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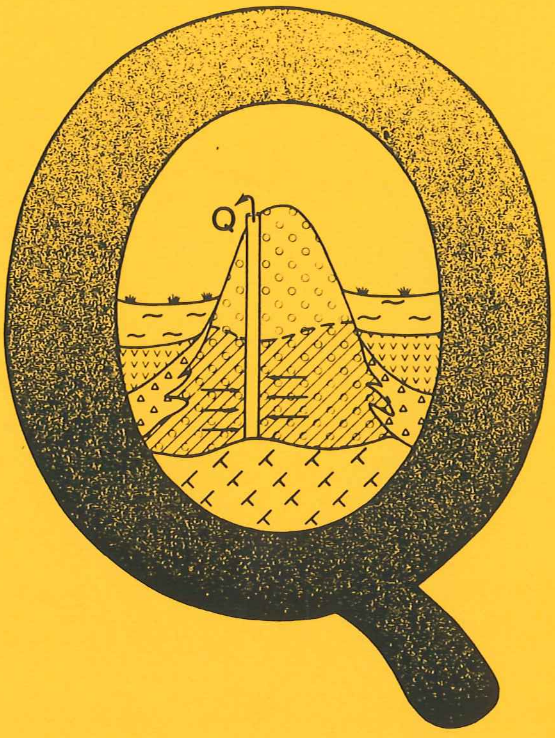
Kvartärgeologi



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NR 36

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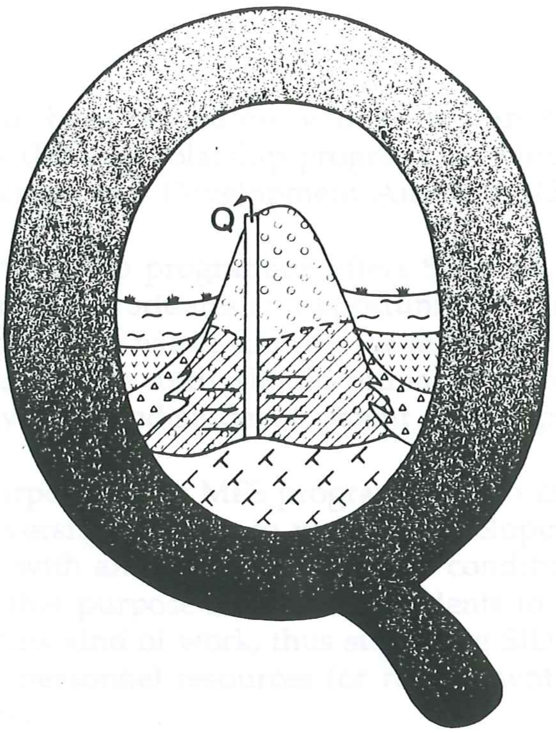

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LUND 1991 NR 36

GEOLOGISKA INSTITUTIONEN LUNDS UNIVERSITET

THE ROYAL INSTITUTE OF TECHNOLOGY

SCIENCE AND ART

INTERNATIONAL UNIT

This study has been carried out within the framework of the Minor Field Studies (MFS) scholarship programme, which is funded by the Swedish International Development Authority (SIDA).

The MFS scholarship programme offers Swedish undergraduate students or recent graduates an opportunity to carry out two months' field work in a third world country for their Masters theses or similar in-depth studies. The study should primarily be conducted in a country supported by the Swedish development aid programme.

The main purpose of the MFS programme is to create interest among Swedish university students to work in developing countries, providing them with an initial experience of conditions in the third world. A further purpose is to attract students to enter into professions suitable for this kind of work, thus supplying SIDA staff and widening the Swedish personnel resources for recruitment into international organisations.

The International Unit at the Royal Institute of Technology (KTH), Stockholm, administers the MFS programme for all faculties of engineering and natural sciences in Sweden.

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## Preface

This ground water study is made by Patrich Holmström, Per Möller and Mats Svensson, University of Lund.

It represents the final project for Master of Science in Geology for Patrich Holmström and for Master of Science in Civil Engineering for Per Möller and Mats Svensson.

Torleif Dahlin at the Department of Engineering Geology, University of Lund and Richard Owen at the Department of Geology, University of Zimbabwe were our tutors during the project.

The project was initiated by the Evangelican Lutheran Church of Zimbabwe (ELCZ) and was financed by the Swedish International Development Authority (SIDA) as a Minor Field Study (MFS).

The project was carried out during the summer of 1990 at Manama Mission, Gwanda District in southern Zimbabwe.


## Acknowledgement

We would especially like to thank;

Mr Torleif Dahlin and Mr Richard Owen for their knowledgable assistance during the project,

Mr Abraham Mdutshulwa Tlou, for very well done work as our field assistant in Manama,

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Mr Willy Legg for everything,

Sister Birgitta Grimheden for lots of things

The Bloom Family for their hospitality,

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the Village Committee for their readiness to meet and listen to us at short notice,

Mr Kjell Warnqvist for some of the illustrations in chapter four and seven,

and last but not least, the whole community of Manama for having us and for making our stay a memorable one.

## Abstract

This paper describes a groundwater prospecting project, including two parts, in the rural area in southern Zimbabwe. The first part deals with a gelogical survey and locating of waterbearing fracture zones with the electromagnetic methods Slingram and VLF, and a resistivity instrument.

The field study consisted of geological mapping and geophysical profiling in an area of 5 km by 5 km. The results from the profiles are commented and interpretated together with the geological observations.

The second part of the project is about groundwater extraction by wellpoints from a river sand dam. A survey was made to find a better location of the wellpoint system, and a study in order to find a better technical solution was also included. The methods used were mechanical sounding in cross-sections, leveling of the groundwater table and collecting of soil samples in an area of 250 m by 1100 m.

Recommendations are made for four borehole sitings for water supply, and concerning the sand dam to change the extraction system to one with a lower intake level.

Keywords: Zimbabwe, Groundwater, VLF, Slingram, Resistivity, Sand dam.

## Summary

Manama Mission is a Lutheran mission station in the Gwanda District, Zimbabwe, that suffers from a shortage in water supply. Its only source of water at present is a sand dam in the nearby Tuli river.

During June, July and August 1990 a ground water study was carried out at the mission. This was done by Patrich Holmström, Per Möller and Mats Svensson, students at University of Lund, Sweden.

The aim was to investigate if improvements can be made concerning the use of the sand dam, and also to investigate the possibilities of drilling boreholes for groundwater supply in the area. A secondary purpose was to compare the different geophysical instruments that were used.

The methods that were used in the study were :

- Prestudies of areal photos.
- Geological mapping.
- Geophysical profiling with Slingram, VLF and resistivity instrument.
- Leveling the basement rock, groundwater level and the surface of the sand dam.

The areal photos gave a clear main fracture direction striking around 290°. During the geological mapping this direction was confirmed. The geological mapping also gave us the geological setting of the area. It mainly consists of gneiss with frequent intrusive dykes of dolerite following the main fracture direction.

The geophysical investigation indicated no waterbearing fractures in between the dolerite dykes and the gneiss. It also clearly indicated that areas of interest for borehole siting always were close to streams or the Tuli river. We found two areas that we believe are interesting for groundwater prospecting. In these areas four spots has been marked for borehole sitings.

The investigations performed on the sand dam gave results that indicated that the present location of the extraction system, a wellpoint system, could not be better. However, the results also indicated big losses of water in the dam due to leakage in the weir and in the river bedrock. Another problem with the sand dam is that the wellpoint system through its design doesn´t allow maximum outtake from the sand dam.

The comparison between the instruments showed that the VLF-instrument, a ABEM WADI, is the most efficient instrument of the three, but that receiving conditions makes it unsuitable in Zimbabwe.The ABEM Slingram 3600 and the resistivity instrument, an ABEM SAS Terrameter 300, showed to be slower, but more reliable.

As recommendations we suggest Manama Mission to drill boreholes according to the instructions in chapter 8 as the first step to improve the water situation at the mission. If this does not give sufficient results, an exchange of extraction system according to suggestions in the chapter 7 and 8 should be carried out. Concerning the comparison of the instruments we recommend the use of Slingram and resistivity instrument for this kind of studies in Zimbabwe in the future.

# TABLE OF CONTENT

# 1 INTRODUCTION

## 1.1 BACKGROUND

Manama is a mission situated in the Gwanda District in southern Zimbabwe. There is a hospital, a secondary school and a bible school (fig 1.1.1). The hospital is now integrated in the governmental health plan of Zimbabwe, being run by the ELCZ in cooperation with The Ministry of Health.

The first missionaries came to Manama in the 1930's. Their aims were medical treatment, education of the people, and teaching christianity. In the beginning their work was very small scale and they only had a small hut for their medical work. For a long time they didn't have any church for the Sunday services or big ceremonies like weddings. Instead of that they used a now very traditional place in the village, the open air under the biggest and maybe 2000 years old Baobab tree. But since the 1950's they've got a white swedish looking church which is all "sold out to the last chair" during the singing Sunday services.

Manama is one of four Lutheran mission stations in southern Zimbabwe and there has always been swedish people working there as hospital staff and teachers. But between 1975 and 1980 when the liberation war came too close and dangerous all the missionaries left the village. After the independence in 1980 the missionaries came back and the hospital and the school has expanded. Today the hospital has a capacity of about 150 patients and a staff of 40, including five missionaries. The hospital is operating in quite a big area with a reception area with a radius of 100 km. The school is a secondary school with 600 pupil and a staff of 25. There is also a small bible school where 20 people stay. Except for a few people most of the inhabitants of the village work either at the hospital or the school.

*Fig 1.1 .1 Manama and its surroundings*

Manama mission is supplied with electricity, running water, flushing toilets and two not very well working telephones.

Since Manama is situated quite close to the borders of both South Africa and Botswana the population isn't as homogeneous as in most of Zimbabwe. Most of the people in the area are Sotho people with their roots in northern South Africa, but a large number of the people are Ndebeles. There are even some people from the Venda tribe. This means that a lot of people speak both the sindebele and the sotho language.

### Problem

The station suffers from an inadequate water supply, which is now based on water extraction from riverbed sand in the Tuli River. During the dry season the water levels in the sand drops, resulting in insufficient yield. A second problem are breakdowns in water supply caused by flooded pumphouse, worn out pump rubbers, lightning etc. A third problem concerns the distribution system within the mission where corrosion reduces water quality and interrupts supply.

## 1.2 AIM

The purpose of this project is to investigate the potential in different ground water sources that could be of interest in the area. This means evaluation of characteristics such as quantity, quality and accesibility concerning these ground-water resources. It also includes recommendations of what should be done based on knowledge obtained. A further purpose is to make a comparison between the three geophysical instruments used during the field work.

## 1.3 RESTRICTIONS

This project does not include investigation, conclusions or recommendations concerning the distribution system within the Manama Mission although this is an obvious problem, nor does it include the implementation of our recommendations.

## 1.4 DISPOSITION

In chapter 2 we present Zimbabwe in general. In chapter 3, "Geology and groundwater", we present the geology and physical geography of Zimbabwe and look at the principle of water bearing fractures. In chapter 4, we will describe how sand dams, a ground water resource of interest for this study, works. In chapter 5, "Prestudy", we present the information obtained concerning the conditions in Manama. Chapter 6, "Fieldstudy", concerns the planning of, methods used in and results given by the field study. Chapter 7, "Discussion and conclusions", gives our conclusions of the results and chapter 8 our recommendations.

# 2 ZIMBABWE

## 2.1 IN GENERAL

Like most of the countries in Africa Zimbabwe started it's modern history as a colony, but since 1980 it's an independent democracy with the primeminister Robert Mugabe.

The population consists mainly of two different kinds of african people, the Shona in the north, about 75 %, and the Ndebele, about 20 %, in the southern part of the country. The total population of about 9 millions (1988) also includes a few percents of white people. The birthrate is 2.9 % a year (1988), which is one of the highest in the world.

Agriculture stands for one of the most important parts of the economy of Zimbabwe, and the most successful crops are maize and wheat. Tobacco, coffee and cotton are cultivated mostly for export. Cattle farming is another big part of the agriculture.

Mining, based on gold export among 50 other different kinds of minerals, completes together with manufacturing the foundation of the Zimbabwean economy. ( Fahlén,1988 )

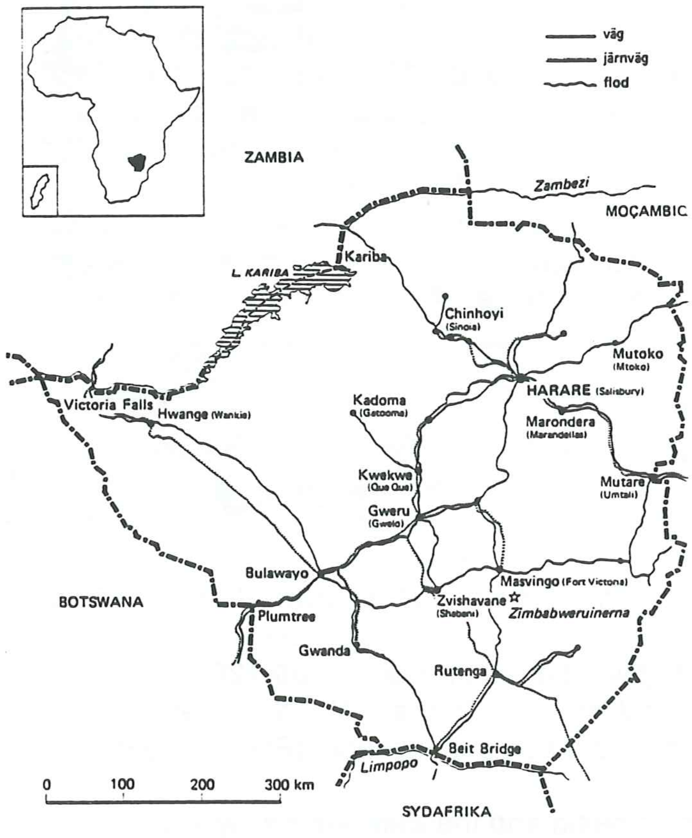



*Fig 2.1 Zimbabwe (Fahlén, 1988)*

## 2.2 GEOGRAPHY

*Zimbabwe* is situated in southern Africa, extending 15° 37' south to 22° 24' south,entirely within the Tropic of Capricorn. The area is 390 759 $km^2$, which means that the country is rather less than the size of Sweden. The bordering countries are Zambia to the north, Mozambique to the east, Botswana to the west and South Africa to the south. Harare is the capital, with a population of about 1 million. The second biggest town is Bulawayo, followed by Mutare as the third and Gweru as the fourth biggest.

Zimbabwe lies mainly on a plateau (see fig 2.2.1), which strikes from NE to SW, and which dips gently towards the SE and the NW, to the low-lying areas of the Sabi-Limpopo basin in the south, and the Zambezi valley in the north (House, 1983). This central plateau or *highveld* lies at an average altitude of 1200-1600 metres, and is a savanna landscape. The area has got the most fertile soils and the richest occurence of minerals.

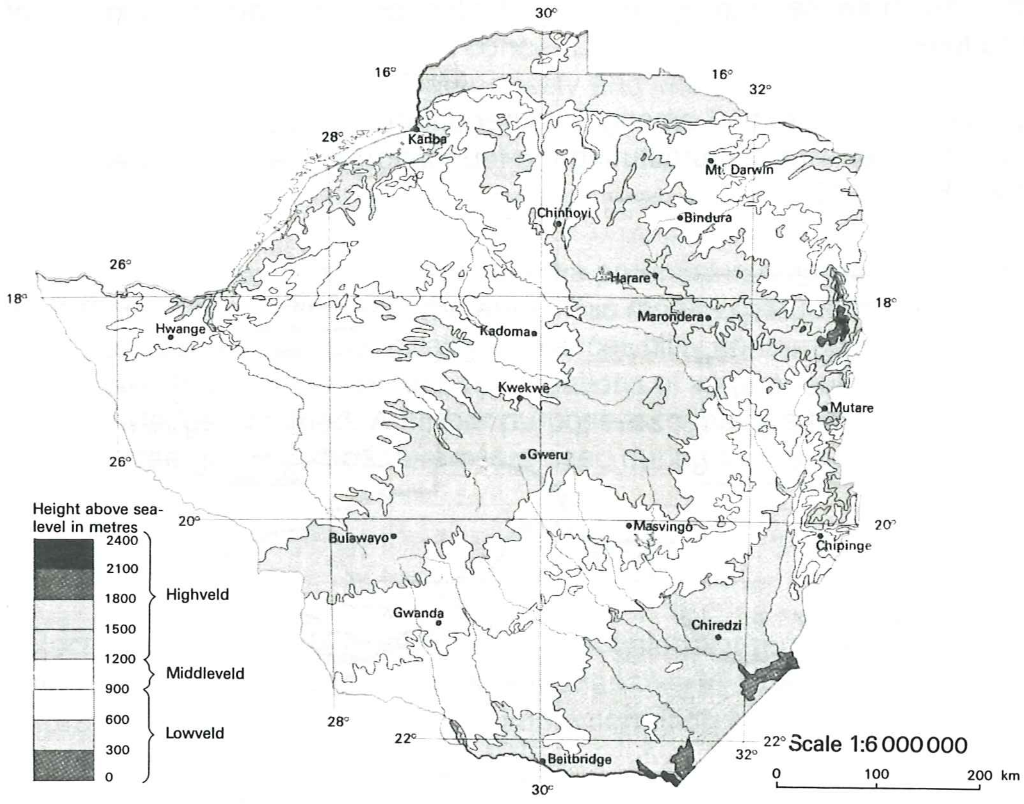



*Fig 2.2.1 The altitude of Zimbabwe. (Fahlén, 1988)*

On both sides of the highveld at an altitude of 900-1200 metres the *middleveld* extends, with its largest distribution to the NW. The vegetation varies depending on altitude from savanna to a scrub-landscape. (Fahlén, 1988)

Along the Sabi-Limpopo basin and the Zambezi valley a flatland poor in rainfall extends called the *lowveld*. On the poor sandy soils of this flatland Mopane trees predominate (House, 1983), and the huge Baobab trees are a feature of the otherwise thorny and scrubby vegetation.

*The Eastern Highlands*, along the border to Mozambique, contain the highest mountain in Zimbabwe, Inyangani (2594,8 m). The more temperate and rainy climate makes the highlands ideal for forest plantation and crops such as tea and coffee.

Other mountains are the Mavuradonha Mountains and the Matusadona Mountains, which mark the *Zambezi Escarpment* in the north, the *Matopo Hills* of granite copjes south of Bulawayo, and the range of hills forming a part of the *Great Dyke* that stretches for more than 500 km from north to south across central Zimbabwe.

The central highveld forms a watershed that divides the drainage pattern of the country into two river systems. The northern system belongs to the *Zambezi river*, the fourth largest river in Africa. It rises in NE Zambia and forms the boundary to Zambia, on which the *Victoria Falls*, the worlds biggest waterfall, and the huge man-made *lake of Kariba* are situated. The southern system belongs to the *Limpopo and Sabi rivers*, which like the Zambezi flows east through Mozambique where it enters the Indian Ocean. The Sabi rises in the central highveld, while the Limpopo, which forms the border to South Africa, rises near Pretoria (House, 1983). Zimbabwe has no natural lakes, though several man-made dammed up lakes act as important sources of water.

## 2.3 CLIMATE

Based on information from the Climate Handbook of Zimbabwe, we know that Zimbabwe has a *tropical* climate, though partly because of its high elevation and inland position the climate is cooler and drier than in most places within the tropics. The temperature pattern is largely controlled by altitude, as the altitude increases the temperature becomes lower.

The countrys stable climate depends partly on the subtropical high-pressure belt south of the Zimbabwe, which protects the country against most of the direct effects of travelling depressions and anticyclones of middle latitudes. The South African highveld plateau protects Zimbabwe from much of the cooler air from the south and SW.

The traditional season sequence of the temperate latitudes doesn´t prevail in Zimbabwe, though some similarities exist. From May to August the *Cool Season* or the winter prevails with south-easterly trade winds, mild and dry climate with day temperatures around 20° -25°C and cold nights.

In September the temperature rises and until mid-November the *Hot Season* prevails. This is the hottest and driest period of the year with day temperatures around 28° -35°C.

A southerly movement of windbelts meet winds of other directions over Zimbabwe, and brings the *Rainy Season* during the summer from November to March. When the airmasses meet, convergence of warm and moist air causes the rain.

During the *Post-Rainy Season* from March to May, when the temperature gradually decreases, a period of transition from rainy to dry season occurs.

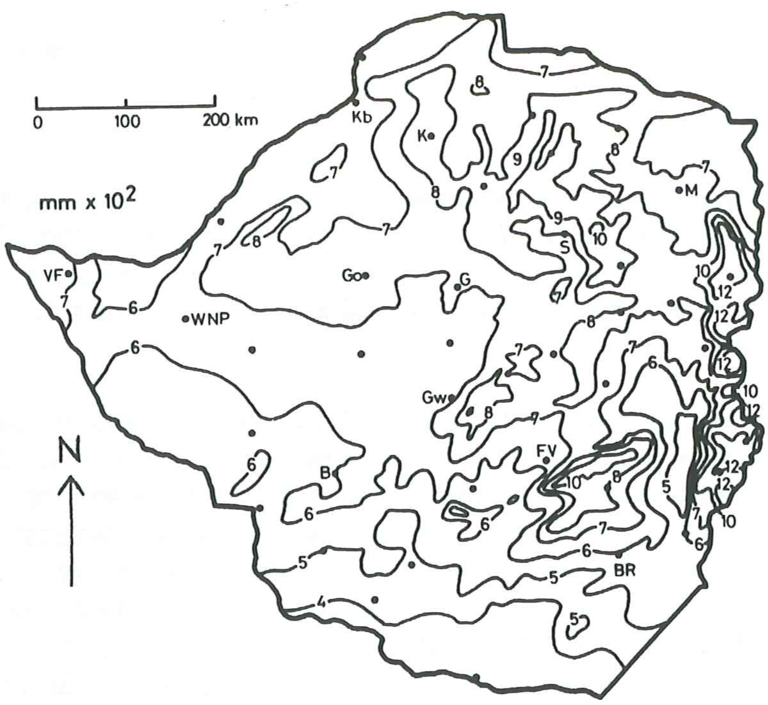



*Fig 2.3.1 Mean annual rainfall. (Climate Handbook of Zimbabwe, 1981)*

The seasonal rainfall of Zimbabwe is higher in the northern and eastern parts of the country than in the southern and western parts (see fig 2.3.1). In the N-E the annual rainfall lies between 700 and 1000 mm, whereas in the SW between 350 and 700 mm. The Eastern Highlands recieve between 1000 and 2000 mm every year, mostly because of the heavy orographic rainfalls along the east-facing slopes. The vegetation of the Zambezi Escarpment suggests orographic rather high rainfall, compared with the comparatively featureless lowveld in the south, which has a mean annual rainfall of less than 400 mm.

## 2.4 GEOGRAPHY AND CLIMATE OF MANAMA

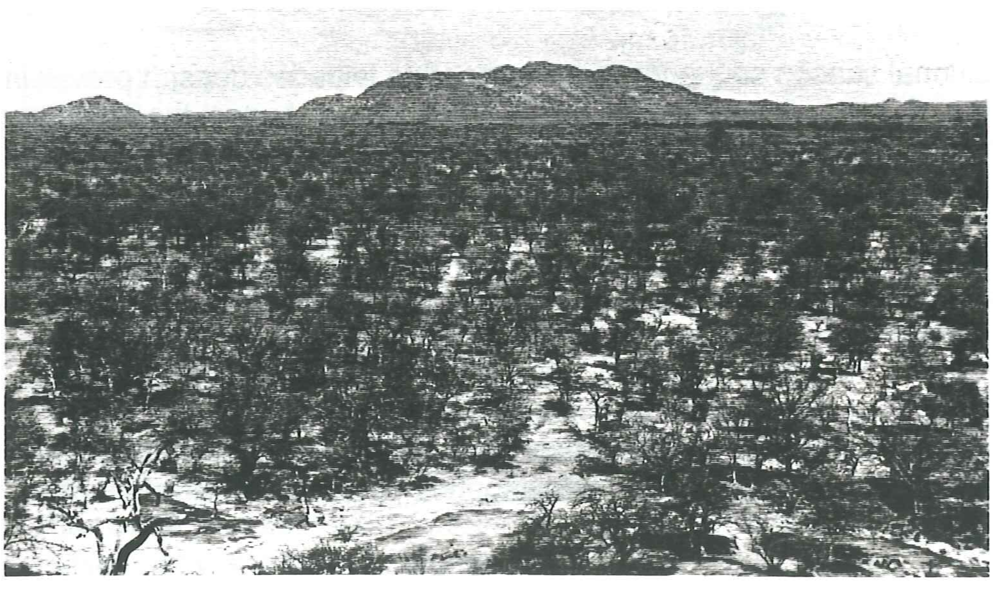


*Fig 2.4.1 Mount Msandane and the flat basement around Manama.*

Manama Mission is situated on the *lowveld* of Southern Zimbabwe along the *Tuli river*, about 30 km north of where the Tuli meets the Shashi river, which forms the border to Botswana. Except for Mount Msandane (937 m) south of Manama only small castle kopjes (see fig 2.4.1) break through the predominantly flat topography around Manama, which lies at an altitude of around 700 metres. The lowveld continues far away in all directions, except to the north of Manama where the hills around Gwanda rises 30 km away (see fig 2.4.2).

Many small rivers join the Tuli river in the area, and cut themselves some metres down in the flat basement (see fig 2.4.3). Like the Tuli, these rivers are dry for most of the year.

The annual rainfall, falling almost entirely during the short rainy season (less than 40 raindays of 1.0 mm or more per year), is very low, about 400 mm. This together with a high annual potential evaporation of around 2000 mm makes the climate of the area very dry (Climate Handbook of Zimbabwe, 1981). Potential evaporation is defined as the amount of water that would be removed from the land surface by evaporation if sufficient water was available.

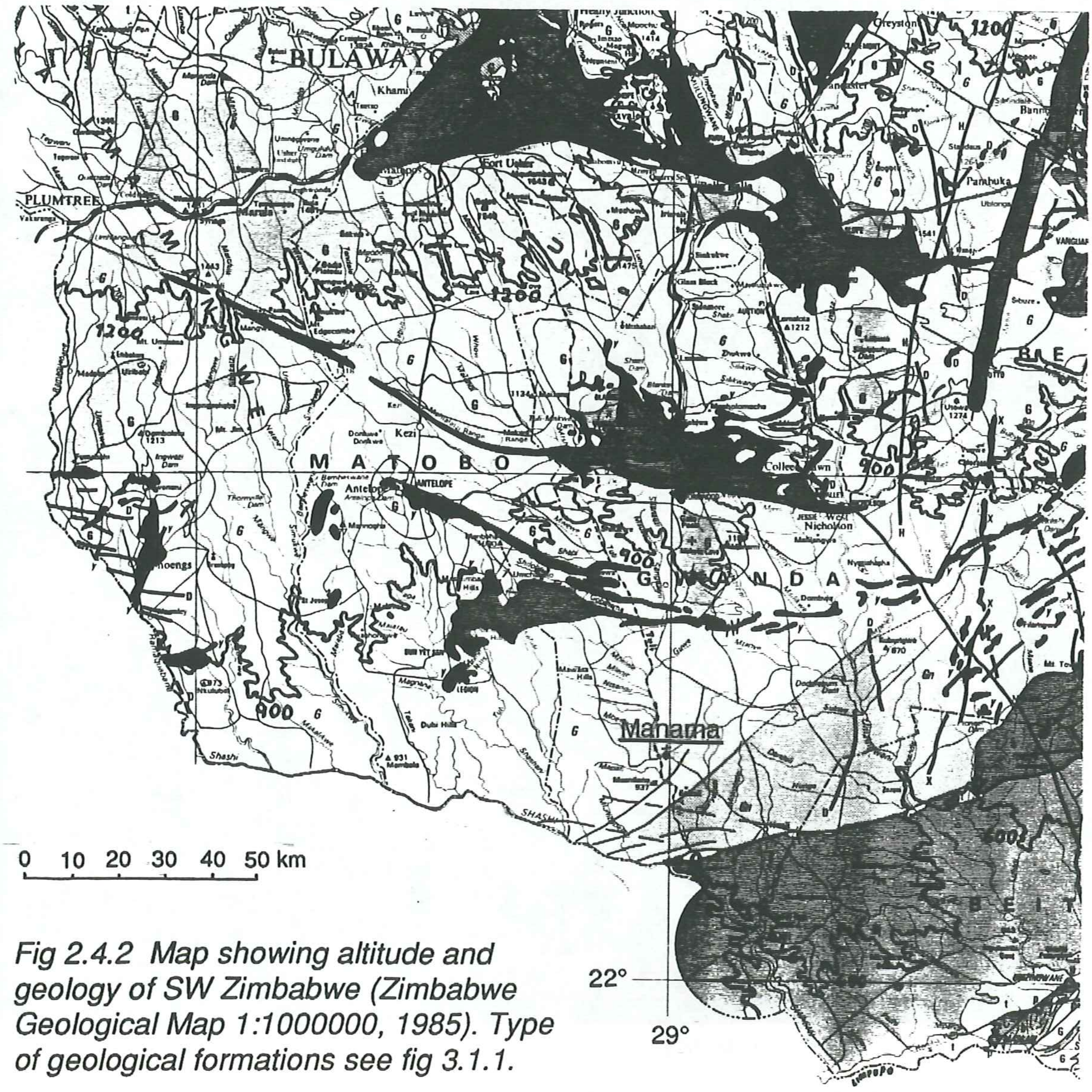



*Fig 2.4.2 Map showing altitude and geology of SW Zimbabwe (Zimbabwe Geological Map 1:1000000, 1985). Type of geological formations see fig 3.1.1.*


*Fig 2.4.3 Aerial photo of the Manama area. Scale 1:25000.*

# 3 GEOLOGY AND GROUNDWATER

## 3.1 GEOLOGY

Africa is basically a huge *continental shield,* which has existed since early Pre-cambrian times. The continent has gone through several orogeneses and mountain building periods, but some regions have been little disturbed during the last 1500 million years and are known as *cratons* (Pritchard, 1979). Zimbabwe is situated on a craton and has a geology typical of cratons, i.e. *the Basement Complex.*

This larger portion of the country (see fig 3.1.1), which excludes the north-western part, consists mainly of *granite* and *gneiss* with relatively small and irregular shaped inclusions of *greenstone belts* or schist belts. The primary rock types of the greenstone belts are lavas with basaltic or andesitic composition, often called greenstones because their primary minerals have been altered to green- coloured minerals like amphibole and chlorite. In all larger beds the greenstones are overlain by sedimentary rocks such as conglomerates, greywackes and arkoses, all to some extent metamorphosed, especially in the north. The oldest group of greenstones are at least 3500 Ma old, while the youngest are around 2700 Ma old. (Stagman, 1978)

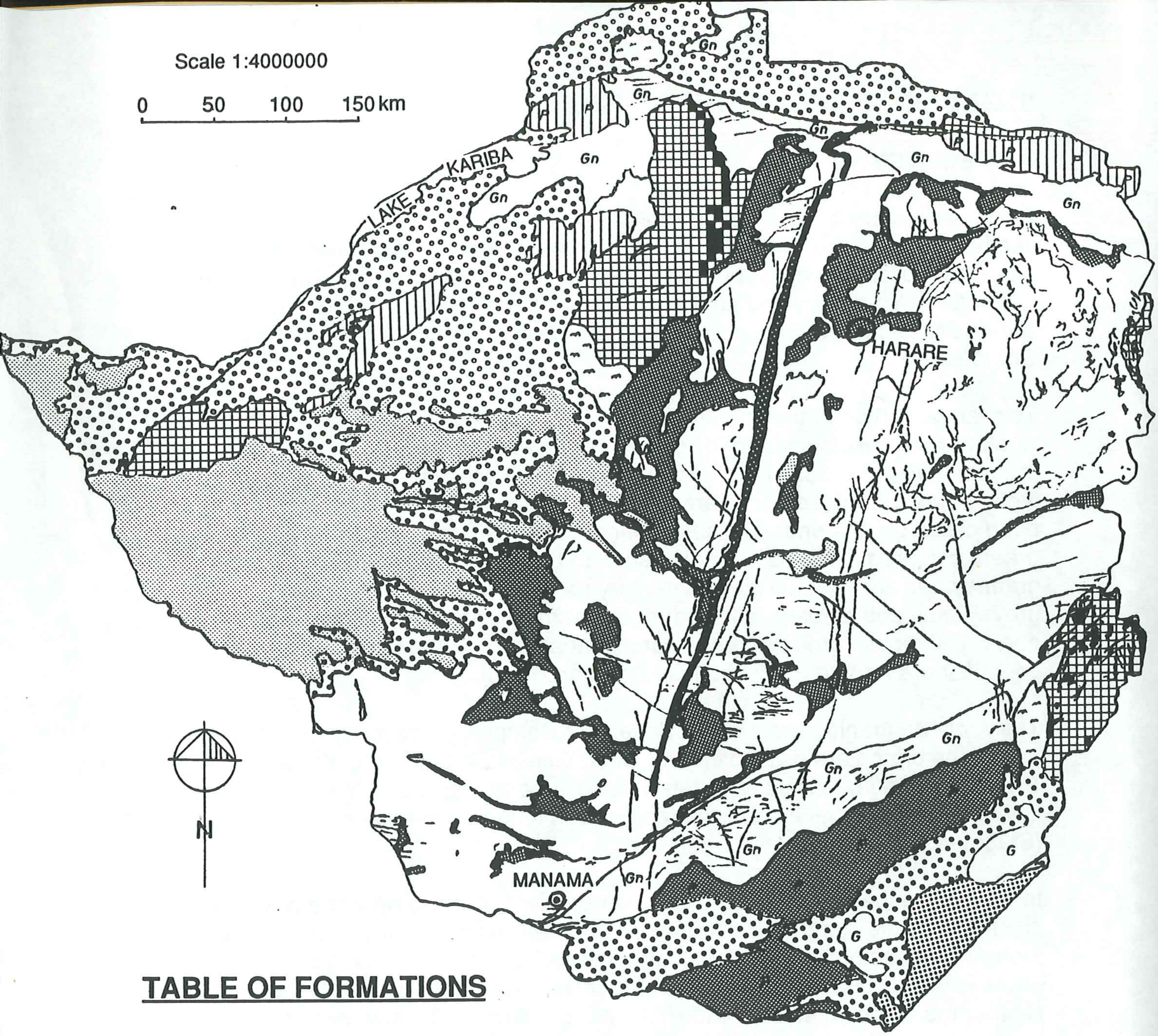
The Archean granitic rocks of the Basement Complex that occupy the greater part of the craton are divided into an *Older Gneiss Complex* and *Younger Granites.* Some gneisses have been found to be at least 3500 Ma old, while the Younger Granites have quite commonly been recorded to be about 2650 Ma old. (Stagman, 1978)

In Zimbabwe the term granite is used in its widest sense to describe coarsely crystalline rocks composed of quartz, oligoclase and microcline with variable though small amounts of dark coloured minerals, biotite and hornblende. True granites with accurate potassic feldspar content are very rare in the country. Neither the Older Gneisses or the Younger granites are by any means homogeneous, but as a rule the older rocks retain more evidece of mixed composition and are clearly banded and gneissic, whereas the younger ones are more homogeneous and massive. (Stagman, 1978)

The gneisses of the Older Gneiss Complex occupy less than half of the granitic terrain and are particularly well developed in the SW and central parts of the country. They are variously foliated or banded grey gneisses and darker coloured migmatites. Almost exclusively they are orthogneisses. In any area bodies of differing lithology may be present, as inclusions of ultramafic rocks in migmatic gneiss well away from the main greenstone belts. (Stagman, 1978)

The granite intrusions are essentially homogeneous, medium- to coarse-grained and form vast sheets and *batholiths* in the central and eastern parts of the country (see fig 3.1.2). Contacts to the greenstone belts are sharp and clear cut.

*The Great Dyke* strikes NNE for 540 km centrally across Zimbabwe and varies in width between 3 and 11 km. It´s in reality not a dyke at all, but is composed of




## TABLE OF FORMATIONS

| TYPE | TIME | | |
|---|---|---|---|
| Alluvium and other superficial deposits | Pleistocene and recent | Great Dyke | Mid Pre-Cambrian |
| Kalahari aeolian sands | Pleistocene and recent | Metasediments and Metavolcanics | Early Pre-Cambrian |
| Sandstone etc. | Cretaceous | Older Gneiss Complex and Younger Granites | Archean |
| Karoo deposits / Basalts | Jurassic-Permian | P Paragneisses | |
| Various sedimentary rocks | Late Pre-Cambrian | Gn, G Gneisses / Granites of various ages | |
| Various sedimentary rocks / volcanics | Mid Pre-Cambrian | Fault / Dolerite | |

*Fig 3.1.1 Geological map of Zimbabwe. (Based on Zimbabwe Geological Map 1:1000000, 1985.)*

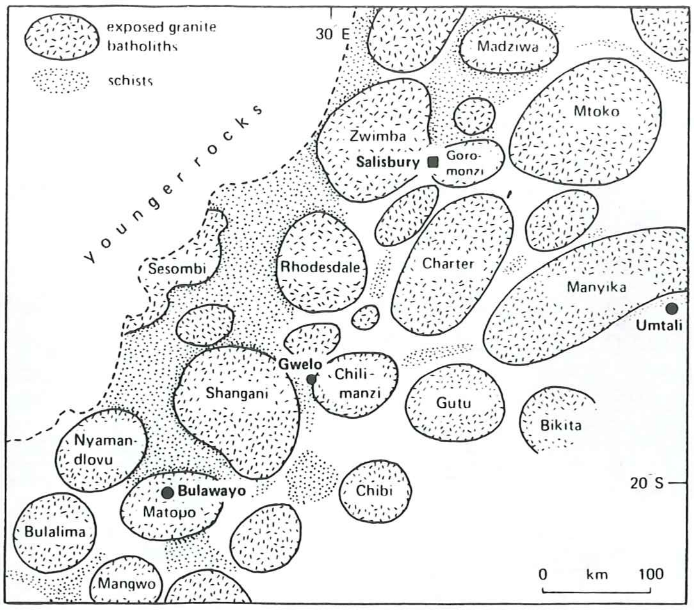



*Fig 3.1.2 Granite batholiths exposed at the surface in Zimbabwe. (Pritchard, 1979)*

four elongated lopolitic complexes, and are together preserved by faulting in a graben of major dimensions. The intrusion of the Great Dyke took place about 2500 Ma ago, after the consolidation of the craton. (Stagman, 1978)

In southern Zimbabwe a large ENE-trending zone of high grade metamorphic rocks called the *Limpopo Mobile Belt* lies between the Zimbabwean and the Kaapvaal cratons. Along the center of the belt a linear zone has suffered intense shear deformation and metamorphism. The intensity of the metamorphic and structural effects decrease in the craton northwards, while a diffuse boundary with local shearing and granite intrusion exists northwards in the belt. Several greenstone belts are strongly deformed in different fold trends, like the arcuate pattern of the belts in the southern part of craton. In the Limpopo Mobile Belt these deformations could be made by a large cratonic block moving to the SW, containing smaller units responding independently. Updoming of granitic batholiths has deformed a lot of the greenstone belts. The major activity of the Belt ceased before the emplacement of the Great Dyke. (Stagman, 1978)

Until the *Karoo* deposition and volcanism began in the late Carboniferous to early Permian times there is no preserved record of sedimentary deposition younger than Archean. Sedimentation continued throughout the Permian and Triassic only to be brought to a close by vast fissure eruptions of mafic lava in the lower Jurassic. On both sides of the Zimbabwean watershed, in the NW and SE respectively deposition took place. Other features of the Karoo era are the very prominent east-trending *dolerite dyke swarms of the Sabi-Limpopo basin.* (Stagman, 1978)

During Tertiary a long period of aridity occurred over a large part of Southern Africa, which the aeolian sands of the Kalahari System bear witness to. These *Kalahari sands* cover a large part of western Zimbabwe, which border the basin-shaped depression that cover a large part of south-western Africa .

## 3.2 PHYSICAL GEOGRAPHY

### 3.2.1 Development of topography

As the rest of Africa, Zimbabwe has over millions of years gone through cycles of *erosion* during *isostatic uplift.* Deep vertical weathering and erosion through scarp retreat have formed flat *pediplanes.* Different generations of pediplanes form a so called *polycyclic landscape,* with each generation at different elevation, the highest surface being the oldest (see fig 3.2.1.1).

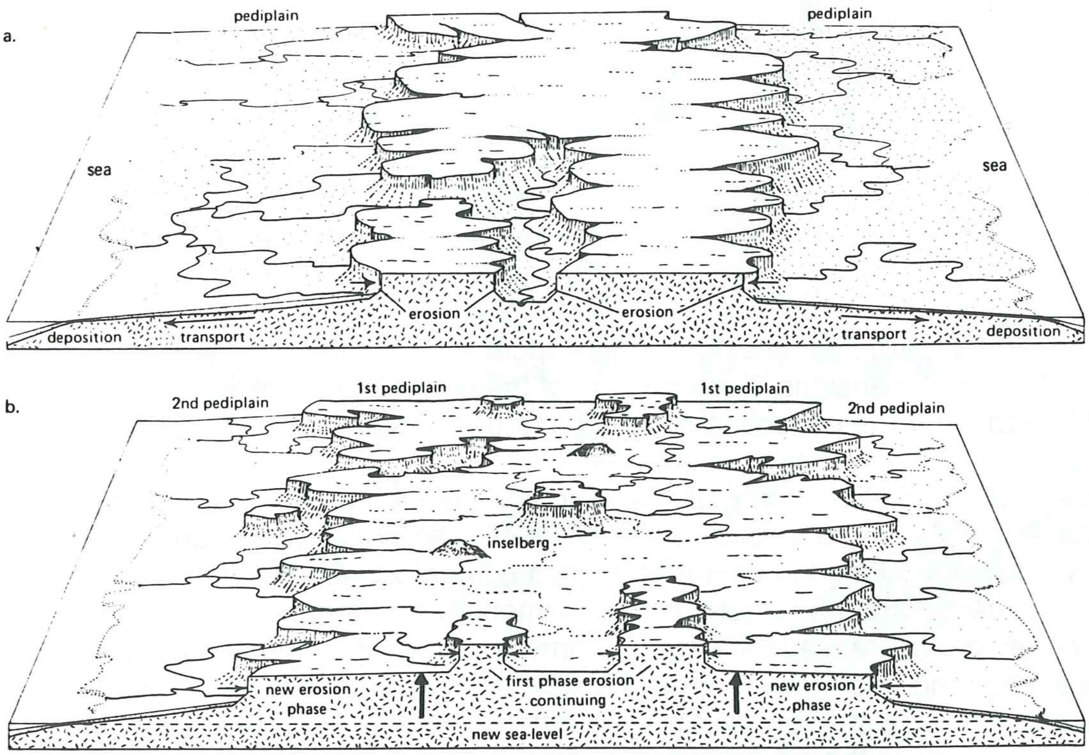



*Fig 3.2.1.1 Principles of pediplanation: a) First face of erosion: sharp retreat and waste material to continental shelf. b) Isostatic uplift and second erosion face extend pediplanes at a new lower level. (Pritchard, 1979)*

The plain and inselberg landscape is typical for Zimbabwe. *Inselbergs* are erosional remnants, often formed from plutonic crystalline rocks, batholiths. When these are massive and unjointed they give rise to *domed inselbergs* or *whalebacks* (see fig 3.2.1.2). More closely jointed rocks are more easily weathered and may form *boulder inselbergs* or *castle kopjes* (see fig 6.3.1.7), (Buckle, 1978). They are often smaller than the whalebacks and rise up on the plains as steep-sided piles of boulders, extended along the main joint direction. Castle kopjes may consist of gneissic rocks as well as of granitic rocks.

*Fig 3.2.1.2 Whaleback at Mbalabala, Zimbabwe.*

### 3.2.2 Weathering

To understand the physical features of the African landscape one has to deal with weathering.

Weathering gradually breaks down the rocks into residuals of increasingly smaller size. The process may be *mechanical*, *biological* or *chemical*, and controlled by several factors.

Maintaining the original composition of the rock, mechanical weathering may break down the rock to rock waste or debris. This may be by: (1) thermal expansion, due to alternate heating and cooling, (2) pressure release, where remowed overlying material causes the rock to expand and joints to be formed, or (3) through crystal growth of salts between the rock grains (Pritchard, 1979).

Chemical weathering is the most important in tropical Africa, and its overburden residuals often lay as a thick cover over the Basement Complex. With water as the main agent, the dominant mechanisms of chemical weathering are hydrolysis and dissolution, with the aid of carbonic acid and $CO_2$ (Jones, 1985). Eventually complete dissolution of the minerals and break down of the rock structure occurs. In a rock such as granite, carbonate salts dissolve first and are washed away. The feldspars break down in steps via various hydrous aluminium silicates into clay minerals, leaving the quartz crystals to form loose residual sand. (Pritchard, 1979)

The availability, circulation and chemical composition of groundwater are the most important controls in chemical weathering. To form a weathering profile these controls have to dissolve the rock and remove soluble products. If the soluble products are not removed, further reactions and weathering is suppressed. (Jones, 1985)

An undisturbed weathering profile, weathered were it stands, is called a *saprolite.* As its degree of weathering increases upwards, the grain size diminishes upwards. The uppermost part is usually a clay, if downward leaching hasn´t occured (Jones, 1985). Under the clay, a zone of leached gravel- to sand-grade quartz may exist, often with the structure of the parent rock preserved, since the chemical weathering takes place without significant volume change (see fig 3.2.2.1). These weathering profiles are deepest on flat or gently undulating surfaces, especially in the humid tropics and where there has been little climatic change over long periods (Pritchard, 1979). Parts of Zimbabwe had a humid paleoclimate, which produced thick saprolites (Jones, 1985).

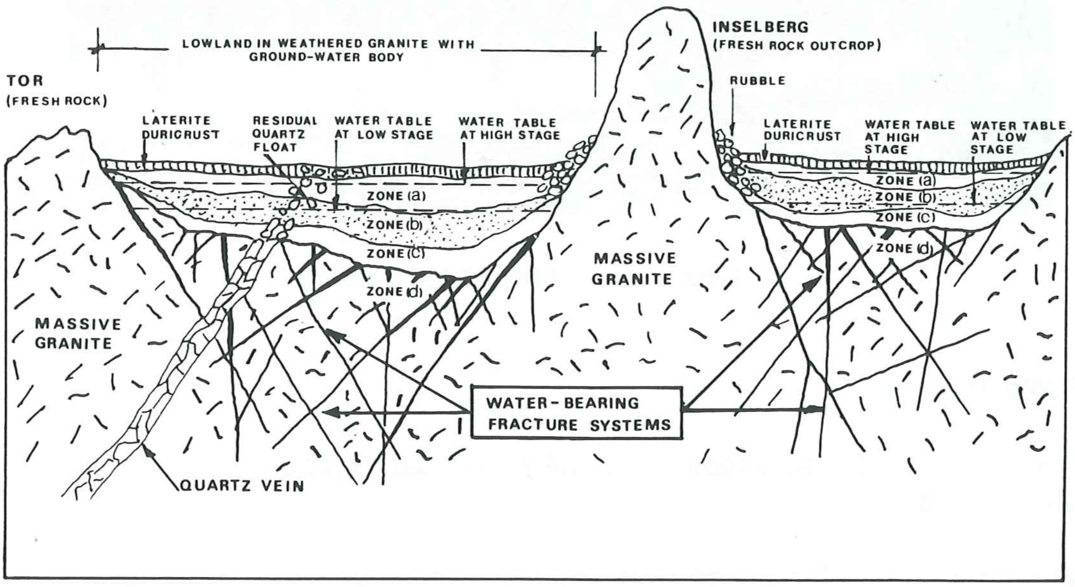



*Fig 3.2.2.1 Lowlands of weathered granite separated by inselbergs. Weathered zone: a) clayey sand, b) clay, c) rock progressivly altered upward to gravel and sand material, d) fresh fractured rock with waterbearing fractures. (UNESCO, 1984)*

The temperature is another control on weathering. When it rises the weathering rate increases. The effect on deep weathering is probably not very important, since the soil temperatures in most places get stable at about 2 metres depth (Ollier, 1988). However, the evaporation is largely controlled by temperature, and it has a direct effect on the waterbalance, which influences the weathering. Another control that effects the waterbalance in the ground is the extent and type of vegetation cover, which influences the surface run-off and the evaporation, and thus the deep vertical weathering.

The composition of the parent rock is important in chemical weathering. A rock such as granite often disintergrates into grains through chemical solution, although the grains often remain rather fresh in apparence. A basic more fine grained rock such as basalt or dolerite, is converted into clay minerals and iron oxides. (Ollier, 1984)

### 3.2.3 Soils

The soils of Zimbabwe mostly bear a very close relation to the underlying rock, and are classed as *"immature"*. Over a great part of the country the climate is too dry for solution products to form before erosion sets in, and sand accumulates in the soil of granite areas. The colour of the soil varies depending partly on the composition of the original granite and partly on the degree of maturity.(Stagman, 1978)

When the rainfall is high leaching will dissolve silicates and residues of weathering will contain ferric and aluminium oxides, which form a *lateritic soil*. This soil type can be found in Zimbabwes rainy eastern highlands. (Stagman, 1978)

In semi-arid climates evaporation causes a concentration of salts below the root zone, especially calcium carbonate, dissolved in ground-water. If the climate has a pronounced wet season the salts will be washed away, but can be deposited in the groundwater discharge areas as *hardpans* of calcium carbonate. (UNESCO, 1984)

### 3.3 WATERBEARING FRACTURES

In the dry areas of the tropics where the potential evaporation often is much higher than the rainfall, the available water is mostly found as groundwater. The metamorphosed and igneous rocks seldom have any *primary porosity*, but *secondary porosity* due to fractures and weathering forms the groundwater aquifers.

When searching for groundwater in hard rocks (igneous and metamorphic rocks), the fractures with the maximum storage capacity are the most interesting. To find these a tectonic model for the fracture pattern has to be established.

The fracture pattern of the cratons originate mostly from the stresses of large scale orogenic movements. These stresses have a similar influence on all hard rocks. If they are too big rupture of the rock develops a fracture pattern. *Shear fractures*, which are a result of movement along a plane, develops at an angle of around 45 ° with the main compressional stress direction. Often two intersecting shear planes develop under the same stress conditions (see fig 3.3.1).

