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Collector Wells System for Sand Rivers
Report on visit to Botswana,
23 November - 9 December 1994

by J Davies, R Herbert and P Rastall

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Executive Summary

Due to the late arrival of drilling equipment, part of the original programme of studies could not be undertaken. However studies that were undertaken have provided new insights into the morphology of sand rivers. Seismic surveys were successfully used to identify the sand river sediment infill/basement interface. A tracer test was successfully used to determine continued groundwater flow through the basal part of the sand river channel near the end of the dry season. Several excavations into the unsaturated zone provided an opportunity to study the sedimentology of that part of the sand river infill in detail. Proposals for the continuation of the original programme of drilling and test pumping and additional studies on the basis of the knowledge gained about the morphology of sand river channels during this study are detailed. Preliminary recommendations of monitoring systems required to determine the sustainability of such collector well systems are included.

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1. Introduction

Sand rivers are a common drainage feature in north eastern Botswana. These ephemeral drainage channels are dry for much of the year, only containing flowing water following localised high intensity storms within their head waters. Geomorphologically they are river channels incised into basement strata, infilled with alluvial sands derived from the weathering of surrounding basement rocks (Fig. 1). According to Moore (1988) there is some geomorphic evidence to show that the Upper Zambezi catchment was once linked to that of the Limpopo River via the course of the present day Shashe River. The main river channels appear to have been incised during an earlier pluvial period when such a drainage pattern may have been present. The infilling sands can contain limited quantities of water, and as such have been used as a source of water via shallow wells sunk into the basal saturated zone as in Fig. 2. Collectively the sand rivers of eastern and north eastern Botswana have been perceived to be a potential major source of as yet under-utilised groundwater. The development of this resource is of great importance within an area that experiences major shortages of water for most of the year. The groundwater resources of such dry river systems can be rapidly recharged by storm rainfall events occurring within their headwaters, commonly causing flash floods that rapidly flow downstream along these wadi like channels.

Five 2m diameter wells have been sunk by the Department of Water Affairs (DWA), two at Tobane, two at Masunga and one at Mathangwane. The aim of this joint DWA/BGS project is the conversion of these large diameter wells into collector well systems through the construction of a series of lateral boreholes from each them into the adjacent sand river system (Herbert, 1992). These lateral boreholes are to be drilled and constructed into the basal, saturated portion of alluvial sands infilling each adjacent channel. The potential for development of the groundwater resources of sand rivers of Botswana is outlined in Wikner (1980) and Nord (1985). Little work appears to have been undertaken since these SIDA funded studies other than recent BGS work (Herbert, 1992).

During the 23rd November - 8th December period a BGS team based at Francistown visited the well sites located at Mathangwane and Masunga (Fig 3). The Selebi Pikwe area was also visited to view the Motloutse sand river, and toxic deposits seeping from the slimes dams of the Selebi Pikwe Mine. Studies to be undertaken during this period were to include the test pumping of two or more of the completed collector well systems, as well as application of the hammer seismic survey method to study sand river morphology (see TORs in Appendix A). Unfortunately, due to shipment problems resulting in the late arrival of necessary drilling equipment from the UK, drilling of laterals could not be begun until near the end of this period. Studies undertaken therefore included determination of the nature of the basal morphology of sand river channels, the sedimentology of the sand infill, and assessment of a method of determining rate of groundwater flow within saturated basal sands towards the end of dry seasons. Activities undertaken by the BGS hydrogeologist during his visit to Botswana are described in diary form in Appendix B.

The geology of the north-eastern part of Botswana encompassing the five collector well sites is described by Crockett et al (1974) and Key (1976). Both the Masunga and Mathangwane areas are underlain by Precambrian age granitic xenolithic gneiss into which have been intruded by Karroo age dolerite dykes. The gneissic rocks form the main source material for the sands that infill the adjacent sand rivers, these sands being composed of subangular to subrounded fragments of opaque quartz and white feldspar.

Figure 1 The Tati sand river at Masunga site B.

Figure 2
Collecting water from a shallow well dug into the bed of the Tati sand river at the Masunga sand pit site.

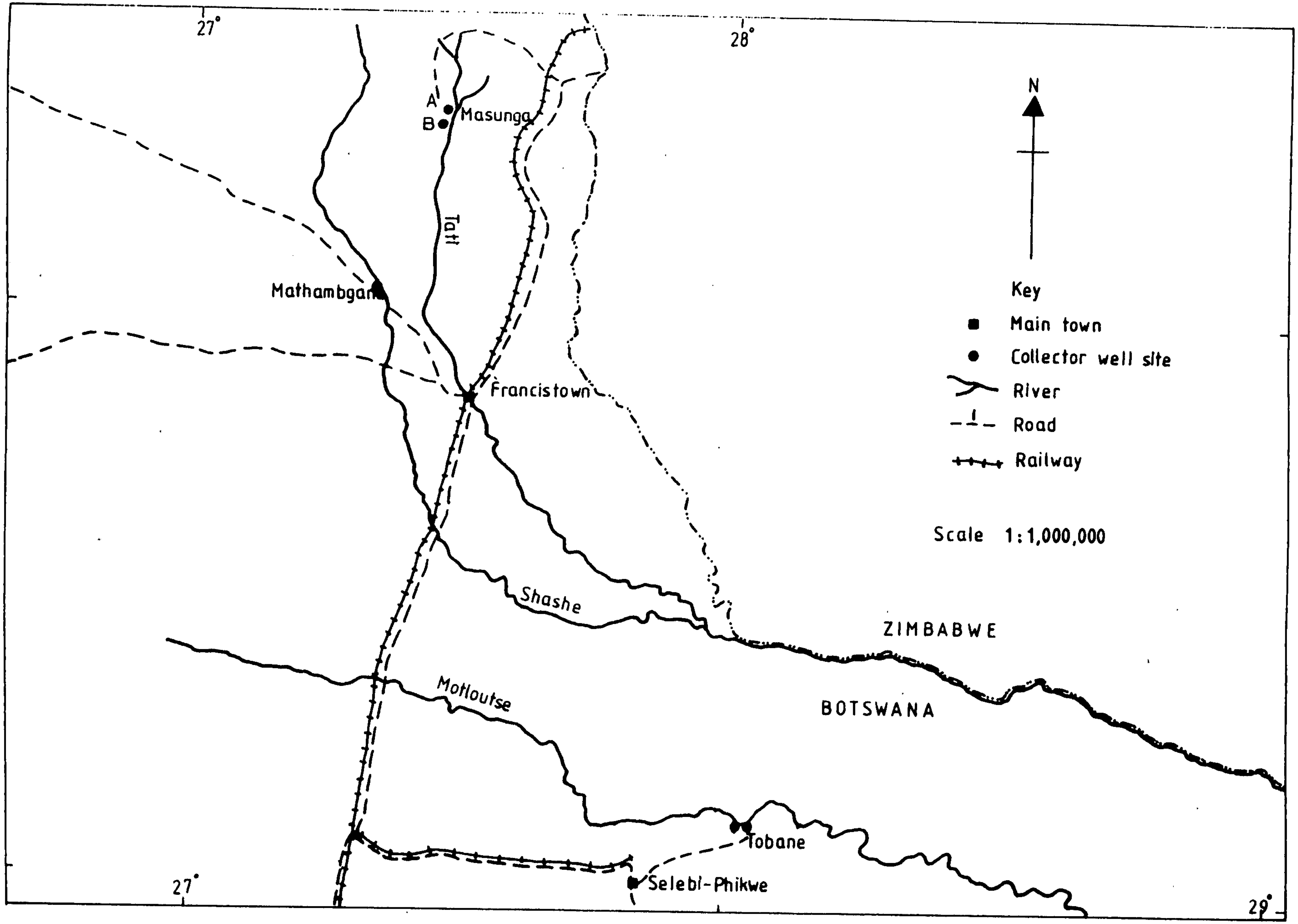


Figure 3 Collector well sites location map.

2. Studies Undertaken

2.1 HAMMER SEISMIC SURVEYS

A total of eight hammer seismic profiles were run, one across the river at Mathangwane and seven at Masunga where three longitudinal profiles were run along the river axis and four profiles crossing the river channel (Fig. 4). The Location of the profiles run at the Masunga sites are shown on Fig. 5. A crew of two or three persons was employed to produce a seismic signal using a hammer and aluminium strike plate source, recorded at each shot point on an ABEM MINILOC seismic refraction system (Fig. 6) (Davies,1994). The results obtained were analysed using the MINILOC system. The analyses indicate depths to channel base, that correlate well with depths obtained from dynamic probe traverses, as presented in Appendix C.

More detailed depth of channel and sediment infill data were obtained from a ground-penetrating-radar (GPR) traverse of the Tati River. This survey was undertaken adjacent to the Marang Hotel by consultants surveying old mine workings in the area of the Francistown Hospital. Details of the system used and the results obtained are presented in Appendix D. The GPR system and methods of data analysis are described in Beres and Haeni (1991).

2.2 SEDIMENTOLOGY

The structure of sediments above the saturated zone were studied at an extensive sandpit (Fig. 7) excavated within the bed of the Tati River with the Masunga area midway between the two collector well sites (Fig. 5). 18 samples were obtained for grain size analysis and age dating, 15 from this sand pit and 3 from a cattle watering pit excavated in the bed of the sand river adjacent to site A. The geological section A at the sand pit is shown on Fig 8a. An interpretation of the geology and structure of these sediments, including cross bedded coarse sands and gravels, medium to fine sands, peats and clays, as typical of an alluvial sequence deposited by a meandering river, is shown in Fig. 8b. The geological logs of this and the other sections are presented in Appendix E.

2.3 AQUIFER FLOW DETERMINATIONS

A 2m deep screened borehole was jetted into the saturated zone from the bottom of the 3.5m deep cattle watering pit (Fig. 9). A PhOX conductivity bridge was used to determine the initial conductance of groundwater within this borehole. Following the addition of 300 gms of common salt to the groundwater in the borehole, the water in the borehole was agitated to ensure that most of the salt had dissolved. The conductivity bridge equipment was then used to monitor the rate of dissolution of a salt solution, initially at one minute intervals, for a period of 1.5 hours. The results and analysis of the data collected are presented in graph form (Fig. 10). The rate of salt dissolution can be used to determine the velocity of groundwater flow through the saturated zone.

2.4 DRILLING OF LATERALS

With the belated arrival of the necessary drilling equipment, drilling of laterals out of the first well at Masunga was started on 7th December. The laterals are to be drilled at a nominal 100 mm diameter using drag bits or down the hole hammers as conditions permit through consolidated material. 88.9 mm slotted steel screen will then be drilled into unconsolidated sand formations using a moling technique involving the use of disposable end caps and compressed air as a flushing medium. This

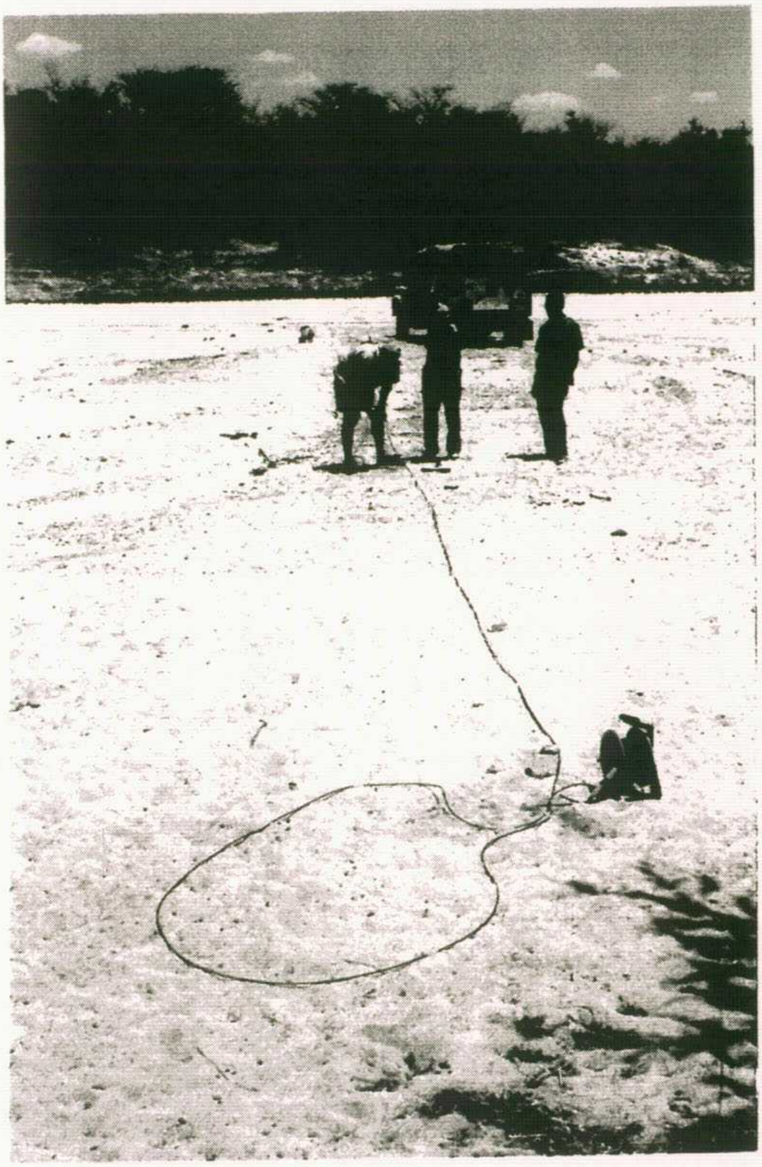


Figure 4 Hammer seismic survey across the Tati sand river at Masunga site A.

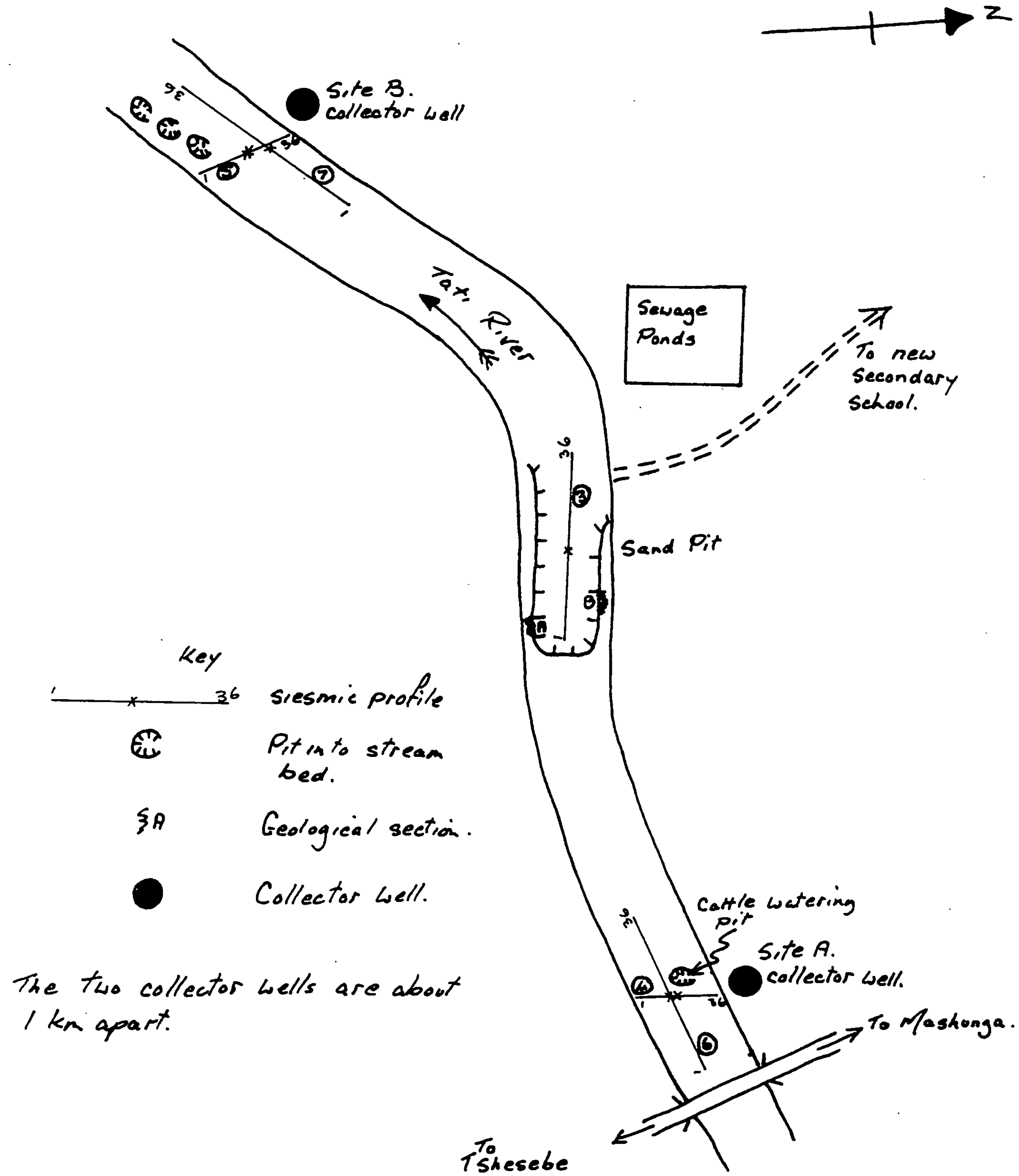


Figure 5 Sketch map of the Masunga area showing locations of seismic profiling points, collector well sites and geological sections.

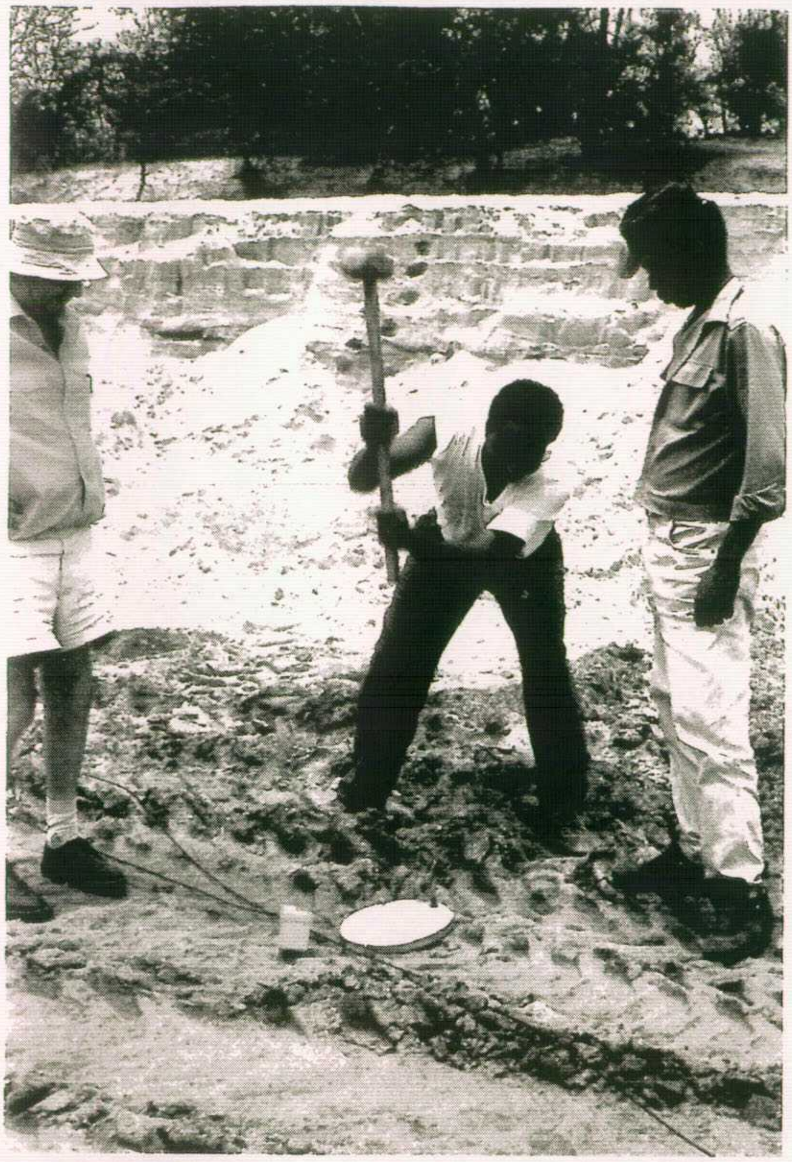


Figure 6
Production of a seismic signal, by hammering an aluminium plate adjacent to a triggering device.

Figure 7 Masunga sand pit excavated into the bed of the Tati sand river to the top of the basal saturated zone.

