INVESTIGATION OF GROUND WATER POLLUTION ASSOCIATED WITH WASTE DISPOSAL : DEVELOPMENT OF AN ENVIRONMENTAL ISOTOPE APPROACH

Report to the
WATER RESEARCH COMMISSION

by

B Th Verhagen[1], M J Butler[1],
M Levin[2], D G Walton[2]

[1]Schonland Research Centre for Nuclear Sciences
University of the Witwatersrand

[2]Earth and Environmental Technology Department
Atomic Energy Corporation of SA Ltd

WRC Project No 311/1/01
ISBN 1 86845 739 7

INVESTIGATION OF GROUND WATER POLLUTION ASSOCIATED WITH WASTE DISPOSAL: DEVELOPMENT OF AN ENVIRONMENTAL ISOTOPE APPROACH

FINAL REPORT

Investigators: [1]B Th Verhagen [2]M Levin
[1]M J Butler [2]D G Walton

Emanating from Water Research Commission project 311 entitled:

Research on the development and evaluation of geohydrological and isotope hydrological methodologies for the identification of areas suitable for waste disposal

[1]Schonland Research Centre for Nuclear Sciences
University of the Witwatersrand
P O Wits, Johannesburg 2050

[2]Earth and Environmental Technology Department
Atomic Energy Corporation of SA Ltd
P O Box 582, Pretoria 0001

JANUARY 1996

CONTENTS

CONTENTS (CONT.)

CONTENTS (CONT.)

CONTENTS (CONT.)

CONTENTS (CONT.)

LIST OF TABLES

LIST OF TABLES (CONT.)

LIST OF FIGURES

Page

LIST OF FIGURES (CONT.)

LIST OF FIGURES (CONT.)

LIST OF FIGURES (CONT.)

ACKNOWLEDGEMENTS

The authors wish to thank first of all the Water Research Commission for the financial support, management and encouragement in pursuing this complex study. In particular, they are grateful for the extended time granted in which to bring the project to a satisfactory conclusion. Thanks are due to present and past members of the Steering Committee for their constructive criticism and helpful suggestions.

Mr A G Reynders
Mr H M du Plessis
Mr F P Marais
Prof. G E Blight
Mr L Bredenhann
Dr B B Hambleton-Jones
Dr T Kok
Dr G Tredoux
Dr J C Vogel
Dr D B Bredenkamp
Dr V Cogho
Dr M Levin
Prof. B Th Verhagen
Ms D G Walton

Grateful acknowledgement is herewith also given to:

EMATEK of the Council for Scientific and Industrial Research for the major input in geophysical field work and analysis;

the Department of Water Affairs and Forestry for the invaluable contribution in borehole drilling and an extensive gravity survey;

the staff of the Environmental Isotope Laboratory of the Schonland Research Centre, and the staff of the Chemical Laboratory of the Atomic Energy Corporation for the numerous isotope and chemical analyses;

Mr Pienaar, Formerly of the AEC, for his dedicated field work;

the Municipalities of Midrand, Centurion (formerly Verwoerdburg), Johannesburg and Pretoria for making available information on the areas of study;

WasteTech for extensive information on their Clayville landfill site;

the operators of various quarries in the Midrand area and in particular the management and staff of Cullinan Brickworks, for information on, and access to, their properties;

the Institute for Ground Water Studies of the University of the Orange Free State for their support in the Bloemfontein landfill studies;

the typing staff of EET for sterling efforts in the preparation of this final report and various progress reports; and the numerous firms and private standholders in the Olifantsfontein area for giving access to their boreholes and providing the team with often invaluable verbal information.

EXECUTIVE SUMMARY

Ground water is a resource which is becoming increasingly important as South Africa's fresh water supplies become overcommitted. At the same time, this resource is most prone to pollution from waste disposal. Unless clear guidelines are given and useful approaches to impact assessment developed, major damage could be inflicted on ground water resources which are being, or may have to be harnessed for domestic supply.

This study develops and evaluates in particular the use of environmental isotope hydrology in assessing ground water vulnerability to waste disposal. The original project objectives were:

1. To determine the potential of isotope hydrological methodologies for waste disposal site identification and how they could complement and support geohydrological methods
2. A feasibility study to select suitable areas; survey existing information; gather new geohydrological, chemical and environmental isotope data: collate and evaluate this data in terms of its applicability in site investigation
3. With a positive outcome of the feasibility study to intensify the investigation with strategic drilling and pump testing, and to elaborate the developed methodologies to other areas and other geohydrological situations.

The Olifantsfontein area of Clayville in Midrand was selected, as it is an area of some importance to existing and potential future potable water supplies. The area of study at Midrand is underlain by Transvaal dolomites. A waste disposal facility occupies a worked-out clay quarry in a deposit (outlier) of Karoo sediments.

The structure, geology and geohydrology of the area are described in some detail. Ground water flow is northwards and is constrained by a system of compartmentalising dykes. Considerable differences in ground water level and chemistry are found at different sides of some of the dykes. Geophysical observations delineate areas of weathering of the dolomites and possible channels of preferential ground water flow.

An initial hydrocensus provided extensive analytical data on hydrochemistry and environmental isotopes. Isotopic data showed that the entire area of study is prone to infiltration of surface water and is therefore vulnerable to surface pollution. Ground water mobility was found to decrease markedly with depth. No specific information could be obtained from dolomite below or near Karoo outliers, as existing information on and newly-drilled boreholes at such locations was found to be inadequate.

Correlations between data sets of various isotopes and chemistry revealed that there exists considerable contrast between the regional flow system and local recharge. The isotopic contrast is inferred to be due to the distinct isotope signal of the Rand Water mains supply. A significant correlation is seen between certain dissolved ions and isotopes, suggesting a possible distinction between urban/industrial and agricultural pollution. The generally low level of this pollution during the period of study in relation to that observed in the control area, gives rise to the concept of "incipient pollution", as it can be identified as such by its environmental isotope association.

Ground water flow relationships between compartments could only be partially established through the drilling of study-related boreholes and hydrochemical and isotopic analysis. No existing or specially drilled boreholes were adequately sited or constructed to establish the relationship between Karoo and dolomite ground water, or assess the behaviour of water in the Karoo. These questions were of primary importance in the project formulation.

In order to overcome this shortcoming, three boreholes were drilled, during the final phases of the study near a worked-out quarry containing effluent derived from Rand Water mains. Isotope measurement on the water extracted from the drilling material at different depths established the extreme heterogeneity of transmissivity of the Karoo and its intrinsic unsuitability as a competent sealing layer against leachate transport in sanitary landfills operated in such worked-out quarries.

Four smaller studies, which ran partially concurrently with the Midrand study, were undertaken at other waste disposal sites, to obtain information from different geological environments.

Boreholes drilled a decade earlier to assess pollution of shallow ground water at the Waterval landfill disposal site in western Johannesburg were found to have all collapsed. However, surface water transport from the site could be established through the presence of artificial tritium, probably derived from the site, and its possible influence on the surrounding ground water.

A survey of ground water at the Linbro Park landfill site, north-east of Johannesburg, established the inadequacy of the available ground water monitoring network. Interpretation of the (inadequate) information from the existing boreholes suggests that, in spite of the rapid turnover time of the ground water, there is at present no evidence of leachate pollution.

Isotopic and chemical observations on monitoring boreholes at the northern and southern landfills of the city of Bloemfontein, and on some private boreholes, give an indication of the leachate transport from these sites in a Karoo environment. At the northern site, there is evidence of increasing ground water pollution and leachate transport to ground water through surface drainage. At the southern site, the influence of leachate can be established at nearby farm boreholes, probably due to overland flow following major rainfall events. Artificial tritium, and possibly radiocarbon, are present in both sites and may act as definitive tracers of leachate transport.

The main conclusions from the study were:

1 That environmental isotope hydrology is an indispensable component of any study assessing actual and potential ground water pollution.

2 That isotope information, powerful though it is in transport studies, can only be fully exploited when seen in the context of the geohydrology and hydrochemistry of the system studied.

3 In this holistic context, environmental isotopes are appropriate technology and an economical way of obtaining important and sometimes unique information in geohydrological studies.

4 Isotope data can establish "incipient" pollution, a concept of great importance in the timeous identification and rehabilitation of pollution sources.

5 In the Gauteng area, the Rand Water mains supply has an isotopic signal which differs substantially from that of most ground water in the area. This difference can be exploited for tracing anthropogenic inputs into ground water and any pollution it may carry. Isotopic contrasts between different recharge water sources could be exploited in other environments.

6 At least some landfill sites contain artificial radionuclides which can be exploited as unique low-level tracers for leachates from such sites into surrounding water systems.

7 At all the landfill sites studied, ground water monitoring networks were found to range from inadequate, to totally inoperative and in need of upgrading.

8 Worked-out quarries in Karoo outliers in dolomitic terrain should not be used for purposes of sanitary landfilling, which should rather be placed on surface to facilitate safer future management.

9 The complexity of the Olifantsfontein geological environment has been established and has highlighted the need for extensive investigations following a site specific approach.

The recommendations as a result of this study are as follows:

- Environmental isotope studies should be incorporated in the geohydrological evaluation of areas associated with waste disposal operations. Such isotope studies should be conducted taking a holistic approach, as part of a comprehensive geohydrological and hydrochemical investigation of ground water vulnerability and leachate transport.

- A comprehensive environmental isotope survey is a relatively rapid, highly cost effective means of obtaining a preliminary assessment of the geohydrology of areas where little *a priori* information is available. As the geohydrological and hydrochemical framework of an area becomes more firmly established, it becomes possible to evaluate the isotope data on a more sophisticated and quantitative basis.

- Particular attention has to be given in dolomitic terrain to the design and maintenance of reticulation and sewage systems, to land usage and to the release of all waste water into natural drainage systems and the environment in general.

- Where no more suitable areas can be identified near dolomitic terrain, landfill sites should be established on Karoo outliers. Such sites should however be designed on surface rather than in worked-out quarries, to utilise the full profile of the undisturbed deposits as a barrier against contamination of the dolomitic ground water.

- Before establishing a landfill site on such outliers, a detailed study of the Karoo should first be conducted, in order to establish the competence and thickness of the argillaceous deposits.

- In spite of the fact that environmental tritium concentrations in southern African rain have dropped to near-natural values since the bomb peak in the mid-sixties, it remains a recommended and practical tool in the semi-quantitative assessment of recharge to, and thus the vulnerability of, ground water. Artificial tritium found to be present in some waste disposal sites, provides a very sensitive tracer for leachate transport from such sites.

- Incipient pollution to Clayville dolomites poses a potential threat to existing and future ground water supplies. The transport of ground water to the eastern compartment and the Sterkfontein spring from the western compartment, tentatively demonstrated in this study, should be firmly established by a more intensive, integrated geohydrological investigation.

- Sanitary landfills should all have properly designed, equipped, and operated ground water monitoring systems, based on production-standard boreholes. Siting, drilling and testing of such boreholes should be done professionally, to adequately cover possible leachate transport. Sampling and analysis to be done according to recognised procedures.

The conclusions arrived at this study firmly establish the combined methodologies in terms of their potential in investigating pollution-related ground water problems. It is important to note that the approach to their application depends on the individual system investigated. Apart from enumerating the overall principles underlying the various methods, only general guidelines as to their application can be derived. As each area of investigation is different, each investigation will require an individual research approach in order to creatively employ the methods and obtain the maximum benefit from them. It is therefore advisable, and ultimately most economical, to engage the various specialists in the study from the onset.

For the information obtainable, environmental isotope data is highly cost effective. The costs involved in the analysis in a water sample of the full suite of five isotopic parameters, as discussed in this report, may be compared with the costs of a full ionic plus microbiological analysis in a pollution study.

Environmental isotope hydrology is appropriate technology. Isotope techniques are state of the art, are employed worldwide, in particular in geohydrology, and wide experience and expertise have been developed in both their application and interpretation. The specifications for many ground water development and evaluation projects internationally stipulate an environmental isotope input, along with geophysical and hydrochemical studies. South Africa has available local analytical facilities of world standard and internationally recognised expertise in the application of environmental isotope hydrology and is therefore favourably placed to conform to international practice.

1 PROJECT OUTLINE

1.1 Aims and objectives: their development

The Environmental Isotope Group of the Schonland Research Centre, University of the Witwatersrand had for many years been doing research on environmental isotopes as tracers in ground water. Close cooperation had been developed with the Earth and Environmental Technology Division of the Atomic Energy Corporation of South Africa Ltd., inter alia in the field of nuclear waste disposal. This led to the basic concept of the present study which could utilise the combined expertise and facilities of the two groups, with the support of the Department of Water Affairs.

Ground water is a resource which is becoming increasingly important as South Africa's fresh water supplies become overcommitted. At the same time, this resource is most prone to pollution from waste disposal. Unless clear guidelines are given and useful approaches to impact assessment developed, major damage could be inflicted on ground water resources which are being, or may have to be harnessed for domestic supply.

To this end, geohydrological and isotope hydrological studies were conducted jointly by the Earth and Environmental Technology Division of the Atomic Energy Corporation of South Africa Ltd. and the Schonland Research Centre for Nuclear Sciences of the University of the Witwatersrand.

The aim of the project was to determine the most appropriate methodologies to be employed when determining the feasibility of a specific site for waste disposal. Throughout the study special reference was made to the methodology's usefulness and applicability.

Initial investigations during the first year were confined to Clayville in Midrand, an area of known pollution potential where Karoo outliers within dolomite are being used as sites for waste disposal. The study aimed at applying conventional geohydrological methods, including geological and geophysical investigations followed by exploratory drilling to form a basic understanding of the local geology, water levels and hydrogeochemistry. In addition to these conventional approaches measurements of environmental isotopes ^{14}C, ^{3}H, ^{2}H and ^{18}O were to be incorporated to provide information on ground water residence times and origin together with the outlining of recharge areas, and mechanisms by which pollution could enter the ground water system.

The original aim of the project was to evaluate these methodologies in different geological environments, and again discuss their usefulness and applicability. The geology and geohydrology of the Clayville site proved to be extremely complex and it became evident that substantially more research would have to be done in order to effectively determine the geohydrological regime. Once this had been established, discussion of the various methodologies became much more comprehensive and meaningful.

The knowledge and known potential of the methodologies were re-focussed on other areas of different geology which were also known to have pollution potential, and about which some geohydrological information was available. It became apparent while a number of sites were investigated, that existing monitoring networks were either not properly designed to adequately provide the meaningful information needed to monitor the situation, or were no longer functional due to borehole collapse, or were inappropriately sampled. In spite of these shortcomings, the methodologies were applied in different geological environments, and some useful conclusions could be drawn.

1.2 Philosophy

The intention of this study was to explore, and if possible prove, the usefulness of environmental isotope techniques in the assessment of ground water vulnerability to waste disposal. With their unique potential in establishing both the origins and dynamics of ground water, even a quite simple approach to the use of environmental isotopes could provide valuable predictive information on areas which might be considered for various forms of waste disposal. The initial idea was therefore to survey such areas and classify them, much in line with ground water vulnerability mapping. This idea was encompassed in the original title of the project: "Development and evaluation of geohydrological and isotope hydrological methodologies for the identification of areas potentially suitable for waste disposal."

Parallel studies have been done in other countries with the specific aim to identify new areas suitable for repositories of hazardous chemical waste and to classify existing areas as vulnerable and in need of protection. The aims of this project are similar and apply the same methodologies to investigate South African conditions. (Hertelendi and Veres, 1992; and Marton et al 1991). See also IAEA (1983a).

In exploring how such a study could be structured, the need was identified for obtaining data for one or more established waste disposal sites. Such data could then act as a test for the potential predictive capabilities of environmental isotope hydrology. This led to the decision, during the early formulation of the project aims, to focus on the Midrand waste disposal facility, operating at the time in a worked-out clay quarry in a so-called Karoo outlier in the Transvaal dolomites. The site was causing some concern, as the dolomitic ground water of the area was being exploited, and had potential for further development. There is considerable urban development on and around the dolomitic terrain of the Gauteng (formerly PWV) area, and therefore the need for developing a waste disposal policy for such areas is considered important.

It was immediately realised that the enormous contrast in hydrogeological properties between the Karoo outliers and the host dolomitic aquifers, as well as the intrinsic complexity of the latter, would pose formidable conceptual and practical challenges to the methodology. These challenges have in fact fundamentally influenced the time table of this study. Specific questions such as more detailed geohydrology of the area, required inputs from various other organisations, with attendant delays. Assessing the competence of the Karoo could only be tackled once a more intimate knowledge of the area had been established. A possible approach to this problem was then only developed late in the study on the basis of such newly acquired knowledge.

1.3 Historical background

The original aim of the project was to use a variety of well known geohydrological, isotopic and hydrochemical methodologies and combine them to evaluate potential waste disposal sites. This approach was not confined to one specific geological environment and several waste disposal sites were considered favourable for investigation. These were Olifantsfontein, Midrand; Waterfall and Linbro Park, Johannesburg; and north and south disposal sites, Bloemfontein.

During 1990 and 1991 intensive investigation was carried out in the Olifantsfontein area. This was selected for its known potential for waste disposal, ease of access, and the anticipated amount of relevant historical geohydrological data. Meaningful geohydrological data was supplied by the Department of Water Affairs and Forestry, and geological data by Cullinan Bricks. However the standard of historical geological and geohydrological information within the immediate vicinity of the main waste disposal facility, especially water quality, was comparatively low.

The geohydrology of the Olifantsfontein area proved extremely complex. In order to draw up meaningful evaluations and comparisons of the various methods employed it became evident that more time and funds would have to be spent on the investigation of both the dolomites and the Karoo. Drilling equipment and personnel were voluntarily provided by the Department of Water Affairs and Forestry for the first phase of exploratory boreholes drilled at the end of 1991/beginning of 1992. The results confirmed the need for more specific geohydrological information, especially water quality, within the immediate vicinity of the main waste disposal site. Discussions took place with the waste disposal company managing the site and the investigative team, and it was agreed that additional monitoring holes were necessary. Advice on the location of these monitoring holes was given to the disposal company. The positions were considered the best to provide meaningful water samples and provide valuable data for the research work. Unfortunately this advice was not taken and three additional boreholes were drilled to the north of the site where previous exploratory drilling suggested the presence of an extensive "dry" zone within the surrounding dolomitic aquifer. The monitoring holes confirmed this suggestion and are not considered adequate for monitoring purposes in such a vulnerable and important aquifer.

At that stage of the investigation major decisions had to be taken concerning the direction of the project. It was considered necessary to expand and investigate the other areas in more detail. However, it was considered priority to devote additional funds into the Olifantsfontein area in order to compensate for the lack of information gained from the monitoring holes. The methodologies had shown great potential, and additional strategically placed exploration holes would allow a more comprehensive evaluation of the disposal site and the usefulness of the methodologies used throughout the investigation. It was therefore decided that the Waterval, Linbro Park and Bloemfontein sites should remain as preliminary studies, and intensive investigation relating to the Karoo Formation and the influence of the major geological features would be continued in the Olifantsfontein area.

1.4 Structure of the report

In order to test the various isotope methodologies in various geological environments, five areas were studied on a site specific basis;

1) Olifantsfontein/Clayville - Midrand - Karoo outliers within dolomite (infilling of old clay quarries).
2) Linbro Park - Sandton - Weathered granites (infilling of borrow pit/landfill).

3) Waterval - North western suburbs of Johannesburg - Diorite gneisses and granite (landfill) and
4) Bloemfontein - North - Dolerite (landfill)
5) South - Siltstones and sandstones (landfill)

These sites were chosen specifically in relation to a) their geological environment, b) the type of waste disposal that was being practised and c) the availability of monitoring boreholes for adequate data collection and historic information.

Originally all these sites were to be given equal consideration, however due to the complexity of the Olifantsfontein site, more intensive study was done here than the other sites. The final report reflects this situation in that the Olifantsfontein site occupies a much larger percentage than the other four areas. Due to the site specific nature of all the individual studies, each area is reported as a separate chapter and interpreted as a separate entity. The basic and underlying principles however are incorporated in the main conclusions of this report as these applied to all the areas of study.