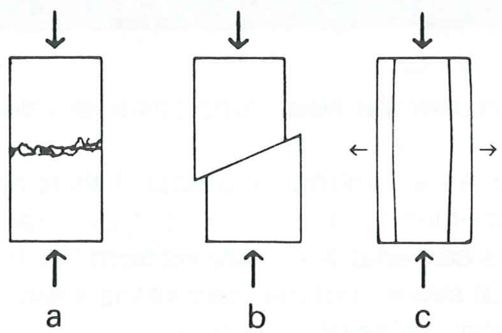



*Fig 3.3.1 Behaviour of rocks under compression: a) compressive failure, b) shear failure, c) tensional failure (Ollier, 1984).*

Along the compressional stress direction *tensional fractures* develop due to parting and dilation perpendicular to the compressional stress direction. These tensional fractures are mostly the open and potentially waterbearing ones. However, dykes often fill up these tensional fracture (UNESCO, 1984). Dykes are important indicators of fracture directions (see fig 3.3.2).

If different fracture patterns with different generations of dykes can be seen, it's important to determine the youngest, since its tensional fractures often are the most waterbearing ones.

The zone between the dyke and the adjacent rock is often fractured and waterbearing. Dolerite dykes are often more resistant to weathering than adjacent rock and can impede groundwater flow from crossing directions. However, in conjunction between dykes and greater fractures, groundwater can often be found. (Clark, 1985)

*Fig 3.3.2 Dolerite dykes rising over the weathered basement near Manama.*

The ideal tectonic model requires an isotropic material. This is often the case on a regional scale, but local properties of the rock, as its type, grade of metamorphism and structures can enable deviations from the fracture pattern (UNESCO, 1984). Such a local steering of the fractures is seen in gneisses and schists, which often shear along planes of weakness.

The vertical extension of waterbearing fractures is limited, but the lateral extension varies a lot. The massive and rather brittle granites split into few,straight and persistent fractures, which have a good hydraulic continuity over long distances. These often large fractures have a high porosity and thereby a high storage capacity for groundwater.

Compared with intrusive rocks, metamorphic rocks, as gneiss, often have small fracture systems, that die out and are replaced by fractures of the same structural system, but which are not in hydraulic continuity. These fractures have a low storage capacity. Strongly folded gneiss areas are very poor aquifers (UNESCO, 1984), since the rock under these circumstances often has a reinforced strength and isn´t easily fractured (Larsson, 1967). Rocks which are of high metamorphic grade are usually strongly recrystallized, and therefore very compact and sparsely fractured.

A hydraulic continuity can exist between different parallel fractures, especially in areas with different major fracture directions.

In arid and semi-arid climates deep weathering is often restricted to zones of fractured rock, where deep percolation is possible (Clark, 1985). This weathering increases the storage capacity of the fractures. When enough groundwater is circulating in the fractures, a saprolite weathering profile can be formed (see fig 3.2.2.1). Its upper clayey part has a high porosity and a low permeability, which slow down percolation into the fractures. At the base, where more coarse grained weathering material intersect with the fresh fractured rock, a higher permeability enables the best groundwater outtake.

If the groundwater flow through the weathered fractures hasn´t been sufficient, unremoved clays prevent a good permeability and groundwater outtake. However, according to Clark (1985), it's not uncommon with a high porosity and permeability in weathered granite and granitoid gneisses, since weathering of these rock types doesn't give high proportions of clay minerals.

Groundwater recharge depends of course on the annual total rainfall, but in hard rock areas of low relief with arid and semi-arid climates, which have a high potential evaporation, the intensity and duration of the rainstorms are the central factor. A lot of the rainfall leaves the ground surface as run-off and reaches the streams. Groundwater recharge by infiltration from streams dominate in very dry areas (UNESCO, 1984). Fracture aquifers are then recharged, since rivers and streams tend to follow fracture lines.

The major water quality problem in fracture aquifers is that of man-made *pollution*, often from fertilizers, since the open recharge paths through the fractures mean that there is little protection against pollution (Clark, 1985). Except for the pollution the principal problems are caused by high concentrations of *chloride, iron and flouride.*

Generally the quality of groundwater in the Basement Complex is good, with a low salinity (Clark, 1985). Hard rock weathering hardly contributes to the chloride concentration in groundwater (UNESCO, 1984). However some processes can lead to build-up of solutes. These are evaporation, transpiration, in situ leaching and hyperfiltration (a process by which the transport of some solutes is retarded by interaction with clay minerals ). The latter two would be favoured by the typical subdued topography and limited depth of active groundwater flow systems in basement terrain (BGS/ODA). Also if the groundwater circulation is very local, i.e. when water in one set of fractures doesn´t connect with that in other sets, a local enrichment of salts is favoured (UNESCO, 1984).

This kind of shallow groundwater in basement terrain may have a high iron content because of solution of iron from lateritic soils. Iron is frequently mobile and may be transported considerable distances as colloids (BGS/ODA).

Flourine is relatively enriched in continental igneous rocks, but its solubility is limited by the poor solubility of flourite ($CaF_2$ ). High calcium concentrations favour low flouride concentrations in the groundwater, so when Ca has largely been removed, there is no check on the F content. (BGS/ ODA)

In regions with seasonal recharge from rainfall and with an active groundwater circulation, groundwater quality tends to be best. But where the recharge is small and sporadic and evaporation rates are high, the quality tends to be poor with accumulated salts in the residual groundwater. Commonly in semi-arid and arid regions of the tropics and the sub-tropics, where the annual rainfall is less than about 600 mm, the groundwater in hard rock terrains is often of poor quality with total dissolved solids greater than 3000 mg / l (UNESCO, 1984). The quality of the groundwater may however change when an outtake is made, since the groundwater circulation often improves, which gives a depletion of solutes.

Even if the groundwater quality in crystalline bedrock aquifers is sometimes rather poor, it´s mostly better than the in dry areas less frequent alluvial aquifers, and much better than water from open dams and rivers.

# 4 SAND DAMS

## 4.1 THE PRINCIPLE

In semi arid areas where there is very seasonal rainfall and there are no boreholes connected to aquifers like fracture zones in the basement rock, people have to stick to the shallow groundwater and try to store it in some way. This can be done by two different types of groundwater dams that are suitable for developing countries:

- *Subsurface dam* and (fig 4.1.1)
- *Sand dam* (fig 4.1.2)

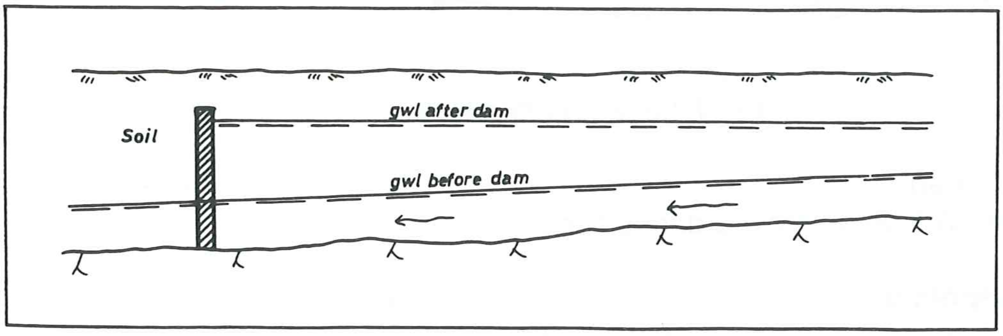



*Fig 4.1.1 Subsurface dam (Modified from Destouni and Johansson, 1989)*

The *Subsurface dam* is built as a barrier in the river alluvium below the surface in order to stop the natural groundwater flow.

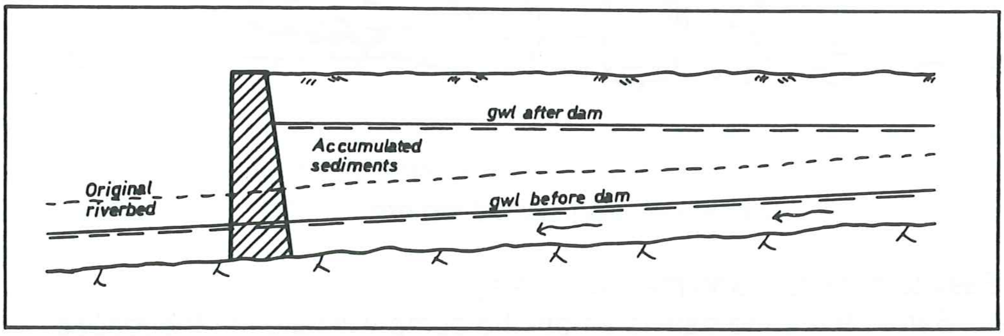



*Fig 4.1.2 Sand dam (Modified from Destouni and Johansson, 1989)*

The *Sand dam*, which is the only type considered in this project, is built as a weir in a stream or in a river preferably on top of bedrock in order to create a new reservoir. The construction is carried out in the dry season. The water speed will be reduced by the weir during flood and this will cause coarse material transported by the water to settle upstream the weir. Every year some decimeters of material is accumulated and eventually there is a new manmade aquifer built up, which will store the water for use in the dry season.

To get the dam functioning as well as possible it's very important to found the concrete weir on bedrock and also get it connected to solid rock at both ends. This is to get the wall resistant to flood situations and to keep the leakage under the weir as low as possible. (Destouni and Johansson,1989).

To get the water out of the sand dam there are basically three different kinds of extraction systems.

**1 Hand dug wells** with perforated concrete rings or stone rings

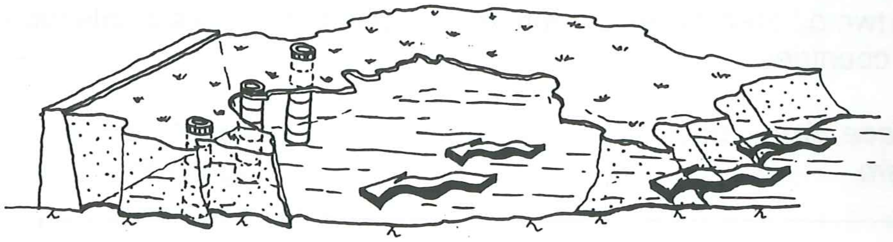


*Fig 4.1.3 Hand dug wells.*

Advantages: Cheap.
Disadvantages: Will be destroyed during flood.

**2 Vertical wellpoints**

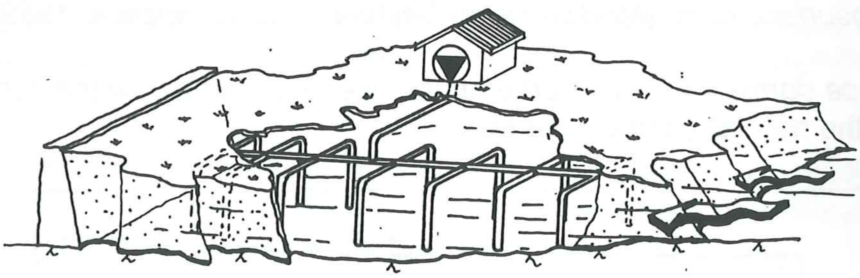


*Fig 4.1.4 Vertical wellpoints.*

Advantages: Easy to construct and maintain the system.
Disadvantages: Before the sand dam is empty the pump will take in air because of too low groundwater table, and that will damage the pump.

**3 Horizontal pipes**

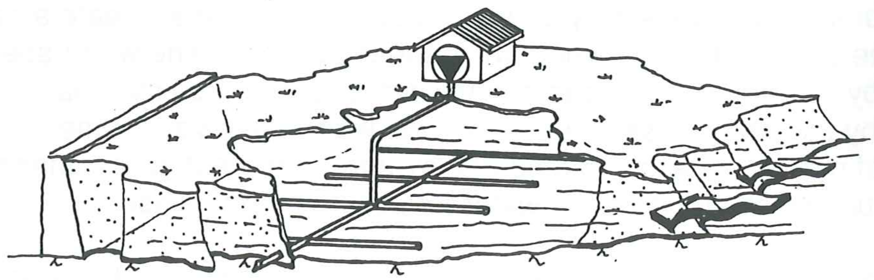


*Fig 4.1.5 Horizontal pipes.*

Advantages: It's possible to get as much water out of the sand dam as possible because of the location of the pipes at the bottom of the aquifer.

Disadvantages: Hard to build because it demands digging below the groundwater table. Hard to repair and maintain the system without digging the pipes up.

Expensive.

## 4.2 PURIFICATION

A big advantage compared to an open surface dam is the purification the sand causes, and it's made in two ways. Mechanically, the sand prevents all big particles from reaching the extraction system, and through the filtering also a lot of suspended and dissolved material will be accumulated on the sand grains. (Englöv and Nilsson, 1979)

The other way of purifying the water is biological. There will pretty soon be a thin film of micro-organisms growing on the surface of the sandgrains. These micro-organisms acts as the purification system as they feed on bacteria and other organic material in the water that percolates through the sand down to the extraction system. (Hammer, 1986). The micro-organisms are essential because in the rural area there seldom exists any artificial purification, and in many places a lot of cattle walk the riverbed in the dry season doing what they have to do. Some villages are also sending their unpurified outlets into the river.

## 4.3 LOSSES

The rain that will fall during only three or four months of raining every year has to last for the people for the whole year. However, the water is very hard to collect and are lost in four different ways that all causes a drawdown of the groundwater table.

The losses are:

* Extracted quantity of water
* Evaporation
* Seepage
* Transpiration

### Extracted quantity of water

The amount of water that will be extracted from the sand dam varies a lot depending on type of extraction system, pumps, the transmissivity of the material in the sand dam, etc.

## Evaporation

Evaporation losses from a sand river bed occur at high rates immediately following saturation, with the rate decreasing as the groundwater table drops. Results based on experiments carried out by Wipplinger (1958 ) show that when the depletion of the the grondwater table is about 1 m the evaporation stops (fig 4.3.1). (Wipplinger, 1958).

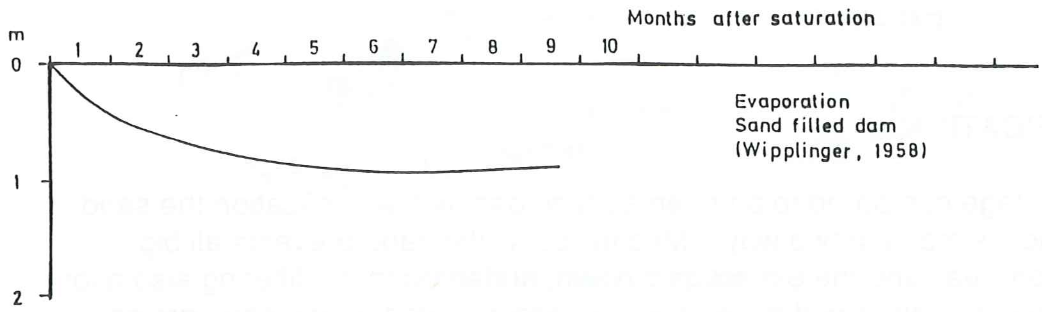



*Fig 4.3.1 Evaporation, sand filled dam. (Wipplinger,1958)*

## Seepage and transpiration

Seepage losses are controlled by the permeability and porosity of the bedrock, and since we're handling gneiss/ granite, especially the degree of fracturing. There's also a leakage possibility at the connection between the weir and the bedrock.

To estimate the rate of the seepage it's necessary to make a water budget analysis. See chapter 7.2.6.

The transpiration losses via the root system is very hard to estimate and it's very much varying between different sand reservoirs, type of vegetation etc. However, the effects of transpiration are likely to be more pronounced in small river channels. ( Owen, 1989 ).

# 5 PRESTUDY

## 5.1 LINEAMENT STUDY

In the prestudy for this project the only available material about the area was *aerial photos* (in the scale of 1:25 000 and 1:65 000), *Landsat satellite images* (1:250 000) and the large scale *geological maps* for Zimbabwe (1:1000 000). Detailed geological maps from the Manama area have not been avaliable.

As a first part of the investigation we accomplished a lineament study. A *lineament* is a large scale linear feature, which expresses itself in terms of topography. These linear features are often controlled by faulting or jointing and may thus be zones with a higher waterbearing capacity. They are marked on the aerial photos by drainage patterns, vegetation lines and changes in tone (Greenbaum, 1987). The lineament study gave us a tectonic model to use in the field study, since the large scale fracture pattern often coinside with small fractures visible in the field.

The available satellite image gave a regional view over the area, with the main lineaments and geological setting. Four main geological areas are visible : In the lowlands south of Manama the Karoo basalts cover everything (see fig 2.4.2). Between this area and Manama the NE to SW trending structures of the Limpopo Mobile Belt are clearly visible. From around Manama and about 30 km northwards the Older Gneiss Complex makes up the geology, relatively structureless and flat. North of this zone the Antelope greenstone belt trends east to west.

The main lineaments, taken from the satellite image, combined with fault and shear lines from the geological map, show three main directions. Clearest are the shear lines in the high grade metamorphic Limpopo Mobile Belt, trending from NE to SW. The drainage pattern of the small rivers east of Manama coinside with this direction in the nearby bordering Mobile Belt. This shear zone is cut by large fault lines, trending WNW. They continue very distinctly through the Older Gneiss Complex area, though turning to NW in the north. The direction of these lineaments coinside with the direction of the Shashi river and the Antelope and Gwanda greenstone belts. The Tuli river cuts through the area in a SSE direction. It forms a lineament, mostly very straight, in a direction typical for all major rivers south of Bulawayo. It can be seen on the geological map as fault lines, cutting through all the different zones of the basement.

On the larger scale of aerial photos these lineament directions are still valid (see fig 5.1.1). They are mostly traced in the drainage pattern of small rivers, whose flowpaths are probably controlled by fault lines. The WNW trending lineaments are clearly dominating the area, controlling the drainage direction of rivers west of the Tuli river and controlling the bends of the rivers east of the Tuli. The small inselbergs SE of Manama extend in this direction.

The rivers east of the Tuli, roughly coinside with the lineament direction of the Mobile Belt towards the NE, but often have a deviation from this direction, which may result from more fold structurally controlled lineaments. Otherwise the only fold structure pattern around Manama is the arcuate extent of the hills around Mount Msandane.

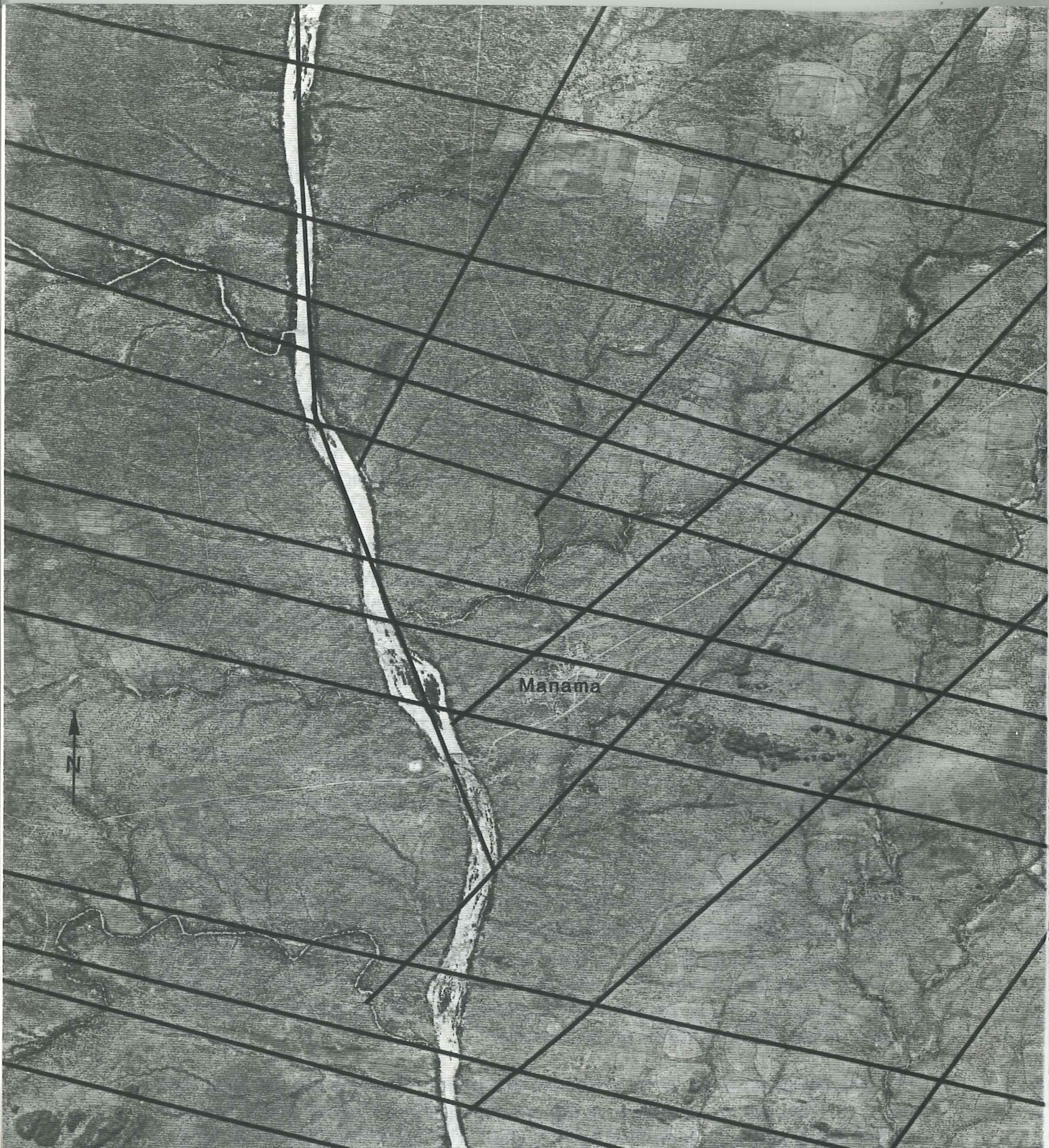



*Fig 5.1.1 Major lineaments for the area around Manama.*

## 5.2 BOREHOLES AND WELLS AROUND MANAMA

In order to obtain information about geohydrology and geology in the area we visited the Well archive at the Ministry of Energy and Water Resources Development in Harare. Below is a list of the information about some of the boreholes that should be in the area. The information is obtained from drilling protocols. We have added the distance to Manama Mission. Sstone stands for Sandstone and BC stands for Business Centre.

| Borehole NO | Date | Total depth (m) | Depth to water (m) | Yield (l/h) | Casing diameter (mm) | Material from top to bottom | Distance (km) from Manama | Location |
|---|---|---|---|---|---|---|---|---|
| B 3560 | 100484 | 50 | 16 | 6000 | 150 | Sstone/Basalt/Granite | 3 | Manama BC |
| B 3561 | 280584 | 42 | 6 | 8000 | 150 | SoftHardstone? | 25 | Hwali BC |
| B 4244 | 030388 | 60 | dry | dry | - | Sstone/Granite | 3 | Manama BC |
| B 4155 | 291187 | 65 | 10 | 666 | - | Granite | 22 | Kafusi |
| B 3688 | 310585 | 60 | 10 | 4500 | 150 | Sstone/Basalt/Sstone | 10 | - |
| B 3687 | 241084 | 48 | 43 | 2500 | 150 | Soft Sstone/Hardstone | 15 | Zenzele |
| B 3704 | 120785 | 36 | 6 | 3100 | 150 | Granite | 10 | Mnyabezi school |
| B 4482 | 130689 | 60 | 14 | 460 | 125 | Overburden clay | 15 | Mpaya school |
| B 4483 | 070689 | 40 | - | 6 | 125 | Overburden/Sandgranite | 25 | Bulobela dam |
| B 3957 | 040786 | 60 | 4 | 9000 | 125 | Basalt/Granite | 25 | 6km north Bulobela |
| B 3559 | 020884 | 50 | - | 4186 | 150 | Granite | 22 | Kafusi |
| B 3296 | 250684 | 36 | - | 6000 | 150 | Granite | 22 | Kafusi |

Table 5.2.1 Borehole data

The data obtained from these drilling protocols are very peculiar. For example, many of the rock types discribed do not exist in the area.

The yield is estimated through a very short pumping test, ~ 6 hours, thus telling nothing about long time yield, only about hydraulic conductivity close to the borehole. There is also a check if the water level returns to original level after the completed pumping test. This check gives the same information. Concerning the location of the two holes at Manama BC we noticed that these were incorrectely marked in the well archive map. One thing deduced from the information above is that water is often available and not very deep down.

Two of the holes (B 3560 and B 4244) were located in Manama BC, only 3 km east of Manama Mission. We later found out that the hole that wasn't dry worked for several years with a hand pump fitted to it. Later an electrical pump was fitted in the hole, which emptied it in a couple of months. This caused concerned authorities to remove the pump. We checked the water level in this hole. It was 20 meters below the ground surface on the 25-06-90.

In the surroundings of Manama there are some wells which were excavated through digging or blasting.We were told that several of them did not work properly.

Within the mission station there are three wells. Two of these are dry, but the third is used successfully for small scale irrigation in the school area. This well is not very deep, about 8 meters. It yields about 10 cubic meters per day.

### 5.3 WATER QUALITY

The tap water in Manama was tested through LWF, Bulawayo by Criterion Laboratory, Bulawayo. Below is a modified copy of the results.

---

Samples taken : 7-9-89
Samples received: 8-9-89
Particulars : Tap water from Manama Mission extracted from the Tuli river.

Results : (As mg/l where applicable)

General : Cloudy with suspended particles

| | | |
|---|---|---|
| Conductivity | (mS/m) | 24.5 |
| pH | | 7.4 |
| Turbidity | (NTU) | - |
| Total Hardness | ($CaCO_3$) | 179 |
| Calcium | ($CaCO_3$) | 113 |
| Magnesium | ($CaCO_3$) | 66 |
| Sodium | (Na) | 6.5 |
| Potassium | (K) | 2.0 |
| Iron | (Fe) | 2.40 |
| Manganese | (Mn) | 0.11 |
| Alkalinity | ($CaCO_3$) | 112 |
| Chloride | (Cl) | 9 |
| Sulphate | ($SO_4$) | 76 |
| Phosphate | (P) | 0.7 |
| Ammonia | (N) | 0.3 |
| Nitrate(N) | (N) | 0.5 |
| Flouride | | 0.8 |
| Approx dissolved salines | | 150 |
| Oxygen absorbed 4h 27°C | | 0.6 |

| Bacteriological Patogen. | Plate Count / ml | Coliforms / 100 ml | Faecal Col. / 100 ml |
|---|---|---|---|
| LAB. Ref APA 29 Proteus | TNTC | + | + |

TNTC = Too numerous to count

Remarks: Chemically, the parameters tested are in accepted range exept for iron which is too high and is likely to impart unpleasent tastes and odours. Bacteriologically, the water contains high numbers of viable bacteria in addition to the presence of coliforms, faecal coliforms & pathogenes. This water should be adequately chlorinated/disinfected to reduce the plate count to below 100 and to rid the water of the coliforms and pathogenes before consumption.

---

*Table 5.3.1 Tap water quality in Manama.*

This test was carried out just after the wellpoints had been relocated. During this relocation leaves and perhaps other biological/bacteriological contaminations got in to the location pit. Knowing how the biological purification process in a sand filter works (see chapter 4.2) one can expect that the bacteriological quality of the water in this test is not representative for normal conditions. During normal conditions the water should be of better (bacteriological) quality. Another fact that indicates this is that we (like many others in Manama) drank the water directely from the taps during our whole stay without getting sick.

# 6 FIELD STUDY

## 6.1 PLANNING

### 6.1.1 Definition of the task

**Fracture zones**

The one and only purpose was to find waterbearing fracture zones. The common way to do that ( except for the traditional stick )is to use different geophysical instruments with which it's possible to profile the area. To get the best result it's preferable to locate the profiles perpendicular to the fractures. That gave us the following tasks;

* Find the supposed direction of the fractures and get a clear view of the local fracture pattern and geology.

* Choose geophysical methods.

* Find the waterbearing fractures.

**Sand dam**

Our aim for Manama sand dam, Tuli river, was to find out;

* the volume of the aquifer,

* if the aquifer is split in more than one basin and, if so, find the unused ones,

* the type of material in order to estimate its porosity and permeability,

* if there is any leakage,

* type of extraction system that is used in it.

### 6.1.2 Investigation plan

To answer the above questions we decided to use the methods and instruments stated below.

**Fracture zones**

* Rock mapping

* Fracture mapping (direction of fractures and foliation)

* Geophysical methods ; 1 Slingram

2 VLF

3 Resistivity

The Slingram and VLF give similar information but we chose them both to make a comparison between their suitability for this kind of job and area.

**Sand dam**

* Leveling the dam and its surroundings.

* Sounding with steel rods.

* Leveling the groundwater surface from constructed groundwater pipes.

* Soil sampling

* Personal discussions with people in charge of the extraction system .

### 6.1.3 Time schedule

Our total stay in Zimbabwe consisted of eight weeks, of which we spent the first one in Harare and the other seven in Manama.

**Week 1**

The first week we spent in Harare discussing the project with our tutor Richard Owen, borrowed some geophysical instruments from the Ministry of Energy and Water Resources and collected a lot of other useful information that we needed.

**Week 2**

It´s very important to know the area that will be investigated and that´s why we spent the second week reconnaissancing and fracture- ang geology mapping an area of about five by five km, with Manama in the centre.

**Week 3-4**

Because we wanted to find out the depletion of the groundwater table in the sand dam, by leveling the surface of it in constructed groundwater pipes, we were very eager to get these pipes down as soon as possible. Therefore we spent week three and four, which were the hottest weeks, down on the riverbed leveling, sounding, getting the pipes down and collecting soil samples.

**Week 5-7**

In the four weeks that was left we had to cover quite a big area in order to find waterbearing fracture zones. That meant at first three weeks major profiling in a gridnet all over the area with our two "fastest" geophysical instruments, Slingram and VLF.

**Week 8**

The last week we spent on short geophysical profiles in the most interesting areas which we had found through our results from the major profiling. We now added our Resistivity instrument to the profiling.

## 6.2 METHODS - GROUNDWATER IN HARD ROCK

### 6.2.1 Fracture and geological mapping

As a first part of the field work in searching for groundwater in hard rocks, a fracture mapping together with a geological mapping has to be carried out. In fracture mapping the *strike direction* of every fracture and, if it's possible to measure, the *dip* of the fracture are measured with a compass. All fractures larger than a certain minimum (mostly around 2 m) size should be measured, and if the fracture is very clear and unweathered, or if it's part of a fracture zone, this should be recorded.

The examination of fractures in bedrock outcrops reveals the correlation of the local fracture pattern with regional lineaments. Mostly these patterns coincide and show the same main fracture directions, which decide in which directions the geophysical investigations should be carried out.

A geological examination of the bedrock outcrops, where facts as *rock type, grain size*, *colour, fracture infillings* and structural components as *folding and fissility* are recorded, can give a hint of what kind of aquifer to expect and where to find it. These properties, which can vary a lot, can also explain deviations from the main fracture pattern.

A dyke is a geological feature, which is one of the most important parts of a tectonic model in hard rock.The strike direction of the dyke must be recorded, as well as the width and its variation along the dyke.

### 6.2.2 Geophysics

Two of the methods used in this survey are the VLF-method and the Slingram-method. They are both electromagnetic (EM) methods.

Electromagnetic methods rely on the principle that the secondary EM-effects (induced field) are measured when a radiowave (primary field) passes through the ground.

If an in time varying electromagnetic field is produced on the surface of the ground, currents will flow in sub surface ground conductors in accordance to the laws of electromagnetic induction. These currents give rise to secondary electromagnetic fields which distort the resultant field observed at any point on the surface. In general the resultant field, which may be picked up by suitable search coil, will differ from the primary field in intensity, direction and phase (see fig 6.2.1) and reveal the presence of a conductor. (Parasnis,1979)

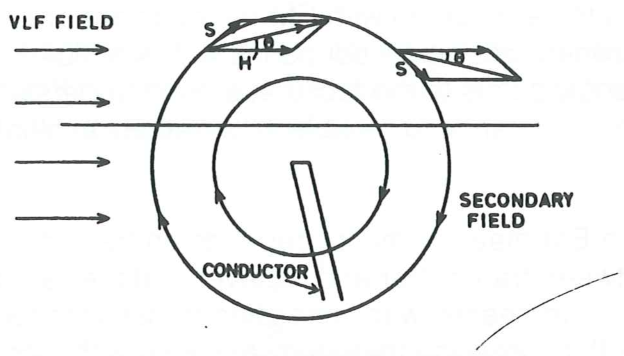



*Fig 6.2.1. At the presence of a conductor the primary field (VLF-field) will give rise to a secondary field (see fig 6.2.2). (Parasnis,1979.)*

The secondary field S in an observation point differ generally from the primary (P) field in question of phase.

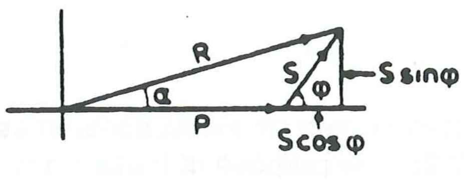



*Fig 6.2.2. Phase diagram. The x-axis represent P's phase, while S in this case phasewise is ahead P with the angle . (Parasnis, 1986).*

It is customary to express the real (Re) and the imaginary (Im) components of the induced signal as percentage of the primary field amplitude.

Some advantages  of EM-methods (generally) compared to other geophysical methods are:

- Fastness in field.
- The equipment is not heavy.
- No contact with ground needed.

Some of the disadvantages are:

- Certain geological formations or combinations of formations can make the evaluation of the data more or less impossible. For example, a conductive overburden such as clay can shield off underlying conductors of interest from the primary field making these hard to detect, or several conductors close to each other will interact and make the results hard to evaluate adequately.

- Human made conductors such as electrical cables, metal fences and water pipes will disturb the measurements thus making measurements in such areas meaningless.

Examples of conductors to be detected with EM-methods are ore deposits, water bearing fracture zones, geological boundries with significant resistivity difference etc. This strongly points to the fact that a good understanding of the geology in the area is of importance to be able to correctely evaluate the data obtained.

The penetration depth in EM-measurements depends on transmitting frequency, distance between transmitter and receiver and the resistivity of the ground. Penetration depth increases with increasing transmitter-receiver distance. It increases with decreasing frequency and also with increasing resistivity in the ground.

The geophysical investigation is carried out by measuring along profiles in the terrain.

The field data is presented as graphs plotted to the distance. One is not looking on isolated values but for a sequence of values with a significant shape. These are called anomalies.

**The VLF-method**

The VLF-method uses transmitters located far away, sometimes up to ten thousand kilometers (see fig 6.2.3). The purpose of these transmitters is to communicate with military submarines. Transmitting frequences are ranging between 15 to 30 kHz. For radio applications these are  very low frequences, hence the name VLF.

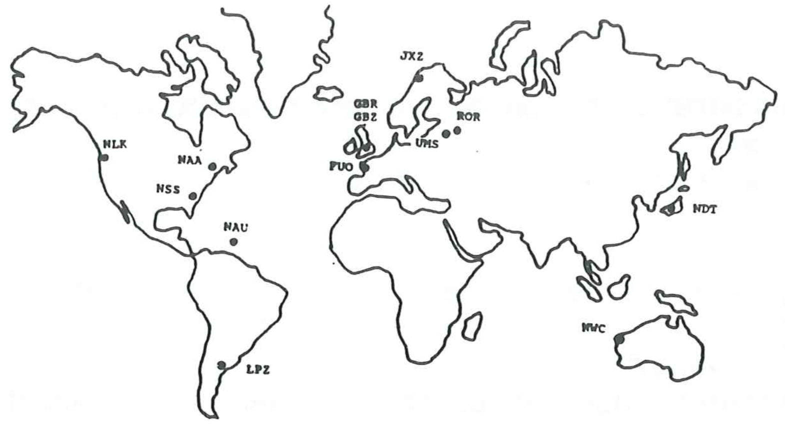



*Fig 6.2.3. Commonly used VLF transmitters. (Fransén et al, 1988.)*

For detection of conductors in the ground the optimum location of the transmitter is in the strike direction of the conductor and in order to obtain significant anomalies the measuring profile should cross the conductor perpendicular.

During ideal conditions (good receiving conditions and a very long uniformed conductor) a VLF-anomaly from a sheet conductor, for example a water bearing fracture zone, could look like shown below.

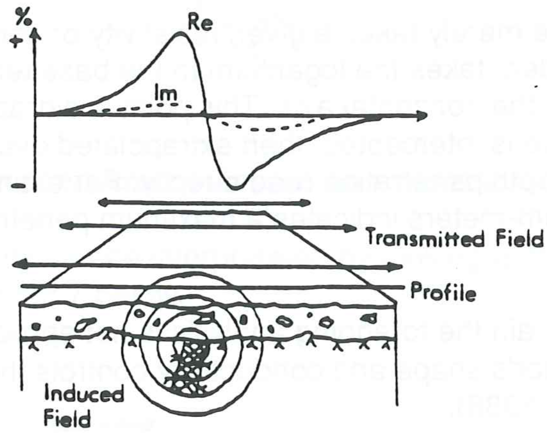



*Fig 6.2.4. An ideal VLF-anomaly over sheet conductor. (Follin,date unknown.)*

The current systems that are induced in geological conductors such as ore deposits, water bearing fracture zones etc are very complex (Dahlin, 1987). This makes more detailed interpretations of the anomalies a bit hazardous.

Some interesting things to know before evaluation of VLF-anomalies are stated below.

*Penetration depth*

To determine the depth penetration in conductive terrain the following chart can be applied (see fig 6.2.5).

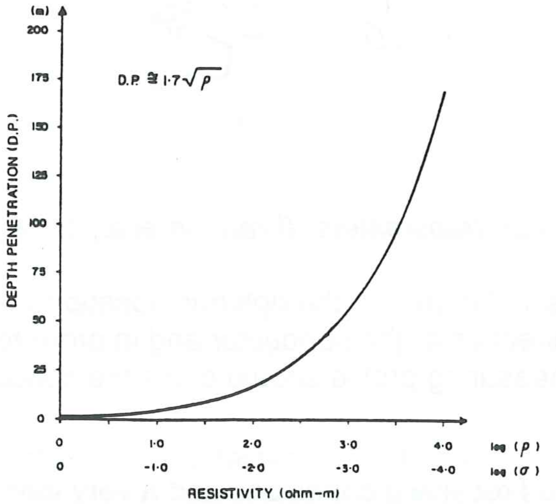



*Fig 6.2.5. Depth penetration diagram for VLF. ( Wright, 1988.)*

To use the chart, one merely takes a given resistivity or conductivity for the host rock and/or overburden, takes the logarithim to the base ten (log) of it and locates this value on the horizontal axis. This point is extrapolated directly upward until the curve is intercepted, then extrapolated over to the vertical axis, and the maximum depth penetration read directly. For example, a host resistivity of 1000 ohm-meters indicates a maximum penetration of 55 meters (Wright, 1988).

In highly resistive terrain the foregoing analysis is not applicable. In these situation the conductor's shape and conductivity controls the maximum depth of detectability (Wright, 1988).

If the medium surrounding the conductor is only partially shielding the target, then the maximum detection level is a complex combination of these two cases. Indeed, a whole host of other factors such as; electrical noise, geological noise, instrumental resolution, and even operational procedures affect the maximum limit of detection depth (Wright, 1988).

*Receiving conditions*

Receiving conditions are effected by the distance to the transmitter. In Zimbabwe, with very long distances to the main VLF-transmitters around the world, the signal is quite low. This makes the receiving conditions sensitive to atmospheric background noise.

*The complexity of the geology*

Every anomaly should be considered as the result of the summed effect of all existing secondary EM-fields. For example; two conductors close to each other will distort the anomalies over each conductor and make detailed evaluations of the anomaly difficult.

With an understanding for the above stated there are several more detailed interpretations that can be made.

Depth to the top of a sheet conductor can be approximated to h=ΔX/2 according to the fig 6.2.6 below. However, if strike length or depth extent is limited, this can change to become equal to the full distance between peaks . (Wright, 1988.)

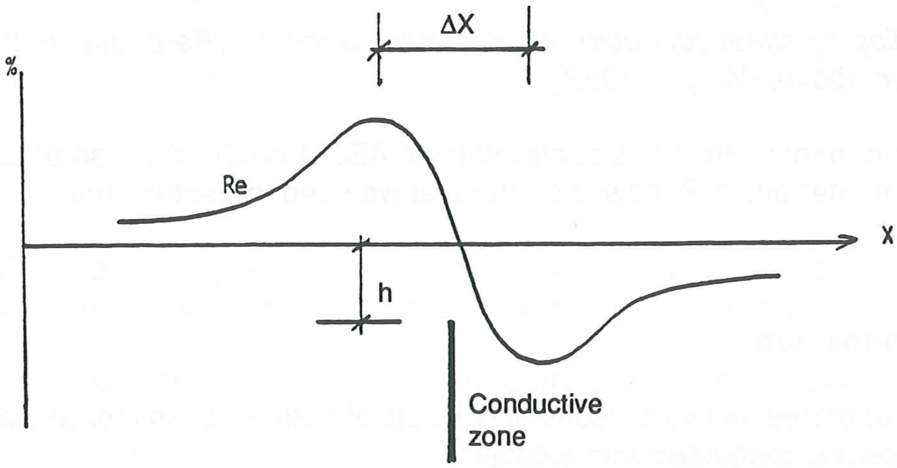



*Fig 6.2.6. Depth to sheet conductor. (Hansson and Jeppsson, 1982.)*

The degree of conductivity can be interpretated by looking at the Im-phase in an anomaly shown in figure 6.2.7 below.

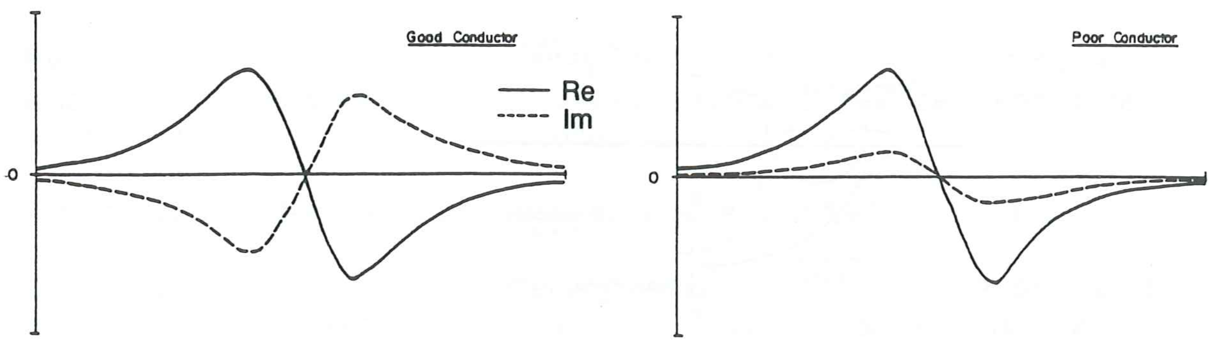



*Fig 6.2.7. Good conductor contra poor conductor. The shape of the left anomaly can also be caused by a conductive overburden - for example clay with water content. (Wright, 1988.)*

If the sheet conductor has a dip, this can be interpretated sometimes (see fig 6.2.8).

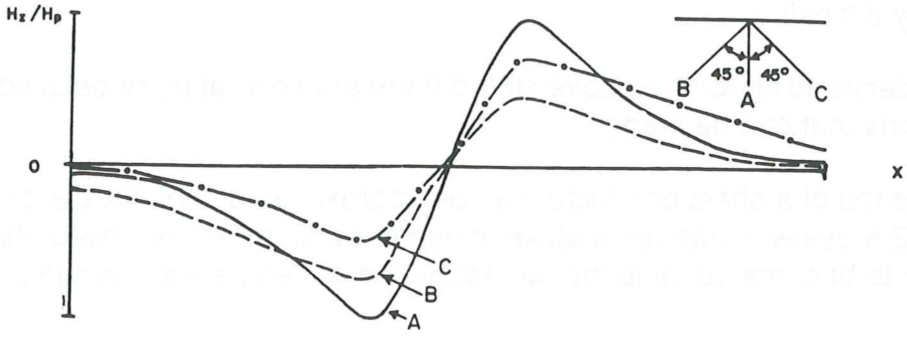



*Fig 6.2.8. A dipping sheet conductor will distort the anomaly (Re-phase) in the manner shown above. (Wright, 1988.)*

The VLF - instrument used in this survey was an ABEM WADI. We also brought a portable computer and a Bondwell printer that we used for plotting the anomaly-graphs.

### The Slingram-method

A slingram is operated by two persons. It consists of both a transmitter and a receiver. These are connected with a cable.

An EM-field (primary) is produced through the transmitter coil, when profiling is done over a conductor the primary field will cause the conductor to produce a secondary field (see fig 6.2.9). The receiver registrates how the total field varies from the primary field.

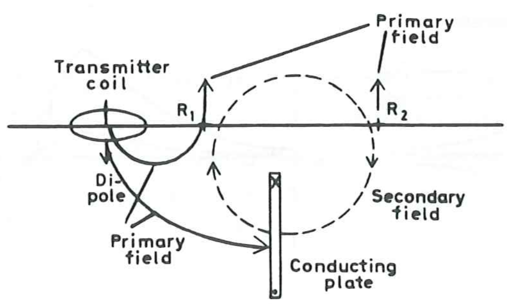



*Fig 6.2.9. When profiling over a sheet conductor with a Slingram the transmitted primary field will give rise to a secondary field. (Parasnis, 1979.)*

The cable is used to keep a constant distance between the transmitter and the receiver, and for sending a reference signal giving information to the receiver about the transmitted primary field.

One can choose different cablelength. The length will effect penetration depth and of course field handling. Common for water prospecting is 60 meters, which was used in this survey.

During ideal conditions a slingram-anomaly from a sheet conductor (for example a water bearing fracture zone) could look like shown below.

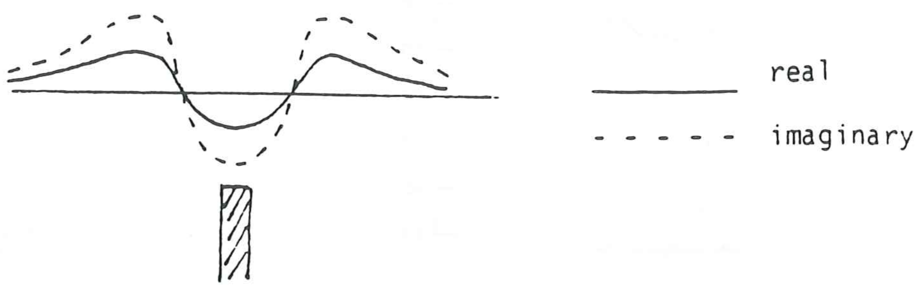



*Fig 6.2.10. Ideal Slingram-anomaly over a vertical sheet conductor, for example a water bearing fracture zone. (Jämtlid, date unknown)*

As mentioned earlier the conditions in field are seldom as the ideal case.

Some interesting things to know before evaluation of slingram-anomalies are done are stated below.

*Penetration depth*

The penetration depth is generally said to be 0.7 x cable length during good conditions.

*The complexity of the geology*

Every anomaly should be considered as the result of the summed effect of all existing secondary EM-fields. For example; two conductors close to each other will distort the anomalies over each conductor.

*Errors in spacing between transmitter and receiver and their orientation*

It is of importance that the transmitter and receiver coils are coplanar orientated. It is also of interest to know that profiles made in steep terrain will require a compensation of the measured values. Of great importance is that the spacing between transmitter and receiver is kept constant. especially the Re-values are sensitive to spacing errors; a spacing error of 2 % will cause a 6 % error in the Re-value (Keller, date unknown).

With an understanding for the problems mentioned above there are some more detailed evaluations that can be made from the slingram-anomaly.

Depth to conductor can be sometimes be interpretated by looking at the shape of the anomaly. As showed in the figure below, a shallow buried conductor will cause an anomaly with larger amplitude than a deeply buried conductor.

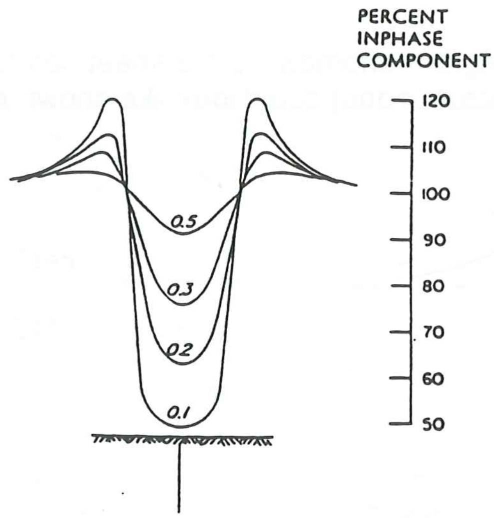



*Fig 6.2.11. Slingram anomlies observed over vertical sheet conductor for various d/r. d is depth of cover, r is the receiver-tranmitter distance. (Keller, date unknown.)*

The dip can also sometimes be interpretated if very clear and significant anomalies has been obtained (see fig 6.2.12).

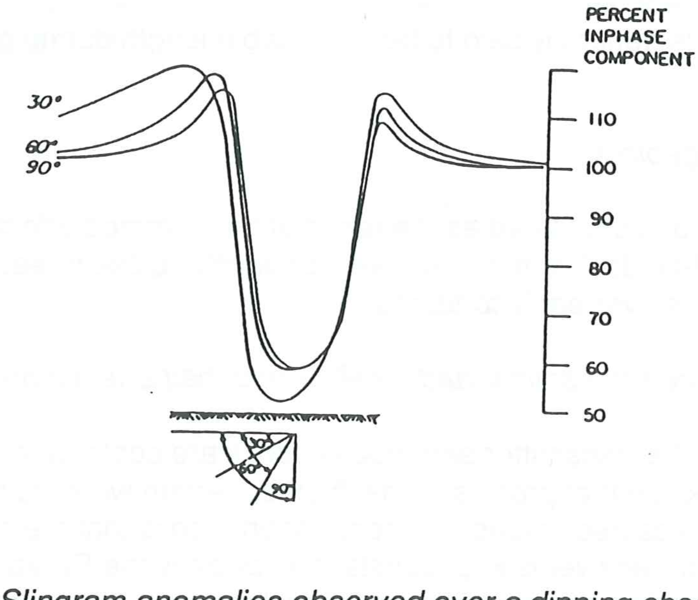



*Fig 6.2.12. Slingram anomalies observed over a dipping sheet conductor. (Keller, date unknown.)*

To interpretate if it is a good conductor (for example an ore body) or a poor conductor (a water bearing fracture zone) one can compare the Re-phase with the Im-phase in the anomaly. As showed in figure 6.2.13 a poor conductor will have a larger amplitude in the Im-phase compared to the Re-phase.

