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HYDRAULIC FRACTURING: Further Investigations on its Use on Low Yielding Boreholes in the Basement Rocks of Zimbabwe

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EXECUTIVE SUMMARY

A second phase of study of Hydraulic Fracturing (HF) was implemented to achieve a greater understanding of the borehole flow system, to evaluate the use of proppants and to understand the HF process further.

Three boreholes that were visited were treated with HF. Pressure plots achieved during the treatment showed that fracturing occurred at two of these boreholes.

A Pump-Out Test has been devised for testing low-yielding boreholes and has shown that the positions of fluid inflow can be recognised by changes in the slope of the recovery.

Internal inspection of the boreholes with a borehole colour TV camera confirmed that inflow was occurring at the positions indicated by the recovery. It was seen to occur as seepage or jetting of water from discrete fractures in the borehole wall.

An attempt to fracture a 3m test interval of solid rock at one site showed 140bar was not sufficient to fracture a solid granite gneiss. However the associated pressure measurements revealed that the HF unit was only delivering maximum pressure intermittently and this was not fully efficient.

HF applied to a section of borehole wall having a groundwater active fracture opening produced discoloured and silty water after the HF pressure was released. This implied that some cleaning of the fissure network had occurred and a possible connection with the weathered zone existed.

Recovery measurements made soon after applying HF showed potential increases in yield occurring. However, repeated tests proved that it was necessary to allow the borehole to rest after HF in order that the natural recovery can be observed. Allowing a rest period of 24 hours before retesting seemed to be adequate and reduced the observed increases in yield dramatically.

Geophysical logging during the testing showed a downhole colour TV camera was an invaluable aid to identifying suitable intervals for placing packers and distinguishing groundwater active fractures from others, as well as examining the effects of HF. Other geophysical log measurements provided information on characteristics of the rock mass.

An appropriate routine for the application of HF has been established.

Only one application of HF was made with the addition of proppants and it was seen that no further improvement in the yield was made. Further investigations on this technique is required and the effectiveness of HF in differing rock types needs to be studied.

The companion report (Herbert et al., 1991) should be read. The conclusions made there still stand. The prime recommendation from that report being that HF should be used on all failed boreholes as a first measure, thus reducing the overall redrilling costs significantly.

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1. INTRODUCTION

1.1 Background

Basement aquifers are important in the arid and semi-arid regions of the world because of (a) their widespread extent, (b) there are no alternate water supplies and (c) as yet only 30% of the rural population has access to clean water. Occasionally high yielding boreholes (>5 l/sec) can be drilled in basement. These boreholes tap highly fractured zones or dykes. Unfortunately the locations where this can be done are few. Basement aquifers are commonly exploited by drilling slim (4-8" diameter) boreholes to about 30 or 40m depth at the point of need. Geophysical siting techniques are used to try and ensure that infrequent water-filled fissures will be struck and yield will be adequate for a handpump. Median yields of these wells are about 0.3 l/sec. However, many dry holes are drilled (10-50%; Wright et al., 1989).

Hydraulic fracturing (HF) is a technique in regular use by the oil industry for increasing the yield of very deep boreholes in consolidated sedimentary formations. Figures 1 and 2 illustrate HF. Figure 1 is stylised, in reality there is little known about the geometry of fractures in the basement and this is likely to change from place to place. In addition, there may or may not be a weathered zone and the watertable may be within it or in the fractured hard rock beneath. HF can be achieved by setting a packer or pair of packers near the base of the borehole. Water is then injected beneath the top packer at great pressures in order to create fractures. This will then increase the permeability of the rocks near the borehole and/or connect the borehole with the network of fractures that occurs naturally in the rock mass.

1.2 Objectives of Study

It was the aim of the study to decide how effective HF can be in increasing yields of water supply boreholes drilled in low-yielding

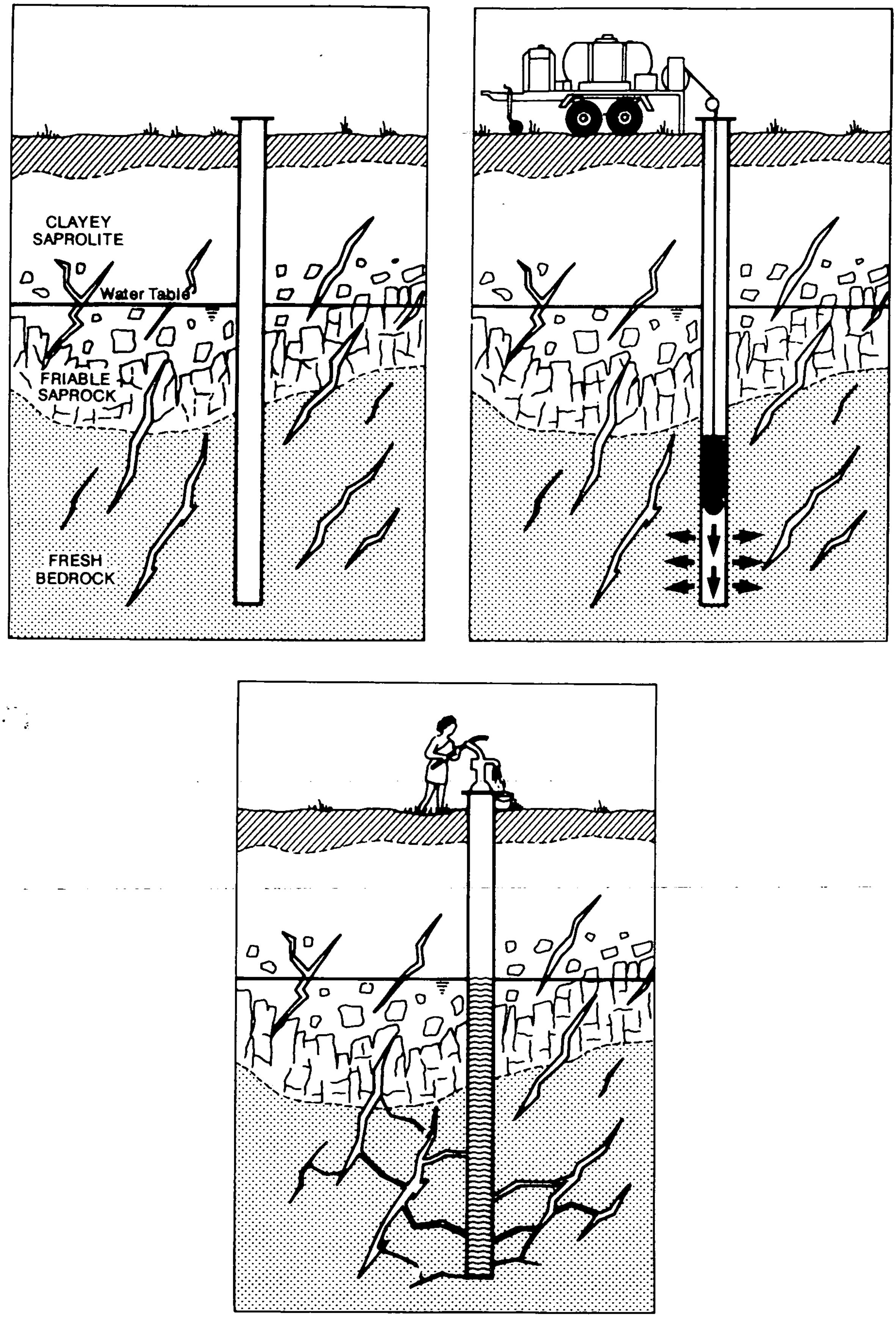

Figure 1. A Representation of the Hydraulic Fracturing Process

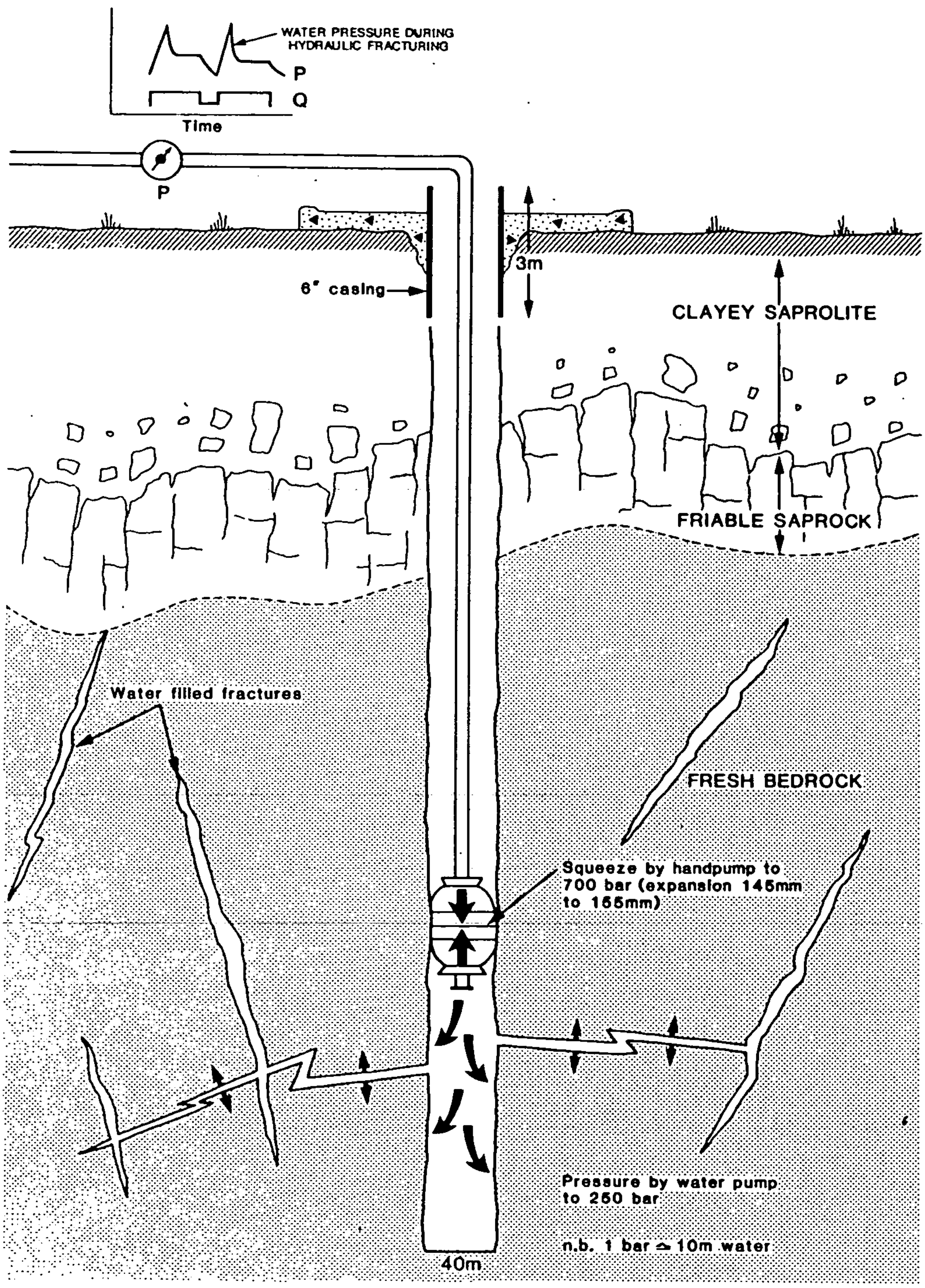

Figure 2. The Typical Situation when Hydraulic Fracturing in Masvingo

basement rocks to fairly shallow depths. In an earlier study assessing the use of HF in boreholes, twelve low-yielding boreholes were treated by this method. It was concluded that HF had been successful in 50% of the boreholes treated with an increase in yield of between 10 and 240% and was therefore a valuable technique. The pilot study recommended that HF be used as a matter of routine on low-yielding boreholes, due to its low cost and ease of application. An earlier report of this study has been made (Herbert et al., 1991).

Due to the success of the pilot study it was decided to do a follow-up study (phase 2). The aims of this were to (a) achieve a greater understanding of the borehole flow system. This would be by using a specially designed pump-out test and the use of a colour borehole TV camera. (b) evaluate the use of proppants. Proppants are widely used in the oil industry during HF to keep open the newly created fractures which increases the yields of wells. (c) understand the HF process itself further. Observing the propagation of fractures by pressure recording methods hoped to achieve this.

1.3 Scope of Report

The present report describes the field activities in Zimbabwe in October 1992. This comprised the visiting of eight sites. HF was administered at three of these sites and two of the sites were visited to assess the best way to use the TV equipment. The remaining three sites were not treated. This was due to problems with submersible pumps and in one case the risk of getting the packer assembly stuck due to a narrowing of the borehole. Results of tests, assessments of success and recommendations for future use of HF are made.

2. SECOND PHASE OF FIELDWORK

2.1 Programme of Work

The work was carried out with the same Atlas Copco HFU-140 unit as used on the pilot study (Plate 1). This was on loan from the MLAWD (Ministry of Lands Agriculture and Water Development formerly the MEWRD). Operation of the HF unit was done by the BGS contract driller with the work supervised by the main author. Local labour was employed to help with the manual work at each site.

To assess the effectiveness of the TV logger two boreholes at Mushandike Battle Camp were visited before HF began. The boreholes had been drilled the month previously by the MLAWD. One borehole had struck water the other was dry. The result of this trial was to learn that it might be necessary to pump the borehole dry before TV logging if turbidity of the water obscured the borehole wall details.

Detailed HF experiments were carried out at Maramba School. This work included the only use of proppants. At the end of these trials the generator on the HFU-140 failed. This meant that the submersible pump, essential for the Pump-Out tests, could not be used. The inability to do Pump-Out tests seriously jeopardised the trials and a new generator was required. A three-phase generator was not available, but a single phase pump and generator were obtained.

Zvirikure School was the next site visited but unfortunately before HF experiments could start the starter unit for the new pump failed and could not be replaced. A new pumping system was required. Zvirikure was abandoned (mainly due to the long distance from Masvingo) and the equipment was set up at Madamabwe. An air lift pump had been obtained from one of the new HF units recently delivered to Harare and it was hoped that this would be successful. Unfortunately, again, this pump failed to work: due to poor design it could not deliver an adequate water flow. By this time a three-phase generator had been located but unfortunately this unit would not be available for use until only a few days before the trials were due to end.

Plate 1. Atlas Copco Aquasplit HFU-140

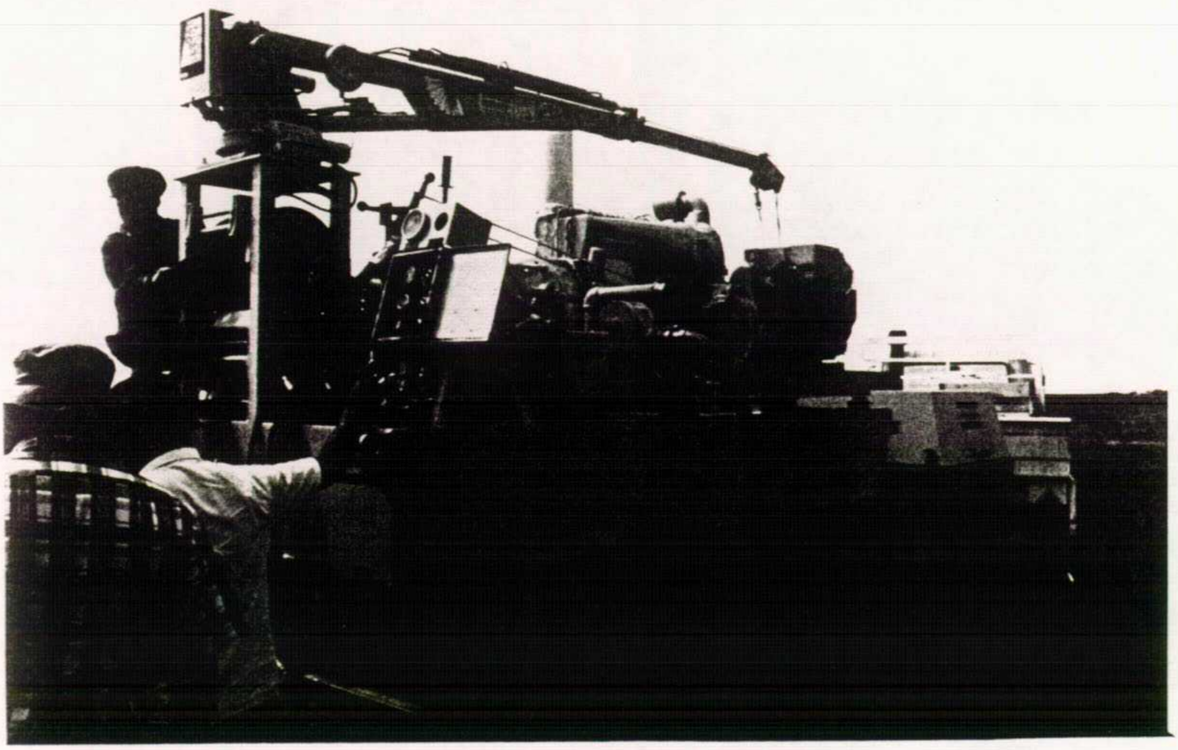

Plate 2. Atlas Copco HFU-140 Mk II

The BGS team decided to abandon trials in Masvingo Province and attach itself to work being supervised by Atlas Copco in Harare. This work was for training MLAWD and DDF (District Development Fund) staff in the use of the new HF units. The new units were the improved HF unit, the HFU-140 Mk II (Plate 2). Observations during HF were made at two boreholes at Macheke and Chinyika Clinic. A third site at Mudzudzu in Goromonzi, was not treated because the TV log had shown that the borehole drastically narrowed some distance down in the weathered zone.

