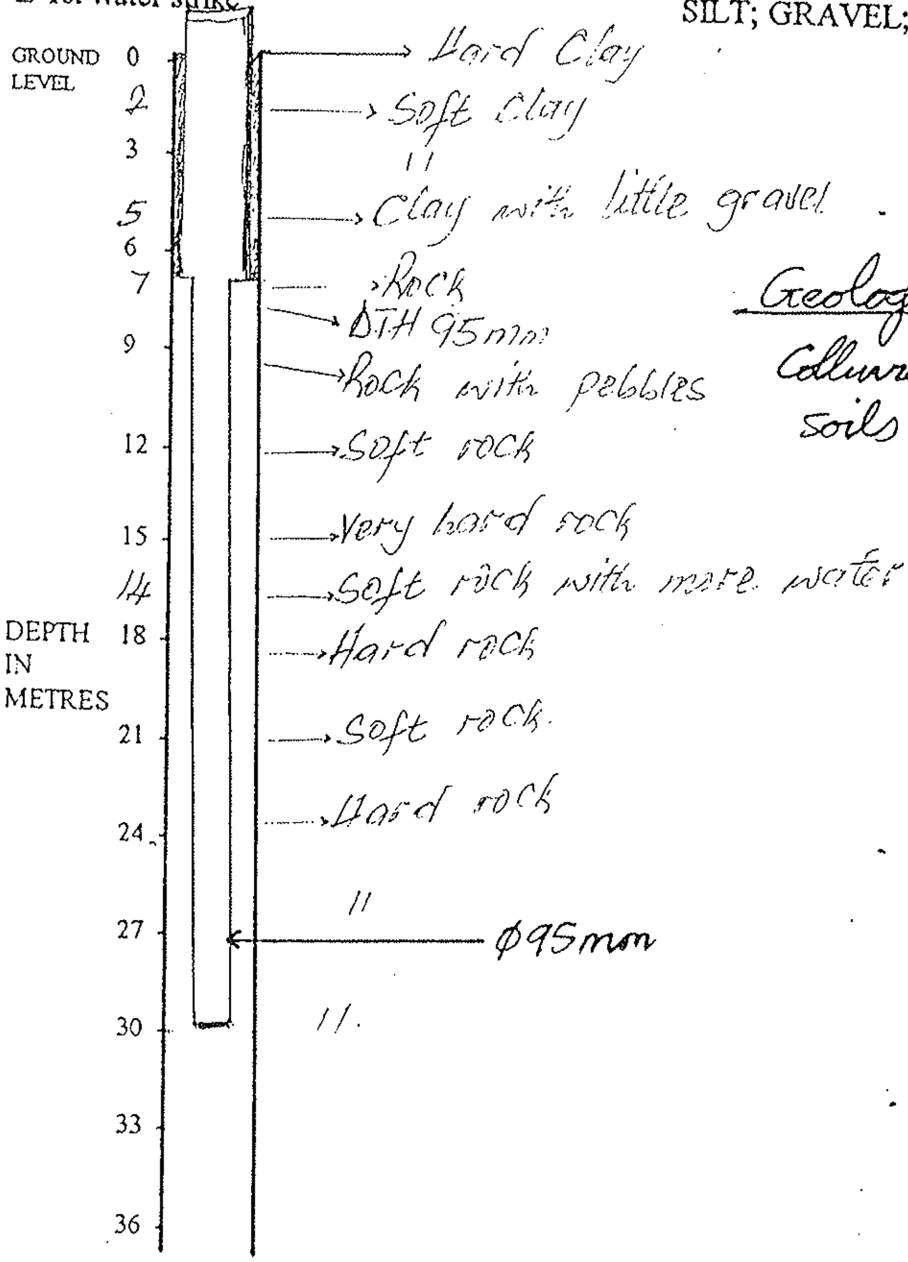
AIR OR MUD HOLE	AIR	meters
1st WATER STRUCK AT:	12.0	meters
WATER LEVEL RISES TO:	9.5	meters
FINISHED DEPTH OF HOLE:	30	meters
DEPTH OF CASING (IF ANY):	7	meters

DESCRIPTION OF HOLE

1. Make special note of depths of:
- ☐ changes in soil type
- ☐ static water level
- ☐ 1st water strike

AND

2. Show soil types:
CLAY: WET/MOIST/DRY
SAND: FINE/MEDIUM/COARSE
SILT; GRAVEL; ROCK



Geology.
Colluvium & residual soils, granitoid gneiss.