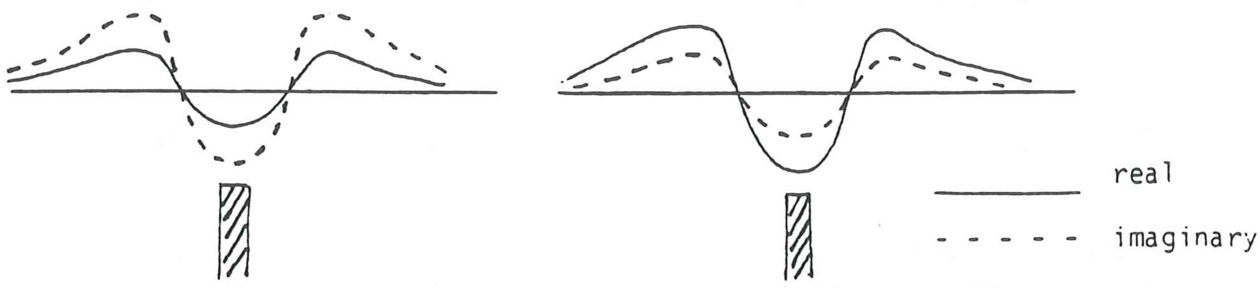
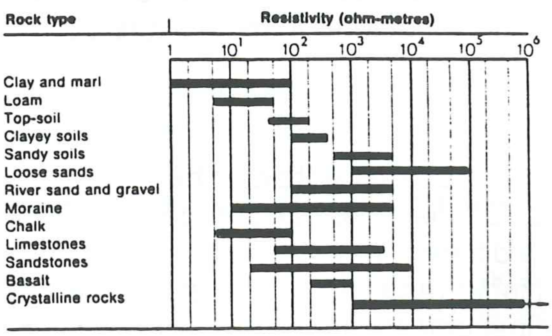



*Fig 6.2.13.A poor conductor (left) compared with a good conductor (right). (Jämtlid, date unknown)*

The instrument used in this study was a ABEM Slingram 3600, with a transmitting frequence of 3.6 kHz. It was borrowed from the Ministry of Energy and Water Resources Development in Harare. As mentioned earlier it is operated by two persons and needs recharging after one day of field work.

## Resistivity methods

Resistivity is a material constant depending on the capability of electric conductivity in the material. This capability will vary for different kinds of soils and rocks and with the water content of these materials (see fig 6.2.14). The resistivity increases with decreasing conductivity. Water bearing fracture zones and soils below the ground water table will have low resistivity compared to the surrounding ground.




| Type of water | | Resistivity in ohm-metres |
|---|---|---|
| Meteoric water, derived from precipitation | | 30–1000 |
| Surface waters, in districts of igneous rocks | | 30– 500 |
| Surface waters, in districts of sedimentary rocks | | 10– 100 |
| Ground water, in areas of igneous rocks | | 30– 150 |
| Ground water, in areas of sedimentary rocks | | larger than 1 |
| Sea water | | about 0.2 |
| Water for human use | (highest permissable salt content 0.25‰) | larger than 1.8 |
| Water for irrigation and stock watering | (highest permissable salt content 0.7 ‰) | larger than 0.65 |

*Fig 6.2.14. Resistivity of soils and rock (left) and natural water (right). (Kollert, 1969.)*

Two types of the configuration of the electrodes are common for resistivity measurements, the Schlumberger configuration and the Wenner configuration.

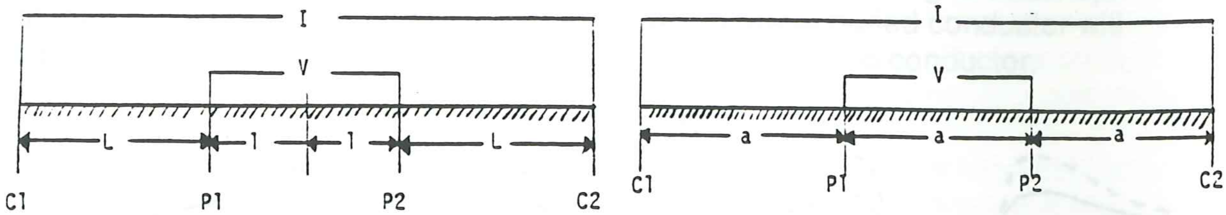



*Fig 6.2.15. Schlumberger (left ) and Wenner configurations. (Olsson and Jönsson, 1982)*

In both configurations four electrodes are used. By applying current through the ground between the two outer electrodes and measuring the potential between the inner electrodes, resistivity can be calculated.

Schlumberger configureation is usually used for vertical sounding. This means measuring how the resistivity varies vertically in one point.The current electrodes are moved outwards symmetrically while the potential electrodes are fixed.

Often, the Wenner configuration is used for resistivity mapping. Mapping means measuring how resistivity varys along a profile in the terrain. An electrode array with fixed electrode distance is moved along the profile.

If the ground consists of materials with different resistivity, which it almost always does, the resistivity achieved is an apparent resistivity. This is an average resistivity of the different material's resistivity. For vertical sounding, when resistivity in different stratas has to be calculated, the following assumptions are made:

- The strata are homogeneous conductors.
- The strata have horizontal and parallel boundries. (Kunetz,1966)

These assumptions are hardly fulfilled in the geological settings expected around a weathered fracture zone in igneous rock covered with an overburden. This indicates that sounding to obtain the depth to the basement rock can be hazardous. Resistivity mapping on the other hand, is still suitable for detections of resistivity differences along a profile, thus indicating fracture or/and weathered zones containing water.

**Penetration depth**
If there is only one strata aproximately 50 % of the current will pass the middle point of the configuration within the depth of L. On the other hand, if there is a two layer strata the penetration depth will vary in a different way. Generally one can say that if there is a two strata situation with higher resistivity in the upper layer, then the penetration depth will increase. The instrument used in this study was an ABEM Terrameter SAS 300 which was borrowed from the Department of Engineering Geology, University of Lund. It can be handled by one person but preferably by two persons.

## 6.3 RESULTS - GROUNDWATER IN HARD ROCK

### 6.3.1 Fracture and geological mapping

In search for bedrock outcrops, a reconaissance in an area of about 3 km in radius around Manama was carried out. Three areas, suitable for fracture measurment, were found (see fig 6.3.1.2).

**Area 1**

In this area, from the northern part of the islands in the Tuli River up to the first two connecting rivers, there are frequent outcrops projecting through the sand like big boulders (see fig. 6.3.1.1). Only the larger slabs of rock were big enough for fracture mapping. All the mapped fractures were as minimum some metres long and irregular, curvilinear fractures were ignored.

*Fig 6.3.1.1 Fracture and geological mapping by Mats in Area 1. In the background the boulder-like bedrock outcrops and the Tuli bridge.*

The strike of 260 fractures was measured. The main fracture direction is between 260° and 300°,with a peak at 280° -290° (see fig 6.3.1.3 and fig 6.3.1.4). A majority of the fractures are almost vertical (80° -90°). A set of closely parallell fractures, which sometimes is weathered below the level of the adjacent bedrock, is here called a fracture zone. Eight of nine observed fracture zones in the area have a direction of 280°-290°. A few major dolerite dykes were found in this area. All of them strike in the main fracture direction.

The rock in the area is gneiss, ranging in colour from light red to light grey and grey. The gneiss is medium to coarse grained and often clearly banded, with a foliation trending in many different directions. However, in the mouths of the two connecting rivers the foliation of the gneiss was directed in the main fracture direction.

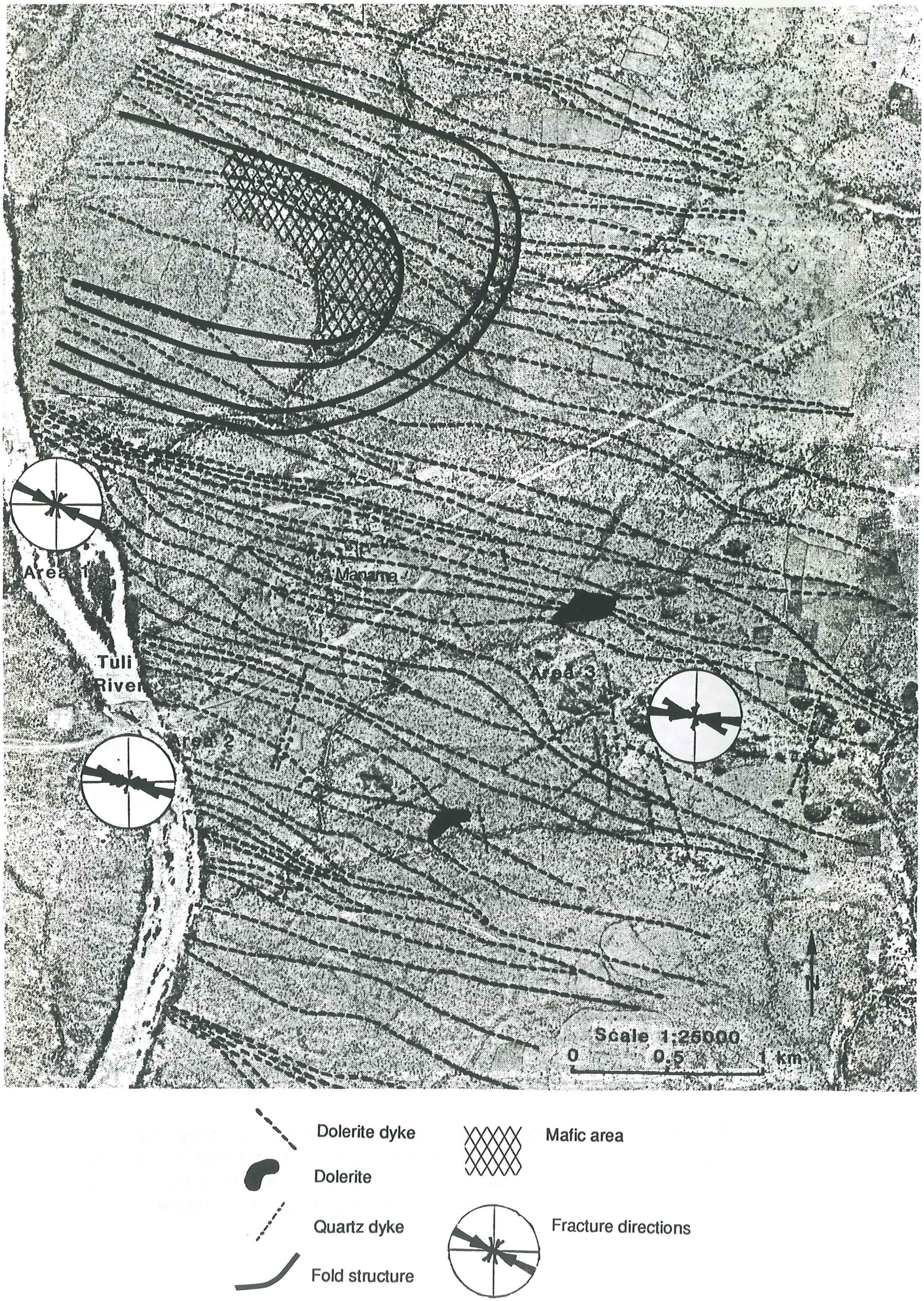



*Fig 6.3.1.2 Geological map of the Manama area.*

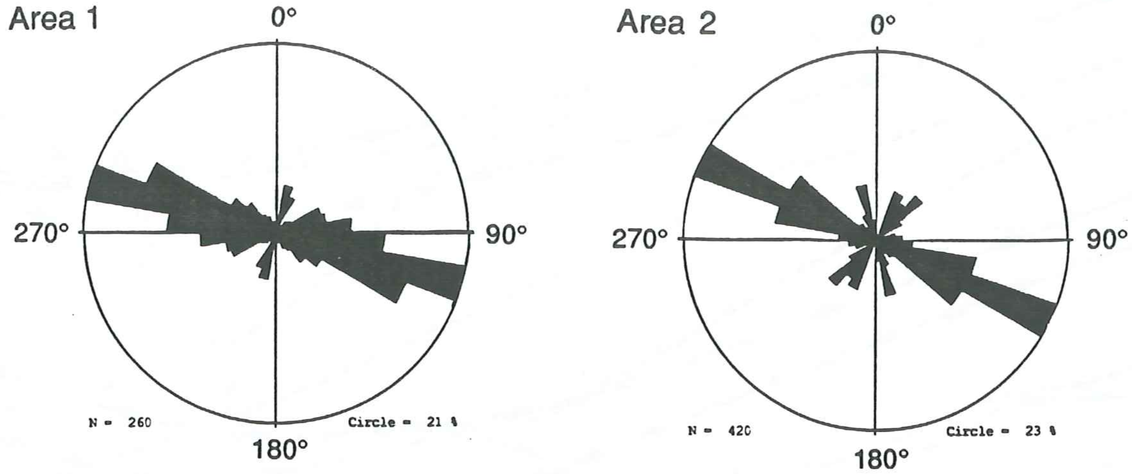



*Fig 6.3.1.3 Fracture directions of Area 1 and 2.*

**Area 2**

This area is located immediately south of the Tuli weir (see fig 6.3.1.5), but it also includes bedrock outcrops around the small river south of Manama. South of the weir the riverbed is almost free from alluvium. Some bedrock outcrops are boulder-like, but most are flat bedrock outcrops with long persistent fractures. A through, about 300 m long and filled with water, is crossing in a direction of around 300°. This structure might be a result of a linear zone of weakness in the rock, that has been weathered and eroded.

*Fig 6.3.1.5 The Tuli weir and bedrock outcrops of Area 2.*

A few wide pegmatite veins were observed in this part of the Tuli riverbed, which all show a direction of about 40 °. The main fracture direction for the second

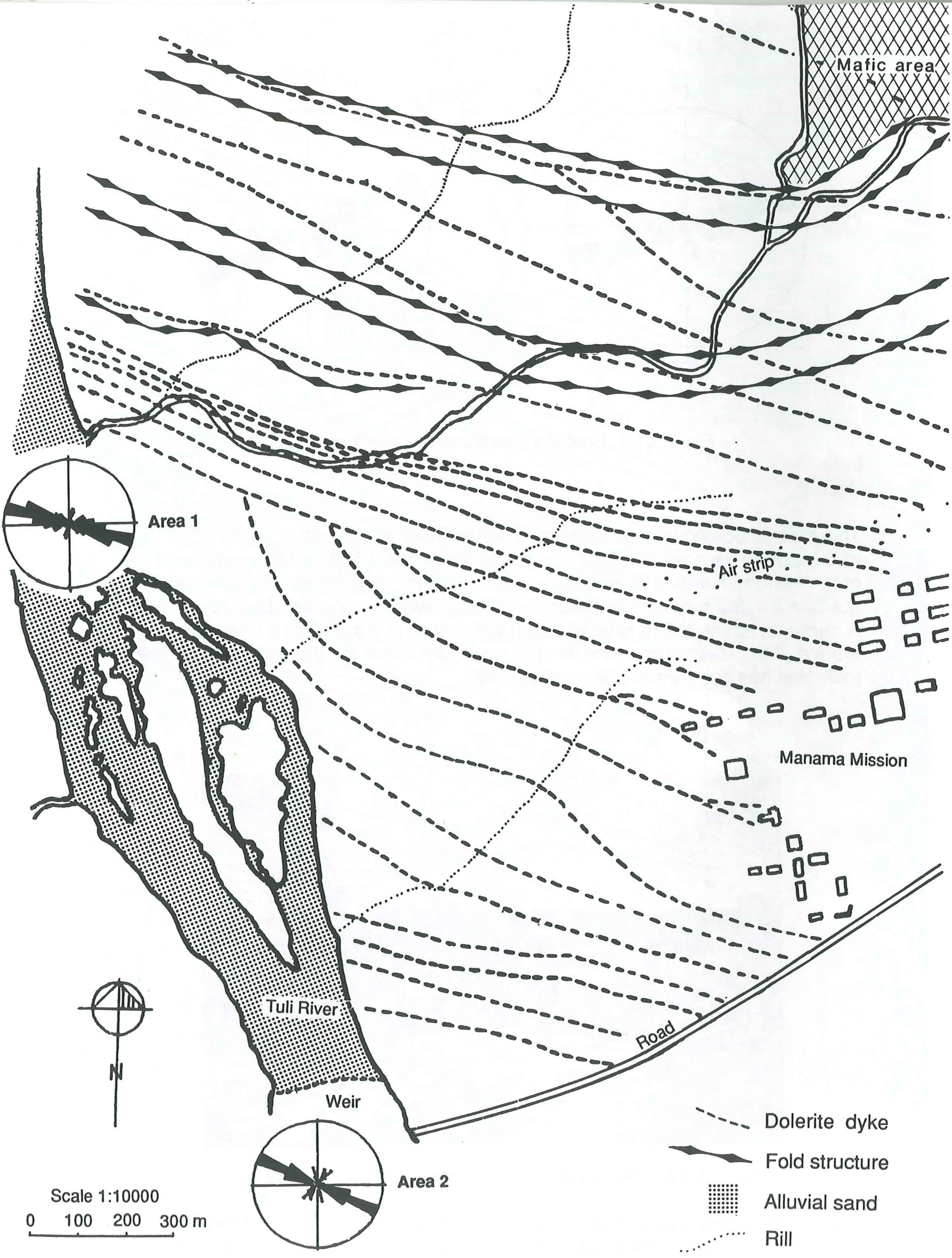



*Fig 6.3.1.4 Geological map for the area west and north-west of Manama.*

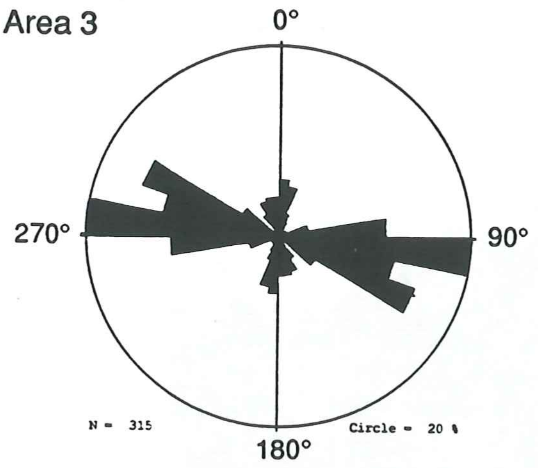
area is in the range of 280 ° - 310 °, with a pronounced peak at 290 ° - 300 ° (see fig. 6.3.1.3). The strike of 420 fractures was measured. The dip was measured for 155 of those fractures, and the majority was about vertical. South of the weir we also found 33 fracture zones, of which a majority coincided with the main fracture direction of area 2.

On both riverbanks close to the bridge quite flat domes of granitic outcrops are situated. These are almost unfractured. Otherwise the rock ranges south of the weir from granitic to gneissic with light grey and red colours. The gneiss is often chaotically banded with intermixed colours. The rocks are medium to coarse grained. Around the small river south of Manama the rock is gneissic, grey and medium to coarse grained.

**Area 3**

The last area for fracture mapping is situated around the castle kopjes SE of Manama. Its flat bedrock outcrops rise insignificantly above the adjacent weathered ground. The rock is gneiss and granitic gneiss, grey coloured and medium to coarse grained. The 315 measured fractures are mainly directed between 260° and 300°. However, the peak in the fracture pattern is lying more easterly than before, in the direction of 270 ° - 280 °. A second peak trends 290 ° -300 ° (see fig 6.3.1.6).

Area 3




Total

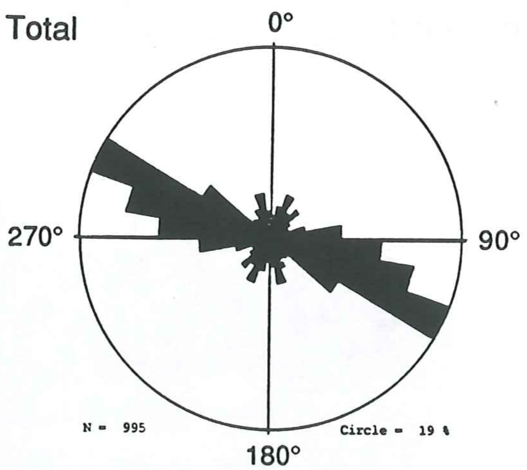



*Fig 6.3.1.6 Fracture directions of Area 3 and the Total area (areas 1,2 and 3).*

The rocks of the kopjes are gneiss with some more granitic parts. They have a very low frequency of fractures.

**Total fracture pattern in the Manama area**

The 995 measured fractures for the whole area (areas 1,2 and 3) shows only one major fracture direction. It´s broad and strike between 260° and 310 °, with a peak at 290° - 300° (see fig. 6.3.1.6). This main WNW direction coincides with the more regional lineament direction seen on the aerial photos.

### The mafic area

The bedrock around Manama consists almost entirely of gneiss and granitic gneiss, though one small area is an exception. About 1 km north of Manama two small rivers meet (see fig 6.3.1.2), and north of this conjunction an area, darker than the surroundings can be seen on the aerial photos. This area is built up of a dark mafic rock with light quartz grains inside it. The rock has been detected as a quartz-hornblende granulite.

In the middle of this area a local miner has blasted out a few holes along a quartz dyke in a search for precious stones and gold. Around this quartz dyke veins of albite can be seen and these two minerals are also chaotically intermixed with hornblende. Considering the high, easily erodable, hornblende content of this mafic area it was surprising to see it rise above the adjacent gneissic basement. However, the rock is very hard and it all seems highly metamorphic. This mafic area had a sharp border to the adjacent gneiss.

### Dolerite dykes

The dolerite dykes are one of the dominating features in the geology around Manama. They were localized and marked on map throughout the survey. This gave us a tight pattern of dolerite dykes, all trending in the same direction as the major fracture direction of the area. The dykes have a spacing not often more than 100 meters and are 10 - 30 meters wide, some even wider. Their width is mostly constant along the length of the dyke. The dykes are continuos, straight and linear through the area and only a few could be seen turning.

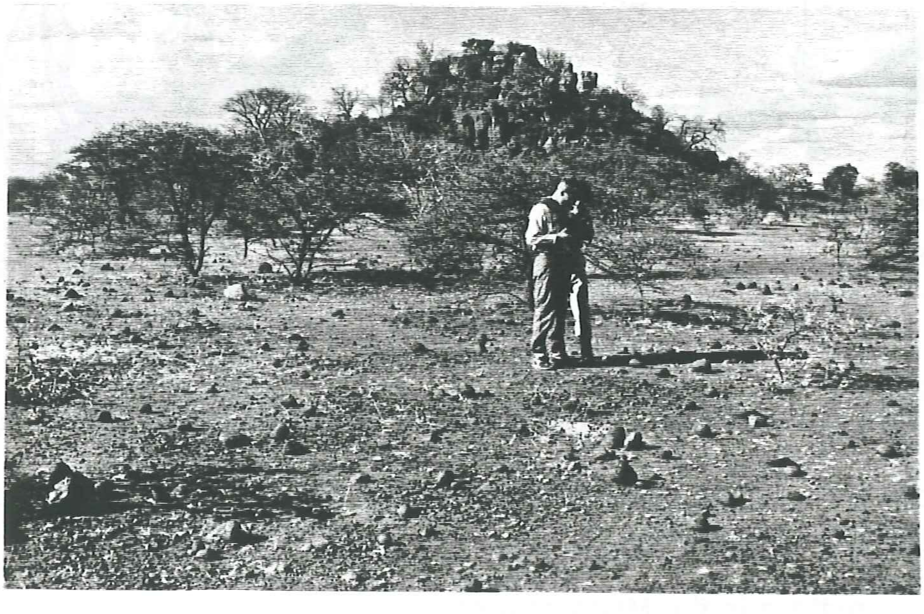
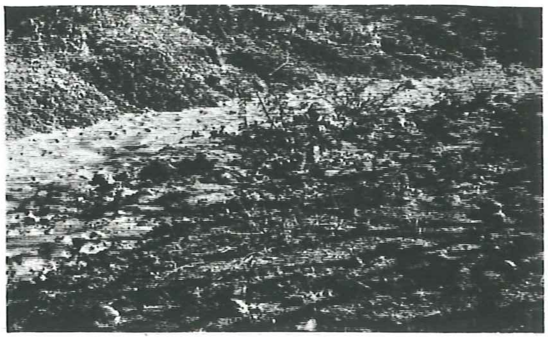


*Fig 6.3.1.7 Geological mapping of a dolerite dyke with its spherical weathered stones. In the background a castle kopje.*

On the weathered ground, the dolerite dykes can be distinguished due to the occurence of brown spherical weathered stones and tiny outcrops of very fractured dolerite dyke (see fig 6.3.1.7). Where the bedrock is better exposed, as in the small rivers and streams, more fresh and unweathered dolerite dykes can be seen (see fig 6.3.1.8). These dykes often show a gradation of mineral and/or rocktype across their width. The outer parts consist of the regular, fine grained dolerite, where contraction-fracturing has resulted in centimeter thick lenses in a direction almost perpendicular to the dyke (see fig 6.3.1.9). Towards the center of the dykes, the composition changes to a olivine-bearing type, which is more coarse grained and due to weathering, yellow to rust-coloured. In some very wide dykes, parts ( often meters wide ) are built up of epidote, sometimes with small quartz veins within them.



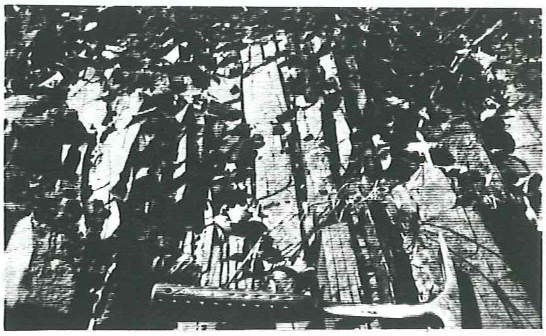


*Fig 6.3.1.8 (left) Alluvium from a small stream running in a dolerite dyke. The stream has eroded its path in the olivine-bearing part of the dyke.*

*Fig 6.3.1.9 (right) Typical contraction fractured dolerite.*

The boundary between the dolerite dykes and the adjacent gneissic basement is in some places very well exposed, and often shows a clear cut boundary between the two. However, in the margin of some wide dykes a transition zone was observed. This zone shows a hybrid rock with a porphyric texture of feldspar and quartz grains and a groundmass similar to the dolerite. This is a result of contact metamorphism, that have "welded" the different rocks together.

A large number of the small rivers and streams, that flow in a westerly to north-westerly direction, run along dolerite dykes. Several of the riverbends, which are turning from SW to west, seems to be governed by the occurence of dolerite dykes.

**Quartz dykes**

Some tens of quartz outcrops were found around Manama. Most of them occur as isolated accumulations of quartz, difficult to trace in any direction as a dyke. However, south of the castle kopjes a few pronounced quartz dykes can be followed in a NNW and a NE or a NNE direction. Two of these can be seen crossing right in between the two biggest castle kopjes (see fig 6.3.1.2). 300 meters south of that point a large accumulation of quartz, between 50 and 100 meters wide, can be observed in a shallow quarry. Here quartz dykes from different directions meet, and also a west-north-westerly dolerite dyke can be seen in the quarry, cutting through the quartz as a proof of that the dolerite dykes are younger than the quartz dykes.

## Fold structures

In the Manama area, which largely miss bedrock outcrops because of weathering, large fold structures in the basement are hard to find in the field. However, after compilation of the field observations and reinterpretation of the aerial photos back home, a large fold structure has been found 1 km north of Manama (see fig 6.3.1.2). On the aerial photos it shows as arcuate formed streakes of darker soil coinciding with river bends, by the vegetation pattern and the pronounced shape of the dark mafic area. The fold seems to be isoclinal, with its legs and axial plane pointing in an almost NW direction.

## Hardpans

Along the small rivers, especially at their lowest part close to the Tuli river, and in the riverbanks of the Tuli south of the dam, deposits of calcium carbonate hardpans were found. These sheets are formed by chemical precipitation from flowing water. They are mostly very hard, have a white or very light brown colour and contain rock clasts of gravel size. At the eastern rivermouth, 1.5 km north of the Tuli dam a 3.5 meters high section of calcium carbonate hardpan was found.

## Soils and weathering

The soils in the area are immature pale-coloured and sandy, without any organic top-soil material. The combination of intense growing, heavy seasonal rains, drought and clearing of vegetation by man seems to cause heavy soil erosion. Everywhere signs of intense run-off can be seen, in form of gullying and small rills. They are however not eroded deep down, since the bedrock is close to the groundsurface (see fig 6.3.1.10). In some slopes close to small rivers, sharp gullies have been eroded to the depth of about one meter. They show a coarse grained weathering profile, not easily eroded, and often bedrock at their base.

*Fig 6.3.1.10 Gully formed by intense run-off.*

All over the area small bedrock outcrops show that the weathering isn´t deep, though a few places indicate a deeper weathering. For instance, one km NW of Manama on the north side of the small river, a white spot can be seen on the aerial photos. In the field it turns up as a flat, vegetation-free and outcrop-free area with an almost white sandy soil, indicating that downward percolating water has leached the soil (see fig 6.3.1.11).

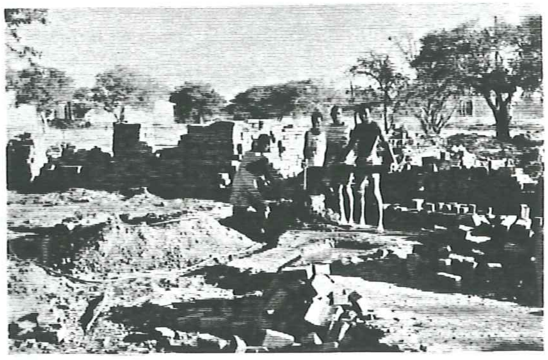


*Fig 6.3.1.11 (left) Area with white sandy soil, probably due to leaching by downward percolating water, indicating deep weathering.*
*Fig 6.3.1.12 (right) Brickmaking at Manama mission.*

Inside Manama village more than one meter deep pits are dug into a clayey soil, which is used for brickmaking. This soil also indicates deep weathering (see fig 6.3.1.12) and is probably a remanent from a period of a more humid climate.

### 6.3.2 Geophysics

The total length of geophysical profiles carried out around Manama was;

30 km of Slingram profiles,
30 km of VLF profiles and
2200 m of resistivity profiles.

We started with a system of long profiles, covering the whole investigation area. The purpose of these profiles was to find interesting areas that should be more thoroughly investigated. In all the long profiles VLF and Slingram were used parallel except when receiving conditions for the WADI (the VLF-instrument) not were suitable. No resistivity profiles were performed in the long profiles since the method is to slow for this kind of general mapping.

The direction of all profiles was chosen in order to cross possible water bearing fractures perpendicular according to the results from the lineament study and the fracture mapping.

In order to get a clear view of the results from the long profiles, the profiles with marked anomalies are presented in an areal photo (see fig 6.3.2.1). On the basis of the results from the long profiles, we selected five areas for more detailed investigations. The location of these areas are also shown in figure 6.3.2.1. Each plotted profile graph can be found along with comments and interpretations in appendix A.


*Figure 6.3.2.1. Aerial photo presenting the long profiles, anomalies and the areas that were chosen for detailed investigations. Scale 1: 20 000.*

The selecting criterias for the areas that were chosen for detailed investigations were:

**Area A**

* Significant and corresponding anomalies were found with both instruments in this area.

* Geologically interesting area because of intersecting streams, possibly caused by geological weakness zones, parallel to a possible secondary northeastern fracture direction.

* Short distance to the Mission, approx 600 m.

* No disturbing manmade conductors in the area.

**Area B**

* The Slingram anomali correlates with the NNE to SSW direction of the small river and the foliation of the bedrock outcrops.

* The area shows a high degree of weathering.

A problem in the southern part of area B was its close location to an electric power cable that gave us limited possibilities to use our geophysical instruments.

**Area C**

* Significant and corresponding anomalies in both instruments.

* A possible fracture, parallel to the major fracture direction, might drain the sand dam.This could mean a substancial yield from a future borehole at location

* Closeness to the existing distribution system.

**Area D**

* Contact between different rock types.

* Intersecting streams possibly controlled by fractures in the contact zone between different rock types.

**Area E**

* Very big, significant and corresponding anomalies in both instruments. Where the anomalies occur, the foliation and the direction of the small stream is parallel to the major fracture direction.

* Where the subsidery in this area connect to the Tuli river, a big wall of cracked up angular blocks was seen. At the same place an open groundwater surface was seen.

* The area show a high degree of weathering.

* No disturbing manmade conductors in the area.

In two of these areas, C and E, we also used resistivity mapping as a supplementary investigation method. The profiles that were carried out in each detail area are shown in the areal photo below (fig 6.3.2.2). The plotted graphs for each profile are shown together with comments and interpretations in appendix A.

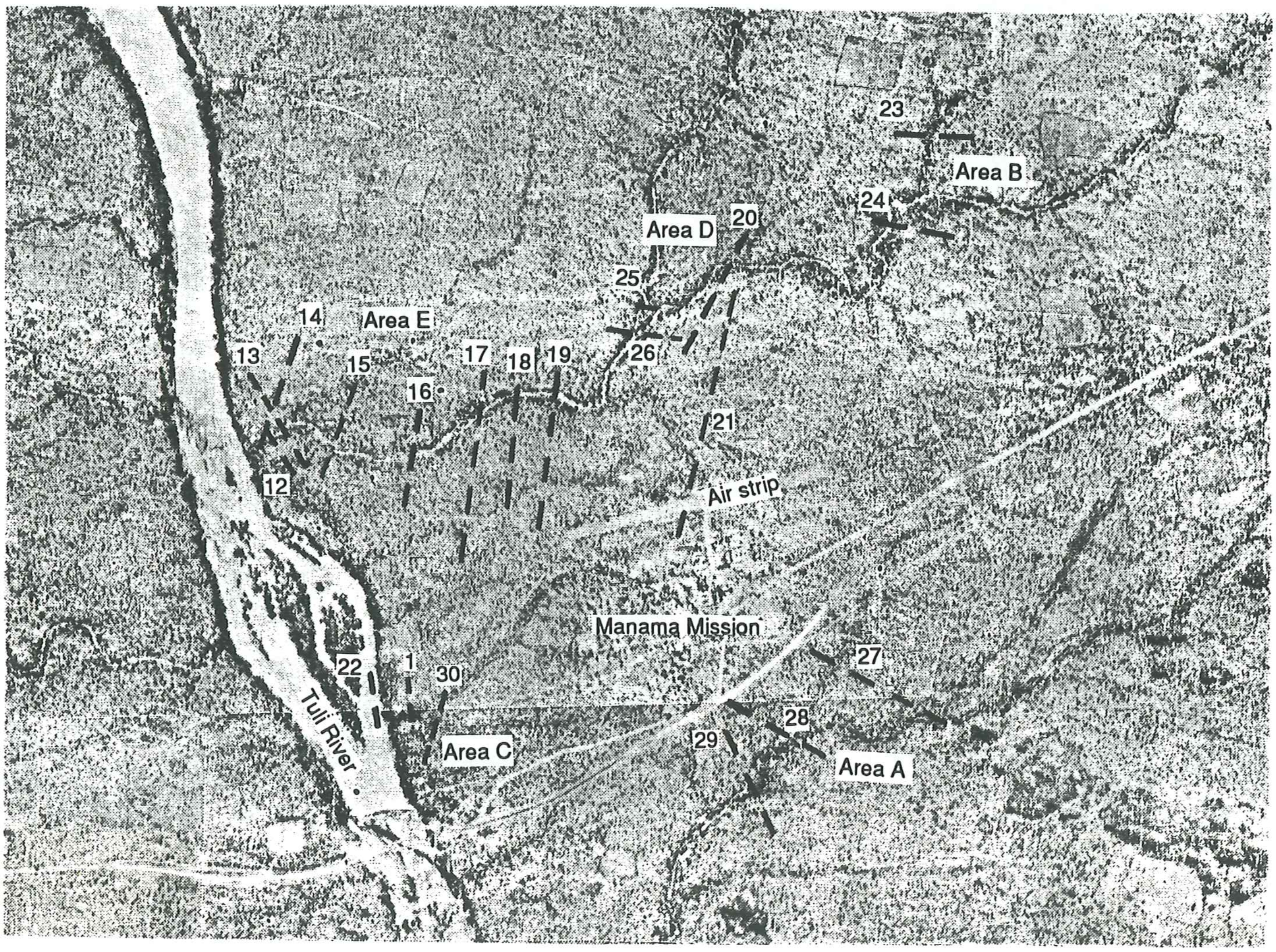



*Figure 6.3.2.2. The profiles perfomed in the selected areas. Scale 1: 20 000.*

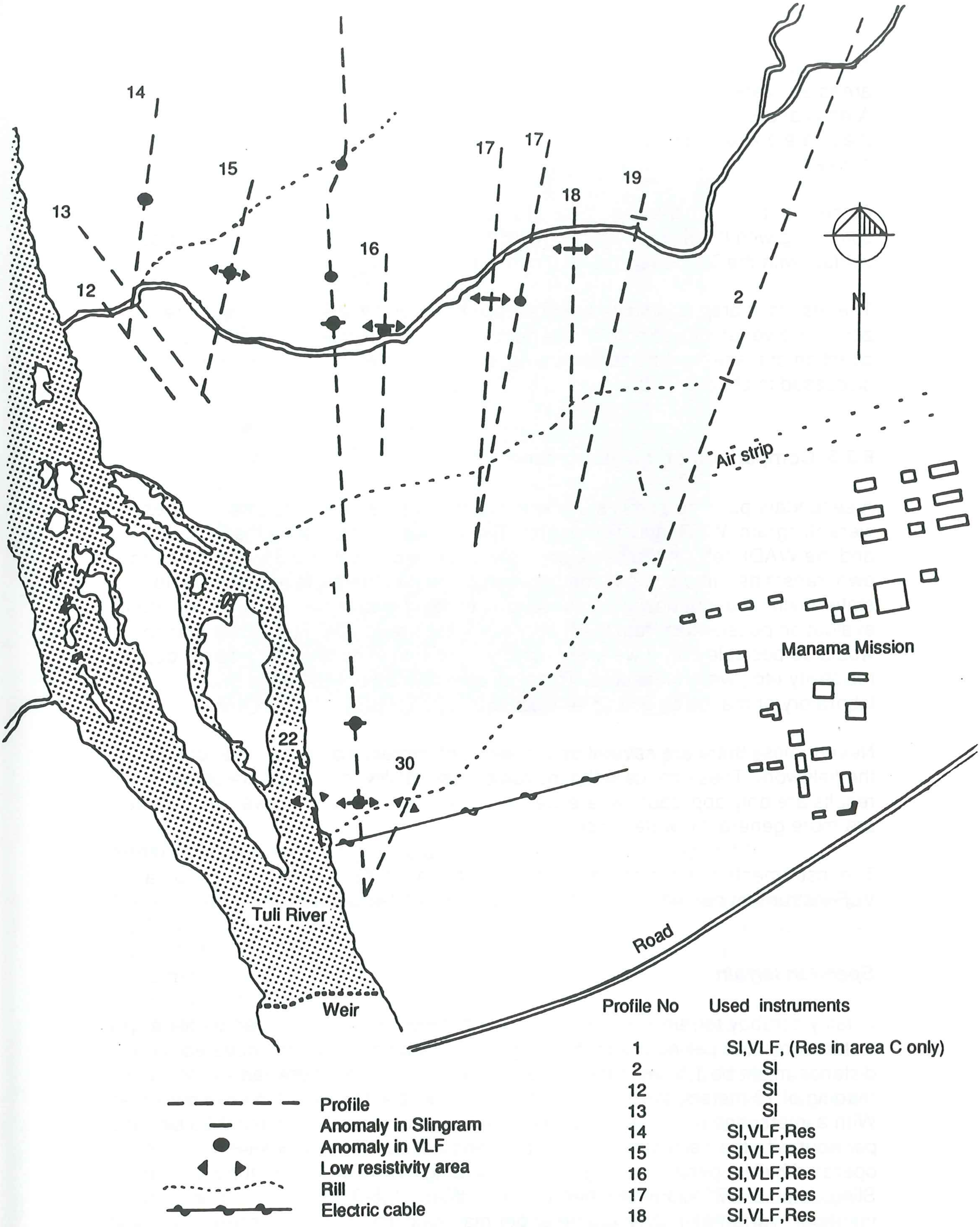



*Figure 6.3.2.3 Anomaly map over the selected areas C and E. Scale 1: 10 000*

| Profile No | Used instruments |
|---|---|
| 1 | Sl,VLF, (Res in area C only) |
| 2 | Sl |
| 12 | Sl |
| 13 | Sl |
| 14 | Sl,VLF,Res |
| 15 | Sl,VLF,Res |
| 16 | Sl,VLF,Res |
| 17 | Sl,VLF,Res |
| 18 | Sl,VLF,Res |
| 19 | Sl |
| 22 | Sl,Res |
| 30 | Res |

Sl =Slingram,
Res = Resistivity

The results from the detailed investigations enabled us to rule out some of the areas as interesting for groundwater exploitation. These areas were A, B and D. Area C and E, on the other hand, showed more promising results. Therefore these are presented in a map (see fig 6.3.2.3) where profiles and anomalies are marked.

As seen in the map, the anomalies in area C indicates a water bearing fracture coinciding with the main fracture direction of the whole area. A possible hydraulic contact with the Tuli River makes it interesting for ground water exploitation.

The results in area E indicate the presence of several water bearing fracture zones. However, based only on the geophysical results, the extension and direction of these fracture zones are not easily interpretated. This will be further discussed in chapter 7, "Discussion and conclusions".

### 6.3.3 Comparison of the instruments

A secondary purpose of this study was to compare the used instruments. These were Slingram, WADI and Terrameter. Two of these instruments, the Slingram and the WADI, rely on the same principle, but one of them, the Slingram, has its own transmitter. In a comparison between the instruments it is not possible to state anything about how good these are in finding conductors and if the different evaluation possibilities from the theory really are applicable. Such a comparison would be possible only if we knew exactly what kind of conductors (shape, depth, resistivity etc ) were measured. This type of study can only be done in a laboratory or maybe by drilling verification.

Nevertheless there are several observations of interest that were made during the fieldwork. These concern the instruments suitability in field. Some of the results are only applicable where we were, the lowveld in Zimbabwe, while some are more general for waterprospecting.

The instruments that the comparison concern are; an ABEM Slingram 3600, a VLF-instrument named ABEM WADI and a ABEM Terrameter SAS 300.

#### *Speed in terrain*

In fairly scrubby terrain, common in the Zimbabwes' lowveld, one can profile a distance of 1 km per hour with the Slingram. Following a road, the covered distance might be 1,5 km in the same time. With a distance between every reading of 10 meters, the figures for the WADI will be 2,5 and 3 km per hour. With a interspace of 10 meters between every reading we performed 0.25 km per hour with the Terrameter. Since the Slingram and the Terrameter is operated by two persons, this gives the following kilometers per manhour: Slingram, 0.5-0.75 kilometers per manhour. WADI, 2.5-3.0 kilometers per manhour. Terrameter, 0.12 kilometer per manhour. The Slingram is the instrument that is most effected by obstacles like vegetation because of the long cable and many times a machete had to be used to make the profiling possible.

Figure 6.3.3.1 shows Mats taking a reading with the Slingram.

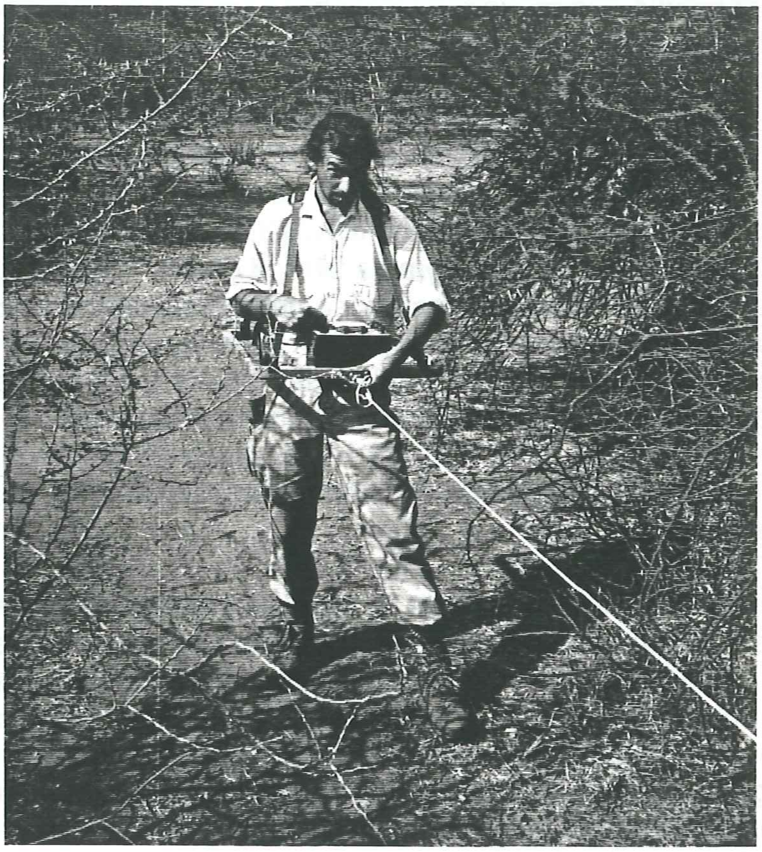


*Fig 6.3.3.1 Mats handling the reciever unit of the Slingram in the sometimes scrubby terrain around Manama Mission.*

### *Sensitivity to electro-magnetic disturbances (Slingram and WADI)*

There is one major difference between the two instruments. As mentioned earlier the Slingram includes its own transmitter, making it very reliable in fieldwork. The signal that is sent by the transmitter is so strong that it is very hard to disturb the instrument. The Slingram was disturbed once during the time we did geophysics ( ~25 days ). According to the manufactor in Sweden, ABEM, this could only be explained by temporary airborn electro-magnetic activity in the area.
The WADI on the other hand, relies on independent transmitters located very far away from Zimbabwe. This causes the signal to be very low and therefore very sensetive to electro-magnetic background noice. In our case the conditions were often so bad that the VLF-instrument was impossible to use. Sometimes the conditions were acceptable but still effected by background noise. Generally the conditions were not acceptable in the noon. In the morning the receiving conditions could vary between acceptable and not acceptable. These conditions have been experienced in similar studies 1988 (Franzén et al, 1988) and 1989 (Persson & Stenström, 1989) in other parts of Zimbabwe.

*Possibility to detect EM-disturbances (Slingram and WADI)*

If there is a disturbance this will cause readings that are not caused by the geology. Since the electromagnetic field behaves according to physical laws, the operator can determine if a change in the readings is caused by a change in the geology or something else, providing that the operator has some understanding of physics, the instrument and the geology.

The Slingram has an analogue needle indicating the value of the reading. This is very direct in the sense that the operator directely sees if there is something "strange" going on.This is not the case with the WADI. The WADI stores every reading digitally and shows it on a display as a filtered graph. This can be of help for preliminary interpretation while profiling during good receiving conditions, but it has an big disadvantage; it alienates the operator from the results. Since the filtered graph sometimes shows false anomalies (not due to geology) because of altered receiving conditions, this "alienation" can be very hazardous.

*Human made conductors*

All of the instruments reacts for conductors. A big disadvantage with electromagnetic methods is that human made conductors, such as metal fences, metal pipes and electric cables will cause big anomalies if a profile crosses such a conductor. These anomalies have so great impact on the measurements that it's no use to do a measurement profile were such conductors are present, for example in a village. Both of the EM-instruments are equally effected. The Terrameter (instrument unit can be seen in figure 6.3.3.2) can be effected by conductors only if these are in electrical contact with the ground.

*Figure 6.3.3.2. Abraham, our assistant and Per during evaluation of performed resistivity measurements. The Terrameter can be seen to the right.*

**Recharging**

The Slingram had to be recharged after approx. 7 hours of operation. This is one or two days of fieldwork. The WADI needed recharging after approx. 30 hours and the Terrameter after 6 hours of fieldwork. Recharge is done over night for all instruments.

**Learning how to operate the instruments**

The Terrameter and the WADI are instruments with several more functions than the Slingram. Still all three instrument are easy to learn how to operate, the Slingram because it is a simple instrument to operate, the two others because they have good manuals.

**Price**

1990 the price for a Slingram was ~ 100 000 SEK, for an WADI it was ~ 35 000 SEK and for a Terrameter it was ~60 000 SEK.

## 6.4 METHODS - SAND DAM

### 6.4.1 Leveling

The leveling of the surface of the dam was made with a WILD leveling instrument rigged on a wooden tripod. Since we weren't interested in the absolute altitude but relative levels between the dam and its surroundings, we didn't need to connect our level system to a real one. As a reference point we used a steel nail in concrete on the solid rock, which they probably used for the same purpose when they built the bridge in 1982. We gave it a relative height of 10 m.

We measured the altitude of the sand dam surface at our gridnet points and continued about 25 meters outside the riverbed on both sides.

*Fig 6.4.1.1 Leveling of the sand dam by Patrich.*

### 6.4.2 Sounding

In order to find out the thickness of the sand layer in the sand dam, a very simple sounding-method was used. We used connectable, 1 m long steel rods with an 8 mm diameter, which we pushed down in the sand by hand force.

First of all we had to start pegging a gridnet all over the dam so that we could find and document the exact location of every sounded point. This gridnet was then used to orientate all of the further sand dam investigations.

### 6.4.3 Groundwater pipes

The altitude of the groundwater table was measured in groundwater pipes that we put down in the riverbed. We also used open pits dug in the riverbed by people from a close village. These holes had a visible groundwater table.

With this measurement we wanted to find out the sinking velocity of the groundwater table and analyse if the dam is split up in different basins. We also wanted to know if there was a drawdown funnel around the wellpoint system.