2.2 Field Methods

2.2.1 Pump-Out Test for the Second Phase

Due to the difficulty in assessing changes in yield before and after HF from the long-term pumping tests used in the pilot study, a new pump-out test was devised. Figure 3 summarises the Pump-Out test designed to measure the performance of boreholes in hard rock terrain. The test requires the borehole to be emptied quickly which minimises the effects of changing boundary conditions. This can be achieved for low-yielding boreholes if $Q_c \sim 1.261T$ (Herbert et al., 1991) for which handpump rates are generally more than adequate. The recovery of the water level is then monitored. If the borehole system is like that in (a) of Figure 3, identification of the points of water entry to the borehole can be made. These points are identified by reductions in the rate of recovery as they become submerged.

2.2.2 Use of the Downhole TV Camera

A borehole video camera was used in phase 2 to observe and record the borehole wall features before and after HF. The camera used was a UK-manufactured TELESPEC TS 951 CCD colour camera of 51mm diameter. It was equipped with a wide angle lens allowing an axial (downhole) view of the borehole. For close-up examination of the borehole wall, a small mirror was set at 45^0 in the field of view to provide a simultaneous side (radial) view. The camera was coupled to a rotate unit which permitted almost a full 360^0 rotation for scanning the walls. Lighting, focus and rotate functions were controlled via a panel at the surface and the assembly with guide centralisers (Plate 3)

Aims:
To assess the success of hydraulic fracturing (HF) of boreholes (bh) and specifically to:

(a) assess rate of recovery before and after HF
(b) find the levels of yielding fissures

The BH flow system:
There are discrete points of water entry connected to the main aquifer, often the perched water in the weathered zone. Fig. A represents this and Fig. B shows the plots expected.

BH recovery behaviour: The discharge, Qf, from each fissure is related to its frictional resistance to flow, Rf, i.e. Qf=Rf.Hf. Hf is the head across the fissure. Hf will be constant when bh level is below entry point. It will reduce slowly with rise above it. Breaks in slope are expected at entry points on the recovery curve.

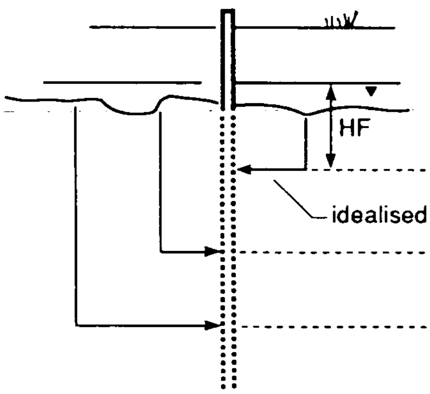

Figure A

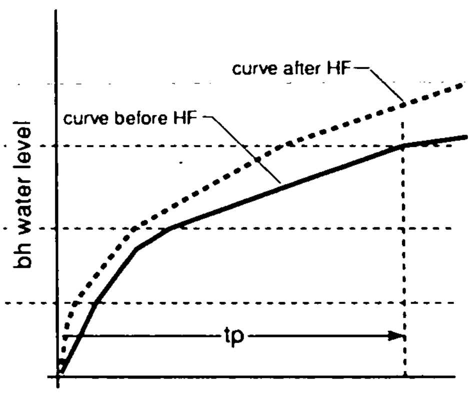

Figure B

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Figure 3. Pump-Out Test for the Second Phase

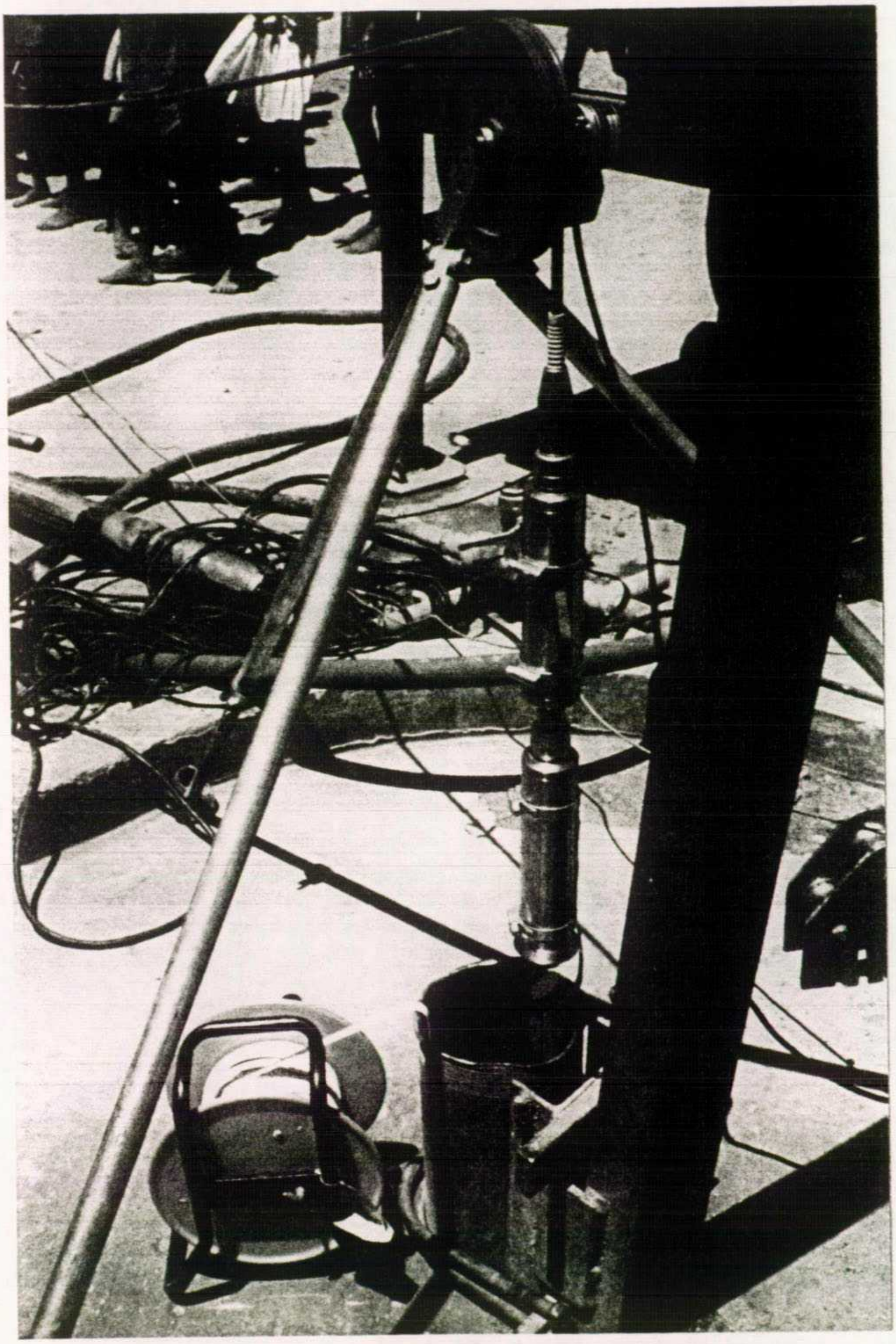


Plate 3. Borehole TV Camera Assembly

was lowered on special cable by hand. The depth was recorded via a pulse encoder fed to the video monitor. Borehole details and other thematic information were input via a keyboard and the surveys were recorded on VHS cassette. The whole system, control unit, camera assembly, video recorder and colour monitor were powered from a small (1000W) generator .

Experimentation at the two sites at Mushandike Battle Camp showed that the camera gave best results in emptied boreholes. The camera was quickly lowered to the base of the well after each stage of HF. A video recording was made as the camera was raised up the borehole.

2.2.3 HF Pressure Monitoring

An Atlas Copco well monitor (on loan from the MLAWD) was used with a Druck pressure transducer, capable of recording 140bar of pressure, to monitor the HF water pressure during the trials. The transducer was attached from the HF unit's own pressure gauge. This monitoring showed the peak pressure applied, the length of time that HF was administered and whether any fracturing occurred.

2.2.4 Pressure Readings in Observation Boreholes

Pressure readings were made in three observation boreholes drilled at 5, 10 and 30m away from the Maramba School borehole. Analogue safety pattern gauges were used, again capable of measuring up to 140bar. The observation holes were drilled such that measurements of time taken for fracturing to reach these distances and the pressure of HF water at these points could be made. A fourth hole was drilled to the base of the weathered zone and observations were made during HF to see if HF water was emerging in the weathered zone. Construction and positional details of these boreholes are shown in Figure 4. One observation hole was drilled 5m from the Zvirikure School borehole but as this borehole was not treated no measurements were taken.

2.2.5 Geophysical Logging

The pilot-study showed that some of the physical properties of the hard rocks were outside the design range of normal logging probes, and of a range of measurements made, caliper, gamma ray, point resistance,

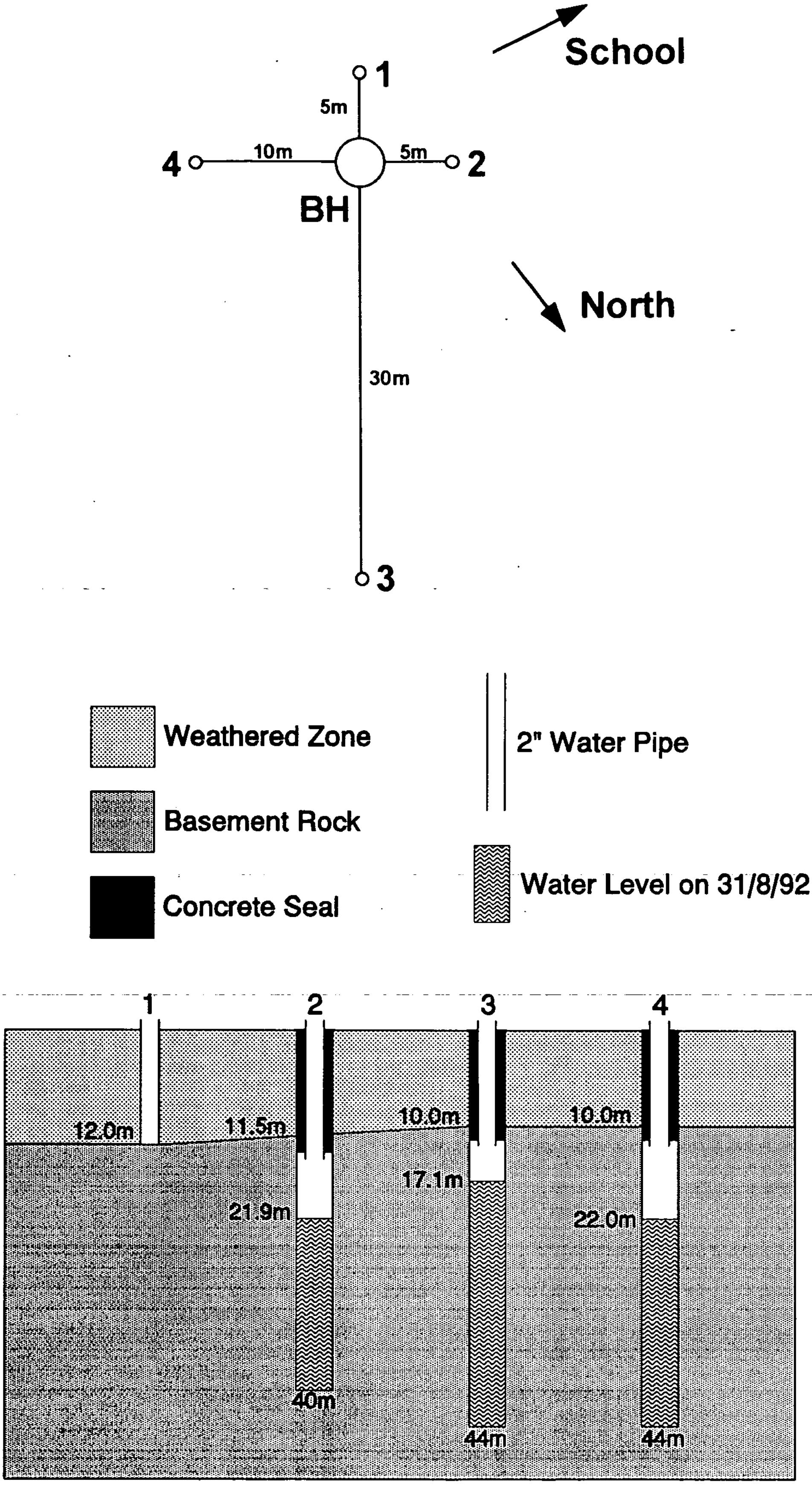


Figure 4. Location and Construction Details for the Observation Holes Drilled at Maramba School

spontaneous potential and neutron logs were more useful. For phase 2 a small hand-operated SIE T-450 logger, powered from the vehicle battery was used to make measurements to characterise the rock mass and properties of the borehole fluid. The measurements made included caliper, gamma-ray, point resistance, spontaneous potential, fluid electrical conductivity and fluid temperature. Details of these measurements is given in Appendix A.

2.2.6 Use of Proppants

Proppants are widely used by the oil industry when using HF (Mallinger et al., 1964). Proppants are of various materials; sand, glass beads etc. which are suspended in the injection fluid in the hope that they will imbed themselves in any new cracks and so keep them open when the injection pressure is released. Small amounts of sand were used in the second phase. Only small amounts of proppants were used as it can be shown that small fractures filled with fine sand will not enhance the yield of a borehole significantly. The prime aim of a proppant must be to keep open the fissures created by the HF process.

A simple hopper and tube device was constructed to introduce the proppants into the injection water. The tube was placed in the pipe leading to the treated borehole and sand was placed in the hopper. Before HF commenced it was allowed to fall into the tube beneath. When HF began the water then carried the sand down into the borehole.

2.2.7 Measurement of Volume of Water Pumped into Borehole

A simple comparison of the water depth in the HF units tank before and after HF was used to achieve an approximate water volume added for the HFU-140 Mk I. The onboard volume meter was used to approximate the volume of water added on the HFU-140 Mk II.

3. RESULTS

3.1 Geophysical Logging

The geophysical logs recorded were processed using the BGS WELLOG ® interpretation and presentation package and are presented as composite log plots in Appendix B. Where a borehole video survey was run relevant comments from the video have been incorporated in the diagrams. (The full survey was recorded on VHS tape). No geological information was available but for some boreholes it was possible to make simple lithological distinctions based on the TV inspection and the log measurements, and this has been done for Maramba School.