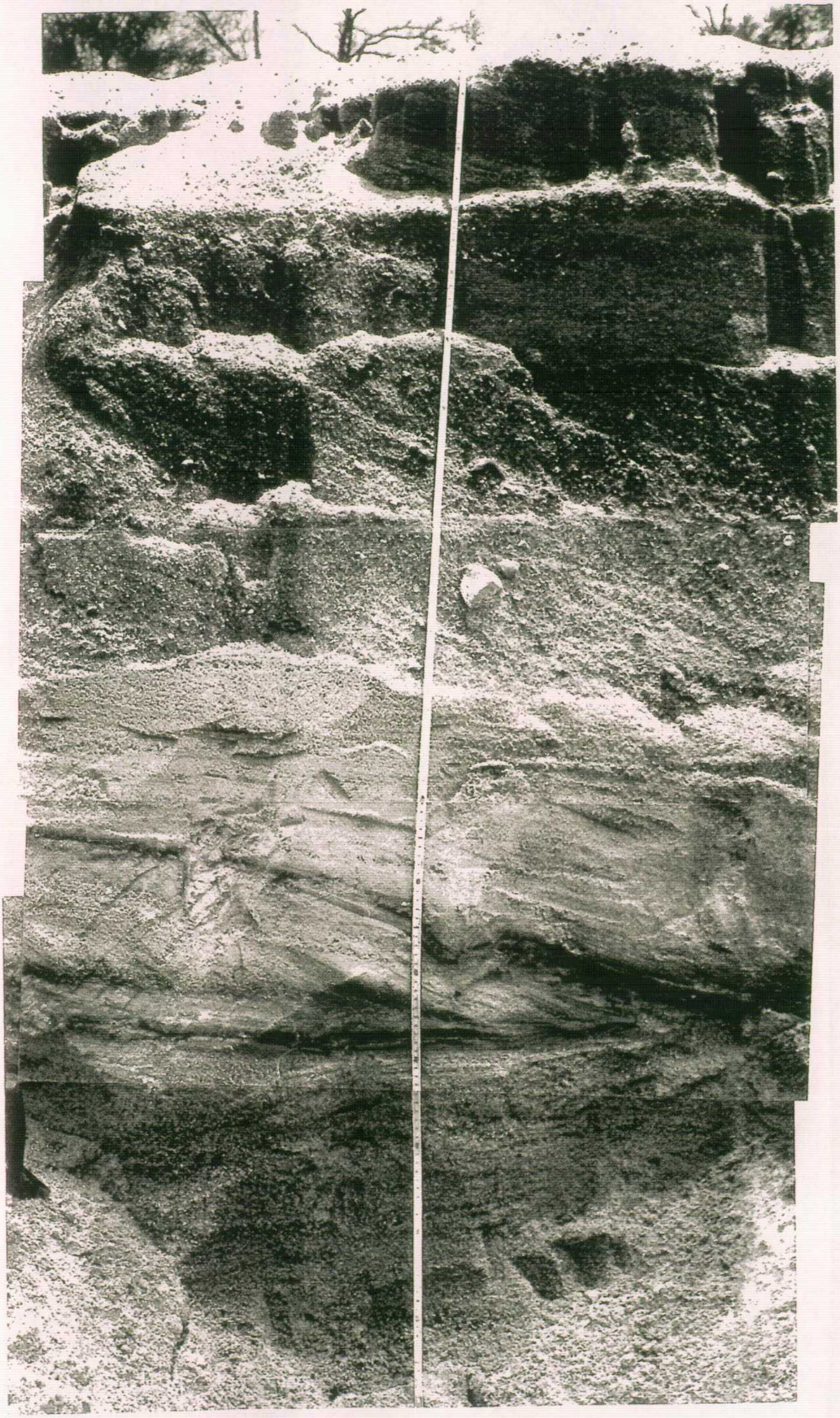


Figure 8a Section through sand infill within the Tati sand river above the saturated zone

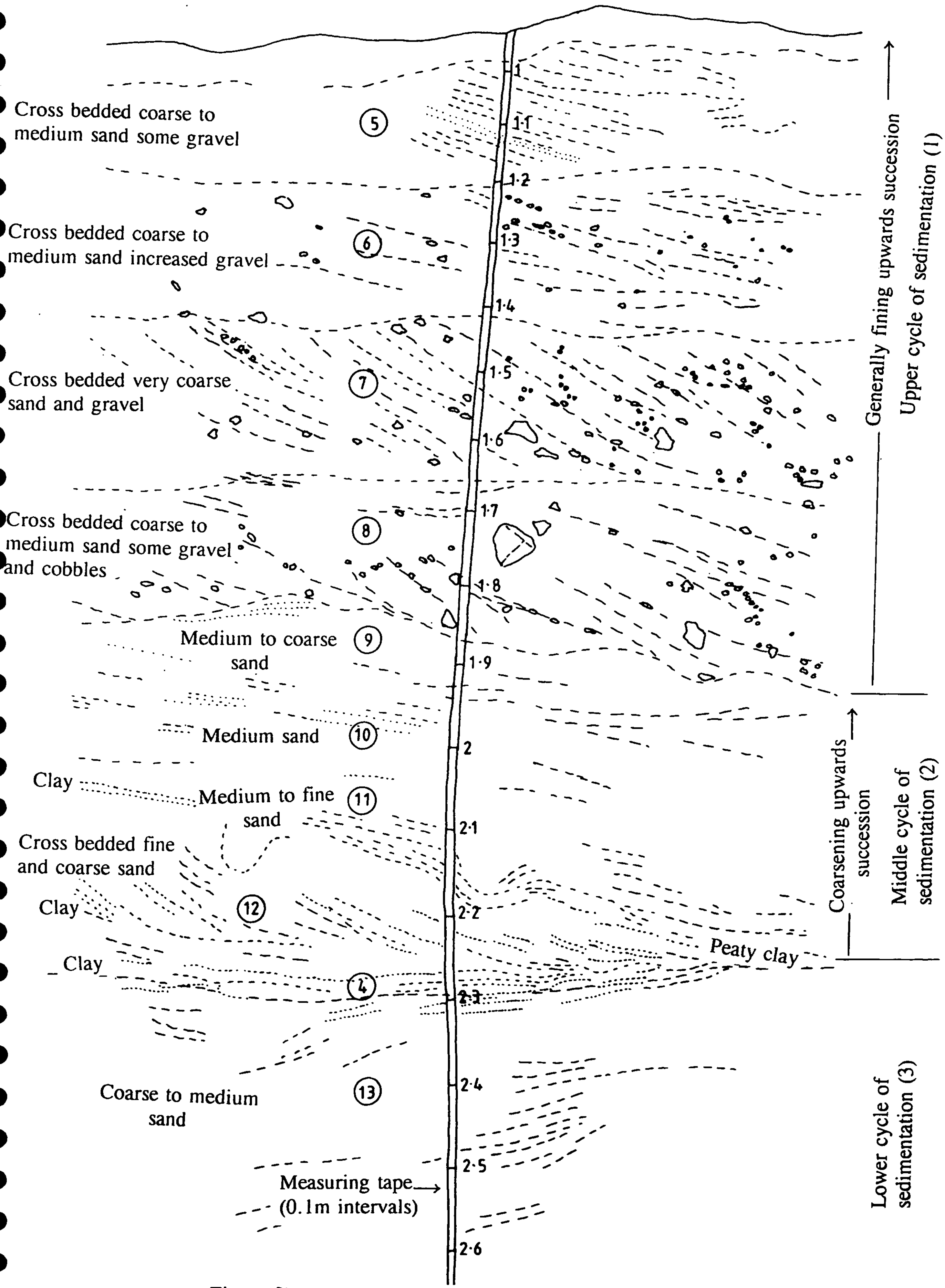
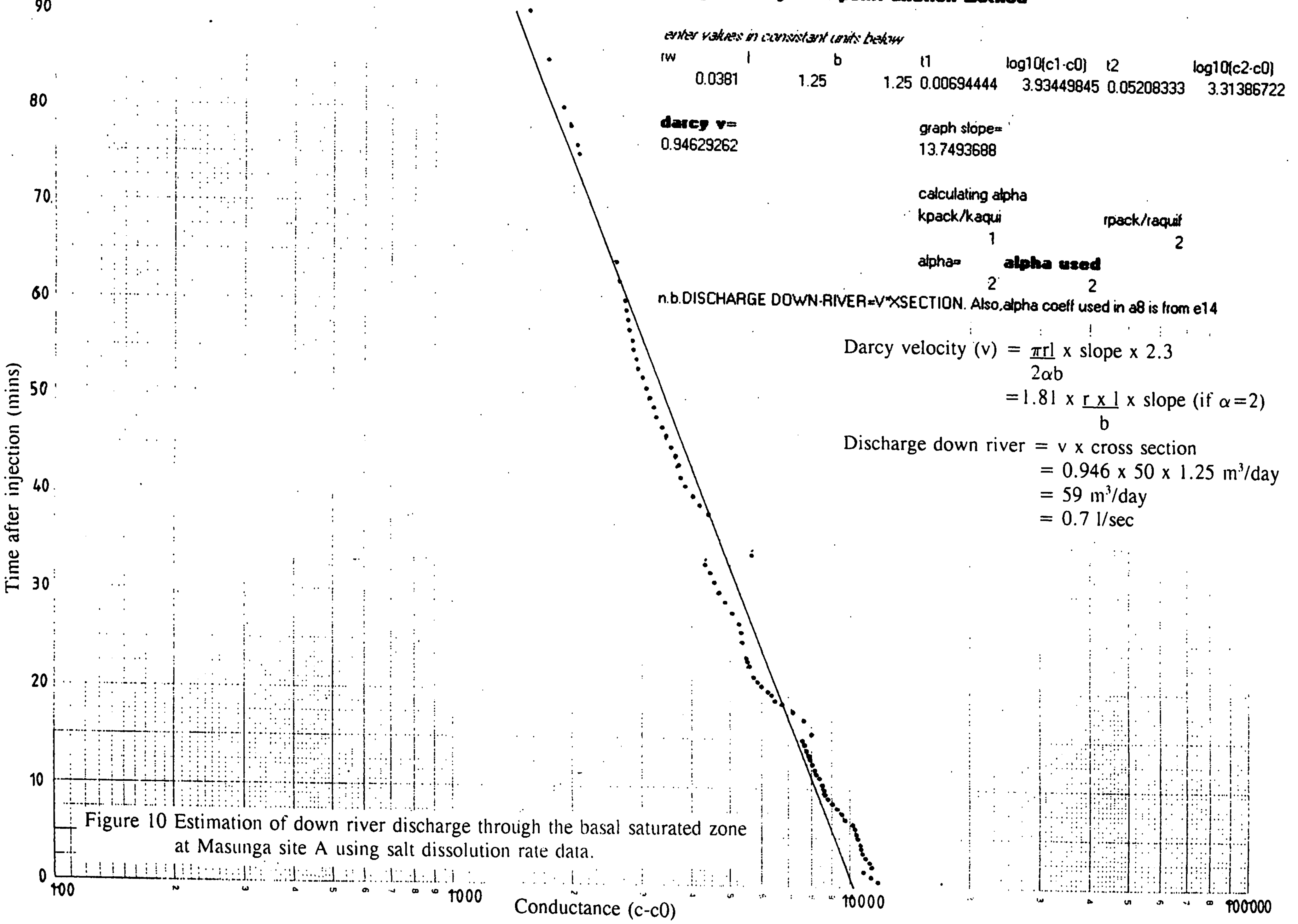


Figure 8b Interpretation of section in Figure 8a showing main sedimentary structures, decimetre scale and location of samples taken for grain size analysis(⑤).

Figure 9 Jetting monitoring well, for aquifer flow determination using salt dissolution, into the basal saturated zone at the bottom of a cattle watering hole at Masunga site A



darcy velocity from point dilution method

enter values in consistant units below

rw	l	b	t1	log10(c1-c0)	t2	log10(c2-c0)
0.0381	1.25	1.25	0.00694444	3.93449845	0.05208333	3.31386722

darcy v=
0.94629262

graph slope=
13.7493688

calculating alpha
kpack/kaqui
1

rpack/raquif
2

alpha=
2

alpha used
2

n.b.DISCHARGE DOWN-RIVER=V*XSECTION. Also,alpha coeff used in a8 is from e14

$$\text{Darcy velocity } (v) = \frac{\pi r l}{2\alpha b} \times \text{slope} \times 2.3$$

$$= 1.81 \times \frac{r \times l}{b} \times \text{slope (if } \alpha = 2)$$

$$\text{Discharge down river} = v \times \text{cross section}$$

$$= 0.946 \times 50 \times 1.25 \ m^3/day$$

$$= 59 \ m^3/day$$

$$= 0.7 \ l/sec$$

Figure 10 Estimation of down river discharge through the basal saturated zone at Masunga site A using salt dissolution rate data.

latter system was used to emplace an observation borehole within the basal saturated sands below the cattle watering pit at Masunga site A. The erection of the drilling rig within the Masunga site A. well is shown on Fig. 11 and the rig in operation is shown on Fig. 12. Three laterals were drilled at this site before departure of the driller from Botswana on 16th December.

2.5 VISIT TO OTHER SITES

A short visit was undertaken to the Selebi Pikwe site upstream of the Tobane site to view the seepage of toxic fluids from the mine's slimes dams, and look at the nature of the Motloutse River. Undertook a visit the old collector well sites at Chidibe and Borolong.

3. Results

3.1 THICKNESS OF CHANNEL SAND INFILL

The results of the hammer seismic surveys appear to correlate with the depths of sand infill within the sand river channels determined using dynamic probe traversing. At Masunga site B, 4 to 5 metres of sand infill are indicated from the results of both seismic profiling and probing (Fig. 13). A similar thickness of sand was indicated by these methods at Masunga site A. However at the Masunga Sand Pit site a sand thickness in excess of 10m was indicated from the seismic profiling results.

3.2 NATURE OF ALLUVIAL SEDIMENTS

Grain size analysis of samples collected from sites at Masunga indicate marked variation in grain size distribution and sediment texture with depth through the unsaturated zone. Equipment used for grain size analysis of the sand sample collected is illustrated in Fig. 14. The grain size analyses of 16 samples collected are presented in Appendix F. Only alluvial sediments and their structures above the water table were available for inspection at each of the three sites investigated at Masunga.

The sediments exposed within the cattle watering pit at the Masunga A. site are composed of subangular to subrounded coarse sand and gravel sized particles of opaque quartz and white feldspar with some medium to fine sand. The feldspars weather to form kaolin with time. This sequence is seen to fine upwards from a basal lag gravel, through coarse sand and gravel into cross bedded coarse to medium sand.

Within the Masunga sand pit exposures two distinct fining upwards cycles of coarse sand deposition are recognisable separated by a coarsening upwards clayey fine to medium sand cycle (Figs. 8a and 8b). These sequences were deposited under differing climatic conditions, as indicated by the variation in grain size, cross bedding, and peaty clay content present.

The lower cycle of sedimentation (3) between 2.3-2.6 m is composed of well graded coarse to medium sands (Fig. 8b). These fine abruptly upwards into the middle coarsening upwards cycle of sedimentation (2). The lower part of this cycle is characterised by divergent peaty clay layers interbedded with thin cross-bedded fine to coarse sands. These pass upwards initially into well graded medium to fine sands, that are succeeded by medium sands and thence upwards into medium to coarse sands. The presence of peat and the well graded nature of the sediments of the upper part of the cycle

Figure 11
Emplacement of
lateral drilling
equipment at
Masunga site A

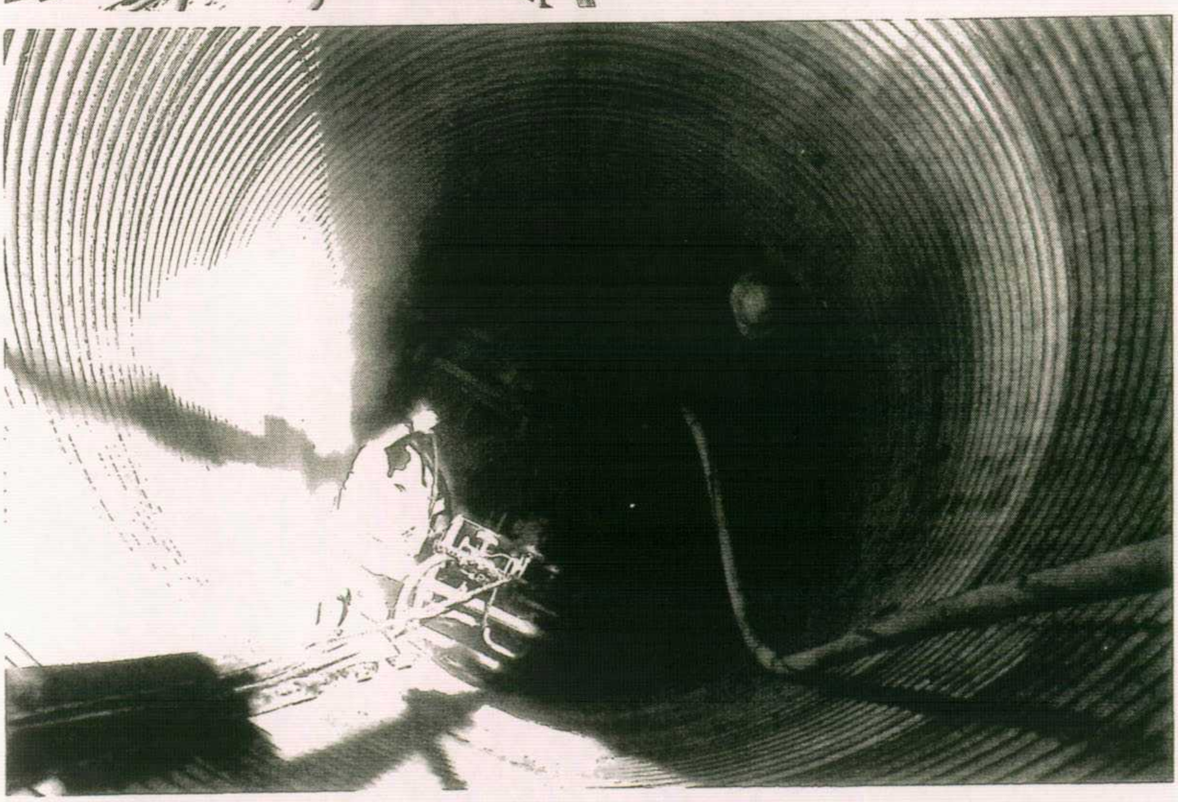
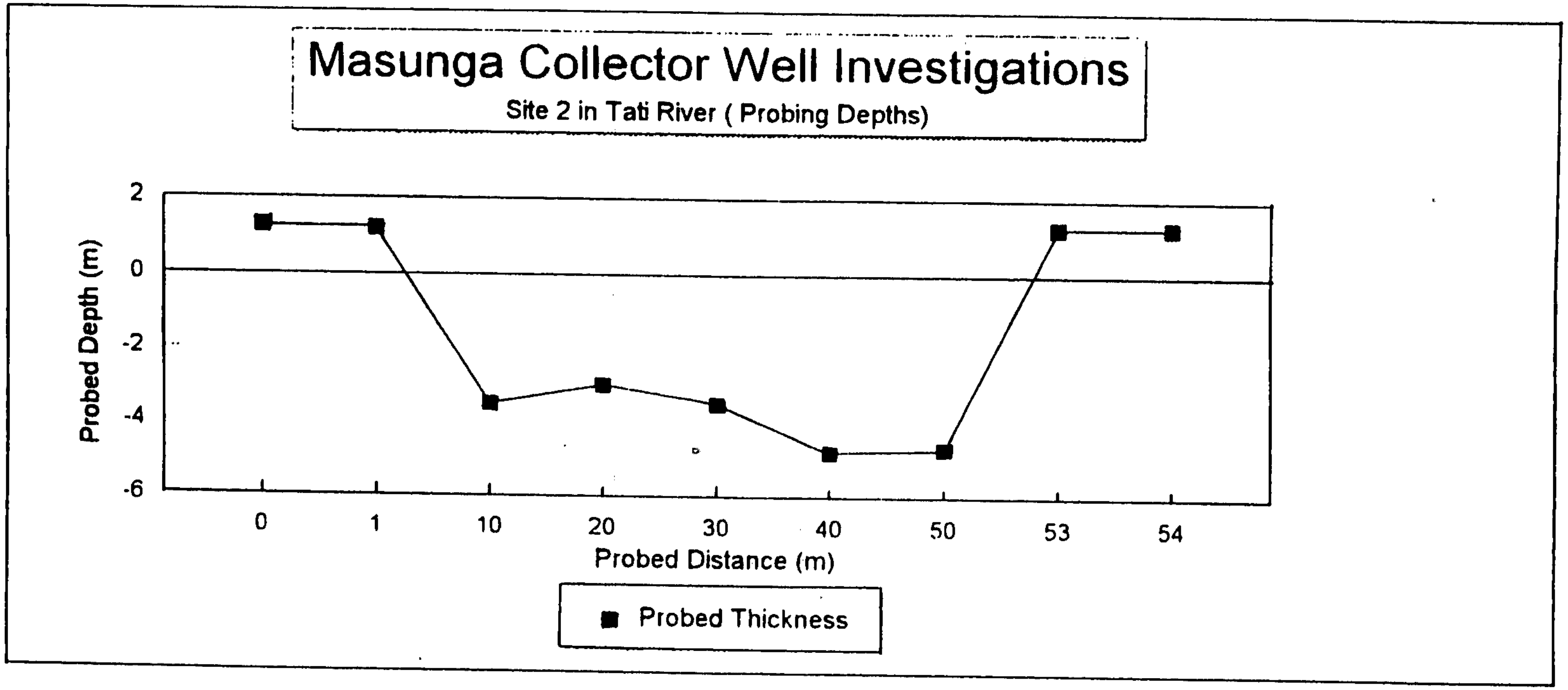


Figure 12 Drilling in progress at Masunga site A.



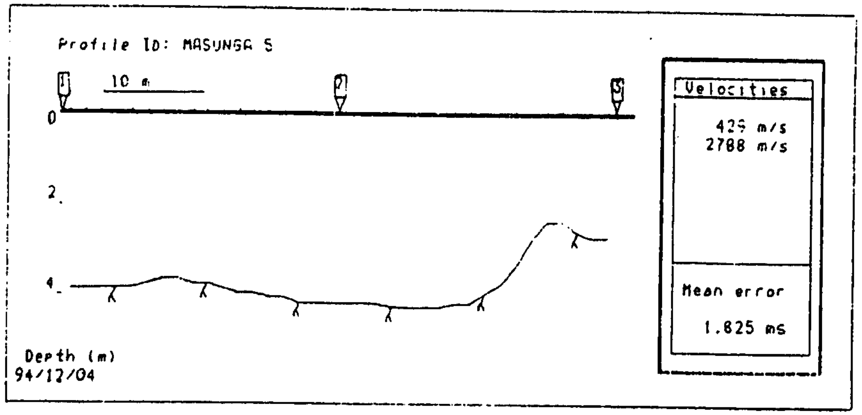


Figure 13 Comparison of sand infill determinations undertaken at Masunga site A using the probing (a) and siesmic profilling (b) methods.