We had quite a hard time find enough material to make our pipes of. Eventually we had three different types of pipes: (1) Galvanized steel pipes which we cut a lot of slices in, and then tightened to an arrow at the bottom end. Most of the pipes were of this type. The second type was (2) old steel wellpoints of the kind that are presented in the extraction system in fig 6.5.5.2. We also had a few (3) plastic pipes. We could easily hit down the steel pipes with a sledge hammer, but the plastic ones we had to dig down and it was very hard to get them below the groundwater table.

The total number of pipes were 27 and the location of the pipes is visualized in fig 6.5.1. We tried to get some pipes down on the island but the compact material made it impossible.

The altitude of the groundwater table in the pipes was measured two times a week.

### 6.4.4 Alluvial material

In an alluvial aquifere like the sand dam at Manama the primary properties of the material, like *particle size* and *sorting*, determine the properties of the groundwater flow and the porosity. The *porosity* of the material determine how much water the alluvium can hold. If the distribution of the different kinds of material is known, this can explain variations in the *permeability*.

To find out what kind of material a shallow alluvial aquifer concists of, test pits must be dug. The materials of different layers are then classified ocularly and if necessary samples can be taken, for a more exact soil sieving analyse. In this study soil sieving analysis were only made for a few typical samples.

It´s important that the test pits are dug as deep as possible. However, it´s very difficult to dig below the groundwater table.

In the Manama sand dam most of the test pits were located to the southern part, since this part is interesting for groundwater extraction and because most of the groundwater pipes were located there (see fig.6.5.1). Test pits were also dug where a different material was expected, as in the most southern part where a dark and silty material was seen in the surface, and on the islands, where a fine material was expected. To get an as complete picture of the material as possible, the pits were mostly widely spread. However, in a few places there were short distances between the pits, since local changes in the material were expected.

## 6.5 RESULTS - SAND DAM

### Introduction

The results from the investigation will be presented in the same order that they were carried out and completed.

In the map below, fig 6.5.1, you can see the location of the gridnet, which was the orientation base for all the dam investigations, and also identical with the cross sections where we made the soundings.

The map also shows the location of the groundwater pipes and the test holes where we took our soil samples.

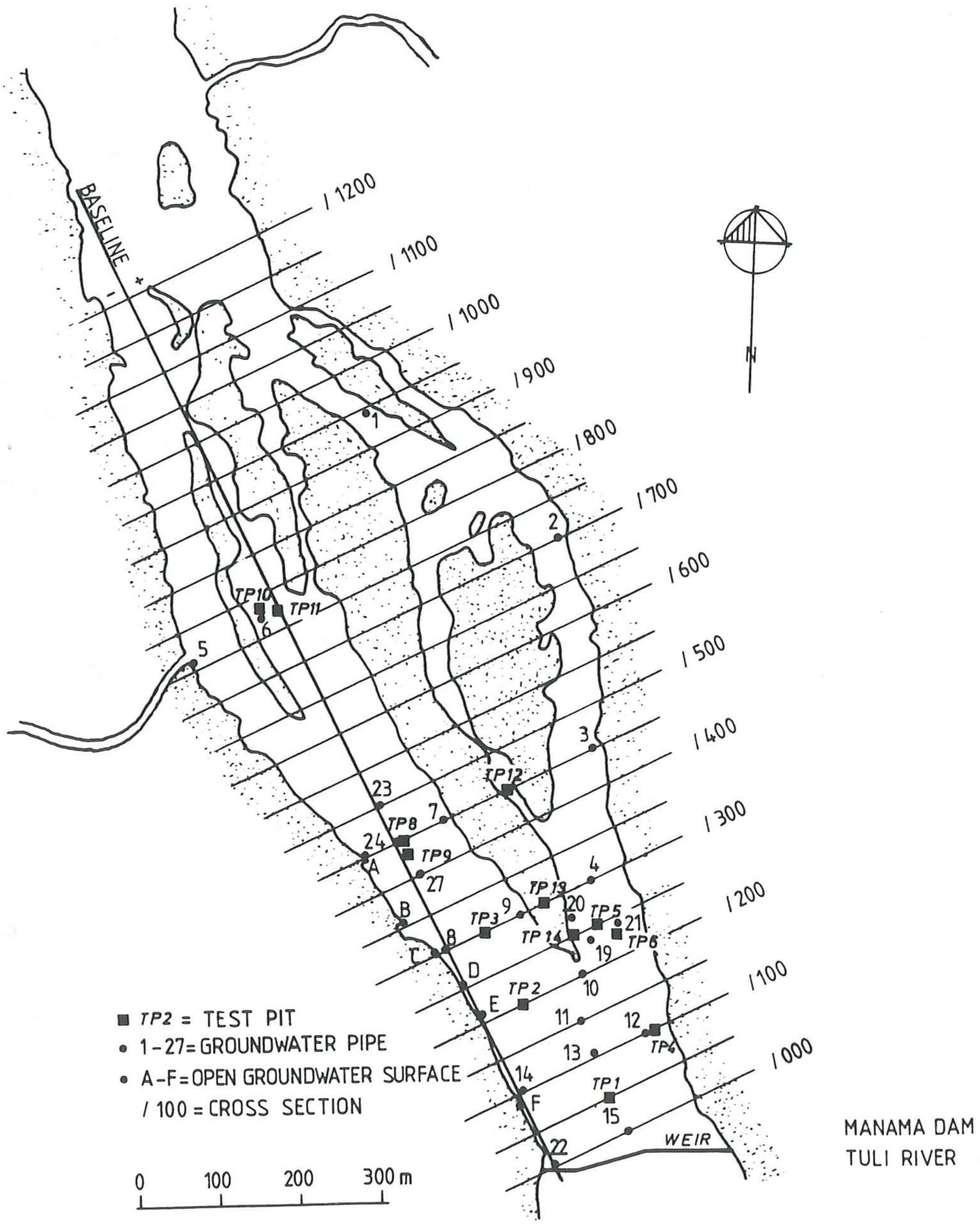



*Fig 6.5.1 Manama sand dam, Tuli river. Location of groundwater pipes, test pits and cross-sections.*

### 6.5.1 Leveling

The leveling of the sand dam gave us the shape of its surface and were also fundamental for the soundings.

### 6.5.2 Sounding

Even though the amount of sounded points added up to more than 200, the material in the dam made it a less hard job than we expected. At about 80 % of the sounded points we felt a very clear stop when we hit the rock. The only places we didn't reach the bedrock at was on the island and at a very few places on the riverbed. The reason was too silty and compact material.

The largest depth between the surface and the bedrock was about four meters and appeared in the southern part of the dam. The altitude of the surface of the bedrock seems to vary quite a lot, especially on the west side of the islands, but without doubt, the more north the sections goes the more shallow the bedrock comes. On the west side of the islands the bedrock goes very shallow in section /950 and on the east side in section /900.

All of the soundings are presented as cross sections in the scale H 1:100 and L 1:1000 in Appendix B. Below we present a few typical sections and also two profiles from the south to the north, fig 6.5.2.1-6.

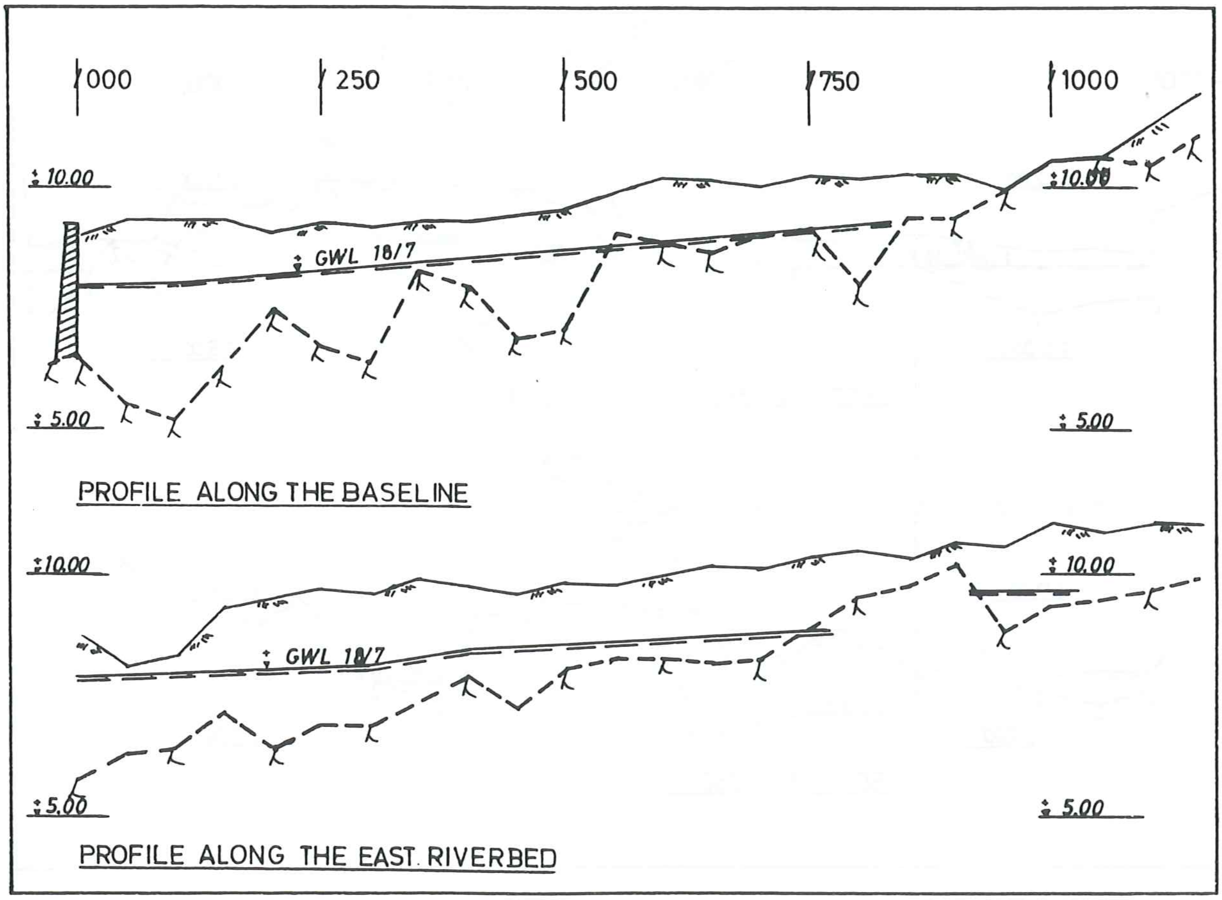



*Fig 6.5.2.1-6.5.2.2 Profiles of Manama sand dam, Tuli river.*

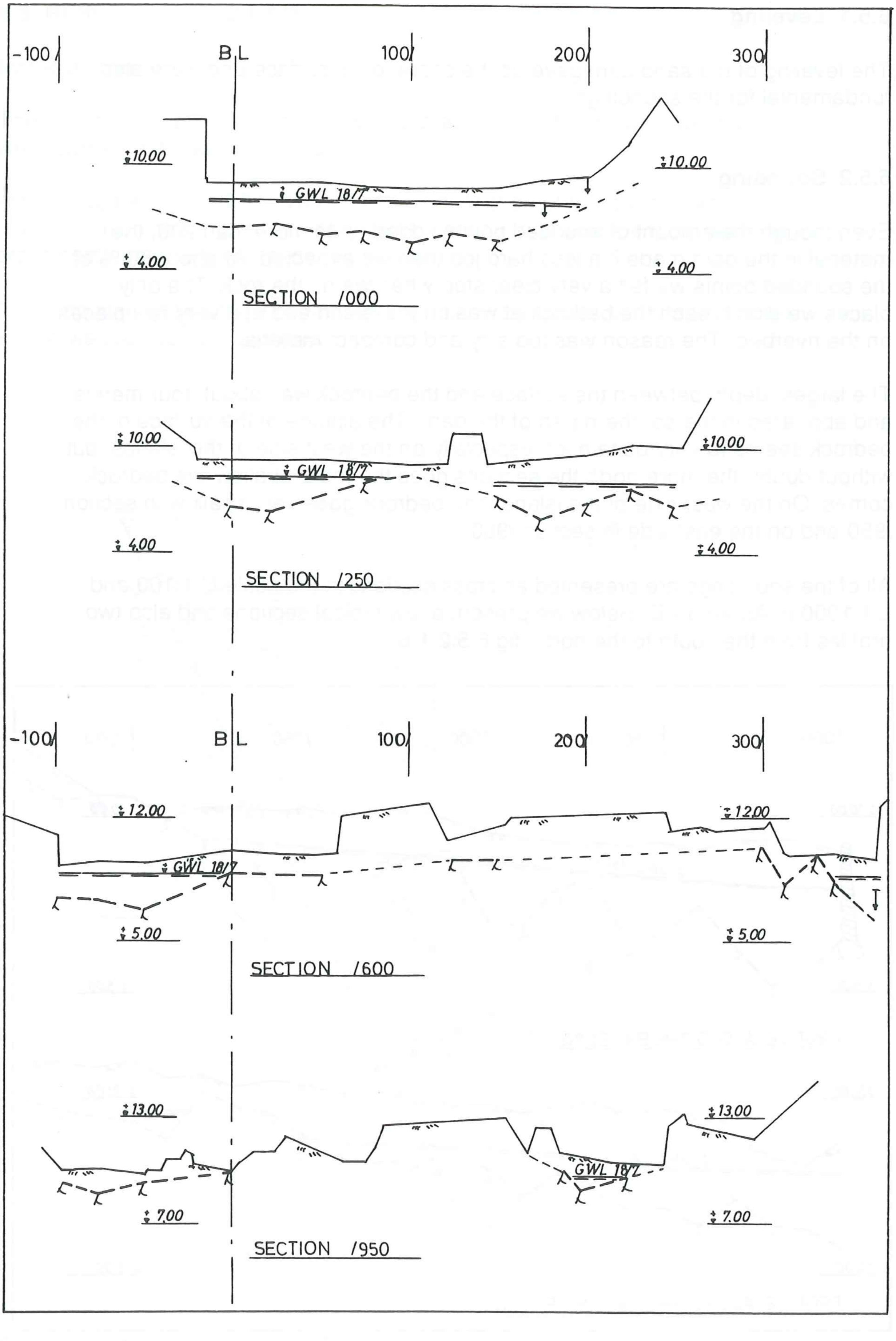



*Fig 6.5.2.3-6.5.2.6 Cross-sections Manama sand dam, Tuli river.*

### 6.5.3 Groundwater pipes

Altogether we put down 27 groundwater pipes. The location of these are found in fig 6.5.1. No 1 - 27 are pipes and No A - F are open groundwater surfaces. In Appendix D the readings are presented and they are also converted to a groundwater altitude map shown in fig 6.5.3.1. The depletion of the groundwater table between the two last readings is continuosly calculated and also shown in Appendix D. The observations were made between 120790 and 070890, totally 26 days.

Only one pump was used for the extraction system until 010890, after which the system was alternatingly run by that pump and a bigger one.

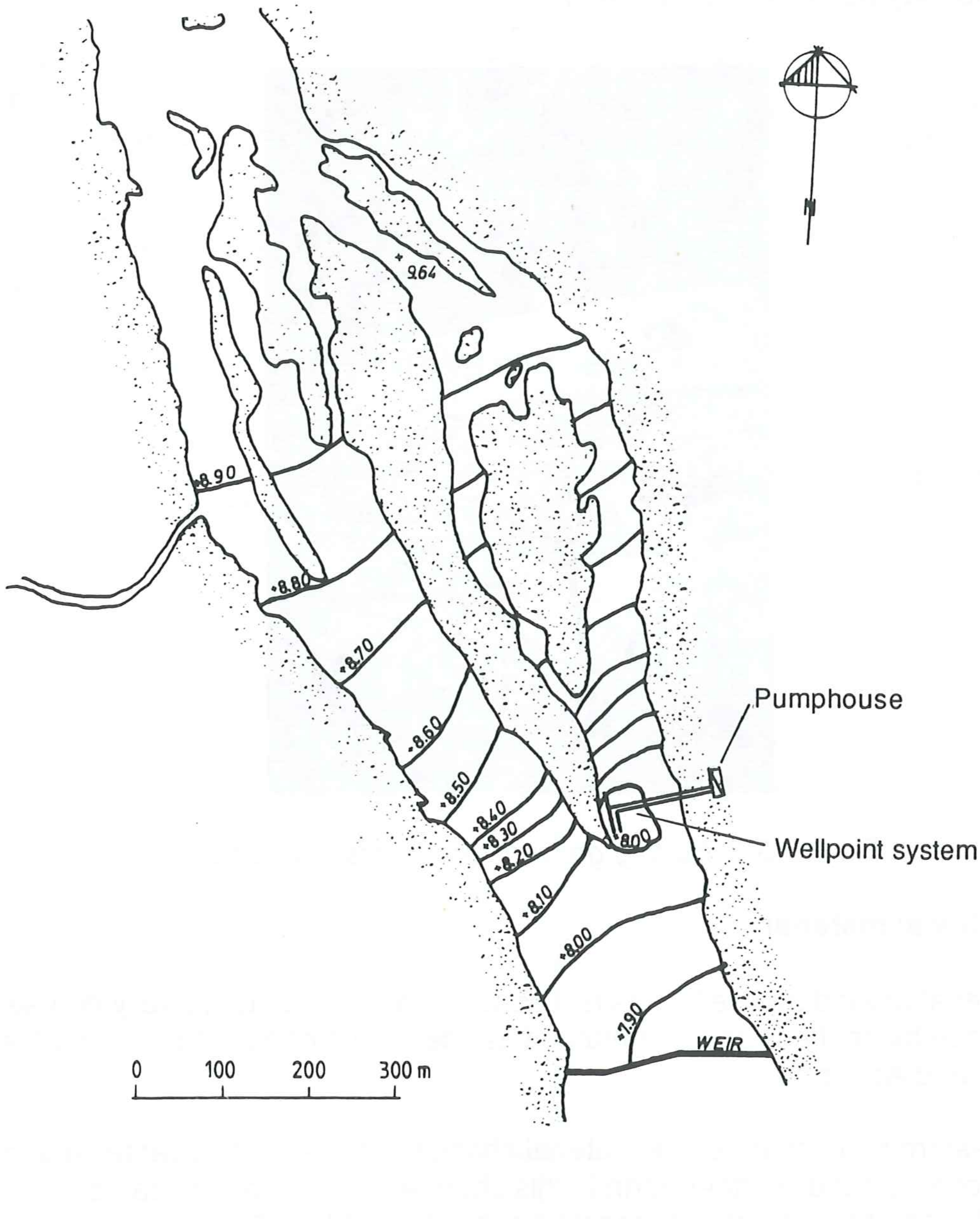



*Fig 6.5.3.1 Groundwater altitude180790.*

### Gradient

A calculation of the gradient in the stream direction between pipes No 2 - 15 and No 5 - 15 both give a gradient of 1.3 ‰.

### Depletion

The mean depletion of the groundwater table is very uniform over all the pipes and is calculated to be about 9 mm/day. There is a smaller variation in the pipes closest to the wellpoint system but that might be explained by the variable pumping.

It is notable that there is a significant difference in the altitude of the groundwater table between pipe No 9 and No 20, see fig 6.5.1. These are both situated close to the wellpoint system, but on different sides of the island, thus indicating that the island may act as a hydraulic wall.

*Fig 6.5.3.2 Putting groundwater pipes in position.*

### 6.5.4 Alluvial material

The material around the wellpoints is a sorted coarse sand to gravelly coarse sand. Close by, in the island, the material is finer, more compact silty sand (see fig. 6.5.1 and Appendix C).

In the western main channel the material changes from sand to coarse sand and gravelly coarse sand. Further north in this channel local variations can be seen. Test pit No 11 shows a gravelly coarse sand, while pit No 10 has a silty material.

South of the big island, at pits No 2 and No 4, the material is gravelly coarse sand. But in a zone, within about 100 metres from the weir, layers of silt exist in the otherwise sandy to gravelly material. A silty surface layer of about 0.2 m covers most of this area. When groundwater pipes No 15 and No 22 were put down, a similar silt layer was found about one metre down. Local people have earlier put down wellpoints in this area and have then found silt layers of a few decimetres on this level and further down in the alluvium.

Generally the alluvium in the Manama sand dam is sorted sand to gravelly coarse sand, except for the material in the islands, the southernmost part of the sand dam and in a few other places.

### 6.5.5 Water supply system

Manama mission depends completely on the Tuli River as water resource. Across the river there is a weir. It was built by the Lutheran World Federation (LWF) and was constructed as an open water dam. It was soon filled upp with sand carried by the river during flood.The dam therefore now acts as a sand dam. The weir is 250 meters long across the river and the height vary between 4.2 in the middle and 3.2 on the sides. It is built of concrete in 1956. There are gates at the base of the construction. These are supposed to be used to flush out sedimented material. By now the gates are jammed by rust and by the fact that weir is completely filled up with sand. These gates leak water at a rate varying according to the waterlevel in the sand dam.

The water is extracted from the sand dam by a wellpoint system.

There are two rows with 10 respectively 16 wellpoints. Each of these rows are connected to pipes (2.5 respectively 3.0 inch diameter) that leads to the pump house on the east side of the river bank (see fig 6.5.5.1 ).

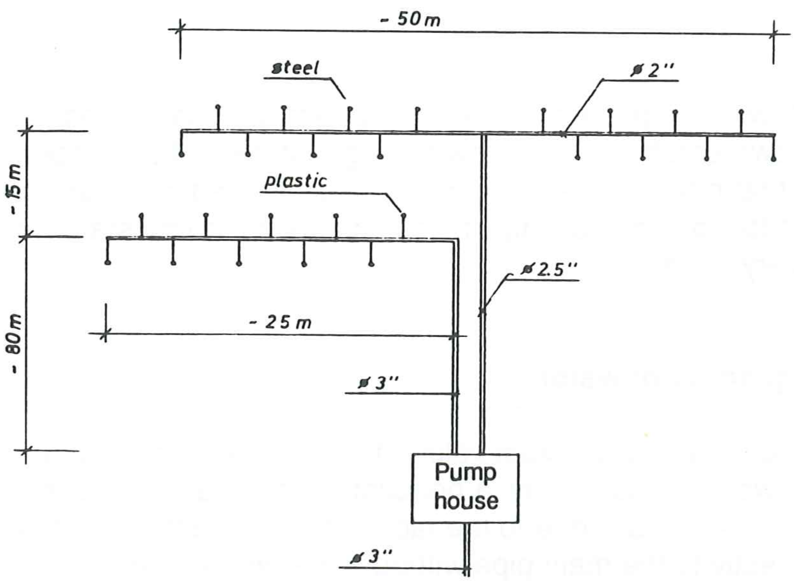



*Fig 6.5.5.1 Wellpoint system, plan view.*

There are two different types of wellpoints in Manama; factory made in iron and self made in PVC. They are put down vertically in the sand by digging and hammering until they reach the rock, see fig 6.5.5.2. The iron ones let the water in through holes and the PVC ones in slits.

In the pump house these pipes are connected to two Mono pumps. Simplified they work by screwing the water through a rubber stator with a spiral shaped steel rotor. These Mono pumps sucks the water through the wellpoint system and pumps it into the main pipe (3 inch asbestos) that leads the water to the mission. This main pipe leads the water to two storage tanks from where the water is distributed through the common reticulation system to different parts of the mission. The hospital has a direct subsidary pipe connected to the main pipe due to problem with the common reticulation system.

This project does not comprise the reticulation system within Manama although this is an obvious problem in Manama with rust, leakage and frequent breakdowns.

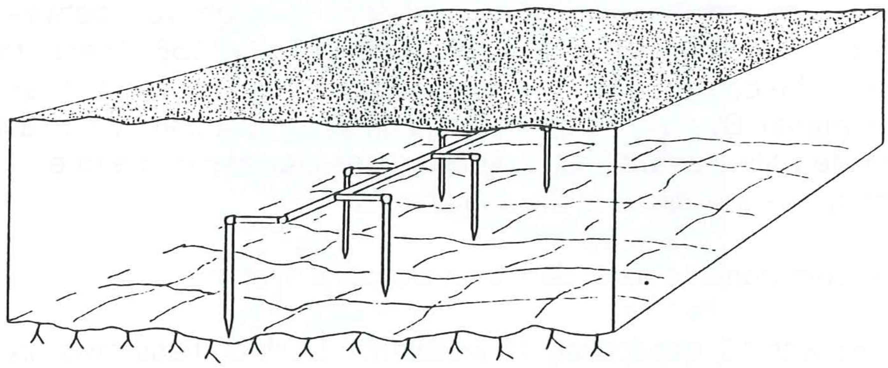


*Fig 6.5.5.2 The wellpoint system shown in a three dimensional sketch diagram.*

### Problems

The main problem with the present extraction system and the pumps is when the level of the groundwater table goes below the highest level of the intake holes in the wellpoints. At that moment the pump takes in air instead of water and that causes the pumps to work inefficiently. It also causes the pump stator (made of rubber) to break very soon.

### 6.5.6 Extracted quantity of water

It was impossible to measure an exact value of the daily extracted quantity of water because of two reasons. Firstly, a noncontinuos extraction because of varying pumping and secondly, due to the fact that the hospital have their supply pipe connected directly to the main pipe without passing the main storage tank. However, with the available facts we have done an estimation of the extracted quantity of water.

The height that the pump had to lift the water was 20 meters.

The pump used was a Mono pump D62 with a rotational speed of about 1000 - 1200 rpm. From the pump-curve we get a theoretical Q of 12 000 l/h.

Since neither the electricity supply nor the pump work efficiently all the time, both their maximum output are reduced to 80 % each. Because of problems with sand settling in the main supply pipe and the long distance to the storage tank (800 m) even the pipe efficiency is reduced to 80 %.

$$Q_{real} = ( 12000/ 1000 ) \times 24 \times 0.8 \times 0.8 \times 0.8 = \mathbf{150\ m^3\ /\ day}$$

### 6.5.7 Leakage

The leakage loss from the sand dam is very hard to measure. A possible leakage through fractures in the bedrock at the bottom of the sand dam is estimated in a water budget analysis in chapter 7.2.6.

We could observe a visible leakage in two points. The first was a very common type of leakage for this kind of building, leakage between the concrete weir and the bedrock it was founded on. The amount of leaking water was impossible to measure. The other way of leakage we observed was through some of the gates at the lower part of the weir. The amount of water that was leaking through these gates decreased during our 7 weeks stay. The first week ( 280690 ) we made a rough estimation of the leakage to 5 l/s (about 400 $m^3$/day). Seven weeks later the leakage through the gates was zero.

# 7 DISCUSSION AND CONCLUSIONS

## 7.1 GROUNDWATER IN HARD ROCK

The fracture pattern around Manama shows only one major and clear fracture direction, which strikes in a western to north-western direction (see fig 6.3.1.5). The large amount of dolerite dykes also parallels to this direction (see fig 6.3.1.2). Thus, this direction is interpreted to be the tensional direction, which mostly is the waterbearing one. With this clear and distinct pattern there was high expectations from the begining to find waterbearing fractures in the main fracture direction, especially in the contact with some of the many dolerite dykes.

Few anomalies were found after several long VLF and Slingram profiles crossing the main fracture direction and the dolerite dykes (see fig 6.3.2.1). At the dolerite dykes just a few small anomalies occured, which might seem strange. However, instead of what is often the case, that the contact between the dolerite dyke and the adjacent bedrock is fractured because of thermal contraction, we have seen that the huge dolerite dykes around Manama have transformed the contact-zones. Contact metamorphism has obviously "welded" the dykes together with the adjacent bedrock and prevented fractures to form between them.

The poor result soo far and indications of a secondary fracture direction made us to put some geophysical profiles almost perpendicular to the earlier profiles. This secondary direction, striking between NNW and NW, can be seen vaguely in the fracture pattern, in the direction of pegmatite and quartz dykes (see fig 6.3.1.2) and in the main direction of the small rivers around Manama. But the result was very poor, with just a few anomalies.

The gneissic bedrock, which predominates in the area, is another geological obstacle for good waterbearing fractures. As earlier mentioned gneiss has small groundwater storage capacity, due to small and disconnected fractures. Dyke material may has filled up the perhaps once existing larger and better connected tensional fractures.

A good connection between different fracture systems is in this area largely stopped by the big number of dolerite dykes. The bad connection gives small and restricted aquifers.

A few areas with different geological conditions show less fractures, dolerite dykes and geophysical anomalies than the rest of the area (see fig 6.3.1.2). This is probably because of their greater strength and resistance to fracturing and weathering. These areas are the following : (1) the castle kopjes, which rise up just because they are a core of more resistant bedrock, (2) the mafic area, which is compact because of the high grade of metamorphism and (3) the large fold structure north of Manama, where the structural form in itself may has reinforced a strength in the material against fracturing.

Despite the unfavourable geological conditions for groundwater storage in the area, the lack of available surfacewater to form groundwater must be considered as the greatest problem. Most of the small amount of rain falling in the area probably leaves as run-off to the small rivers. Then there isn´t enough water left to fill up the possible fractures. These circumstances seems to prevail over most of the area.

In those places where we believe to have found good fracture aquifers, we also observed several co-operating factors, favourable to grondwater formation and storage. These co-operating factors seems to be nessisarily for good groundwater aquifers in a dry area like at Manama.

A central factor seems to be the proximity to the small rivers, which obviously recharge the fractures. The access to water from these rivers has favoured deep weathering in the fracture zones, and has thereby increased the groundwater storage capacity of the fractures.

The locations of the supposed larger waterbearing fracture zones in the area are mostly situated where the fracture directions coincides with the foliation of the gneiss. However, since weathering at these locations is concicierable, it´s difficult to find any bedrock outcrops for measuring the foliation and fracture directions. However, when the sometimes limited information from the field and the geophysical results are put together with observations from aerial photos, a reasonable correlation between the direction of the fracture zones and the larger structural trends of the geology can be made.

This relation most likely exist around the small river north of Manama. The large fold structure in this area is seen on the aerial photos as bands of dark weathering material about one hundred metres wide. The outermost bands coincides with the small bends of the river and are crossed by the geophysical profiles No 19 and 24, and also coincides with the anomalies in profiles No 1,2,4,9,18,19 and 24 (see fig 6.3.1.4 and fig 6.3.2.3). This coincidence with the outer part of the fold structure shows that this part is more easily fractured and weathered than the adjacent rock.

In area B, the field observations indicated that the location of the anomaly on profile No 9 is deep weathered (can also be seen as a white spot on the aerial photo - see fig 6.3.2.2). The anomaly together with observations from aerial photos indicates a direction of a probable fracture zone towards NNE. This direction coincides with the foliation observed in the riverbed just south of where the electrical cable crosses the river. Earlier this direction has been stated as a secondary fracture direction.

The anomalies on profile No 18 and 19, together with the river direction at this location, mark a probable fracture zone in the main fracture direction, which coincides with the outer limb of the fold structure and its direction. This pattern prevails in the whole area to the west, area E.

In area E a structure, which is followed by the river path 200 metres south of it, is easily seen on the aerial photos (see fig 6.3.1.4). The foliation direction measured in the area shows the same trend as the structure, which mainly coincide with the main fracture direction. This linear trend together with the geophysical anomalies points to a strike of around 280° for the waterbearing fractures in this area.

The anomaly on profile No 15 indicates a fracture zone that can be followed via profile No 1 to the anomaly on profile No 17 (see fig 6.3.2.3). Profile No16 has an anomaly that can be connected with the more western anomaly on profile No 1. However, the lack of anomalies on adjacent profiles shows that the waterbearing fractures are relatively short in this area. The quite long fracture zone between profile No 15 and 17 is missing an anomaly on profile No 16, thereby indicating that there isn´t any hydraulic continuity between those two points.

Hopefully an hydraulic continuity exists between different parallel fractures in this area, since indications of two major fault lines in the secondary north-eastern direction have been found. The first was seen near the river mouth as a sharp wall, cracked up into many angular blocks and the wall stroke in a direction that could be followed in a small stream towards NE (see fig 7.1.2). A similar wall was found on the western side of the river, close to the anomaly on profile No 17.

*Fig 7.1.2 A rock wall cracked up into angular blocks.*

Area E with all its anomalies is restricted to the south by a wide set of huge dolerite dykes. These dolerites are supposed to act as a groundwater barrier for the waterbearing fractures north of them. The zone north of the dykes, which is a few hundred metres wide, is almost totally free from dolerite dykes. This low-lying zone, which partly consists of the white vegetation-free area north of the river, is probably an area of deep weathering. The best anomalies in the whole Manama area are found in this zone. One important factor to this is the large drainage area of the recharging river.

On profile No 17, close to the river, and on profiles No 1 and 16, just north of the river, the most promising anomalies were found. These indicate the existence of good waterbearing fractures and must be concidered as the best locations for groundwater extraction in the whole Manama area. However, the resistivities were so low that they may indicate waterbearing clays in the weathering profile, which means low permeabilities. However, all weathering material in this zone, seen in gullies, river banks and on the flat ground is sandy.

North-eastward trending waterbearing fracture zones are indicated by the geophysical anomalies in area A (see fig 6.3.2.1). Their direction is the same as of the small river in the area. The western most anomaly is found in this river. Any continuity of these fracture zones has not been found by the parallel geophysical profiling in the detail study of the area. This, together with the rather small anomalies, makes the area less interesting for groundwater exploitation.

Area C seems to have one of the clearest fracture zones in the Manama area (see fig 6.3.2.3). The anomalies on profile No 22, 1 and 30 indicate a straight waterbearing fracture line in a direction of 280°. Several bedrock outcrops close to this line indicate a shallow weathered fracture zone.The connection with other parallel fractures is probably not good, since dolerite dykes strike closely parallel to this fracture line. The rather good geophysical anomalies of this restricted fracture system probably depend on a good groundwater recharge from the Tuli river. This makes the fracture zone possible for groundwater extraction. It must however be stated that these anomalies don´t indicate a fracture zone as large as those in area E.

There are some more "detailed" evaluations from the geophysics that can be mentioned. All the Slingram anomalies has the typical look of poor conductors. This is typical for waterbearing fracture zones. The same goes for the VLF-results, allthough not as clear, probably due to the receiving conditions.

For some very interesting spots interpretations about the depth to the assumed fracture zone can be made; e.g. the anomaly at 1100 metres in profile No 1 (Area E) has a distance between the highest and the lowest value of ca. 100 metres. This indicates a depth of 50 metres to the conductor. In the same profile at 190 metres the anomaly indicates a depth to the conductor of ca. 15 metres. For the whole investigation area there are no indications of a general dip direction of the supposed waterbearing fractures.

Concerning the resistivity measurements, these definitely indicate water in the investigated material. As mentioned above the apparent resistivity sometimes was so low that it indicates clay, at least at the top of the presumed fracture zone.

The quality of the groundwater, taken from a future borehole in a hard rock aquifer around Manama, is very difficult to predict. However, some general conditions, that could influence the groundwater quality, seems to prevail around Manama. These conditions, which can all lead to an local enrichment of salts, are; a low rainfall, a subdued tophography, probably a limited depth of active groundwater flow systems in the basement and rather small and restricted fracture systems (see p. 18).

Even though the quality of the water taken from a future borehole will have a rather high concentration of some solutes, it should be better than the water taken from the sand dam today.

## 7.2 THE SAND DAM

### 7.2.1 Aquifer - boundaries, material and extraction system

**Boundaries**

Is it likely to find well defined boundaries in a river sand dam like this? When you put the information from the profiles, the cross-sections and the groundwater-pipes (compare no 1 and 2) together, you get a view of some kind of rock threshold crossing the river/dam from the section /900 on the east side to section /1000 on the west side. It won't be a complete wall, since the shape of the bedrock surface probably still contains a few deeper points that allows some refilling of the dam. But the refilling will probably not be as big as the outtake and losses.

On the western side of the river we could see the bedrock outcrops along the major part of it and that makes it a clear boundary of the dam. On the eastern side we saw almost no outcrops and the river bank at the shore was sometimes meters high. That could indicate that the river alluvium continues outside the visible river boundaries along this side.

**Islands**

What about the islands? Are they a part of the aquifer or not? The material in the riverbed was (with a few exceptions) found to be sorted and coarse, while the soil samples from the islands and in the sections of the island shores showed a finer material. The fact that we never got through with the sounding rod indicates a more compact material. From the cross-sections (fig 6.5.2.1-6 and Appendix B) you can see no clear trend in the adjacent bedrock which points to the fact that the islands would be built up completely by rock.

The groundwater pipes No 9 and No 20 are situated only 50 metres from each other, on different sides of the island but show a big difference in the level of the groundwater table.

All this together makes it reasonable to interpret the islands as hydraulic barriers, though parts of them may be a part of the aquifer, but with less permeability than the adjacent dam material.

**Basins**

The gradient of the groundwater table is continuos all over the dam (see chapter 6.5.3) and that together with the shape of the bedrock (see fig 6.5.2.1-6) shows that the dam is working as only one basin. However, when the depletion has gone very far, as at the very end of the dry season, the aquifer might be split up in a few "pots", but that won't be of any great importance.

**Material**

The soil samples that were taken show, with a few exceptions, that the sand dam is composed of a coarse and sorted sediment all over the sand dam. This means very good permeability, which is also indicated by the low drawdown funnel around the wellpoints. Large scale tests that have been carried out in a lot of riverbeds in the same region shows a porosity of 15 %. (Owen, 1989). See table 7.2.1.1.

| *Aquifer type* | *Source Rock* | *Alluvial Plain* | *Open Channel* |
|---|---|---|---|
| Well sorted aquifers | Crystalline | 5–7 | 15 |
| (Mature river and Kalahari type) | Sedimentary | 5–7 | 15 |
| | Aeolian | 3–7 | 15 |
| Poorly sorted aquifers | Crystalline | 2–3 | 10 |
| (Scarp aquifers) | Sedimentary | 2–3 | 10 |
| | Aeolian | 2–5 | 10 |

*Table 7.2.1.1 Average specific yield values (%) used for alluvial aquifers in Zimbabwe. (Owen, 1989)*

### Extraction system - Location

One solution of the problem that the intake level of the wellpoints is too high could be to relocate them to a deeper place. However, with a close look at the cross-sections (Appendix B) and the two profiles (fig 6.5.2.1-2) we find that the present location is the best one, because of the low altitude of the bedrock.

### Extraction system - Technically

Because of the lack of drawings and written descriptions it was very hard to get an exact view of the construction of the wellpoint system. Another problem was the impossibility to compare the function of the two different kinds of wellpoints because they only used the part with the steel wellpoints during our stay. But through discussions with the people we found that the plastic type of wellpoints, with slices instead of larger holes (as the steel pipes) give less silt and sand following the water through the pump than the old steel wellpoints.

Anyway, without doubt the largest problem with an increase of the extracted amount of water from the sand dam, is the too high intake-level, which causes the pump taking in air when the depletion of the groundwater table goes too low. This air causes the pumps to break down.

### 7.2.2 Leakage - A Water Budget Analysis

To find out if the water losses of the sand dam are caused by more than the extraction and the evaporation we have made a water budget analysis. The analysis is quite conservative because of many of the parameters are calculated in an approximate way. A few presumptions have to be stated about the level of the waterflow in the river/ sand dam during the year.

*3 months of flooding* : After such a period the groundwater table is at the surface of the sand dam. The groundwater table then start to fall.

*2 months*: During this period the evaporation accounts for the main part of the losses. The lost amount of water is about 1 m, see chapter 4.3.

*7 months*: This is the period that the sand dam has to support the Mission with water.

**Volume of the aquifer**

The volume of the aquifer has been calculated from the cross-sections and with the boundaries stated above. The islands and the area outside the visible river have been excluded.

| | |
|---|---|
| Sand volume | 450 000 $m^3$ |
| Area of the aquifer | 205 000 $m^2$ |
| Porosity | 15 % |

=> Volume water, $V_W$ = 450 000 x 0.15 x = 67 000 $m^3$

**Losses**

Evaporation ( 1 m ) = 1.00 x 205 000 x 0.15 = 31 000 $m^3$

Outtake ( 150 $m^3$/day, see chapter 6.5.6 ) = 150 x 30 x 7 = 32 000 $m^3$

> Of course there is an extracted amount of water during the two evaporation months as well, but that is included in the amount of evaporated water.

===> $V_W$, end of dry season = 67 000 - 31 000 - 32 000 = 4 000 $m^3$ **(A)**

Even though it's on the limit it's still enough water for the present required amount. Theoretically. Destouni and Johansson, 1989, has found that the last 15 - 20 % of the water is very hard to get out from the dam. This correlates well with the fact that people told us they were running out of water at the end of the dry season and also the fact that the pumps broke down because of too low level of the groundwater table, causing the pumps draw in air. But at that time there is still a reasonable amount of water left in the dam.

From the readings of the groundwater altitude a mean lowering of the water levels of 8.2 mm/day during the measured period has been calculated, see Appendix B. With the presumption that the refilling of the dam is zero after the flood period that is identical with a loss of :

Loss = Lowering x Area x Porosity = 0.0082 x 205 000 x 0.15 = 250 $m^3$/day

The calculated extracted quantity is stated to 150 $m^3$/day.

=> **Leakage** = 250 - 150 = **100 $m^3$/day** ( <=> 40 %) **(B)**

### 7.2.3 Conclusions

The first calculation, A, gives the fact that the dam could contain enough water for the present required amount of water. However, to get it out the present extraction system has to be improved or exchanged so that the intake level comes much deeper. Each 10 mm:s deepening makes the system work one more day.

Through the second calculation, B, we find that there's probably a leakage of at least 100 $m^3$/day from the dam.

During our first weeks in Manama we could see a reasonable leakage through the gates in the weir, very approximately estimated to 5 l/s. Surprisingly this leakage was zero a few weeks later, but the groundwater table was still going down with the same speed. An explanation could be that the groundwater table reaches a critical level where a layer of clay makes any water passage impossible. The fact that the depletion of the groundwater table continues at the same rate shows that this leakage is only a small part of the total leakage.

The main part of the leakage must be between the weir and the bedrock and through joints and fractures at the bottom of the dam, and these are impossible to make impermeable.

If the losses ( outtake and leakage ) are 250 $m^3$/day the water wouldn't last as long as it does, (( 67 000 - 31 000 ) / 250 = 140 days ). Therefore there must be some refilling of the dam from upstream.

The conclusion is that because of the big leakage it's impossible to make the water to last longer by using less.

To get more water out from the dam there are principally two solutions.

1 *Make the weir higher,*

and keep todays extraction system. This would rise the level of the groundwater table, but also increase the amount of leakage because of the increased pressure-head difference across at the weir.

Making the weir higher would also increase the infiltration of groundwater to possible fractures in the adjacent basement rock. For example, if a successful borehole would be drilled close to the river sand dam (see "Recommendations") and it could be prooved that it was connected to the river aquifer via a fracture, a higher weir would increase the available aquifer. However, this would be an expensive solution.

2 *Lower the intake level of the extraction system*

The estimation that every 10 mm:s lowering of the intake level gives the Mission one more day of available water, makes an extraction system consisting of horizontal pipes at the very bottom of the dam an attractive solution. Such pipes can be arranged in many different ways. They can be arranged as as galleries, (see fig 7.2.3.1) in a radial formation connected to a central well or in a more right-angled formation (see fig 7.2.3.2) also connected to a central well or directly to a main pipe to the pump.

There are a few disadvantages with systems like this. To get them down to the bottom of the dam you have to dig long trenches below the groundwater level and that demands pumping while digging. This could be a problem because of lack of such pumping equipment. Once the pipes are located at the bottom it's hard to maintain and repair them. Therefore the length of the pipes should be made twice the required length from the beginning. (Driscoll, 1986)

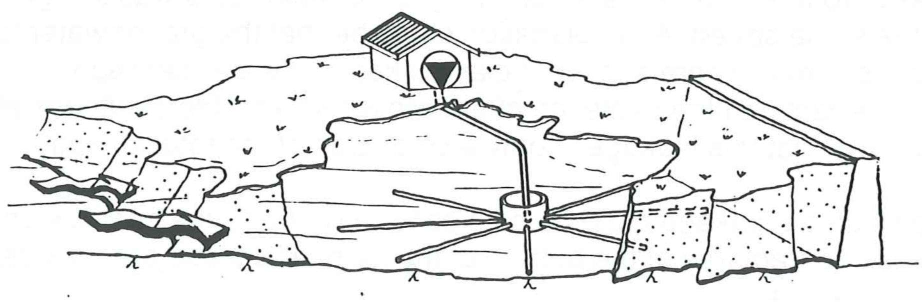


*Fig 7.2.3.1 Galleries, radial formation.*

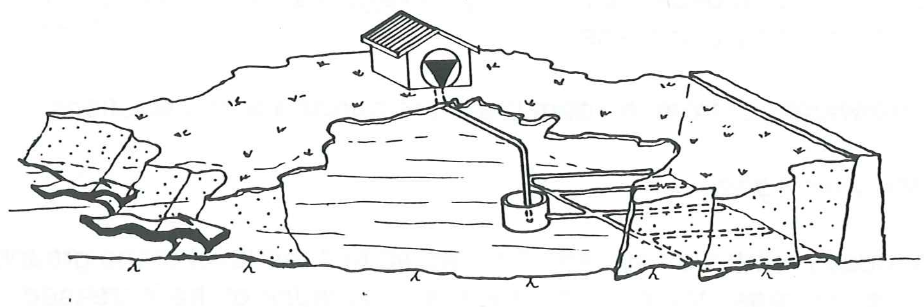


*Fig 7.2.3.2 Galleries, right-angled formation.*

Another way of lowering the intake level, although not as efficient as above, is to use concrete rings with an artificial filter at the bottom end, see fig 7.2.3.3. (DHV, 1979). It will be needed a couple of these to compensate the present system, but compared to horizontal pipes they are easier to get down since you can dig inside the concrete rings, and use them as a casing when you get below the groundwater table.

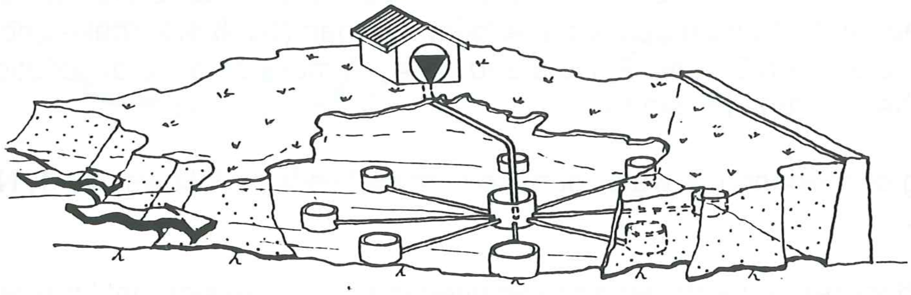


*Fig 7.2.3.3 Wells with artificial filter.*

## 7.3 COMPARISON OF THE INSTRUMENTS

A geophysical survey is one part of the work in a water prospecting project. It is of great importance that the different parts of the field work can be planned and then carried out as planned.

The Slingram and the WADI both function according to the same principles, thus giving results of the same kind. The problem with human made conductors is equal for the Slingram and the WADI, the Terrameter is less effected. As long as you are using the instruments in rural areas this does not effect the investigations very much.

There are, however, differences in efficiency and reliability. The WADI, providing suitable conditions, is no doubt the most efficient of the instrumets. It is much faster, lighter, needs only one person for operation, has longer intervals between recharging etc. However, during conditions such as in Zimbabwe, it is not reliable in the sense that you can plan, and then achieve what you have planned. There are portable VLF- transmitters that maybe can provide the WADI with suitable receiving conditions in areas such as in Zimbabwe. However, this was something that we did not have the opportunity to try.

The Slingram and the Terrameter must be cons77idered as reliable instruments for tasks such as in this report, therefore they are more suitable than the WADI. The Terrameter is not efficient enough for general profiling, but it is suitable for detailed investigations.

# 8 RECOMMENDATIONS

## 8.1 GROUNDWATER EXPLOITATION

### Boreholes

Based on the conclusions in chapter 7 we recommend Manama Mission to drill and equip boreholes for fresh water production. We have found four spots favourable for boreholes. These spots are located in the areas refered to as "E" and "C" in earlier text and maps. On the following map (fig. 8.1:1) these spots are marked as borehole NO 1, No 2, No 3 and No 4. (A more detailed description will be sent to the Manama Mission.)

The ranking concerning the water outtake possibilities is as follows: **No 1, No 4, No 2, No 3.**

They should therefore be drilled and exploited in this succession until the results concerning water quantity are satisfying.

The highest yield expectation in each hole might be 4 $m^3$/hour.
If water is found during drilling, this doesn't necessary mean that it is a hole that can give the requested quantity during the whole year. Therefore it might be a good idea to drill at least two or maybe all four holes while drilling contractors are in Manama, even if there is water found in every hole while drilling.

Drilling depth should be at least **50** metres in area E ( borehole No 1, No 4 and No 2). If water is strucked, drilling should continue through waterbearing zone/zones and into dry rock until 6 -10 metres of dry rock has been penetrated.

Drilling depth should be at least **25** metres in area C (borehole No 3). If water is strucked, drilling should continue through waterbearing zone/zones and into dry rock until 6 -10 metres of dry rock has been penetrated.

### The sand dam

If drilling of the proposed boreholes will be impossible or unsuccesful, improvements of the sand dam can be carried out, thus making it possible to extract more water from it. The best solution is to make a new extraction system. A choice from one of the types shown in fig 7.2.3.1 - 7.2.3.3, will give the lowest intake-level.

## 8.2 COMPARISON OF INSTRUMENTS

The Slingram and the Terrameter are suitable instruments for water prospecting in rural areas in Zimbabwe.

The WADI is not recommendable for water prospecting in Zimbabwe because of bad receiving conditions. However, a portable transmitter might be able to provide the WADI with better receiving conditions.