2 THE MAIN STUDY AREA - OLIFANTSFONTEIN

2.1 Introduction

The study area selected is located in Midrand between Pretoria and Johannesburg. It was selected because i) the dolomites within the area have been studied previously by the Department of Water Affairs and a number of boreholes have been incorporated into the Emergency State Water Scheme. The potential for major future abstraction therefore exists. ii) The Sterkfontein spring lies within the region and is already utilised and contributes approximately 28 megalitres per day to Pretoria's water supply. iii) Borehole water is and has been used extensively by agriculture, industry and residents within the area, and both ground water and the spring water are susceptible to pollution. iv) The area hosted an active waste disposal site together with an extensive industrial development.

The siting of waste disposal sites in Karoo outliers within dolomitic formations is a common practice throughout the Gauteng province.

Reservations concerning the complexity of the geology were confirmed as a result of detailed investigation. Consequently the aims of the project were modified and involved more geological and geohydrological investigation in this area, with less emphasis on other geological environments.

2.2 Land use

The town of Clayville covers an area of some 5,25 km^2 and includes industrial and residential areas. The major portion of the town lies on chert-rich dolomites of the Monte Christo Formation.

Livestock farming is carried out throughout the area surrounding the town. More intensive crop cultivation is practised in the northern part of the study area just south of Pinedene station. Crops include maize, vegetables and fruit.

There are many clay quarries within the Karoo sediments. Some of the clay deposits are still being worked, the main quarries being the brickworks just east of Sterkfontein Spring in Karoo outlier 2, the Cullinan Midrand plant on the western side of Karoo outlier 1 and the Olifantsfontein pit on the south-eastern part of Karoo outlier 3 (Figure 2a).

There are two waste disposal facilities situated within the study area. The main site, which was closed in 1992, is located in the south-eastern portion of Karoo outlier 3. The other is an old dumping site located directly on dolomite which is not currently being used in an official capacity. A verbal report refers to an earlier disposal site using a worked-out quarry, closed many years previously and the area rehabilitated.

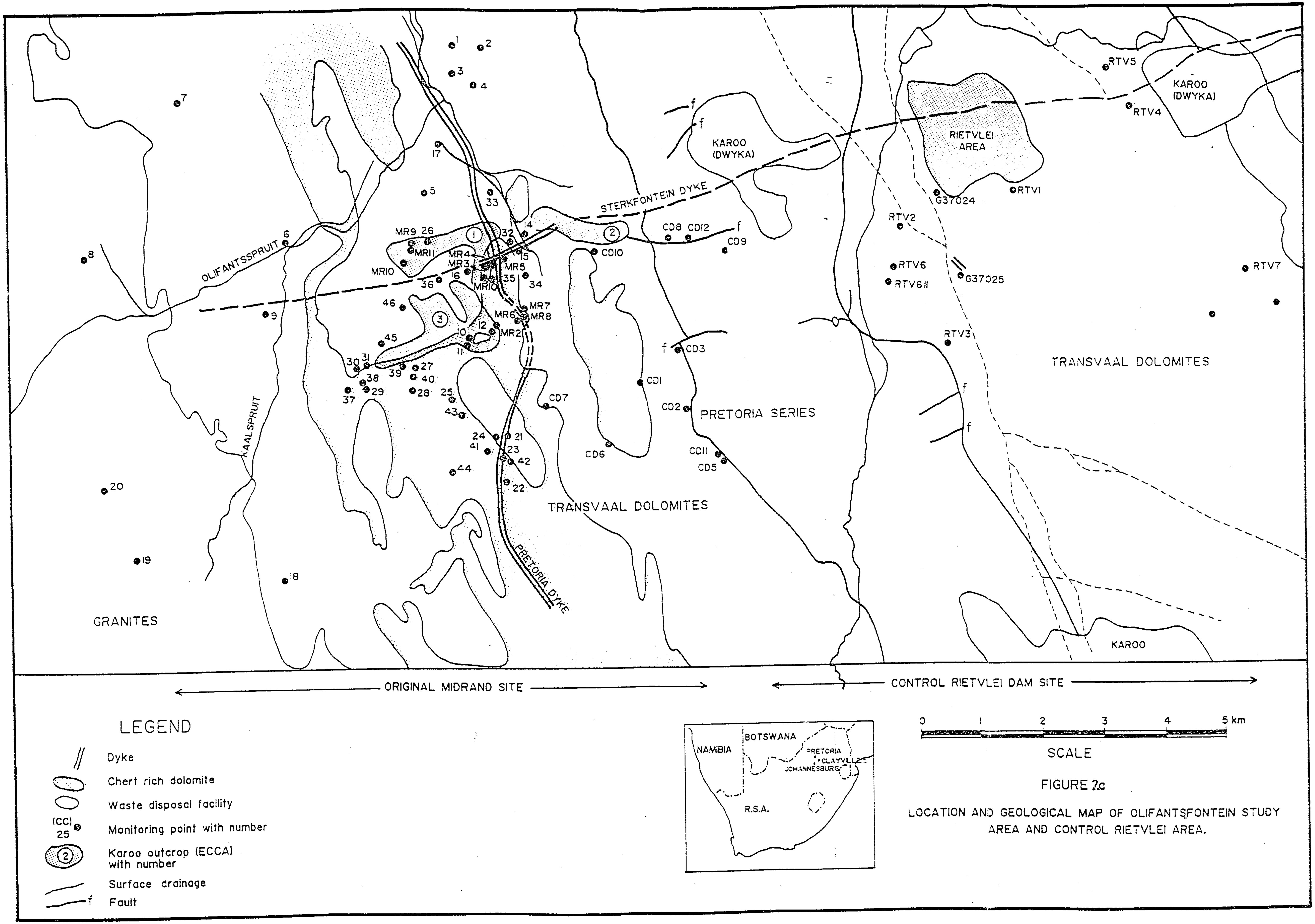


FIGURE 2a

LOCATION AND GEOLOGICAL MAP OF OLIFANTSFONTEIN STUDY AREA AND CONTROL RIETVLEI AREA.

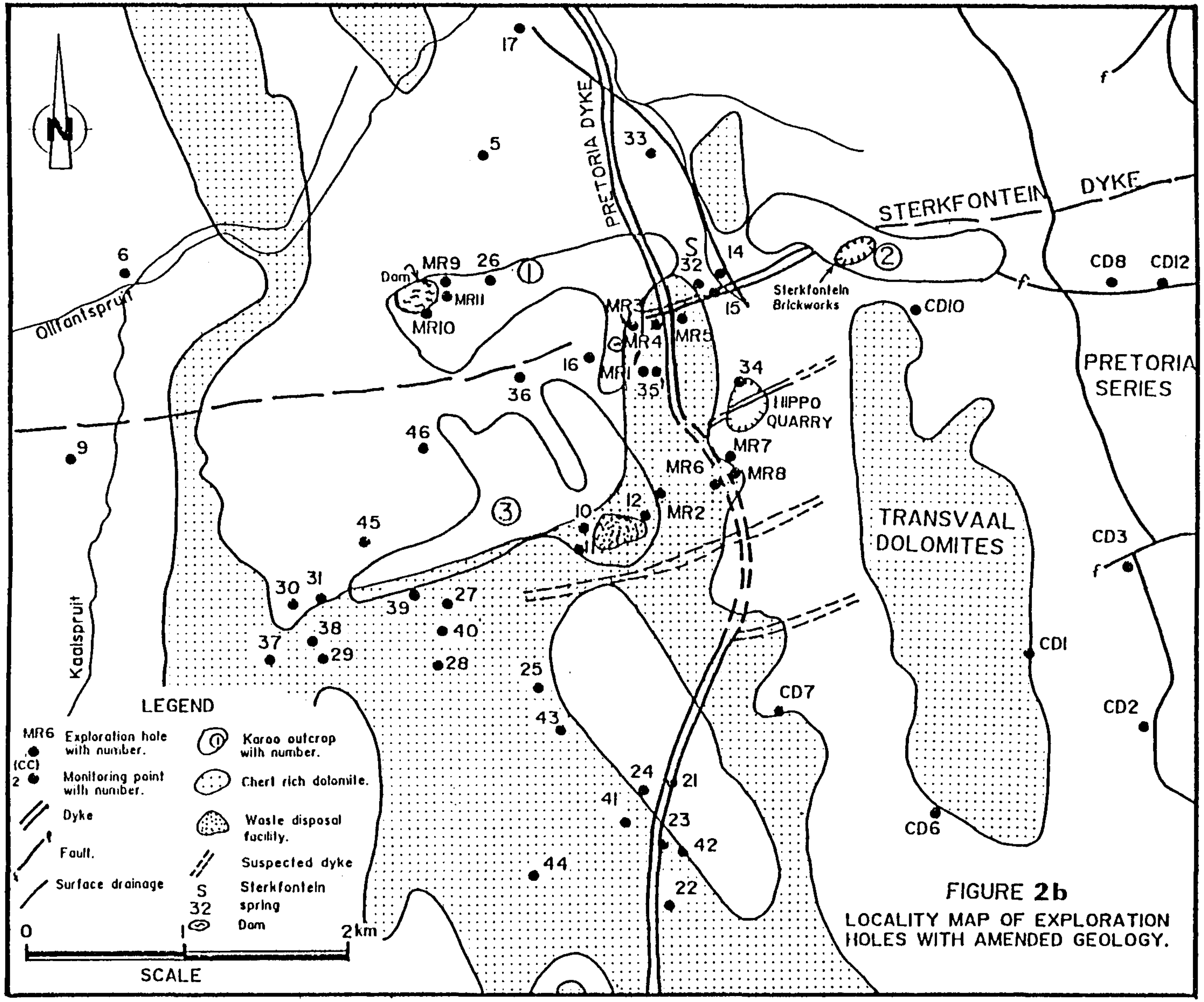


Figure 2b Locality map of exploration holes with amended geology

2.3 Physiography

2.3.1 Topography and surface drainage

The town of Clayville lies at an altitude of approximately 1 520 to 1 530 m.a.m.s.l. The area has a gentle relief which slopes to the north towards the Sesmylspruit approximately 3 km north of the northern boundary of the study area. Superimposed on the general relief are valleys formed by surface drainages, such as the Olifantspruit flowing in a north-easterly direction towards the Sesmylspruit, and the Kaalspruit and its tributaries flowing in a northerly direction into the Olifantspruit (Figure 2a).

A poorly defined ridge striking NNW/SSE is evident on the eastern side of the study area. This has formed as a result of a variation in geology, where the chert breccias and quartzites of the Pretoria group lie unconformably on the dolomites of the Transvaal sequence.

2.4 Climate

The area experiences a sub-humid warm climate. The mean daily maximum temperature recorded at station 0513/382 2 (Irene), is 24,1 °C with an average daily minimum of 7,6 °C. This has been calculated over a 20 year time period. The relative humidity averages 74% with the highest value in March (82%) and the lowest in September (65%). This has been calculated over a 9 year period. A potential evapotranspiration of 742 mm has been calculated by Hobbs (1988) following the Thornthwaite method. This only slightly exceeds the mean annual precipitation rate of 709 mm measured over a 9 year period (1975 - 1984), at station 0513/385 (Irene). Longer term rainfall records from 1916 to 1985 at station 0513/382 give an average of 689 mm per annum. The wettest month is January and the driest is July.

3 REGIONAL GEOLOGY

3.1 Introduction

All three major rock units of the Transvaal Sequence are present within the study and control areas. In decreasing age, these are the Black Reef Quartzite Formation, the mainly dolomitic Chuniespoort Group and the Pretoria Group (mainly quartzite and shales).

The Black Reef Quartzite Formation outcrops to the west in a very narrow strip averaging 200 to 300 m in width. The Pretoria Group outcrops to the east. The most extensive formation within the area under investigation is the Chuniespoort Group, striking north-south with an average width of 8 km.

This group consists of the five formations of the Malmani Subgroup and the two overlying formations, the Penge and Duitschland Formations. (SACS 1980) However both the Penge and the Duitschland Formations are absent in the study area, together with the upper Frisco, a chert free dolomite of the Malmani Subgroup. The remaining four dolomitic formations outcrop extensively throughout the study area. These are, in decreasing age, the Oaktree, Monte Christo, Lyttelton and Eccles Formations. These outcrop from west to east respectively. SACS (1980) reports the general stratigraphic thickness of the succession in the central Transvaal to be 1430 m. The thickness of individual formations is given in Table 1 (after SACS 1980).

3.2 The Oaktree Formation

This was described by Kaffri *et al.* (1986) as a highly siliceous, bluish or dark grey dolomicrite. Light grey siliceous or calcitic patches together with thin shale horizons have also been reported by the above authors. The shale horizons become increasingly abundant towards the base of the formation.

3.3 The Monte Christo Formation

This formation occupies the central portion of the study area and underlies a large percentage of both the residential and industrial area of the town of Clayville. It is also the formation on which the Karoo outlier housing the waste disposal facility lies.

It is typically a light coloured recrystallized chert banded dolomite, the lower portion of which contains stromatolites. Very few exposures of this formation are available. Conditions within the dolomite were determined through exploratory drilling, carried out by the Department of Water Affairs, and test drilling done as part of a feasibility study to investigate the mining potential of the Karoo clay.

Table 3.1 The General Lithostratigraphy of the Transvaal Sequence

Group	Formation		Lithology	Thickness (m)
	Rayton		Beynestpoort Quartzite	1 200
			Silty shale, andesitic lava	
			Feldspathic quartzite	
			Shale	
			Quartzite	
			Subgraywacke and shale	
			Baviaanspoort Quartzite	
			Shale and quartzite	
	Magaliesberg Quartzite		Orthoquartzite	300
	Silverton Shale		Silty and graphitic shale with thin interbedded limestone	600
	Daspoort Quartzite		Orthoquartzite	80 - 95
	Strubenkop Shale		Iron-rich shale	105 - 120
			Iron-rich quartzite	
	Hekpoort Andesite		Andesitic lava, agglomerate and tuff	340 - 550
			Conglomerate, tuffaceous quartzite and shale	
	Timeball Hill		Shale	270 - 660
			Diamictite	
			Klapperkop Quartzite wacke and ferruginous quartzite	
			Graphitic and silty shale	
	Rooihoogte		Quartzite	10 - 150
			Shale	
			Bevets Conglomerate Member	
			Breccia	
	Eccles		Chert-rich dolomite with large and small stromatolites	380
	Lyttelton		Dark chert-free dolomite with large elongated stromatolitic mounds	150
	Monte Christo		Light coloured recrystallised dolomite with abundant chert; stromatolitic; basal part oolitic	700
	Oaktree		Dolomite, becoming darker upwards. Chocolate-coloured weathering	200
	Black Reef Quartzite		Shale	25 - 30
			Quartzite	
			Arkosic grit	

Exploration drilling further to the north of the study area revealed that the chert present in the formation can vary from black through grey to white in colour (Hobbs 1986).

This was confirmed by exploratory drilling in the study area. Boreholes MR 6 and MR 8 (Figure 2b) were found to be on extremely weathered grey, chert rich dolomite similar to Monte Christo Formation. The areal extent of this formation is believed to be greater than depicted on existing geological maps. Figure 2b gives an amended version of the geology of the area.

During exploratory drilling to evaluate clay resources, near surface conditions in the immediate vicinity of the waste disposal facility revealed weathered chert fragments in a sparse matrix of very slightly clayey sand with isolated patches of wad (Wiid 1985). Penetration rates indicate that the formation has a moderately dense consistency. Pockets of wad were recorded in most test holes together with minor cavities and severe drilling air loss in some instances.

3.4 Lyttelton Formation

This formation is recognised as a dark chocolate coloured dolomite with a low percentage of chert. Siliceous horizons are present as indicated by diamond drill exploration holes sunk by SAMANCOR on the farm Doornkloof 391JR, located to the north of the study area (Hobbs 1988). Sizeable stromatolitic mounds are also a known characteristic of this formation and were noted by Hobbs (1988) in the sidewall of the open cast Lyttelton Dolomite Mine. More locally, smaller elongated mounds were observed in the face walls of the Hippo Quarry situated in the eastern portion of the study area.

Well developed weathering structures in the form of pinnacles and wad are observed on the western face of Hippo Quarry. This, together with the extremely weathered nature of the dolomite beneath the waste disposal facility and either side of the Pretoria dyke (MR 6 and MR 8), indicate that well developed weathered zones are associated with the contact between Lyttelton and Monte Christo dolomite (Figure 2b).

3.5 Eccles Formation

This is a chert rich formation with hard, well cemented chert breccia in a siliceous matrix. The formation contains stromatolites and therefore resembles the Monte Christo Formation in its basal portion.

The basal unit of the Transvaal Sequence lies unconformably on the intrusive granitic basement referred to as the Halfway House Granite by Van Eeden in 1972 (SACS 1980). It was dated at 3204 ± 65 Ma (Swazian Age) by Allsopp in 1961 (SACS 1980). Subsequently Jansen (1977) has pointed out that this determination may have been based on the younger granodiorites of the intrusive and that the granitic basement itself is possibly older. The minimum age of the Transvaal Sequence is given by SACS (1980) as ranging from 2318 ± 17 Ma, based on age determinations on acid volcanics below the Black Reef Formation in the north- western Transvaal, to 2460 ± 120 Ma based on acid volcanics of the Groblersdal Group underlying the Black Reef Formation in the eastern Transvaal.

3.6 Karoo deposits

Earlier research has revealed the complexity of the Karoo outliers. In order to evaluate their potential for containing waste disposal, it is important to highlight the geology and their stratigraphic relationship with the underlying dolomites.

The main exposures of the Karoo Formation are indicated in Figures 1a and 2b. However it is evident from the results of the field survey/hydrocensus that numerous smaller outcrops exist, probably associated with sinkhole development in the underlying dolomitic formation. The situation of the major Karoo deposits suggests that they are in some way associated with either the dyke system within the study area or contact zones between two dolomitic formations. Preferential ground water movement along brecciated dolomite in close proximity to the dykes, may have led to more intensive dissolution. The damming up and preferential movement of water along the contact between chert rich and chert poor dolomite would also lead to more intensive dissolution. This in turn would favour the formation of sinkholes into which Karoo deposits would slump or be deposited. Day (1980) recognises three dyke systems in the southern Transvaal, one of which is an east-west striking system of post Karoo age. Day associates the Sterkfontein dyke with this post Karoo system. Disturbance and dissolution of the dolomite close to the dyke would thus provide ideal conditions for the preservation of the overlying Karoo deposits via slumping into palaeokarst or developing karstic features.

There are three major exposures of Ecca Karoo deposits within the study area, all of which have been mined at various localities. Regionally the sediments comprise diamictites, carbonaceous shales, mudstones, mudclast conglomerates, fossil bearing shales and sandstones (Wilkins *et al.* 1987). The outcrops within the study area are smaller and very much more shallow than those described by Wilkins *et al.* just to the north-east of Irene. Karoo deposit 1 (Figure 2a), has an irregular shape, its depth being in excess of 70 m on the western side. Karoo deposit 3 (Figure 2a), is also irregularly shaped with a maximum thickness of 30 m (Wiid, 1985) in the south-eastern portion.

Figures 3.1 through to 3.4 give an indication of the stratigraphic and lithographic nature of the Karoo deposits in Karoo deposit 2 (Figure 2a). Exploratory drilling done on the western portion of Karoo deposit 1, just north of the Sterkfontein dyke recorded thicknesses of 30 to 35 m, similar to those recorded by Wiid for the outlier south of the Sterkfontein dyke (Karoo outlier 3).