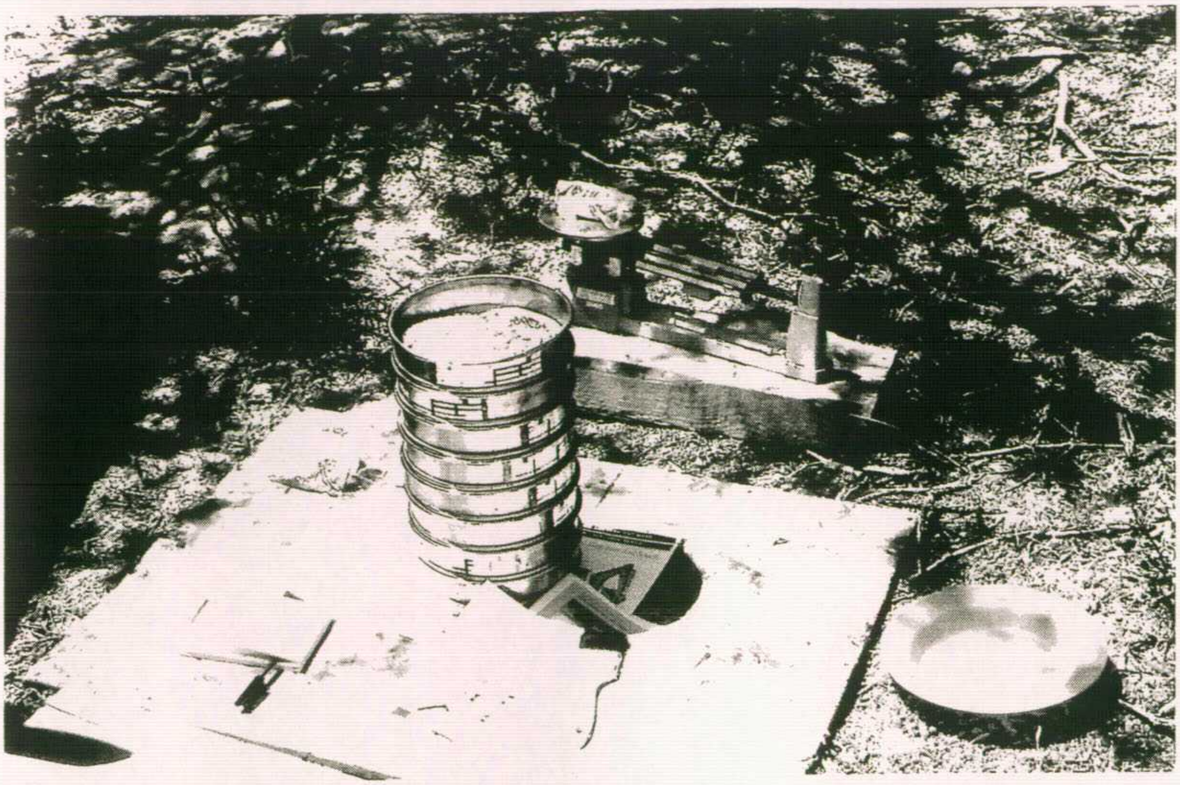


Figure 14 Equipment used for sediment grain size analysis.

indicate that they were deposited during more temperate pluvial conditions when stream flows were more consistent throughout the year. Perhaps the radio carbon dating of the peat deposits will provide evidence for the dating of this period. The grey clay layer, although relatively thin was fairly persistent along the entire sand pit exposure. The upper cycle of sedimentation (3) is dominated by poorly graded, cross bedded, coarse sands and gravels that gradually fine upwards through a series of 4 stacked cross bedded units (Figs 8a and 8b). These sediments were deposited under the current climatic regime of dry season high velocity, high volume but short lived flood events that occur in response to high intensity but localised rain storms.

Similar coarse grained sands and gravels were noted exposed within a dug pit to the water table adjacent to the Masunga site B.

The nature of the underlying basal sediments that include the dry season saturated zone is unknown. However some indication of their age of deposition may be shown by the degree of weathering of these sediments, especially decomposition of included feldspars to kaolin clay. The latter would affect the permeability of these sediments and hence affect their long term sustainability as aquifers, if present.

3.3 DRY SEASON GROUNDWATER FLOW RATE

Analysis of monitoring data by plotting rate of salt dissolution versus time indicates occurrence of groundwater flow through the saturated basal layer at Masunga under dry season conditions (Fig. 10). A Darcy velocity of 0.946 m/d was calculated which when applied to the cross section area of the saturated part of the sand filled channel indicates a possible flow rate of 0.7 l/sec. This is a first indication that groundwater flow can continue within sand river system through the dry season.

3.4 DRILLING RESULTS

At the first drilling site the drilling rig had to be mounted upon timber packing to enable drilling to be undertaken at the correct depths. Three laterals were drilled at the Masunga A. site at depths of 7.90m, 6.90m and 6.40m from the large diameter well, normal to the river bank, stacked above one another (Fig 15).

Prior to drilling, the water table in the sand river was noted at 3.1m below the sand infill surface whereas in the adjacent well the water table lay at 7.9m below the same reference level, a difference of 4.8m indicating the perched nature of the sand river aquifer in relation to the underlying weathered basement aquifer. The coarse sands and gravels occurring within the unsaturated sand river infill had been logged within the adjacent cattle watering hole. The observation borehole sunk through the bottom of the latter hole indicated the presence of unconsolidated alluvium to at least 1.5m within the saturated zone.

The results of drilling conducted at Masunga site A. are summarized on Fig 15. Lateral Bh1 was drilled to a distance of 28.5m using a 100m drag bit with air flush. Following break out of the compact but weathered basement material this borehole was drilled through very weathered biscuit type saprock before re-entering the compact basement. Following break out from the bank material lateral Bh2, drilled 1m above Bh1 but in the same direction, passed through compact clayey material before encountering a hard quartz band at 21m. An additional quartz band was encountered at 23m before the hole drilling into unconsolidated alluvial gravels. Drilling was halted due to the possibility of gravel collapsing back onto the hammer preventing further drilling. Lateral Bh3 was drilled 0.5m above Bh2 but in the same direction. Following break out from the basement bank material this borehole penetrated compact clayey material before encountering a hard quartz band at 21m. Beyond

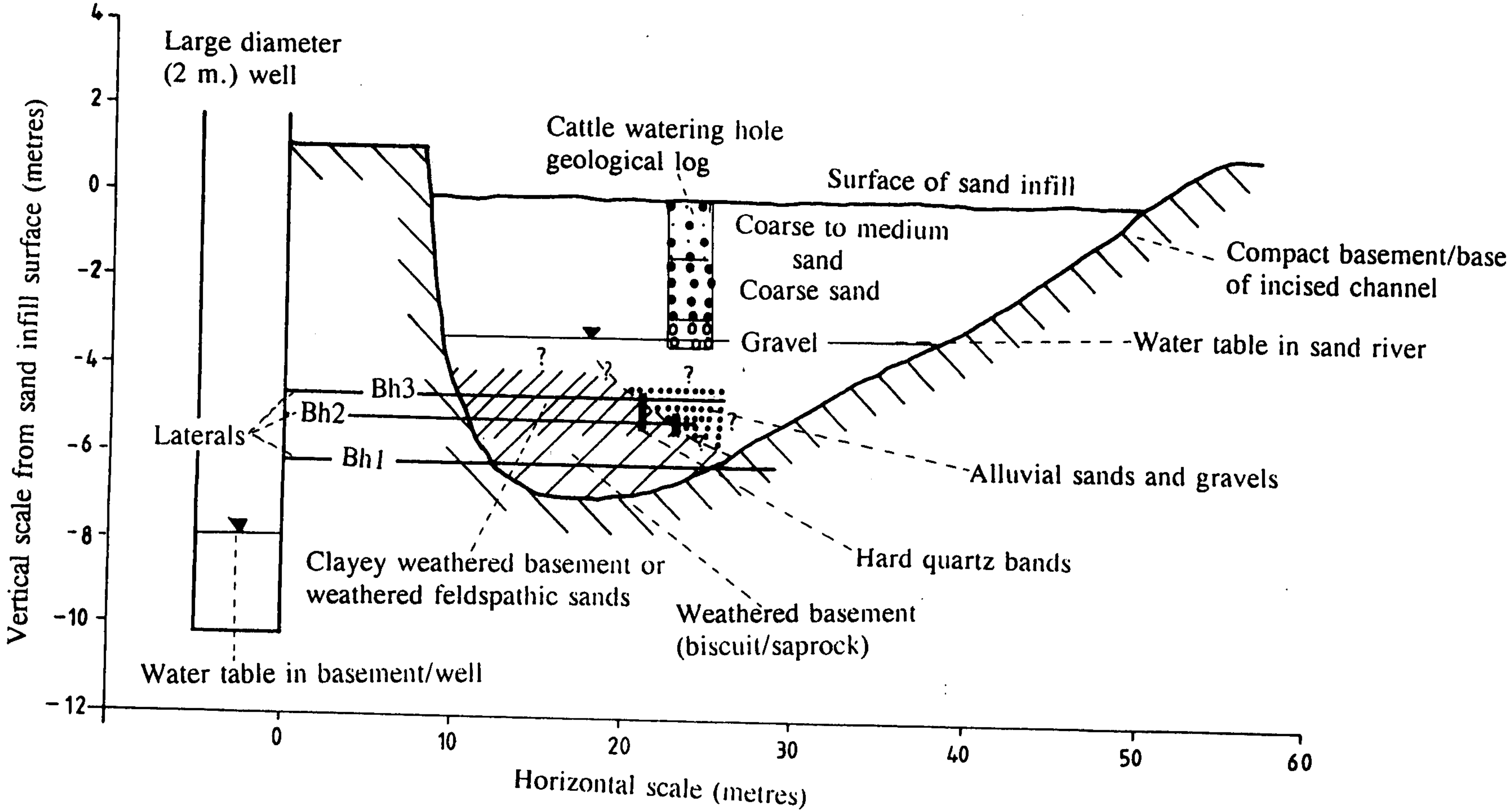


Figure 15 Drilling results at Masunga site A

this band unconsolidated alluvial gravels were encountered. Following drilling none of these boreholes produced water although drilled into the basal saturated zone. The driller advises that with this form of drilling this situation is not unusual, and that the boreholes will probably start to flow after several days. The compact clayey material is possibly either very weathered basement material or alluvial sands within which detrital feldspars have been weathered to kaolin type clay.

3.5 RELATED ISSUES

Potential pollution of the sand river groundwater resource may occur from the seepage/overflow of waste water from a sewage treatment plant newly erected midway between the two Masunga collector well sites (Fig. 16). The situation has been brought to the attention of the DWA who are taking necessary action.

4. Conclusions

The late delivery of drilling equipment and spares to Francistown resulted in delay in the execution of the planned programme.

4.1. Since neither the drilling nor the test pumping programme could be undertaken it was verbally agreed with DWA that Mr Peter Rastall would return to undertake these outstanding works. Proposals for his remaining inputs are presented below.

4.2. Due to the delay in drilling, as mentioned above, the activities of the hydrogeologist were restricted, however some alternative studies were undertaken. The results of these were discussed and proposals for a second phase of inputs, as verbally agreed with DWA, are presented below.

4.3. The groundwater system within sand rivers is now better understood as indicated by:-

The sedimentology of the unsaturated zone, as studied at Masunga, indicates a complex pattern of alluvial deposition by a sinuous, river constricted within an incised meandering channel. Grain size varies from silts to coarse sands and gravels.

The detailed nature of the basal saturated lay remains unclear. However flow through this layer towards the end of the dry season has been recognised at Masunga site A. This is an important indication for the long term sustainability of the system.

Depth of sand infill and channel configuration can be determined using geophysical methods such as seismic refraction and ground-penetrating-radar methods.

4.4. Drilling of laterals has commenced at the first site at Masunga A. The first results indicate that only part of a given channel defined by probing and geophysical techniques may contain unconsolidated alluvial sand infill. More detailed studies of the morphology of sand river channels is required.

Figure 16 Sewage water treatment plant located adjacent to the Tati River upstream of Masunga site B.

5. Proposals for continuation of the current drilling and test pumping programme

Mr Rastall should return to Botswana during January - February 1995 to undertake the drilling of the remaining collector well laterals, undertake pre-drilling short term pumping tests and post drilling long term tests. This programme will require the same DWA inputs as identified within the original TORs.

5.1 PROPOSALS FOR ADDITIONAL BGS WORK

Mr Davies should return to Botswana during the June - July period to develop a methodology for the assessment of the groundwater resources of sand rivers and their sustained, long term usage, based upon detailed studies at the Masunga site. To fully understand the nature of the groundwater resources of sand rivers there is a need to determine:-

1. The geological nature of the sand river infill and the surrounding basement strata, using results obtained from test well drilling and geophysical surveys.

2. The hydraulics of the sand river system and that of the surrounding basement strata, using data obtained from a series of piezometers installed within the sand infill and adjacent basement strata and the accurate levelling and monitoring of water levels.

3. The hydrogeology of the sand river system and its relationship with the underlying basement strata, through the use of data derived from short term and long term pumping tests, to determine the groundwater resources of the sand rivers.

Within the Masunga area a series of piezometer boreholes need to be installed within the channel sands of the Tati River at 100m intervals between the two collector wells to determine water table gradient variations with time. In addition a series of piezometer boreholes need to be installed within the basement strata adjacent to the river channel to determine interaction if any between the sand rivers and basement strata. Detailed samples of channel sands need to be collected with depth from the channels sands for grain size analysis and permeability determinations, especially from the basal saturated layer which is understood least of all. These sediment variations also need to be assessed across the river channel via three or four series of exploration boreholes drilled across the channel. These boreholes should be drilled by U100 coring or similar technique that permits the acquisition of sufficient sample material while permitting the boreholes to be equipped for use as piezometers. The drilling of these boreholes needs to be supervised by an experienced hydrogeologist who will also undertake the analysis of the sediment samples obtained.

It is anticipated that the drilling of the necessary piezometers will take at least two weeks following mobilisation of the necessary drilling equipment to site.

Seismic profiling along the river should indicate the nature and configuration of the channel bed.

A reference spot height needs to be created for the levelling of water level and piezometer reference heights for determination of river and basement aquifer water table gradients with time.
The detailed test pumping of the two collector well systems will need to be undertaken. Each programme of testing should include the use of multi-step tests, short term and long term constant discharge and recovery tests. Such a series of tests should take at least one week per site following

mobilisation of the necessary test pumping equipment to site.

Using the data produced from the above programme a methodology to assess the groundwater resources of sand rivers and their long term sustainability will be proposed.

These works will need to be undertaken during the June - July period after the rains when water levels have declined to those to be expected at the height of the dry season. A BGS hydrogeologist must be present to supervise works on site and undertake analysis of samples and data obtained.

Equipment and personnel requirements for the proposed project extensions would include the following elements.

5.2 BGS INPUTS REQUIRED

Objectives

1. To convert the remaining four wells sunk by DWA adjacent to sand rivers into collector wells by drilling two adits per well, from each well through the hard rock river bank into the base of the sand of the sand rivers to not more than 20m in length.

2. To determine the best method of horizontal drilling by using different drill strings.

3. To undertake short term pumping tests before and after installation of the laterals.

4. To undertake a detailed study of the geological, hydrological and hydrogeological nature of the Tati sand river between the Masunga collector well sites with the aim of developing a methodology for the assessment of the groundwater resources of sand rivers and their long term sustainable usage.

BGS will require payment for the following inputs

(a) Provision of horizontal drilling rig and transportation with crane

(b) Services of BGS driller at £150 per day + 10% handling charge for the duration of the work including remobilisation to Zimbabwe (c. five weeks work [or 35 days]

(c) Additional flat nosed disposable tips for moling

(d) Additional air fare for the driller Heathrow-Gaborone and return (ordinary) - at cost

NB: The driller would undertake the above works during the January-February 1995 period.

(e) Services of BGS hydrogeologist SSO
Five weeks Botswana (35 days), two weeks UK,
Preparation and writing up:
Salary with OH, Honorarium, subsistence
Travel; air fare Heathrow-Gaborone-Francistown and return (ordinary) - at cost.

NB: The services of the hydrogeologist would include: analysis of test pumping data produced by the driller, supervise the drilling of test and piezometer boreholes within the sand river and the adjacent basement, analysis of data and samples produced, carry out detailed pumping tests upon the two collector well systems, analysis of data, advise upon long term monitoring of these systems, produce methodology for the development of sand river systems.

(f) All running costs and repairs, and provision of necessary spares for the efficient operation of BGS/DWA equipment. The BGS driller will obtain receipts and submit these to BGS for subsequent billing of DWA.

(g) Equipment required for the monitoring of water levels and variations in water quality as required to undertake test pumping and associated works.

5.3 DWA INPUTS REQUIRED

(h) DWA to select mode of delivery of strings, spares etc by sea or air freight.

(i) DWA to ensure that temporary import certificate for BGS rig and lorry crane is kept up to date.

(j) DWA to provide a 100 psi, 220 cfm compressor (or two smaller)

(k) DWA to provide trained DWA drillers to assist in the drilling of laterals etc

(l) A test pumping unit, capable of extracting 2-10 l/sec against 20m head; this should be electrical, with integral generator sited on the surface and use a flexible delivery hose.

(m) DWA to provide a complete drilling unit with crawler rig and crew for the drilling of necessary test and piezometer boreholes (24 - 30 number to 15m maximum depth). These holes need to be drilled at a diameter of at least 4" within the sand infill to ensure that sufficient material is obtained for grain size analysis especially from the basal saturated zone. Necessary 2" and 4" pvc screens and casings to be provided by DWA.

(n) DWA to provide necessary 4x4 transport and site accommodation for the hydrogeologist

(o) DWA to provide equipment for grain size analysis of sediment samples.

5.4 TIMING

Mr P Rastall has been verbally requested to return to Botswana during mid January to continue the drilling and testing of the remaining four collector well systems.

Mr J Davies has been verbally requested to undertake detailed studies of the sand river system at Masunga during June-July 1995.

6. Provisional recommendations of monitoring system to estimate the sustainability of collector wells

1. The morphology of sand river channels is more complex than first thought. Therefore detailed investigations should be undertaken of the morphology of typical sand river channels, including weathering patterns within the underlying basement strata and the nature of the channel infill sediments including age of deposition.

2. The tracer method of determining the presence of groundwater flow within the saturated basal zone was successfully demonstrated. Additional monitoring boreholes need to be installed to permit verification of the method and assess variation of flow across a given channel.

3. Long term monitoring of water levels within a sand river channel and the underlying basement aquifer system need to be undertaken to recognise the presence of any interaction between the two aquifer systems during the year. Rates of flow along sand rivers during periods of flood need to be assessed especially during the upper coarse grained, dry season unsaturated zone.

4. The impact upon open linear fault structures passing beneath sand river channels upon inter aquifer flow needs to be determined. The well at Masunga site B has apparently been constructed into such a structure.

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Acknowledgements

Mr Signorelli, Mr Carlson and Mr Hagstrom are thanked for their stimulating discussions and kind assistance. The DWA drilling crews in north east Botswana and the DWA staff at Francistown proved to be most helpfull to the progress of the project.

Appendix A

TERMS OF REFERENCE

Programme of Work

Objectives

1. To convert the five wells (three completed, two being located) being sunk by DWA adjacent to sand rivers into collector wells by drilling two adits per well, from each well through the hard rock river bank into the base of the sand of the sand rivers to not more than 20m length.

2. To determine the best method of horizontal drilling by using different drill strings

3. Services of a hydrogeologist: to review all existing data on sand river behaviour, carry out pumping tests on collector wells, best estimate of sustainability of yields and recommendation of monitoring system to refine above.

Inputs required of DWA

DWA to provide a temporary import certificate for BGS rig and lorry-crane.

DWA to provide a 100 psi, 220 cfm compressor (or two smaller).

Ideally same labour force as for Borolong site including assistance from trained DWA drillers.

A pump testing unit, capable of extracting 2-10 l/sec 20m head; this could be electrical, driven by generator sited on surface and use a flexible delivery hose.

Appendix B

DIARY

November

23rd Departed from London (Heathrow) on flight BA057 to Gaborone.

24th Arrived at Gaborone at 11.30 am where met Mr G Signorelli of the Department of Water Affairs (DWA) and collected Avis hire car. To the new DWA headquarters building where discussed work programme and status of imported equipment with Messers Signorelli and Carlson. Also met the head of the Groundwater Unit, Mr Kari. Informed that drilling equipment had been cleared through customs and was being transported to Francistown DWA. Looked at available reports on sand rivers, including Wikner (1980) and Nord (1985), as well as volumes 5 and 6 of the Water Master Plan for Botswana, describing hydrogeology and hydrology respectively. Informed by Mr Signorelli that he would be on leave during the next week and that he would return to the office on 5th December. Also met Mr Hagstrom, in charge of a rapidly declining DWA drilling facility. Met Mr J Farr at the offices of Wellfield Consultants for an informal discussion.

25th Visited the headquarters of the Botswana Geological Survey where met the Director, Mr Mchacha. Discussed the geology of the north-eastern are of Botswana with Dr Key, and the hydrogeology of that area with Ms Hargreaves. Collected copies of relevant maps and reports. Discussed the Maun groundwater study of DWA with Dr Key and Ms Hargreaves, studied a draft of the contract document. Returned to Gaborone from where flew on Air Botswana flight BP57 to Francistown. Met at Francistown by Mr P Rastall and driven to the Marang Hotel.

26th Undertook a cursory study of the Tati sand river adjacent to the hotel. To Francistown DWA where collected hammer seismic equipment from the back of the 4x4 drilling unit truck. Drove to the collector well site at Mathangwane where informed by Douglas, of the siting/well sinking team TA, that the well was not yet completed due to a boulder at depth and this remained to be cleared using explosives. Sorted out hammer seismic equipment and undertook a test profile across the sand river. Drove to a drill camp adjacent to Sebina to view a crawler mounted Atlas Copco drilling rig, used to drill boreholes within sand rivers. The large compressor used to supply air to this rig will be supplied by DWA to power the collector well drilling system, even though it proved to be of too large a capacity for the efficient use of that system last time. Drove on to Masunga where visited two collector well drilling sites, noting alluvial sand sediment structures exposed in a cattle watering point excavated into the bed of the sand river at the first site. Returned to Francistown via Tshesebe. Purchased necessary adaptor plugs and batteries. Undertook analysis of seismic data.