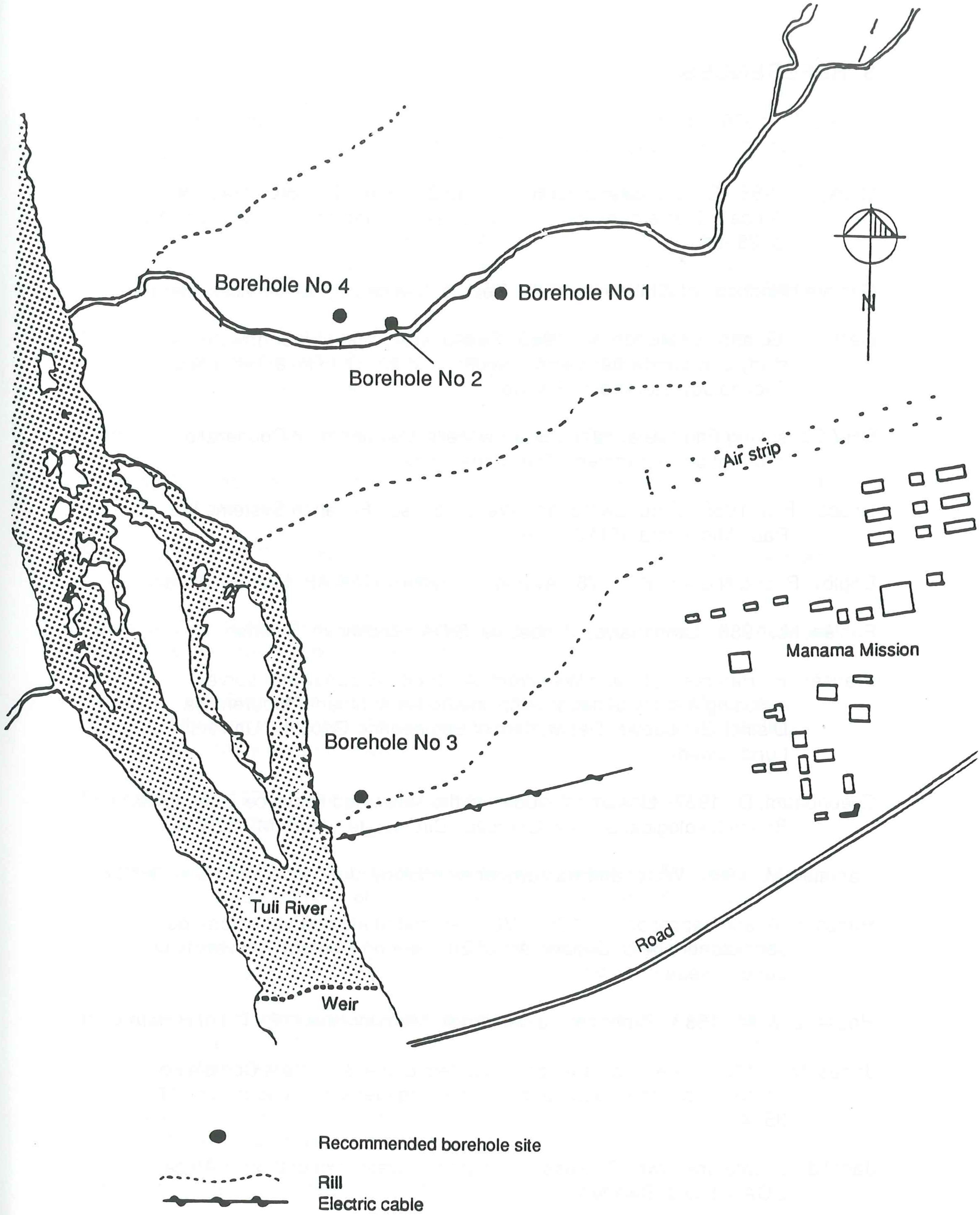



*Figure 8.1.1. Recommended borehole sites. Scale 1: 10 000.*

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For each profile we give facts, comments and interpretations, exept for the detail investigations, where we give a interpretation for each area.

The strength of the VLF- signal was varying between 12 and 14 according to the signal strength value that is measued with the WADI. It should be between 10 and 50 according to the WADI manual.

The profiles are presented as in the following order:

**Long profiles** (general profiling)

**Detail investigations, area E**

| Profile No | Page |
|---|---|
| 1 | A39 |
| 14 | A40 |
| 15 | A41 |
| 16 | A43 |
| 17 | A45 |
| 18 | A47 |
| 19 | A48 |
| 21 | A49 |
| 13 | A50 |
| 12 | A50 |

GENERAL PROFILING

PROFILE NO 1

Date: 240790
Direction S - N
Length: 3380 m
Frequences: Slingram 3.6 kHz
VLF 19.2 kHz

Comments

Anomalies are found at the distance of 110, 185, 340, 1000, 1100 and 1340 m. At the end of the profile (from 2350 m) the VLF-graph fluctuates but this can be explained by low VLF-signal ( error message was given).

An el power cable was crossed at the distance 110 m.

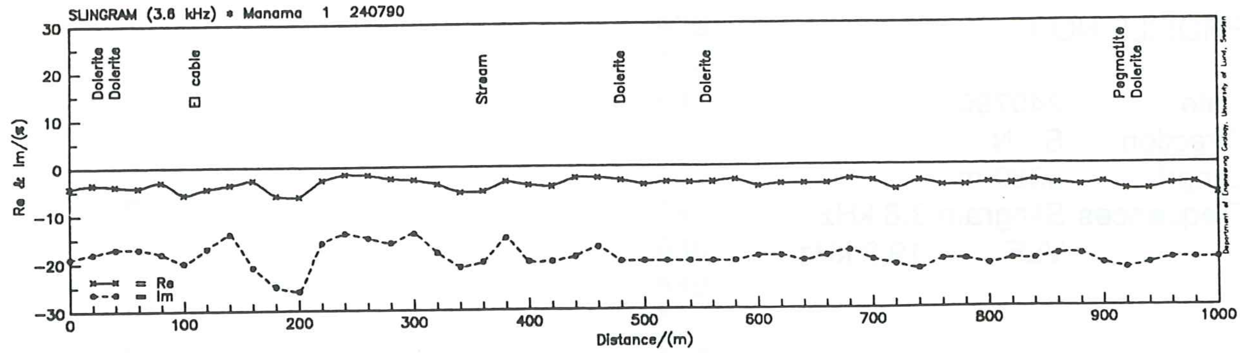
Of special interest are the anomalies where the two instruments correlate well. These are the ones at 185 and 1100 m.

Interpretation

The VLF-anomaly at the distance 110 m is probably caused by the el power cable.

The rest of the anomalies could be caused by waterbearing fracturezones.

Because of the big anomaly-amplitude the anomalies at 185 and 1100 m are of greatest interest.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Re & Im/(%)
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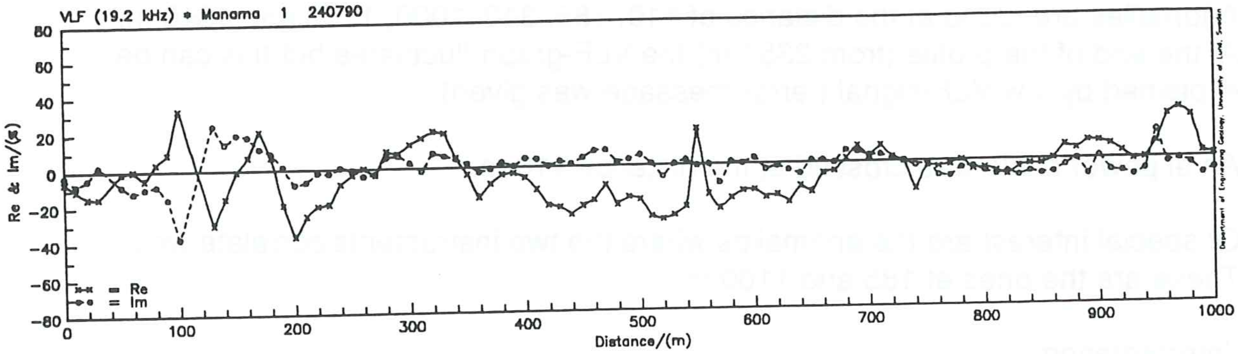
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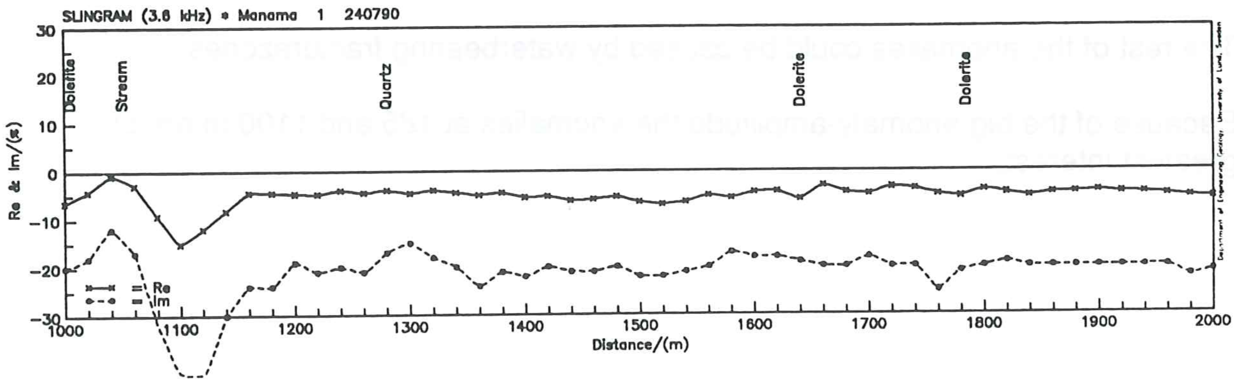
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Re & Im/(%)
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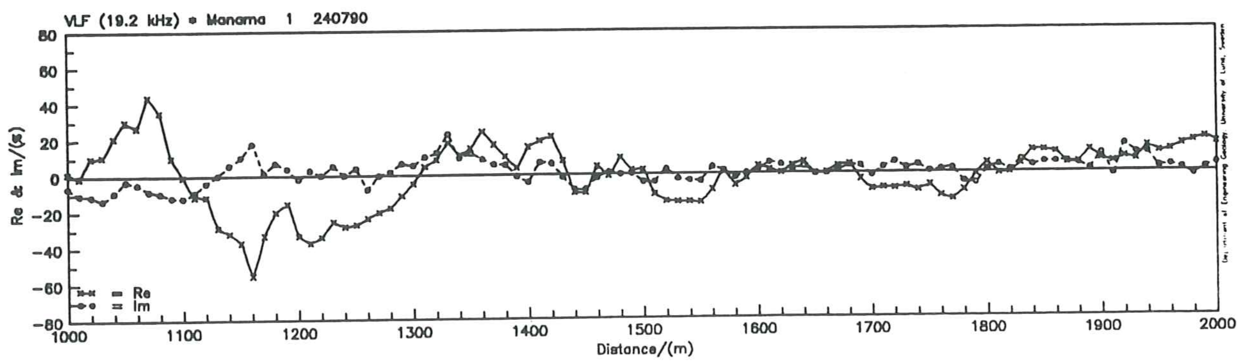
Distance/(m)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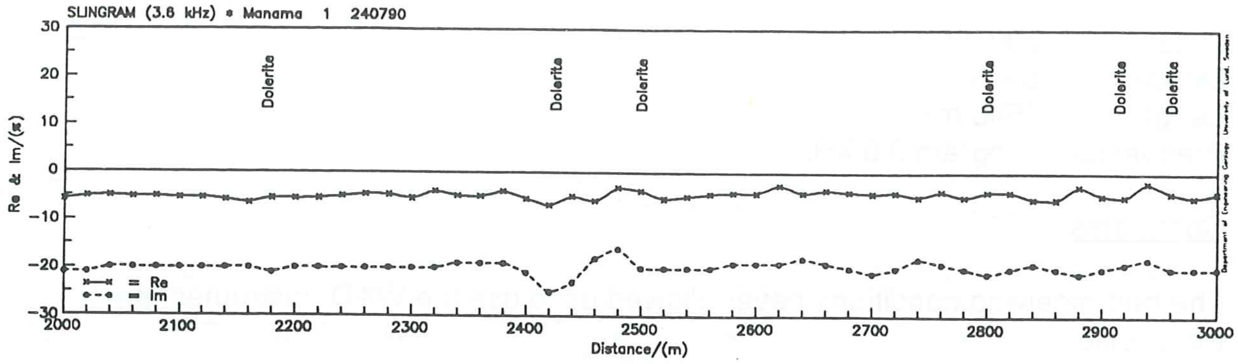
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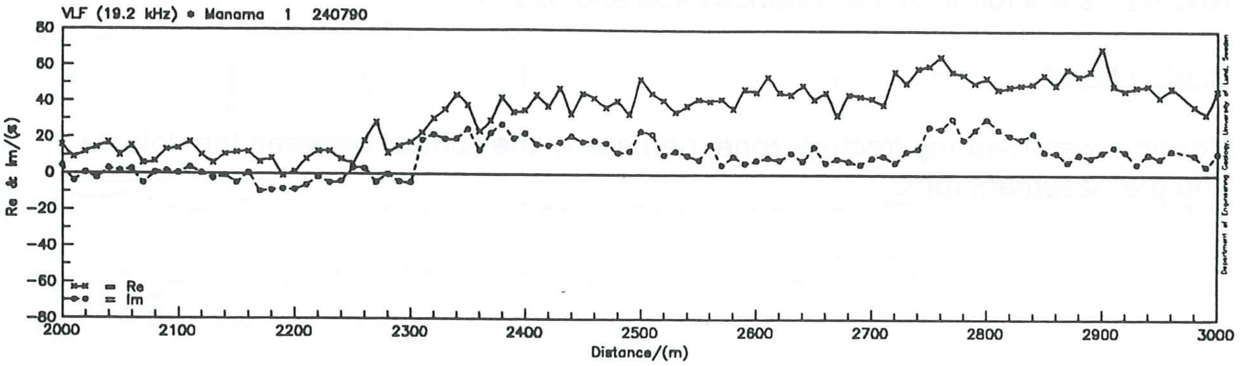
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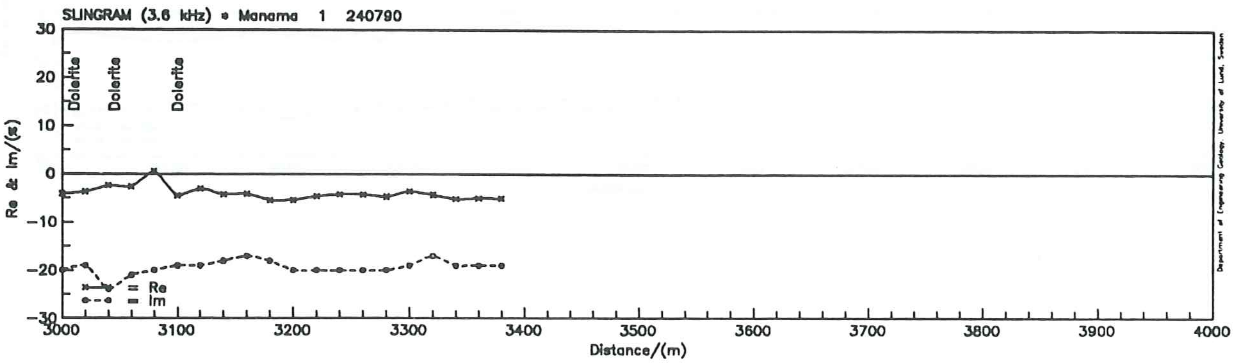
Distance/(m)
= Re
= Im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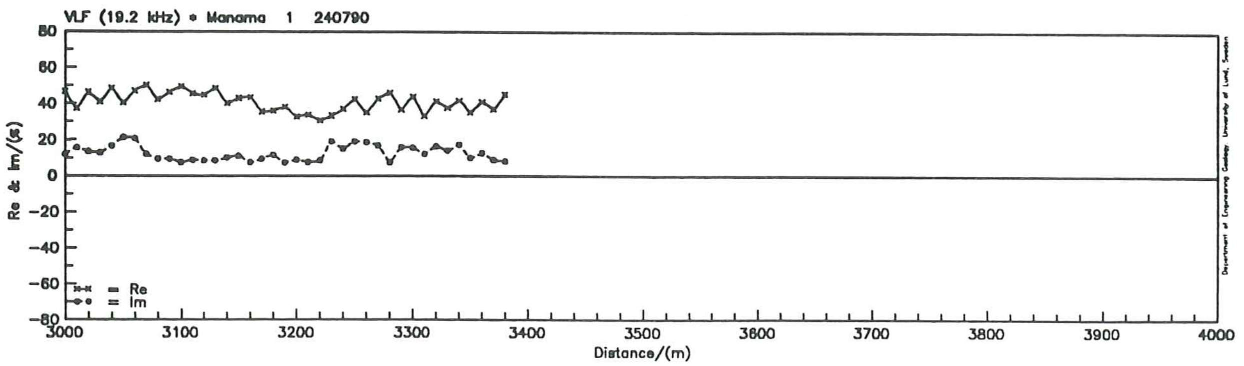
Dolerite
Re & Im/(%)
Distance/(m)
= Re
= Im


VLF (19.2 kHz) * Manama 1 240790
Re & Im/(%)
Distance/(m)
= Re
= Im

PROFILE NO 2

Date: 230790
Direction S - N
Length: 2540 m
Frequences: Slingram 3.6 kHz

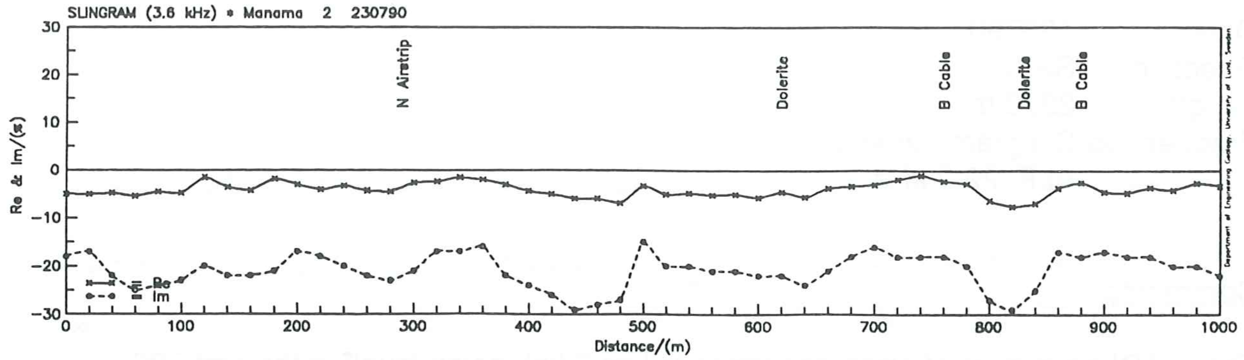
<u>Comments</u>

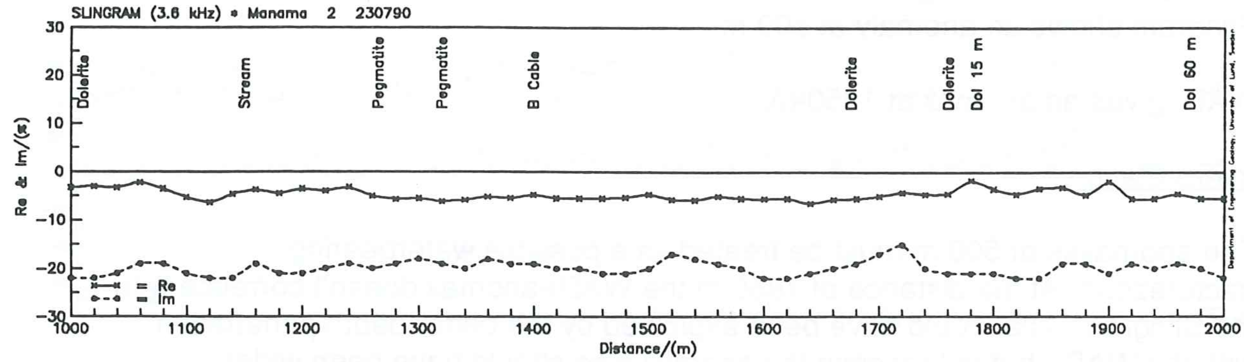
The bad receiving conditions never allowed us to use the WADI-instrument in this profile.

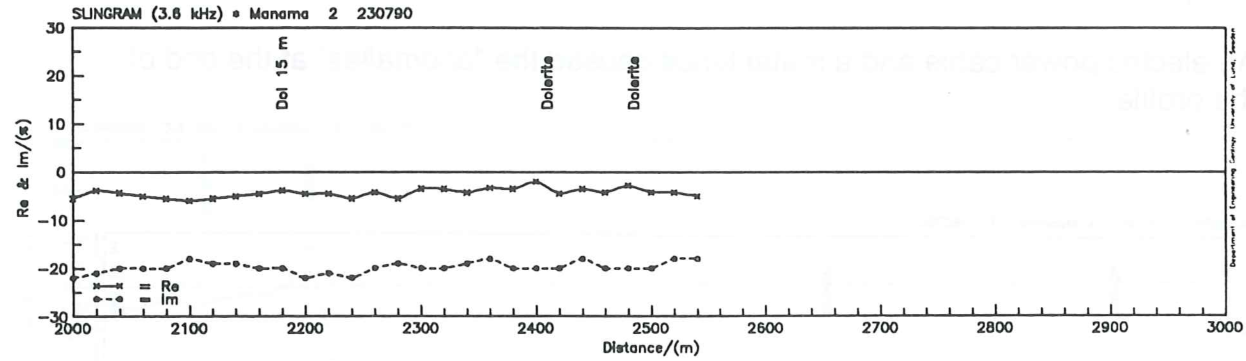
Anomalies are found at the distances 450 and 820 m.

<u>Interpretation</u>

Possible waterbearing fracture zone, perhaps at the contact between the dolerite and the basement rock.


SLINGRAM (3.6 kHz) ∘ Manama 2 230790
Re & Im/(%)
Distance/(m)
N Airstrip
Dolerite
B Cable
Dolerite
B Cable
Re
Im
Department of Engineering Geology, University of Lund, Sweden


SLINGRAM (3.6 kHz) ∘ Manama 2 230790
Re & Im/(%)
Distance/(m)
Dolerite
Stream
Pegmatite
Pegmatite
B Cable
Dolerite
Dolerite
Dol 15 m
Dol 60 m
Re
Im
Department of Engineering Geology, University of Lund, Sweden


SLINGRAM (3.6 kHz) ∘ Manama 2 230790
Re & Im/(%)
Distance/(m)
Dol 15 m
Dolerite
Dolerite
Re
Im
Department of Engineering Geology, University of Lund, Sweden

PROFILE NO 3

Date: 180790
Direction: S - N
Length: 2220 m
Frequences: Slingram 3.6 kHz
VLF 22.2 kHz

## Comments

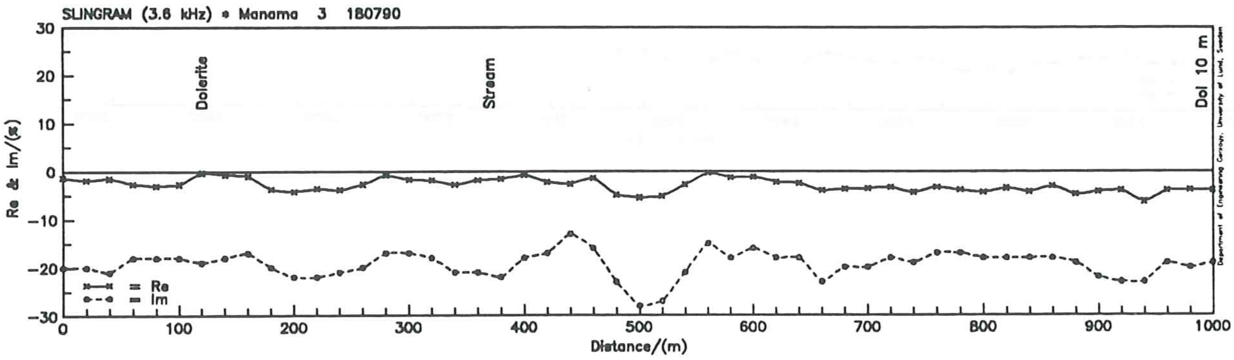
The WADI gave a lot of error messages telling "High noise level" in the first 700 meters, and the readings are therefore not reliable on this part. In this section the Slingram shows an anomaly at 500 m.

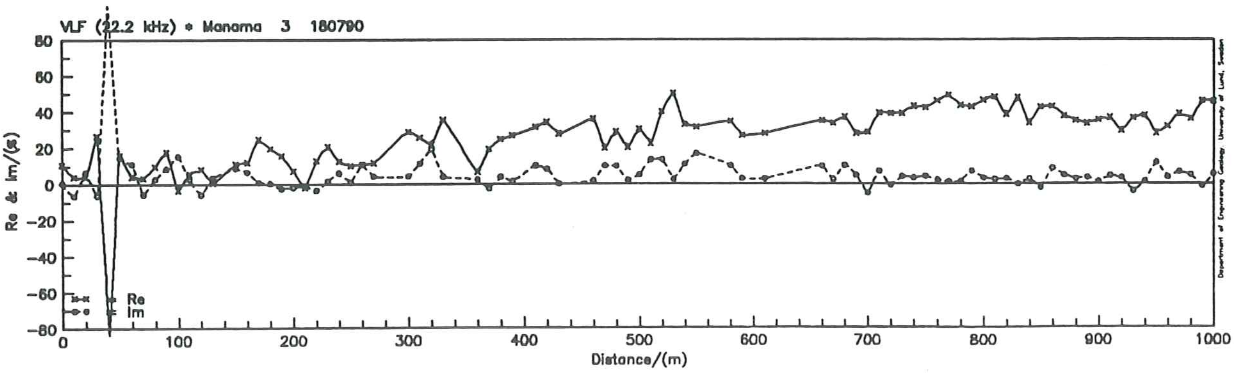
WADI gives an anomali at 1850 m.

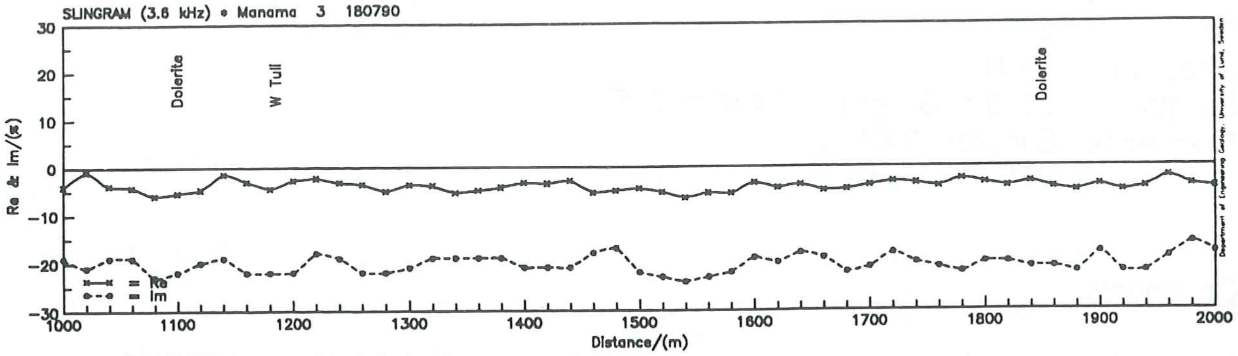
## Interpretation

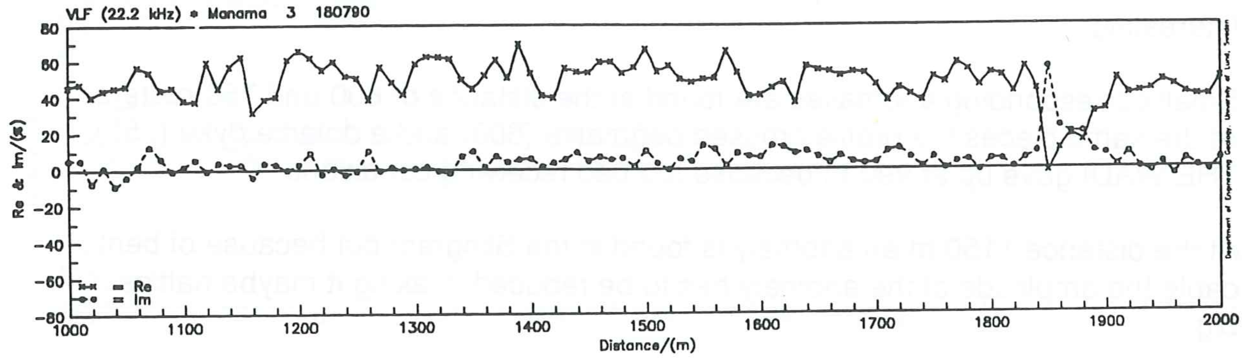
The anomalies at 500 m must be treated as a possible waterbearing fracturezone. At the distance of 1850 m the WADI-anomali doesn't correlate with the Slingram. That could have been explained by the better depth penetration with the WADI, but in that case the anomali also should have been wider. Interpretation impossible.

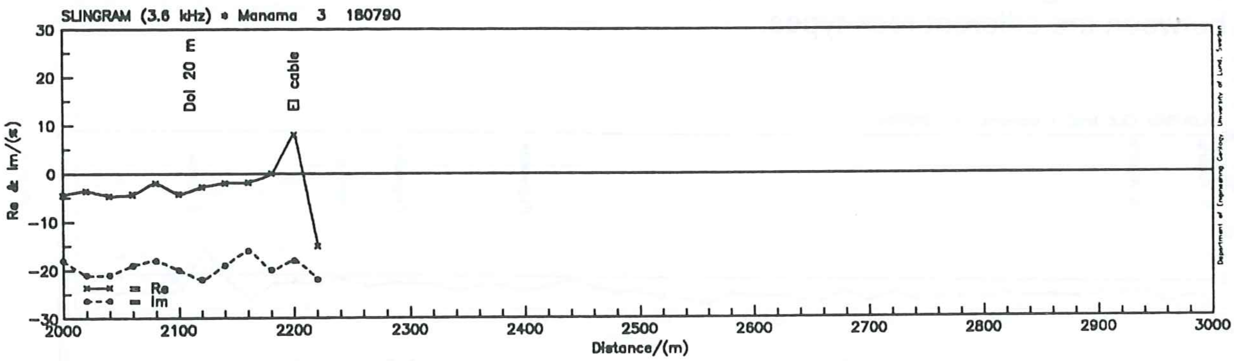
An electric power cable and a metal fence caused the "anomalies" at the end of the profile.

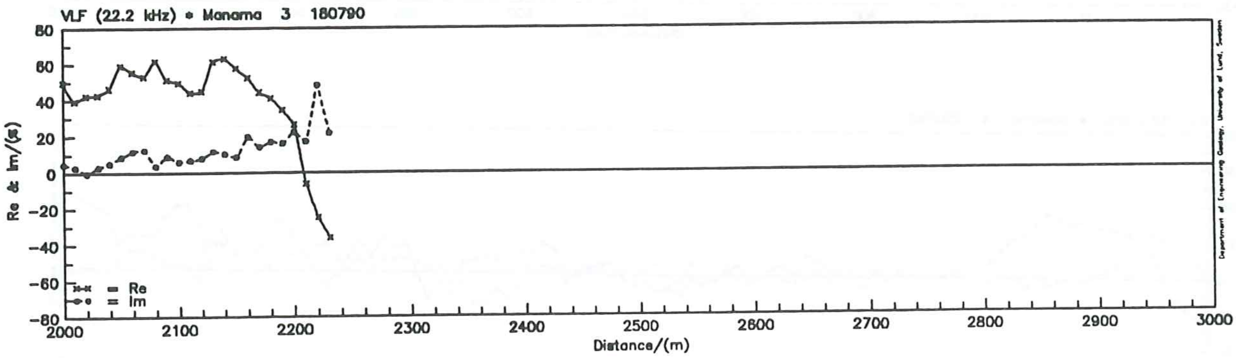



SLINGRAM (3.6 kHz) * Manama 3 180790
Dolerite
W Tull
Dolerite
Re & Im/(%)
Re
Im
Distance/(m)
Department of Engineering Geology, University of Lund, Sweden


VLF (22.2 kHz) * Manama 3 180790
Re & Im/(%)
Re
Im
Distance/(m)
Department of Engineering Geology, University of Lund, Sweden


SLINGRAM (3.6 kHz) * Manama 3 180790
Dol 20 m
El cable
Re & Im/(%)
Re
Im
Distance/(m)
Department of Engineering Geology, University of Lund, Sweden


VLF (22.2 kHz) * Manama 3 180790
Re & Im/(%)
Re
Im
Distance/(m)
Department of Engineering Geology, University of Lund, Sweden

PROFILE NO 4

| | |
|---|---|
| Date: | 200790 |
| Direction: | S - N |
| Length: | 2200 m Slingram, 1480 m VLF |
| Frequence: | Slingram 3.6 kHz |
| | VLF 22.2 kHz |

## Comments

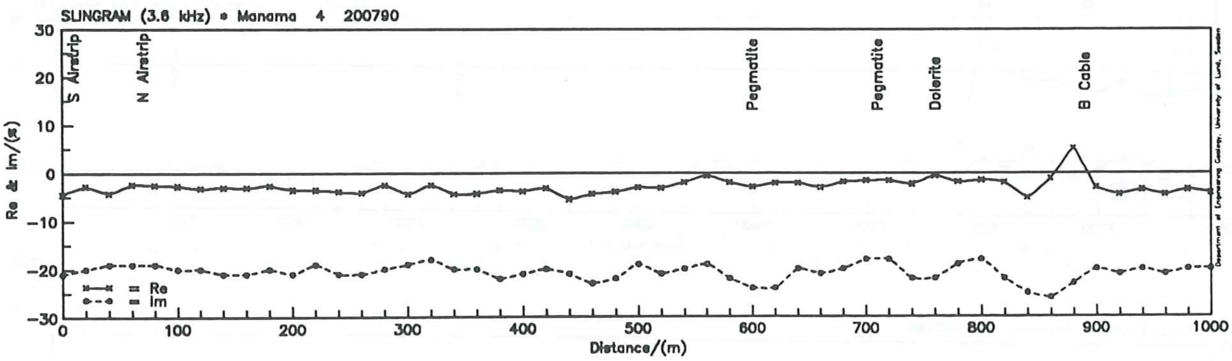
The WADI-graph shows a strange shape in the very beginning which is hard to explain, but since it has no equal feature in the Slingram we don't consider it as interesting.

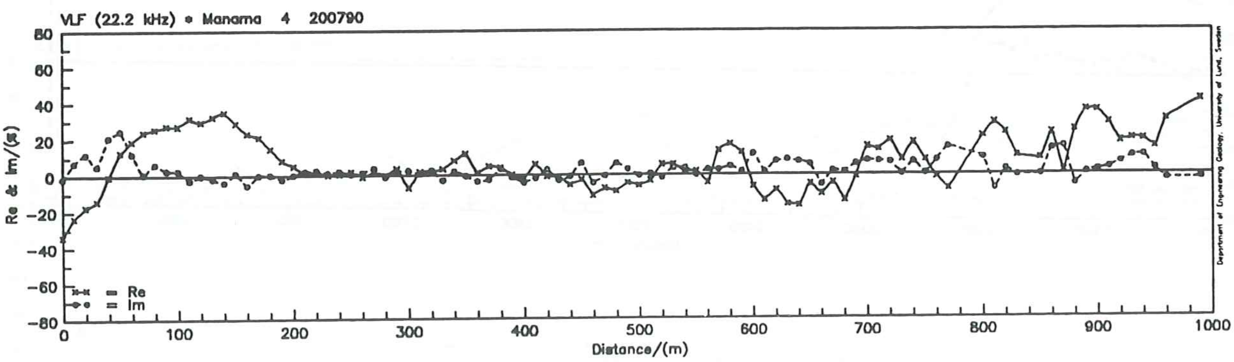
Small corresponding anomalies are found at the distance of 600 and 750 meters. At the same places the profile crossed pegmatite (600) and a dolerite dyke (750). THE WADI gave up at 990 m because too bad receiving conditions.

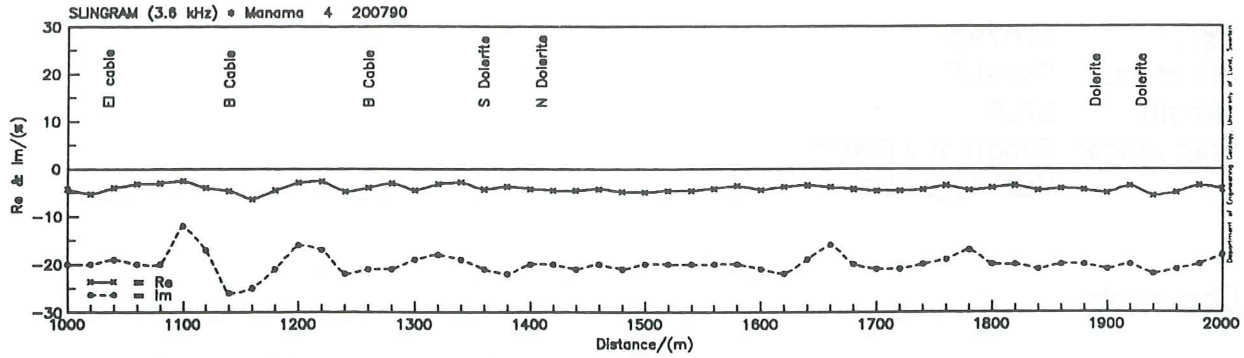
At the distance 1150 m an anomaly is found in the Slingram but because of bent cable the amplitude of the anomaly has to be reduced, making it maybe half as big.

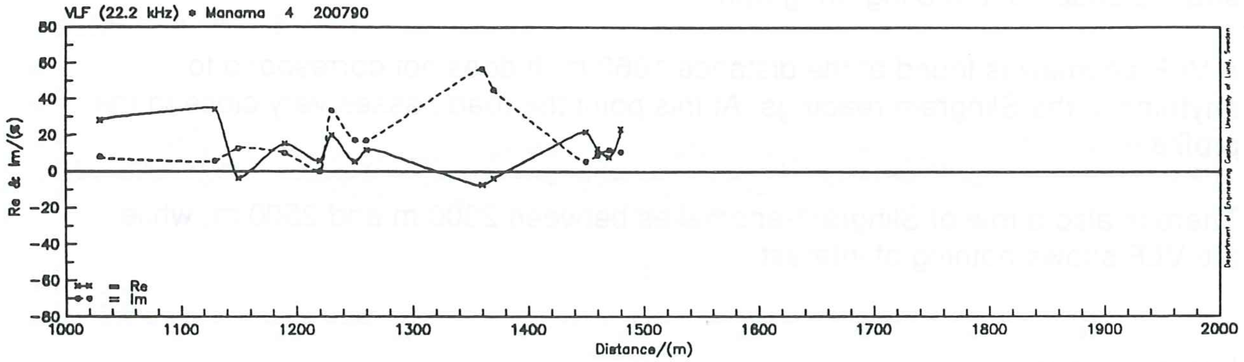
## Interpretation

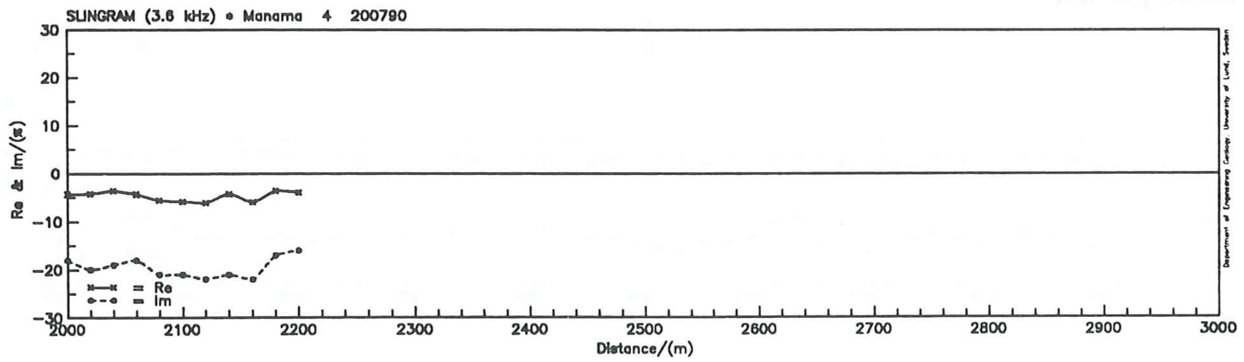
The relatively small anomalies could be caused by not very deep and small waterbearing fracture zones. In the two first cases it could be in the contact between the different rock-types.




SLINGRAM (3.6 kHz) * Manama 4 200790
El cable
B Cable
B Cable
S Dolerite
N Dolerite
Dolerite
Dolerite
Re & Im/(%)
= Re
= Im
Distance/(m)
Department of Engineering Geology, University of Lund, Sweden


VLF (22.2 kHz) * Manama 4 200790
Re & Im/(%)
= Re
= Im
Distance/(m)
Department of Engineering Geology, University of Lund, Sweden


SLINGRAM (3.6 kHz) * Manama 4 200790
Re & Im/(%)
= Re
= Im
Distance/(m)
Department of Engineering Geology, University of Lund, Sweden

PROFILE NO 5

Date: 170790
Direction: SW -NE
Length: 3720 m
Frequence: Slingram 3.6 kHz
VLF 18.2 kHz

Comments

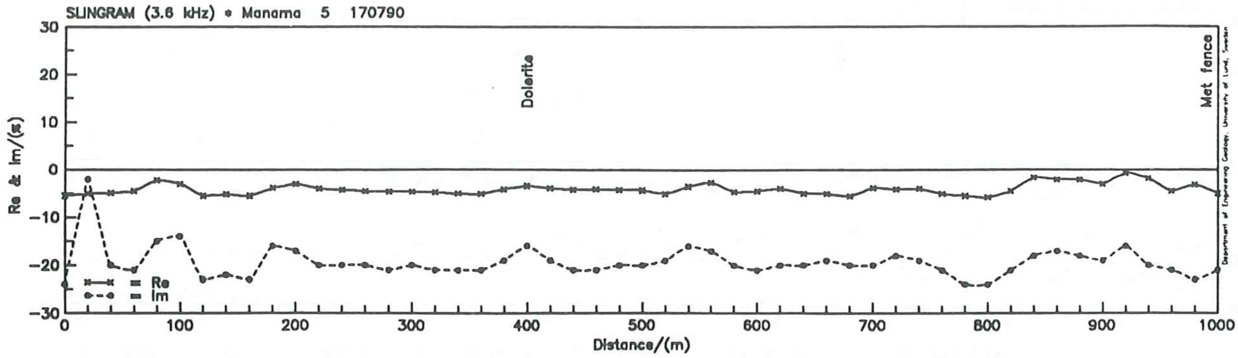
The profile starts close to the concrete and steel bridge. This could explain the strange shape of the Slingram graph.

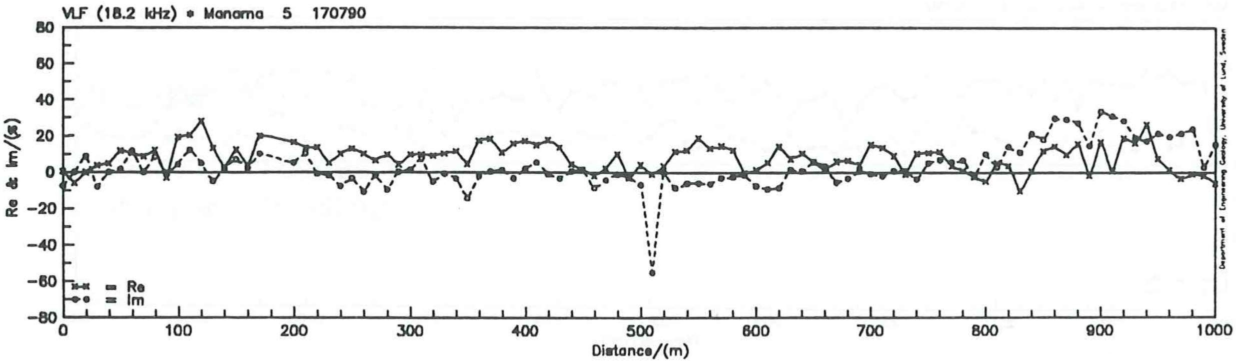
A VLF-anomaly is found at the distance 1060 m. It does not correspond to anything in the Slingram readings. At this point the road passes very close to the profile.

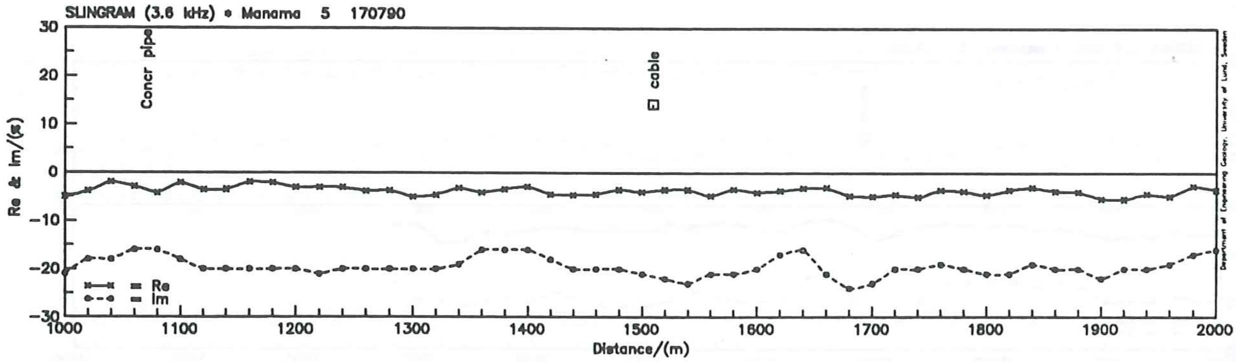
There is also a row of Slingram-anomalies between 2000 m and 2500 m, while the VLF shows nothing of interest.

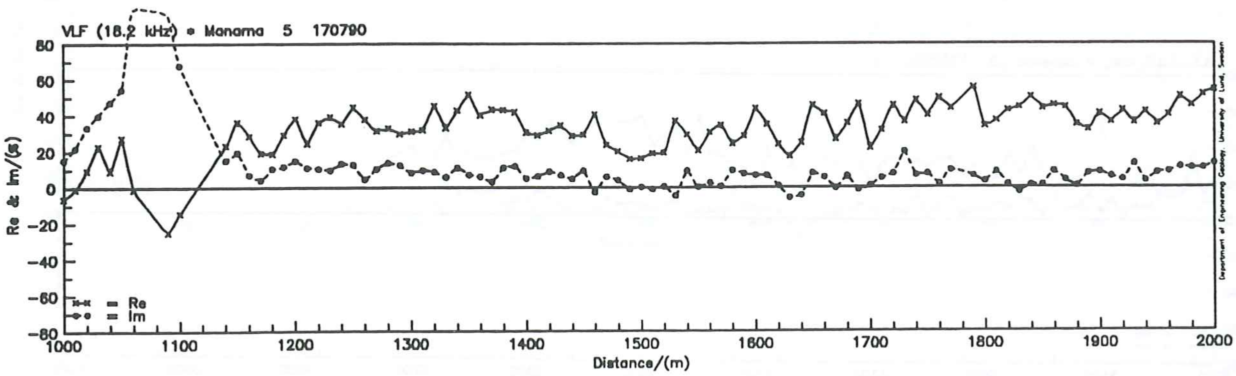
Interpretations

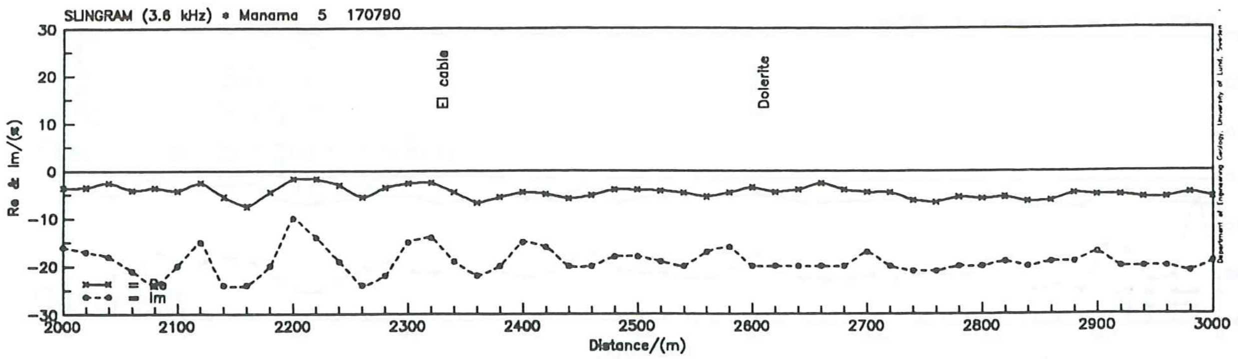
All the anomalies found in this profile are probably due to manmade conductors like electric power cables, metal fences etc. which were present at, or close to, these points.