In the Karoo outlier 3 the quarry face described by Wiid (1985) is unfortunately no longer visible but from the available information on other faces and small exposures the description is supported. Another quarry situated just to the north- west of the waste disposal pit has now been almost entirely backfilled. A detailed geological description of the sediments is therefore not possible as no fresh quarry faces are available. Only the very top few metres of the sediments are exposed and consist of reddish soils underlain by moderately hard khaki shales. Cross bedding could be seen but no slump structures were evident. Generally, bedding is regular and near horizontal. Outcrops of a coarse sandstone are observed at exposed patches at the bottom of the quarry. The logs of test drilling done by Cullinan Bricks indicate this to be the basal layer of the Karoo. Figure 3.5 is an isopach map of the Karoo sediments which generally do not exceed a depth of 30 m. They consist of medium

Figure 3.1 Karoo (Ecca) outlier 2 - showing significant faulting

Figure 3.2 Karoo (Ecca) outlier 2 - showing stratigraphic succession, faulting and seepage

Figure 3.3 Karoo (Ecca) outlier 2 - showing micro fracturing in upper deposits and seepage

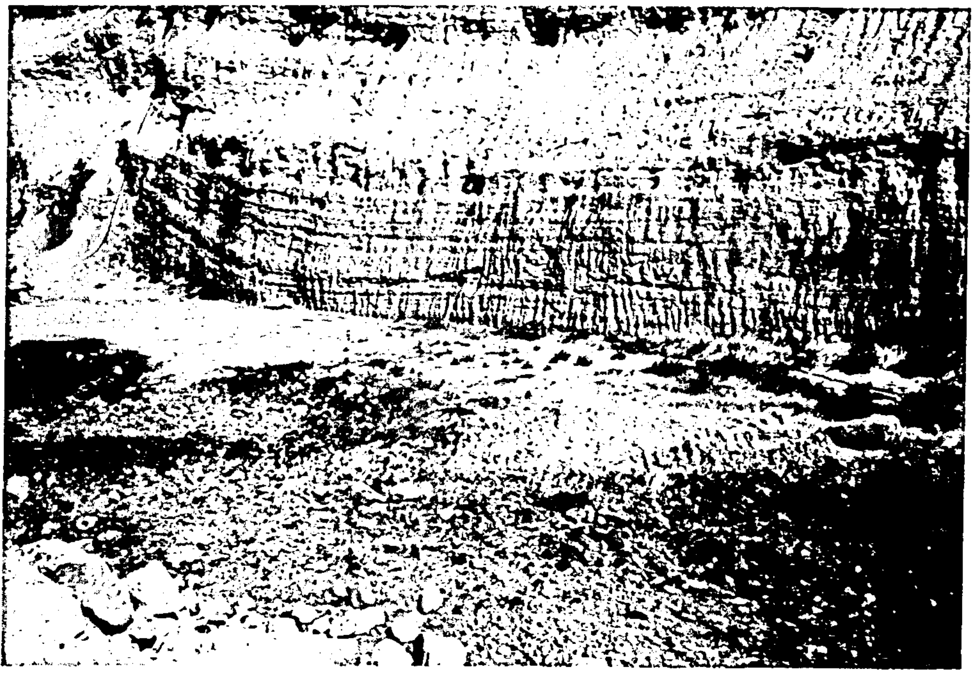


Figure 3.4. Karoo (Ecca) outlier 2 - showing stratigraphic and faulting associated with slumping

to coarse grained grit underlain by soft to moderately hard yellow khaki, slightly micaceous shale. Cross bedding is evident together with slump structures. Sediments are heavily jointed and appear to be randomly orientated. Within slump structures bedding planes can exhibit dips of up to 50°. Joints are generally steeply dipping and are sometimes close to vertical. More pronounced joints contain hard wedges of ferruginized gouge material. These may have been formed by the introduction of oxygen into the kaolinite rich deposits forming Fe-oxides (Wiid 1985).

The pronounced ferruginized joints have a distinct lineament in a predominantly east-west direction, parallel to the contact of the Monte Christo and Lyttelton formations. The lineament and position of these features indicate marked and fairly rapid subsidence into sinkholes associated with the weathered zone at the contact of the two dolomitic formations.

The contact between the consolidated Karoo deposits and the dolomites is always unconformable and gradients are highly variable. Chert breccia and chert residua have been found to underlie the Karoo deposits. (Wilkins *et al.* 1987). This was also recorded locally at the contact of the most southerly Karoo outlier within the study area. The nature of the contact is illustrated in Figure 3.6. This cross section as drawn using the information obtained from the test drilling done by Cullinan Holdings Ltd. before the quarry came into operation. Location of the cross section is given in Figure 3.5. Chert breccia and chert residue was found in every exploratory borehole that penetrated both Karoo and the underlying dolomitic formation.

Figures 3.7 and 3.8 give a three dimensional impression of the topography of the dolomite beneath Karoo outlier 3, housing the waste disposal facility and the western portion of outlier 1 respectively. The topography is highly irregular and deep depressions are present which suggest dolomite sinkhole development.

In most cases the drill holes went to the basal layer of carbonaceous clay or coarse sandstone which is considered to be near the contact of the Karoo and the dolomite. It must be stressed that the exploration holes drilled by Cullinan Minerals did not penetrate dolomite. The depth and topography given are therefore not precise, but nevertheless give an appraisal of the situation. The contact of both outliers displays similarity in that quite steep sided depressions exist, with the exception that the main depression in Karoo outlier 1 appears to be more linear in nature, suggesting a more fluvial mode of deposition (Figure 3.8).

Exploration drilling associated with this project in the eastern and western areas of outlier 1 (Figure 2a) revealed that a dolerite sill forms the contact between the Karoo and the underlying dolomitic formation. The Karoo at the eastern locality is approximately 20 m thick and the sill has a thickness of 10 m. Chert-rich dolomite was encountered below this. Towards the west a sill is at a depth of approximately 65 m. It is positioned within extremely weathered dolomite below 50 m of Karoo deposits. Phase 1 of exploratory drilling in this project did not indicate the presence of sills south of the Sterkfontein dyke.

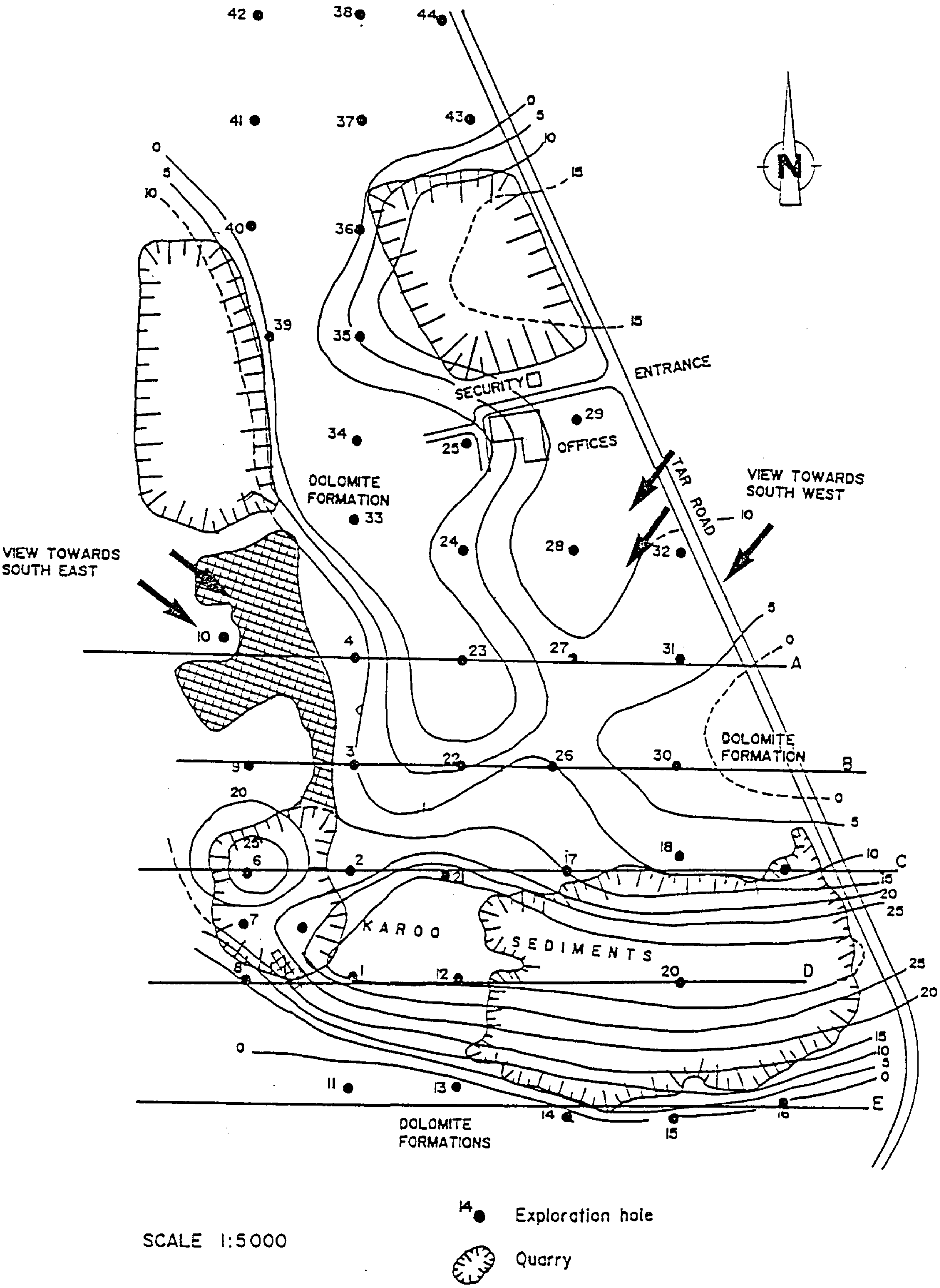


Figure 3.5 Isopach map of Karoo sediments at the Clayville waste disposal facility. (After Wiid 1985)

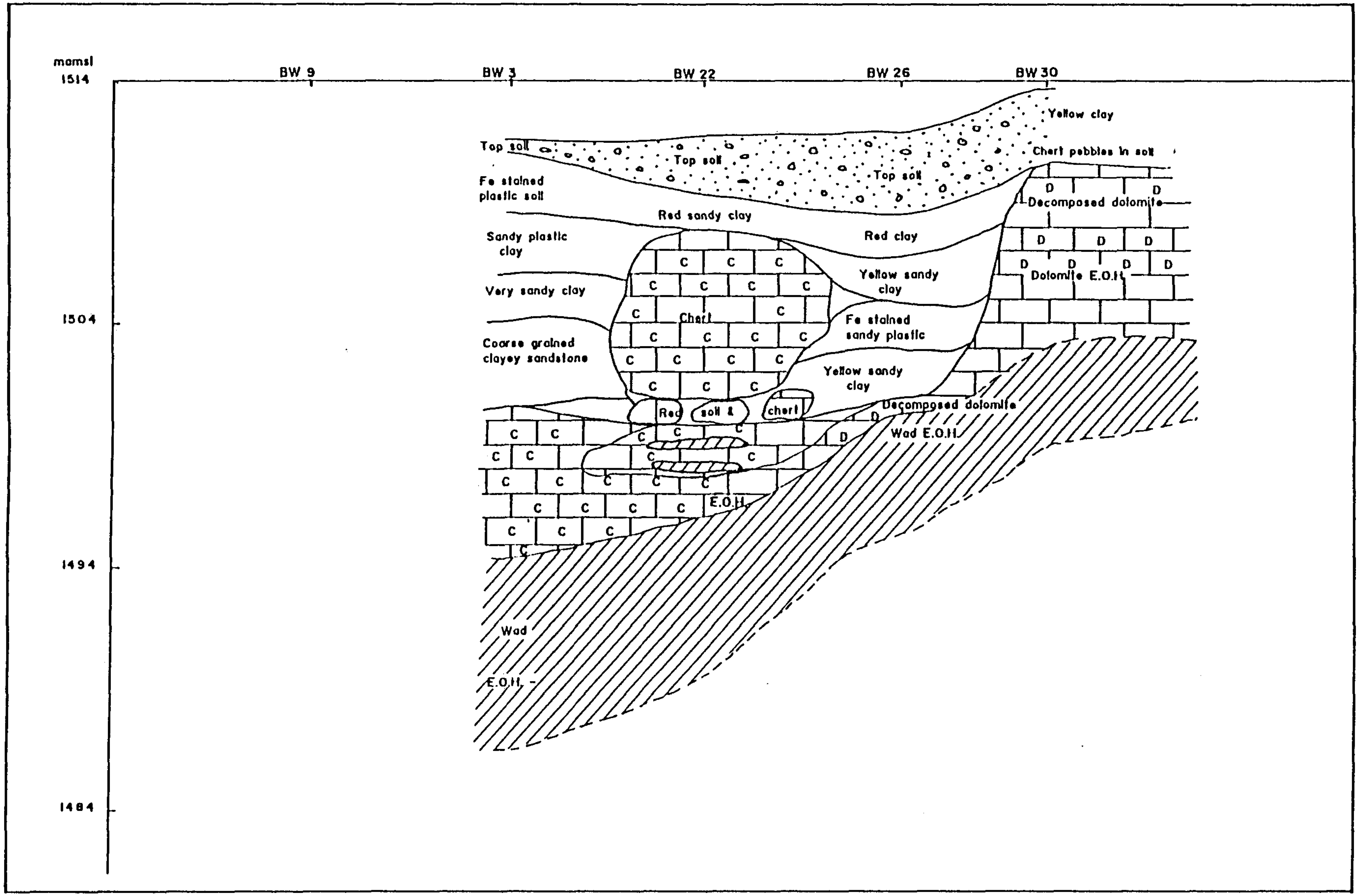


Figure 3.6 Section B Vertical scale 1 cm = 2 m
Horizontal scale 1 cm = 25 m
E.O.H. End of hole

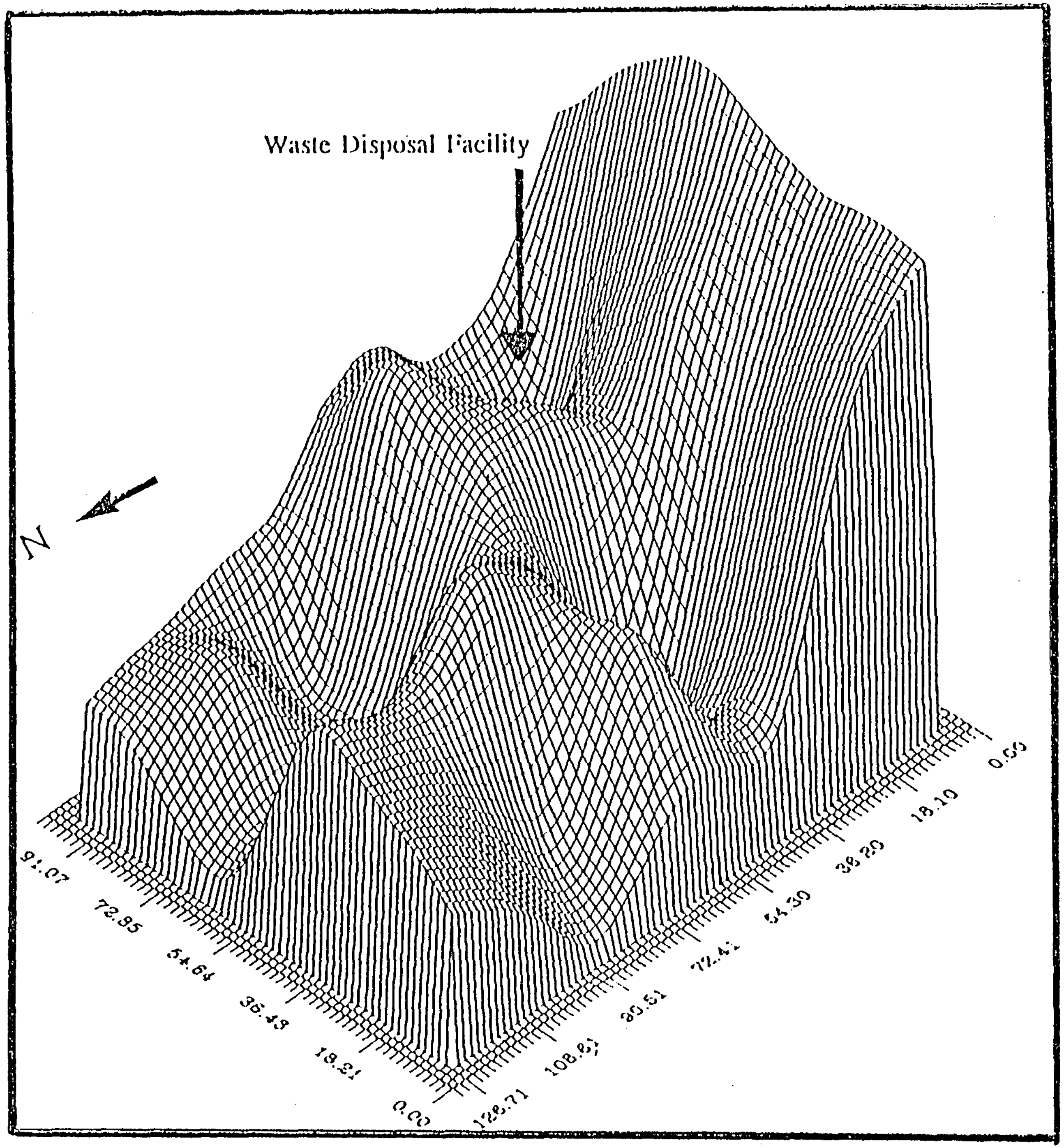


Figure 3.7 **MIDRAND - Clayville Cullinan Brickworks and Waste Disposal Facility Topography of underlying dolomite viewing towards the south-east (Figure 3.5)**

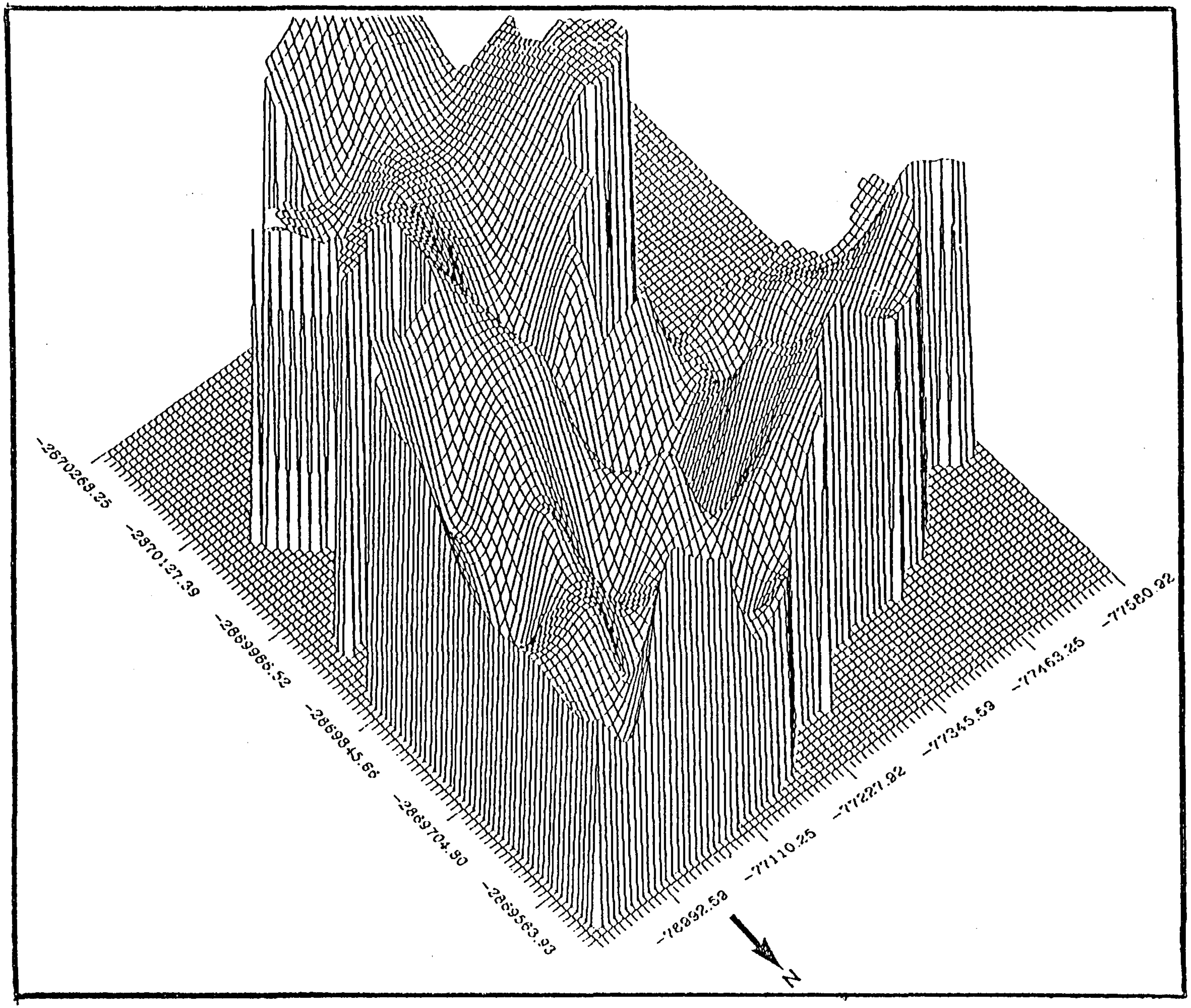


Figure 3.8 **MIDRAND - Cullinan Brickworks - Midrand plant. Basement topography viewing towards south-west**

3.6.1 The association of the Karoo outliers with the underlying dolomite and their mode of deposition

Ecca sedimentation took place during the retreat of the Permo-Carboniferous glaciers. It is an essentially lacustrine deposit and consists of an aerially restricted carbonaceous shale overlain by widespread mudstone deposits. The carbonaceous shale has been recorded within the Karoo deposits of the study area but its occurrence is of a localised nature. It occurs in both the outliers north of the Sterkfontein dyke, and in the 'control' outlier, at Rietvlei Dam. The limited thickness, distribution and fine grained organic nature of the deposits, suggests accumulation of muddy detritus within a body of water with restricted circulation. This is indicative of a small lake or swamp type environment. It is therefore appropriate to assume that karstic subsidence had taken place before the sedimentation process forming low lying, local vlei areas into which these sediments could be deposited. Reference is made to the carbonaceous flint deposit in the southern outlier (3), but this is only recorded in one test hole located to the west of the waste disposal facility where the Karoo deposits are thickest.