Generally the borehole was geophysically logged after removal of the hand pump. The submersible pump was used to first empty the borehole and the television camera was run in the empty borehole as the water level recovered. The borehole camera is designed for use under water but the water clarity may limit its usefulness. The first borehole inspected (Mushandike Battle Camp) had just been drilled (previous 24 hours). It had not been clearance pumped, and the camera showed 5m of clear water below which it was too turbid to see borehole wall details. TV logging below fluid level after removal of the pump showed good visibility in some holes, but in others, where sediment from the bottom of the hole and sides had been disturbed or where there was rust from the casing or pump in the water, there was only limited visibility. TV logging in the empty hole immediately after removal of the pump generally proved ideal. Inflow of water could be observed directly although it was not everywhere successful. In Macheke borehole high velocity water entry from the weathered zone through a slot in the casing near the surface cascaded silty water down the borehole walls which then made recognition of additional inflows difficult (Plate 4). Nevertheless the technique was generally very successful for surveying the boreholes and identifying inflows. Although only used for a short period the TV camera also provided much valuable information on borehole construction and other features eg. unexpected presence of slotted casing (Macheke) (Plate 4), tree roots at 18m (Chinyika), fluted borehole walls corresponding to button bit shape (Mushandike dry

Plate 4. Water Entry from Slot in Casing. Macheke Borehole

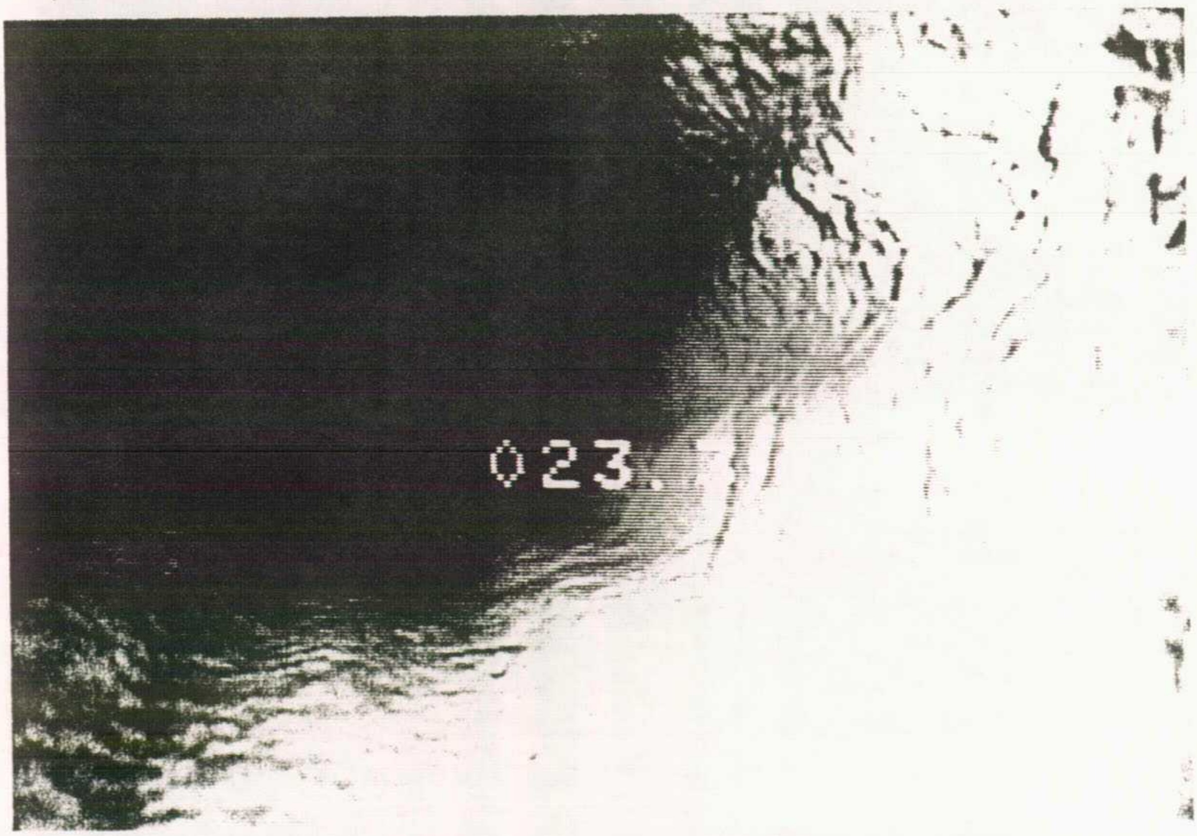


Plate 5. Mushandike Grenade Range Dry Borehole

borehole) (Plate 5) and collapse (Mudzudzu) as well as providing critical information for setting the packers, observing the effects of fracturing, and guiding fishing operations to retrieve broken pipe. Sticks, pen tops and bottle tops were sometimes seen in the boreholes.

The caliper and gamma ray logs were run in the empty hole during recovery. The PR/SP and fluid EC/T measurements required fluid in the borehole and were therefore run towards the end of recovery prior to running the packer, or after the HF, depending upon circumstances. On later trials all the logging was done on first arrival at the site.

The fluid EC/T logging was not satisfactory. These logs should be run under different hydraulic conditions, ideally prior to pumping, during recovery and after fluid injection with a period of time to allow equilibration. It was not practical to run the fluid logs on occasions and only a single transient fluid log profile is available for each borehole. However, information on water inflows normally given by these logs was given more easily by the television survey.

Comments on the geophysical logs and the television surveys run in the boreholes are given in Appendix C. The most complete suite of logs was run in the Maramba School borehole. In the other boreholes only a limited number of logs were run. Details of all the log measurements made are given in Table 1.

3.2 Hydraulic Fracturing

The HFU-140 Mk-I and Mk-II both had a maximum pressure output of 140bar and a maximum pumping rate of 350 l/min. The Mk-I had a 2,000 litre water tank and the Mk-II had a 3000 litre water tank.

Table 2 summarises the results of the HF trials in the four boreholes that were treated. Pressure plots of each trial are shown in Appendix D.

Borehole	Depth (m)	Geophysical logs run							Notes
		Vid	CAL	GR	PR	SP	EC	T	
Mushandike Battle Camp	22	✓	-	-	-	-	-	-	Newly drilled, WL 16.2m, water cloudy below 5m.
Mushandike Grenade R'e	30	✓	-	-	-	-	-	-	Newly drilled dry hole, uncased, fluted walls.
Maramba School	47.6	✓	✓	✓	✓	✓	✓	✓	Base casing 9.2m, water entry 25.4, 42.2-43.4m.
Zvirikure School	45	-	✓	✓	✓	✓	-	✓	
Madamabwe	56	-	-	✓	✓	✓	-	-	
Macheke Vill. No. 1	35	✓	-	✓	✓	✓	-	✓	Water entry through slotted casing 7.3m.
Mudzudzu nr. Goromonzi	47	✓	-	✓	✓	✓	-	✓	TV log showed ⌀ @ 4-4.7m too narrow for packers.
Chinyika Clinic	52	✓	-	✓	✓	✓	-	-	Base casing 7.2m, tree root @ 18m.

Vid = borehole CCTV
CAL = caliper (inches)
GR = gamma ray (counts/sec)
PR = point resistance (ohms)
SP = spontaneous potential (mV)
EC = fluid elec. cond. (μS/cm)
T = fluid temperature(°C)

TABLE 1. Summary of Geophysical Log Measurements Made

Site and Test No.	Packer used	HF packer interval	Peak pressure (bar)	Mean pressure (bar)	Length of time HF	Volume of water (l)	Rate of water (l/min)	Fracture shown on plot	Additional information	Fig. No.
Maramba School - 1	Double	32.3-35.3m	~140	-	?	?	-	No	Pipe broke	-
" - 2	Double	38.3-41.3m	129.4	68.8	1m00s	?	-	No		D1
" - 3	Double	38.3-41.3m	128.7	68.1	1m20s	?	-	No	Pipe broke	D2
" - 4	Double	24.5-27.5m	51.9	25.7	7m00s	1000	143	No		D3
" - 5	Double	24.5-27.5m	55.2	20.8	8m20s	?	-	No	Proppants used	D4
Macheke Vill. No.1	Single	26.0-35.3m	112.5	-	7m30s	3000	400	Yes		D5
Chinyika Clinic - 1	Double	29.0-32.0m	153.6	-	4m30s	750	167	Yes		D6
" - 2	Double	32.0-35.0m	87.6	-	1m20s	750	563	No	Water came round packer	D7
" - 3	Double	35.0-38.0m	89.5	-	3m30s	1500	429	Yes		D8
" - 4	Single	45.0-52.9m	128.6	-	10m00s	2250	225	Yes		D9

Table 2. Summary of Hydraulic Fracturing Programme and Results

The plots from Maramba School show a wide fluctuating range of pressure and hence mean pressures are quoted in Table 1 for these trials. These plots contrast with the pressure plots obtained from Macheke and Chinyika Clinic. This is thought to be due to a problem within the Mk I's pump possibly due to perished seals. This problem probably accounts for the major vibration encountered when HF pressure is applied using this unit, even on the previous visit, and caused the pipe breakages listed on Table 2.

There is no pressure plot from Maramba-1 because channel 1 of the well monitor was inoperative, all subsequent tests were done using channel 2.

No fracturing is thought to have occurred at Maramba even when 140bar of pressure was applied to unfractured rock (Maramba-1). The first treatment of the fracture at 26m (Maramba-3) produced dirty water when the HF pressure was released after HF (Plate 6). It was clear that the existing fracture/entry point had been back flushed and cleaned out to some degree. It may also point to a possible connection between the fracture and the weathered zone.

Possible fracturing for the other boreholes is shown on the pressure plots and all are suggested by a sudden drop in pressure followed by a steady decline in pressure. Macheke shows this to best effect with the pressure peaking at 110bar and the pressure after fracturing dropping to a steady 50bar after about 8 minutes.

The pressure gauges installed on the observation holes at Maramba School did not register any pressure during any of the trials. The hole drilled to the basement (Obs-1) also did not receive any water during the trials. It was thought necessary to fill the holes with water before HF and this was done in Obs-2 before Maramba-4 and in Obs-3 before Maramba-5 (see Figure 4). This result may suggest that the observation holes were not connected to the pressurised fracture network although water levels in Obs-2 were observed to fluctuate with levels in the pumped borehole whilst it was being drilled.

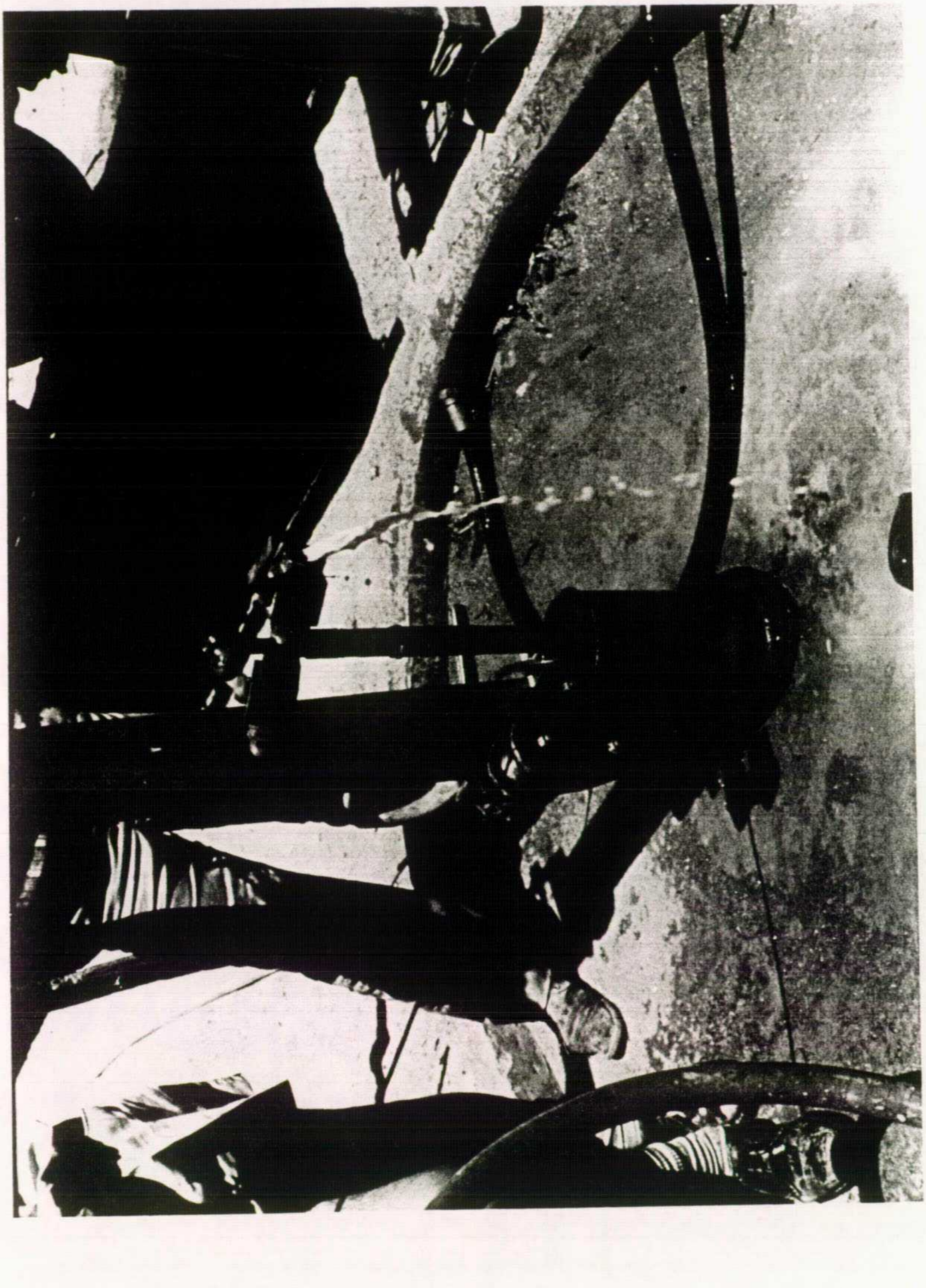


Plate 6. Discoloured and Silty Water Ejected after HF Pressure Released. Maramba School

The observation hole drilled at Zvirikure School was not useful since no trials were done at this site due to the problems with the HF unit.

3.3 Pump-Out Tests

Full tests were only done at Maramba School. At the other boreholes tested all recovery tests were done by the trainees. These tests were not comprehensive although results are shown. Pump-Out tests results are tabulated in Appendix E.

Figure 5 shows the results obtained from Maramba School. The points of water entry are clearly defined at 26m and 42m confirming the TV inspection. The Pump-Out test run immediately after HF of the 25-28m interval without proppants clearly shows that the time of recovery from 43m to 26m had reduced from 4 hrs 14 min to 3 hrs 17 min (Figure 5). This is equivalent to a potential increase in yield of 23%.

Following HF of the same depth interval, this time using proppants, a Pump-Out test run the following day showed a recovery time of 4 hrs 7 mins; an overall increase in yield of just 3%.

This result could suggest that either a reduction in yield had occurred with the addition of proppants, or more likely that water used for the HF had contributed to the large increase in yield of the first test.

Pumptests done before and after HF at Macheke show a reduction in recovery times between 11 and 9m from 4 mins 28 secs to 3 mins 27 secs, an increase in yield of 23% but again the test was done shortly after HF was completed, so that the scale of increase is questionable.