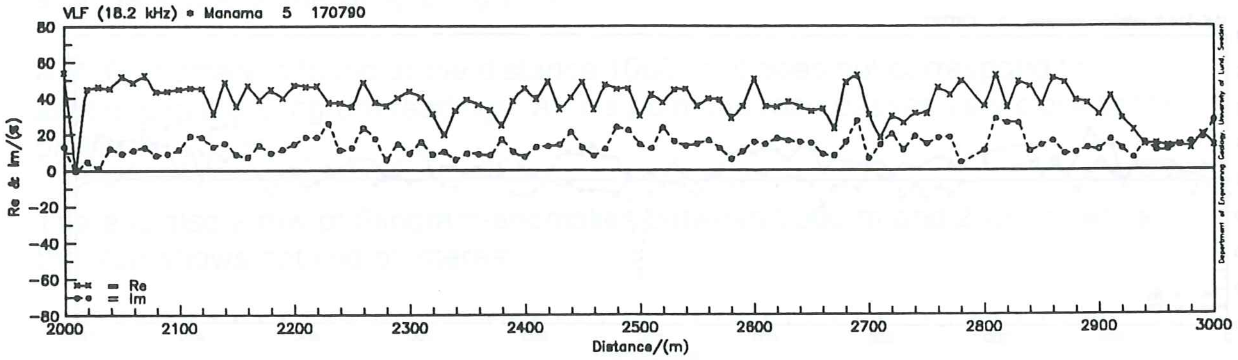

SLINGRAM (3.6 kHz) * Manama 5 170790
Dolerite
Met fence
Re & Im/(%)
Distance/(m)
= Re
= Im

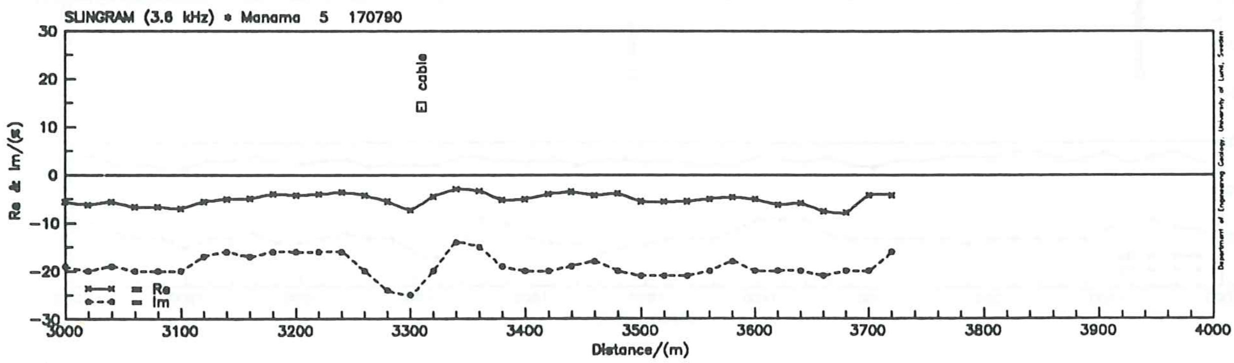

VLF (18.2 kHz) * Manama 5 170790
Re & Im/(%)
Distance/(m)
= Re
= Im

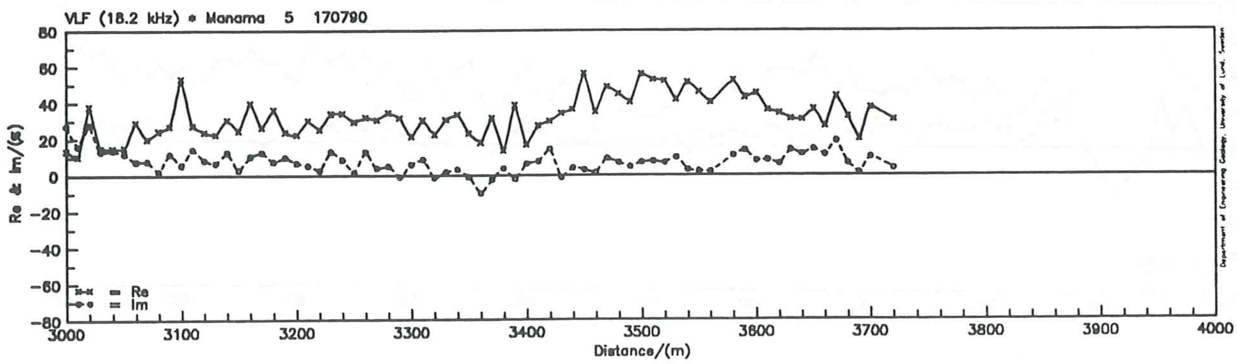

SLINGRAM (3.6 kHz) * Manama 5 170790
Concr pipe
El cable
Re & Im/(%)
Distance/(m)
= Re
= Im


VLF (18.2 kHz) * Manama 5 170790
Re & Im/(%)
Distance/(m)
= Re
= Im


SLINGRAM (3.6 kHz) * Manama 5 170790
El cable
Dolerite
Re & Im/(%)
Distance/(m)
= Re
= Im
Department of Engineering Geology, University of Lund, Sweden


VLF (18.2 kHz) * Manama 5 170790
Re & Im/(%)
Distance/(m)
= Re
= Im
Department of Engineering Geology, University of Lund, Sweden


SLINGRAM (3.6 kHz) * Manama 5 170790
El cable
Re & Im/(%)
Distance/(m)
= Re
= Im
Department of Engineering Geology, University of Lund, Sweden


VLF (18.2 kHz) * Manama 5 170790
Re & Im/(%)
Distance/(m)
= Re
= Im
Department of Engineering Geology, University of Lund, Sweden

PROFILE NO 6

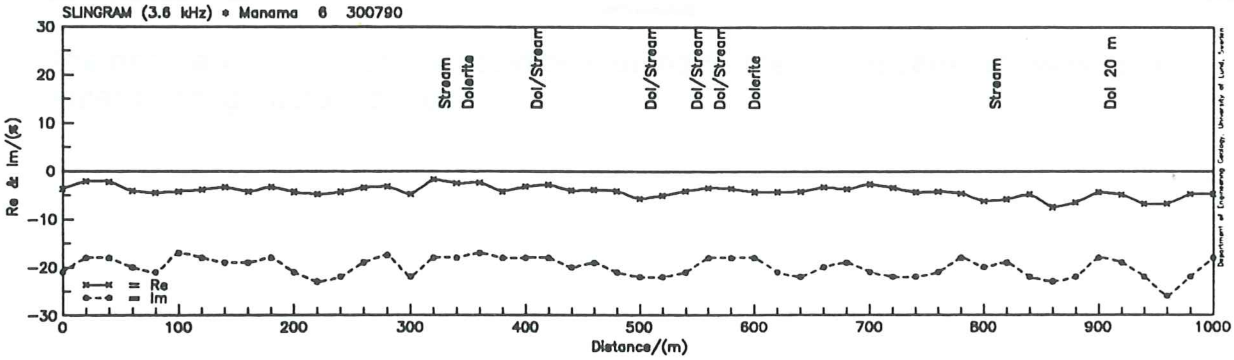
Date: 300790
Direction: S - N
Length: 2260 m Slingram, 320 m VLF
Frequence: Slingram 3.6 kHz
VLF 22.2 kHz

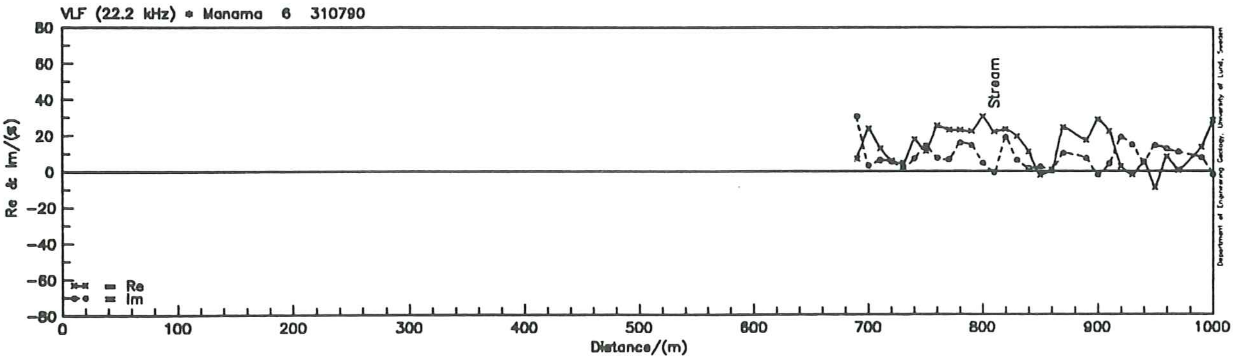
## Comments

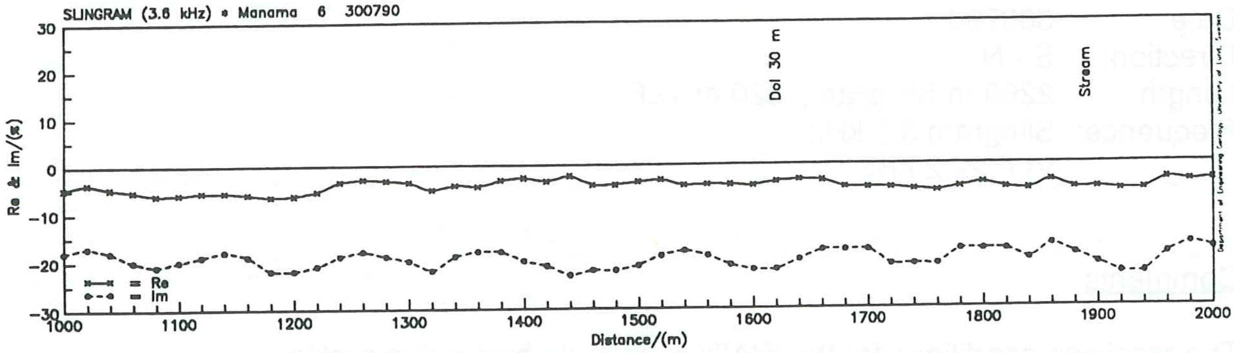
The receiving conditions for the WADI were quite bad in this profile. Nevertheless one can observe a small VLF-anomaly at the distance 910 m.

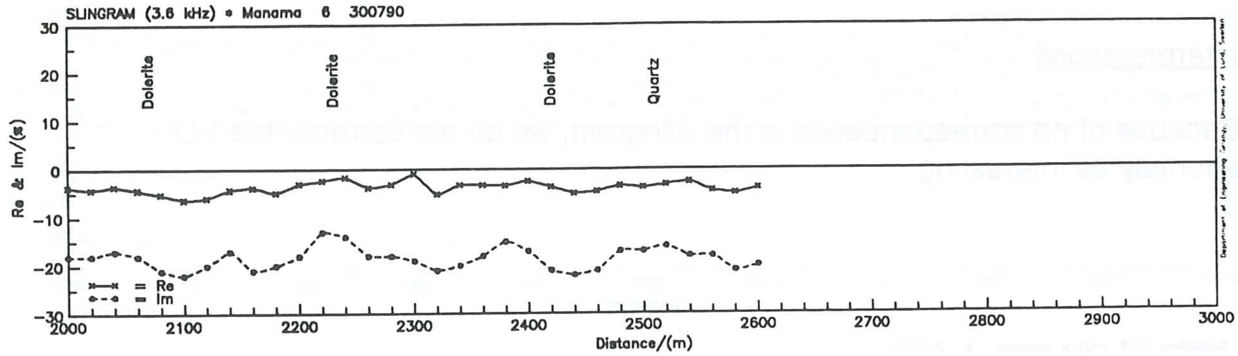
## Interpretations

Because of no correspondence in the Slingram, we do not consider the VLF-anomaly as interesting.




SLINGRAM (3.6 kHz) * Manama 6 300790
Dol 30 m
Stream
Re & Im/(%)
Distance/(m)
Re
Im


SLINGRAM (3.6 kHz) * Manama 6 300790
Dolerite
Dolerite
Dolerite
Quartz
Re & Im/(%)
Distance/(m)
Re
Im

PROFILE NO 7

Date: 140790 Slingram, 310790 VLF
Direction: S - N
Length: 3580 m Slingram, 3200 m VLF
Frequence: Slingram 3.6 kHz
VLF 22.2 kHz

Comments

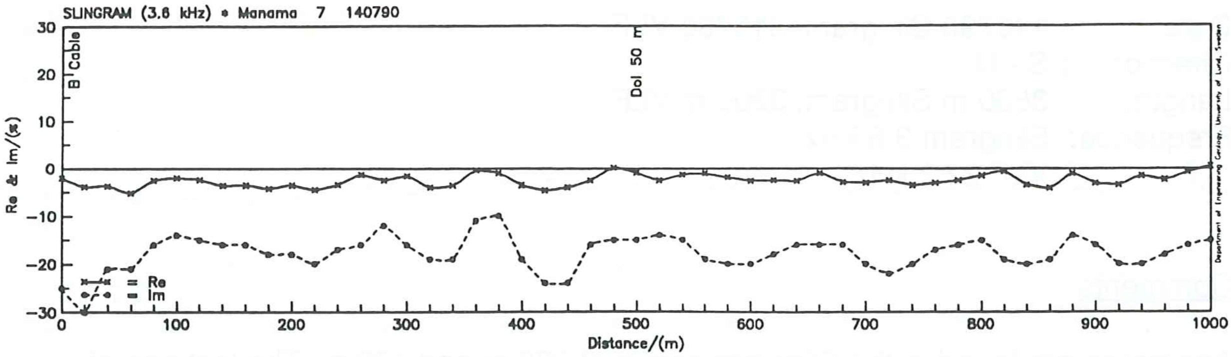
Anomalies are found in the Slingram-profile at 330 m and 430 m. The last one of these is in a small stream and in the middle of an area with a lot of dolerite dykes.

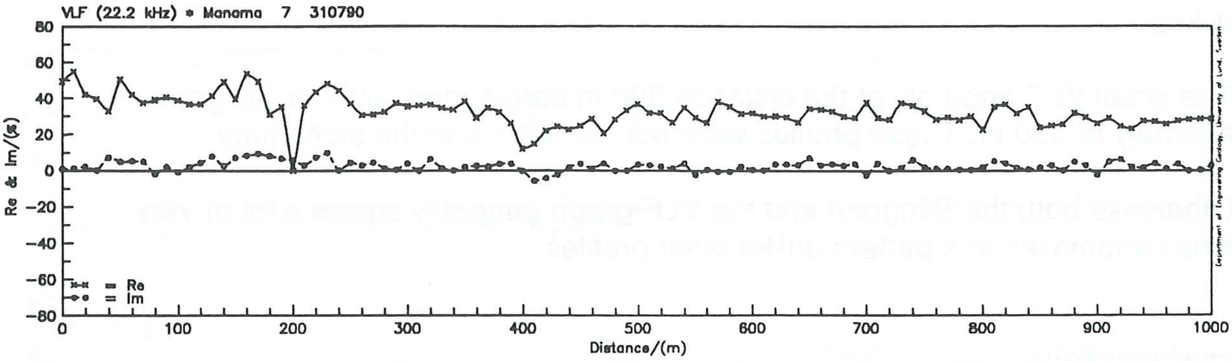
The small VLF-anomaly at the distance 390 m correspond with the Slingram-anomaly at 430 m. These profiles were not carried out at the same time.

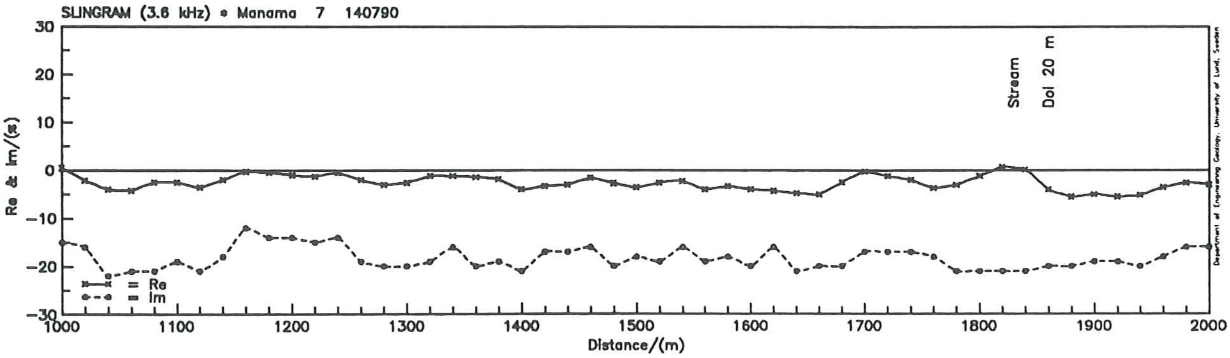
Otherwise both the Slingram and the VLF-graph generally shows a lot of very small anomalies in a pattern unlike other profiles.

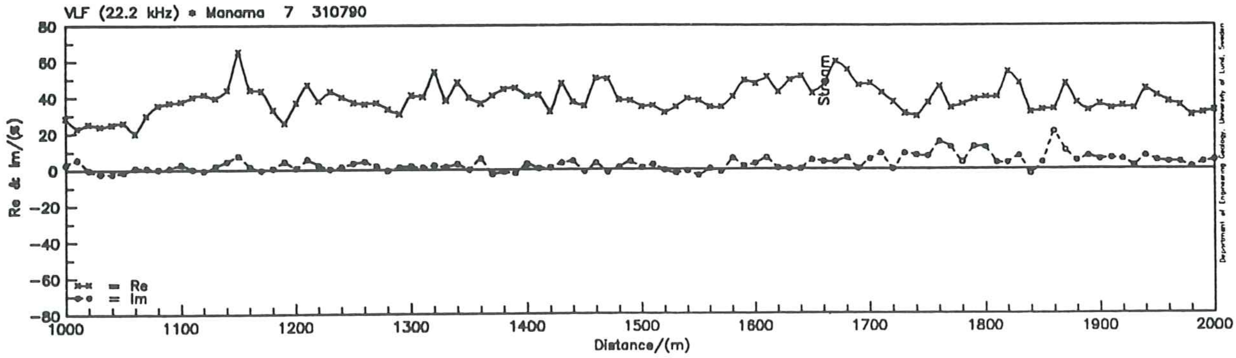
Interpretations

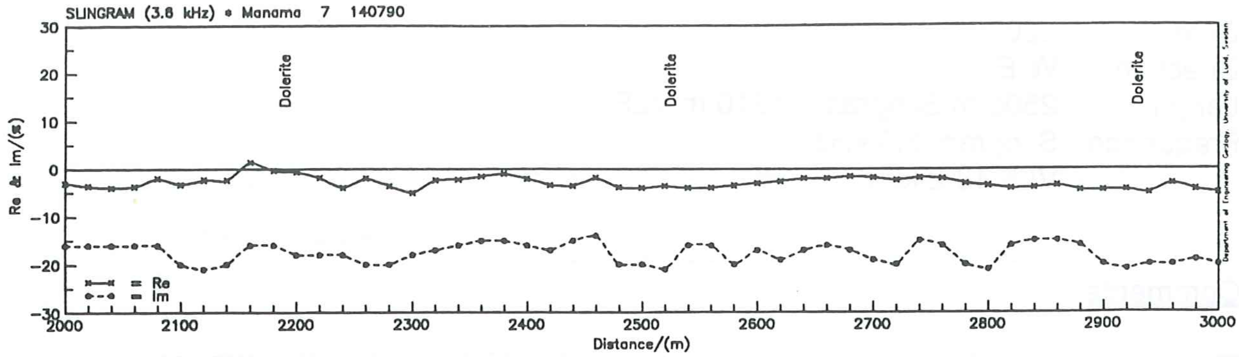
The anomalies in this profile could be caused by many, but generally very small, water bearing fracture zones.


SLINGRAM (3.6 kHz) * Manama 7 140790
B Cable
Dol 50 m
Re & Im/(%)
= Re
= Im
Distance/(m)


VLF (22.2 kHz) * Manama 7 310790
Re & Im/(%)
= Re
= Im
Distance/(m)


SLINGRAM (3.6 kHz) * Manama 7 140790
Stream
Dol 20 m
Re & Im/(%)
= Re
= Im
Distance/(m)


VLF (22.2 kHz) * Manama 7 310790
Stream
Re & Im/(%)
= Re
= Im
Distance/(m)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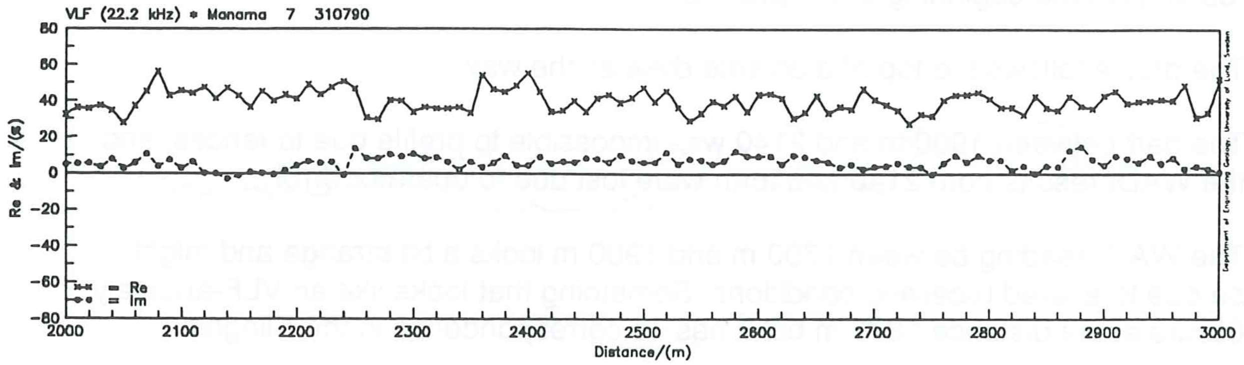
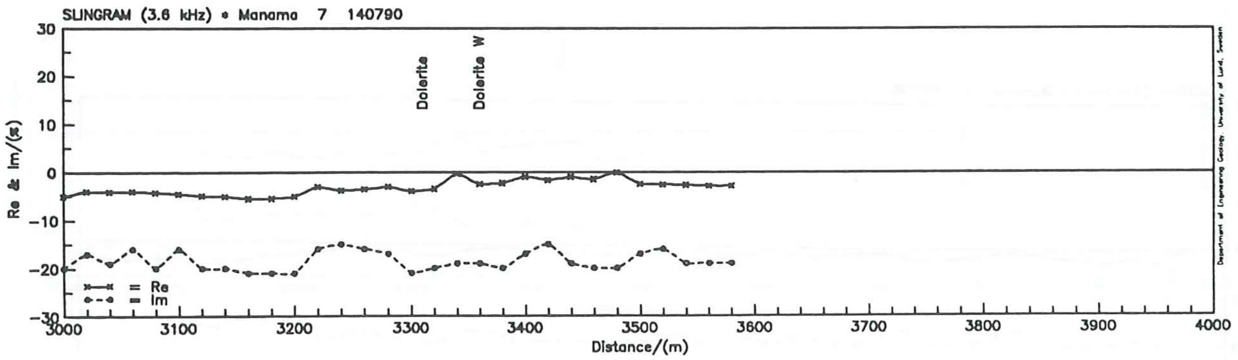
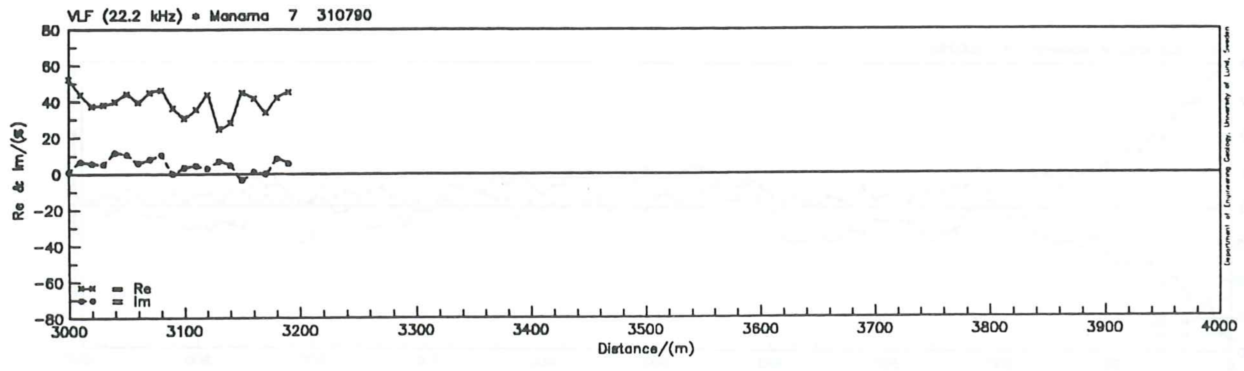
Dolerite
Dolerite
Dolerite
Re & Im/(%)
Re
Im
Distance/(m)


VLF (22.2 kHz) * Manama 7 310790
Re & Im/(%)
Re
Im
Distance/(m)


SLINGRAM (3.6 kHz) * Manama 7 140790
Dolerite
Dolerite W
Re & Im/(%)
Re
Im
Distance/(m)


VLF (22.2 kHz) * Manama 7 310790
Re & Im/(%)
Re
Im
Distance/(m)

PROFILE NO 8

Date: 200790
Direction: W-E
Length: 2500 m Slingram, 1910 m VLF
Frequence: Slingram 3.6 kHz
VLF 18.2 kHz

## Comments

The profile starts close to an electric power cable which explains the strange readings in the beginning of the profiles.

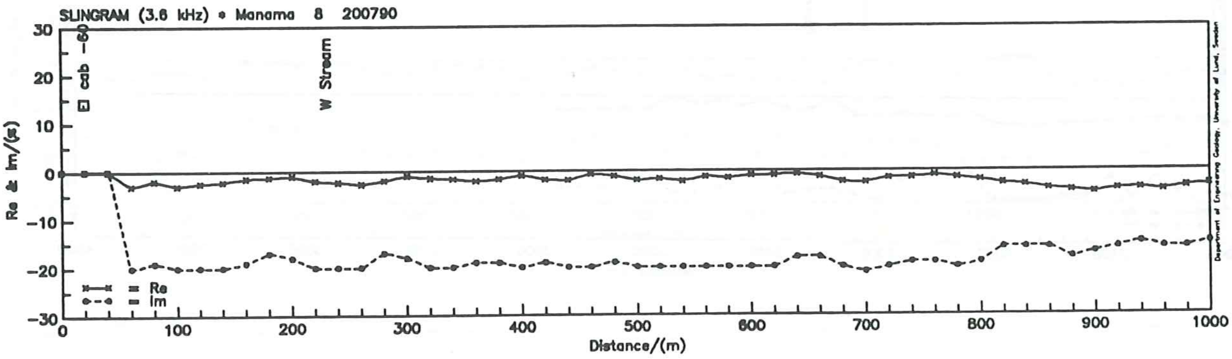
The profile follows the top of a dolerite dyke all the way.

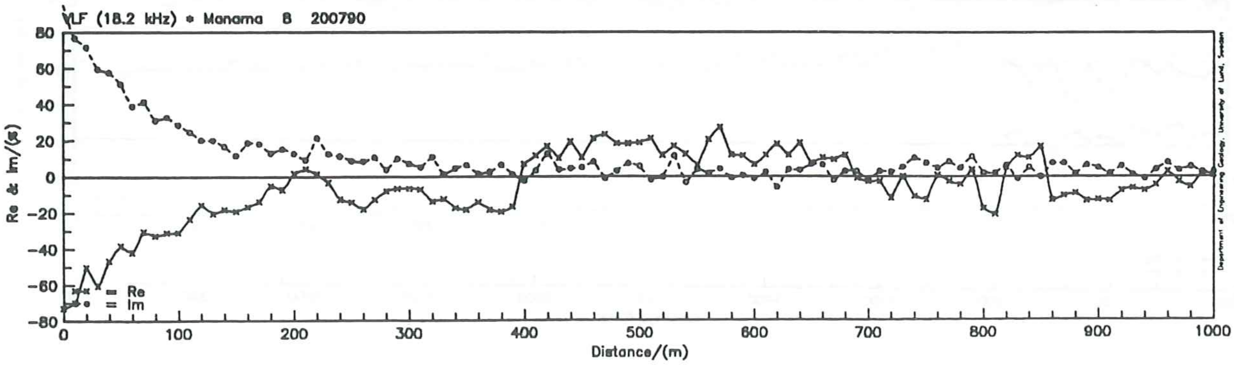
The part between 1900 m and 2140 was impossible to profile due to fences, and the WADI results from 2140 and forth were lost due to operator error.

The WADI-reading between 1700 m and 1900 m looks a bit strange and might be due to altered receiving conditions. Something that looks like an VLF-anomaly occurs at the distance 1870 m but it has no correspondence in the Slingram.

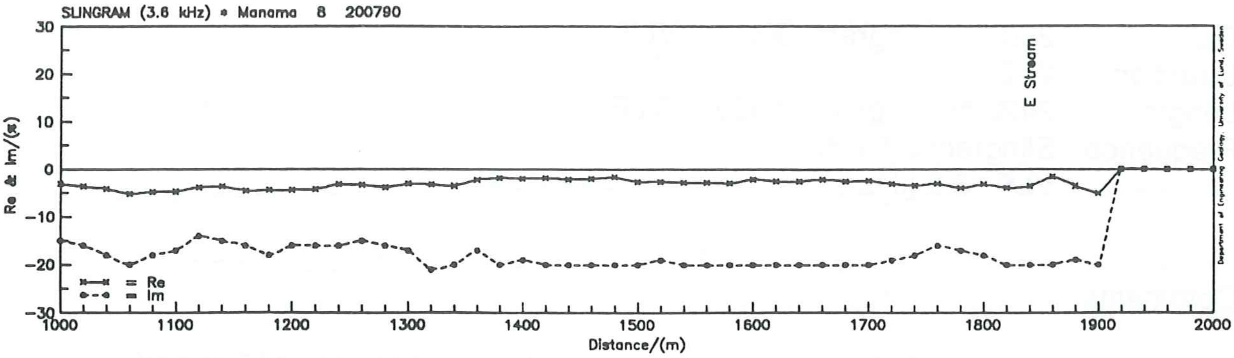
## Interpretations

No water bearing fracture zones could be interpretated.

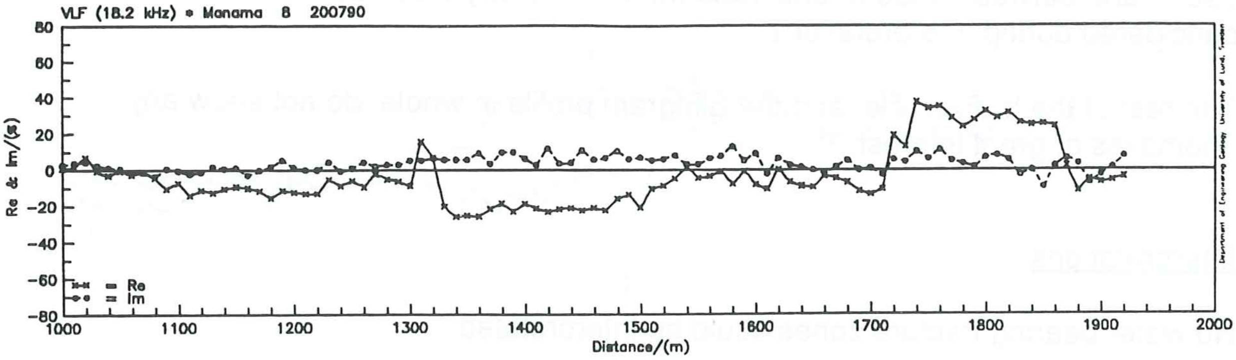


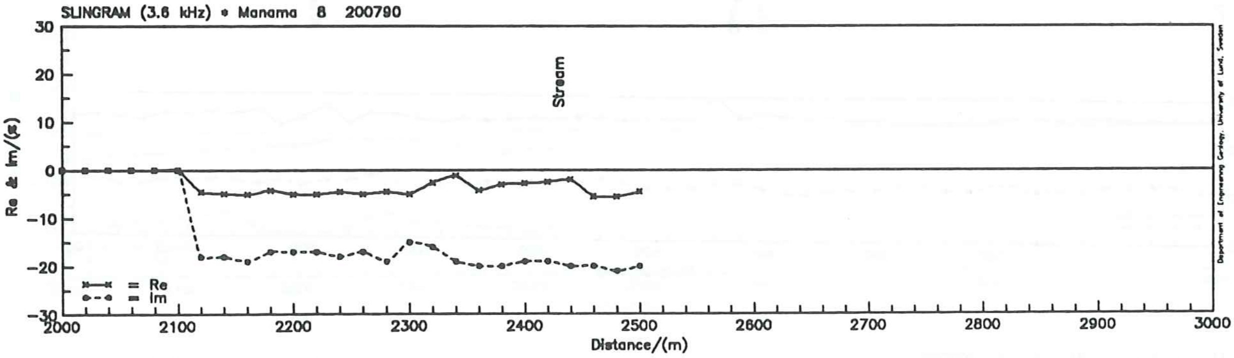
SLINGRAM (3.6 kHz) • Manama 8 200790




VLF (18.2 kHz) • Manama 8 200790




SLINGRAM (3.6 kHz) • Manama 8 200790



PROFILE NO 9

Date: 250790 Slingram, 300790 VLF
Direction: W-E
Length: 2420 m Slingram, 1990 m VLF
Frequence: Slingram 3.6 kHz
VLF 18.2 kHz

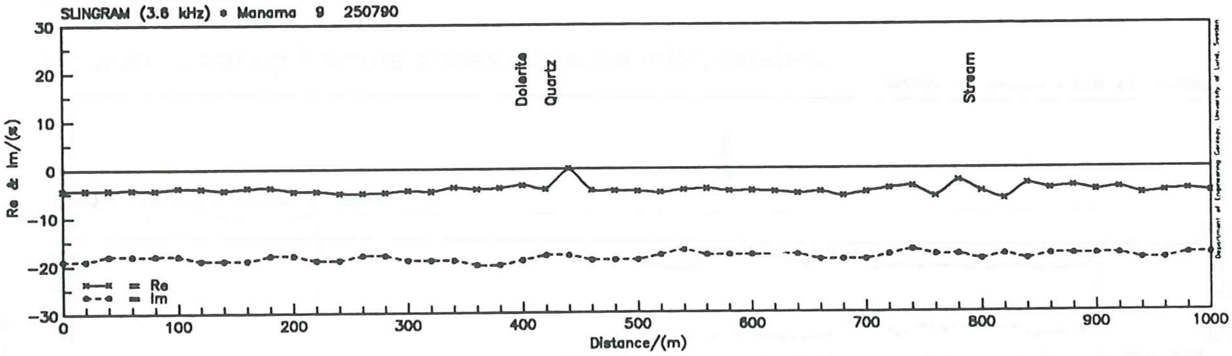
## Comments

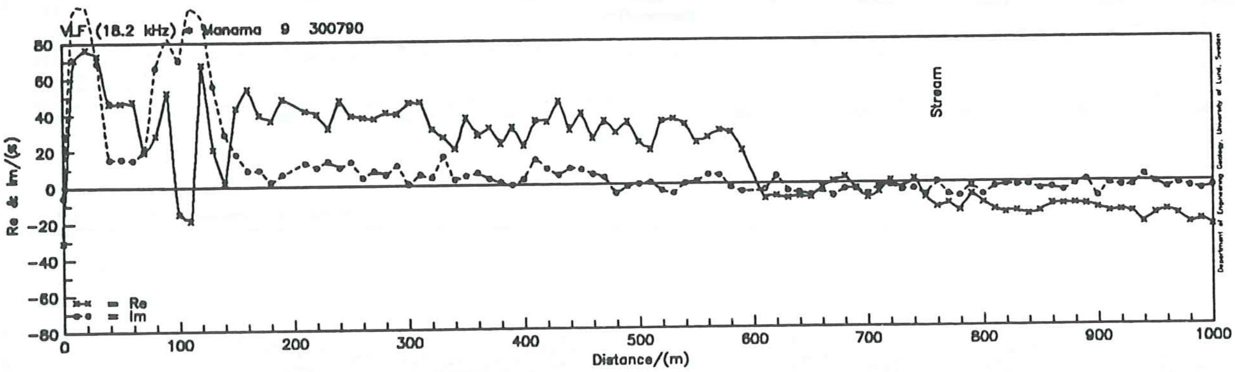
The VLF-readings are influenced by a lot of disturbances between 110 m and 590 m and between 1390 m and 1880 m, which is why these parts are not to be concidered during interpretations.

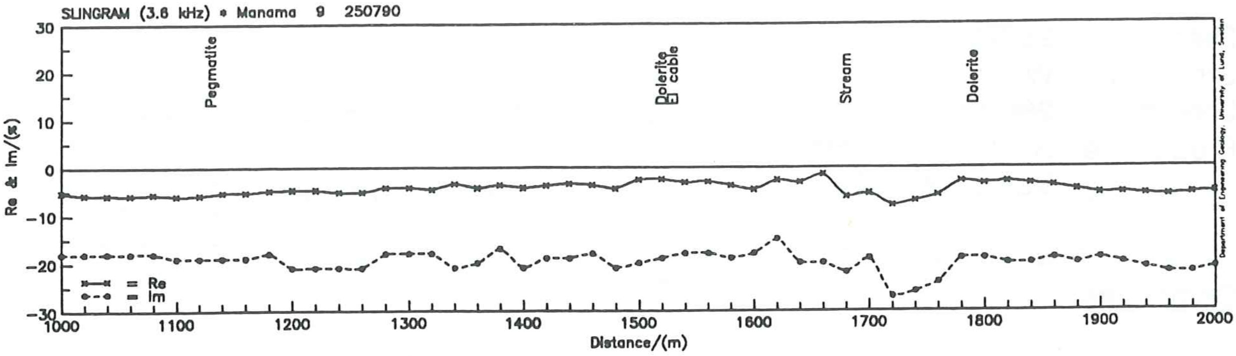
The rest of the VLF-profile, and the Slingram profile in whole, do not show any anomalies of great interest.

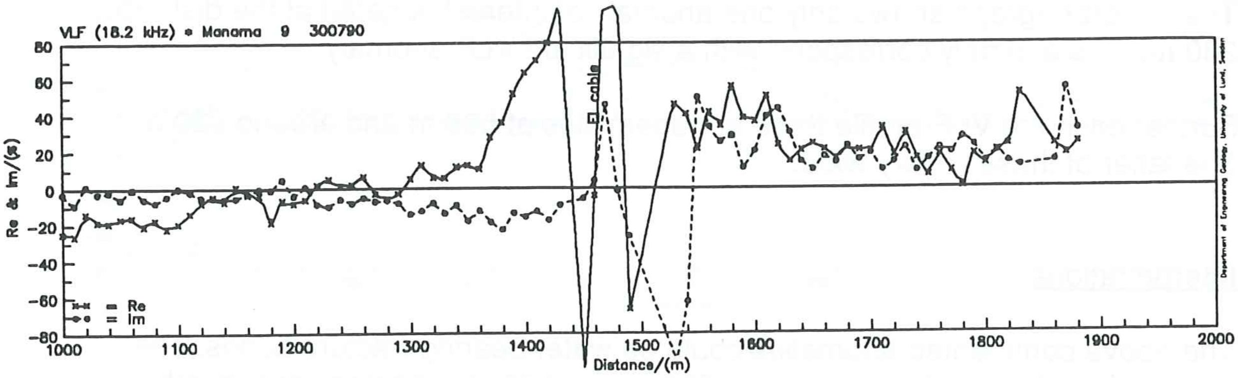
## Interpretations

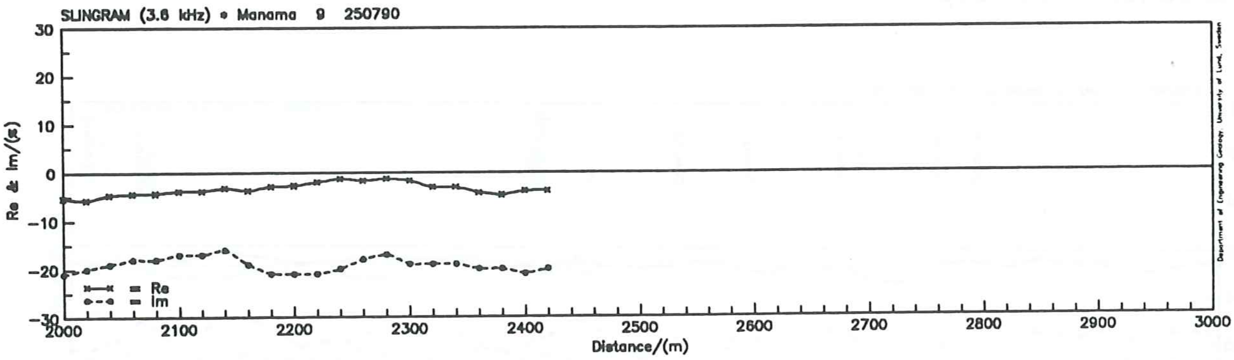
No water bearing fracture zones could be interpretated.




SLINGRAM (3.6 kHz) * Manama 9 250790
Pegmatite
Dolerite
cable
Stream
Dolerite
Re & Im/(%)
= Re
= Im
Distance/(m)
Department of Engineering Geology, University of Lund, Sweden


VLF (18.2 kHz) * Manama 9 300790
cable
Re & Im/(%)
= Re
= Im
Distance/(m)
Department of Engineering Geology, University of Lund, Sweden


SLINGRAM (3.6 kHz) * Manama 9 250790
Re & Im/(%)
= Re
= Im
Distance/(m)
Department of Engineering Geology, University of Lund, Sweden

PROFILE NO 10

Date: 280790
Direction: W-E
Length: 2660 m
Frequence: Slingram 3.6 kHz
VLF 18.2 kHZ

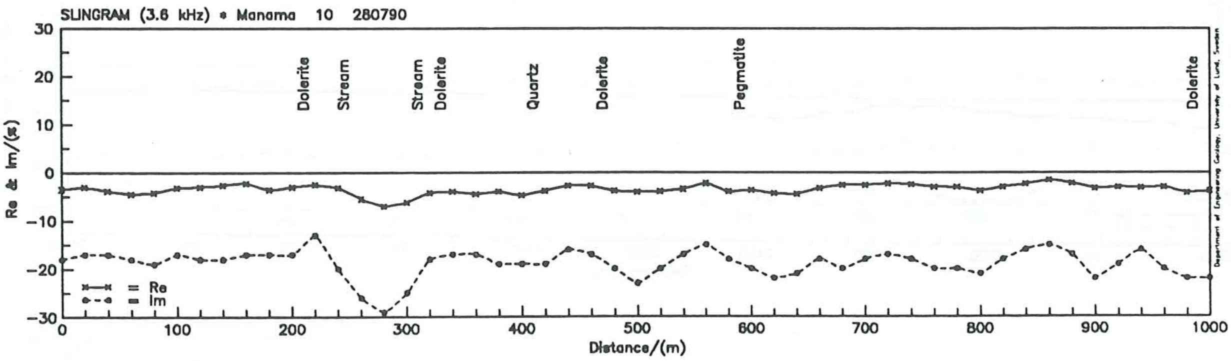
## Comments

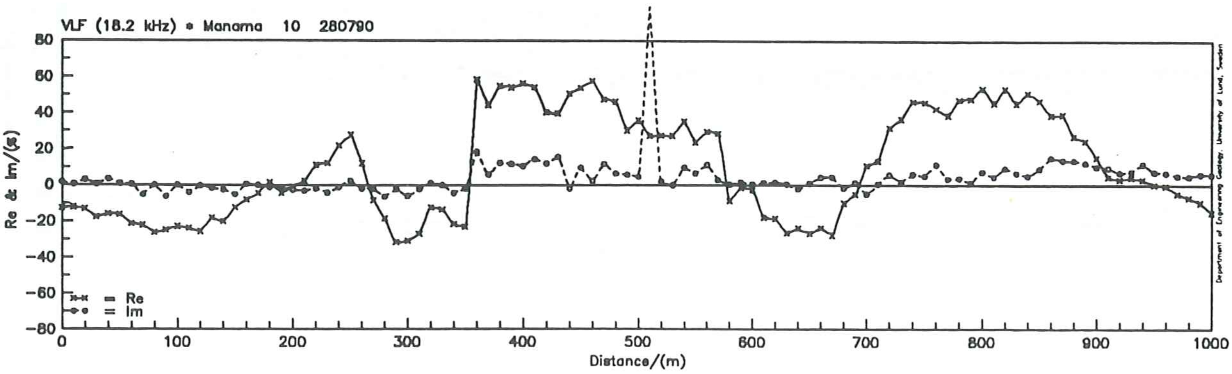
The Slingram-graph shows only one anomaly of interest, located at the distance 280 m. This anomaly correspond with a significant VLF-anomaly.

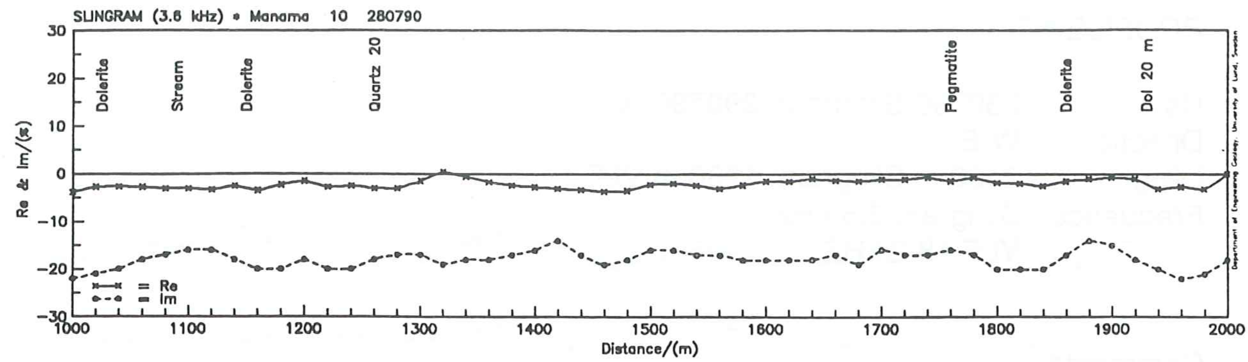
Further on in the VLF-profile there are anomalies at 590 m and around 920 m. The latter of these is very wide.

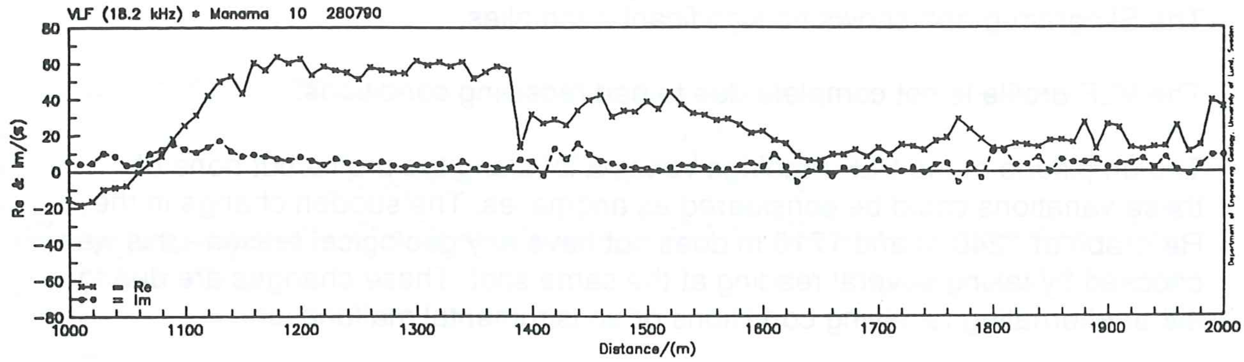
## Interpretations

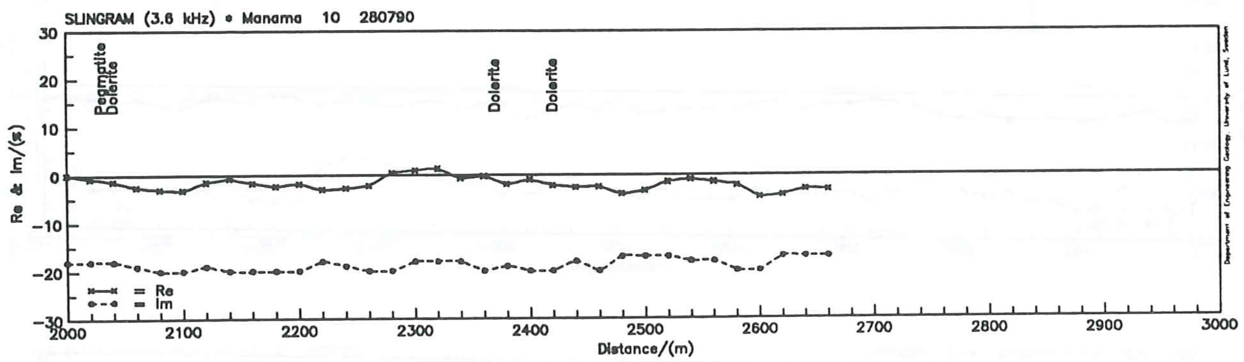
The above commented anomalies could be water bearing fracture zones. The wide shape of the VLF-anomalies at 590 m and 920 m indicates great depth (~100 m, see chapter 6.2.2 "Depth to conductor"), which could explain why they are not found in the Slingram-readings since the Slingram couldn't be expected to penetrate this depth.

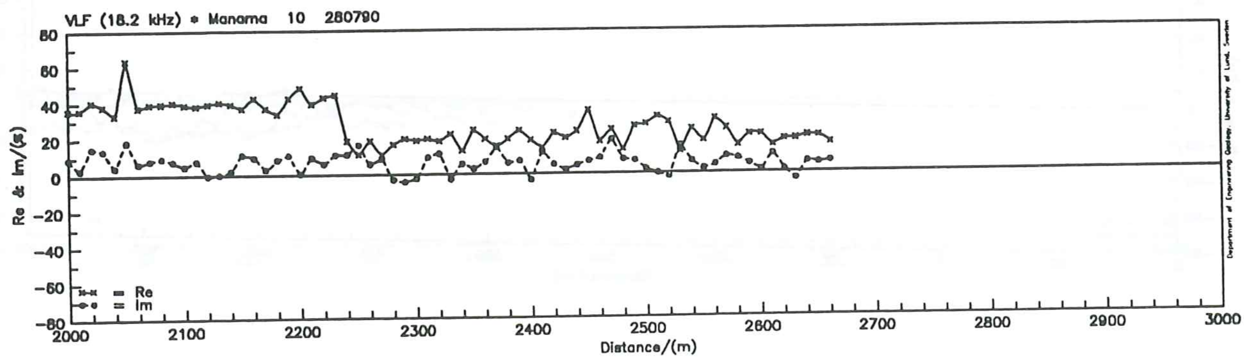



SLINGRAM (3.6 kHz) * Manama 10 280790
Dolerite
Stream
Dolerite
Quartz 20
Pegmatite
Dolerite
Dol 20 m
Re & Im/(%)
= Re
= Im
Distance/(m)


VLF (18.2 kHz) * Manama 10 280790
Re & Im/(%)
= Re
= Im
Distance/(m)


SLINGRAM (3.6 kHz) * Manama 10 280790
Pegmatite
Dolerite
Dolerite
Dolerite
Re & Im/(%)
= Re
= Im
Distance/(m)


VLF (18.2 kHz) * Manama 10 280790
Re & Im/(%)
= Re
= Im
Distance/(m)

PROFILE NO 11

Date: 280790 Slingram, 290790 VLF
Direction: W-E
Length: 2480 m Slingram, 1760 m VLF
Frequence: Slingram 3.6 kHz
VLF 18.2 kHZ

Comments

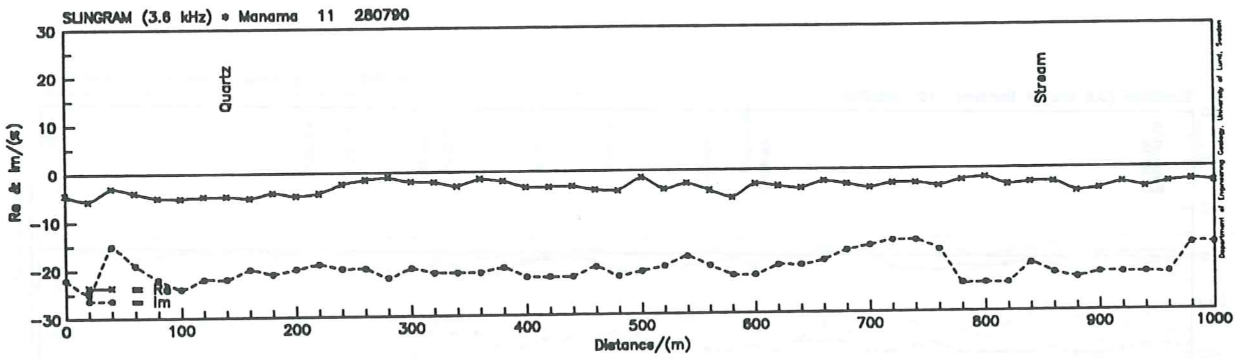
The Slingram-graph shows no significant anomalies.