The slump structures and jointing associated with the mudstones could be a result of continued karstic subsidence, or to dewatering and compaction of the existing sediments. This 'settling' process led to the formation of topographic lows into which fluvio-lacustrine sandy clays and sandy lobes were deposited.

The formation of sinkholes within the study area may still be taking place. Wilkins *et al.* (1987) mentioned that within their study area situated approximately 15 km to the north of this particular site, thirty six surface sinkholes have developed since clayey silt and sandy silt soils were deposited in late Tertiary and Quaternary times.

Sinkholes have recently developed on a local scale within the residential section of Clayville. The erection of a block of flats had to be abandoned due to sinkhole development.

3.7 Intrusives

3.7.1 Dykes

As mentioned previously three major dykes intersect the area under study: the Pretoria, the Sterkfontein and the Pinedene dykes (Figure 2b).

Day (1980) recognises 3 dyke systems in the southern Transvaal based on magnetic signature, direction of strike and age relative to the Karoo Sequence:

- a negative magnetic signature, of pre-Karoo age and referred to as the Pilanesberg dyke system;

- a positive magnetic signature, also of pre-Karoo age and referred to as the north-south trending East Rand dyke system;

- a positive magnetic signature, of post-Karoo age with an east-west strike.

It has been previously believed that the latter two systems are represented in this particular area, but recent geophysical investigations have cast some doubt on this. The Pretoria dyke has been considered to belong to the second system, but electromagnetic traverses have identified a different signal to that which would be expected had the dyke belonged to the East Rand dyke system. It is a syenite dyke with a near vertical dip, but just east of Clayville a dip of 20° to 25° to the west was recorded by Jansen (1977).

The second major dyke in the area is the east-west striking Sterkfontein dyke. It is mainly composed of an equigranular, fine to medium grained olivine dolerite. Geophysical investigations of this structure however, found the magnetic signature was not strong and was difficult to distinguish. No further structural information was gained from the study except that the dyke does appear to be dipping slightly to the north. Day suggests that this dyke is of post Karoo age thereby conforming with his east-west dyke system.

The third dyke is the NW-SE striking Pinedene dyke, consisting of a medium grained dolerite. This dyke intersects the Pretoria dyke in the vicinity of Pinedene railway station and continues in a south-easterly direction until it terminates against the Sterkfontein dyke. A lack of any magnetic anomaly to the south of the Sterkfontein dyke indicates that the Pinedene dyke does not continue in this direction.

3.7.2 Sills

There are a number of sills present in the Chuniespoort Group within the study area. Very few outcrops occur but their presence is confirmed by extensive drilling throughout the area carried out by the Department of Water Affairs. One exploration hole drilled in the vicinity of the intersection of the Pretoria and Sterkfontein dykes, revealed the presence of two sills within six meters vertically of each other. It is uncertain as to whether the dolerite features are sills; it is believed they could be part of a composite Pretoria dyke.

On a more regional scale, Jansen (1977) postulates that the sills were intruded into weaker zones produced by tensional stresses induced during the updoming of the granite core during the initial stages of the formation of the Bushveld Igneous Complex. Study of the 1:50 000 geological map of the area does suggest an association with the structural features of the region, especially the concentric strikes and the centrifugal dips of the Chuniespoort Group rocks around the dome shaped Halfway House Granite.

3.8 Geological interpretation using geophysical investigations

Geophysical investigations were undertaken primarily to help locate and investigate geological structures and formations in the study area. A major portion of the geophysical work was carried out by EMATEK, CSIR. A gravity survey was carried out by the Department of Water Affairs and Forestry.

3.8.1 Electromagnetic traverses

This method did not prove effective in identifying dykes. Highly conductive zones were identified, but exploratory boreholes MR 1 and MR 2 indicated that, although highly conductive they were associated with dry powdery wad layers.

3.8.2 Magnetic traverses

14 magnetic traverses were done by EMATEK at various localities, the positions of which are given in Figure 3.9. Six were done along the same lines as the electromagnetic profiles. The Pretoria dyke was located using magnetics along profile 9 which cut the dyke perpendicularly, and was characterised by a prominent double peak positive anomaly (Figure 3.10). This anomaly pattern was also noted by Hobbs (1988) when magnetic traverses were being carried out in the area to the north of Irene. The double peak character has been explained by Meyer *et al.* (1992) as representing a dyke having chilled margins with higher magnetic susceptibility. This theory was substantiated by the same authors after modelling. Profile 3 which also cuts the Pretoria dyke perpendicularly, did not give the double peak anomaly. The field data was totally different from that expected from a profile cutting both perpendicularly and obliquely. This new evidence indicates that possibly the Pretoria dyke does not deviate as previously thought, but continues in a north-south direction, with a change in composition due to weathering, or changes in its angle of dip. The anomaly picked up along profile 3 may well be associated with a separate dyke striking east-west first suspected by Wiid (1985) as a consequence of a discrepancy in water level data to the south of the waste disposal facility. A further two positive anomalies were identified along profile 4 (Figure 3.9), and have been attributed by Meyer *et al.* to two east-west striking dykes. An east-west striking dyke has been identified in the field at Hippo quarries. It can be assumed that this feature is related to the most northern anomaly on profile 4. This dyke shows central weathered dolerite material with very calcified margins. This configuration is most probably responsible for the double peak anomaly seen in Figure 3.10. The same geological condition could apply to the Pretoria dyke which also shows a positive double peak anomaly. A very interesting observation is that the anomaly associated with this east-west striking dyke is not observed on profile 1 located to the west of the Pretoria dyke. It would therefore seem appropriate to assume that the east-west striking dyke is terminated by the Pretoria dyke.

3.8.3 Resistivity profiling and depth soundings

All the profiles showed a similar response to the electromagnetic profiles. The conductive zones outlined with resistivity correlated very well with the positions of those conductive zones highlighted using the electromagnetic method. Soundings were restricted to a limited area around the waste disposal facility. They were done in order to determine the condition of the dolomite with depth. The sounding curves indicate that conditions within the dolomite vary considerably and can be attributed to the varying chert contents of the formation both laterally and vertically. Some profiles reach resistivities of less than 100 ohm.m and can be most probably attributed to pockets of wad or deep weathering within the dolomite.

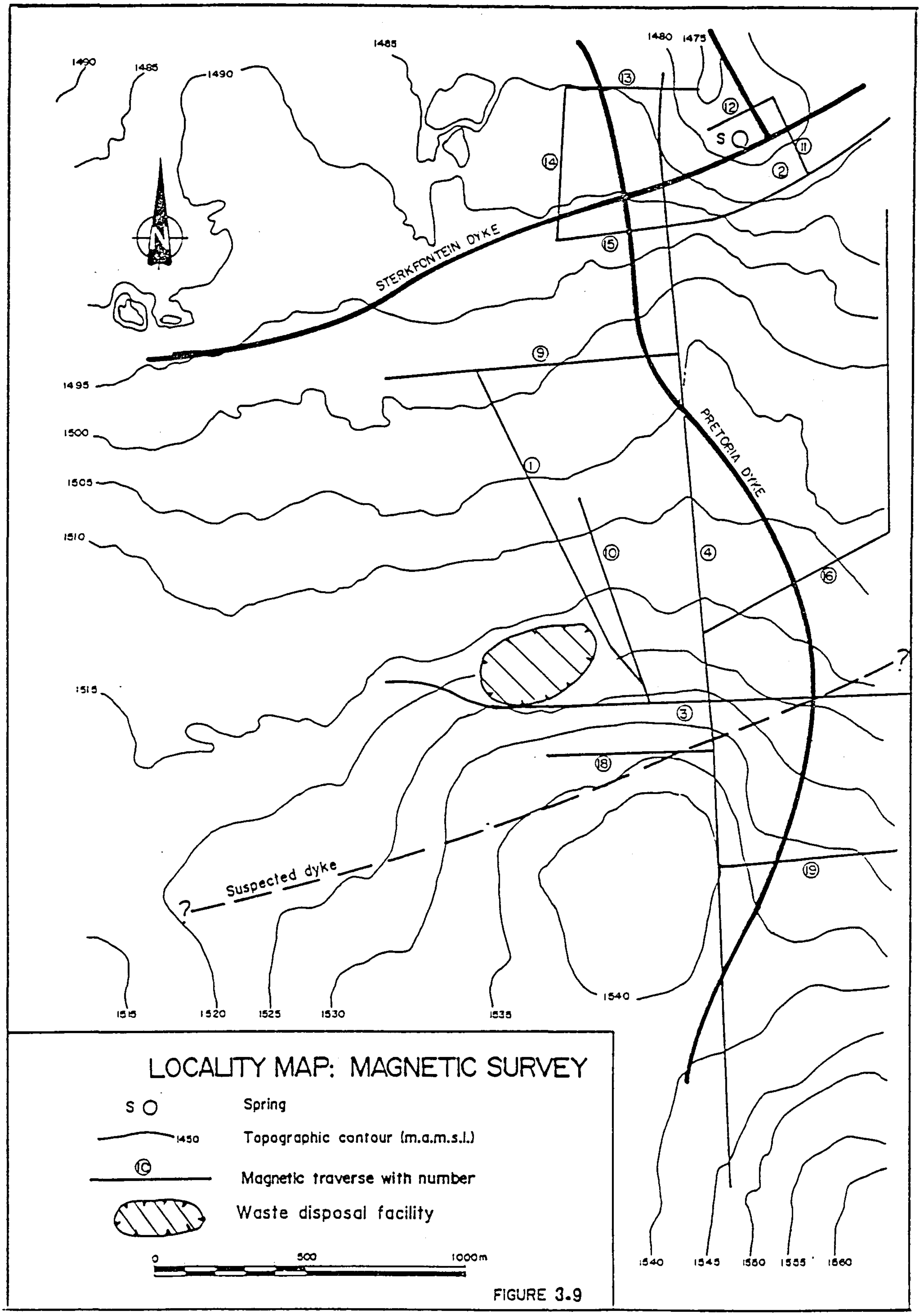


Figure 3.9 Locality map: magnetic survey

3.9 Gravity survey

3.9.1 Field procedures and data reduction

The main aim of this survey was to delineate leached zones in the dolomitic aquifer or palaeokarst features which could act as channels through which ground water could move.

The survey was done on a 50 * 100 m grid over an area of approximately 5 km^2 around the waste disposal site. A locality map is given in Figure 3.11. A total of 680 gravity stations were surveyed and processed and the resultant residual gravity map is given in Figure 3.12. Terrain corrections were later applied to the data where surface topography was thought to have affected the readings, but the corrected residual gravity map did not differ significantly from the original. Most corrections fell below the survey accuracy, which in this case was estimated to be approximately 0,02 mgal.

3.9.2 Data interpretation

Geological logs of existing boreholes were used to confirm the accuracy of the regional gravity field. The Pretoria dyke is visible as a high gravity trend on the residual map but the Sterkfontein dyke is not so noticeable.

Lower residual gravity values are associated with pre-Karoo dolomitic formations in which lies Karoo sediments. The lowest values are highlighted in Figure 3.12. There is a prominent east-west trending gravity low in the vicinity of the waste disposal site with low values extending to the south of the study area where chert outcrops can be seen. The low values could then also be associated with weathered dolomite overlain by a thin cover of Karoo. Exploratory drilling carried out in the eastern portion of the linear gravity low near the Pretoria dyke proved this to be true (MR 6 & MR 8, Figure 3.12). The weathered nature of the dolomite favours ground water flow, therefore an association can be made with gravity low trends and probable ground water flow patterns. This conclusion together with the discontinuity of the high gravity values associated with the Pretoria dyke highlighted the need for exploratory boreholes MR 6, MR 7 and MR 8.

The previous geological mapping has terminated the Monte Christo Formation at the margin of the Karoo. Study of the gravity data suggests that the chert rich dolomitic formation is a little more extensive than previously mapped. The Monte Christo formation extends beyond the margin of the Karoo up to the northern boundary of the waste disposal facility, and may extend in a north-easterly direction towards the Sterkfontein dyke.

Even if differentiation between deposits is difficult, a gravity survey is a geophysical method which should be employed in a dolomitic environment to at least delineate areas which merit further study via more detailed geophysics and exploration holes.

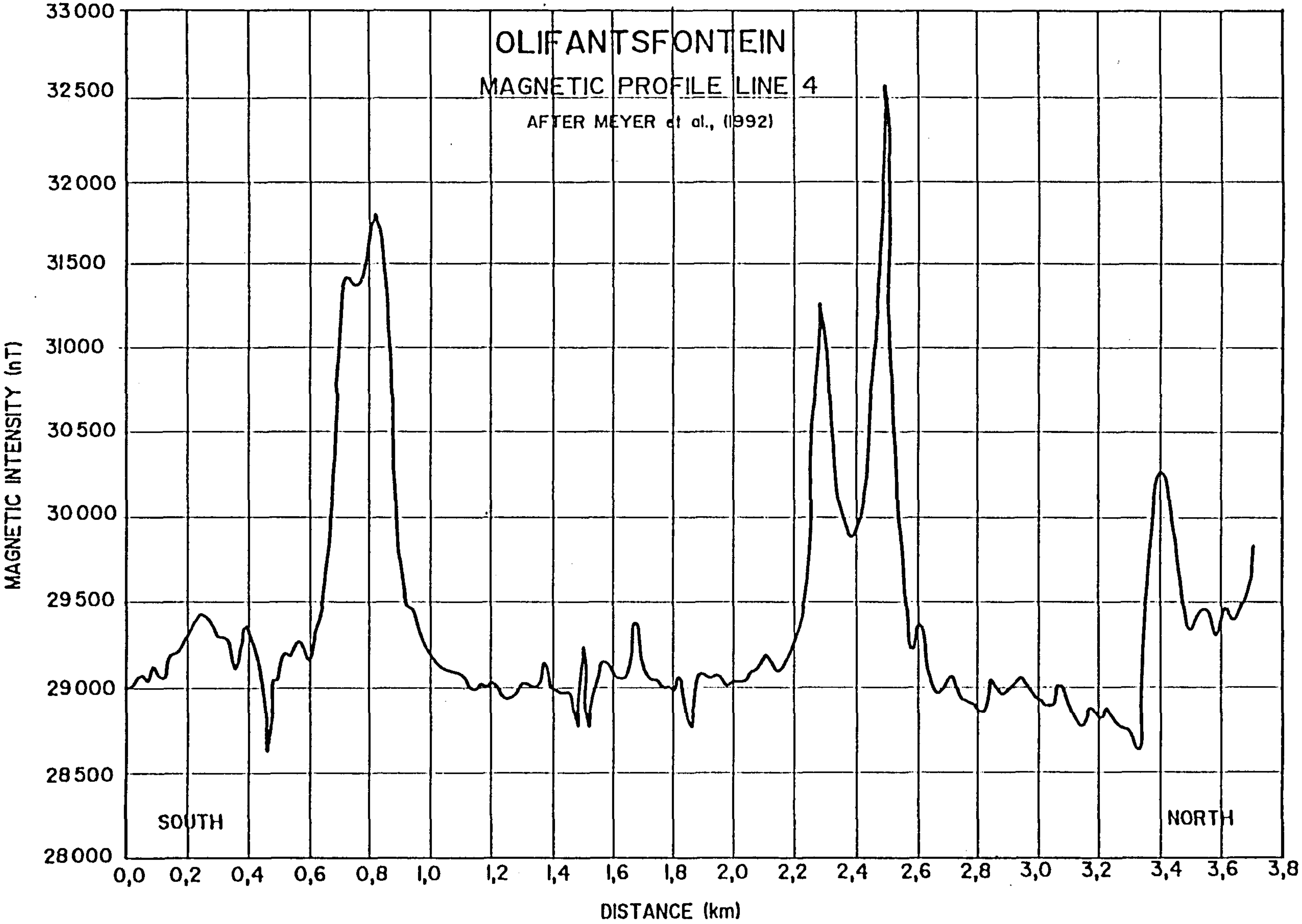


Figure 3.10 Olifantsfontein, Magnetic profile line 4 (after Meyer *et al.*, 1992)