27th Drove to Selebi-Pikwe, the nearest large town to the Tobane collector well drilling site, located more than 200 km south of Francistown. Assessed the availability of accommodation at Selebi-Pikwe. Viewed leakage of toxic materials from the base of the slimes dams from the local copper-nickel mine, and the nature of the nearby Motloutse Sand River. Attempted to drive to Tobane along the river but forced to return to Selebi-Pikwe by a punctured tyre. Returned to Francistown.

28th Drove to Masunga, 2 hours drive from Francistown in old BGS landrover that has done well over 300,000 miles. Undertook hammer seismic traverse at first site (A). Undertook prolonged analysis of this data at Phil's Inn Bar using small generator to power the printer unit, as rechargeable batteries are u/s. Drove along river to site B, about 1 km down stream of site A. En route noted a large sandpit excavated into the bed of the sand river to supply raw materials for the construction of an adjacent secondary school, being undertaken with Chinese aid. At site B undertook a second hammer seismic profile, the sunny weather being VERY HOT at >40 degrees C in the shade - but no shade! Returned to the sand pit where took photographs of the sedimentary structures displayed within the 3.5m deep section through a sand river down to the saturated zone. Noted sewage settlement/evaporation pond constructed by the Chinese as part of the secondary school infrastructure located adjacent to the Tati Sand River midway between the two collector well sites. Returned to Francistown where reconfirmed return flight to Gaborone with Air Botswana. Undertook analysis of seismic data.

29th Suffered second puncture on landrover therefore obtained a replacement set of tyres. Sorted through three drilling equipment packages, of which two were OK but the third was found to contain a white, four burner, low pressure gas cooker. Obviously the contents of this package had not been checked by customs, the clearing agent nor the Department of Water Affairs stores on arrival in Gaborone! Without the necessary package of spares and temporary drill pipe drilling could not be started. Contacted Demco and DWA about missing package. Visited the old collector well sites at Borolong and Chidibe, where these systems still await equipping. Returned to Francistown past an old mine dump where cyanide leaching of gold from old dump material was being undertaken. Discussed the use of ground and down hole radar systems with team undertaking a survey of old mine workings beneath the newly completed Francistown Hospital complex. They promised to supply the results of a test survey of the sand deposits within the Tati River adjacent to the hotel.

30th Missing package of drilling equipment had been located by DWA but awaited clearance from customs. Yet another puncture! Took 2" perforated pipe and 0.5" drill pipe to the Masunga site A. Obtained sediment samples from the 3.5m deep pit adjacent to the site. Jetted in 2m of perforated steel pipe into the bottom of the pit into the saturated zone. This operation took about 10 seconds, the time it took for the wiring on the large compressor to short and burn out! Monitored the dissolution of a salt solution placed within the borehole for one and a half hours. The temperature in the sand pit was $>>40^o$ degrees at midday. Douglas to Gaborone to obtain dynamic probing data from the first three sites and a nest of test sieves for grain size analysis. Returned to Francistown in search of a small compressor. Informed Shell Hagstrom of problems experienced with the compressor, who will send a mechanic as soon as possible. Fairly heavy rainfall experienced during the day.

December

1st Discussed the lack of a compressor and clearance of the missing package of drilling equipment with Leif Carlson and Shell Hargstrom of DWA Gaborone. Travelled to Masunga through heavy rain between Francistown and Tshesebe, however no rainfall had occurred at Masunga. Logged two faces within the main sand pit and obtained a series of 13 sediment samples for grain size analysis and two peat samples for age dating. Undertook a seismic profile along the floor of the sand pit. Returned to Francistown to sort out pipe fittings at DWA and undertake analysis of seismic data.

2nd Loaded equipment at DWA Francistown and transported drilling equipment to site at Masunga. Still no mechanic at site. Returned to Francistown.

3rd Drove to Masunga where met the DWA driller at site A. Obtained the services of two labourers and undertook two seismic profiles, one at site A and the other at site B. Returned to Francistown where undertook analysis of seismic data.

4th Power cut for most of the day. Printed out seismic analyses.

5th Discussed progress with Mr Signorelli at DWA Gaborone. To DWA where tried to obtain the use of a balance for grain size analysis. Drove to Masunga where met the TA in charge of the siting team. Obtained a set of sieves minus the base pan. Undertook two longitudinal seismic profiles, one at site A and the other at site B. Returned to Francistown to continue analysis of seismic data.

6th Store seismic equipment at the DWA Francistown stores. Obtained the use of a triple beam balance. Undertook the grain size analysis of 14 sediment samples at the Marang Hotel.

7th Drove to Masunga where observed the drilling rig being erected within the site A well. Undertook analysis of two sediment samples. Drilling of first lateral begun, reached a depth of 5m when drilling halted for the day. Well had been pumped dry by 07-30, the water table returning to its original level by 13-30. Determined the depth location of the drilling rig within site B. Returned sieves to Douglas and drove back to DWA to return beam balance. Completed packing of bags, checked out of hotel and flew on flight BP51 to Gaborone.

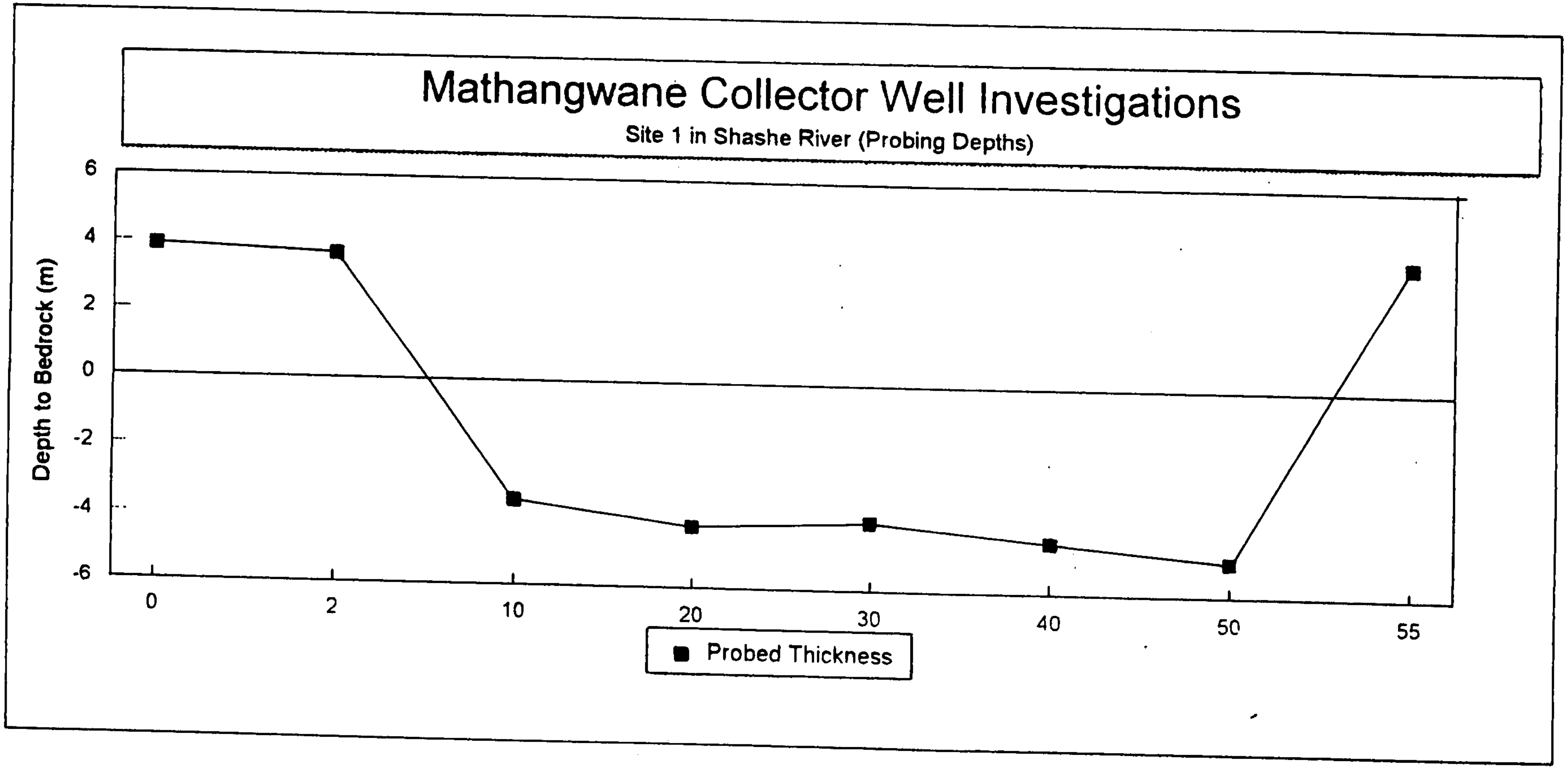
8th Held discussions with Mr Farr of Wellfield Consultants before driving to DWA where discussed results and proposals for future works with Mr Signorelli and Mr Kari, head of the ground water branch. Prepared a short note on items discussed. Met Mr Cheney with whom discussed the main results of the Macheng project before being taken to Gaborone airport where boarded flight BA056 to London Heathrow.

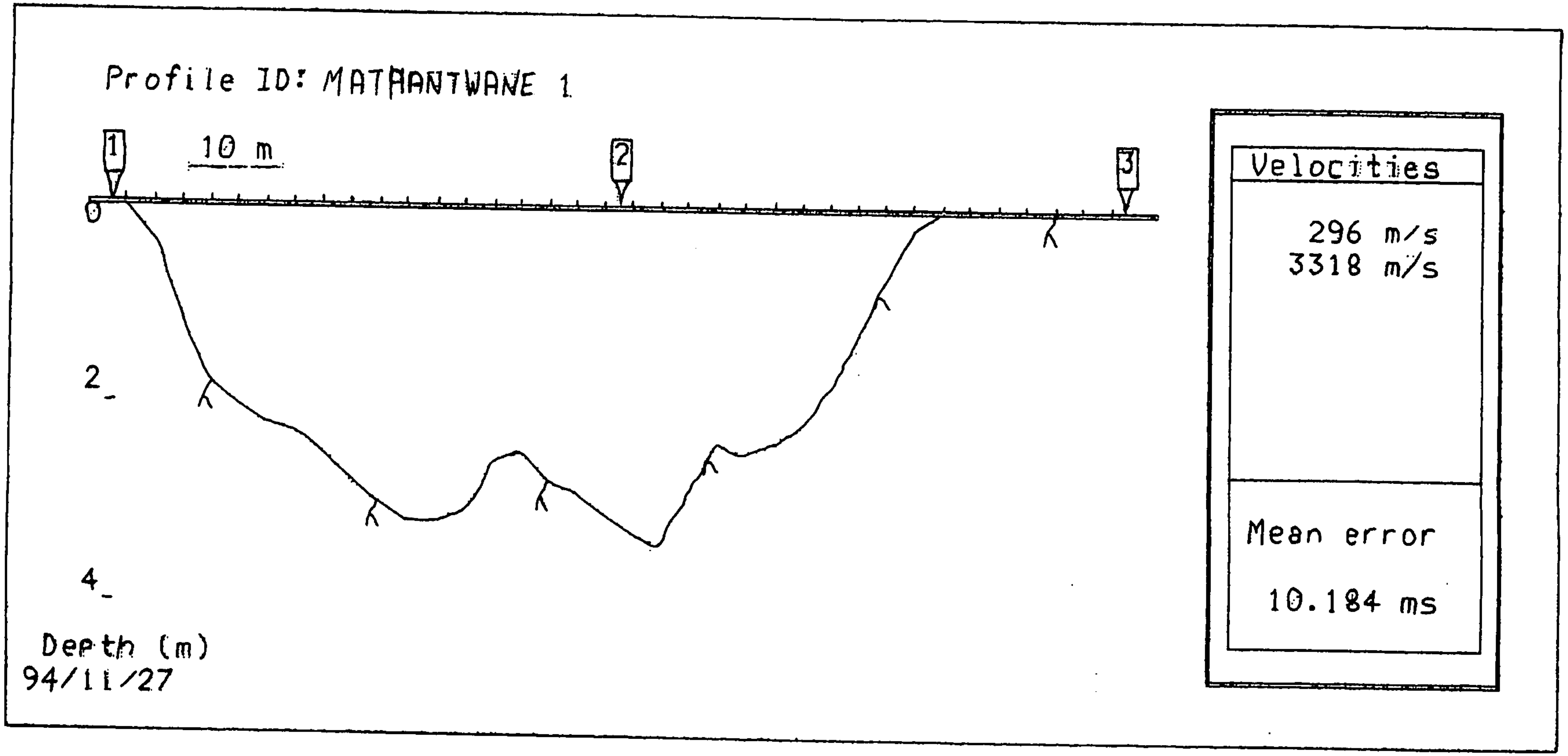
9th Arrived at London Heathrow at 05-25.

Appendix C

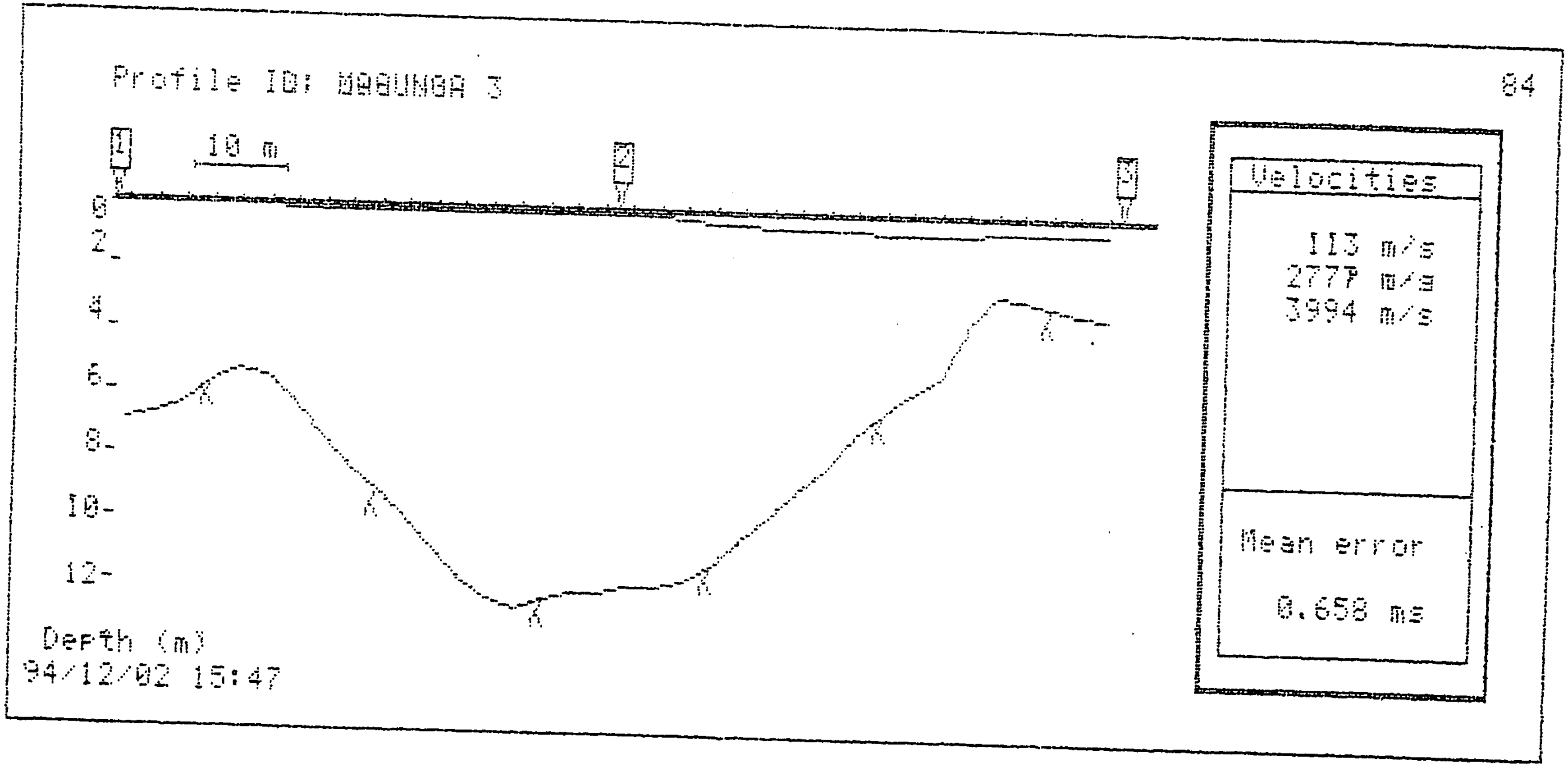
Results of Dynamic Probing Surveys and Hammer Seismic Traverses

Cross section Distance	Probed Depth
0	3.9
2	3.7
10	-3.5
20	-4.2
30	-4
40	-4.5
50	-5
55	3.8





Profile ID: MATAANTWANE 1
10 m
1
2
3
0
2
4
Depth (m)
94/11/27
Velocities
296 m/s
3318 m/s
Mean error
10.184 ms

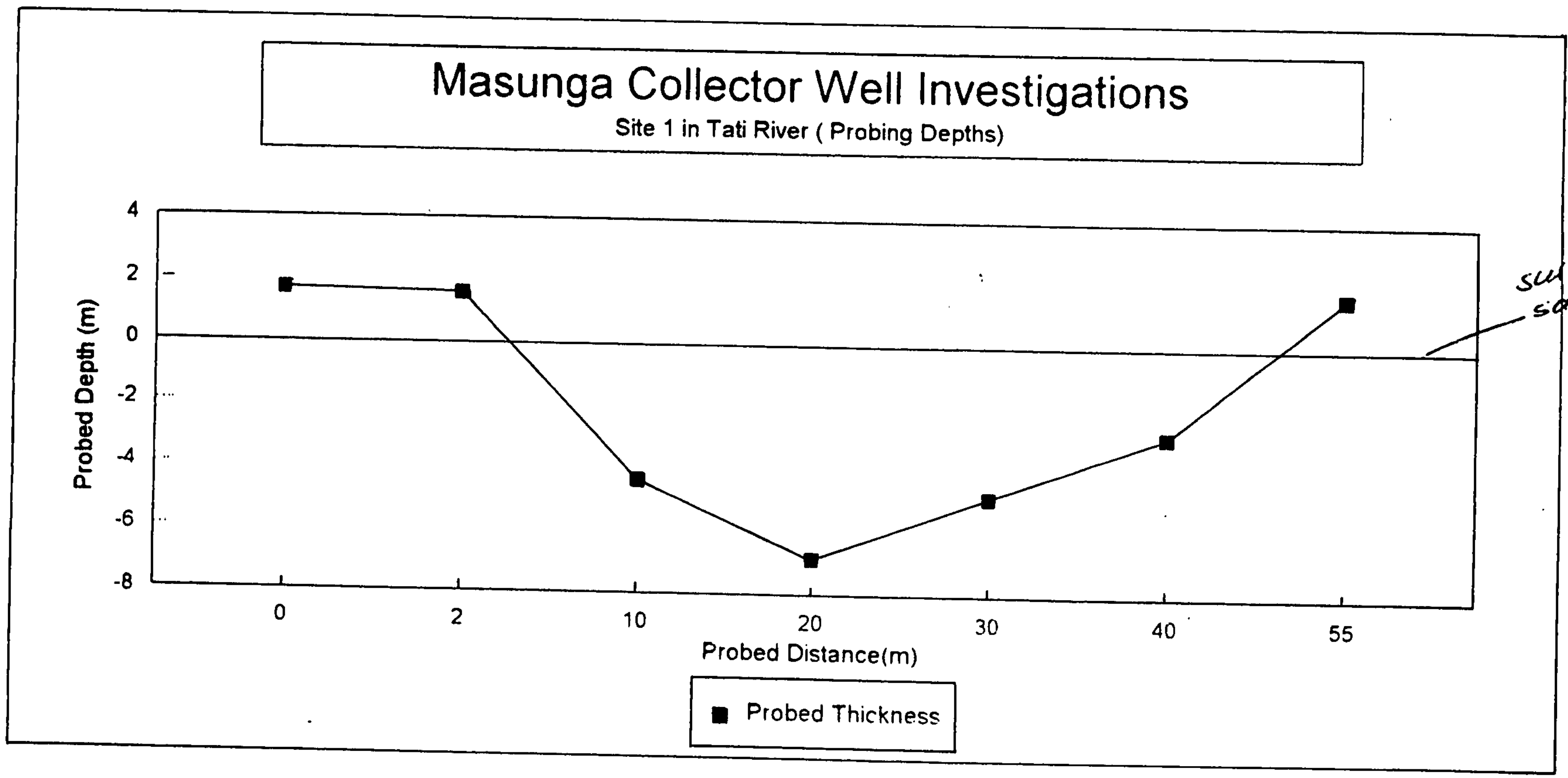


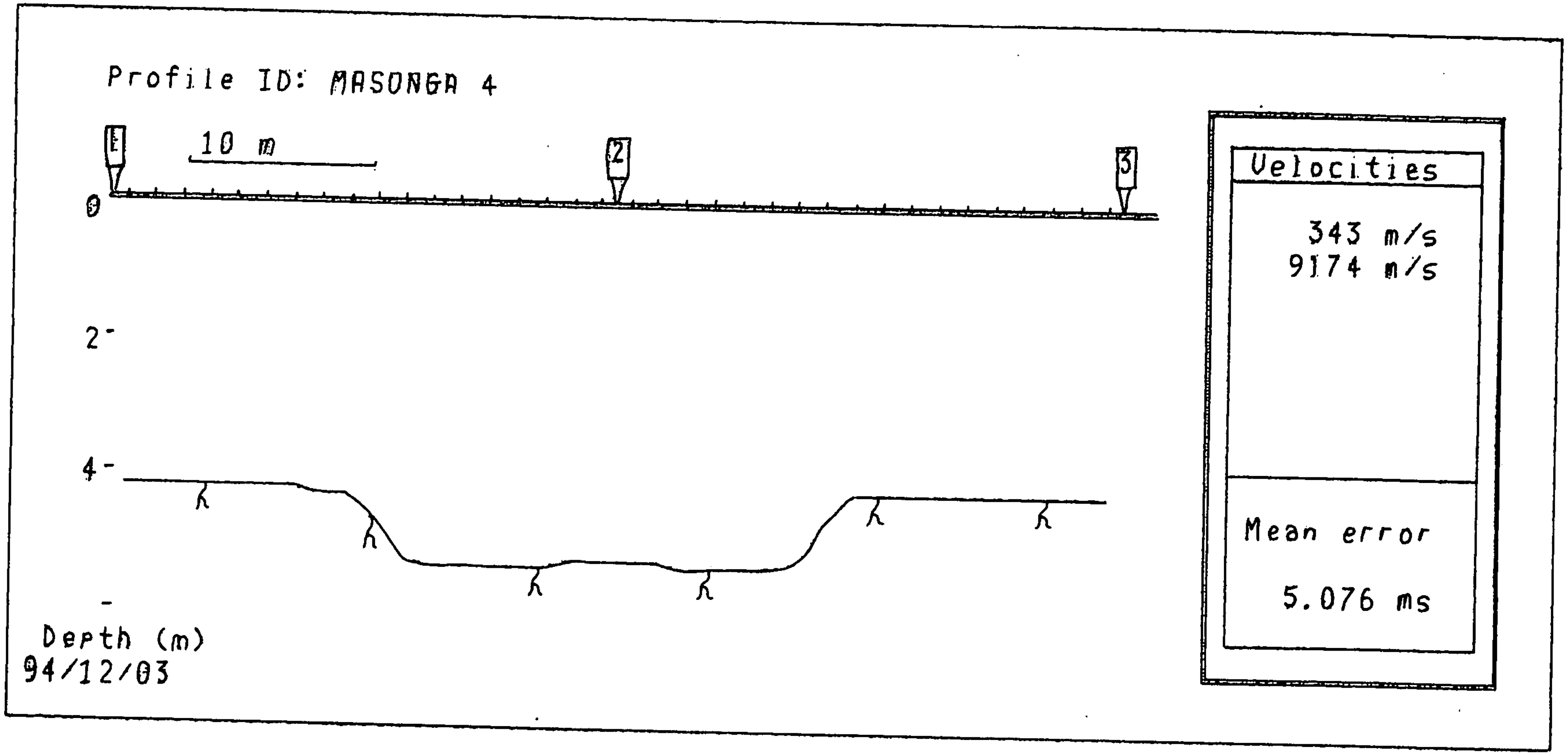
Profile ID: WABUNGA 3
84
1
10 m
2
3
0
2
4
6
8
10
12
Depth (m)
94/12/02 15:47
Velocities
113 m/s
2777 m/s
3994 m/s
Mean error
0.658 ms