At Chinyika Clinic the recovery time between 28 and 23m had decreased from 23 mins 33 secs to 14 mins 8 secs equivalent to an increase in yield of 40%. Again these tests were done on the same day as HF. For comparison a Pump-Out test run the following day (before the single packer HF) showed an apparent decrease in yield. This result confirmed (a) the need to allow the borehole to rest after HF if natural rates of

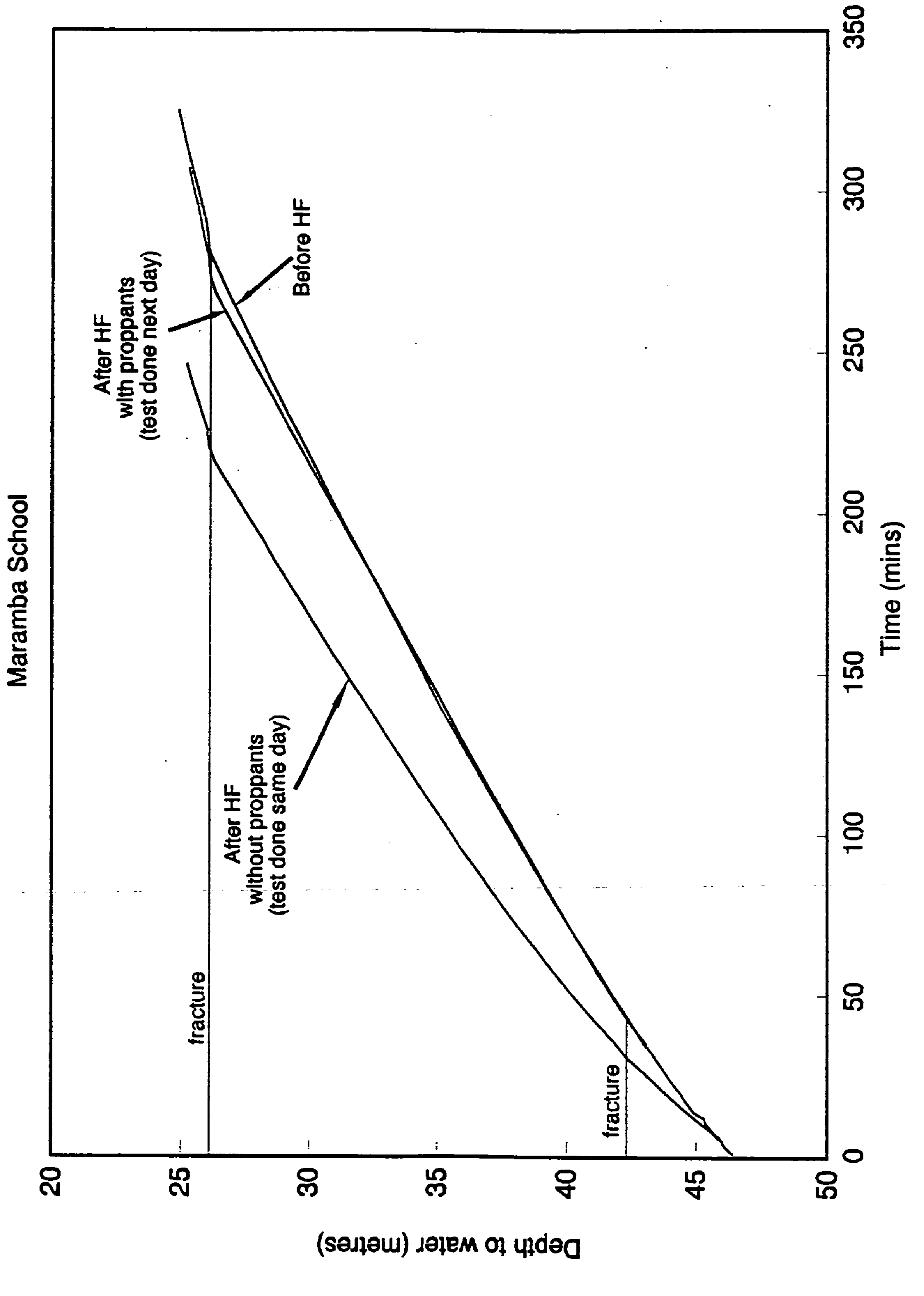


Figure 5. Results of Pump-Out Tests at Maramba School

recovery are to be measured and (b) the need for standardisation of test procedure.

4. COSTS

The costs of HF have been worked out based on the more numerous results obtained from the pilot study (Herbert et al., 1991).

The 1990 cost of the HFU-140 was £58,000. Assuming (a) the life of the unit is 10 years, (b) annual maintenance runs at c. 5%, (c) an interest rate of 8% and (d) 100 boreholes could be treated per year, then the present value of this unit/borehole is **£77.5**. Local labour (1 supervisor and 2 men) costs are c. **£20** per borehole.

The 1990 logging equipment cost (assuming calliper and resistivity tools only) was about £18,000. Assuming the same maintenance and interest rates as for the HFU-140, the 1990 value of the logging equipment/borehole is **£24.0**. A hydrogeologist would be required to run the logger and do the Pump-Out tests. This cost per borehole might be **£100**.

Thus, the total cost of HF per borehole in the manner described was about **£221**. Minor costs for fuel and transport of HFU to site have not been included.

The 1990 cost of drilling a new 40m deep borehole was about £1,050. Allowing for a 40% failure rate, the average drilling cost to ensure a successful replacement borehole would have been c. £1,470.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Summary of Geophysical Logging in Hard-Rocks

1. Caliper, gamma ray, point resistance and spontaneous potential log measurements each provide information on characteristics of the rock

mass.

2. Fluid electrical conductivity and fluid temperature measurements can be applied in hard rocks but require careful planning to optimise the log measurements. Comparison of pre-pumping, pumping and after injection fluid EC/T profiles should provide information on fluid inflow in low-yielding boreholes.

3. Borehole television survey has proved to be the most useful geophysical technique. It was used to identify lithology, examine borehole construction, identify fractures and in conjunction with pumping, distinguish groundwater-active fractures, as well as provide critical information where to seat packers and examine the effects of HF. It was also used to guide a successful fishing operation to retrieve a broken pipe downhole.

5.2 Conclusions from Second Phase

It is clear from the results of this second phase of work that it is easy to misinterpret the effectiveness of HF. First usual pumping test techniques are inappropriate; secondly, the borehole must be allowed to rest after HF before retesting. It is recommended that the Pump-Out Test be used before and one day after HF if yield estimates are to be made. Also, because the improvements in yield are seen as a faster rate of recovery, the users must be informed that the borehole can be emptied more frequently. It would be easy for them, in low-yielding boreholes without borehole dippers, to continue unaware of any change. This is because the only water they can abstract is that in storage in the boreholes and this amount will remain constant whatever the rate of recovery. All that can be done is to increase the frequency with which the borehole can be emptied.

5.3 Recommendations for the Application of Hydraulic Fracturing

Figure 6 is a flow chart that allows a programme to be designed for HF work at a borehole. For example, if the HF team does not have a caliper and a TV logging device and if the Pump-Out test does not

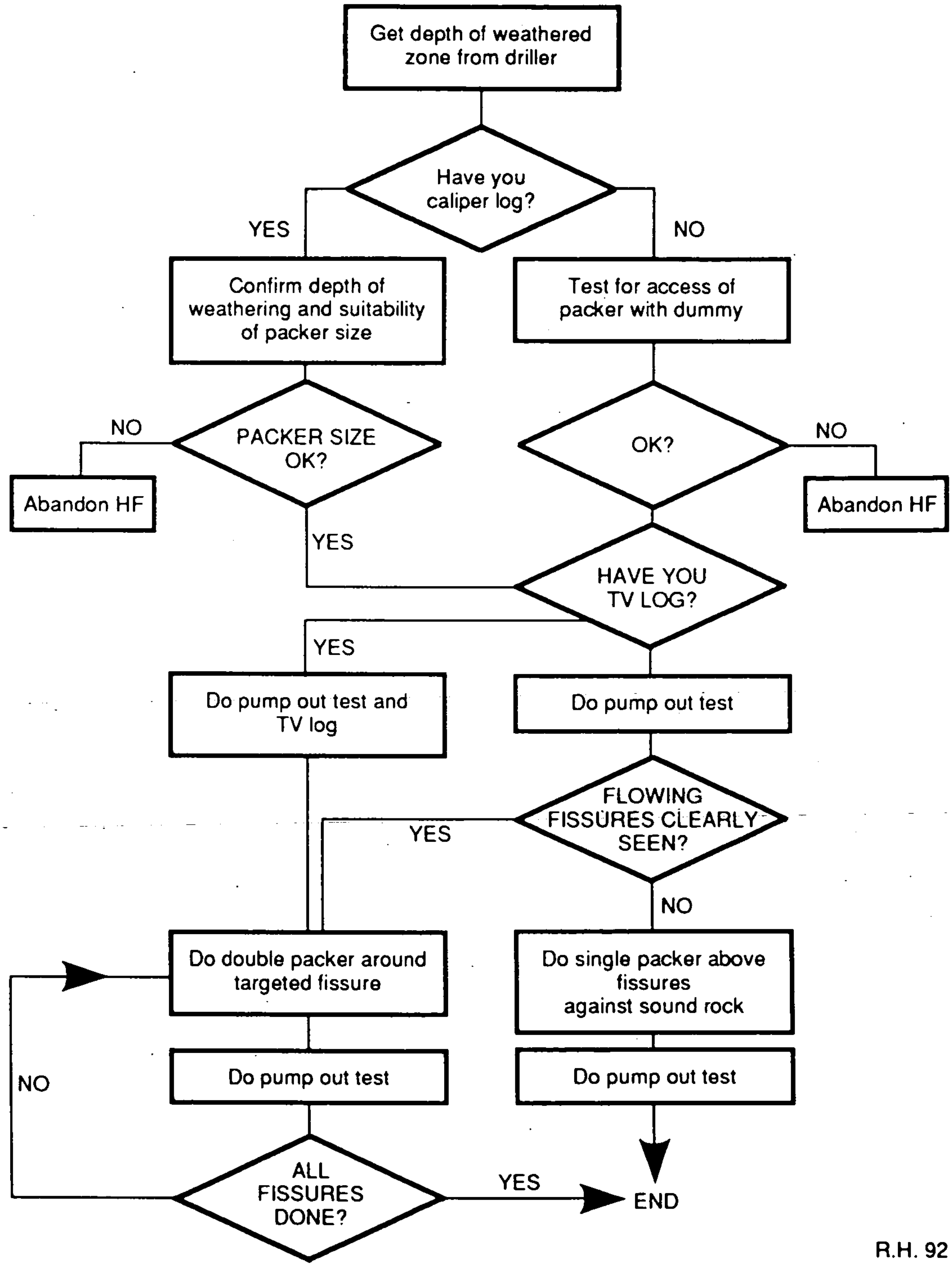


Figure 6. Designing a Procedure for Hydraulic Fracturing

clearly identify the depths to the flowing fissures, a single packer should be used against the top of the hard rock. This last procedure was in fact adopted throughout almost all of the pilot study work (Herbert et al., 1991). In addition the following observations and recommendations are made:

(a) The HF equipment used and its operation are complex. A team should be dedicated to its use and be fully employed in HF.

(b) Many boreholes exist where HF cannot be done. The borehole can be entirely in weathered rock, the construction of the borehole may not allow insertion of a suitable packer size or the borehole may need de-sanding. Ideally a team should inspect all boreholes and de-sand as appropriate before the borehole is designated suitable for HF.

(c) Further work is necessary to see if proppants are worthwhile and if relatively high-yielding boreholes could benefit from HF. Its effectiveness in different rock types is also not fully understood.

5.4 Hydraulic Fracturing vs. Redrilling

In the Masvingo area about 40% of borehole yields are effectively dry. Also, it seems, hydraulic fracturing will be about 50% successful in increasing their yield (based on pilot study). Alternatively, sufficient new boreholes could be drilled to improve the situation at an average cost of c. £1,500. The comparable average cost of HF, followed by new drilling in case where HF is not successful, is c. £850.

Thus, clearly even in areas like Masvingo, where it is thought particularly difficult to employ HF successfully, HF should be used as a first measure on all failed boreholes consequently reducing the overall redrilling costs significantly.

ACKNOWLEDGEMENTS

The Ministry of Lands, Agriculture and Water Development of Zimbabwe and especially the Chief Hydrogeologist have contributed significantly to the work done in this study. They provided the HFU-140 for the work at Maramba School and they and the District Development Fund gave permission to observe the HF training exercise. The Overseas Development Administration of the UK funded all the UK inputs to the study as part of the Engineering Advisors R & D programme for hydrogeology. Peter Rastall, driller, was responsible for logistics and mechanics during the study; his efforts are particularly recognised.

REFERENCES

Herbert et al., 1991, A pilot study of hydraulic fracturing used in low yielding wells in the basement rocks of Masvingo, Zimbabwe. BGS Report No. WD/91/4.

Mallinger, M A, Rine, F H and Howerd, G C 1964. Development and use of propping agent spacers to increase well productivity. API Drilling and Production Practices.

Wright et al., 1989. The Basement Aquifer Research Project 1984-89: Final Report to the Overseas Development Administration. BGS Report No. WD/89/15.

APPENDIX A : Geophysical Logging Measurements

Caliper measurements

The caliper log is a measurement of the variation in borehole diameter. It is generally obtained with a 3-arm caliper probe. The caliper arms are opened electronically when the probe is at the bottom of the borehole and variation in borehole diameter is recorded by measurement of the spring-loaded arms as it is winched to the surface.

Hole enlargement occurs alongside softer formations, eg. weathered material , and at large joints or fractures. The probe used was 1 $^{11}/_{16}$ inch diameter and capable of measuring diameter up to 11 inches. It was used in Phase 2 to locate suitable sections of borehole wall for setting the packer assembly and to reveal location of major joints and fracture and the weathered zone.

Natural gamma ray measurements

The gamma ray log is a record of the natural gamma radiation emitted by the rock formations. The probe is simply a gamma ray detector and the log is scaled in counts/second, proportional to the activity. Gamma rays are emitted by all natural rock formations as a result of the random disintegration of radioactive elements naturally present. The elements producing gamma rays are potassium (K^{40}), uranium and thorium (KUT).

The gamma rays emitted by the KUT are of different energies but the log recorded by the equipment is the total count log within the energy window 100keV - 10MeV. Gamma rays are energetic enough to penetrate steel casing and still be detected hence the gamma log can provide valuable information on geological units behind steel (or plastic) casing.

The gamma ray activity is determined by the radioactive mineral content and in most sedimentary rocks the log is regarded as a clay indicator. The KUT elements naturally concentrate in finer-grained materials (clays, silts) where they are absorbed in large surface area layered minerals. In hard rocks the complexity of mineral and chemical composition leads to a less consistent log response. For example the log may show peak responses due solely to biotite (potassium) or potassium rich felsic rocks, and a lower activity alongside darker mafic rocks. The gamma log might also reflect physical processes undergone by the rock mass. eg. a higher activity may identify the weathered zone where it is clayey, or in some circumstances this can be a zone of leaching and the reverse, a lower activity of the weathered rock relative to fresh bedrock may be observed. Fluid circulation or a prior fluid circulation in the rock mass can sometimes be inferred from the gamma log. Uranium oxide is soluble and highly mobile and can be precipitated on joint and fracture surfaces of fluid routes within the rock mass. The logging can identify this local activity where the boreholes intersect such fractures.