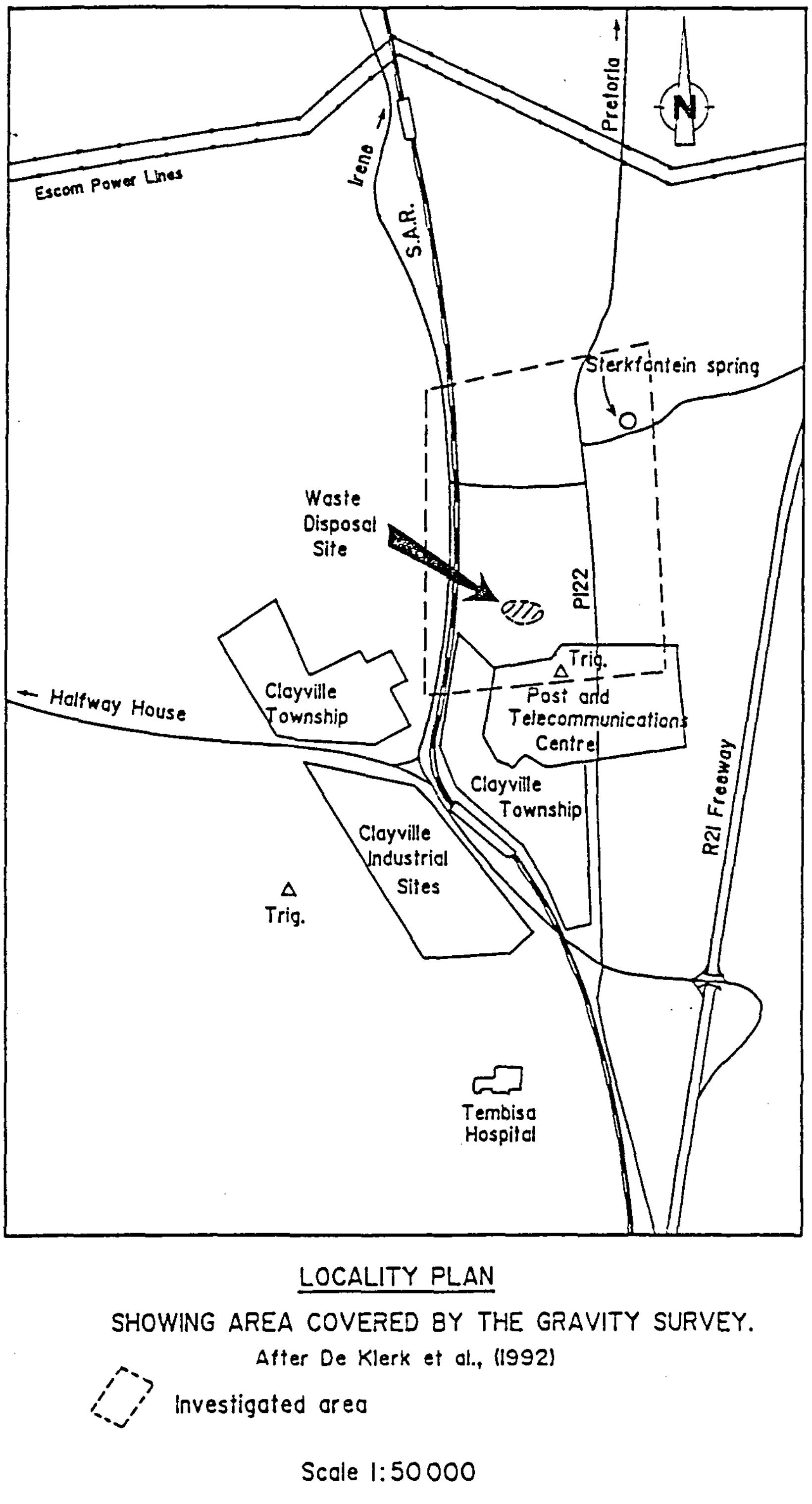


Figure 3.11 Locality plan - gravity survey (after De Klerk *et al.*, 1992)

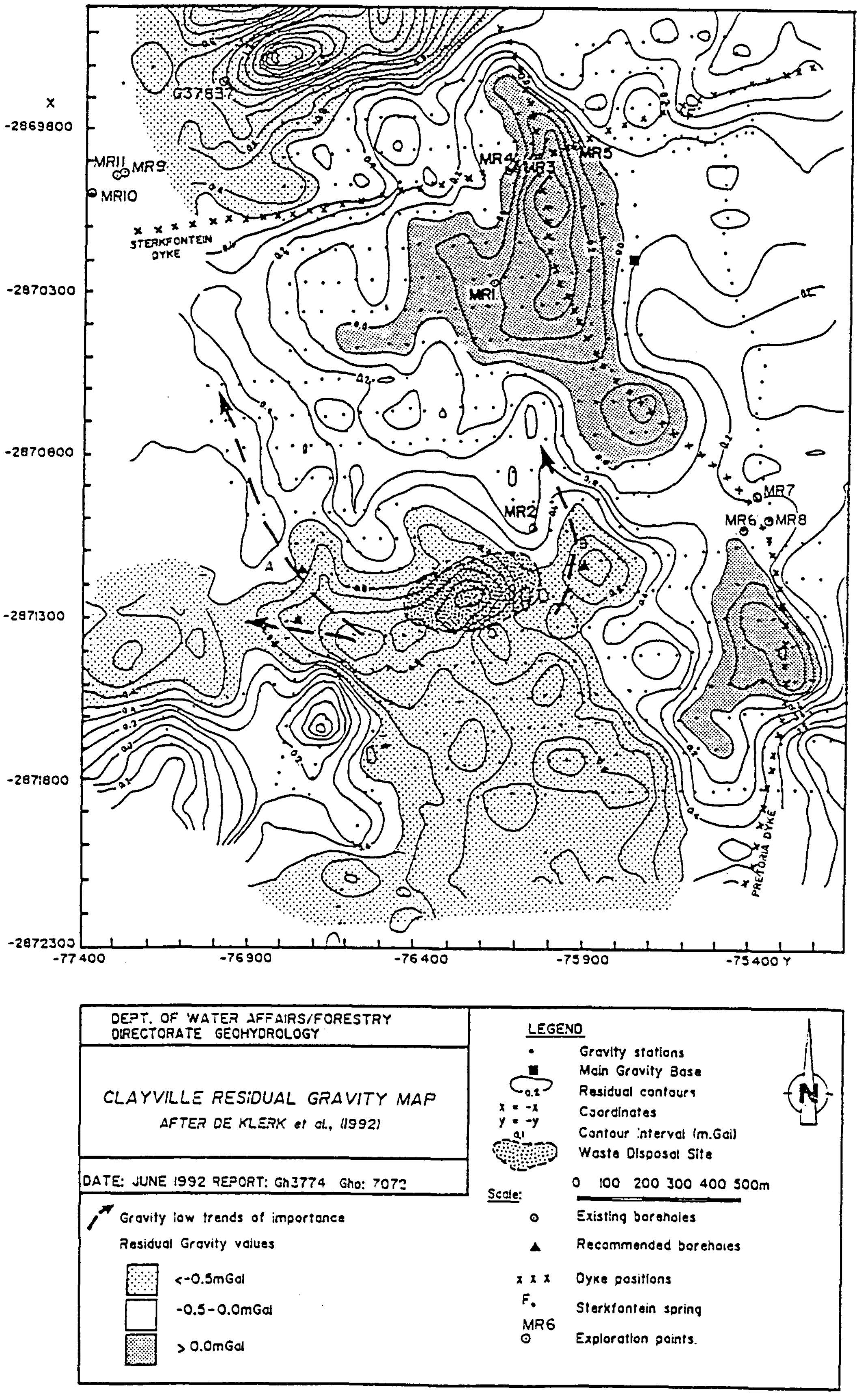


Figure 3.12 Clayville residual gravity map (after De Klerk *et al.*, 1992)

3.10 Exploratory drilling

Eleven exploration holes were drilled throughout the duration of the project. Each one was located for specific reasons and the results have been included in the report where appropriate. All borehole logs are included in Appendix 2. They were all sited in order to optimise the information about the geology and geohydrology of the area. Most were sited as a follow-up investigation relating to geophysical work. Boreholes in the Karoo were sited according to field conditions and were used primarily to obtain water samples and environmental isotope profiles. The condition of the dolomite beneath the Karoo Formation was also investigated with these holes. The locations of all exploratory holes are given in Figure 2b.

4 CONTROL AREA - RIETVLEI

4.1 Introduction

The location of the control area of Rietvlei (Figure 2a), was chosen as a site in which no, or at least very little, urban and industrial pollution was taking place. Agricultural pollution was expected due to livestock farming and experimental farming practices at the centrally located agricultural research centre.

The report by Kok *et al.* (1985) concentrates on the northern part of the control area. It provides a limited number of water levels north of the Sterkfontein dyke and verifies the presence of north-south and northwest-southeast trending dykes running through the region.

4.2 Karoo deposits

The Karoo deposits within the outliers are very similar to those found at the various localities in the Olifantsfontein area. This applies both to the succession, which consists of various shales, siltstones and grits, with a basal carbonaceous shale with thin coal seams, and the maximum thickness of the sediments of some 25 m.

4.3 Geology and geohydrology of the Karoo

Water was intercepted at varying depths within the Karoo. This variation was attributed (Jones 1984) to certain formations such as grits, siltstones and carbonaceous shales acting as aquifers exhibiting confined conditions, while the shales, mudstones and clays behave as aquicludes. Slump structures and fractures within the Karoo sediments may also have some influence on the intercepted water and piezometric levels.

4.4 Geohydrology of the dolomitic formation

Due to the lack of boreholes, a piezometric map of the water levels within the dolomites can not be drawn up. However, water levels suggest that regional ground water flow is towards two springs situated on the southern side of the Sterkfontein dyke in the north-eastern part of the control area. Environmental isotope data suggests that the turn-over time for this system is much greater than that indicated for the system drained by the Sterkfontein spring in the Olifantsfontein area.

4.5 Water quality

Ten monitoring points have been sampled, seven of which have been analysed. The chemical analyses are given in Appendix 3. Most show typical dolomitic ground water characteristics (Johnson, 1975).

Originally it was thought that no ground water pollution would exist in the area, but the quality of the water extracted from monitoring point RTV 2 suggests that this may not be true. This monitoring point is situated on the floodplain of the Rietvlei itself. Pollution may be introduced into the system by surface flow in the spruit. Environmental isotope analyses were able to help clarify some of the complexities (Chapter 8).

5 GEOHYDROLOGY OF THE OLIFANTSFONTEIN AREA

5.1 Introduction

This report is based predominantly on data collected during the project. Very little historical data has been included.

Water level measurements were taken in 30 boreholes in the initial geohydrological survey carried out in 1990. A further 7 water levels extracted from Wiid's report (1985) were added to supplement the existing data. An additional two water levels were added in 1991, and the water level data from the exploration holes was added in 1992 and 1993. All these water levels have been used to produce the regional ground water flow map in Figure 5.1.

5.2 Ground water flow

Regional ground water flow is in a northerly direction, and the compartmentalisation effect associated with the dykes is prominent. One of the possible discharge points of the eastern compartment, south of the Sterkfontein dyke, is the Sterkfontein spring. It has a sustained flow and is at present utilised by Pretoria Municipality to supplement Pretoria water supply. The overflow point for the western compartment is very difficult to locate with the water level data available. The water level data suggests that there are 3 possible mechanisms by which drainage may take place:

i) Baseflow into the western surface drainage (Kaalspruit).

ii) Possible movement through the upper layers of the Sterkfontein dyke, especially at the most westerly point, towards the surface drainage.

iii) Limited movement across the upper portion of the Pretoria dyke where its composition is not fully understood. This section of the dyke is indicated by a dotted line in Figure 5.1.

A very flat water table exists just south of the Sterkfontein dyke. This is a consequence of the weathered nature of the Monte Christo Formation and possibly a well defined interconnecting solution network within the Lyttelton Formation. All exploratory boreholes within Lyttelton Formation had very poor yields, although significant fracture flow can be observed within Hippo Quarry.

Transmissivity values within weathered Monte Christo Formation were very low. MR 8 (Figure 2b) east of the Pretoria dyke yields 0.2 l s^{-1}, whereas MR 5 also in slightly weathered Monte Christo Formation gave a value of 9.1 l s^{-1}. Estimated blow yields of boreholes sunk in Lyttelton Formation ranged from dry to 4 l/sec.

It is likely that ground water flow is in the form of fracture or solution feature flow in both Monte Christo and Lyttelton Formation. However, where Monte Christo is highly weathered, ground water appears to be stagnant or extremely slow moving.

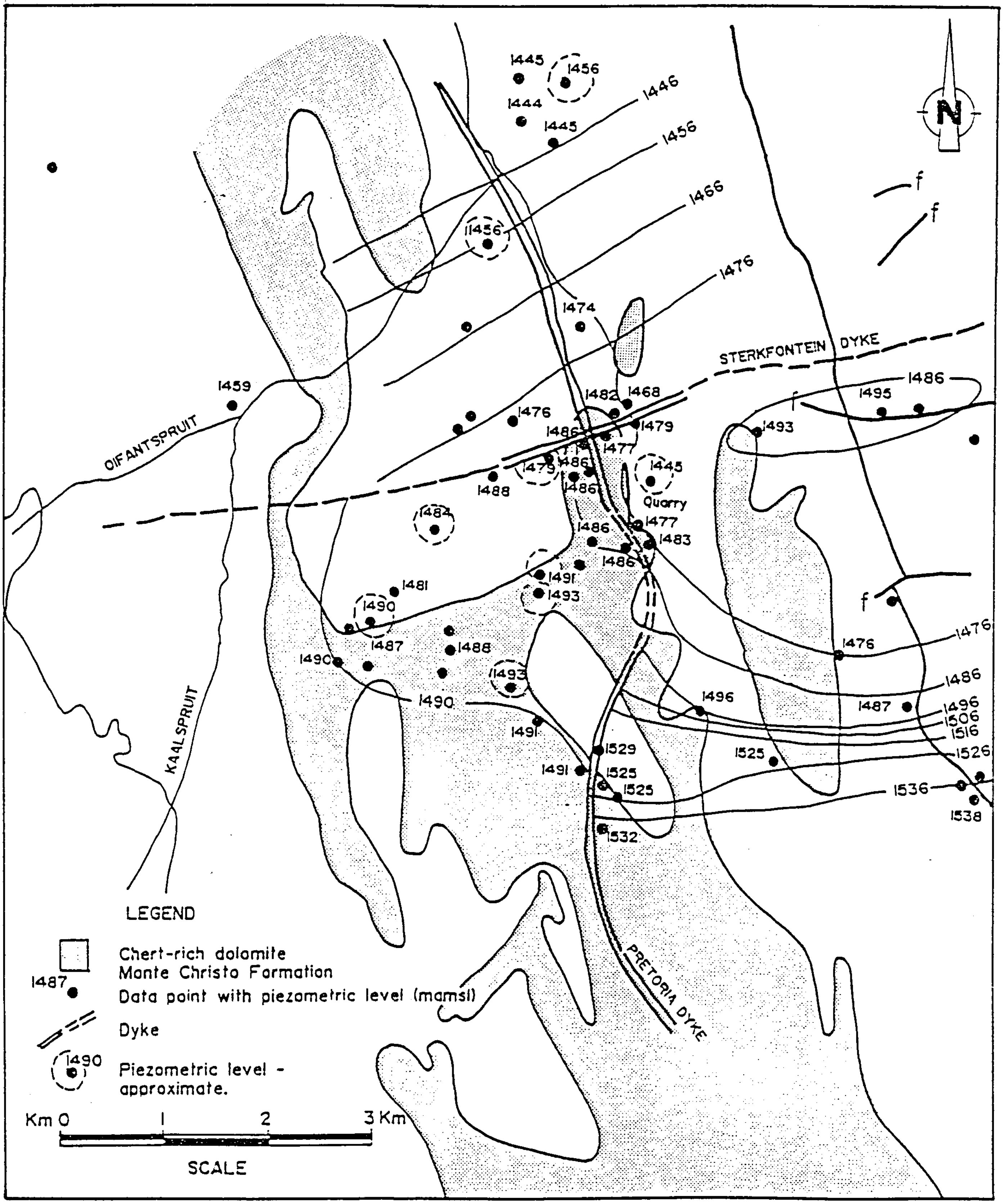


Figure 5.1 Piezometric map of the dolomitic aquifer depicting ground water flow in the Clayville area

It was suggested by Temperly (1987) that the Sterkfontein spring is a result of the more rapid process of erosion along the dyke, lowering the ground surface to the water table, rather than as a direct result of a barrier effect caused by the Sterkfontein dyke. The authors are of the opinion that a combination of barrier effect and preferential erosion contributes to the location of the spring. A number of ephemeral and sporadic springs have been reported along the Sterkfontein dyke and their existence can be explained using the same arguments as those for the Sterkfontein spring. Flow patterns appear more complex in the south-eastern compartment, which may be related to the presence of sills.

The geographic distribution of boreholes suggest that ground water is associated with the contact between chert rich and chert poor dolomite, attributed to preferential dissolution. The water table appears to be governed by natural factors which are, in order of decreasing importance, the topographical relief, the dykes, sills, the Sterkfontein spring, and the different dolomite lithologies.

There is a considerable difference in water level on either side of the Pretoria dyke. Thirty five metres is recorded between monitoring points 41 and 23 in the south with the higher level being on the eastern side. Exploration drilling at the intersection of the two dykes revealed a rest water level difference of only 9 m with the higher level being on the western side. There were reservations as to the validity of this water level on the western side. MR 3 penetrated saturated Karoo before going into the weathered dolomite and the water level might have been influenced by the confined aquifer of the Karoo. Subsequent drilling to the south on either side of the dyke showed a 3 m difference in water level with the higher elevation again on the western side. These water levels are associated with the dolomitic aquifer because the most southerly boreholes went through completely dry Karoo Formation. This indicates that just to the south of MR 6 and MR 8 there is a region where water levels are likely to be at the same elevation. This is considered the most favourable point at which ground water flow across the dyke could occur. Flow rates are likely to be minimal because of the weathered clayey nature of the dolomitic formation as revealed by MR 6 and MR 8, the extremely low transmissivity value at MR 8, and the low rest level gradient.

5.2.1 Transmissivity values

The indications of ground water flow across the Pretoria dyke led to a more intensive investigation. Two pairs of exploration holes were drilled on either side of the dyke at the intersection of the Pretoria and Sterkfontein dykes (MR 4 and MR 3, MR 5), and within the region of low gravity values which continued across the Pretoria dyke (MR 6 and MR 8, Figure 2b and Figure 5.1). Test pumping established very little hydraulic continuity between the western and eastern sides of the dyke. The observation boreholes MR 4 and MR 6 in both localities showed only a 1 or 2 cm reaction throughout the 24 hour duration of the pump tests.

The fast recovery rate of observation hole MR 6 indicates storage within the dolomitic aquifer to be high at this particular location, ground water flow however is limited.

6 ENVIRONMENTAL ISOTOPES

Environmental isotope techniques such as applied in this study rely on small variations in the ratios of the isotopes of the lighter elements (H, C, O) in environmental substances (e.g. water), to provide information on the history of such substances. The radioactive species give time-related information, whilst the non-radioactive species give process-related information. Verhagen et al (1991); IAEA (1983b). The radioactive isotope ratios employed are $^3H/^1H$ and $^{14}C/^{12}C$, and the stable isotope ratios are $^2H/^1H$; $^{13}C/^{12}C$ and $^{18}O/^{16}O$. All isotope analyses were performed at the Environmental Isotope Laboratory of the Schonland Research Centre, University of the Witwatersrand.

6.1 Tritium

Tritium, ^3H (or T) is produced in the atmosphere by nuclear reactions of secondary cosmic ray neutrons. Free tritium atoms are rapidly oxidised to HTO (or $^1H^3HO$) which is then transported to the earth's surface in precipitation, thus entering the hydrological cycle. The natural isotopic ratio in rain is about 5 TU (tritium units, where 1 TU represents an isotopic ratio of $^3H/^1H = 10^{-18}$). Tritium is radioactive and decays through low-energy ß-emission with a half-life λ = 12.43 years. Although at extremely low concentrations, environmental tritium can be detected, using simple but sensitive nuclear counting techniques down to values around 0.2 TU. When rain water infiltrates below the surface forming ground water it becomes more or less isolated from the atmospheric source. The decay of tritium then introduces a time dependent factor, taking as time 0 the moment of infiltration, giving a useful time span of some 100 years.

Since the mid fifties, fallout from nuclear bomb tests has added to the hydrological inventory of tritium, reaching a peak in southern African continental rain of about 60 TU (Figure 6.1). Values have since declined and are at present at near-natural levels. Other anthropogenic sources of tritium add to the environmental inventory. Compared with certain highly-industrialised countries, such sources in the southern African environment are still relatively minor.

6.2 Radiocarbon

Radiocarbon (^{14}C or carbon-14) is naturally produced in the atmosphere by nuclear processes similar to those generating ^3H. Free ^{14}C atoms are oxidised to form part of the atmospheric CO_2 inventory representing an isotopic ratio ^{14}C / ^{12}C of some 10^{-12}. Plants bind the carbon from atmospheric CO_2 during photosynthesis. The $^{14}C/^{12}C$ ratio in wood grown in 1850 is defined as 100 per cent modern carbon (pMC). Radiocarbon is radioactive, decaying through low-energy ß emission with a half-life λ=5730 years. Root respiration and oxidative decay of organic material enrich the air in soil by factors of 100 - 1000 in CO_2, compared to the atmospheric concentration. Infiltrating rain water dissolves this organic ^{14}C labelled CO_2, rendering the water aggressive and initiating the hydrochemical evolution.