X-secton Distance	Probed Depth
0	1.69
2	1.6
10	-4.4
20	-6.9
30	-4.9
40	-2.9
55	1.68

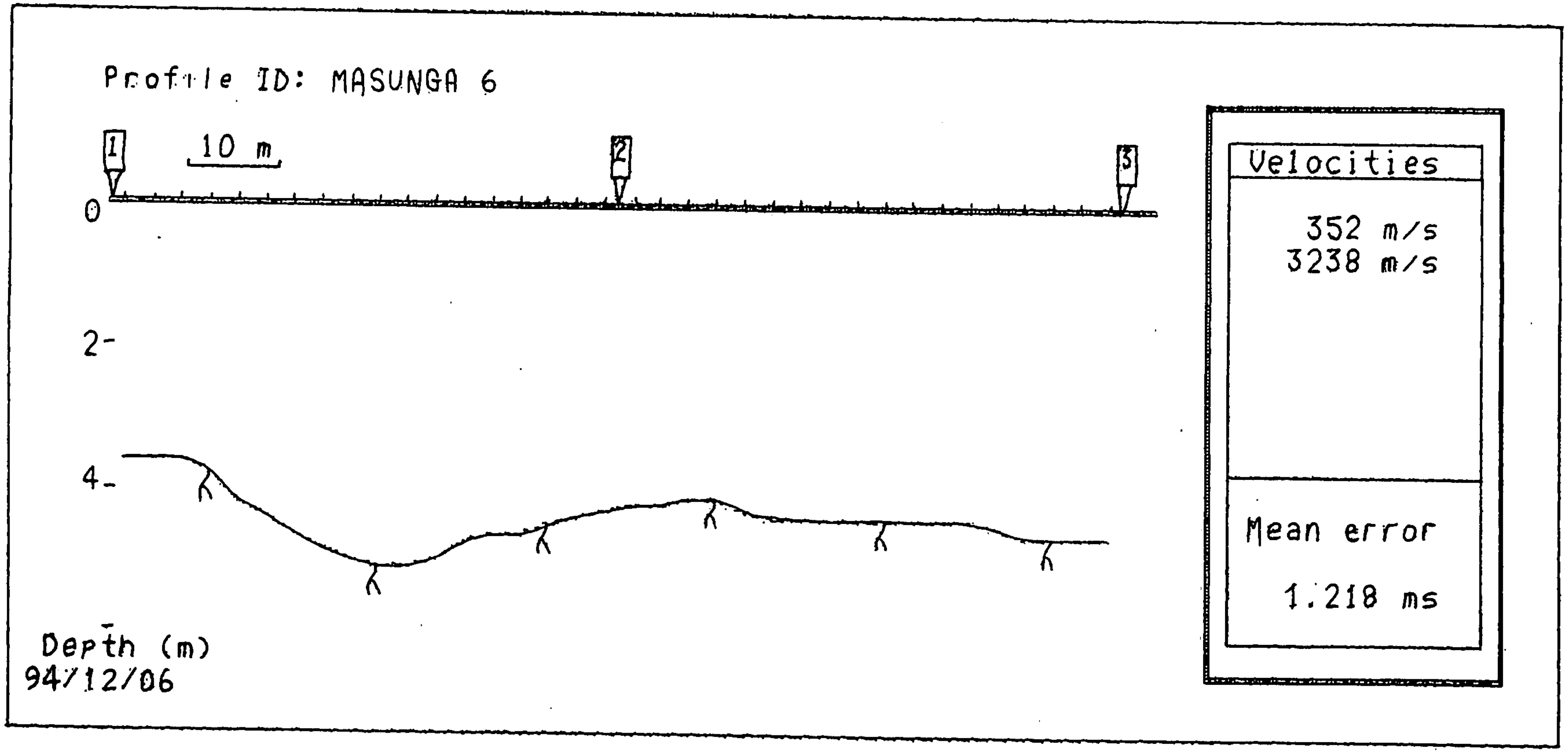
-ve figures indicate probed depth below surface of sand.

ie -4.4 shows that probed depth is 4.4m below surface of sand.

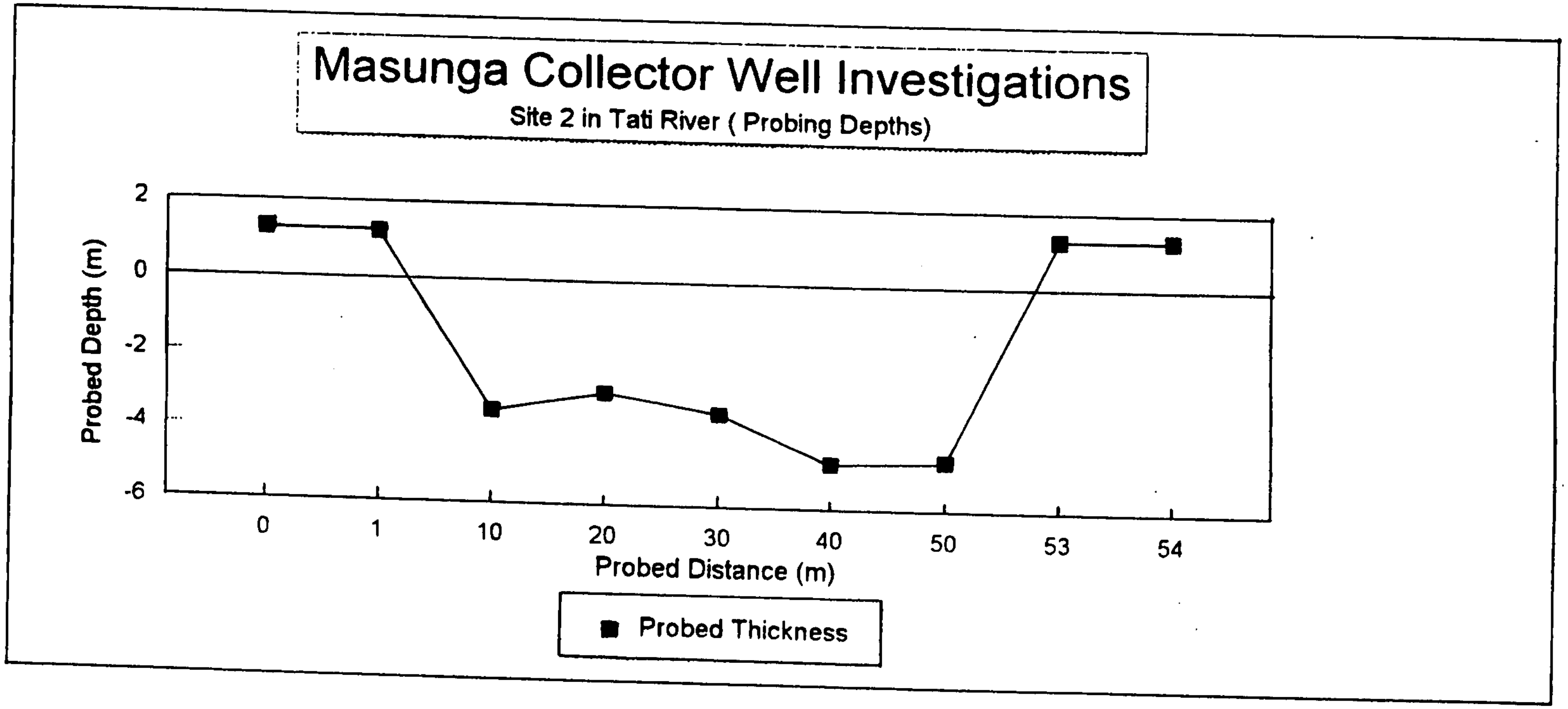


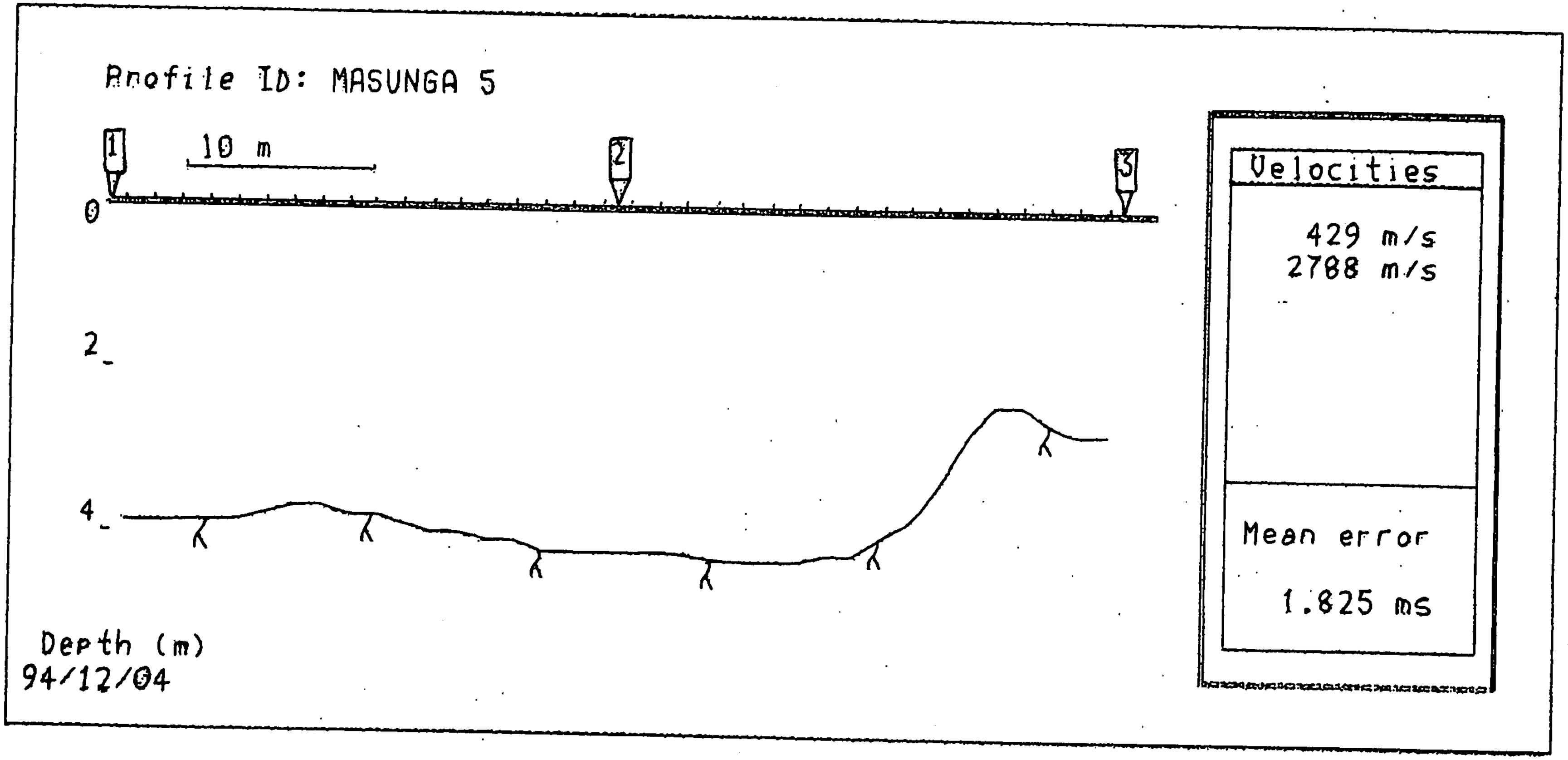


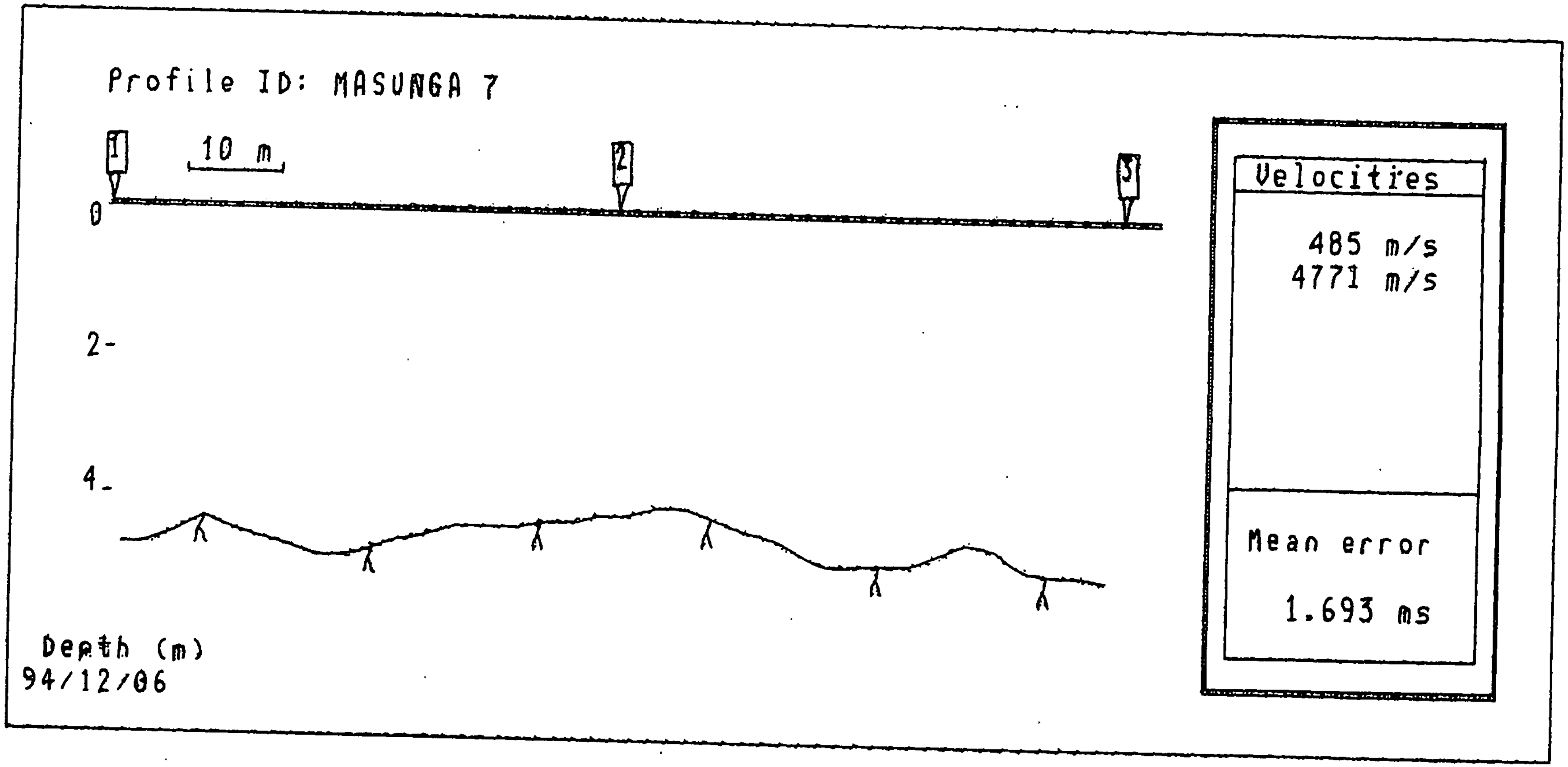
Profile ID: MASONGA 4
10 m
1
2
3
0
2
4
Depth (m)
94/12/03
Velocities
343 m/s
9174 m/s
Mean error
5.076 ms


Profile ID: MASUNGA 6
10 m
1
2
3
0
2
4
Depth (m)
94/12/06
Velocities
352 m/s
3238 m/s
Mean error
1.218 ms

X-section Distance	Probed Depth
0	1.27
1	1.2
10	-3.5
20	-3
30	-3.5
40	-4.8
50	-4.7
53	1.28
54	1.3




Profile ID: MASUNGA 5
10 m
1
2
3
0
2
4
Depth (m)
94/12/04
Velocities
429 m/s
2788 m/s
Mean error
1.825 ms



Profile ID: MASUNGA 7
10 m
1
2
3
0
2-
4-
Depth (m)
94/12/06
Velocities
485 m/s
4771 m/s
Mean error
1.693 ms