Point resistance and spontaneous potential measurements

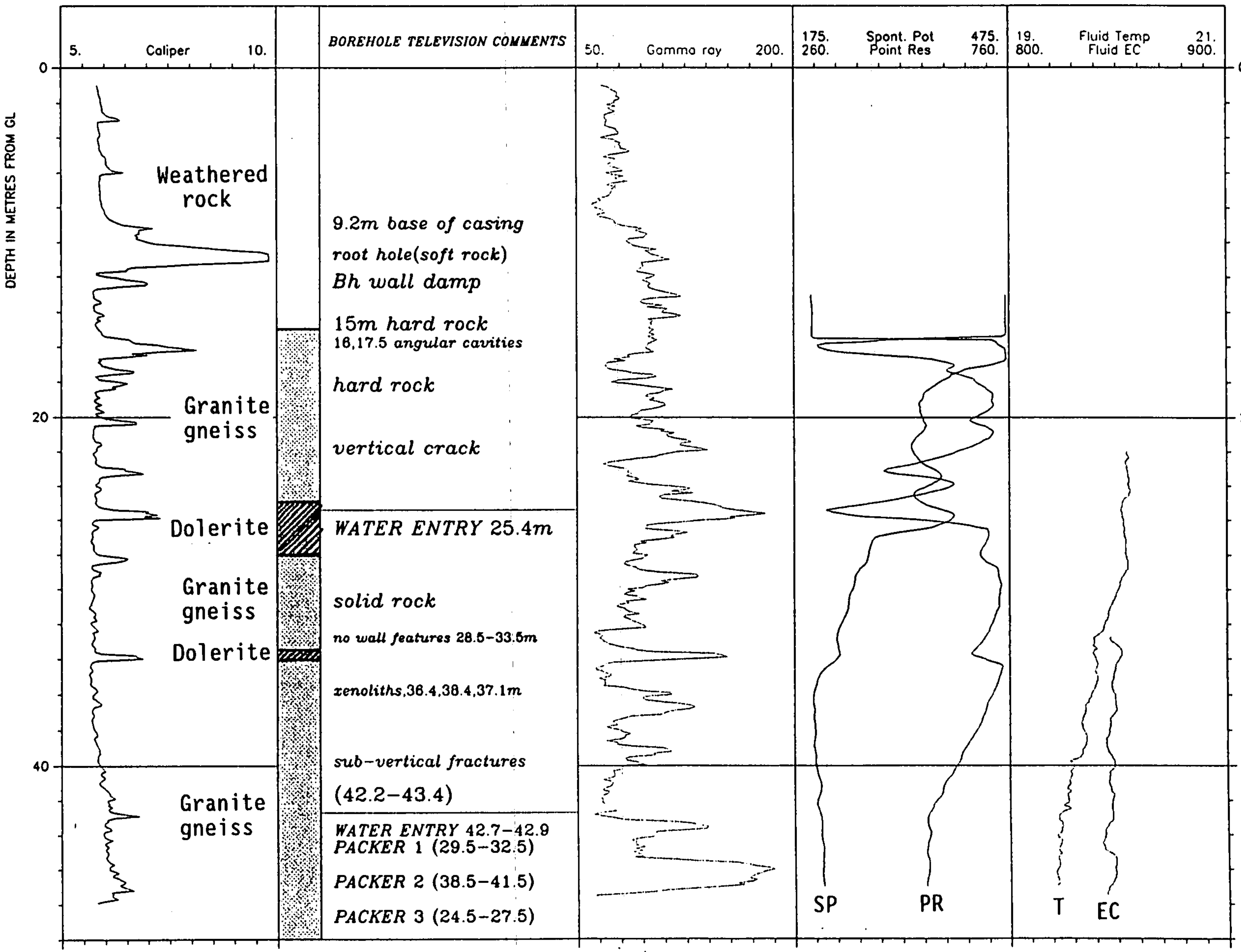
The range of electrical resistivity encountered in hard igneous and metamorphic rocks is very large (10 - 100,000Ωm) and special equipment is required to measure some high values (and low porosities) with accuracy. However, useful information can be obtained using single point resistance (PR) measurements. The PR log represents the varying electrical resistance between a single downhole electrode and a fixed surface electrode. It does not measure the true rock resistivity and is strongly influenced by diameter change, however unlike multi-electrode resistivity measurements its response is symmetrical and bed boundaries are recorded in the correct position, and the relative response is useful for recording the junction between rock units and for correlation.

The spontaneous potential log (SP) is a measurement of the natural potential difference (in millivolts) between a downhole electrode and a fixed surface electrode. The log is the net balance of positive or negative ions at the position of the downhole electrode. In sedimentary rocks changes on the SP log always occur at junctions of porous and permeable beds with non-porous horizons. In hard rocks the natural currents can only enter or leave the borehole fluid at formation junctions and a hard rock SP log therefore shows a series of straight sections linking inflections alongside rock boundaries. These are not then necessarily indications of porous and permeable horizons where there is useful groundwater inflow. The SP log is somewhat unusual in that its response to a rock formation may be positive or negative depending on the pore fluid salinity.

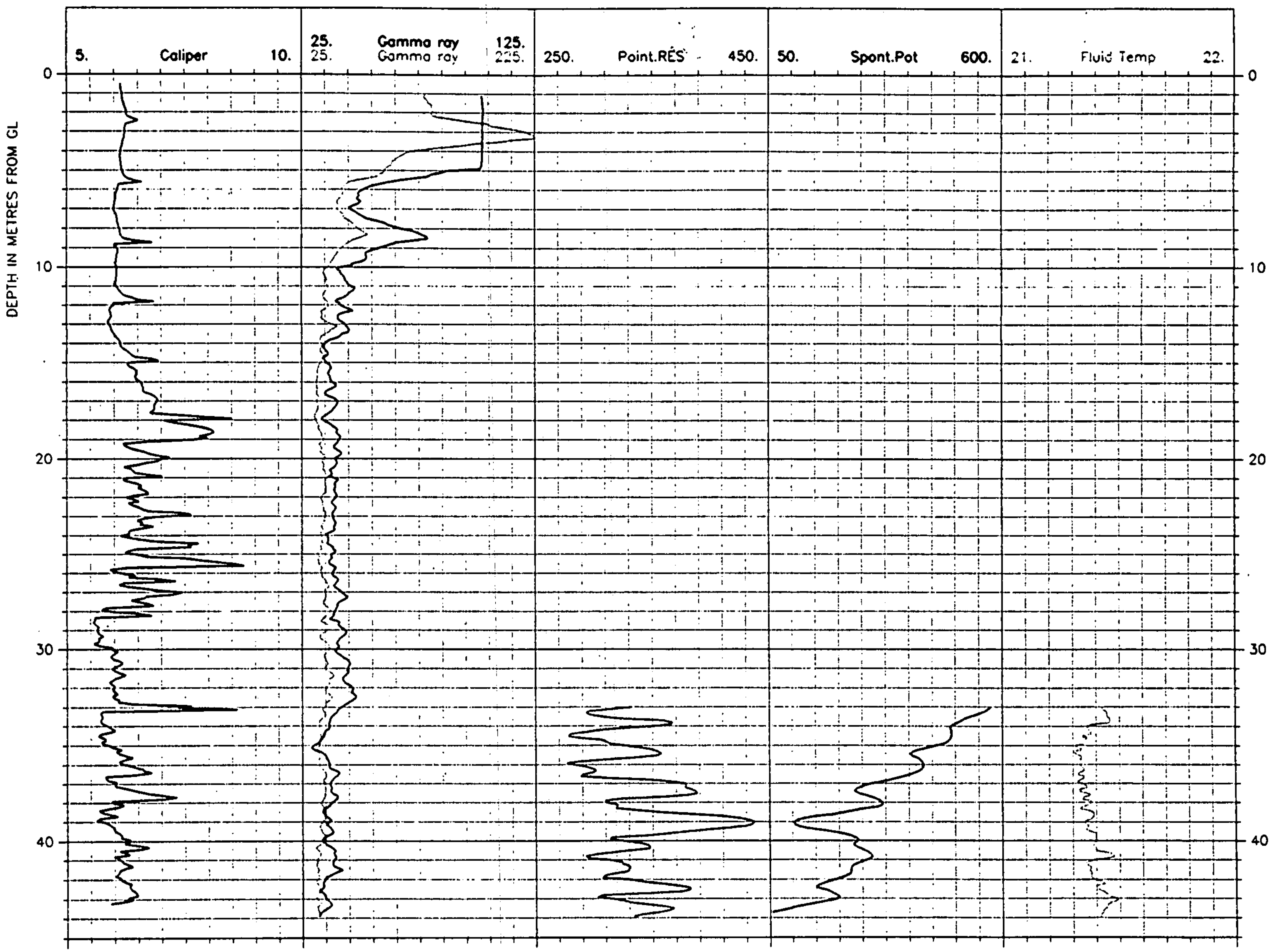
Fluid electrical conductivity and fluid temperature measurements

Measurements of the borehole fluid conductivity (EC) were made with a SONDEX T/C probe and measurements of fluid temperature were made with an SIE temperature probe. Inflow of groundwater to the borehole can usually be detected by a change in either or both of these parameters at the point of entry. Normally fluid logs are run under different hydraulic conditions (usually at rest and during pumping) when a direct comparison reveals the positions of water movement. The fluid log indications of entry are usually confirmed by impeller flowmeter logging during pumping. At points of water entry there is increased velocity of the water moving to the pump. In low-yielding boreholes in Zimbabwe the low yield and large drawdown makes conventional impeller flowmeter logging, (and some fluid logging) impractical. However, because they were low-yielding it was easy to empty the boreholes and the television camera could be used to observe inflows directly from the borehole wall during recovery. At points of water entry the TV camera showed seeping or jetting into the borehole.