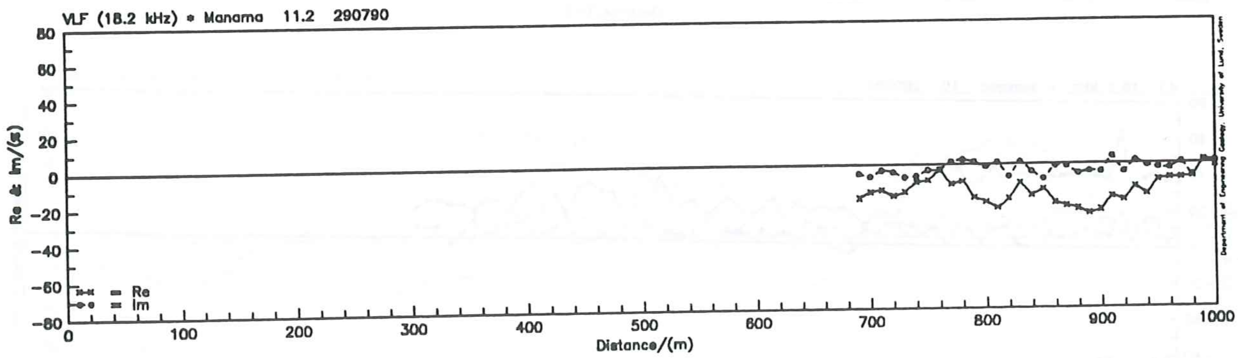
The VLF-profile is not complete due to bad receiving conditions.

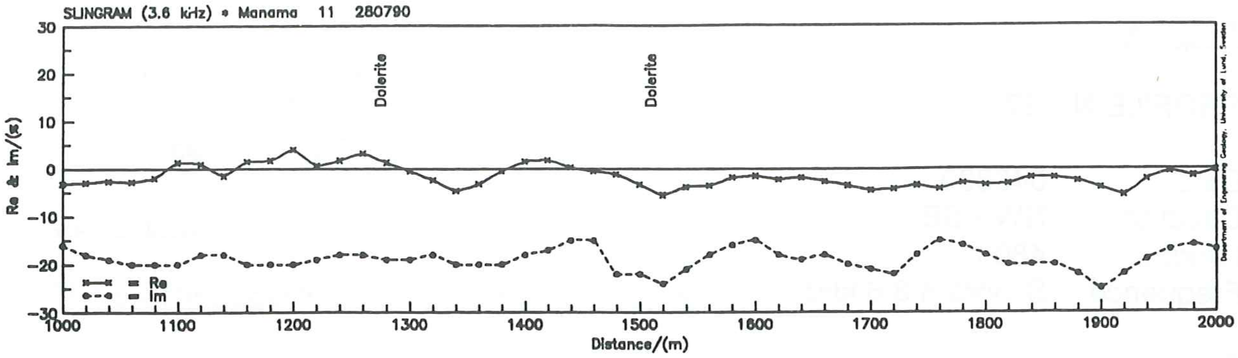
The amplitude of the VLF-readings varies a lot along the profile but none of these variations could be considered as anomalies. The sudden change in the Re-graph at 1240 m and 1710 m does not have any geological reason - this was checked by taking several reading at the same spot. These changes are due to either alternating receiving conditions or an istrumental malfunction.

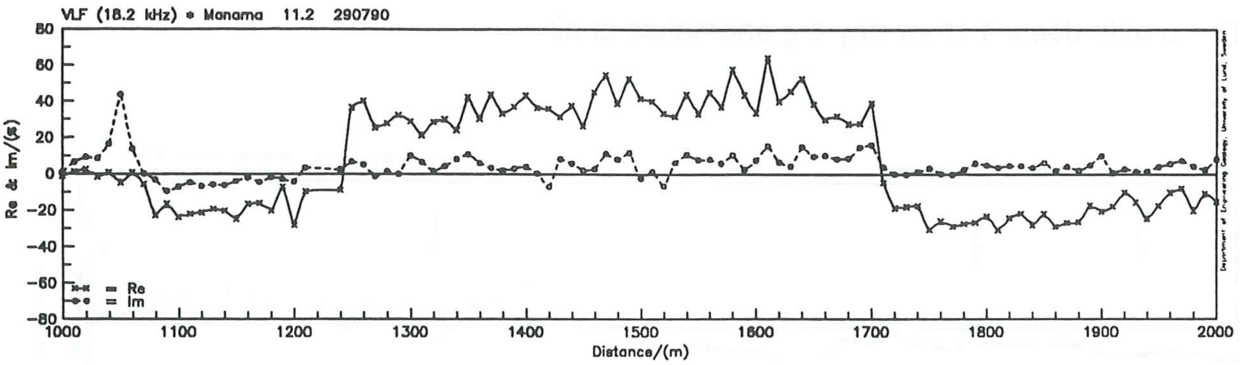
Interpretations

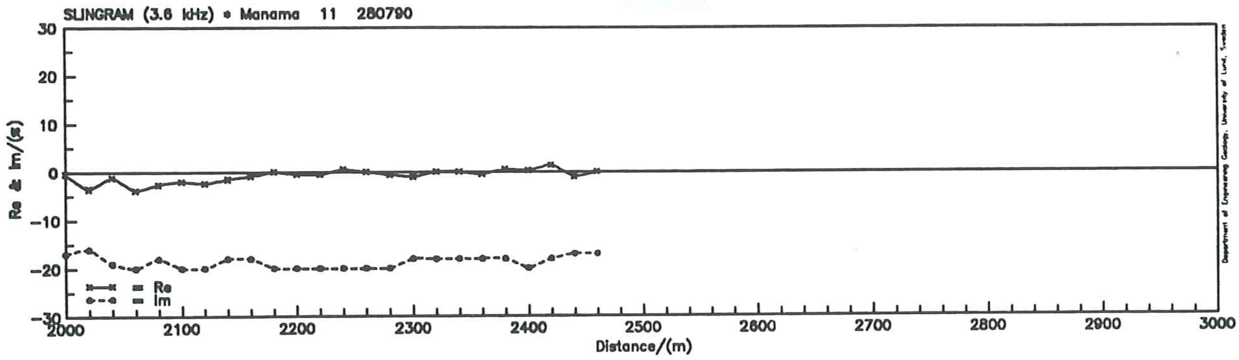
No water bearing fracture zones could be interpretated.

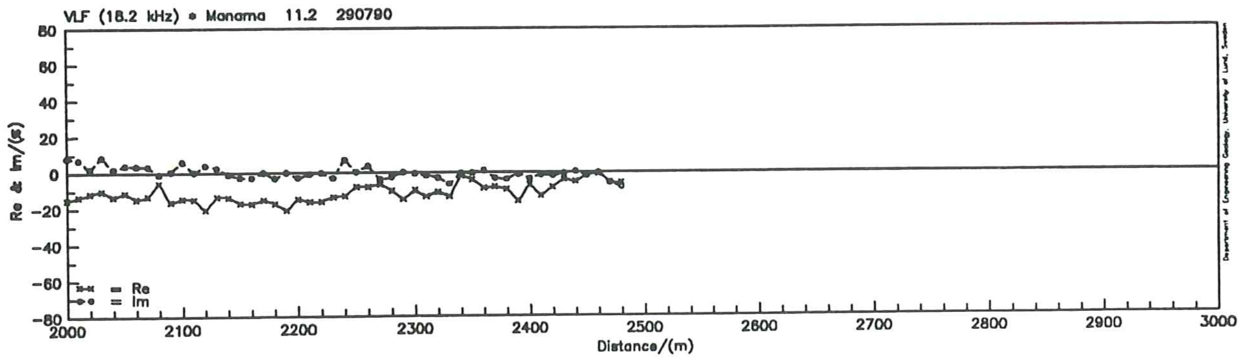



SLINGRAM (3.6 kHz) • Manama 11 280790
Re & Im/(s)
Dolerite
Dolerite
= Re
= Im
Distance/(m)
Department of Engineering Geology, University of Lund, Sweden


VLF (18.2 kHz) • Manama 11.2 290790
Re & Im/(s)
= Re
= Im
Distance/(m)
Department of Engineering Geology, University of Lund, Sweden


SLINGRAM (3.6 kHz) • Manama 11 280790
Re & Im/(s)
= Re
= Im
Distance/(m)
Department of Engineering Geology, University of Lund, Sweden


VLF (18.2 kHz) • Manama 11.2 290790
Re & Im/(s)
= Re
= Im
Distance/(m)
Department of Engineering Geology, University of Lund, Sweden

DETAIL INVESTIGATION

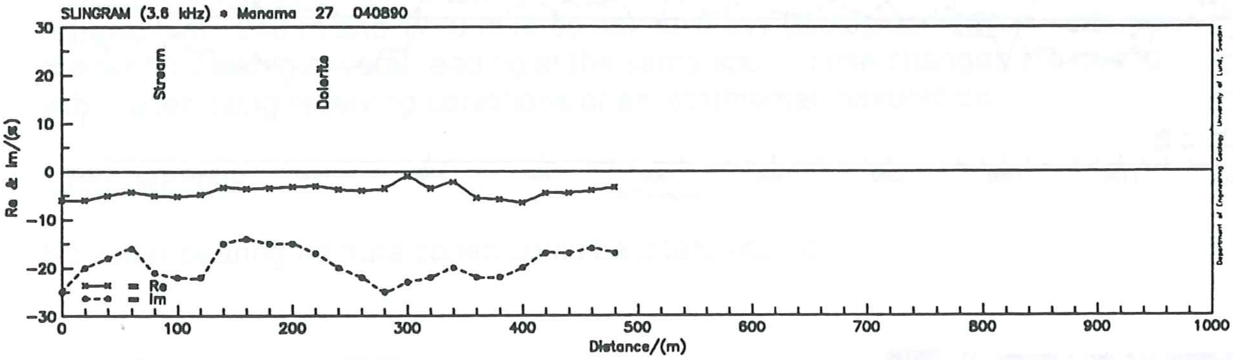
AREA A

PROFILE NO 27

Date: 040890
Direction: NW - SE
Length: 480 m
Frequence: Slingram 3.6 kHz

Comments

The profile doesn't show any big anomalies at all.

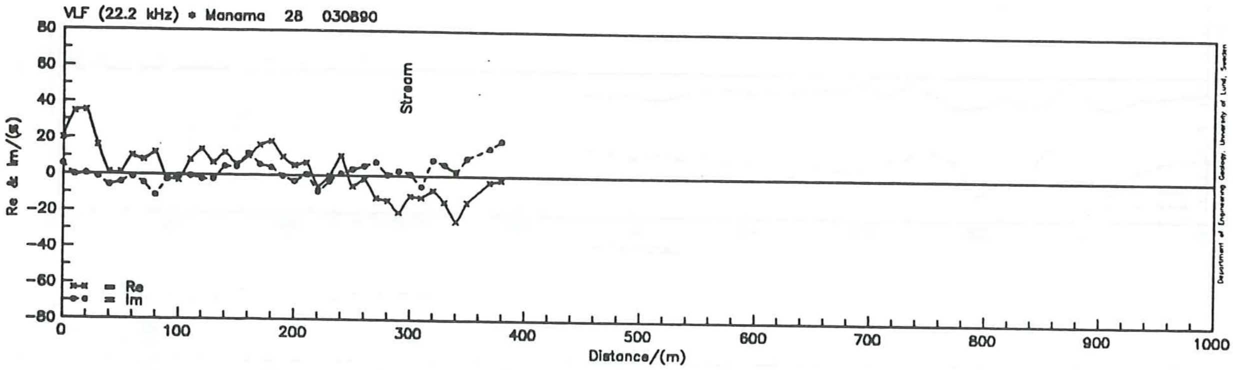


PROFILE NO 28

Date: 030890
Direction: NW - SE
Length: 380 m
Frequence: VLF 22.2 kHz

Comments

The profile doesn't shoe any big anomalies at all.

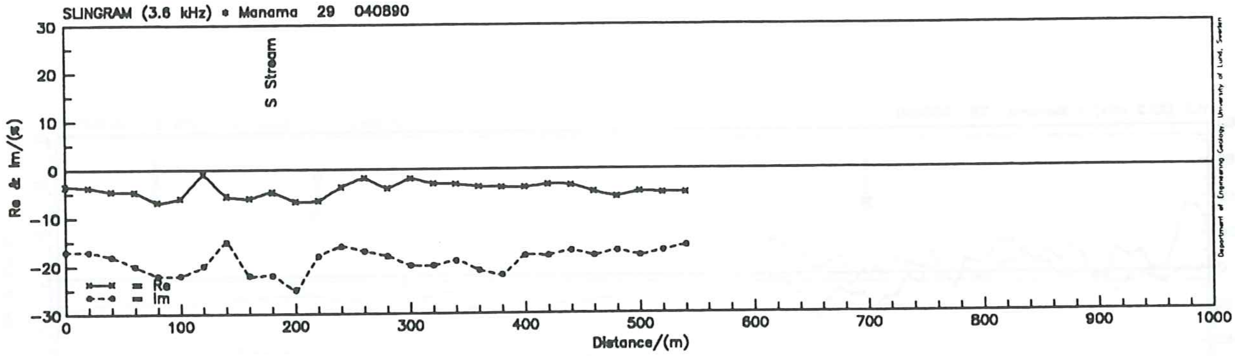


PROFILE NO 29

Date: 040890
Direction: NW - SE
Length: 540 m
Frequence: Slingram 3.6 kHz

Comments

The profile doesn't show any big anomalies at all.




Interpretation area A

The completed investigations in area A indicate that there is a structure in the earlier presumed direction. It is probably a waterbearing fracture zone. However, the results indicate that it is not a waterbearing fracture zone of the size that would be interesting for a borehole.

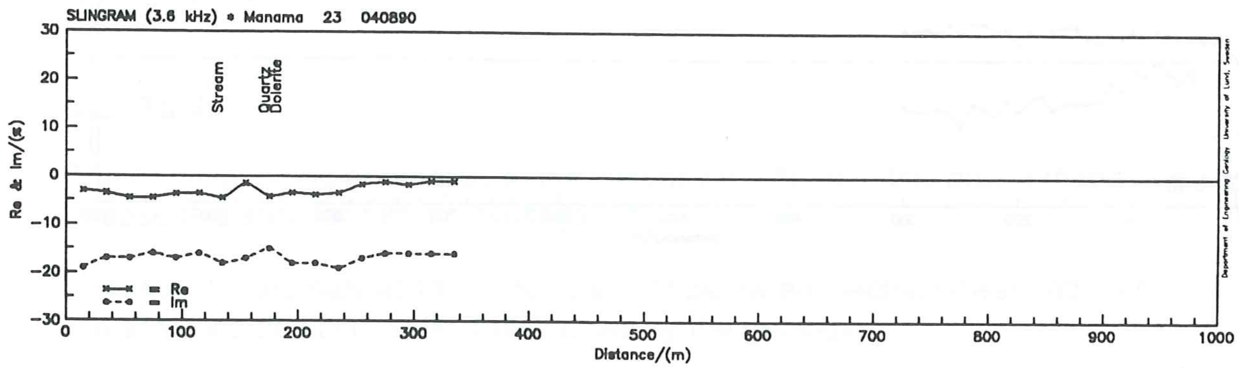
AREA B

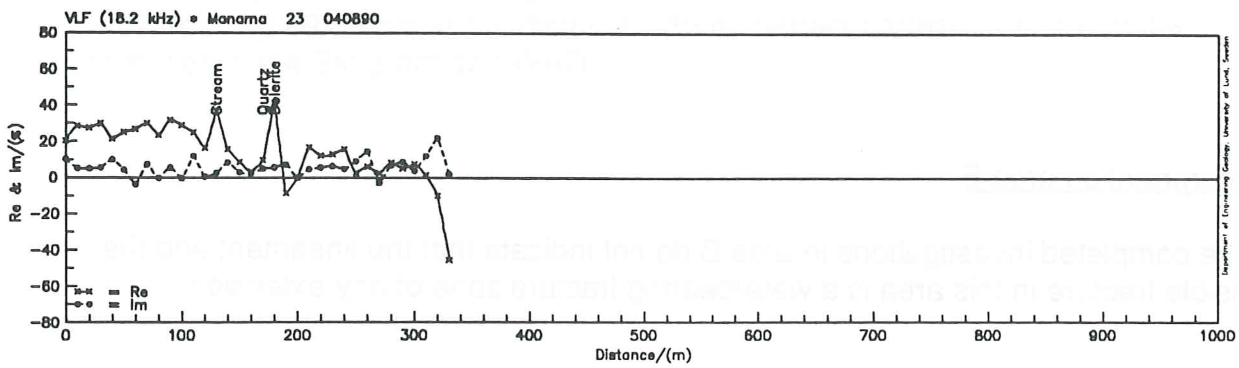
PROFILE NO 23

Date: 040890
Direction: W - E
Length: 320 m Slingram, 330 m VLF
Frequences: Slingram 3.6 kHz
VLF 18.2 kHz

Comments

The profiles do not show any interesting anomalies at all.



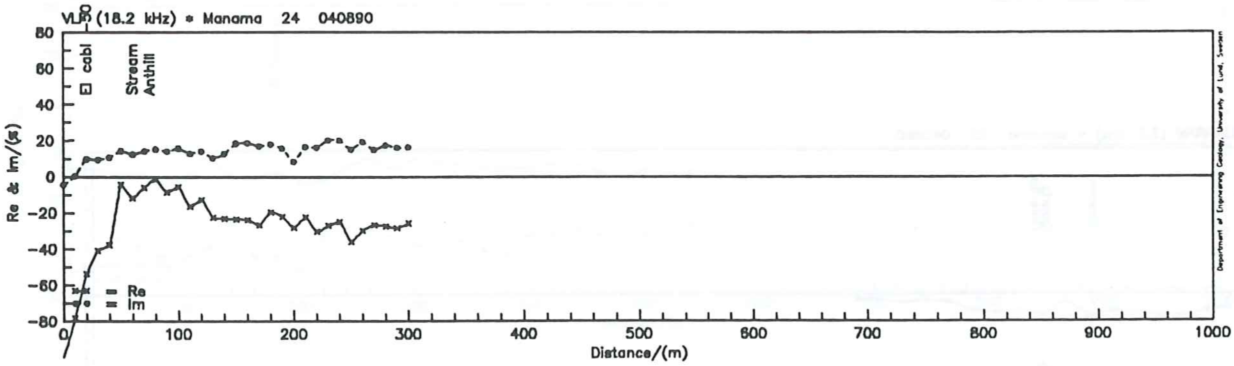



PROFILE NO 24

Date: 040890
Direction: W - E
Length: 300 m
Frequence: VLF 18.2 kHz

<u>Comments</u>

The low readings in the beginning of the profile are caused by an electric power cable. Otherwise nothing of interest.




<u>Interpretation area B</u>

The completed investigations in area B do not indicate that the lineament and the visible fracture in this area is a waterbearing fracture zone of any extension.

AREA C

PROFILE NO 1 (0 - 500 m) ( See GENERAL PROFILING )

Date: 240790
Direction: S - N
Length: 3380 m
Frequences: Slingram 3.6 kHz
VLF 19.2 kHz

*Resistivity*

The interesting part of profile no 1 was completed with a resistivity profile, Wenner configuration.

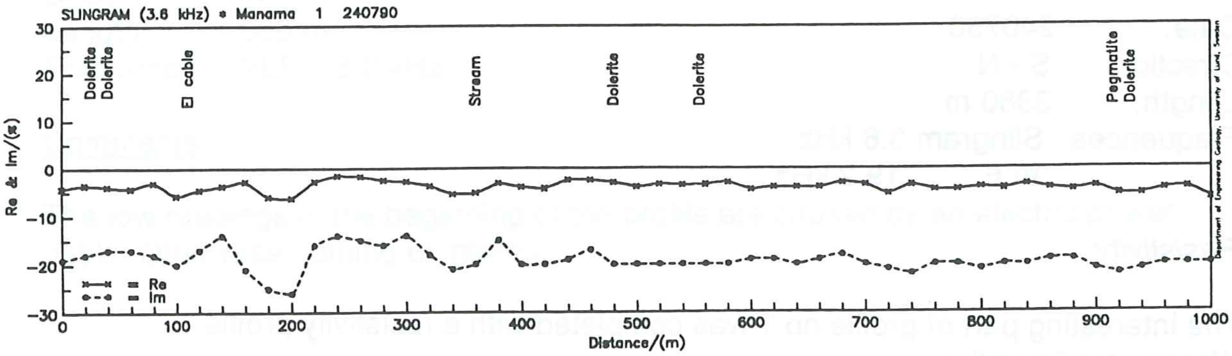
Date: 030890
Length: 120 m
Electrode spacing: 10 m

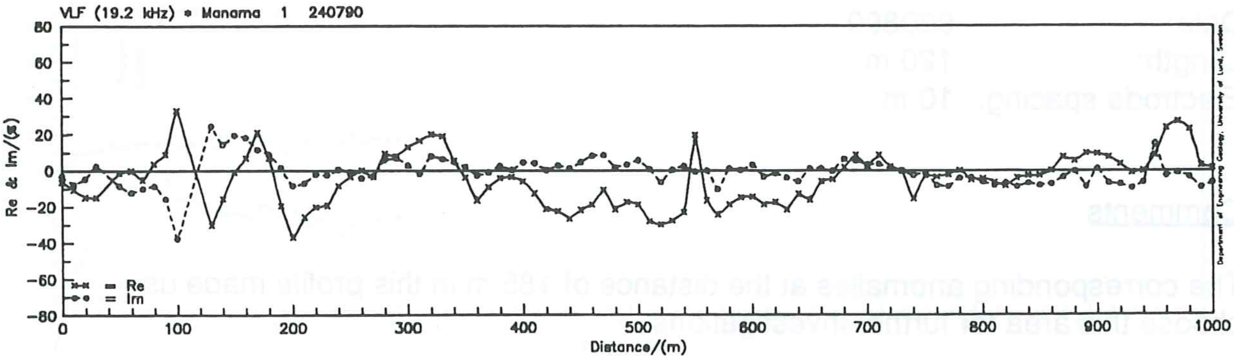
Comments

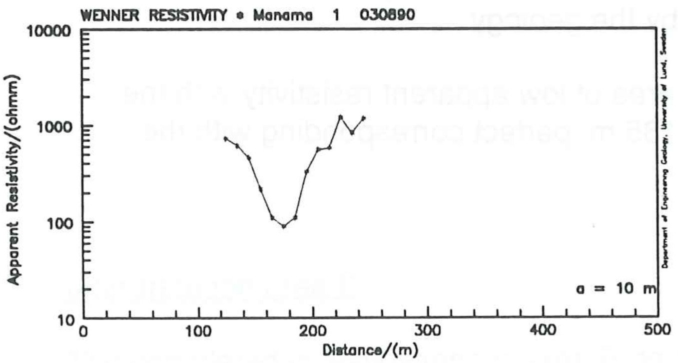
The corresponding anomalies at the distance of 185 m in this profile made us choose this area for further investigations.

The WADI - anomaly at 110 m occurs right below an electric power cable and therefore we don't consider it as caused by the geology.

The resistivity profile shows a significant area of low apparent resistivity with the lowest reading 89 ohmm at the distance 185 m, perfect corresponding with the anomalies in the Slingram and WADI.


SLINGRAM (3.6 kHz) ∘ Manama 1 240790
Dolerite
Dolerite
El cable
Stream
Dolerite
Dolerite
Pegmatite
Dolerite
Re & Im/(%)
Re
Im
Distance/(m)


VLF (19.2 kHz) ∘ Manama 1 240790
Re & Im/(%)
Re
Im
Distance/(m)


WENNER RESISTIVITY ∘ Manama 1 030890
Apparent Resistivity/(ohmm)
a = 10 m
Distance/(m)

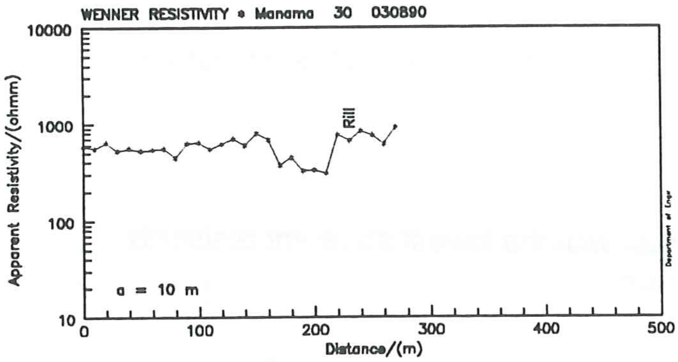
PROFILE NO 30

In this profile only the resistivity instrument was used because of the location close to the electric power cable. The purpose was to find an anomaly corresponding with the ones in profile no1, in our expected fracture direction, 290 °.

Date: 030890
Length: 270 m
Electrode spacing: 10 m

<u>Comments</u>

A significant area of low apparent resistivity is found at the distance of 190 m, and the lowest reading 305 ohmm is found at 210 m.



PROFILE NO 22

The purpose of this profile was to find an anomaly corresponding to the ones found in profile no 1, in our expected fracture direction, 290 °.

Date: 050890
Direction: S - N
Length: 200 m
Frequence: Slingram 3.6 kHz

<u>Comments</u>

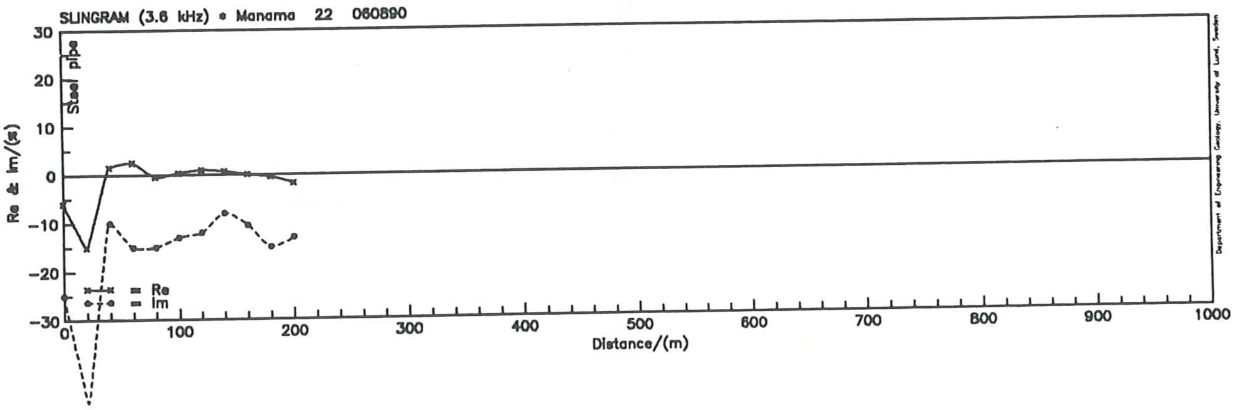
The big anomaly in the beginning is due to the main steel pipe between the wellpoint system and the pumphouse. Otherwise nothing of interest along the profile.

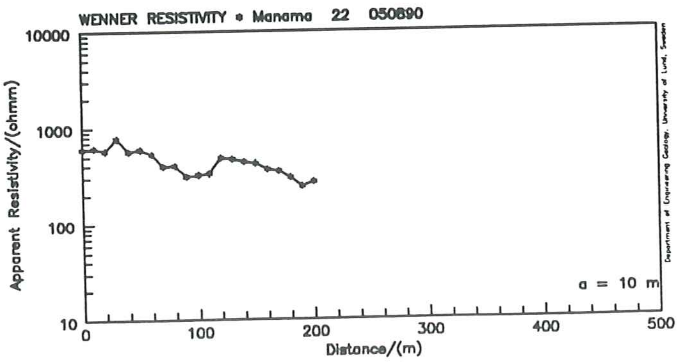
*Resistivity*

Date: 050890
Length: 200 m
Electrode spacing: 10 m

<u>Comments</u>

At the distance of 100 m there is an anomali with the lowest apparent resistivity 298 ohmm. However, it's not very significant.



## Interpretation area C

The anomalies found in area C indicate a possible waterbearing fracturezone in an east - west direction. The indications are not very strong, but geophysical results correlate well with the geological results that gave a main fracture direction that support the above interpretation. It is also likely that a fracture zone this close to the riverbed would be recharged with water from the riverbed.

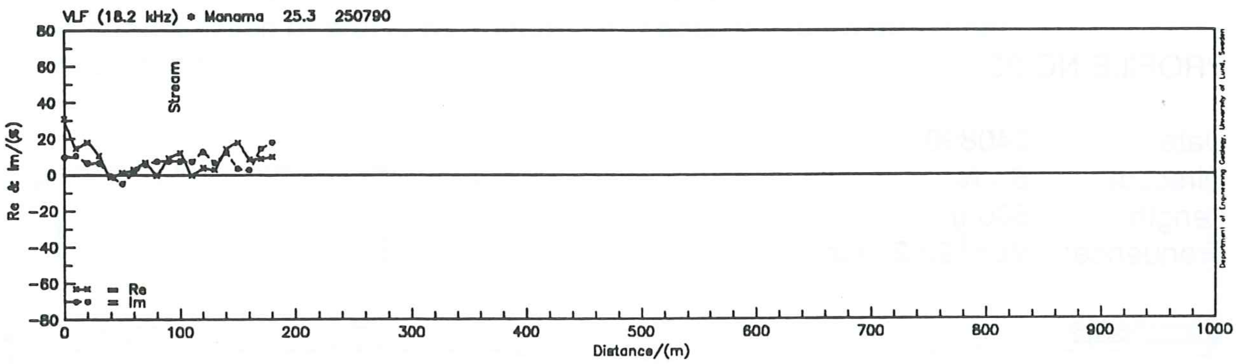
## AREA D

PROFILE NO 25 (3)

Date: 250790
Direction: W - E
Length: 180 m
Frequence: VLF 18.2 kHz

### Comments

No interesting anomalies are found.

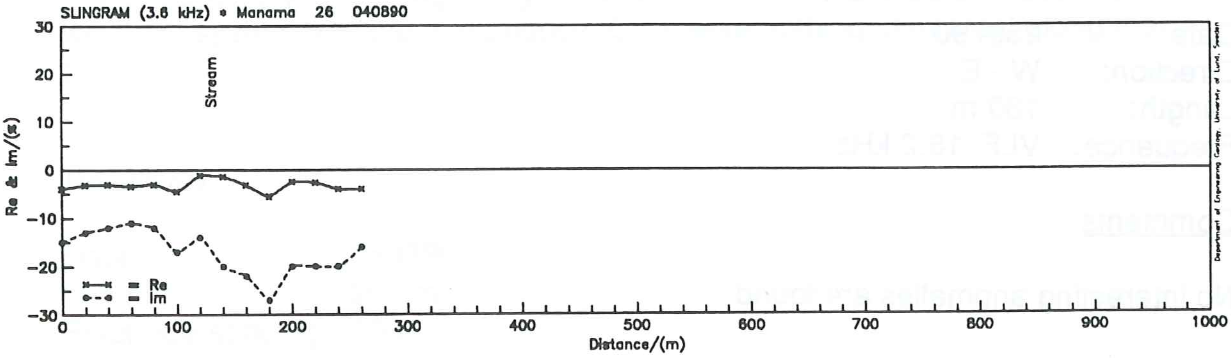


PROFILE NO 26

Date: 040890
Direction: W - E
Length: 280 m
Frequence: Slingram 3.6 kHz

Comments

Small anomaly shown at the distance of 180 m.

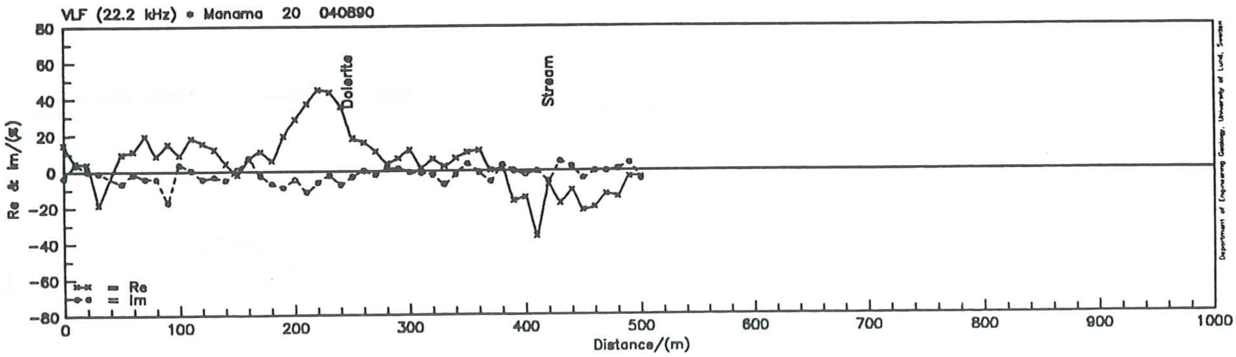



PROFILE NO 20

Date: 040890
Direction: S - N
Length: 500 m
Frequence: VLF 22.2 kHz

Comments

Anomalies are shown at the distance of 260 m and 390 m. However, these do not occur when entering the mafic area, or correspond with anomalies found in other profiles in the area.



## Interpretation area D

The results do not indicate that there are any waterbearing fractures in the contact between the different rocktypes or that the streams follows fractures that are waterbearing.

## AREA E

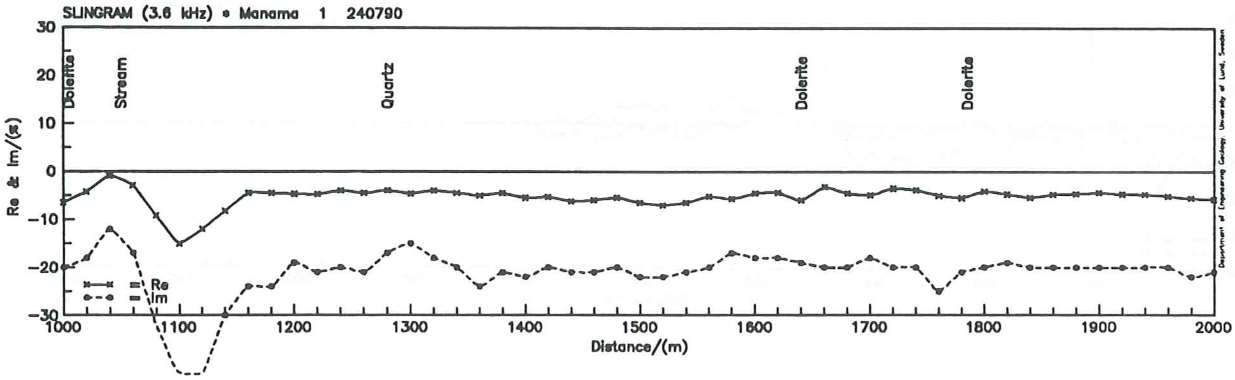
The profiles no 14 - 19 and 21 are carried out with the purpose to find conductors in the direction of 270 ° - 300 °.

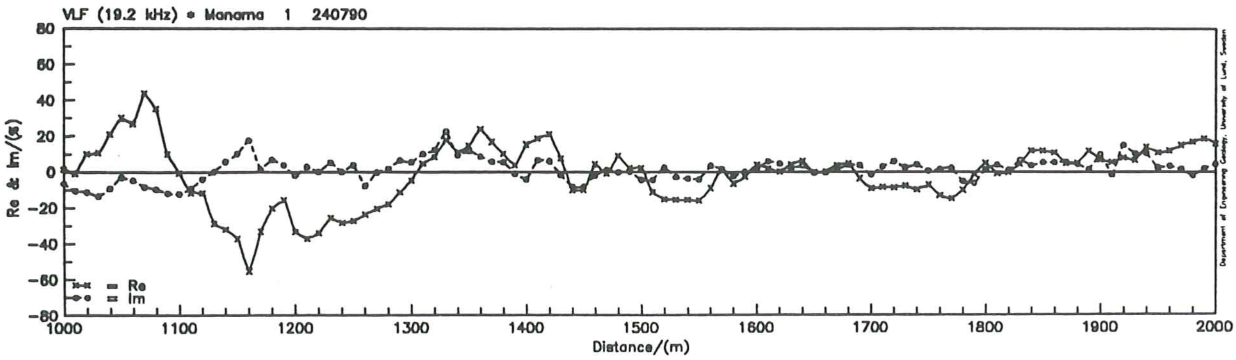
PROFILE NO 1 ( 1000 - 1500 m ) ( See GENERAL PROFILING )

Date: 240790
Direction: S - N
Length: 3380 m
Frequences: Slingram 3.6 kHz
VLF 19.2 kHz

## Comments

The very significant, large and corresponding anomalies at the distance of 1100 m in this section of profile no 1 made us choose this area for further investigation.



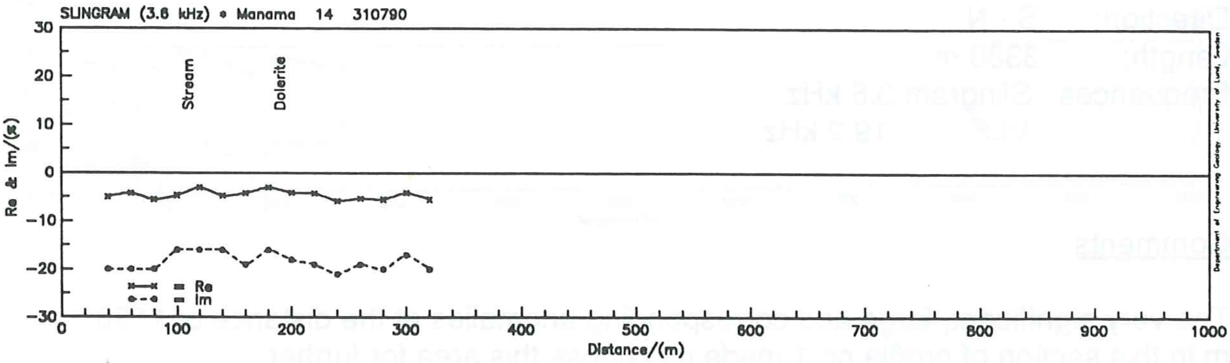



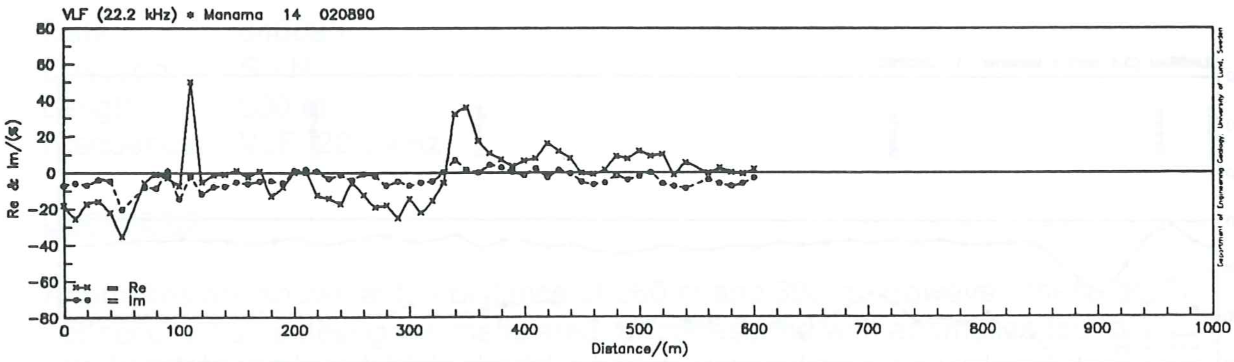
PROFILE NO 14

Date: 020890
Direction: S - N
Length: 280 m Slingram, 600 m VLF
Frequences: Slingram 3.6 kHz
VLF 22.2 kHz

<u>Comments</u>

The Slingram-graph shows no anomalies. Something looking like an anomaly occurs at the distance of 360 m. The distorted shape could be explained by assuming a second anomaly at 430 m.



PROFILE NO 15

Date: 310790 Slingram, 020890 VLF
Direction: S - N
Length: 380 m Slingram, 540 m VLF
Frequences: Slingram 3.6 kHz
VLF 22.2 kHz

Comments

Significant corresponding anomalies are found at the distance of 300 m. The three last readings in the Slingram are given the value zero because of great disturbances. The readings at this points oscillated between maximum and minimum without stopping. According to Mr Jan Lundmark at ABEM this could only be explained by military radio activity in the surroundings.

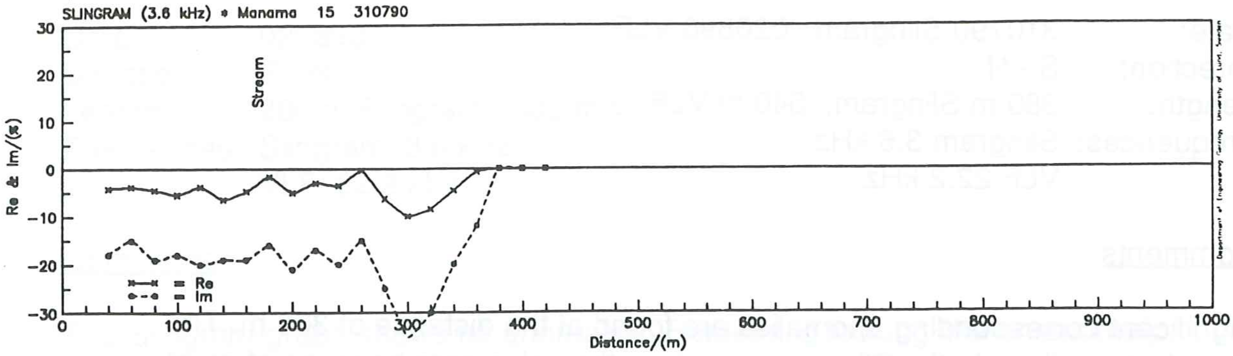
The imaginary part of the VLF-anomali shows a reverse sign that could be explained by a conductive overburden, saturated clay deposits for example .

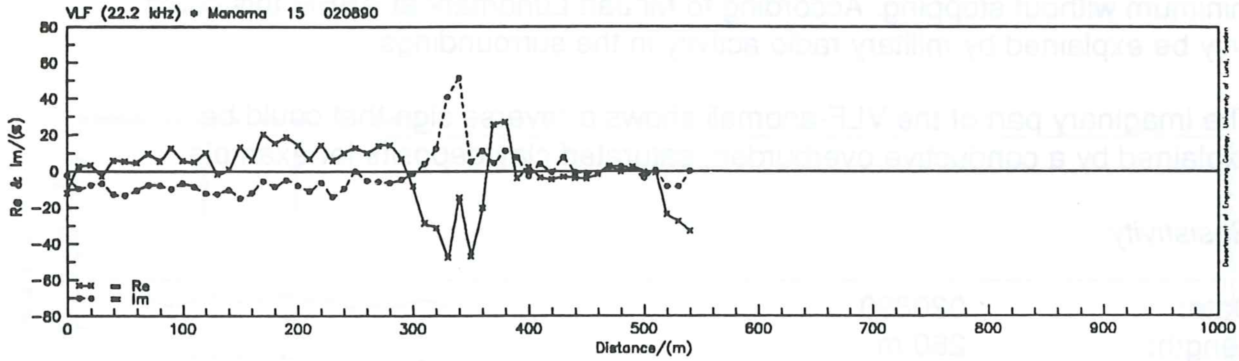
*Resistivity*

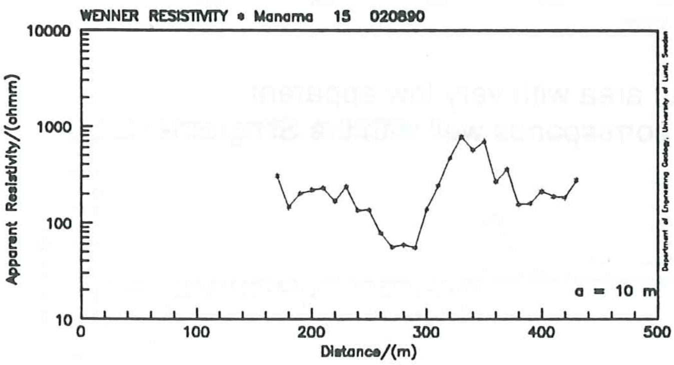
Date: 020890
Length: 260 m
Electrode spacing: 10 m

Comments

At a distance of 110 m the profile shows an area with very low apparent resistivity, the lowest resding 55 ohmm. It corresponds well with the Slingram- and the VLF-anomalies.


SLINGRAM (3.6 kHz) * Manama 15 310790
Stream
Re & Im/(%)
Re
Im
Distance/(m)
Department of Engineering Geology, University of Lund, Sweden


VLF (22.2 kHz) * Manama 15 020890
Re & Im/(%)
Re
Im
Distance/(m)
Department of Engineering Geology, University of Lund, Sweden


WENNER RESISTIVITY * Manama 15 020890
Apparent Resistivity/(ohmm)
a = 10 m
Distance/(m)
Department of Engineering Geology, University of Lund, Sweden

PROFILE NO 16

Date: 310790 Slingram, 020890 VLF
DIrection: S - N
Length: 360 m Slingram, 500 m VLF
Frequences: Slingram 3.6 kHz
VLF 22.2 kHz

Comments

There is a significant anomaly in the Slingram at the distance of 335 m. However, the readings between 275 m and 295 m, and between 375 m and the end, were disturbed in the way that they oscillated. The readings concerning these points are plotted as the approximate oscillating mean value.

The WADI shows an anomali at 320 m. The shape of the anomali isn't very significant, but since there is a clear "build up" between 130 m and 320 m we still consider it as an anomaly.

The two anomalies don't correspond perfectly since they differ by 15 meters.

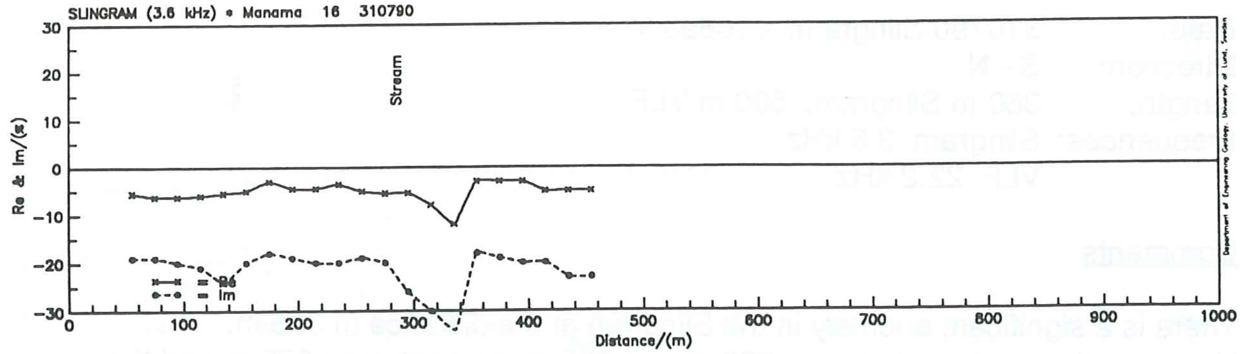
*Resistivity*

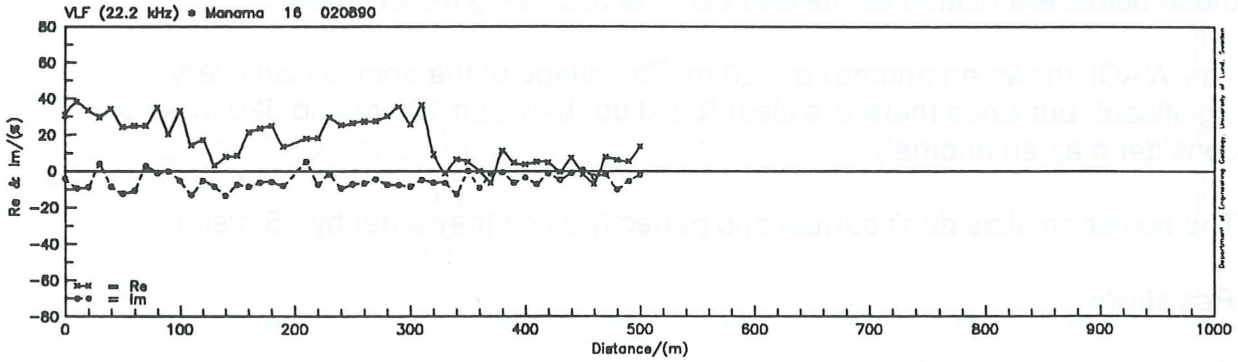
Date: 020890
Length: 280 m
Electrode spacing: 10 m

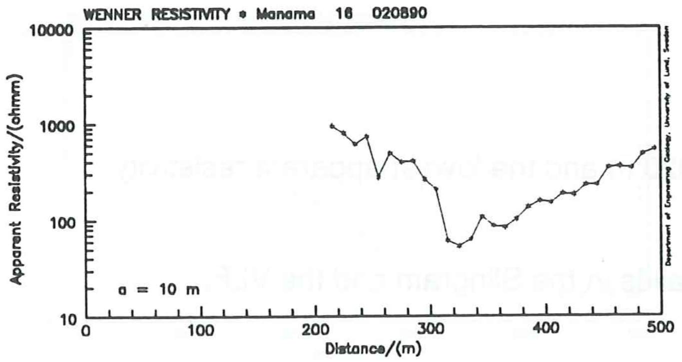
Comments

An anomali is shown at the distance of 320 m and the lowest apparent resistivity reading is 53 ohmm.

This anomaly occurs between the anomalies in the Slingram and the VLF.