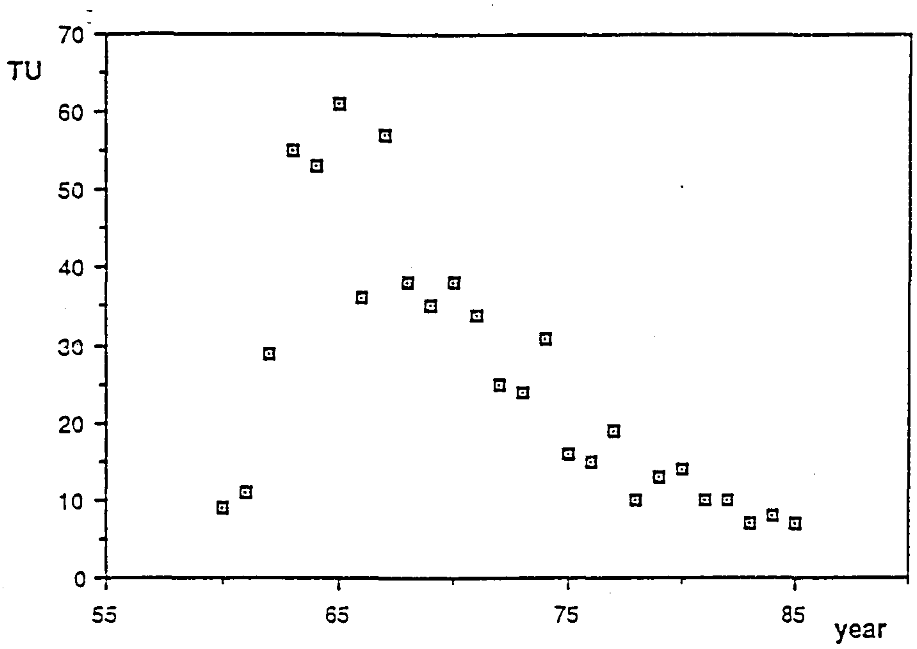


Figure 6.1 **Tritium concentration in South African rain since 1955**

The ^{14}C content of the total dissolved inorganic carbon (TDIC) in the water constituting recharge may be 50 - 100% of the atmospheric source. The lower limit may be approached in limestone terrain, where dissolved bicarbonate may contain as much as 50% carbon derived from limestone, which is ^{14}C-free, to near 100% in crystalline terrain, where biogenic carbon constitutes the only source, (Verhagen *et al*, 1991). As in the case of tritium, radiocarbon can be detected by low-level counting techniques down to values of some 0.2 pMC. Time dependent information on ground water systems can thus be obtained over a useful time span of some 40 000 years. Climatic and other factors have caused significant fluctuations in the ^{14}C content of atmospheric CO_2 over at least the past 10 000 years, and over the past century due to fossil fuel burning. These fluctuations were however of such a scale that they may be ignored in comparison to the uncertainties in the interpretation of radiocarbon data in most ground water applications.

Since the fifties, nuclear test fallout has added significantly to the atmospheric inventory of radiocarbon, reaching a value of some 160 pMC in southern Africa in the mid-sixties. Values have since been declining.

6.3 Stable environmental isotopes

6.3.1 The water molecule

The elements making up the water molecule have rare, heavy isotopes deuterium (^{2}H or D) and oxygen-18 (^{18}O). The isotopic ratios are approximately ^{2}H/^{1}H = 0.015% and ^{18}O/^{16}O = 0.2%, producing water molecules of mass 16, 17 and 18 respectively. These molecules of different mass exhibit small differences in vapour pressure. The isotopic ratios therefore undergo small changes during phase processes such as evaporation and condensation. These small changes in isotopic ratio are expressed as relative differences δ w.r.t. a standard called SMOW (standard mean ocean water) such that:

$$\delta = ((R_{sample} / R_{ref}) - 1) \times 1\ 000\ ‰$$

where R_{sample} and R_{ref} are the ratios of the abundance of the rare, heavy isotope to that of the more abundant, light isotope for the sample and reference (standard) respectively. The isotopic abundances are measured by mass spectrometry.

Water evaporating from the ocean surface will be slightly depleted in the heavy isotopic species, resulting in the vapour leaving the ocean surface being isotopically "lighter" than ocean water, with a negative δ value. Water vapour moving inland will undergo equilibrium processes of condensation and re-evaporation. This will result in the vapour progressively becoming isotopically lighter on moving further inland. The isotopic composition will further be temperature dependent. The result is that the δD - $\delta^{18}O$ values of precipitation worldwide are linearly correlated and lie on the so-called world meteoric water line (WMWL) (Figure 6.2):

$$\delta D = 8\,\delta^{18}O + 10$$

Small differences in the slope of this line, and intercept on the axis (deuterium excess) may occur locally, producing a "local" meteoric water line. The position of a particular analysis on the meteoric water line depends on geographic, temperature and precipitation amount effects. When rain water is captured in closed surface basins, such as lakes or dams, evaporation will cause the remaining water to become progressively isotopically "heavier". The isotopic composition of this water will now plot on a line of lesser slope, called an evaporation line (Figure 6.2). In this way, ground water will carry an isotopic signal revealing processes which occurred before infiltration.

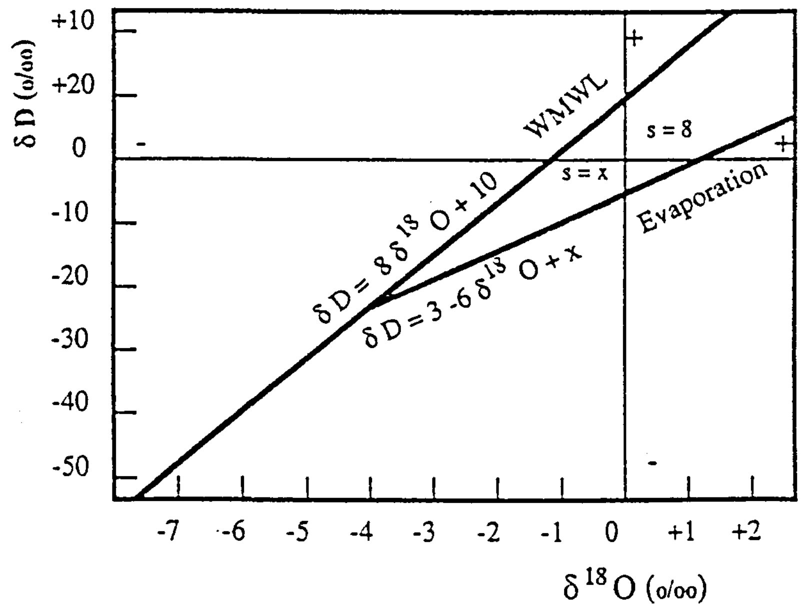


Figure 6.2 δD - $\delta^{18}O$ values of precipitation worldwide

6.3.2 Carbon-13

The carbon stable isotope ratio $^{13}C/^{12}C$ has a nominal value of about 1,1%. Small changes in the carbon isotope ratio are produced, principally in biological processes, during the production and decomposition of organic material. Changes are also produced in dissolved inorganic carbon, through isotopic dilution and exchange processes. These changes are expressed as relative differences w.r.t. a marine carbonate standard, PDB in the same way as stable isotopes of hydrogen and oxygen (see above). Thus atmospheric CO_2 has a $\delta\ ^{13}C = -7‰$. Organic material formed by photosynthesis has $\delta\ ^{13}C$ values in the range of -12 to -26‰. The TDIC in ground water evolves as shown in figure 6.3. ^{14}C undergoes similar changes during the evolution from atmospheric CO_2 to dissolved inorganic carbon. The $\delta\ ^{13}C$ value, along with a consideration of the carbonate chemistry, can in principle be used to "correct" the ^{14}C for such fractionation processes. (Verhagen *et al* 1993).

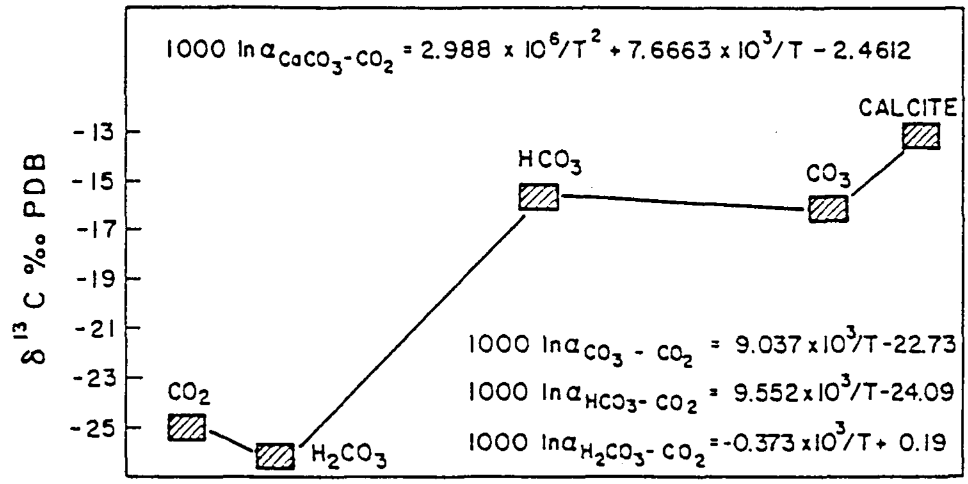


Figure 6.3 **The changes in $\delta\ ^{13}C$ of the dissolved in organic carbon during the evolution from free CO_2 to calcite**

6.4 Sampling procedure

Water samples of 1 litre are taken for tritium and stable isotope analysis. Separate samples are taken for hydrochemistry. For radiocarbon (and $\delta\ ^{13}C$) analysis, some 100 l of water is treated at the sampling point. The water is rendered alkaline and $BaCl_2$ solution is added. After some hours the bulk of the water is drained off leaving the $BaCO_3$ precipitate, which is the sample taken to the laboratory. All the usual wellhead observations (E.C., temperature, pH and alkalinity) are made. The general principle is to allow the pump to run for a time consistent with displacing at least one column of water in the borehole. This principle however cannot always be applied in practice, especially where lower yielding domestic wells are sampled. This may lead to differences in the isotopic and chemical characteristics of samples taken on different occasions. Such variability has been observed when boreholes have been resampled during this project (Section 7.4).

6.5 Approaches to the interpretation of environmental isotopes

6.5.1 The radioactive environmental isotopes

The radioactive decay law states that

$$N = N_0 \, e^{-\lambda t}$$

where N_0 is the original number and N is the final number respectively, of radioactive atoms; λ is the radioactive decay constant and *t* the time . This allows for the calculation of an "age" of ground water, on the assumption that the only change in the concentration of the radionuclide in question is due to radioactive decay. Thus ^{14}C values are often quoted, interpreted in terms of "age". This is a gross simplification in most cases, ignoring as it does the intrinsically dispersive nature of the ground water environment.

In this study, the environmental isotopes, both radioactive and stable, are regarded simply as isotopic tracers, and their measured isotopic ratios are quoted in the appropriate units. No corrections are made to ^{14}C values in terms of the accompanying $\delta\ ^{13}C$. Wherever possible, isotope values are interpreted in terms of an appropriate model in order to obtain time-dependent information. This can be done in various ways. A simplistic short-term "age" classification of ground water is based on the ^{3}H level in southern African precipitation, which reached a peak value of some 60 TU in 1965 and since declined to near-natural values (Figure 6.1). Ground water which at present contains 1 TU and less should therefore be "older" than 30 years. Any more recent addition of rain water containing bomb fallout tritium would have ensured a higher value at present, implying a shorter mean residence time.

In most cases, however, a more realistic approach to the behaviour of ground water has to be taken. All the ground water in the areas studied can be regarded as essentially phreatic. The exponential model is employed here. The model takes as its premise that the transit time from the point of entry of a volume element or molecule into the saturated zone to the point of observation is an exponential function of depth below the water table. This behaviour accords with the nature of karstic dolomite aquifers, such as at Midrand where the porosity and transmissivity will decrease rapidly with depth, and with phreatic aquifers in general.

Taking into consideration also that the input concentration of the isotope in question is variable with time, the exponential mixing model (Verhagen *et al.* 1991) gives the following expression for the concentration of the radioactive tracer:

$$C(t) = \frac{e^{-\lambda t_u}}{T} \int_0^\infty C_0(t - t_u - t')\, e^{(-\lambda + \frac{1}{T})t'} d't$$

where T is the mean residence time (MRT); C(t) is the isotopic concentration at the time of sampling; C_0 the input concentration; λ the decay constant , and t, t_u, and t' respectively the time of sampling, the delay time in the unsaturated zone, and the transit time of a ground water volume element.

The underlying assumption for this model is that uniform areal recharge takes place. The input concentration (C_0) of ^3H and ^{14}C has not been constant with time, but has been varying over the past three decades due to fallout from thermonuclear tests (e.g. tritium; Figure 6.1).

6.5.2 The stable environmental isotopes

In the interpretation of stable isotope values of ground water an important guiding relationship is the world meteoric water line (WMWL). This provides a framework for the comparison of the individual measurements as it is often not possible to assess the input values from various sources. A basic principle is that the stable isotopes are conservative tracers of ground water. Once the water is in the sub-surface and not subject to major changes in temperature, the isotopic signal will be retained even during considerable modifications in hydrochemistry. The stable isotopes are then used as "labels", allowing different parts of the ground water system to be compared and probable genetic relationships established.

6.6 Environmental isotope observations

In the following sections, the data obtained during the initial borehole survey of the Midrand area will be presented and discussed. This data forms part of the comprehensive listing contained in Appendix 4. Some of the isotope data obtained in subsequent detailed studies is presented separately in the appropriate sections.

6.6.1 Tritium

The areal distribution of tritium in ground water of the Olifantsfontein area is given in Figure 6.4. There is widespread presence of tritium at concentrations well above 1 TU. This would indicate that the dolomitic aquifer is subject to general diffuse recharge with more active recharge locally where tritium concentrations approach the mean value in present-day rain water, some 4-5 TU. The variability in tritium values does indicate that the process of recharge is complex and to classify individual recharge sources would entail a more comprehensive approach. As an initial guideline however, the use of tritium in this particular study has proved invaluable 1) in identifying that the aquifer is being actively recharged and therefore vulnerable to surface pollution and 2) identifying local areas of recharge. This of course is dependent upon the distribution and density of the survey points.

In some cases where a particular borehole was known to have penetrated to some considerable depth (>100 m; e.g. CC 24, CD 8), vanishing tritium concentrations are found. According to the exponential model (Section 6.6.3) for a mixed water column, this corresponds to a mean residence time of at least some hundreds of years, or possibly much greater. This is constrained by the corresponding ^{14}C values of about 50 pMC to a few thousand years, depending on the initial ^{14}C concentration.

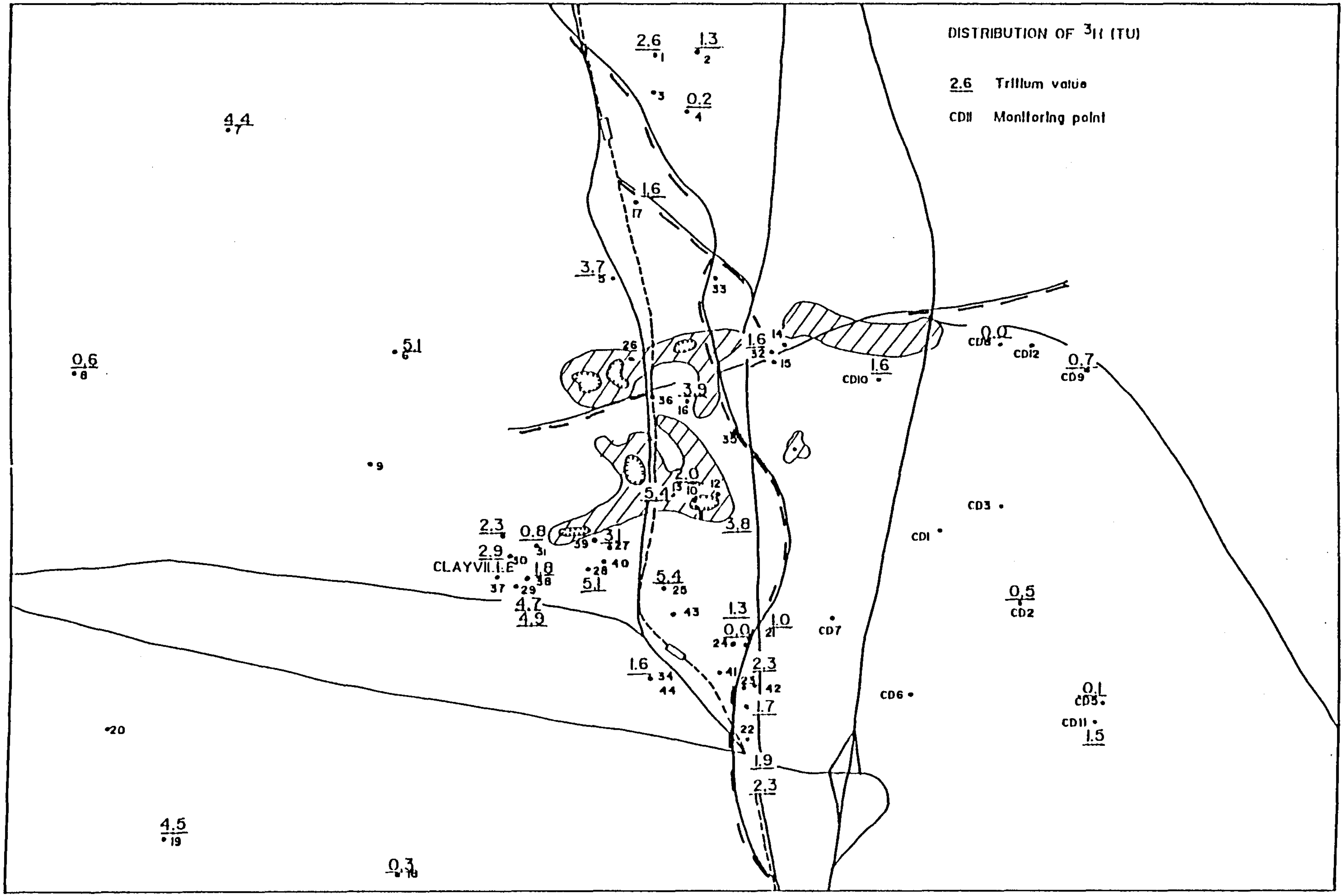


Figure 6.4 Distribution of ³H (TU)

6.6.2 Carbon-13

The measured values of $\delta\ ^{13}C$ for dolomitic ground water of the Midrand area are between -6.4‰ and -13.2‰. This range of values, somewhat high for mostly recently recharged ground water (Figure 6.3) may be ascribed to the fact that part of the development of the TDIC takes place in the saturated zone, resulting in closed-system dissolution of dolomite. The highly variable recharge conditions and hydrochemical pathways may be reflected by the fact that $\delta\ ^{13}C$ values show no clear correlation with geographic location, nor with ^{14}C, or with any of the other isotopic tracers.

6.6.3 Radiocarbon

The concentrations of ^{14}C in atmospheric CO_2 (Zuber, 1986) and ^{3}H in rain (IAEA, 1992; Verhagen, unpub. data) have been used as input data for the exponential mixing model and plotted in Figure 6.5. The curves give the expected relationship between the two isotopes for different mean residence times (indicated). Two curves are shown, representing the assumed extreme values in this environment of the initial (recharge) ^{14}C concentration in total dissolved inorganic carbon (TDIC) as 50% and 90% of the value in atmospheric CO_2.

A comparison of model predictions with the data points suggests that a variety of initial ^{14}C concentrations is established, depending on hydrogeological and hydrochemical conditions. These were much lower than expected from the simple exponential case. Most probably, part of the recharge takes place at relatively low alkalinity (channelled recharge), which introduces less ^{14}C in the observed alkalinity of the mixture than is expected to accompany the observed tritium value.