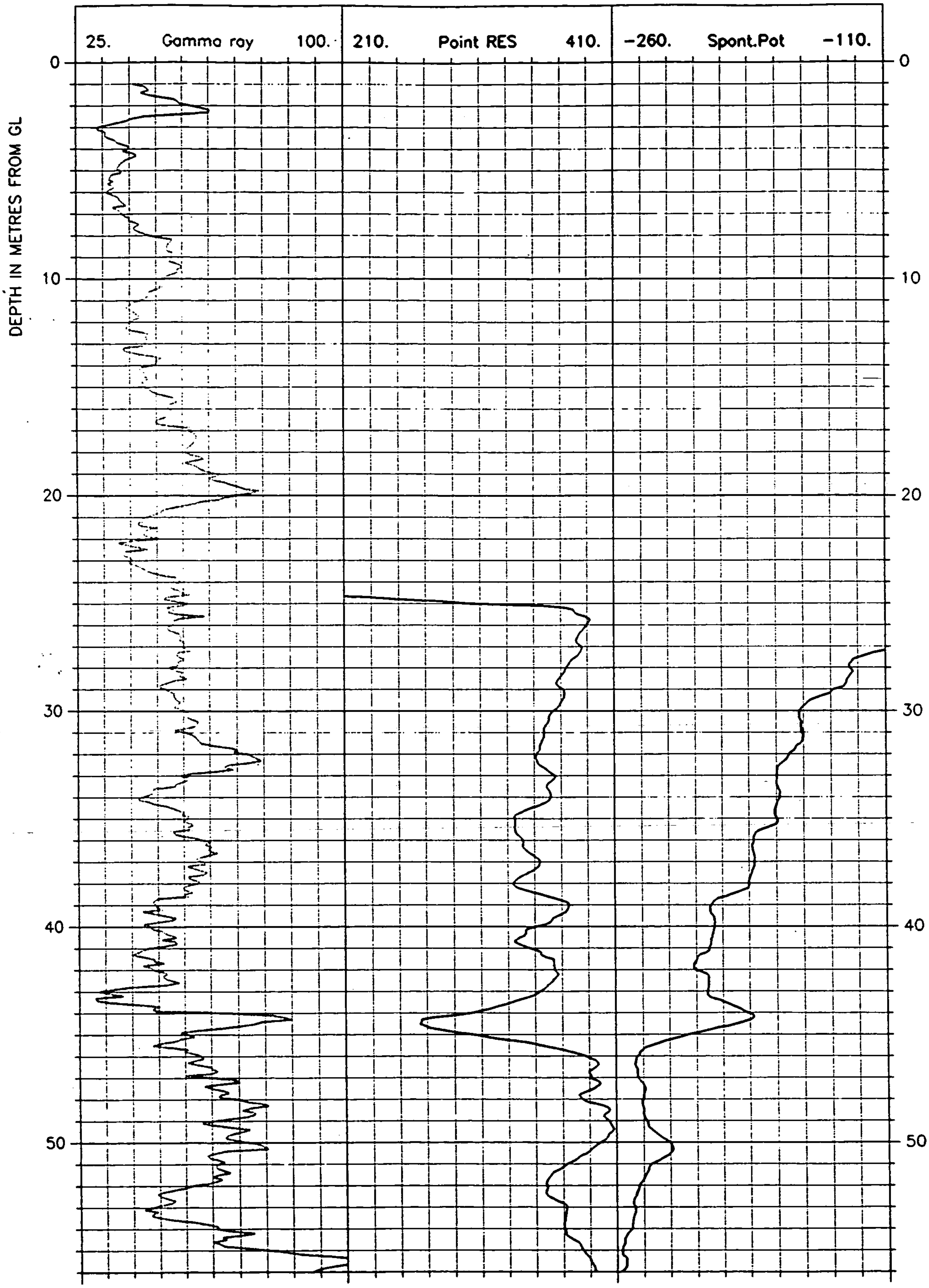
APPENDIX B : Geophysical Logging Plots



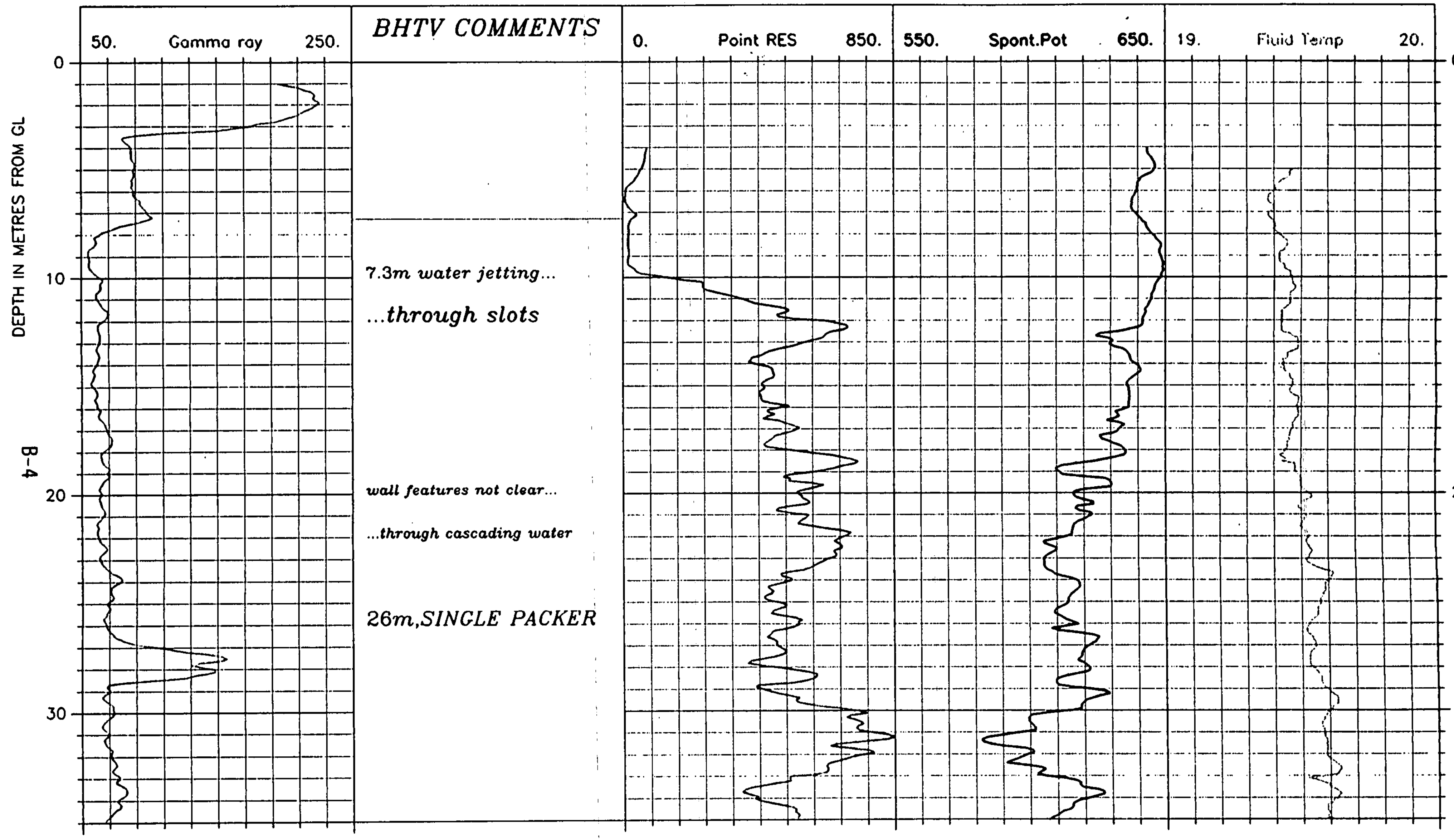
B1 - Maramba School



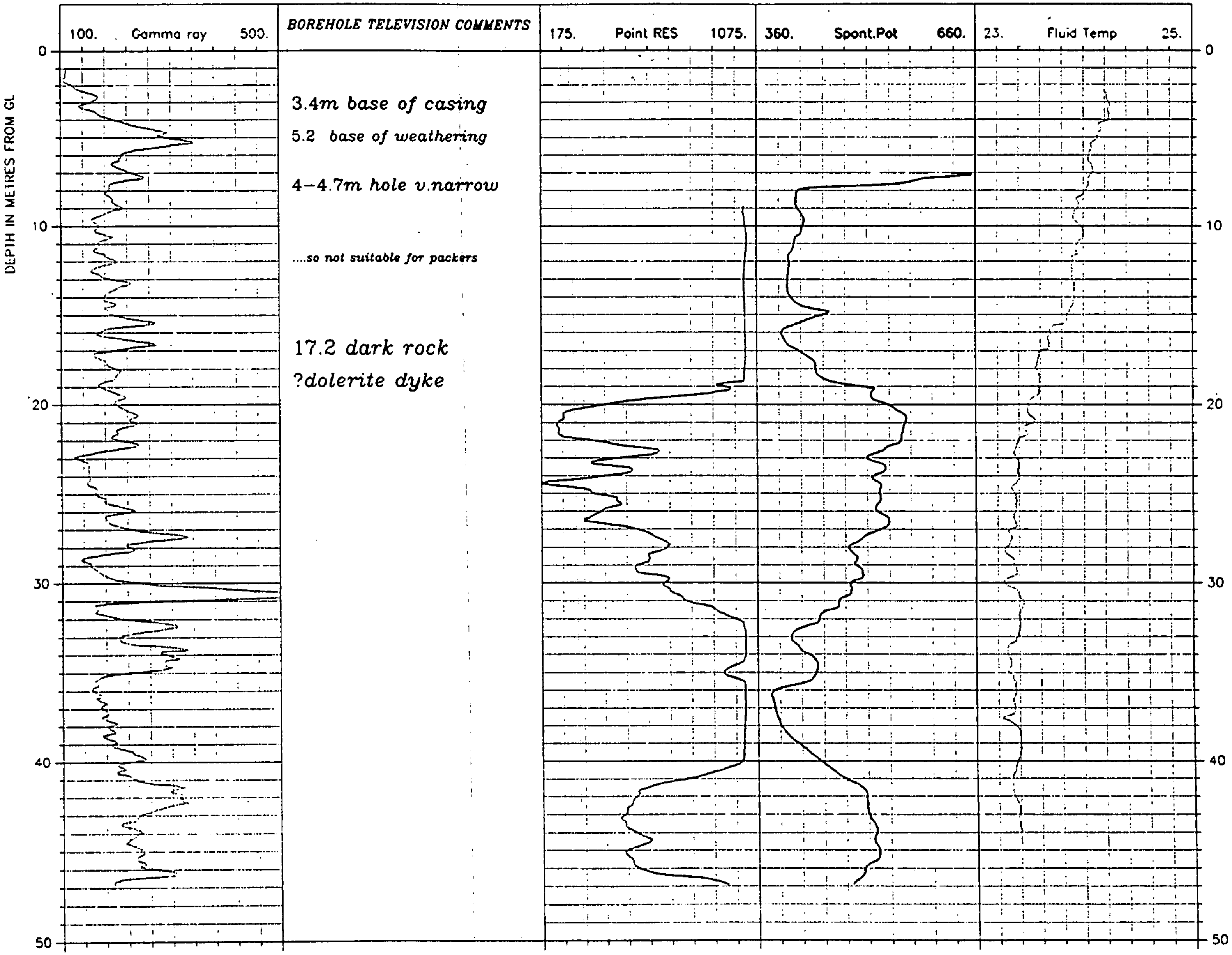
B2 - Zvirikure School



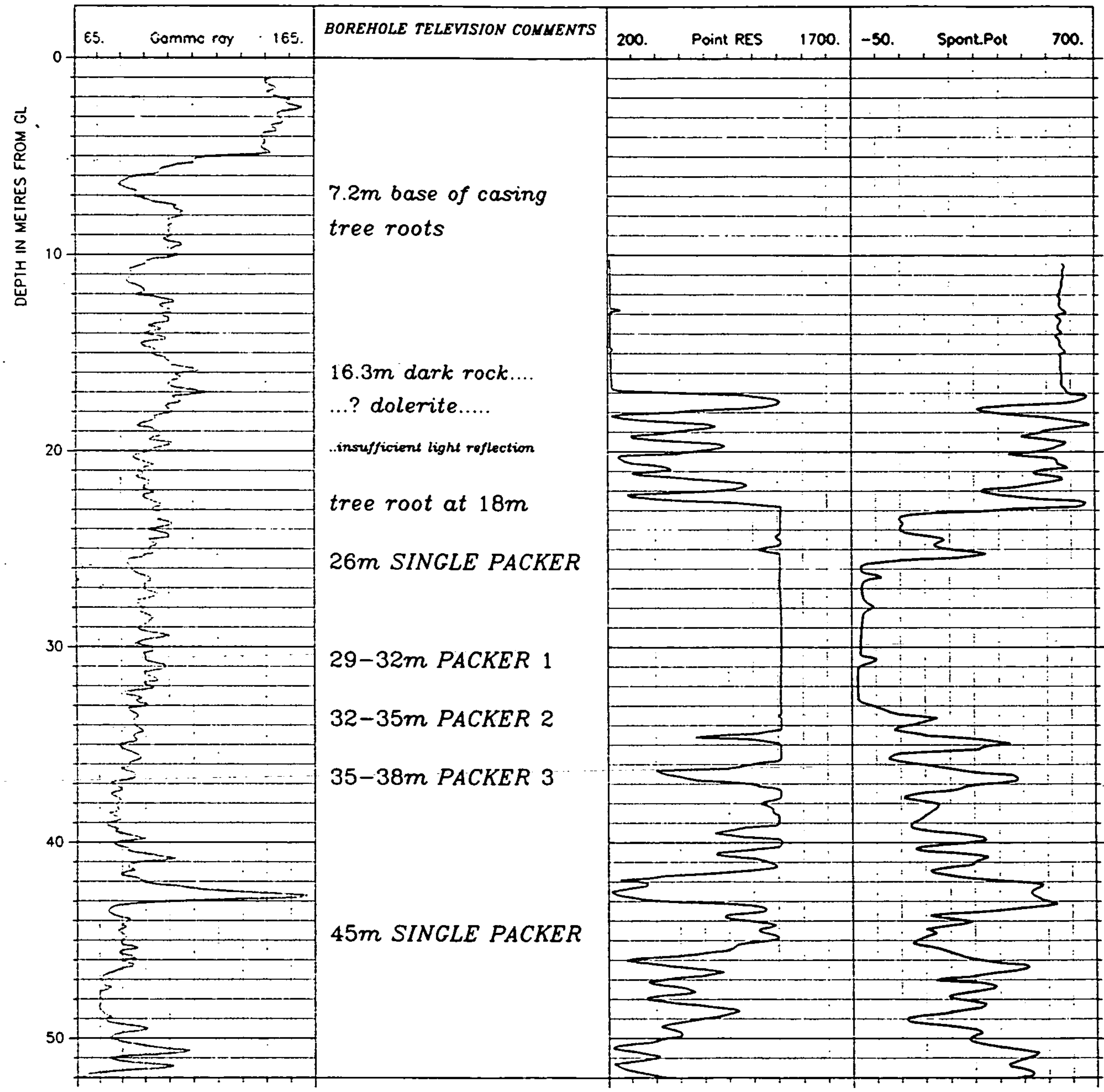
B3 - Madamabwe



B4 - Macheke Village No.1


DEPTH IN METRES FROM GL
100. Gamma ray 500.
BOREHOLE TELEVISION COMMENTS
3.4m base of casing
5.2 base of weathering
4–4.7m hole v.narrow
....so not suitable for packers
17.2 dark rock
?dolerite dyke
175. Point RES 1075.
360. Spont.Pot 660.
23. Fluid Temp 25.
0
10
20
30
40
50

B5 - Mudzudzu



B6 - Chinyika Clinic

APPENDIX C : Detailed Observations from Geophysical Logging

Maramba School (Figure B1)

The caliper log shows a nominal 6 inch diameter hole with 3 x 3m lengths of casing, below which the hole is enlarged to ~ 10 inches from 10-12m still within the weathered zone, where the rock is soft. The rock becomes harder below 12m and the base of the weathered zone was thought to be about 17.0m. Below this depth the log shows 6 discrete enlargements up to 7.5 inches, three of which (25, 26 and 34m) are associated with dolerite, and two (25 and 42m) have associated water entry.

Comments from the borehole video are given in Appendix F and a detailed description of the TV survey is given here. The base of steel casing was noted at 9.2m and a root hole was visible in the borehole wall at 11m implying soft rock. The wall was recognisably damp at 12.6m (seepage) approaching the base of the weathered material. It became harder at 15m and angular cavities were present at 16 and 17.5m. Hard rock at 17.7m, judged by sharp angular fractures and smooth borehole wall, probably marks the base of the weathered zone/top of bedrock. A stick was wedged in the borehole from 23-23.4m. Water was seen entering from a sub-horizontal cavity at 25.4 - 26.1m on the margin of a dark rock band (?dolerite). Below this depth there was solid rock (no wall features) from 28.5 - 33.5m, where a dark rock band (dolerite) was present (33.5 - 34m). Below this several dark xenoliths were identified in the pink/grey granite gneiss. Sub-vertical intersecting fractures and a vertical crack were seen at 39.8m. Water entry was again observed at 42.7 - 42.9m from a nearly vertical crack which extended from 42.2 - 43.4m. The positions the packers were placed are indicated in Figure B1. The packer was first placed over the interval of solid rock (29.5 - 32.5m) and no fracturing was achieved with the pressure available. The second packer was placed at 38.5 - 41.5m over a section having sub-vertical fractures. During pressurising the pressure pipe parted downhole and the TV camera was used successfully to guide the fishing for the broken pipe. The third packer was placed at 24.5 - 27.5m across the existing inflow. The TV survey after HF showed no discernible effect on the borehole wall. However, the inflow was greater in quantity and a further inflow was seen at 23.8m.

The gamma ray log shows a complicated saw-tooth pattern. The steel casing attenuates the signal in the top 9m and a hole enlargement behind the casing might be inferred by the lowered signal from 7 - 9m. The weathered zone is not clearly resolved by the log although it is probably represented by the zone to 17m showing less variable activity. Below, the unweathered hard rock has a very variable gamma activity. The highest alongside the enlargements associated with dolerite and water entry at 25.4m (?radio-element precipitation on fissure surface) and at 46-48m (no water). The gamma activity at the lower water entry (42.7 - 42.9m) is very low.

The point resistance log shows zones of higher resistance coinciding with recognised hard rock and zones of lower resistance associated with hole enlargement and fracturing. Although not accurate the resistance values nevertheless usefully identify the hole enlargements and permit a division into different rock units, eg. lower resistance darker rock, probably dolerite 25 - 38 and 34m, higher resistance 'solid rock', 18 - 20 and 28.5 - 33.5m. Water level is indicated by the log at ~ 16m.

The spontaneous potential log is an approximate mirror-image of the resistance log showing positive peaks alongside the low resistance at enlargements. Below the upper water entry (25.4m) the log is relatively straight alongside the solid rock zone to 33.5m. The water entry at 42.7 - 42.9m shows only a slight negative effect.

The fluid temperature log was run after HF. It represents a transient temperature profile. It shows warmer water (~20^{0}C) near the watertable cooling with depth to ~19.4^{0}C at 46m. It shows warmer water from the upper inflow and above 29m. At the time of logging (October) the injection water was close to mean air temperature (>25^{0}C) and its entry into the fluid column would be seen as a relative warming. The single log is however not very informative and ideally a series of temperature measurements is required.

The fluid EC log was run soon after the pump had been removed. Because the rates of chemical diffusion are very slow compared to thermal conduction, the fluid EC profile remains disturbed for a long period of time. The single log is therefore not very informative and again time-series logging is required to examine the fluid entry points.

In summary the caliper, PR and SP logs identify fractures but their responses are not sufficiently diagnostic to identify the water producing ones. The fluid log measurements normally identify fluid inflow but for technical and logistical reasons conventional fluid logging could not be done. Instead the borehole television proved capable of easily identifying the groundwater-active fractures after emptying the borehole.

<u>Zvirikure</u> (Figure B2)
At the time of logging the water level was 33m so that the PR, SP and fluid temperature logs record only a short saturated section near the bottom of the hole (33-44m). The caliper log shows an irregular walled hole having 5 x 3m lengths of nominal 6" diameter casing. Below the open hole diameter is probably 5.5" but there are several enlargements up to 8.5". The hole is narrowest (close to gauge 5.5") at 28-30, 33-35 and 38-39m where harder rock is inferred. The higher gamma ray activity above 10m possibly reflects the weathered zone. Below the log shows uniform low activity and no distinguishing features, and an induction log would be required to resolve detail. Little can be inferred from the short length of the other logs. Harder rock can be inferred from the higher resistance sections.

<u>Madamabwe</u> (Figure B3)
The gamma ray log differs from that at Maramba School in showing several well defined peaks. The combination of high gamma ray/low resistance at 44 - 45m could represent increased mafic material and or/fracturing, though it is not possible from the restricted logs to identify any fluid inflow.

<u>Macheke</u> (Figure B4)
The video survey showed water jetting through a slot in the casing at 7.3m and this water cascading down the borehole walls obscured identification of any lower inflows. The gamma ray log shows a probable weathered zone to 8m containing an upper more clayey portion

(0-4m). A single peak is shown (26 - 29m) which is also lower point resistance and is possibly dolerite.

The fluid temperature log shows an increasing gradient with depth with the coolest water alongside the inflow in the casing.

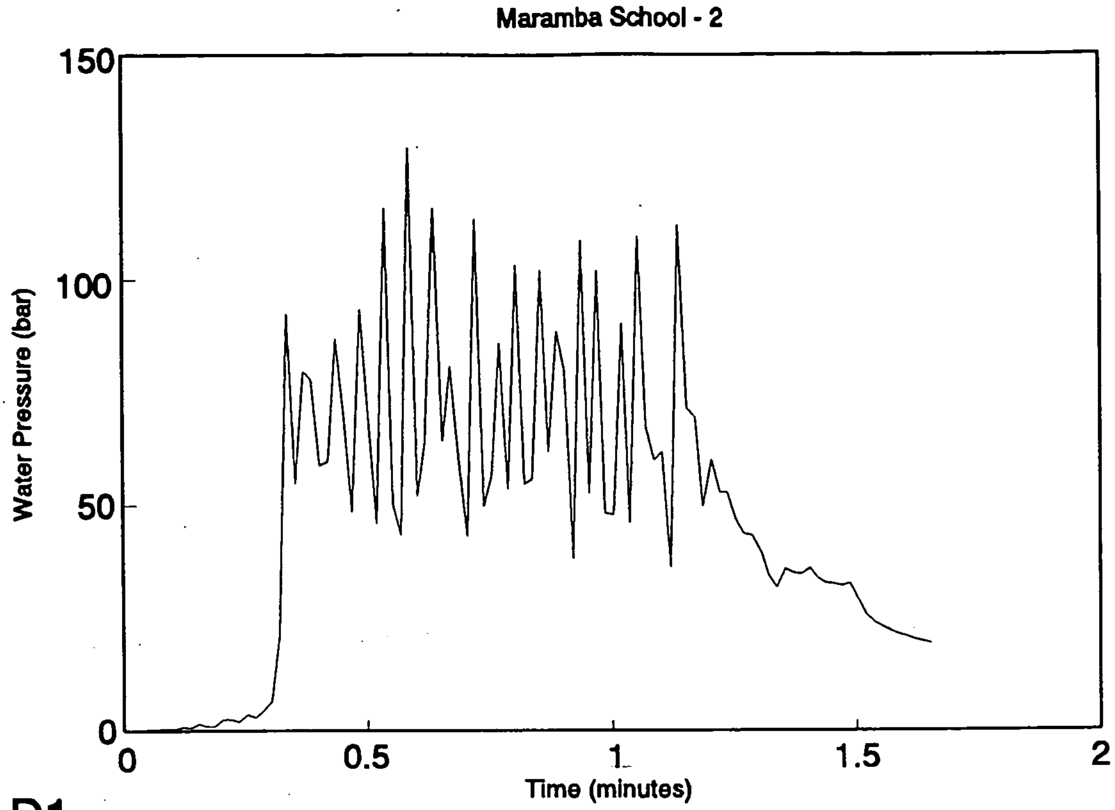
Mudzudzu (Figure B5)
The borehole video showed base of casing at 3.4m (reported 9m) and the base of weathering was judged at 5.2m. A dolerite dyke was inferred by visible dark rock at 17.2m, though this is not evident from the log responses. Water entry was seen at 22.7m (at a low on the gamma ray log).