SLINGRAM (3.6 kHz) • Manama 16 310790
Stream
Re & Im/(%)
Re
Im
Distance/(m)
Department of Engineering Geology, University of Lund, Sweden


VLF (22.2 kHz) • Manama 16 020890
Re & Im/(%)
Re
Im
Distance/(m)
Department of Engineering Geology, University of Lund, Sweden


WENNER RESISTIVITY • Manama 16 020890
Apparent Resistivity/(ohmm)
a = 10 m
Distance/(m)
Department of Engineering Geology, University of Lund, Sweden

PROFILE NO 17

Date: 020890
Direction: S - N
Length: 800 m Slingram, 840 m VLF
Frequences: Slingram 3.6 kHz
VLF 22.2 kHz

Comments

The Slingram shows a classic and significant anomaly at the distance of 520 m.

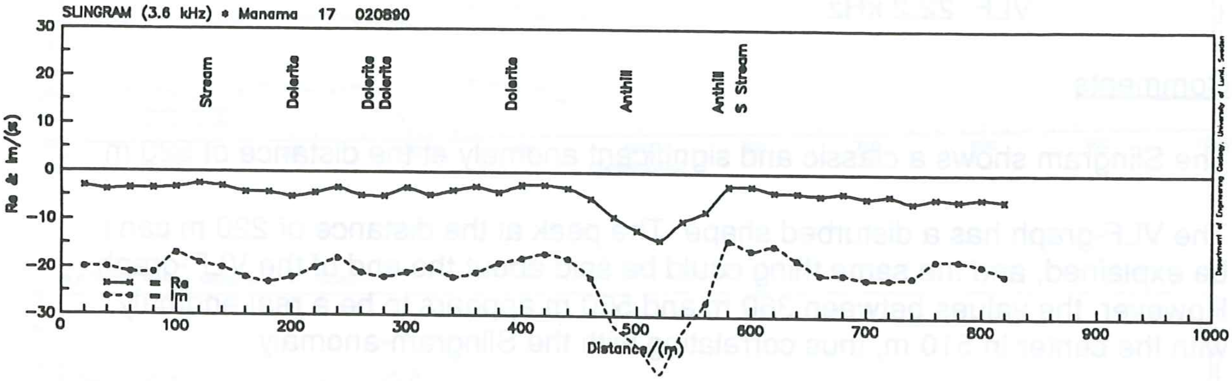
The VLF-graph has a disturbed shape. The peak at the distance of 220 m can't be explained, and the same thing could be said about the end of the VLF-graph. However, the values between 360 m and 560 m appears to be a real anomaly with the center in 510 m, thus correlating with the Slingram-anomaly.

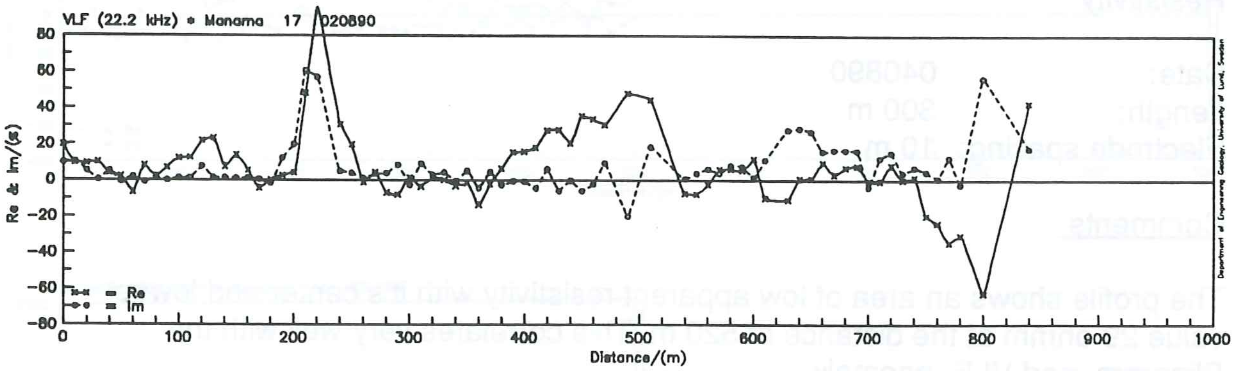
*Resistivity*

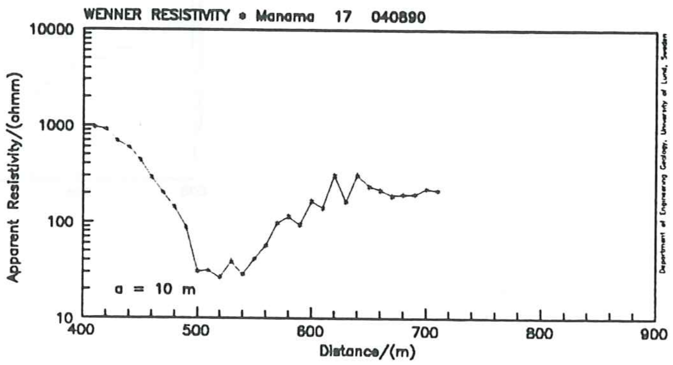
Date: 040890
Length: 300 m
Electrode spacing: 10 m

Comments

The profile shows an area of low apparent resistivity with it's center and lowest value 29 ohmm at the distance of 520 m. This correlates very well with the Slingram- and VLF -anomaly.


SLINGRAM (3.6 kHz) • Manama 17 020890
Stream
Dolerite
Dolerite
Dolerite
Dolerite
Anthill
Anthill
S Stream
Re & Im/(%)
Re
Im
Distance/(m)
Department of Engineering Geology, University of Lund, Sweden


VLF (22.2 kHz) • Manama 17 020890
Re & Im/(%)
Re
Im
Distance/(m)
Department of Engineering Geology, University of Lund, Sweden


WENNER RESISTIVITY • Manama 17 040890
Apparent Resistivity/(ohmm)
a = 10 m
Distance/(m)
Department of Engineering Geology, University of Lund, Sweden

PROFILE NO 18

Date: 050890
Direction: S - N
Length: 440 m
Frequence: Slingram 3.6 kHz

<u>Comments</u>

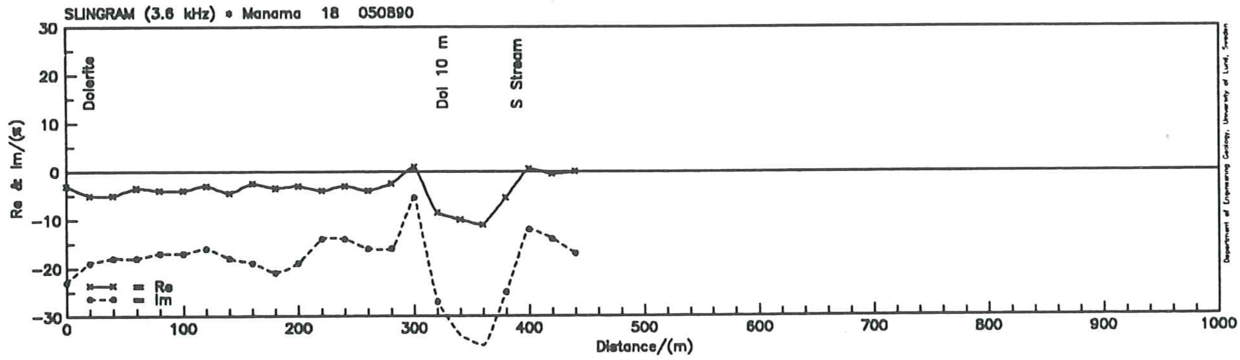
There is a significant anomaly at the distance of 350 m.

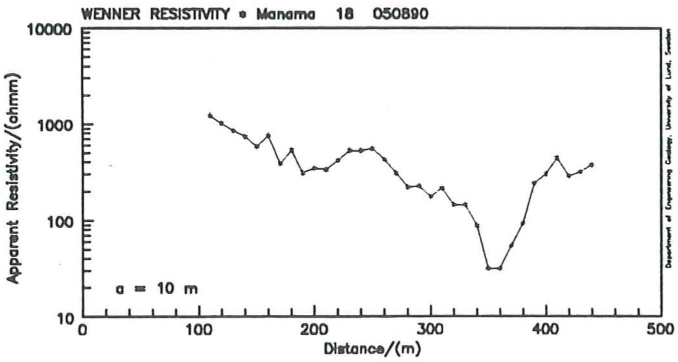
*Resistivity*

Date: 050890
Length: 330 m
Electrode distance: 10 m

<u>Comments</u>

An area of low apparent resistivity with a lowest value of 32 ohmm is shown at the distance of 350 m, which corresponds very well with the Slingram-anomaly.



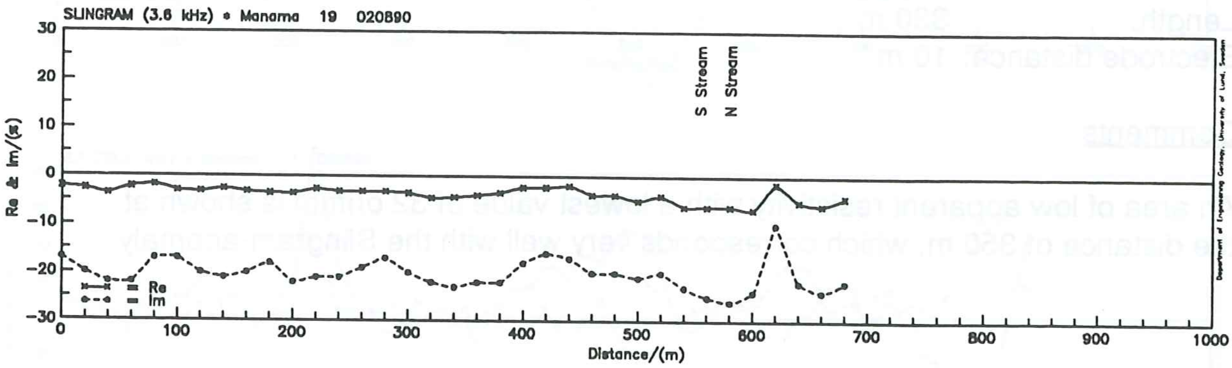



PROFILE NO 19

Date: 020890
Direction: S - N
Length: 680 m
Frequence: Slingram 3.6 kHz

Comments

There is something that could be taken for an anomaly at the distance of 590 m, but it's mostly caused by a single reading at 620 m and therefore a bit unsure.

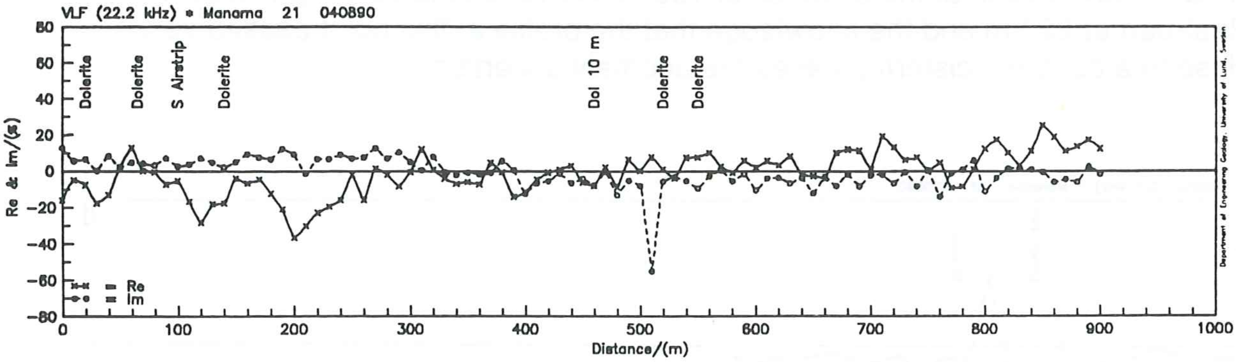


PROFILE NO 21

| | |
|---|---|
| Date: | 040890 |
| Direction: | S - N |
| Length: | 900 m |
| Frequence: | VLF  22.2 kHz |

<u>Comments</u>

Small anomalies are seen at the distances of 90 and 190 m.



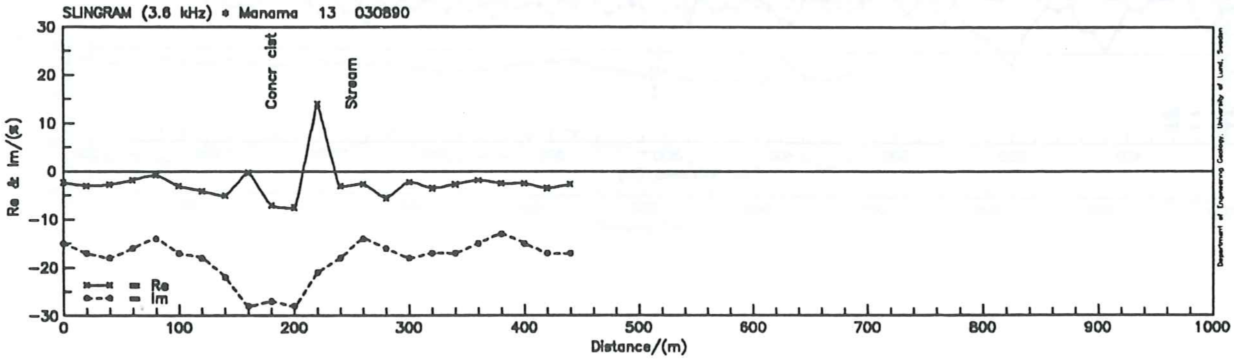
PROFILE NO 13

Profiles no 12 and 13 were carried out with the purpose to investigate a possible fracture zone in a SW - NE direction.

Date: 030890
Direction: SE - NW
Length: 440 m
Frequence: Slingram 3.6 kHz

Comments

An anomaly is seen at the distance of 180 m. However, the very high value in the Real-part at 220 m and the knowledge that the profile at this point passed very close to a concrete cistern , makes the anomaly uncertain.

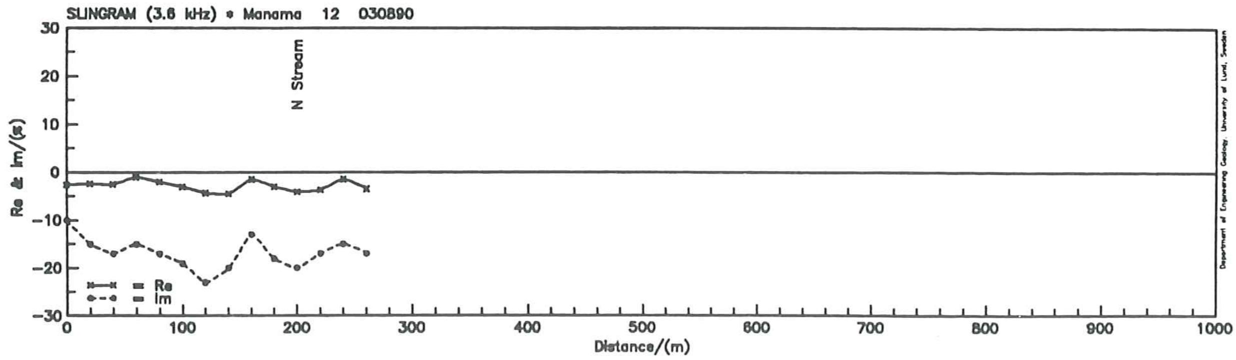



PROFILE NO 12

Date: 030890
Direction: SE - NW
Length: 260 m
Frequence: Slingram 3.6 kHz

Comments

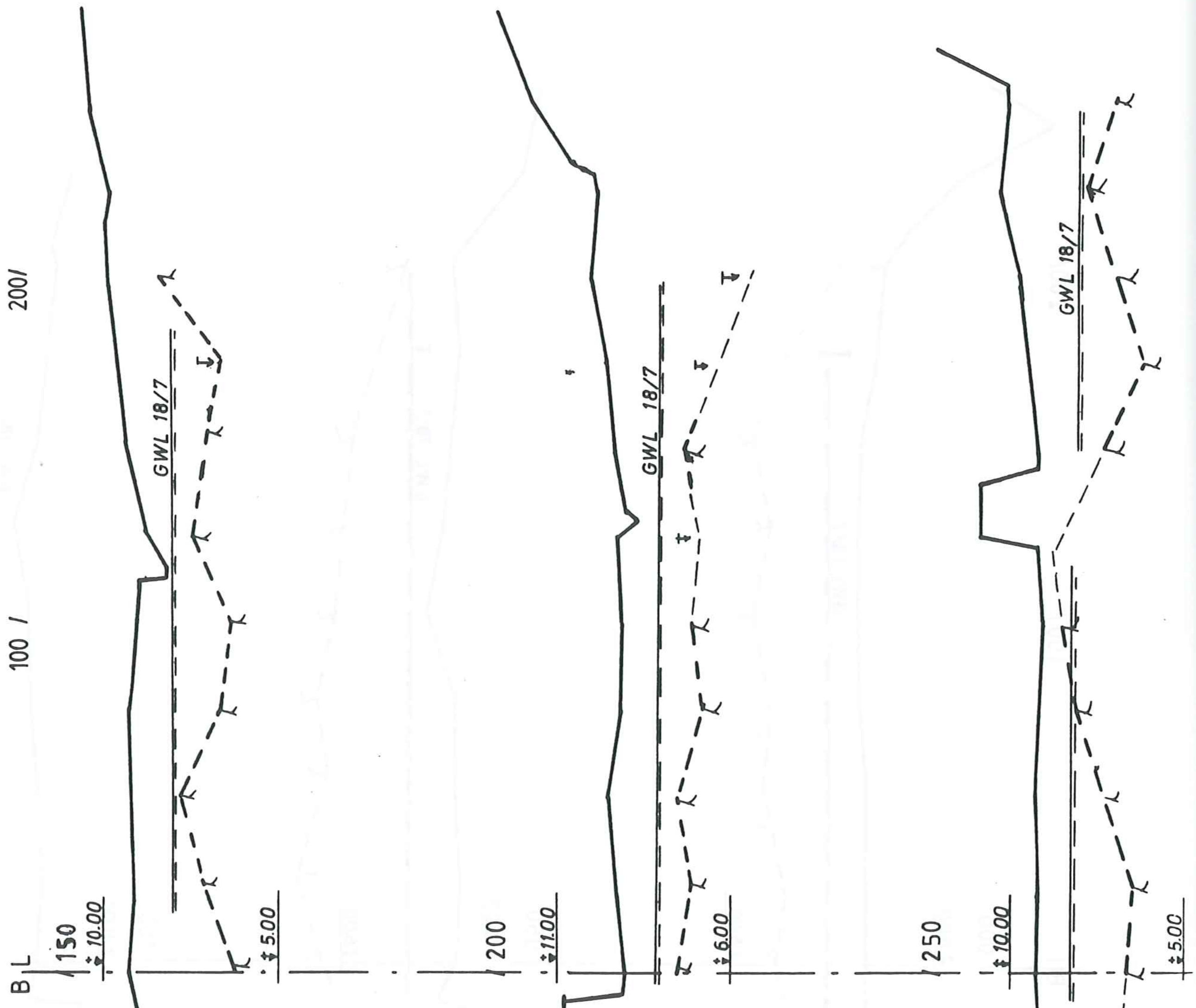
This profile was made to check the reliability of the anomaly in profile no 13. Nothing of interest appeared.



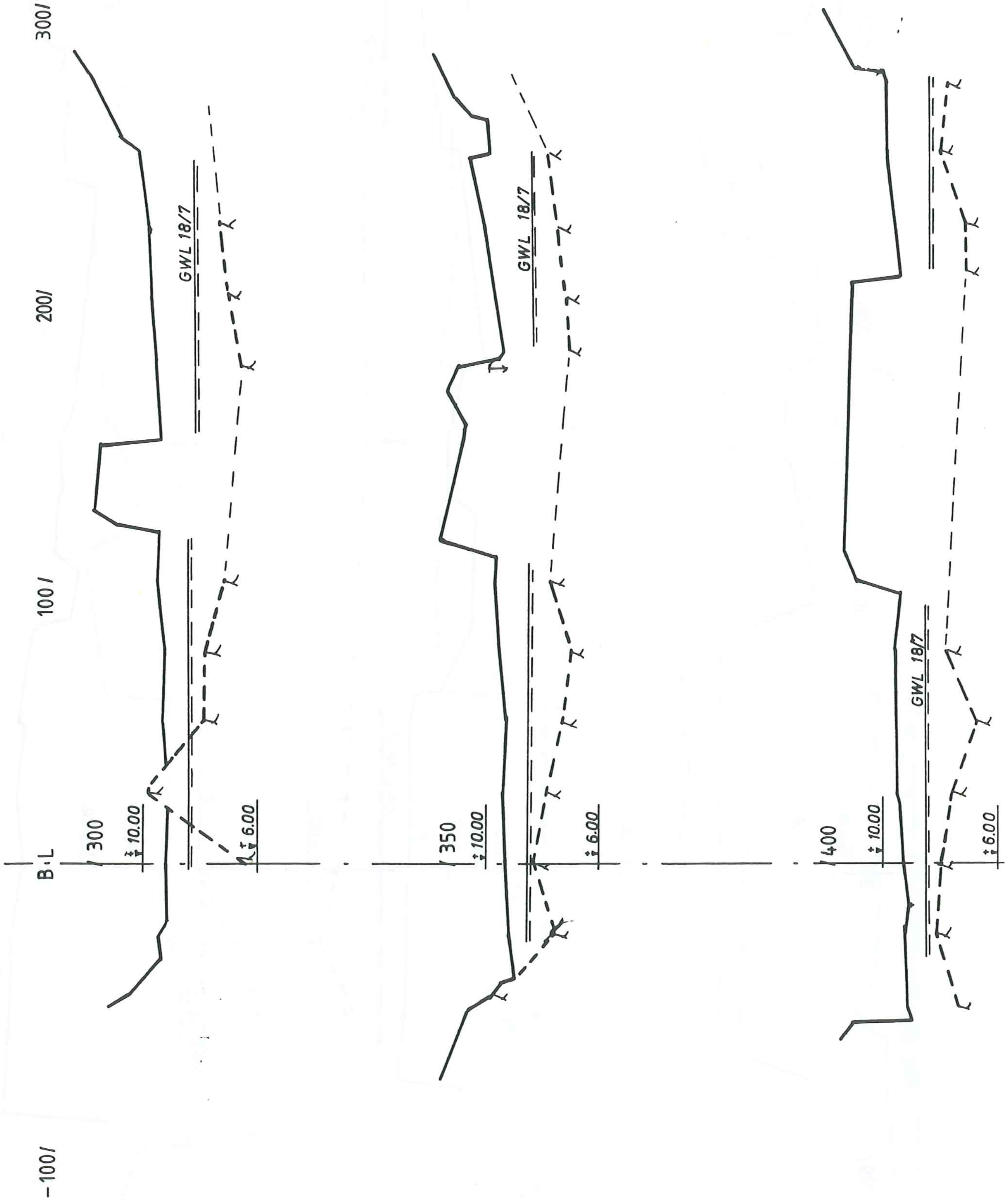
## Interpretation area E

There are several anomalies found in this area that present big amplitudes. These are no doubt waterbearing fractures. The anomalies can not be connected together everywhere in the main fracture direction. This could be explained by that fractures in gneiss seldom are long and straight. Something that is favourable for area E is that the closeby stream probably recharge at least some of the fractures. This is a very interesting area for groundwater prospecting around Manama.

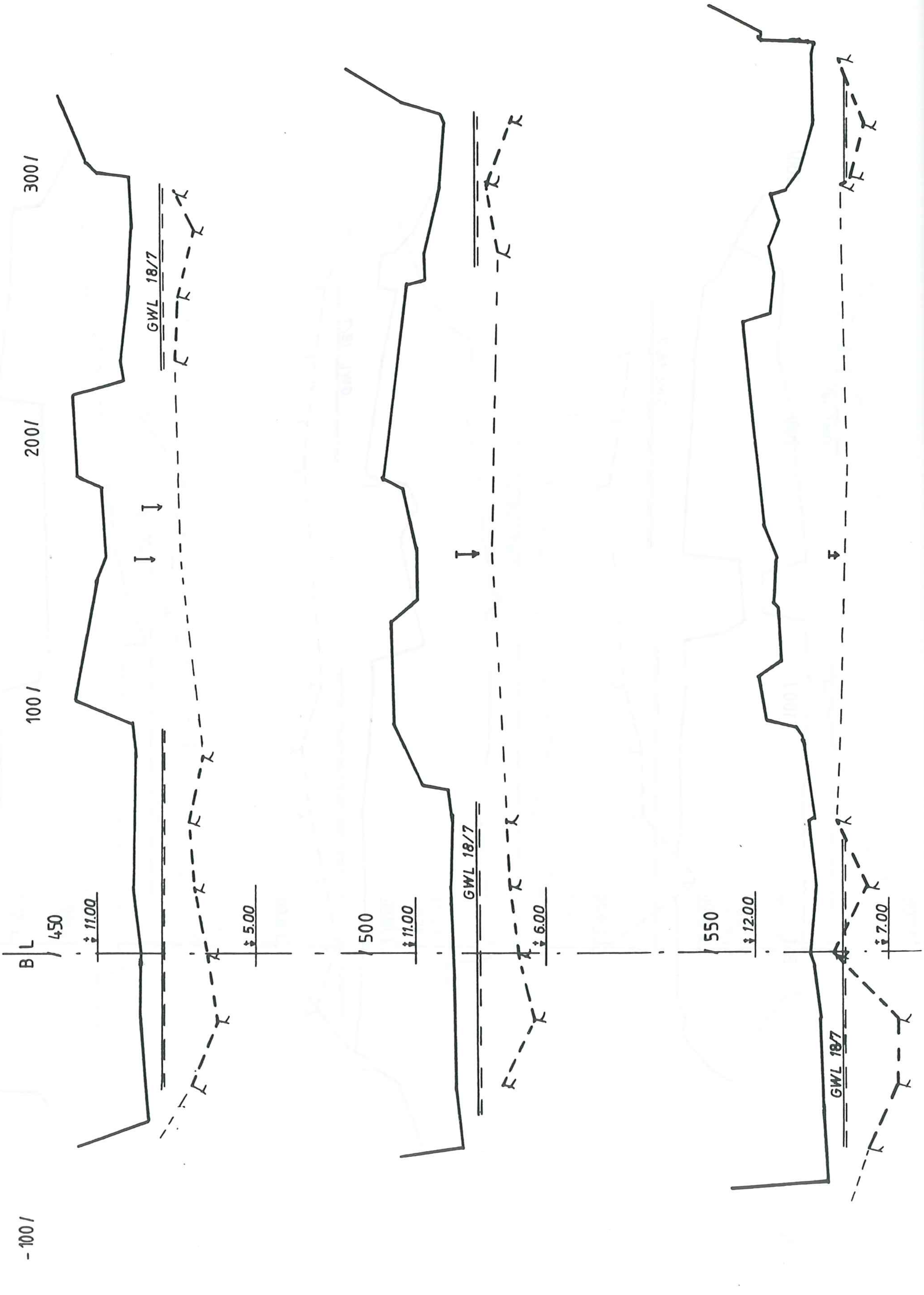

200/
100/
-100/
B L
000
+11.00
+5.00
GWL 18/7
050
+10.00
+6.00
GWL 18/7
100
+11.00
+5.00
GWL 18/7



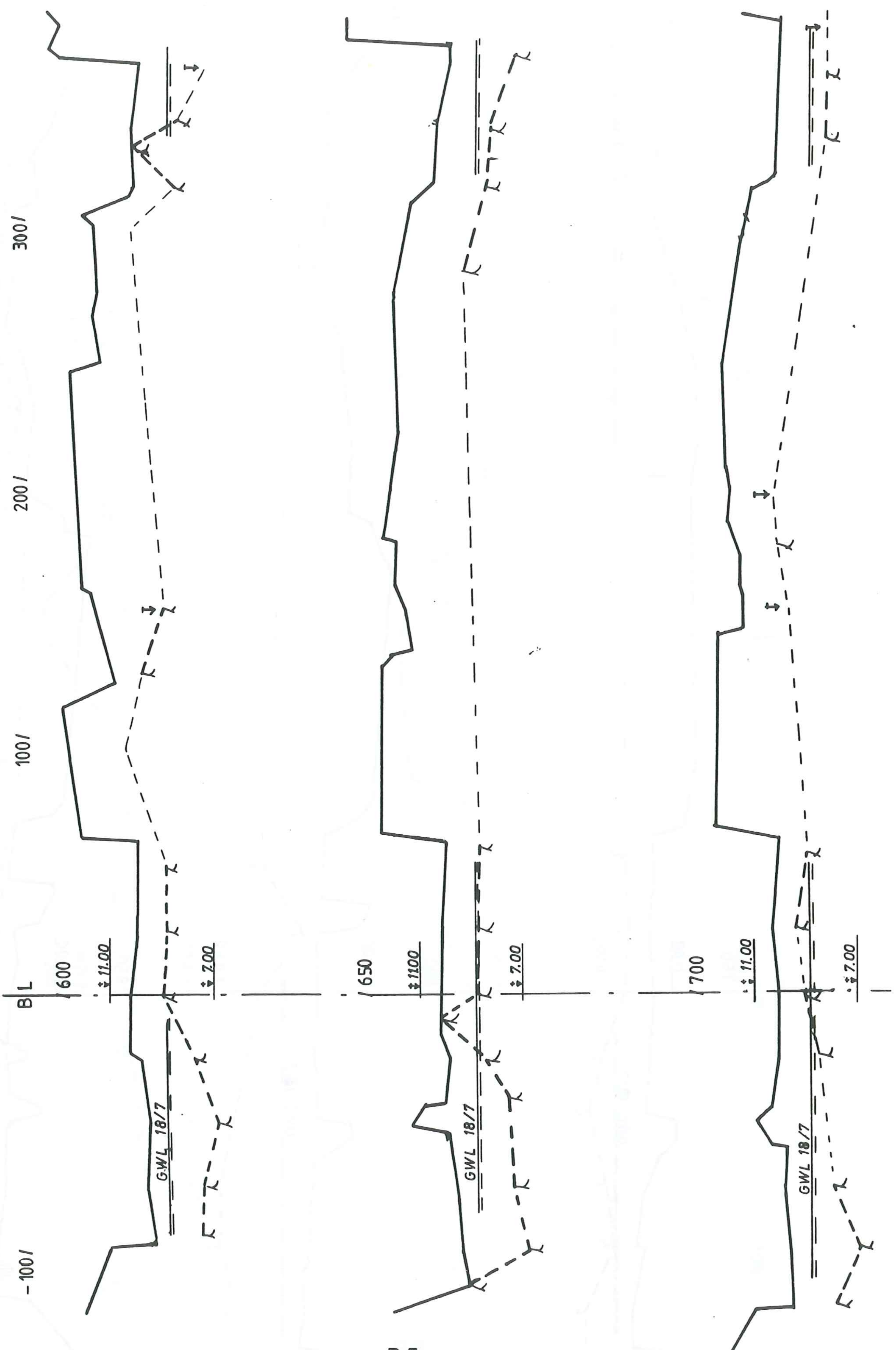
B.L
-100
100
200
150
± 10.00
± 5.00
200
± 11.00
± 6.00
250
± 10.00
± 5.00
GWL 18/7
GWL 18/7
GWL 18/7



300l
200l
100l
-100l
B.L
300
350
400
10.00
6.00
GWL 18/7



300 /
200 /
100 /
-100 /
B L
450
500
550
11.00
5.00
11.00
6.00
12.00
7.00
GWL 18/7
GWL 18/7
GWL 18/7


-100/
100/
200/
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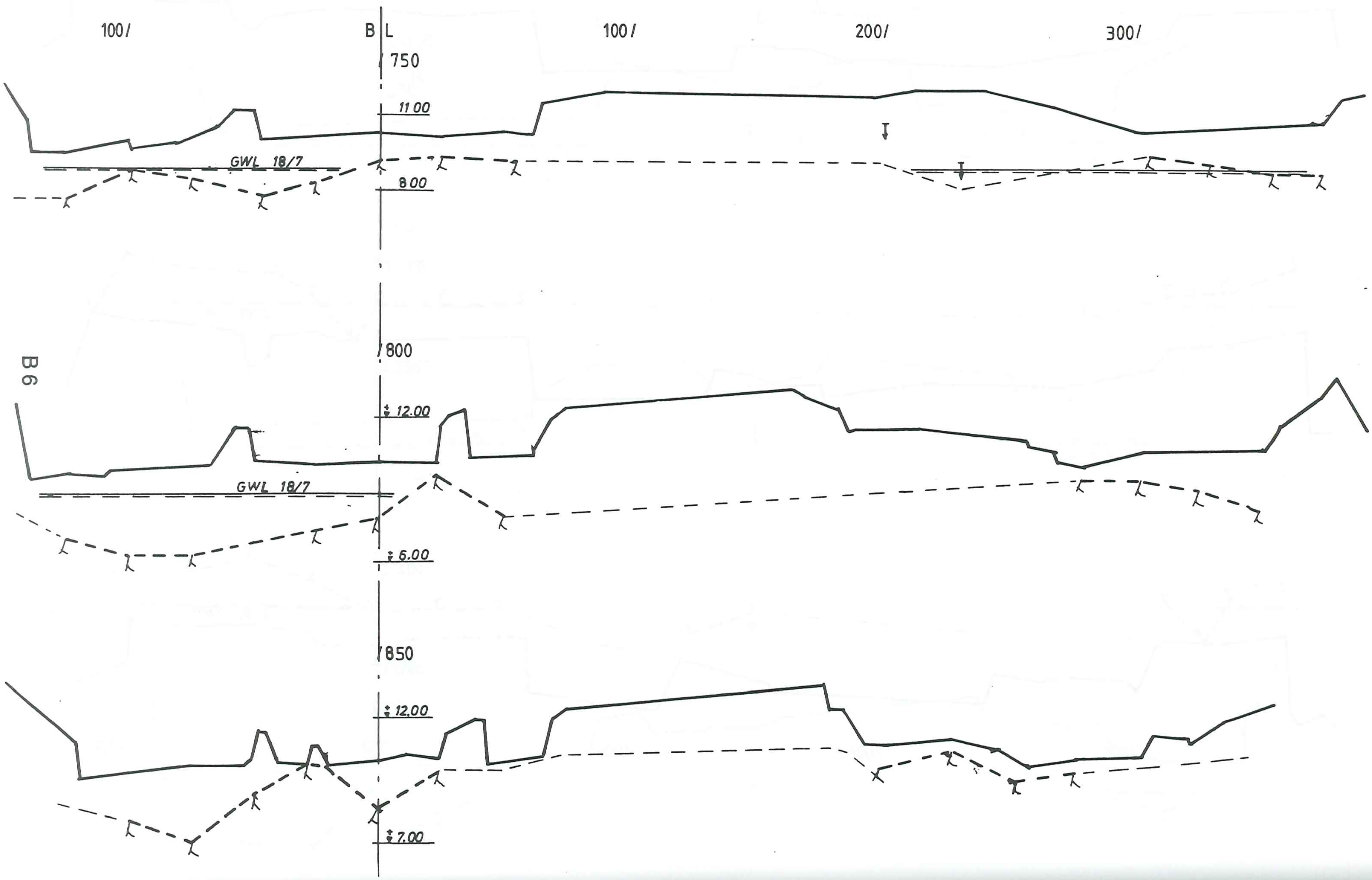
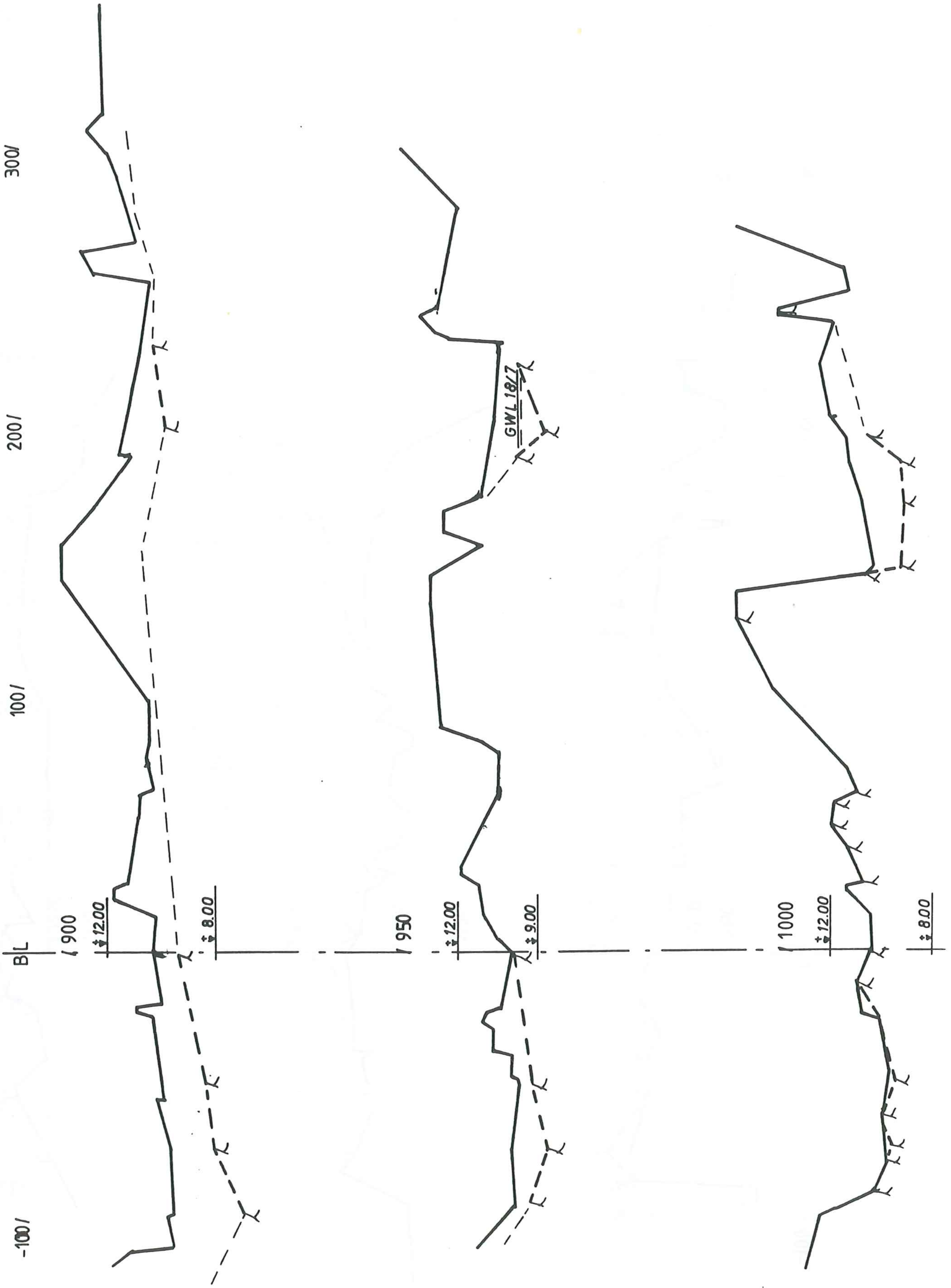
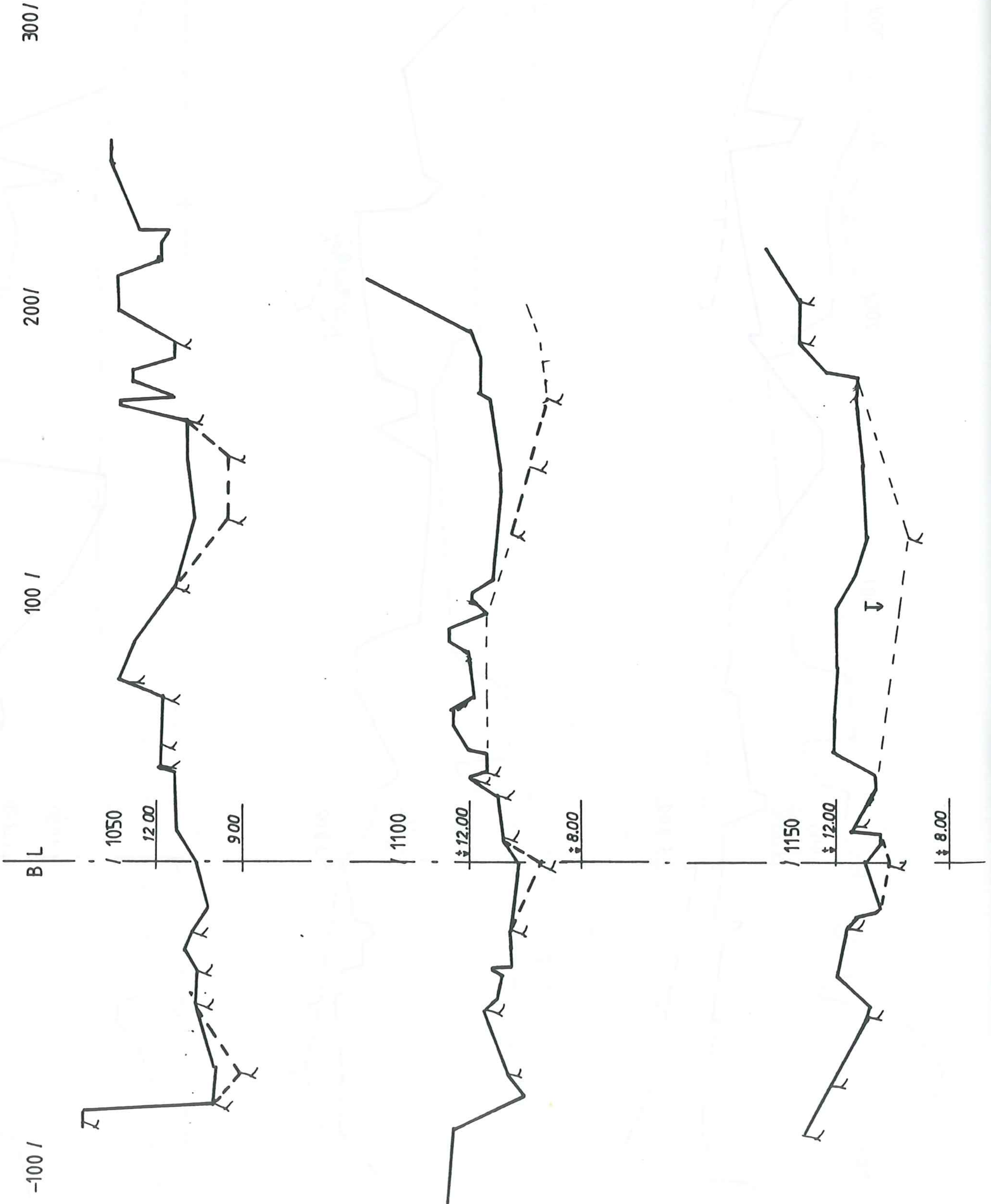
600
650
700
± 11.00
± 11.00
± 11.00
± 2.00
± 7.00
± 7.00
G.WL 18/7
GWL 18/7
GWL 18/7


100/
B L
100/
200/
300/
750
11.00
8.00
GWL 18/7
800
12.00
GWL 18/7
6.00
850
12.00
7.00



-100
100
200
300
BL
900
12.00
8.00
950
12.00
9.00
GWL 18/7
1000
12.00
8.00


-100 /
100 /
200 /
300 /
B L
1050
12.00
9.00
1100
12.00
8.00
1150
12.00
8.00

**RESULT - ALLUVIAL MATERIAL** - Soil classification

| Test Pit No. | Depth below groundsurface (m) | Type of material |
|---|---|---|
| TP 1 | 0.00 - 0.20 | silt |
| | 0.20 - 0.40 | coarse sand |
| | 0.40 - | sandy gravel |
| TP 2 | 0.00 - 0.85 | gravelly coarse sand |
| | 0.85 - | bedrock |
| TP 3 | 0.00 - 0.10 | sand |
| | 0.10 - 0.20 | gravelly sand |
| | 0.20 - 0.90 | gravelly coarse sand |
| TP 4 | 0.00 - 0.50 | gravelly sand |
| | 0.50 - 1.40 | gravelly coarse sand |
| TP 5 | 0.00 - 0.45 | sand |
| | 0.45 - 0.95 | gravelly coarse sand |
| TP 6 | 0.00 - 0.75 | gravelly coarse sand |
| | 0.75 - 1.40 | coarse sand |
| TP 8 | 0.00 - 0.20 | gravelly sand |
| | 0.20 - 0.95 | sand (0.45 - 0.55 lenses of silt) |
| TP 9 | 0.00 - 0.50 | gravelly coarse sand |
| | 0.50 - 0.95 | coarse sand |
| | 0.95 - 1.15 | medium sand |
| TP 10 | 0.00 - 0.70 | gravelly sand |
| | 0.70 - 1.10 | clayey silt |
| | 1.10 - 1.25 | gravelly sandy silt |
| | 1.25 - | gravelly sand |
| TP 11 | 0.00 - 1.45 | gravelly coarse sand |
| TP 12 | 0.00 - 0.10 | gravelly sand |
| | 0.10 - 0.25 | sandy gravel |
| | 0.25 - 1.25 | sand |
| TP 13 | 0.00 - 0.60 | silty sand |
| | 0.60 - 1.20 | sand |
| TP 14 | 0.00 - 1.40 | sand |
| | 1.40 - 1.70 | coarse sand |

| No | GROUNDWATER LEVEL (m) | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 12/7 | | 18/7 | Depl. 6 days | 25/7 | Depl. 7 days | 29/7 | Depl. 4 days | 6/8 | Depl. 8 days | 7/8 | Depl. 1 day | Total depletion 25 days, 12/7 - 6/8 (m) | Comments |
| 1 | +9.71 | | +9.64 | -0.07 | +9.62 | -0.02 | Destr | --- | --- | --- | --- | --- | --- | |
| 2 | +8.86 | | +8.82 | -0.04 | +8.77 | -0.05 | +8.73 | -0.04 | +8.68 | -0.05 | --- | --- | -0.18 <=> 7 mm/day | |
| 3 | +8.52 | | +8.49 | -0.03 | +8.42 | -0.07 | +8.39 | -0.03 | +8.34 | -0.05 | --- | --- | -0.18 <=> 7 mm/day | |
| 4 | +8.15 | | +8.10 | -0.05 | +8.00 | -0.10 | +7.97 | -0.03 | +7.89 | -0.08 | +7.87 | -0.02 | -0.23 <=> 9 mm/day | 26 days |
| 5 | +8.91 | | +8.87 | -0.04 | +8.82 | -0.05 | +8.78 | -0.04 | +8.72 | -0.06 | --- | --- | -0.19 <=> 8 mm/day | |
| 6 | +8.95 | | +8.90 | -0.05 | +8.86 | -0.04 | +8.85 | -0.01 | +8.77 | -0.08 | --- | --- | -0.18 <=> 7 mm/day | |
| 7 | +8.67 | | +8.59 | -0.08 | +8.53 | -0.06 | +8.49 | -0.04 | +8.44 | -0.05 | +8.44 | 0.00 | -0.25 <=> 10 mm/day | 26 days |
| 8 | +8.48 | | +8.43 | -0.05 | +8.37 | -0.06 | +8.34 | -0.03 | +8.28 | -0.06 | +8.28 | 0.00 | -0.20 <=> 8 mm/day | 26 days |
| 9 | +8.43 | | +8.38 | -0.05 | +8.32 | -0.06 | +8.28 | -0.04 | +8.22 | -0.06 | --- | --- | -0.21 <=> 8 mm/day | |
| 10 | +8.11 | | +8.01 | -0.10 | +7.95 | -0.06 | +7.91 | -0.04 | +7.84 | -0.07 | +7.84 | 0.00 | -0.27 <=> 10 mm/day | 26 days |
| 11 | +8.09 | | +8.02 | -0.07 | +7.96 | -0.06 | +7.90 | -0.06 | +7.86 | -0.04 | --- | --- | -0.23 <=> 9 mm/day | |
| 12 | +8.03 | | +7.95 | -0.08 | +7.89 | -0.06 | +7.84 | -0.05 | +7.79 | -0.05 | --- | --- | -0.24 <=> 10 mm/day | |
| 13 | +8.00 | | +7.95 | -0.05 | +7.88 | -0.07 | +7.84 | -0.04 | +7.78 | -0.06 | --- | --- | -0.22 <=> 9 mm/day | |
| 14 | +8.07 | | +8.00 | -0.07 | +7.93 | -0.07 | +7.89 | -0.04 | Destr | --- | --- | --- | --- | |
| 15 | +7.92 | | +7.87 | -0.05 | +7.80 | -0.07 | +7.77 | -0.03 | +7.72 | -0.05 | --- | --- | -0.20 <=> 8 mm/day | |
| 19 | | | +7.97 | | +7.77 | -0.20 | +7.73 | -0.04 | +7.72 | -0.01 | +7.69 | -0.03 | -0.28 <=> 14 mm/day | 20 days |
| 20 | | | +7.98 | | +7.92 | -0.06 | +7.88 | -0.04 | +7.81 | -0.07 | +7.75 | -0.06 | -0.23 <=> 12 mm/day | 20 days |
| 21 | | | +8.01 | | +7.92 | -0.09 | +7.89 | -0.03 | +7.82 | -0.07 | +7.79 | -0.03 | -0.22 <=> 12 mm/day | 19 days |
| 22 | | | +7.94 | | +7.90 | -0.04 | Destr | --- | --- | --- | --- | --- | --- | |
| 23 | | | +8.66 | | +8.62 | -0.04 | +8.58 | -0.04 | +8.52 | -0.06 | --- | --- | -0.14 <=> 6 mm/day | |
| 24 | | | +8.64 | | +8.59 | -0.05 | +8.55 | -0.04 | +8.49 | -0.06 | --- | --- | -0.15 <=> 6 mm/day | |
| 27 | | | +8.58 | | +8.53 | -0.05 | +8.50 | -0.03 | +8.43 | -0.07 | --- | --- | -0.15 <=> 6 mm/day | |
| A | +8.71 | | | | | | | | | | +8.51 | --- | -0.20 <=> 8 mm/day | 26 days |
| B | +8.60 | | | | | | | | | | +8.41 | --- | -0.19 <=> 7 mm/day | 26 days |
| C | +8.47 | | | | | | | | | | Destr | --- | --- | |
| D | +8.28 | | | | | | | | | | +8.01 | --- | -0.27 <=> 10 mm/day | 26 days |
| E | +8.26 | | +8.16 | -0.10 | | | | | | | +8.00 | --- | -0.26 <=> 10 mm/day | 26 days |
| F | +8.03 | | +7.98 | -0.05 | | | | | | | +7.77 | --- | -0.26 <=> 10 mm/day | 26 days |

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