An additional factor is that individual wells may pump mixtures not only from levels with different residence times (the exponential model) but also from ground water components with widely different recharge histories. This model is given support by the relationship between the oxygen-18 and tritium values, plotted in Figure 6.6. A pronounced positive correlation is observed for the set of data. This can be interpreted as a mixture of a deeper, slower moving component (low ^{3}H and more negative $\delta^{18}O$) with a superimposed local recharge component. It might be that the older component is the rump of a now largely immobile ground water body, recharged under different recharge conditions, or that it constitutes a regional, deeper flow system with different conditions and environment of recharge, e.g. to the south (upstream) of the study area.

Tritium values collected from boreholes known to have penetrated to some considerable depth are very low, whereas ground water from much shallower depths has much higher values indicating it to be relatively younger. The same pattern is observed in the ^{14}C values.

Two domestic wells within 100 m of each other have very different ^{14}C values. One struck water >100 m below clay and had a value of 53 pMC, the other struck water below clay at

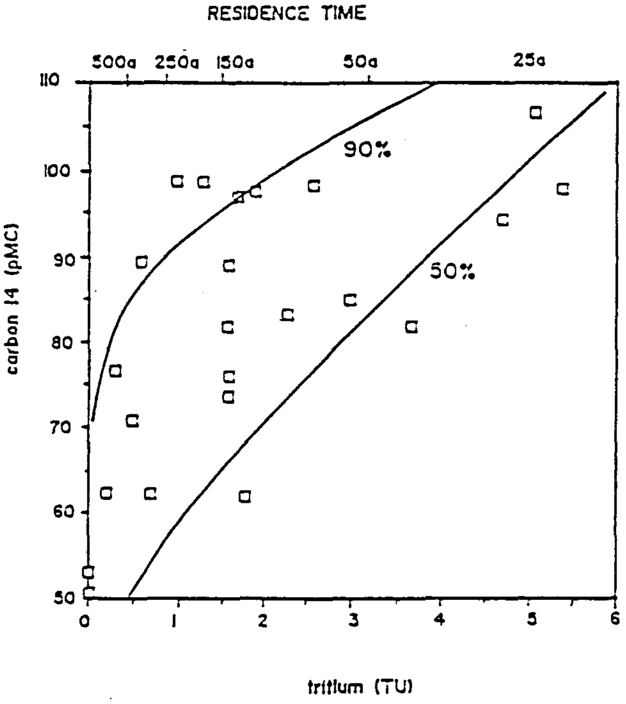


Figure 6.5 ^{14}C vs ^{3}H for all sample points. Exponential model plots for 90% and 50% initial ^{14}C concentration shown

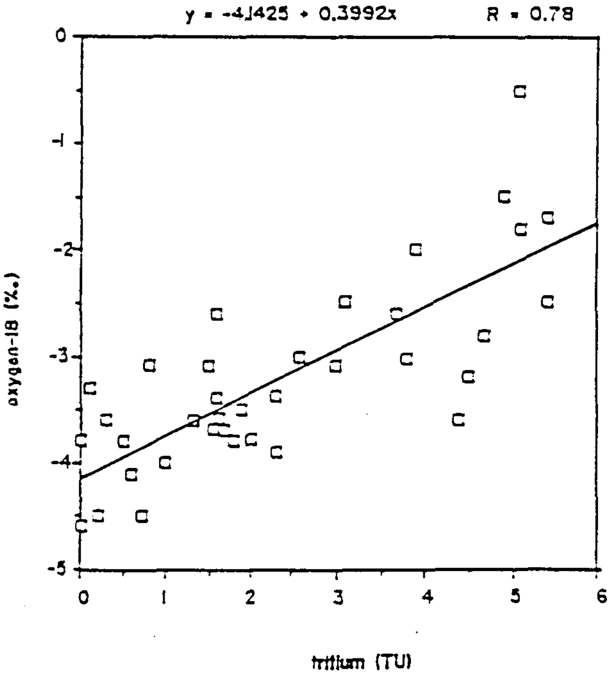


Figure 6.6 $\delta\ ^{18}O$ vs ^{3}H for all sampling points

60 m and had a value of 86 pMC. The aquifer is therefore highly heterogeneous. It can be stated in general that the differences in ^{14}C values suggest a rapid increase in turnover time - or decrease in water mobility - with depth, a common feature in dolomites. At + 100 m depth, a mean residence time (MRT) of some thousands of years is indicated; at 60 m some hundreds of years. Most of the flow appears to take place in the top 20 m or so of the saturated zone, the channels probably becoming less coherent with increasing depth. This is in accord with the nature of local karstification observed in quarries and in oral reports of standowners, or drilling experience.

In a number of cases repeat sampling was carried out which produce a certain degree of variability. This was also noticed in the accompanying $\delta^{18}O$ and general chemistry data. Whereas most results reproduced within statistical uncertainty, a number did reflect a mixture of components of distinctly different mean residence times, as was also suggested in the ^{14}C data. The mixing, and hence variability, is most probably caused by differing pumping schedules such as frequency and length. This is a very common problem when sampling private domestic boreholes (section 6.4), and has been further highlighted in this study (Section 7.4).

6.6.4 Oxygen-18 and deuterium

The considerable variability of $\delta^{18}O$ values over the study area is shown in Figure 6.7. Local characteristics are seen in a number of localities, such as at wells CD 8, CD 12 and CD 9, where the dolomite is partially covered by Pretoria Series rocks. Values of $\delta^{18}O > -2.0‰$ are observed only to the west of the Pretoria dyke. In general, $\delta^{18}O$ values seem to reflect the source of surface water contributing to local recharge, and the proportion of this contribution.

6.7 Oxygen-18 in Various Sources

The value of $\delta^{18}O$ in ground water in this environment is dependent on, i.a.:

a) The isotopic content of infiltrating rain water, taken to be represented by the long-term weighted average ($\delta^{18}O = -3.7‰$) for Pretoria (IAEA, 1992).

b) Surface conditions, which may change from time to time, i.e. surface water bodies, changing irrigation patterns etc., which can variously enrich $\delta^{18}O$ through evaporation.

c) The isotopic content of imported (mains) water, which can enter the sub-surface as mains leakage or waste water. This may be variable, but lies in a range around $\delta^{18}O = -0.5‰$.

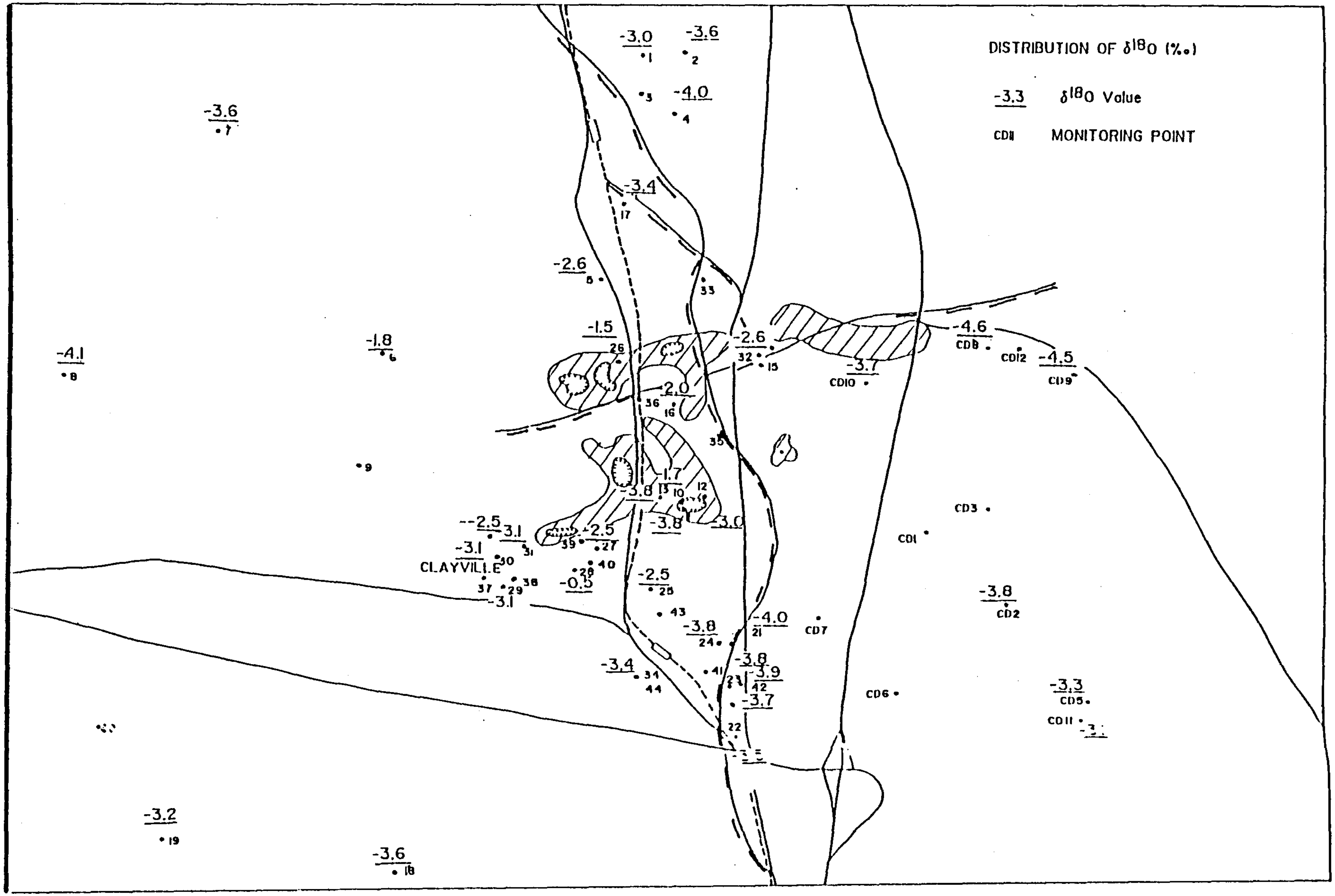


Figure 6.7 Distribution of δ ¹⁸O (‰)

6.8 $\delta^{18}O$ correlation with ^3H

Figure 6.6 shows a plot of $\delta^{18}O$ against tritium for all available data points. The correlation between the two sets is significant and shows that the isotopic character of the recharge producing the older ground water (lower ^3H) lies in a range which differs from at least one component of the more recent recharge. In spite of the considerable scatter, the results establish that in this environment, $\delta^{18}O$ is diagnostic of local recharge in a way similar to ^3H.

6.9 $\delta^{18}O$ correlation with ^{14}C

As ^3H labels the water molecule, it is a direct tracer of water. Carbon-14 however, labels the TDIC (total dissolved inorganic carbon), which in this environment is essentially represented by the variable alkalinity. Rather than the isotopic ratio in TDIC, which can be interpreted i.t.o. residence time, ^{14}C could be used, in analogy to ^3H, to assess the amount of water which enters the ground. To achieve this, the ratio (as pMC) is multiplied by the alkalinity, the resulting product being related to the concentration of ^{14}C in water. Correlations of this product show that the group of sampling points to the south-east of the Pretoria dyke are anomalous. This high ^{14}C, low ^3H and $\delta^{18}O$, high alkalinity ground water constitutes a special case and might represent an area of ground water upwelling, controlled by the dyke, a feature which could be investigated more fully. These four values, and the value for the Sterkfontein spring (CC 32), which as a probable outlet for the entire system is a mixture, are excluded from the following plots.

Figure 6.8 shows a clear correlation of ^{14}C (in pMC) with $\delta^{18}O$ for the remaining points. When (^{14}C alkalinity) is plotted against $\delta^{18}O$ (Figure 6.9) an improved correlation is obtained. Radiocarbon used in this mode becomes an analogue for other solutes in recharge and confirms the conclusions from the ^3H data that $\delta^{18}O$ is diagnostic of local recharge.

6.10 δD correlation with $\delta^{18}O$

The significant range of $\delta^{18}O$ values, as well as a recognition of their possible association, indicated the need for deuterium data. The presence of numerous open water bodies in the study area raised the question whether evaporation is a significant factor in establishing this range.

The results expressed as δD (*‰*) w.r.t. SMOW have been plotted on a conventional δD - $\delta^{18}O$ diagram in Figure 6.10. A linear regression line $\delta D = 7.5\ \delta^{18}O + 6.3$ gives a correlation coefficient of $r = 0.88$. In spite of the overall goodness of fit, the data points scatter considerably. The world meteoric water line (WMWL; $\delta D = 8\ \delta^{18}O + 10$) is shown for comparison. Also shown are individual annual weighted mean values, the long term weighted mean value (IAEA 1992) for Pretoria rain, as well as the range of values for several samples of Clayville (Rand Water) mains. As a number of results were isotopically heavier than the weighted mean in rain, mains water was taken to be an important end member for mixing associated with pollution.

The following interpretation is attempted:

a) The best fit regression line for ground water ($\delta D = 7.5\ \delta^{18}O + 6.3$) can be regarded as both a local meteoric water line and a ground water mixing line. The ground water values overlap with the field of mean annual rain values for Pretoria. Many of the ground water values are however isotopically much lighter than the long-term weighted mean for rain. As was shown above, these values largely coincide with lower ^3H and ^{14}C values and therefore represent the slower-moving deep ground water component.

b) The line is compatible with the interpretation given for the range of $\delta^{18}O$ values. The principal mixing mode is between three end members:

   i) The mean for local precipitation (taken to be approximated by the weighted mean for Pretoria rain ($\delta D \approx -17‰$; $\delta^{18}O \approx -3.7‰$)

   ii) Imported Rand Water mains ($\delta D \approx +6‰$; $\delta^{18}O \approx -0.5‰$). This could include specific waste water sources such as effluent dams and canals.

   iii) The older and deeper, isotopically lighter, ground water component.

c) The scatter of the data points is ascribed partially to lesser and variable degrees of surface evaporation at different recharge sites, each with its own local characteristics, producing a measure of isotope enrichment along evaporation lines with a slope lower than the WMWL. In this way, many points are displaced somewhat to the right of the WMWL.

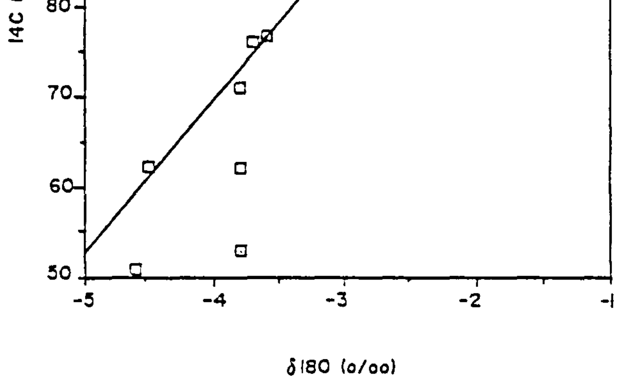


Figure 6.8 ^{14}C vs $\delta\ ^{18}O$ for appropriate sampling points

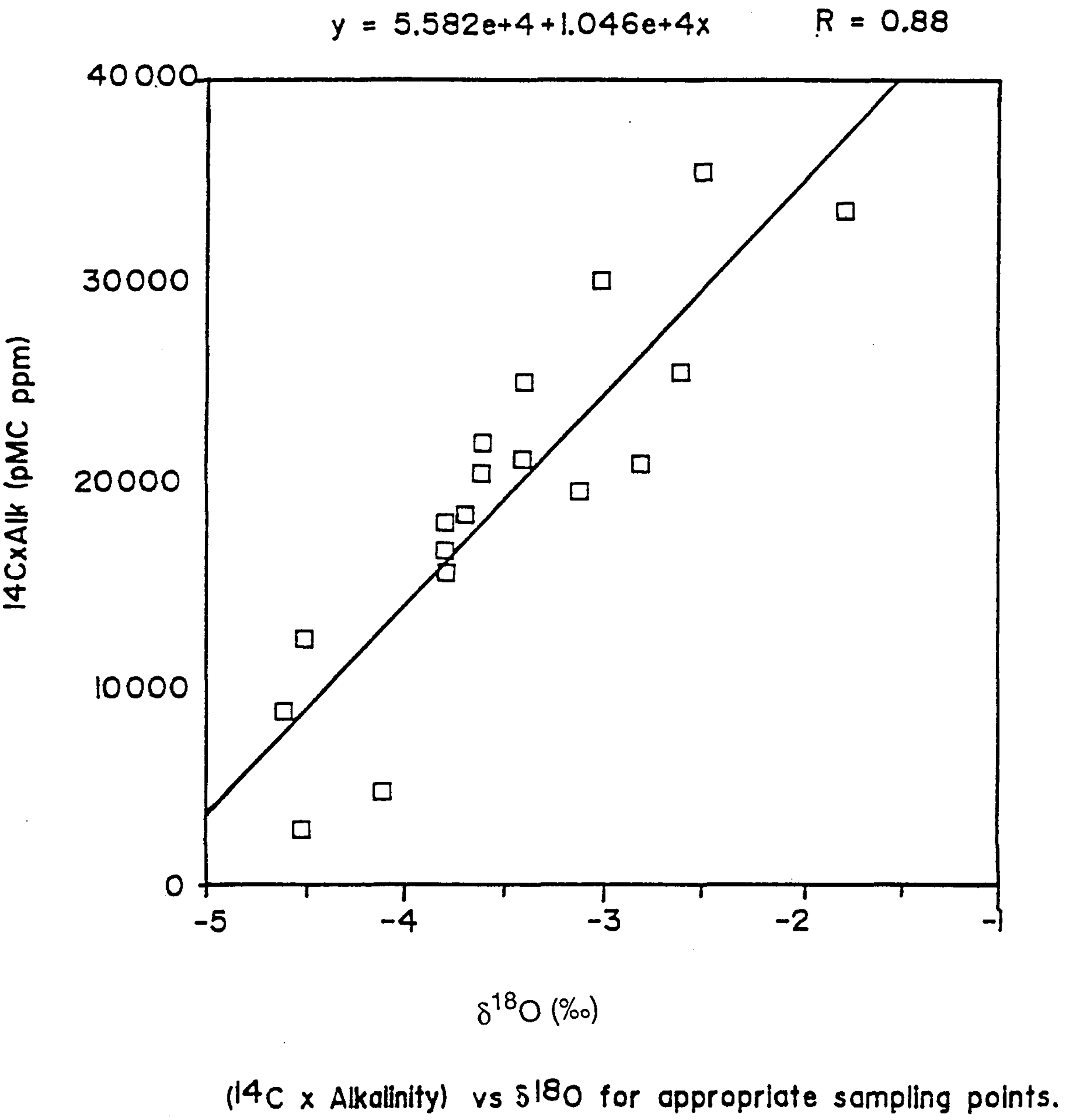


Figure 6.9 (^{14}C x Alkalinity) vs δ ^{18}O for appropriate sampling points

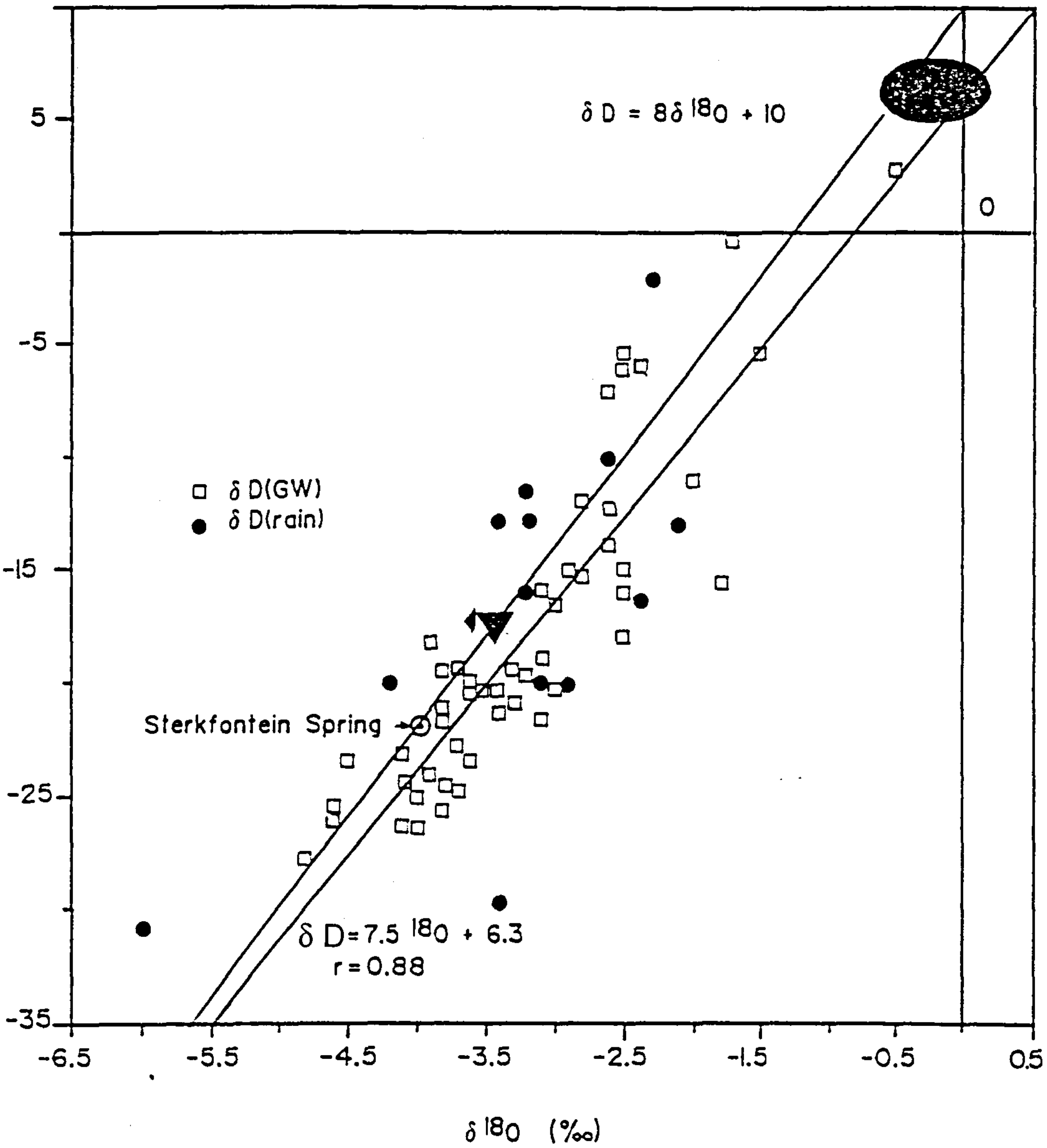


Figure 6.10 δD - δ ^{18}O diagram for: □: All ground water samples. ▼: Weighted mean for long-term Pretoria rain. ●: Approx value for mains water. ●: Weighted means for individual rainfall years - Pretoria

7 HYDROGEOCHEMISTRY OF THE OLIFANTSFONTEIN AND RIETVLEI AREAS

7.1 Fieldwork and sampling

Initial ground water sampling took place during May 1990. Resampling of 19 selected boreholes in both the study and control area took place in 1992. Sampling of the project related holes took place after each phase of drilling. A total of 51 ground water samples were collected plus two surface water samples. An additional eight ground water samples were collected in the control area.