The point resistance log shows high resistance (exceeding the equipment resolution) from 9 - 19m and from 32 - 40m. The very prominent gamma peak at 31m is not matched by low resistance and is probably not a caliper enlargement. Broad zones of relatively softer rock are inferred from the log response at 20 - 27m and 42 - 46m.

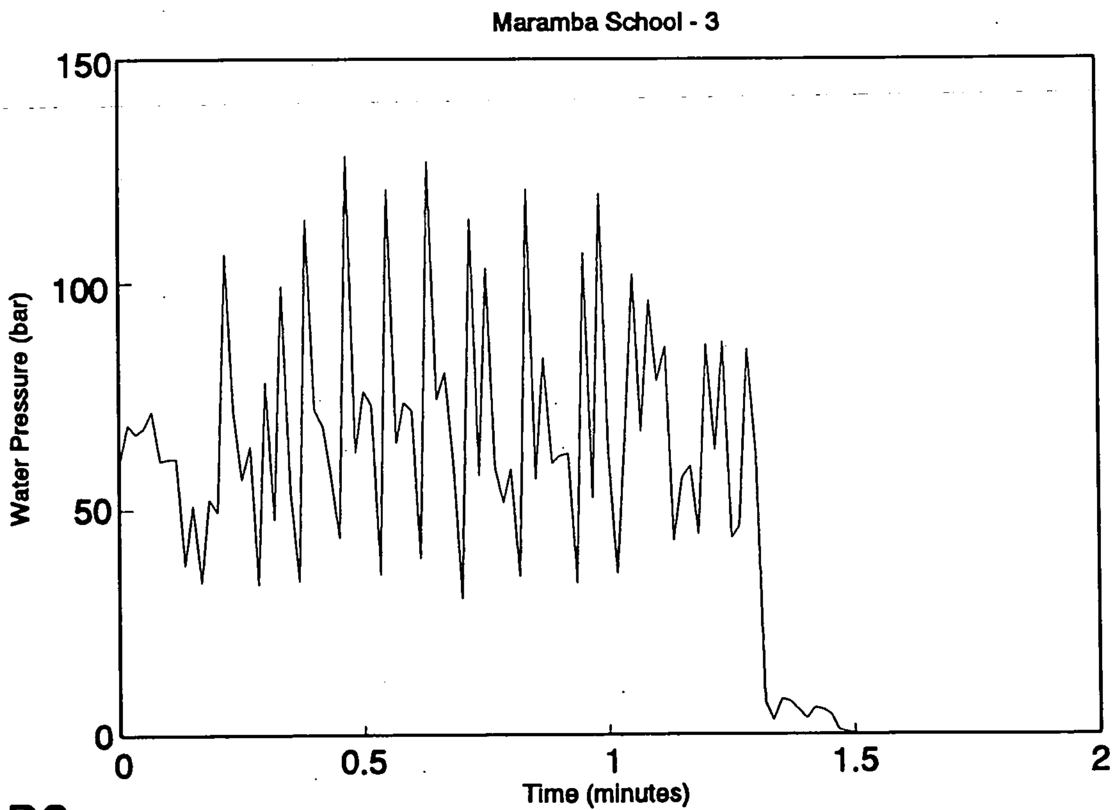
The fluid temperature log shows an inflexion in temperature gradient at the fluid inflow at 22.7m. The television camera provided useful information on the condition of the borehole showing a diameter of ~2 inches at 4 - 4.7m where collapse occurred. The packers could not be inserted past this obstruction and the hole was not treated with HF.

Chinyika Clinic (Figure B6)
The base of casing was at 7.2m below which tree roots were visible. The television logging indicated that there was an inflow of water at 16m. The gamma log shows a higher activity even over the cased interval, and suggests a weathered zone to ~6m. The gamma ray log is relatively uniform showing a peak at 16-17m and 41-42m. No information on water inflow however can be shown by the logging.

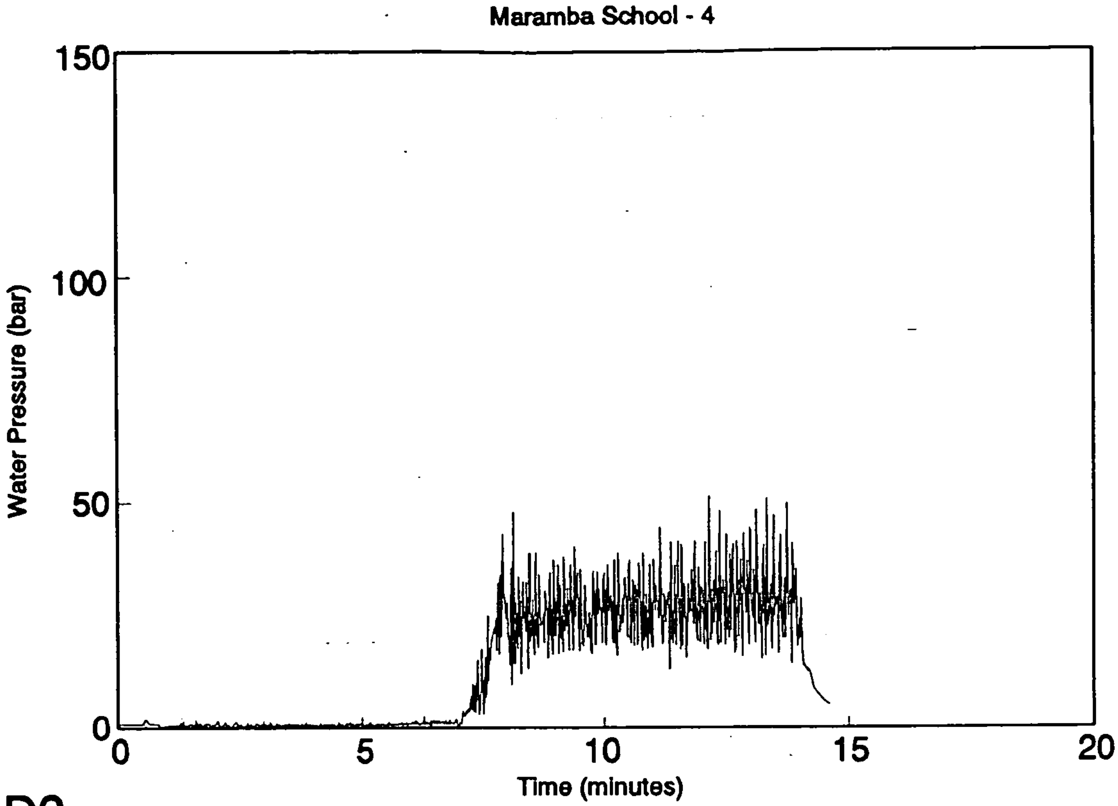
APPENDIX D : HF Pressure Plots


Maramba School - 2
150
100
50
0
Water Pressure (bar)
0
0.5
1
1.5
2
Time (minutes)

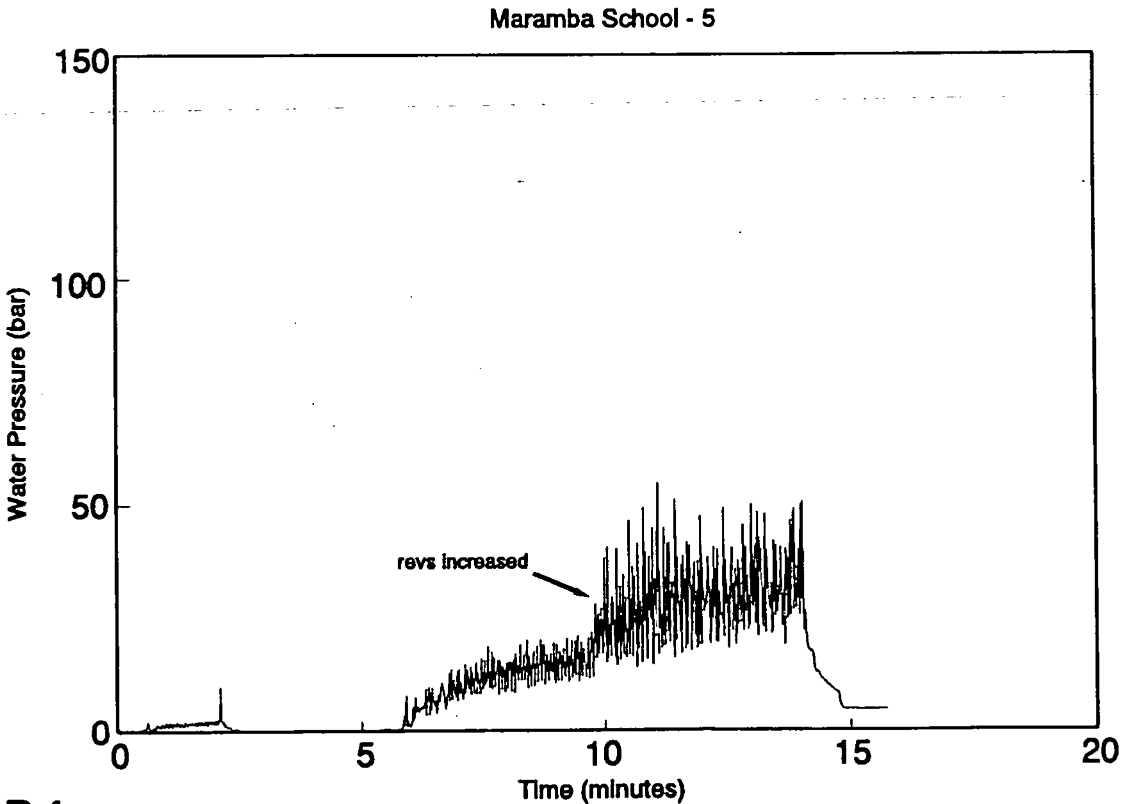
D1


Maramba School - 3
150
100
50
0
Water Pressure (bar)
0
0.5
1
1.5
2
Time (minutes)

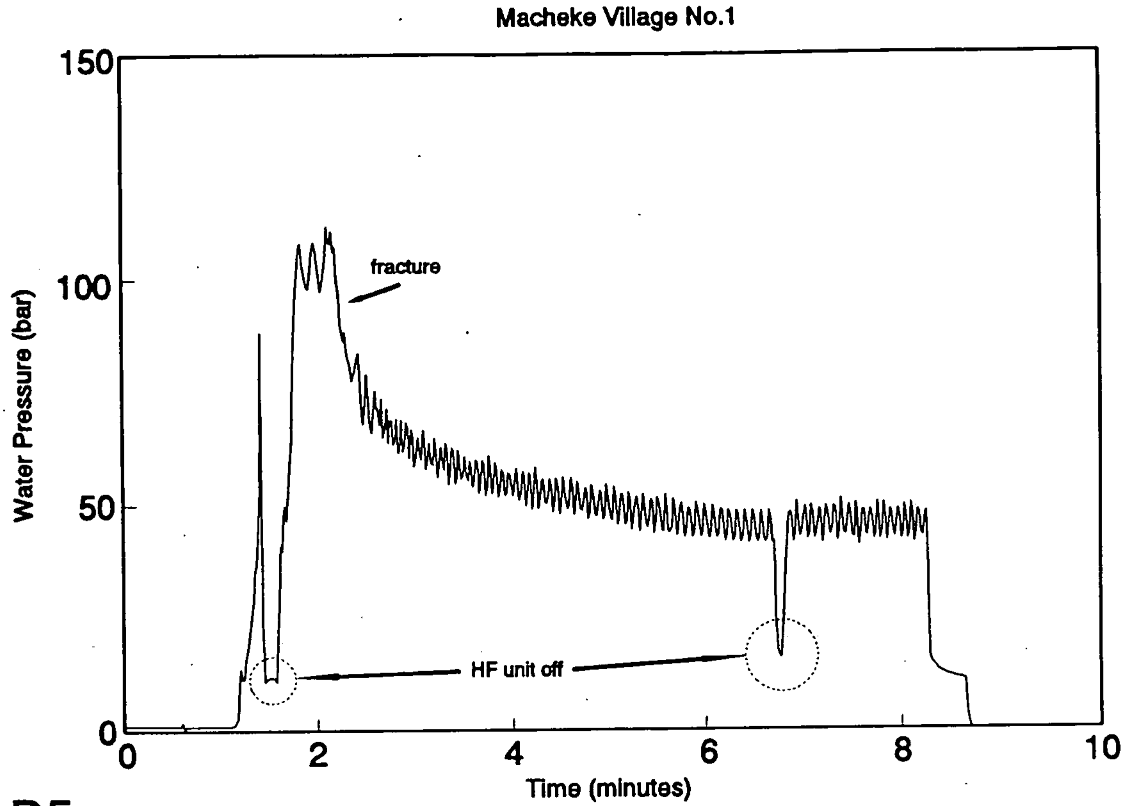
D2


Maramba School - 4
Water Pressure (bar)
150
100
50
0
0
5
10
15
20
Time (minutes)

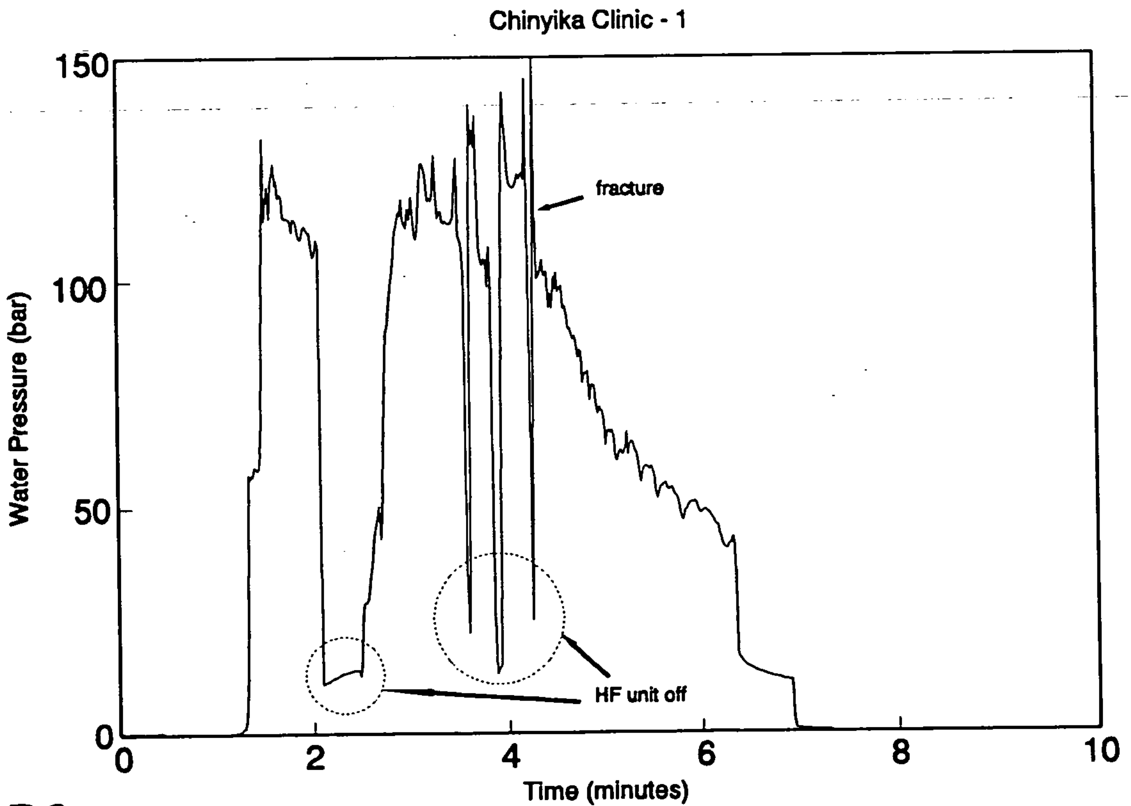
D3


Maramba School - 5
Water Pressure (bar)
150
100
50
0
revs increased
0
5
10
15
20
Time (minutes)