EUREKA Port-A-Rig

DRILLER'S NAME: ABDUL

LOCATION	HOLE NUMBER	DATE STARTED	DATE FINISHED
MPKALI	BJ 306	22-11-96	26-11-96

MWANZA DISTRICT

N. B. Make Sketch Map of Location Overleaf GRID REF: 7445 794 - 153441

AIR OR MUD HOLE	AIR	meters
1st WATER STRUCK AT:	15	meters
WATER LEVEL RISES TO:	8.0	meters
FINISHED DEPTH OF HOLE:	39	meters
DEPTH OF CASING (IF ANY):	1.3	meters

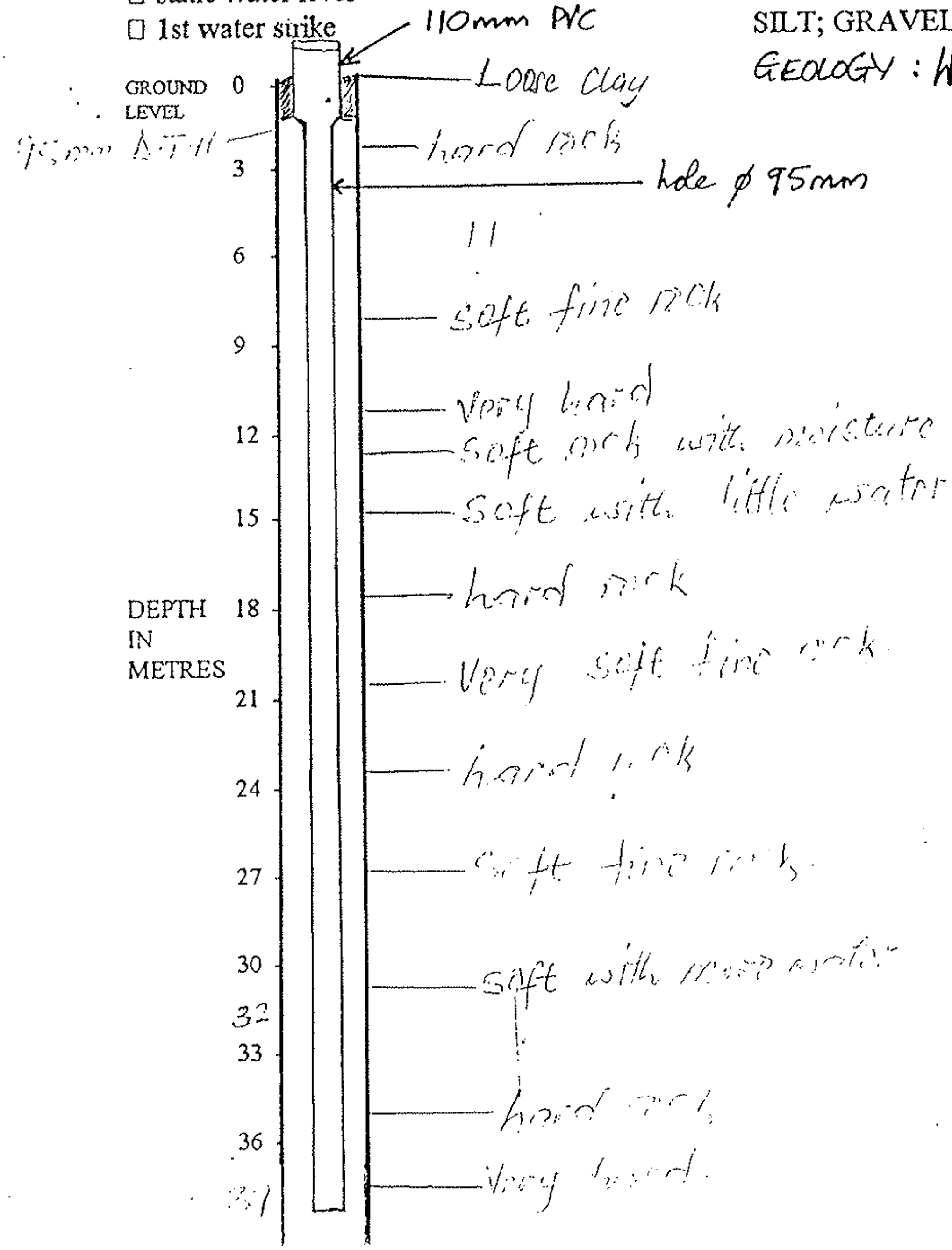
DESCRIPTION OF HOLE

1. Make special note of depths of:
- ☐ changes in soil type
- ☐ static water level
- ☐ 1st water strike

AND

2. Show soil types:
CLAY: WET/MOIST/DRY
SAND: FINE/MEDIUM/COARSE
SILT; GRAVEL; ROCK

GEOLOGY : Hornblende - biotite gneiss



Pump = 2 hr

FIRST HOLE

EUREKA Port-A-Rig

DRILLER'S NAME: V. ABDUL

LOCATION	HOLE NUMBER	DATE STARTED	DATE FINISHED
THUNDAY	BJ 303	14-10-96	16-10-96

PHALOMBE DISTRICT

N. B. Make Sketch Map of Location Overleaf GRID REF: 020709 - 153582

AIR OR MUD HOLE	MUD	meters
1st WATER STRUCK AT:	21	meters
WATER LEVEL RISES TO:	21	meters
FINISHED DEPTH OF HOLE:	26	meters
DEPTH OF CASING (IF ANY):	23	meters

DESCRIPTION OF HOLE

1. Make special note of depths of: AND
- ☐ changes in soil type
- ☐ static water level
- ☐ 1st water strike

2. Show soil types:
CLAY: WET/MOIST/DRY
SAND: FINE/MEDIUM/COARSE
SILT; GRAVEL; ROCK