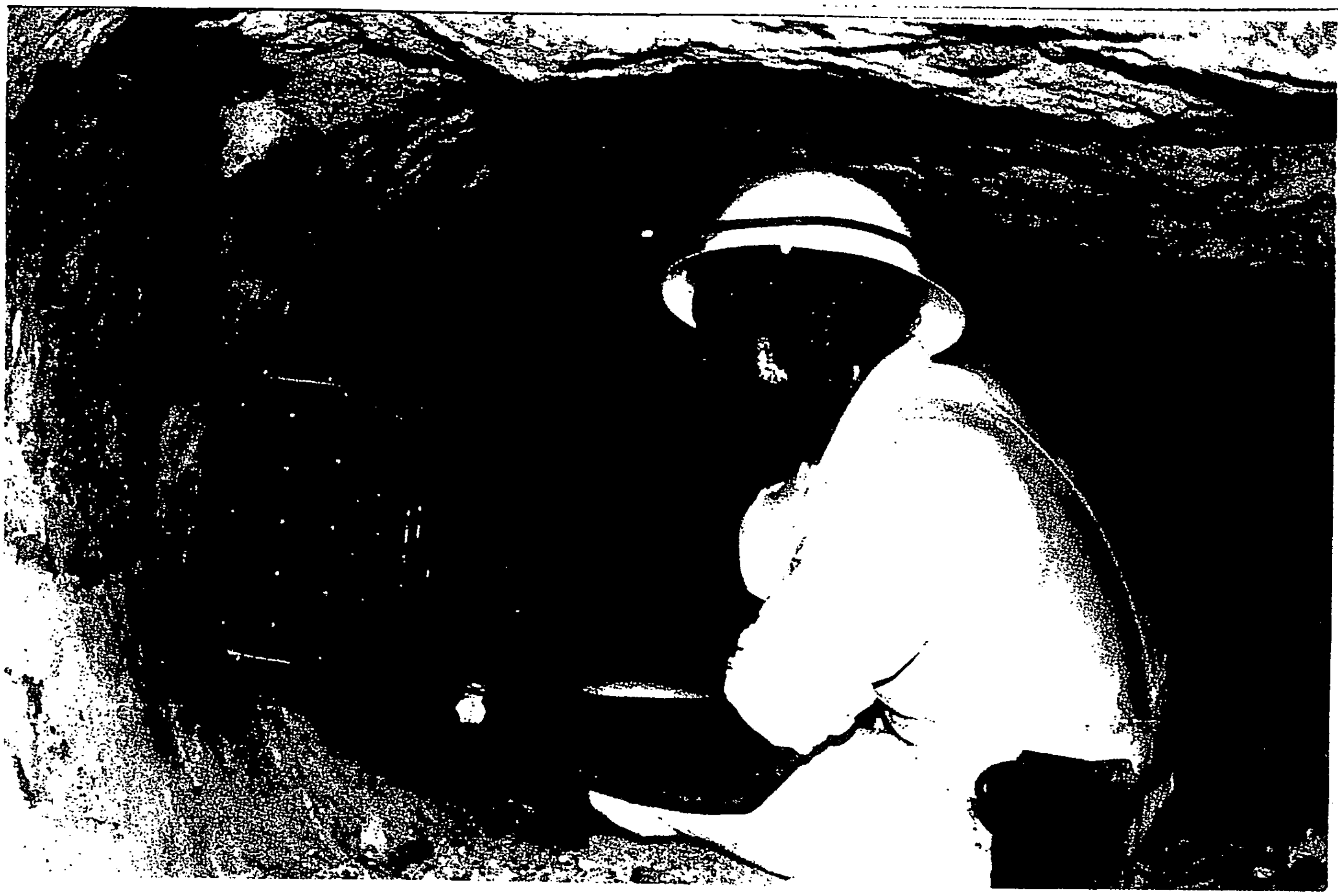
Appendix D

Ground-penetrating-radar (GPR) - details of method and results

Mining
Technology

CSIR

Rolf Frankenhauser



GROUND PENETRATING RADAR FOR MINING

Mining Technology

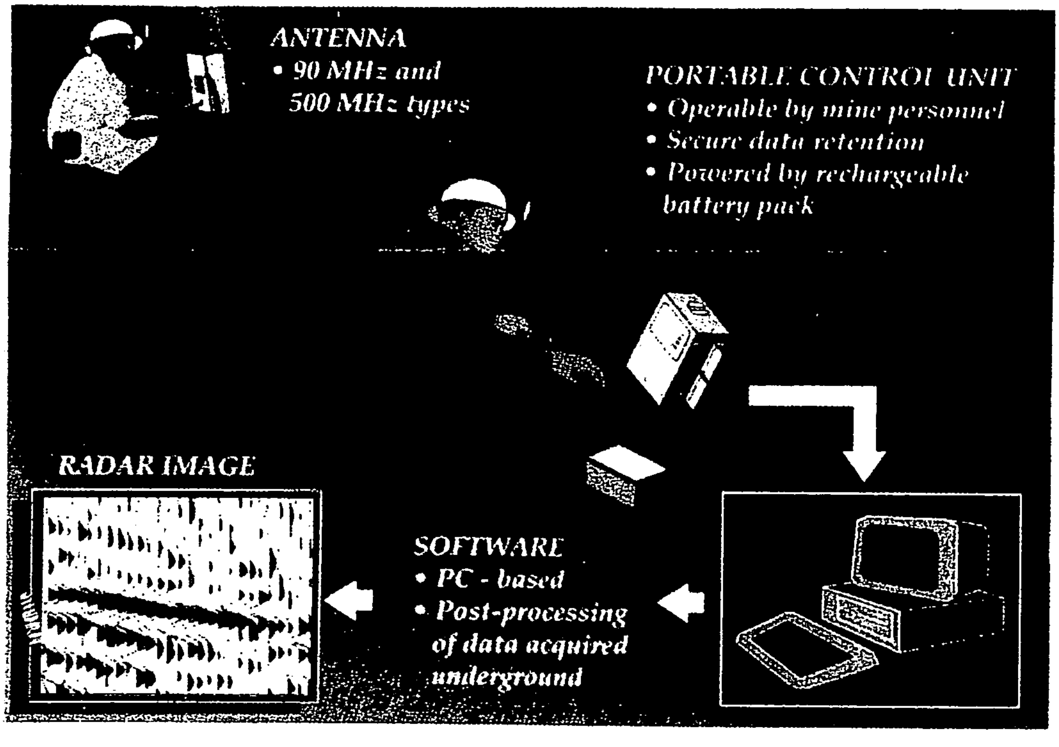
CSIR

Ground Penetrating Radar (GPR) is a geophysical technique used for shallow subsurface profiling which has recently gained acceptance in the mining industry. As a rapid and non-destructive technique, it provides continuous and high resolution images of up to 50 m ahead of mining operations.
GPR assists in day-to-day mining decisions by providing advance knowledge of:

- hazardous features such as faults and dykes, water fissures and rock fracturing,
- general stratigraphy,
- ore body geometry.

OPERATION

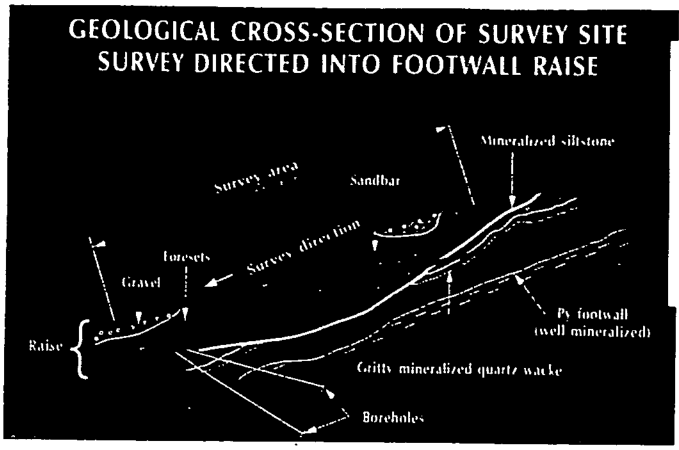
The electromagnetic equivalent to seismic exploration techniques, GPR is a high resolution geophysical method in which high frequency electro magnetic pulses are transmitted into the ground via an antenna. The antenna is moved over the ground or along a rockface, enabling data to be collected rapidly and large areas to be effectively profiled in a short period of time. Data is stored in the internal memory for down loading to a PC, and can be processed within a few hours.

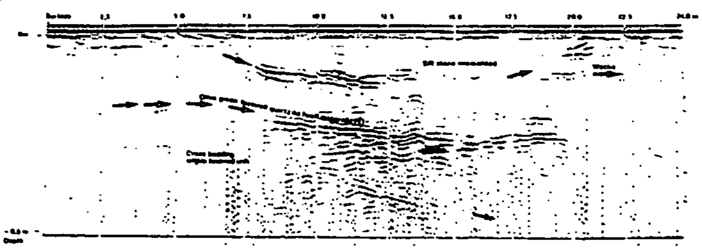


As with any geophysical technique, the performance of GPR is environment specific, with the technique providing excellent results given favourable electrical properties of the host medium and target. It is therefore important to have an adequate advance knowledge of the electrical properties of the geological materials in the target area, and to select the appropriate antenna frequency and other survey parameters.

There is also a trade-off between operating range and resolution (ie the accuracy with which a geological feature can be mapped), ie the lower the range the higher the resolution achieved.

APPLICATIONS (continued)

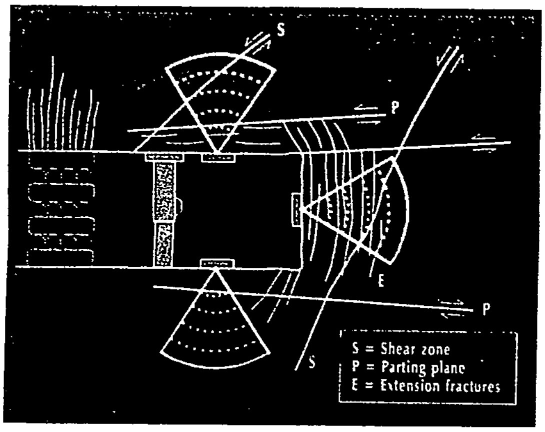


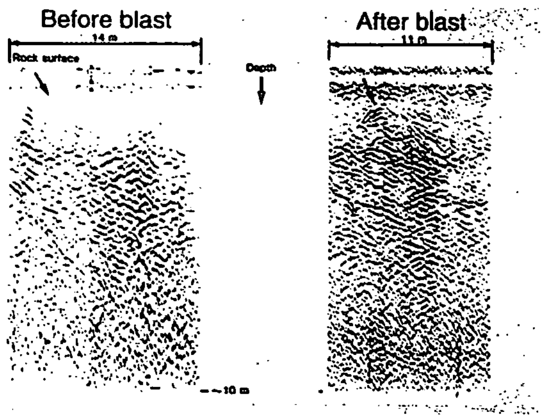


- **Delineation of gold bearing sediments.**

The cross-section of a sedimentological sequence, as mapped from a raise (red outline), of a South African gold mine combined with geological information obtained from two boreholes directed into the footwall of the raise identified: a gold bearing pyrite containing siltstone (white), a mineralized quartz-wacke (red) subcropping against the siltstone and, deeper in the footwall, pyritic grit bands.

The radargram clearly identifies the siltstone, particularly an area of high pyrite mineralization and the well-mineralized cross-bedded pyritic grit bands deeper in the footwall of the raise. Probing depth 8 m, length 23 m.

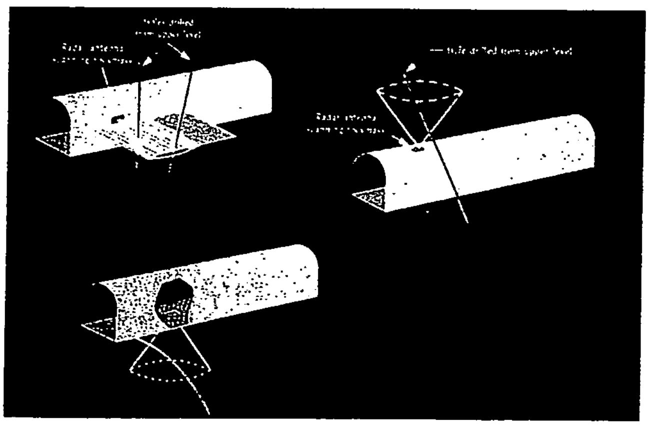


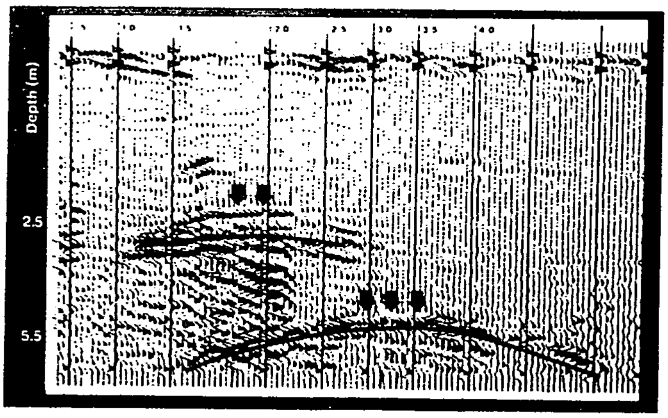


- **Rock fracturing and faulting.**

The schematic shows various applications of GPR to identify and map rock fracturing, shear zones and parting planes.

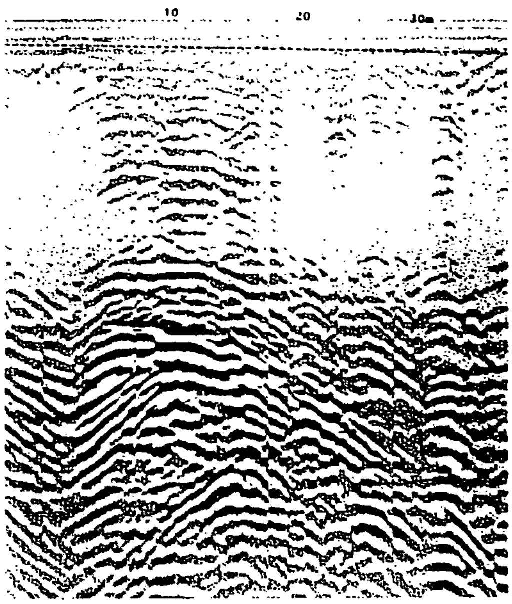
The radargrams depict rock fracturing ahead of a stope face before and after preconditioning blasting. The preconditioning technique uses controlled blasting ahead of the face in short boreholes to fracture and stress relieve rock. It can be seen from the radargrams that the rock fracture conditions have changed showing increased fracturing after the blast. Probing depth 10 m



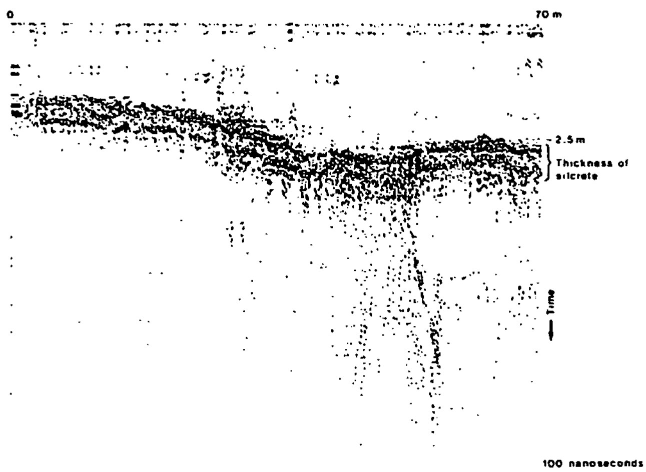


- **Locating off-line boreholes.**

GPR is a fast and cost-effective technique to locate boreholes which are off-line. Several potential GPR-survey configurations are shown in the schematic. The radargram identifies the position of the two off-line boreholes shown in the top left drawing of the schematic.



• **Cavity profiling.** The 40 m long radar profile shows a signature derived from a known cavity in dolomitic rocks. The cavity is located at a depth of approximately 10 m.



• **Overburden profiling.**
Many applications have been identified where GPR can be used to map overburden thicknesses and assess geological horizons of potential economic value. The radargram shows a 70 m long profile acquired next to an open pit where silcrete is mined for road-building purposes. Using GPR, the extent of the deposit as well as overburden thickness variations could be established in this application.

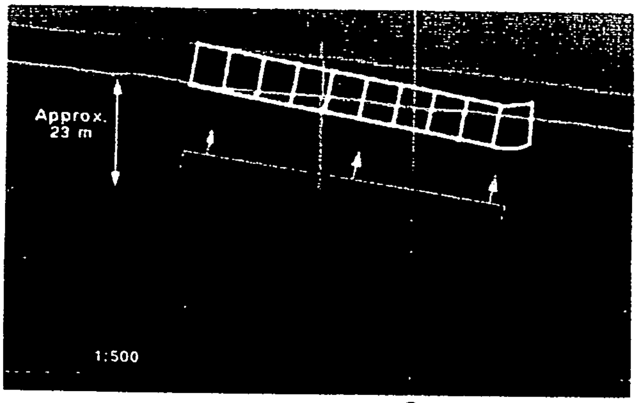
GENERAL PRINCIPLE OF GPR

In a typical impulse GPR system, a transmitter generates short pulses that are radiated into the ground via a broadband antenna. Dielectric interfaces in the subsurface cause a fraction of the pulse energy to be reflected, which is detected by the receiving antenna as a voltage-time transient waveform. In the usual operating mode the antenna is moved over the ground, resulting in a continuous profile.

The GPR control unit triggers the transmit pulses and processes the received reflection signals so that they can be displayed and/or recorded. The upper frequency in the reflected signal is determined mostly by the pulse width and can vary over the approximate range 10 MHz to 1 GHz. The amplitude of the reflections attenuates rapidly with depth of penetration: this effect is compensated for by time varying gain in the receiver. The duration over which "targets" are detectable in the received signal varies from tens of nanoseconds to a few microseconds and determines the maximum achievable depth of penetration. Because the reflectors in the ground are static, most GPR systems record complete signals by using a transmit pulse repetition and receive signal sampling technique, rather than in real time. Pulse repetition intervals are of the order of tens of microseconds, and complete signals are acquired in milliseconds. The control unit allows the operator to adjust parameters such as range gain, filtering, signal duration and acquisition rate.

After recording, radar profiles are post processed on a computer in an analogous way to seismic profiles, although usually by smaller and less complex sets of steps. The result is a two dimensional electrical image of the subsurface that can be interpreted in combination with background geological information.

APPLICATIONS



→ *Survey direction* → *Survey direction*

- **Delineation and mapping of dykes.**

A common geological feature in all mining environments, dykes can lead to rockbursts and falls of grounds.The radargram depicts a dyke over a distance of more than 20 m. The extract of the mine plan shows the position of the dyke as extrapolated from a borehole intersection and as mapped with GPR (white).

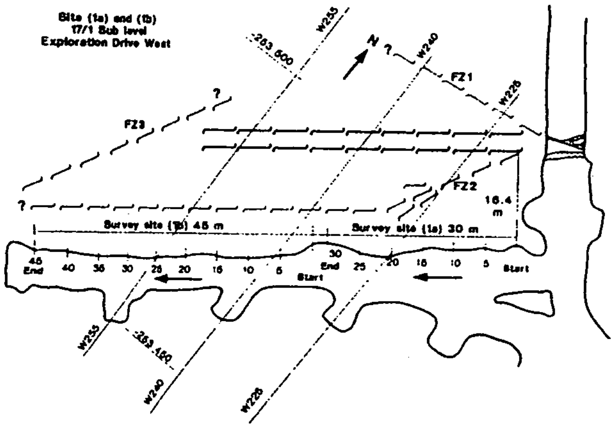
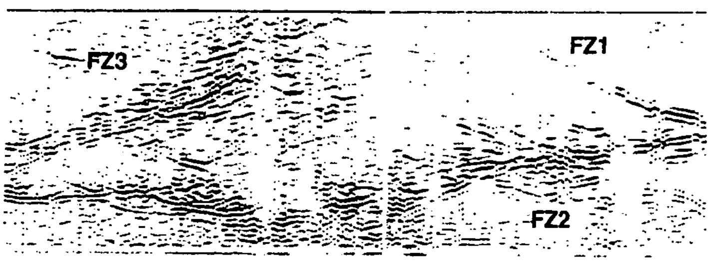


Figure 1 Extract from map. Radar anomalies are shown in red

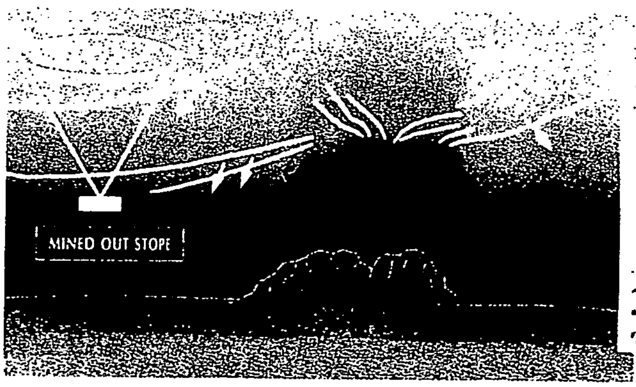


← *Start*

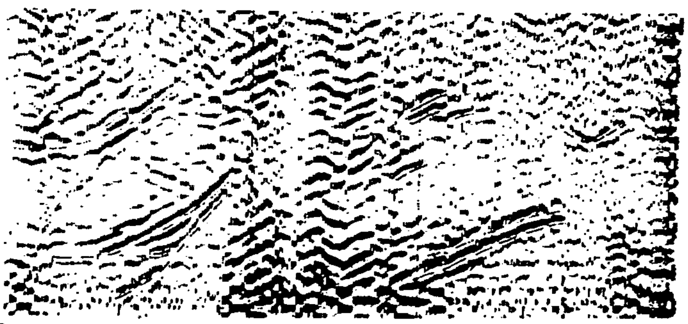
- **Locating water bearing faults and fissures.**

The mine plan extract shows a water-bearing zone that had been intersected in the tunnel mined towards the north-west. The geological extrapolation of the continuation of the structure is shown in black while the fault zones, referred to as FZ1, FZ2 and FZ3, delineated by GPR are shown in red. The radargram shows strong reflections from the water-bearing fault zones. The reflections also indicate splaying as well as swelling and thinning of the fault-zones.

→ *Survey direction*



→ *Survey direction*



- **Hangingwall and horizon control.**

GPR can be used to characterize hangingwall conditions. The illustrated application shows a radargram depicting loose rock slabs in the vicinity of a fall of ground.

GROUND PENETRATING RADAR

Since the 1970s, GPR has been used extensively in solving a wide variety of mainly civil engineering problems, some of which were closely related to the mining industry such as delineating geological discontinuities and sedimentological structures, mapping and assessing fracture zones in potential nuclear waste disposal sites, and searching for mineralization in rock.

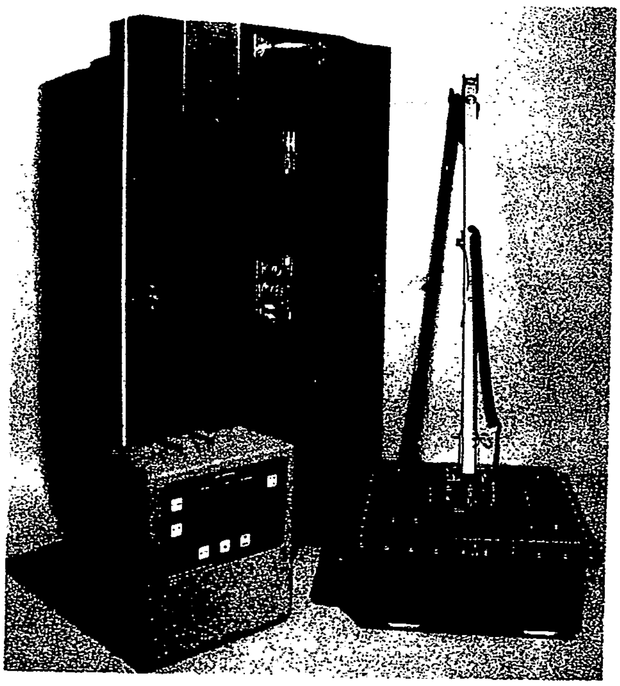
In 1988, CSIR's Mining Technology Division (Miningtek), formerly COMRO, initiated preliminary investigations on behalf of the mining industry into the applicability of GPR in South African mines. These studies indicated that GPR could also be a valuable aid in solving important geological and rock engineering problems. The scope of this initiative was thus expanded, with the emphasis on testing and implementing specific applications for GPR.