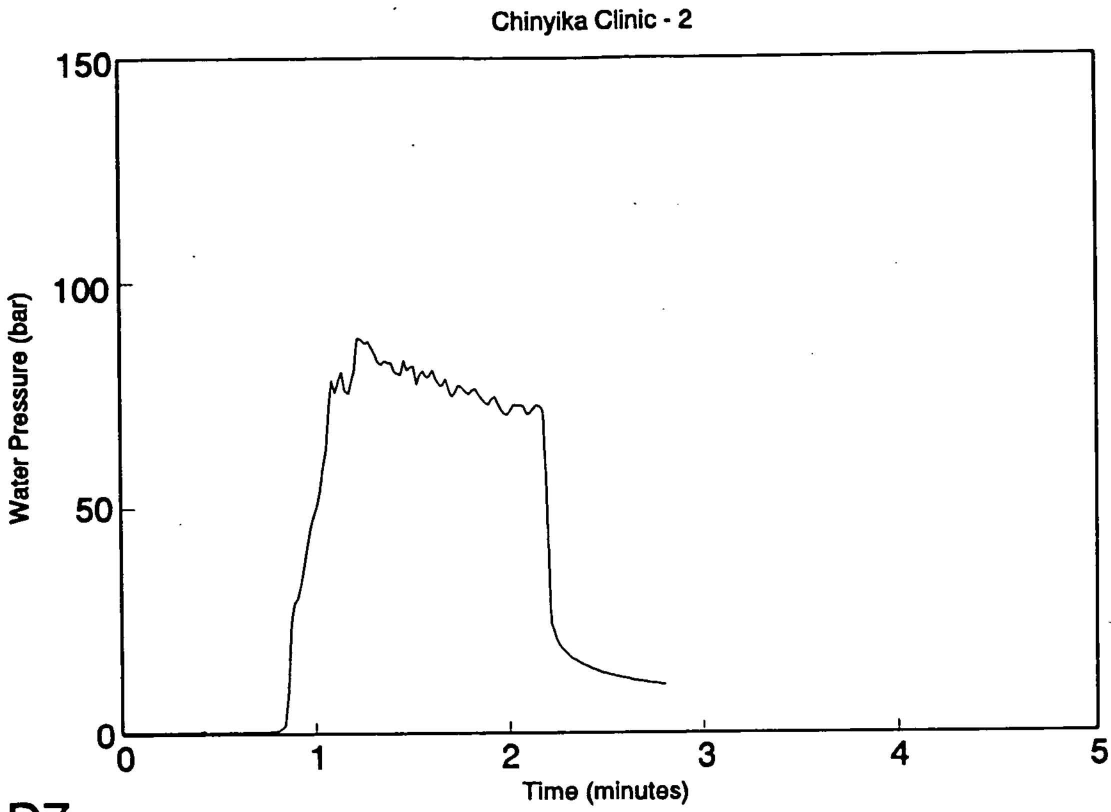
D4


Macheke Village No.1
150
100
50
0
Water Pressure (bar)
fracture
HF unit off
0
2
4
6
8
10
Time (minutes)

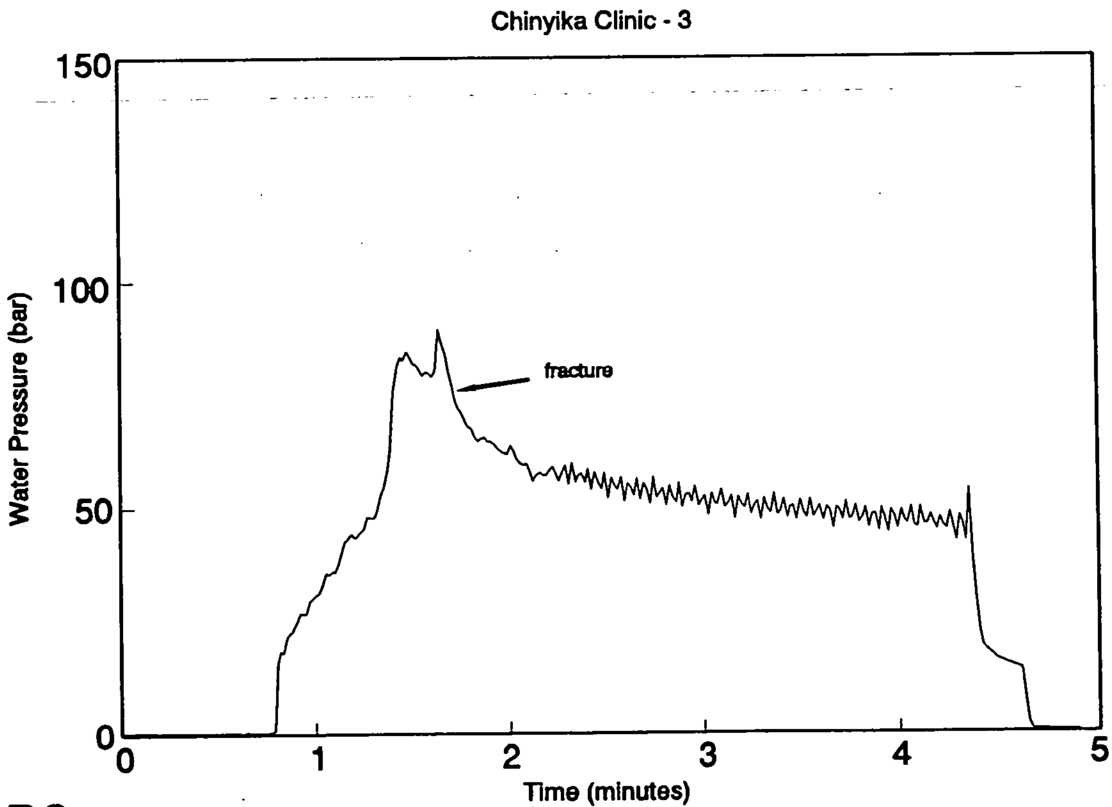
D5


Chinyika Clinic - 1
150
100
50
0
Water Pressure (bar)
fracture
HF unit off
0
2
4
6
8
10
Time (minutes)

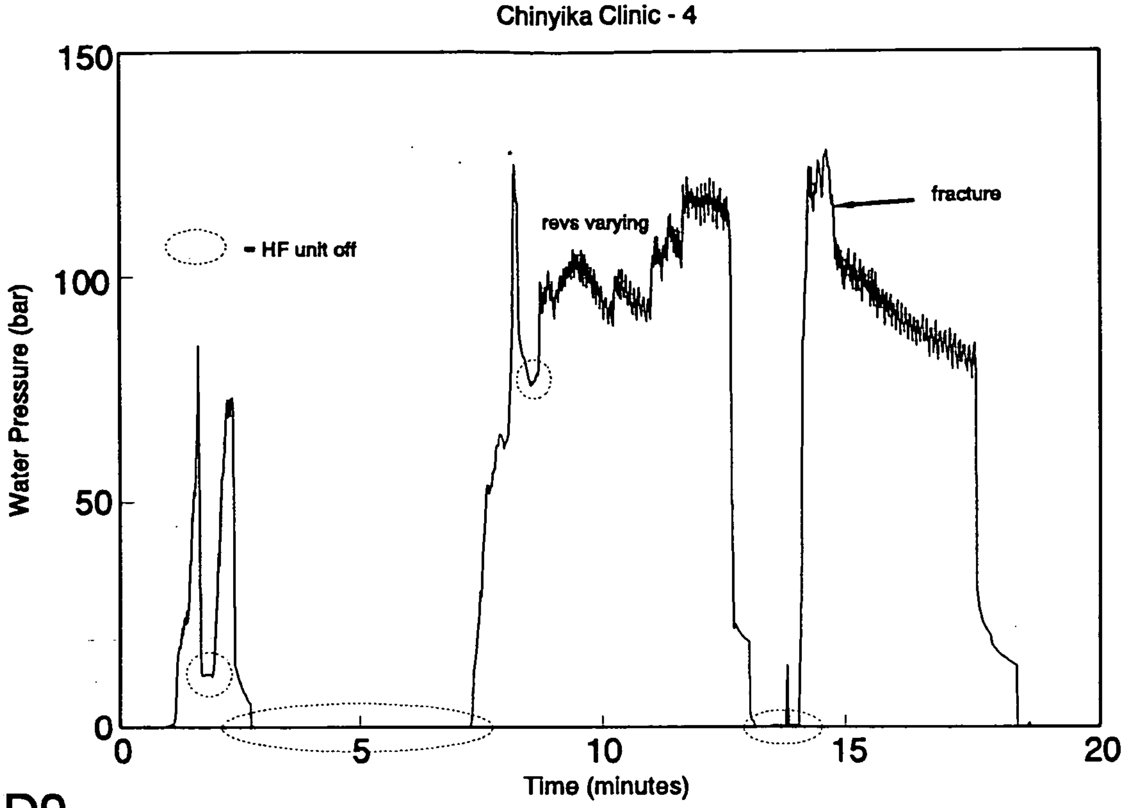
D6


Chinyika Clinic - 2
150
100
50
0
Water Pressure (bar)
0
1
2
3
4
5
Time (minutes)

D7


Chinyika Clinic - 3
150
100
50
0
Water Pressure (bar)
fracture
0
1
2
3
4
5
Time (minutes)

D8


Chinyika Clinic - 4
150
100
50
0
Water Pressure (bar)
0
5
10
15
20
Time (minutes)
= HF unit off
revs varying
fracture

D9

APPENDIX E : Pump-Out Test Results

2nd Phase Pump-Out Test - Recovery

Site : Maramba School - Before HF
Date : 12/10/92
Time : 09h50m

Datum Point : Top Of Casing

Elapsed Time (minutes)	Water Level (mbdatum)	Elapsed Time (minutes)	Water Level (mbdatum)
0	46.400	40	42.597
1	46.245	45	42.190
2	46.130	50	41.787
3	46.025	60	40.992
4	45.922	70	40.203
5	45.822	80	39.443
6	45.704	90	38.705
7	45.610	100	37.982
8	45.509	120	36.549
9	45.405	140	35.073
10	45.308	160	33.790
12	45.109	180	32.450
14	44.912	200	31.122
16	44.720	220	29.820
18	44.530	240	28.549
20	44.360	260	27.305
22	44.160	270	26.683
24	43.978	281	26.043
26	43.790	290	25.906
28	43.622	300	25.582
30	43.449	313	25.171
32	43.280	320	24.955
35	42.961	325	24.795

2nd Phase Pump-Out Test - Recovery

Site : Maramba School - After HF Maramba-4
Date : 14/10/92

Datum Point : Top Of Casing

Elapsed Time (minutes)	Water Level (mbdatum)	Elapsed Time (minutes)	Water Level (mbdatum)
0	45.912	125	32.960
5	45.081	130	32.556
10	44.331	135	32.141
15	43.630	140	31.738
20	42.974	145	31.340
25	42.286	150	30.928
30	41.781	155	30.524
35	41.211	160	30.111
40	40.652	165	29.744
45	40.127	170	29.348
50	39.613	175	28.953
55	39.123	180	28.570
60	38.652	185	28.197
65	38.163	190	27.817
70	37.700	195	27.419
75	37.250	200	27.038
80	36.809	205	26.636
85	36.362	210	26.249
90	35.906	215	26.022
95	35.485	220	25.951
100	35.052	225	25.744
105	34.612	230	25.558
110	34.182	235	25.355
115	33.797	240	25.156
120	33.385		

2nd Phase Pump-Out Test - Recovery

Site : Maramba School - After HF Maramba-5
Date : 16/10/92

Datum Point : Top Of Casing

Elapsed Time (minutes)	Water Level (mbdatum)	Elapsed Time (minutes)	Water Level (mbdatum)
0	43.049	120	33.301
5	42.521	130	32.512
10	42.040	140	31.721
15	41.589	150	30.940
20	41.152	160	30.152
25	40.738	170	29.365
30	40.330	180	28.603
35	39.924	190	27.832
40	39.533	200	27.060
45	39.135	205	26.662
50	38.740	210	26.285
55	38.349	215	26.059
60	37.949	220	26.008
70	37.161	225	25.849
80	36.381	230	25.697
90	35.615	235	25.546
100	34.842	240	25.382
110	34.070	245	25.226

Nb. This test done with 2" pump rising main in borehole. Elapsed times should be multiplied by 1.11 to compare with other tests done in the empty hole.

2nd Phase Pump-Out Test - Recovery

Site : Macheke Village No.1
Date : 30/10/92

Datum Point : Top Of Casing
RWL : 3.39m

Before HF		After HF	
Elapsed Time (minutes)	Water Level (mbdatum)	Elapsed Time (minutes)	Water Level (mbdatum)
0	33.01	0	11.74
1	31.43	1	10.74
2	31.01	2	10.13
3	30.47	3	9.64
4	29.87	4	9.20
5	29.39	5	8.15
6	28.82	6	7.10
7	28.36	7	6.29
8	27.94	8	5.69
9	27.48	9	5.16
10	26.79	10	4.87
15	19.67	15	4.15
20	15.79		
25	12.33		
30	9.97		

2nd Phase Pump-Out Test - Recovery

Site : Chinyika Clinic
Date : 3/11/92

Datum Point : Top Of Casing
RWL : 10.21m

Before HF		After HF	
Elapsed Time (minutes)	Water Level (mbdatum)	Elapsed Time (minutes)	Water Level (mbdatum)
0	34.40	0	29.86
5	32.88	5	27.64
10	31.88	10	25.80
15	30.88	15	24.18
20	30.20	20	22.40
25	29.58		
30	28.77		
35	27.91		
40	26.92		
45	25.85		
50	24.76		
55	23.67		
60	22.57		

Nb. Tests done by BGS before and after double packer HF. Tests done same day

2nd Phase Pump-Out Test - Recovery

Site : Chinyika Clinic
Date : 3-4/11/92

Datum Point : Top Of Casing
RWL : 10.21m

Before HF		After HF	
Elapsed Time (minutes)	Water Level (mbdatum)	Elapsed Time (minutes)	Water Level (mbdatum)
0	18.79	0	25.79
1	18.48	1	25.17
2	18.21	2	24.20
3	17.92	3	23.35
4	17.63	4	22.60
5	17.31	5	22.04
6	17.04	6	21.44
7	16.86	7	21.13
8	16.64	8	20.86
9	16.57	9	20.55
10	16.55	10	20.29
15	15.73	15	18.94
		20	17.69
		25	16.64
		30	16.20

Nb. Tests done by trainees before and after double packer HF. Tests done 24hrs apart.

APPENDIX F : Summary of TV Log Details

Maramba School

Depth (m)		Borehole TV comments
9.2	-	base of steel casing
11.0	-	root hole in borehole wall
12.6	-	borehole wall damp
15.0	-	inferred hard rock
16.0	-	angular cavity, vertical fracturing
17.5	-	angular cavity
17.7	-	hard rock, angular joints
18.5	-	hard rock
22.1	-	vertical crack
23.0-23.4	-	stick wedged in side of borehole
25.4-26.1	-	sub-horizontal cavity
		water entry at 25.4m
25.0-28.0	-	dark rock (dolerite)
28.5-33.5	-	solid rock, no wall features
33.5-34.0	-	coarse dark rock band
34.0	-	pink/grey granite gneiss
		darker xenoliths at 36.4, 38.4, 37.1m
39.4-39.8	-	sub-vertical intersecting fractures
39.8	-	vertical crack in pink granite-gneiss
42.2-43.4	-	vertical crack
		water entry at 42.7-42.9m

Macheke Village No.1

Depth (m)		Borehole TV comments
7.3	-	slots in steel casing, water jetting in water cascading down walls so cannot see features clearly

Mudzudzu

Depth (m)		Borehole TV comments
3.4	-	base of casing
4.0-4.7	-	narrow borhole, ~2" dia., partial collapse, camera on borehole wall
5.2	-	base of weathering
17.2	-	dolerite
22.7	-	water entry or from above

Chinyika Clinic

Depth (m)		Borehole TV comments
7.2	-	base of casing, tree roots below casing
16.3	-	very dark rock, dolerite, no reflected light from borehole wall, water inflow reflecting light
18.0	-	white tree root
30.0 +	-	borehole wall ridged from drilling operation
32.0-37.0	-	turbid water, clear below
base	-	lot of debris, sticks