Through these activities, Miningtek has established an excellent reputation for the in-mine application of GPR, and offers the following services:

- **electrical properties characterization via laboratory measurements, to determine the applicability of GPR in specific geological environments**
- **feasibility and pilot studies**
- **routine GPR surveys and data interpretation**

In addition, dedicated hardware and software have been developed specifically for the in-mine application of GPR:

- **A mineworthy GPR system, the SIR-2M, has been developed by Geophysical Survey Systems Incorporated (GSSI), in collaboration with Miningtek, and jointly funded by the South African mining industry. The system, together with a standard GSSI software package, will be commercially available from GSSI at the end of 1994.**
- **A Windows* based radar processing software package has been developed by Miningtek to be compatible with the SIR-2M system. This software is specifically geared towards the non expert user, as an alternative to the standard GSSI software. The software will be commercially available from Miningtek by the end of the 1994.**



The newly developed GSSI model SIR-2M mineworthy GPR system is designed specifically for routine use in the harsh environment of underground mining operations.

For further information contact *Mining Equipment & Systems,*
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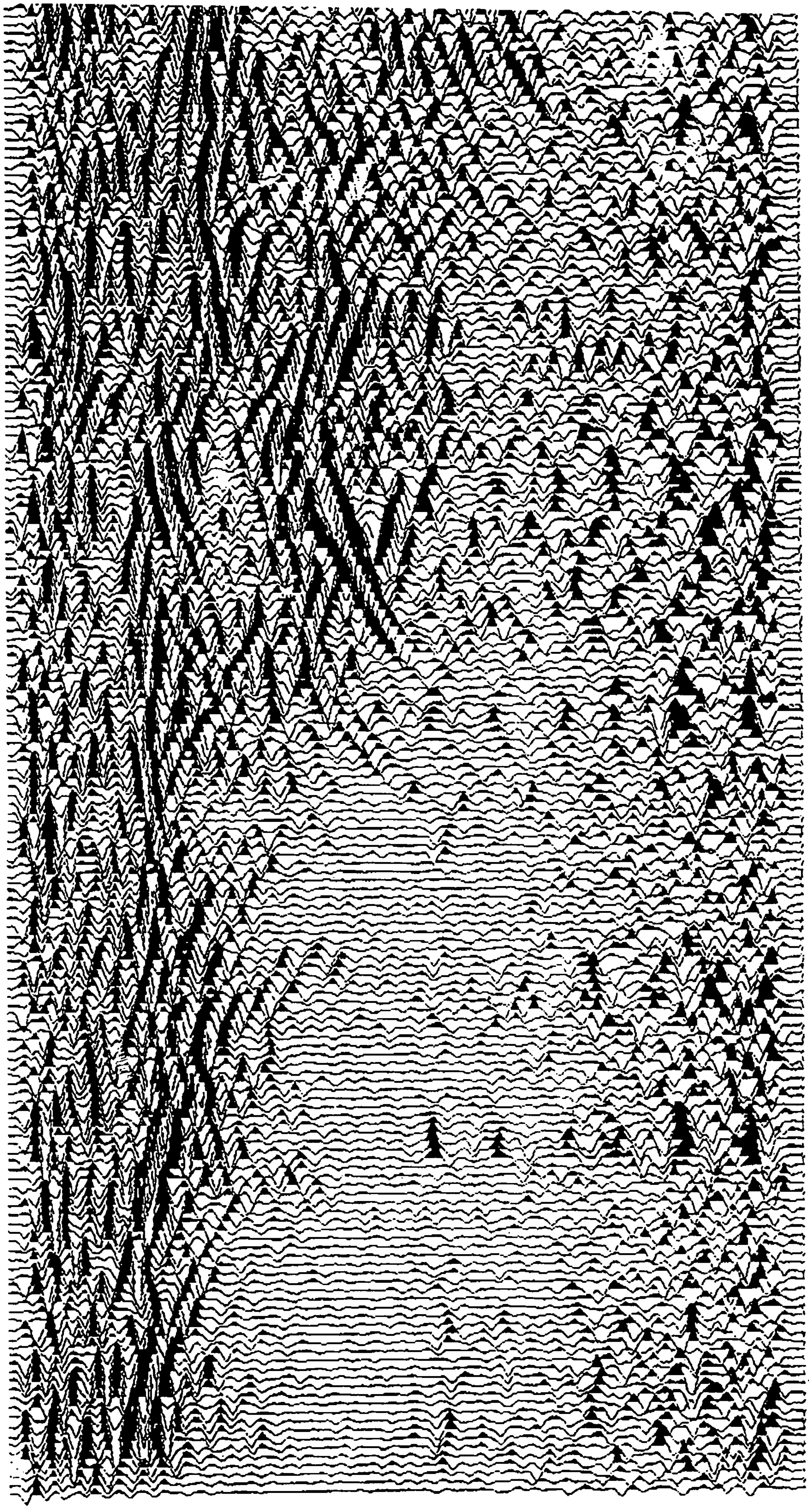
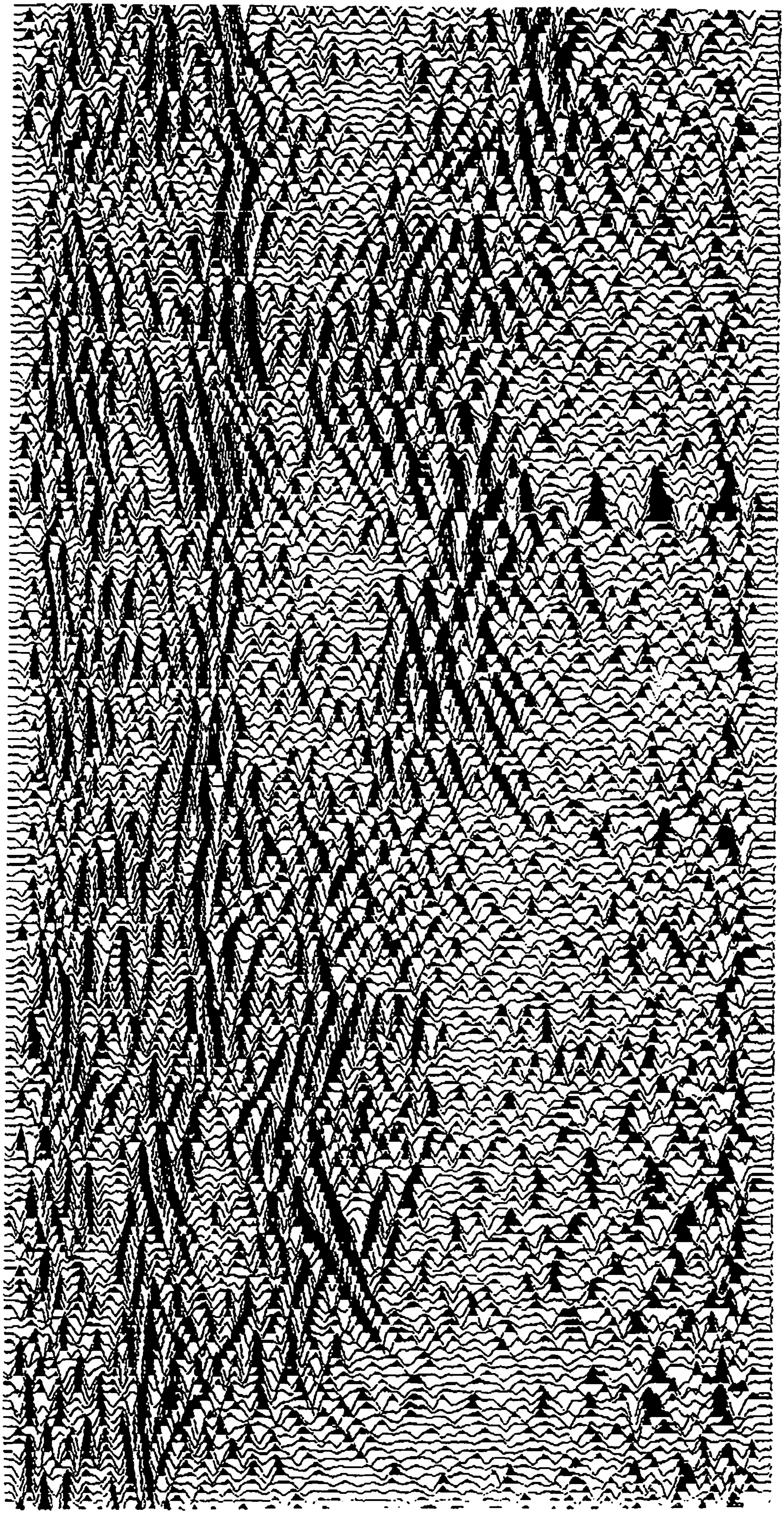
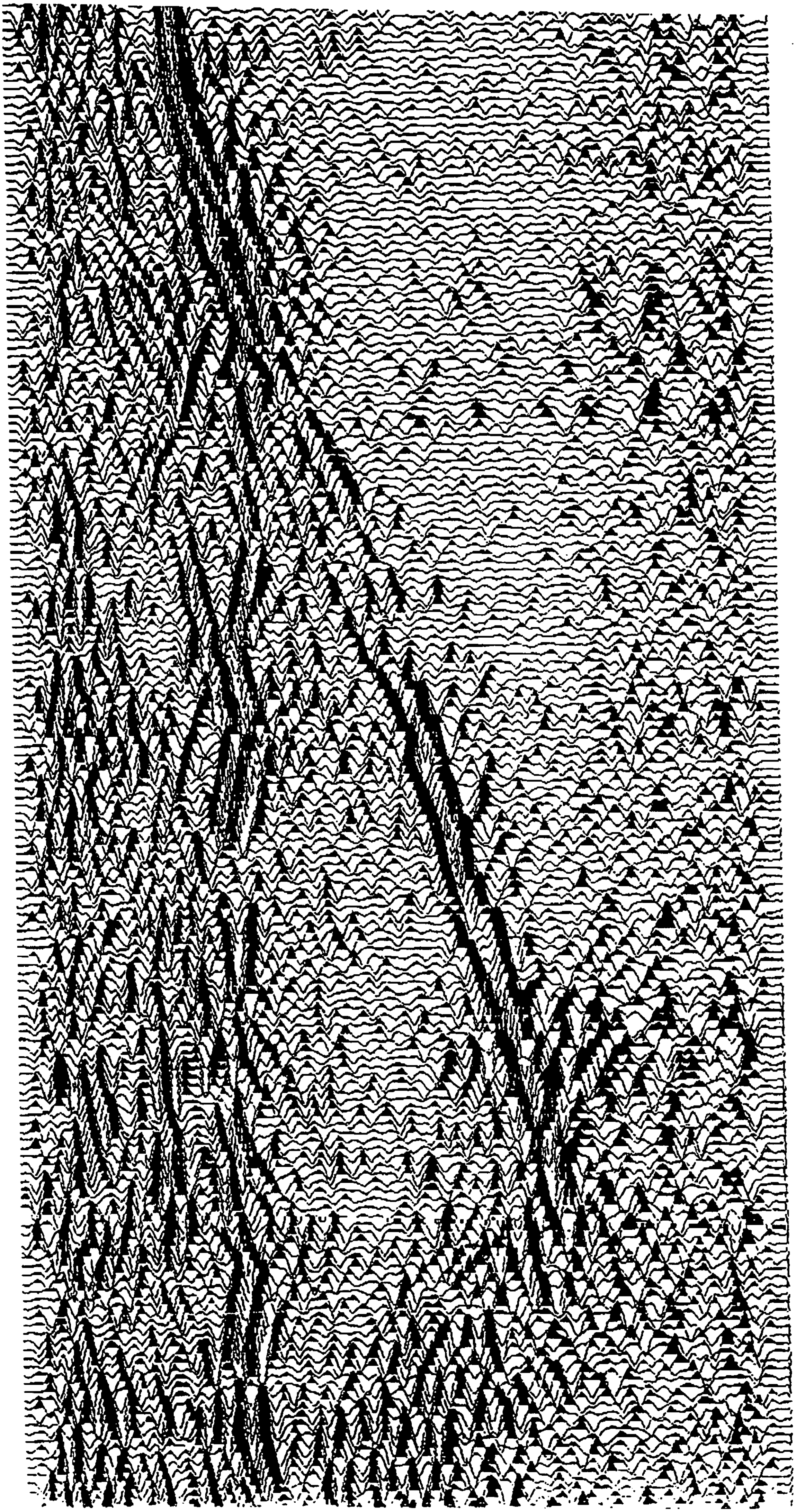
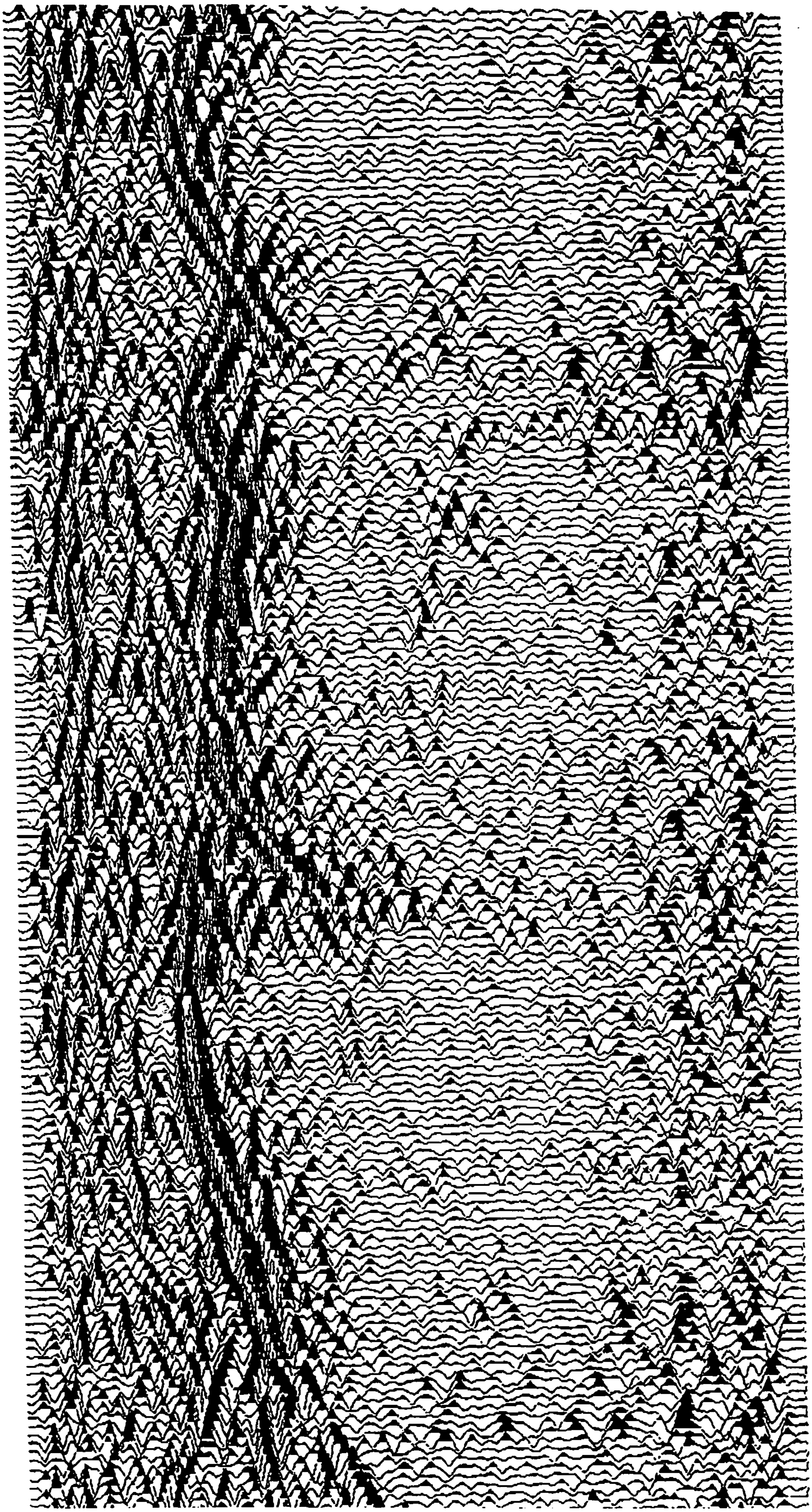
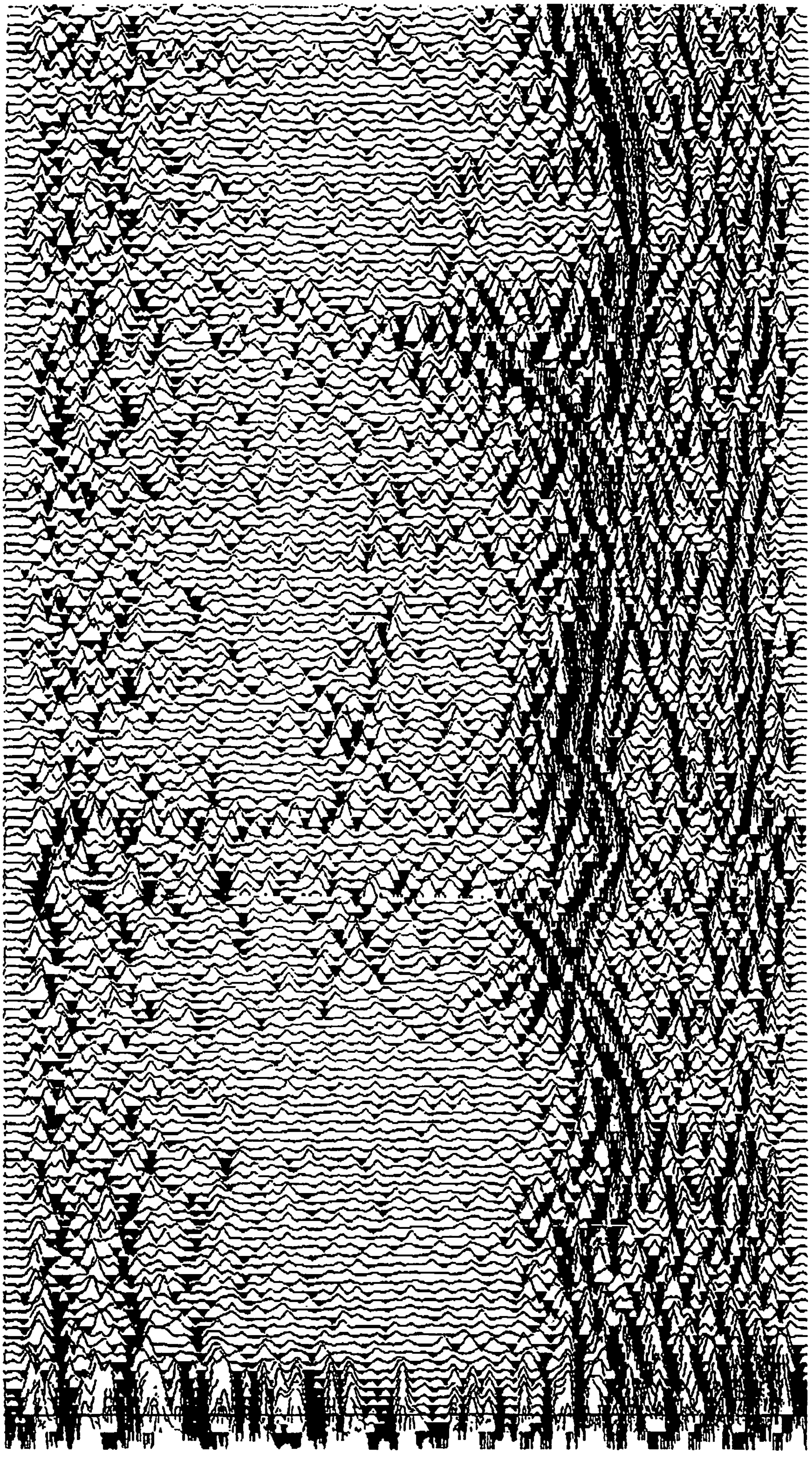










Appendix E

Masunga Site A (Cattle watering pit)

Depth (m)	Lithology
0.00 - 1.40	Coarse to medium cross bedded sands with gravels (sample No. 1)
1.40 - 2.80	Massive dune bedded coarse sands, well graded, feldspathic, very clean but subangular (sample No. 2).
2.80 - 3.50	Angular gravel with coarse sand, basal lag gravel with fragments up to 3" across (sample No. 3).

In general sands are composed of orange stained or grey quartz and white feldspar fragments.

Masunga Sand Pit section A

Depth (m)	Lithology
0.80 - 1.20	Coarse sand and gravel (sample No. 5).
1.20 - 1.45	Coarse sand with some gravel (sample No. 6).
1.45 - 1.65	Gravel and coarse sand, some pebbles at base (sample No. 7).
1.65 - 1.88	Gravel with some pebbles and coarse sand (sample No. 8).
1.88 - 1.95	Coarse sand (sample No. 9).
1.95 - 2.03	Medium sand (sample No. 10).
2.03 - 2.12	Orange fine sand (sample No. 11).
2.12 - 2.26	Grey clay with orange silt
	Fine sand
	Coarse sand with grey to light grey silt and fine sand (sample No. 12).
	Silty grey clay and black peat (sample No. 4).
2.26 - 2.70	Brown-grey coarse sand with quartz and white feldspar (sample No. 13).

Masunga Sand Pit section B

Depth (m)	Lithology
0.50 - 0.80	Gravel and coarse sand
0.80 - 0.95	Gravel and coarse sand (sample No. 14).
0.95 - 1.11	Coarse gravel and coarse sand.
1.11 - 1.32	Coarse gravel and coarse sand with basal lag gravels (sample No. 15).
1.32 - 1.41	Coarse sand (sample No. 16).
1.41 - 1.48	Grey black peaty silt (sample No. 17).
1.48 - >2.00	Gravel and coarse sand (sample No. 18).

Appendix F

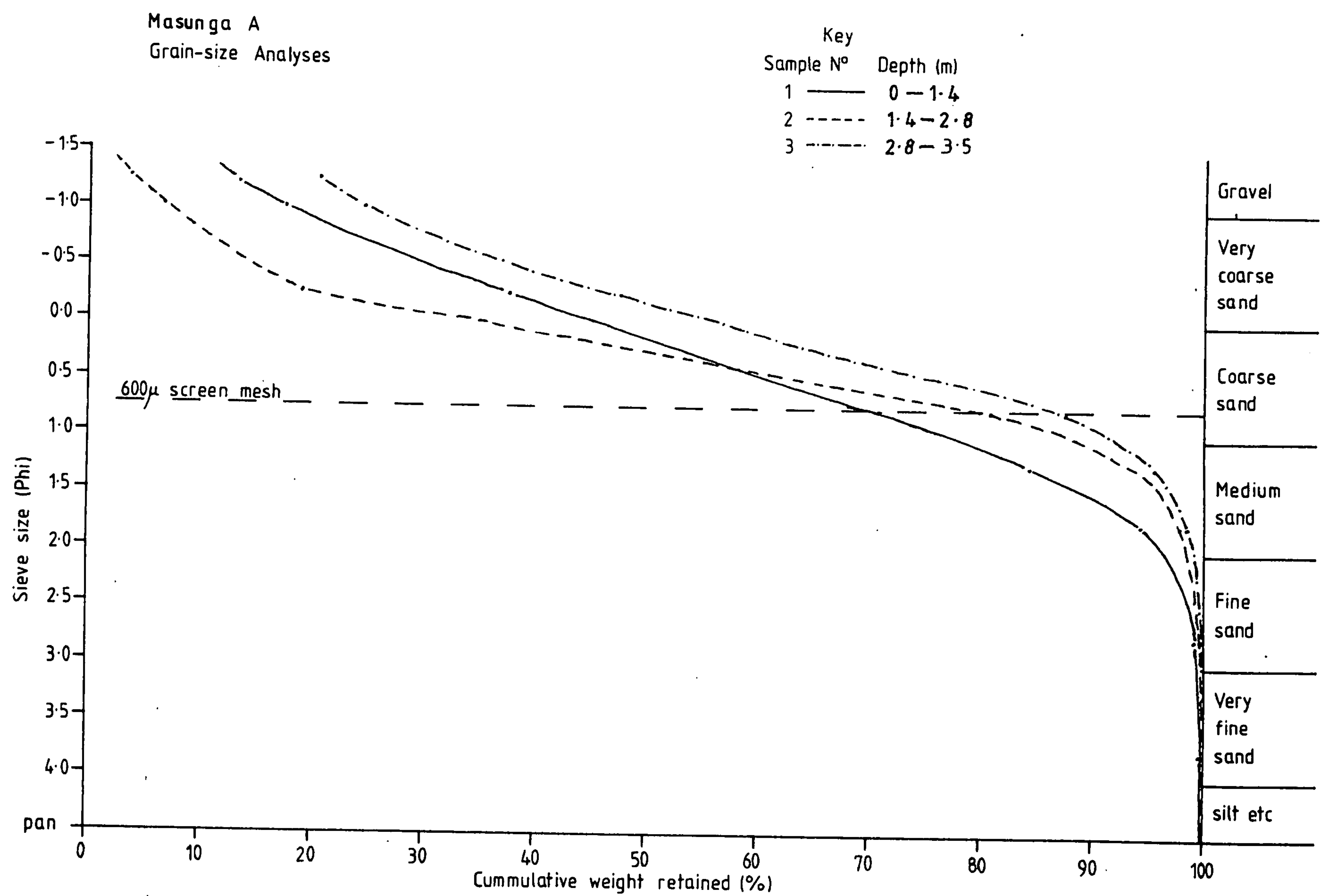
Grain-size analyses

Grain size analyses
DWA/Botswana 1994

Sample No.		bots 1	bots 2	bots 3	bots 5	bots 6	bots 7	bots 8	bots 9	bots 10	bots 11	bots 12	bots 13	bots 14	bots 15	bots 16	bots 18
Section		Masunga	AMasunga	AMasunga	ASand Pit	Sand Pit	Sand Pit	Sand Pit	Sand Pit	Sand Pit	Sand Pit	Sand Pit	Sand Pit	Sand Pit	Sand Pit	Sand Pit	Sand Pit
Depth Interval (m)		0.8-1.4	1.4-2.8	2.8-3.5	0.8-1.2	1.2-1.45	1.45-1.65	1.65-1.88	1.88-1.95	1.95-2.03	2.03-2.12	2.12-2.26	2.26-2.70	0.8-0.95	1.11-1.32	1.32-1.41	1.48->2.0
Sieve size (mm)	Phi	weight retained (gms)	weight retained (gms)	weight retained (gms)	weight retained (gms)	weight retained (gms)	weight retained (gms)	weight retained (gms)	weight retained (gms)	weight retained (gms)	weight retained (gms)	weight retained (gms)	weight retained (gms)	weight retained (gms)	weight retained (gms)	weight retained (gms)	weight retained (gms)
2.36	-1.25	127.5	24.5	137	73	137	267.5	148.5	2.5	0	1	10.5	84.5	159	295	88.5	170
2.0	-1.0	39	25.5	28	47	51.5	71	67	3.5	0.5	1	4	55	41.5	70	27.5	54.5
1.18	-0.25	189	175	151	244	229	183	271	35	4	4	29	212.5	158	225	179.5	244
0.6	0.75	324	396	267.5	243	245.5	98.5	371	165	30.5	6.5	44	272.5	262.5	179.5	327	346.5
0.425	1.25	124.25	95	56.5	70	87	39	84	146	84.5	23.5	17	87.5	87.5	31.5	75	67.5
0.300	1.75	90	34.5	20	43.5	50.5	44	42.5	120	261	275.5	21	65	60	13	18	25
0.15	2.75	48.5	13.5	6	38	33	39	24	83	131.5	191	312.5	39	26.5	7	7.5	10
0.075	3.75	6.5	2.5	1.25	5.5	6	6.5	3.5	7.5	9.5	20	125	8	5.5	1	1	3
Pan		0.6	0.6	0.5	0.8	1.25	1.25	0.6	1.5	1.5	2	30.5	1	1	0	0.5	0.5

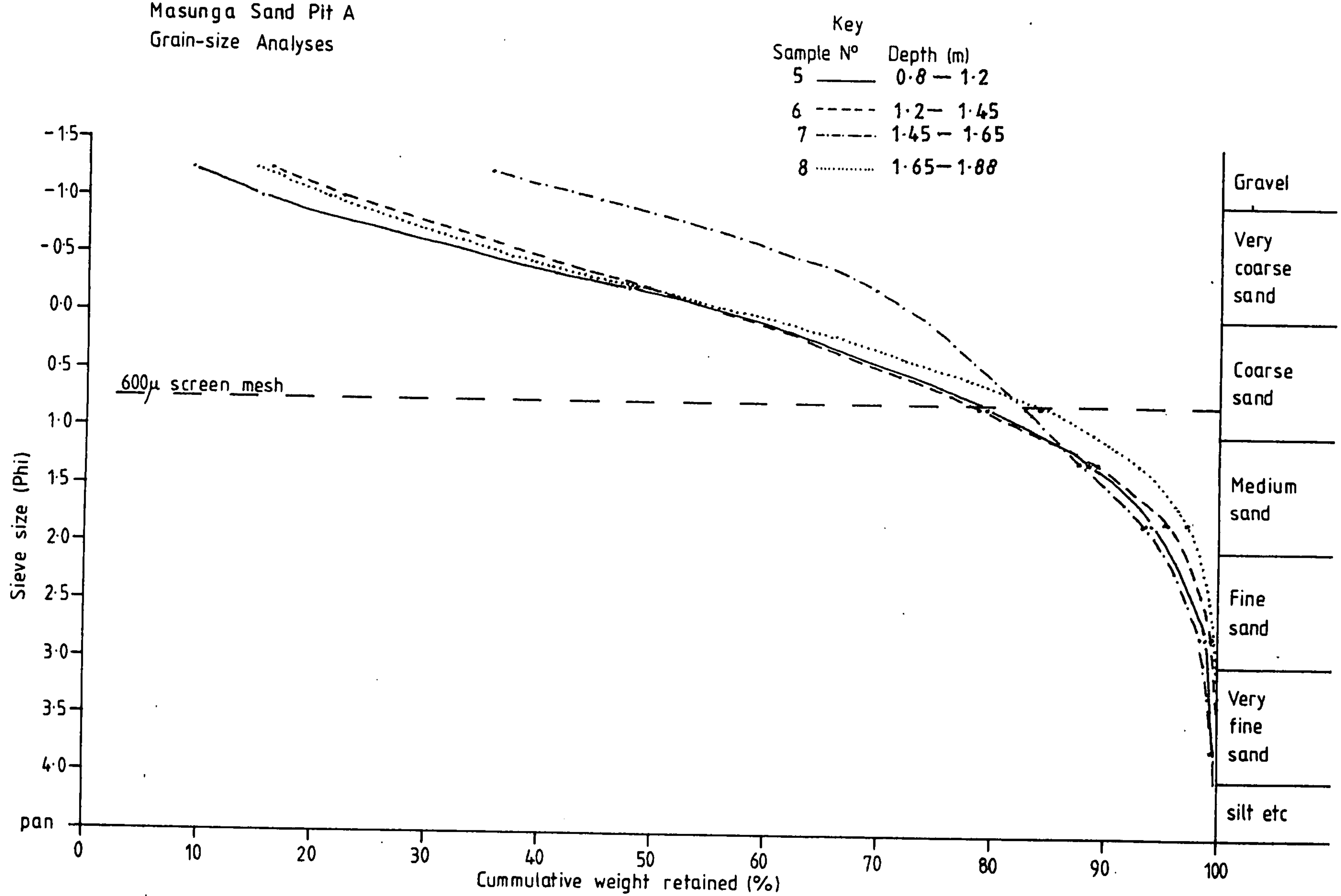
Sieve size (mm)	Phi	cumm.wt. retained (gms)	cumm.wt. retained (gms)	cumm.wt. retained (gms)	cumm.wt. retained (gms)	cumm.wt. retained (gms)	cumm.wt. retained (gms)	cumm.wt. retained (gms)	cumm.wt. retained (gms)	cumm.wt. retained (gms)	cumm.wt. retained (gms)	cumm.wt. retained (gms)	cumm.wt. retained (gms)	cumm.wt. retained (gms)	cumm.wt. retained (gms)	cumm.wt. retained (gms)	cumm.wt. retained (gms)
2.36	-1.25	127.5	24.5	137	73	137	267.5	148.5	2.5	0	1	10.5	84.5	159	295	88.5	170
2.0	-1.0	166.5	50	165	120	188.5	338.5	215.5	6	0.5	2	14.5	139.5	200.5	365	116	224.5
1.18	-0.25	355.5	225	316	364	417.5	521.5	486.5	41	4.5	6	43.5	352	358.5	590	295.5	468.5
0.6	0.75	679.5	621	583.5	607	663	620	857.5	206	35	12.5	87.5	624.5	621	769.5	622.5	815
0.425	1.25	803.75	716	640	677	750	659	941.5	352	119.5	36	104.5	712	708.5	801	697.5	882.5
0.300	1.75	893.75	750.5	660	720.5	800.5	703	984	472	380.5	311.5	125.5	777	768.5	814	715.5	907.5
0.15	2.75	942.25	764	666	758.5	833.5	742	1008	555	512	502.5	438	816	795	821	723	917.5
0.075	3.75	948.75	766.5	667.25	764	839.5	748.5	1011.5	562.5	521.5	522.5	563	824	800.5	822	724	920.5
Pan		949.35	767.1	667.75	764.8	840.75	749.75	1012.1	564	523	524.5	593.5	825	801.5	822	724.5	921

Sieve size (mm)	Phi	% cumm.wt retained	% cumm.wt retained	% cumm.wt retained	% cumm.wt retained	% cumm.wt retained	% cumm.wt retained	% cumm.wt retained	% cumm.wt retained	% cumm.wt retained	% cumm.wt retained	% cumm.wt retained	% cumm.wt retained	% cumm.wt retained	% cumm.wt retained	% cumm.wt retained	% cumm.wt retained
2.36	-1.25	13.43024	3.193847	20.51666	9.544979	16.29497	35.67856	14.67246	0.443262	0	0.190658	1.769166	10.24242	19.8378	35.88808	12.21532	18.4582
2.0	-1.0	17.53832	6.518055	24.70985	15.69038	22.42046	45.14838	21.29236	1.06383	0.095602	0.381316	2.443134	16.90909	25.0156	44.40389	16.01104	24.37568
1.18	-0.25	37.44667	29.33125	47.3231	47.59414	49.65804	69.55652	48.06837	7.269504	0.860421	1.143947	7.329402	42.66667	44.72863	71.77616	40.78675	50.86862
0.6	0.75	71.57529	80.95424	87.383	79.36715	78.85816	82.69423	84.72483	36.52482	6.692161	2.383222	14.74305	75.69697	77.47973	93.61314	85.92133	88.49077
0.425	1.25	84.66319	93.33855	95.84425	88.51987	89.20607	87.89597	93.0244	62.41135	22.84895	6.86368	17.60741	86.30303	88.39676	97.44526	96.27329	95.81976
0.300	1.75	94.14336	97.83601	98.83939	94.20764	95.21261	93.76459	97.22359	83.68794	72.75335	59.3899	21.14575	94.18182	95.88272	99.02676	98.75776	98.5342
0.15	2.75	99.25212	99.59588	99.73793	99.17626	99.13767	98.96632	99.5949	98.40426	97.89675	95.80553	73.79949	98.90909	99.18902	99.87835	99.79296	99.61998
0.075	3.75	99.9368	99.92178	99.92512	99.8954	99.85132	99.83328	99.94072	99.73404	99.71319	99.61868	94.86099	99.87879	99.87523	100	99.93099	99.94571
Pan		100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100

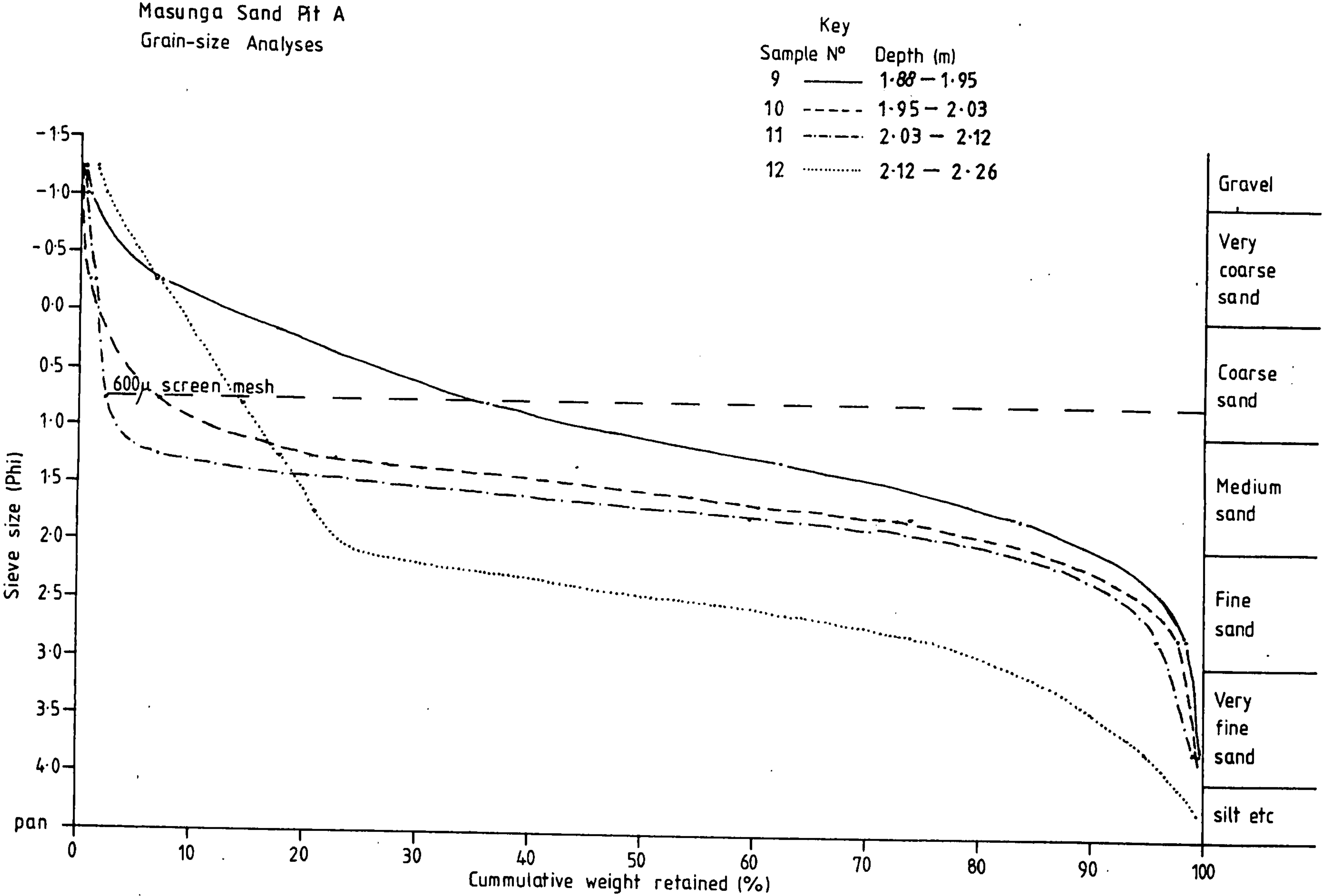


Masunga A
Grain-size Analyses
Key
Sample N° Depth (m)
1 0 — 1·4
2 1·4 — 2·8
3 2·8 — 3·5
600μ screen mesh
Gravel
Very coarse sand
Coarse sand
Medium sand
Fine sand
Very fine sand
silt etc
Sieve size (Phi)
-1·5
-1·0
-0·5
0·0
0·5
1·0
1·5
2·0
2·5
3·0
3·5
4·0
pan
0
10
20
30
40
50
60
70
80
90
100
Cummulative weight retained (%)

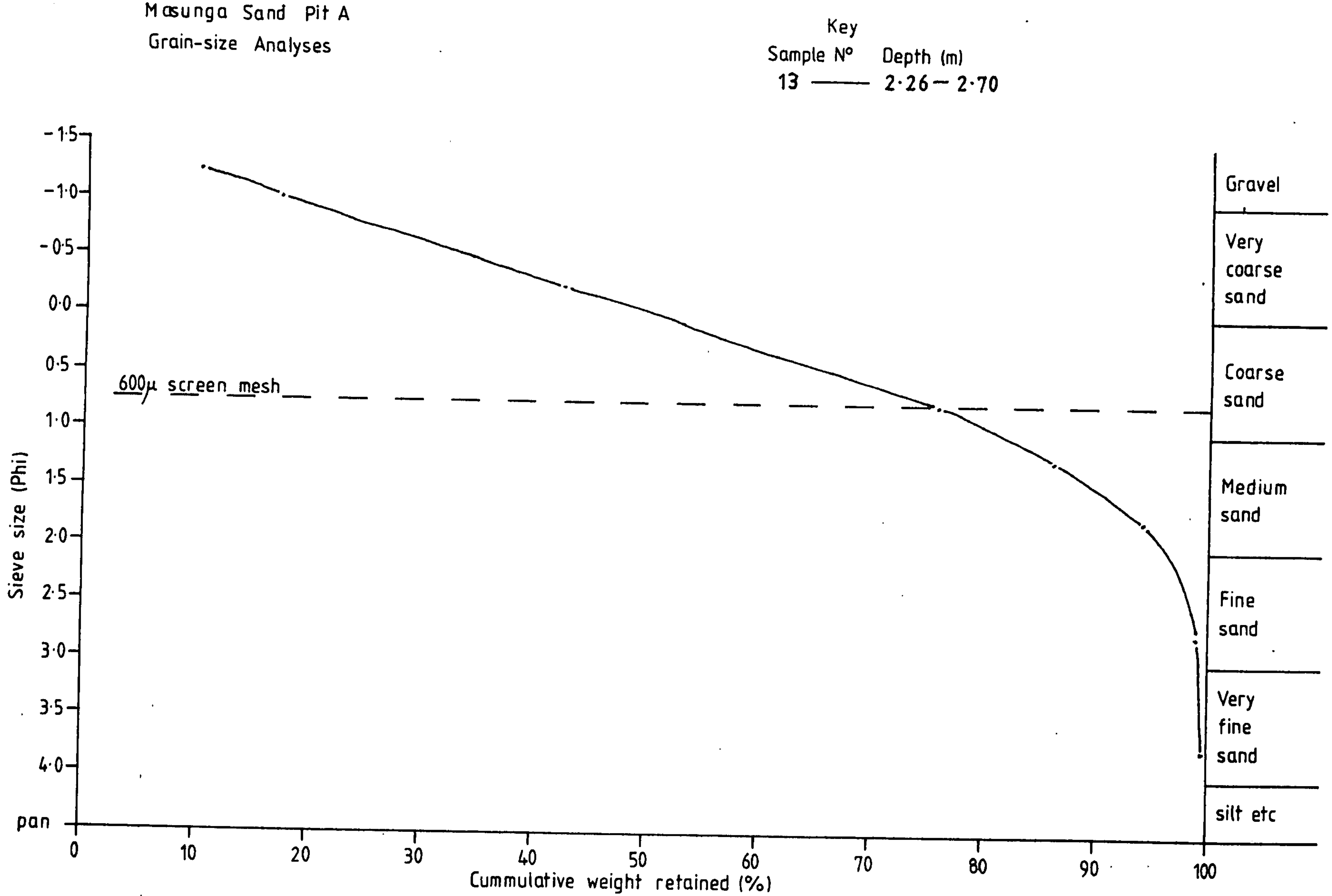
Masunga Sand Pit A
Grain-size Analyses



Masunga Sand Pit A
Grain-size Analyses



Masunga Sand Pit A
Grain-size Analyses



Masunga Sand Pit B
Grain-size Analyses