Temperature, electrical conductivity, pH and total alkalinity were measured at the well-head.

7.2 Ground water characteristics of the Rietvlei area

A Piper diagram is a graphic representation of a ground water's major ion characteristics defined by the relative percentages of the major cations and anions. Figure 7.1 is a Piper plot of ground water chemistry found within the control area. The position in the "diamond" field is typical of ground water associated with dolomitic aquifers. RTV 6II has a lower percentage HCO_3 value in relation to the other anions SO_4 and Cl, moved this sample to a position outside the regional norm and is classified as an outlier.

Polluted borehole RTV2 with high nitrate and sulphate values, gives a ^{14}C value of 100 pMC, indicating rapid turnover (MRT (mean residence time) < 20 years). In addition, this is the only case in the control area where a δD value > -20‰ has been observed. This pollution is therefore derived from surface sources, which may be threatening other ground water occurrences in this area. On the other hand, the remaining deuterium values suggest that such pollution is unlikely to reach the ground water elsewhere given present surface drainage conditions.

7.3 Ground water characteristics of the Olifantsfontein area

Dot maps showing the areal distribution of major cations and anions are given in Figures 7.2 to 7.6. Higher concentrations of SO_4 and Cl are found on the western side of the Pretoria dyke, the industrial and residential areas of the town of Clayville.

Higher alkalinity values appear to be associated with the Pretoria dyke (Figure 7.2). High ^{14}C values in the southern region east of the dyke are associated with fairly low ^{3}H values. This together with high alkalinity values suggests a upwelling system blocked by the barrier constituted by the dyke (cf. Section 6.9).

Point source pollution is indicated by locally high values totally out of context with the general areal distribution pattern. The highest concentration of polluting sulphates and chlorides within dolomitic water is found in the immediate vicinity of the waste disposal

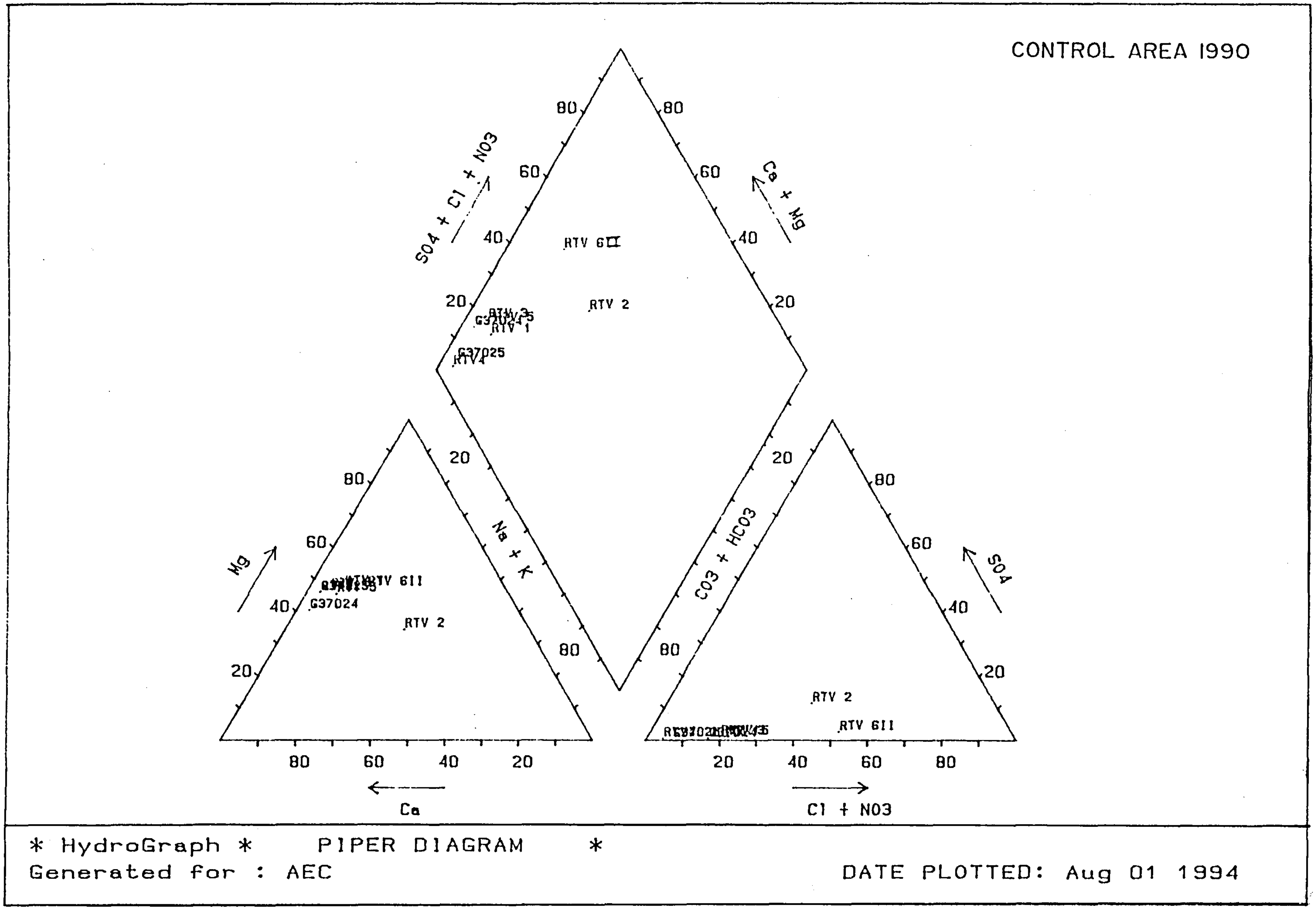


Figure 7.1 **Piper diagram - Control area 1990**

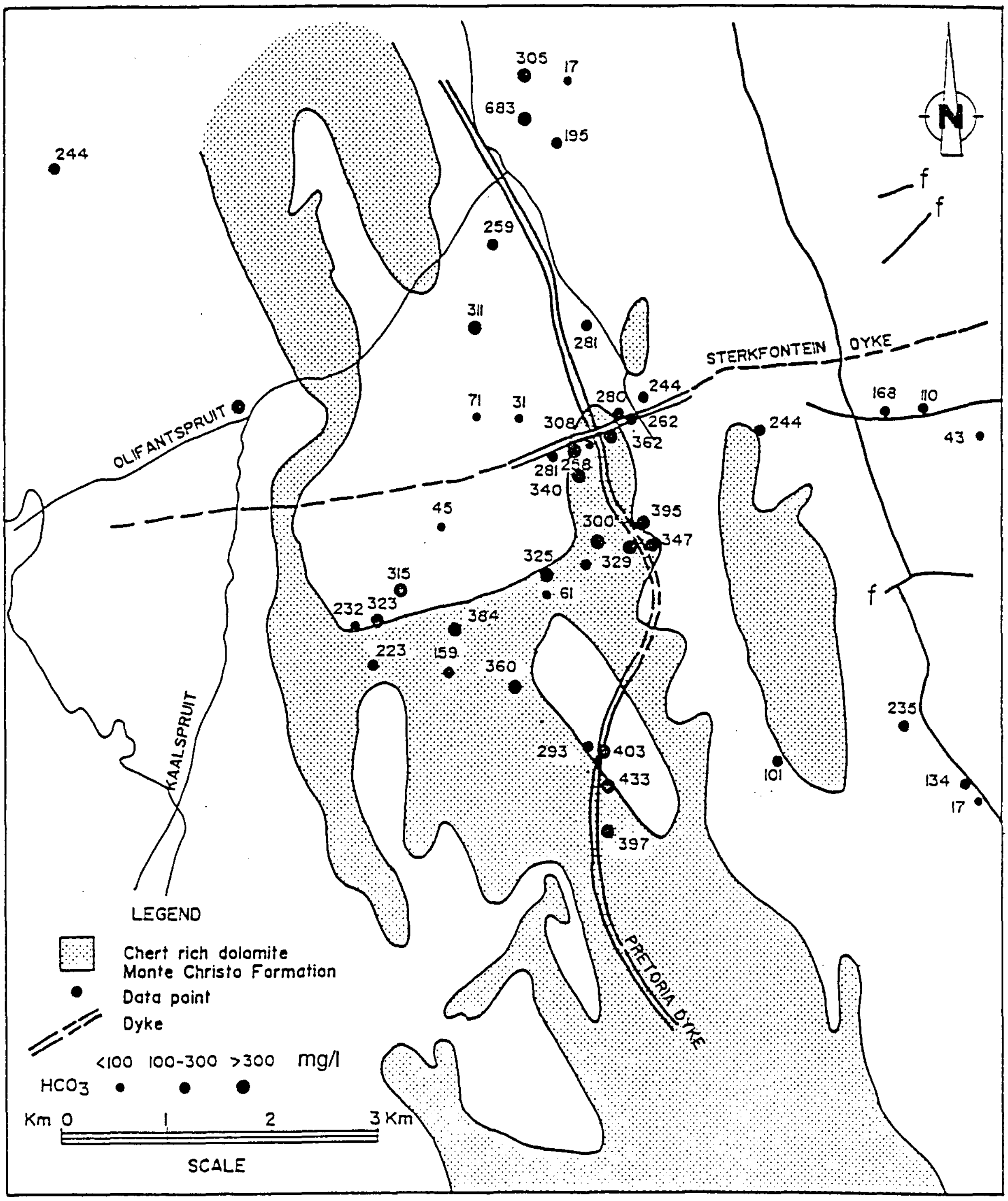


Figure 7.2 HCO_3 values 1990 - 1994 (mg/ℓ)

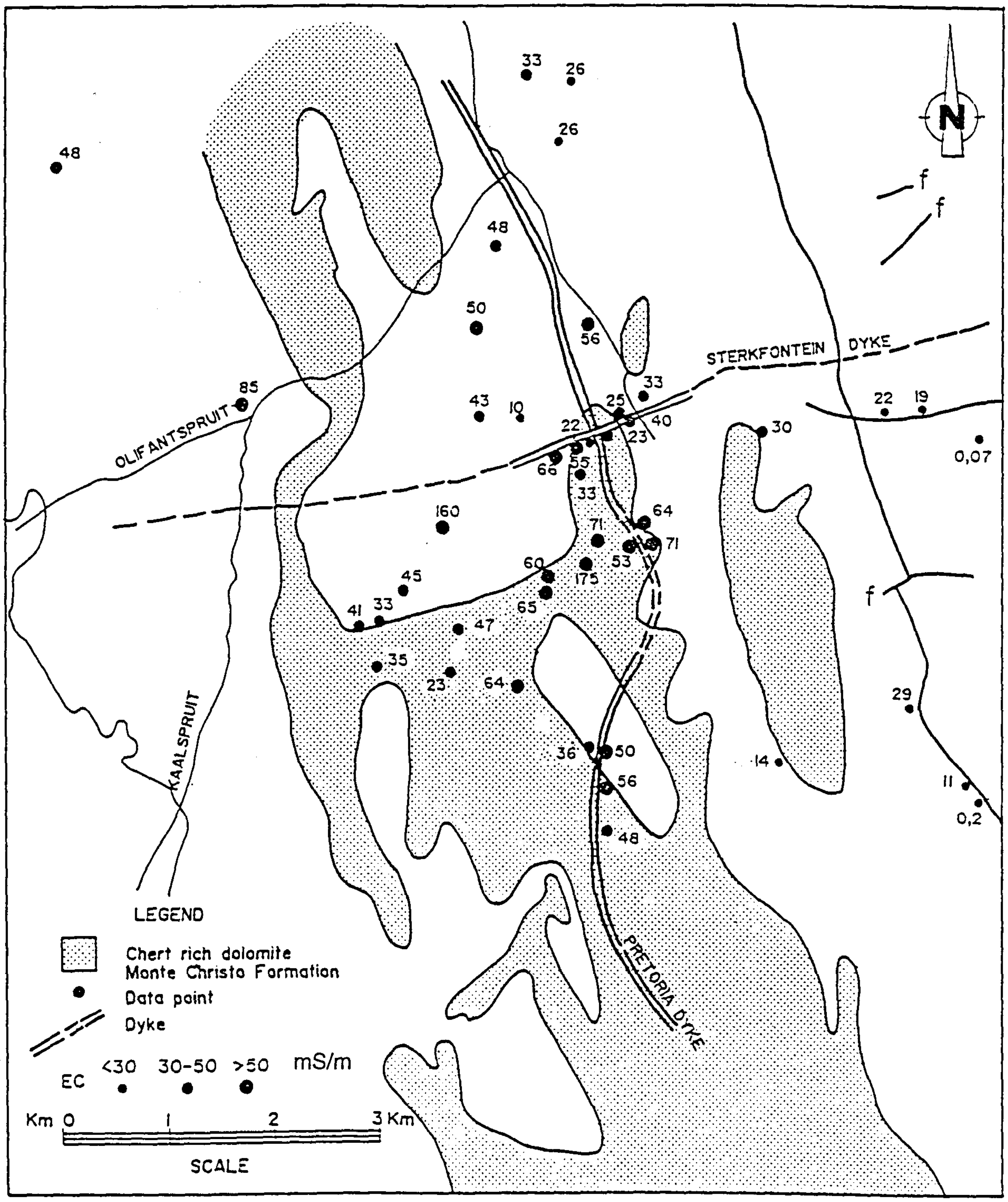


Figure 7.3 E C values 1990 - 1994 (mS/m)

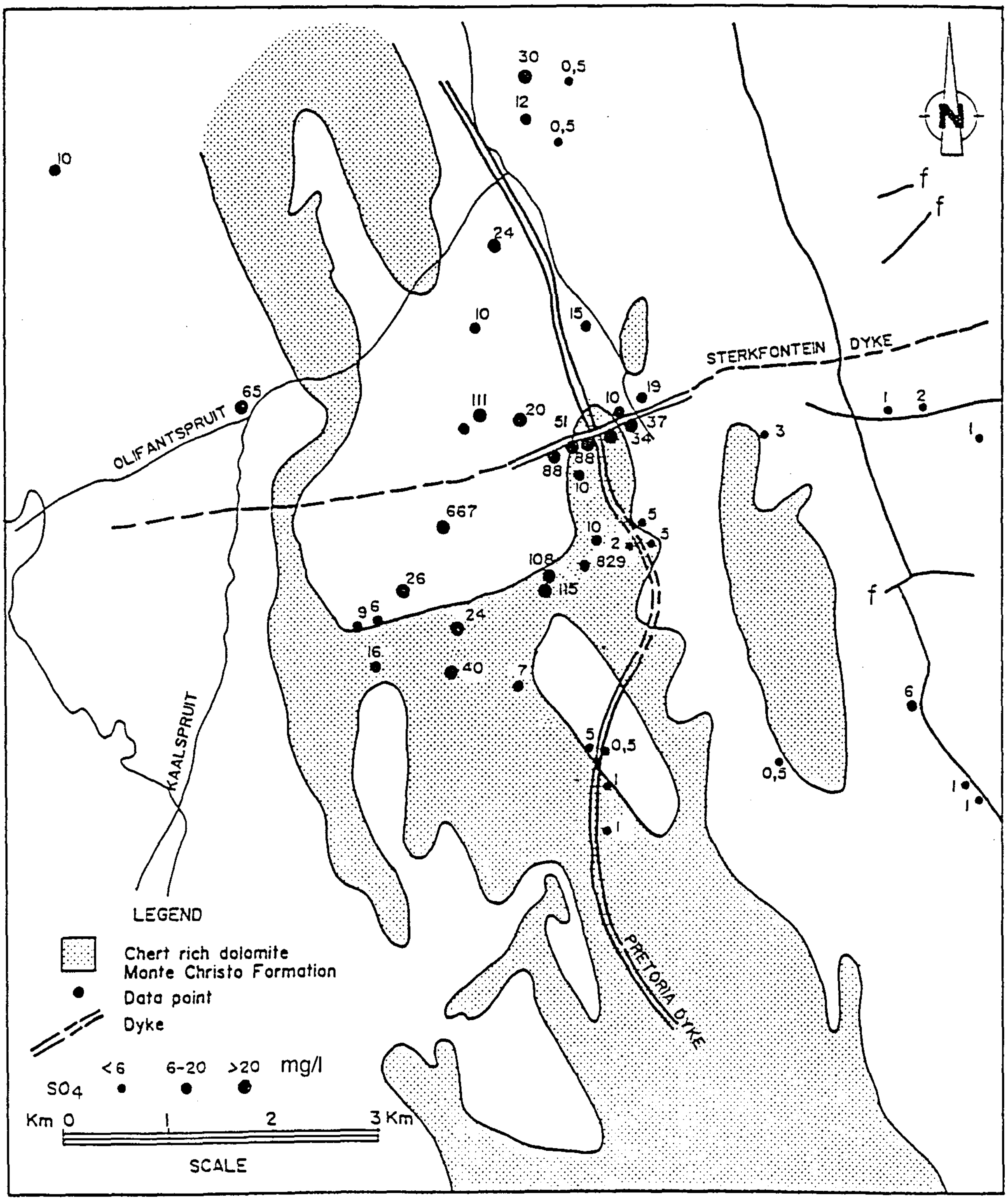


Figure 7.4 SO_4 values 1990 - 1994 (mg/ℓ)

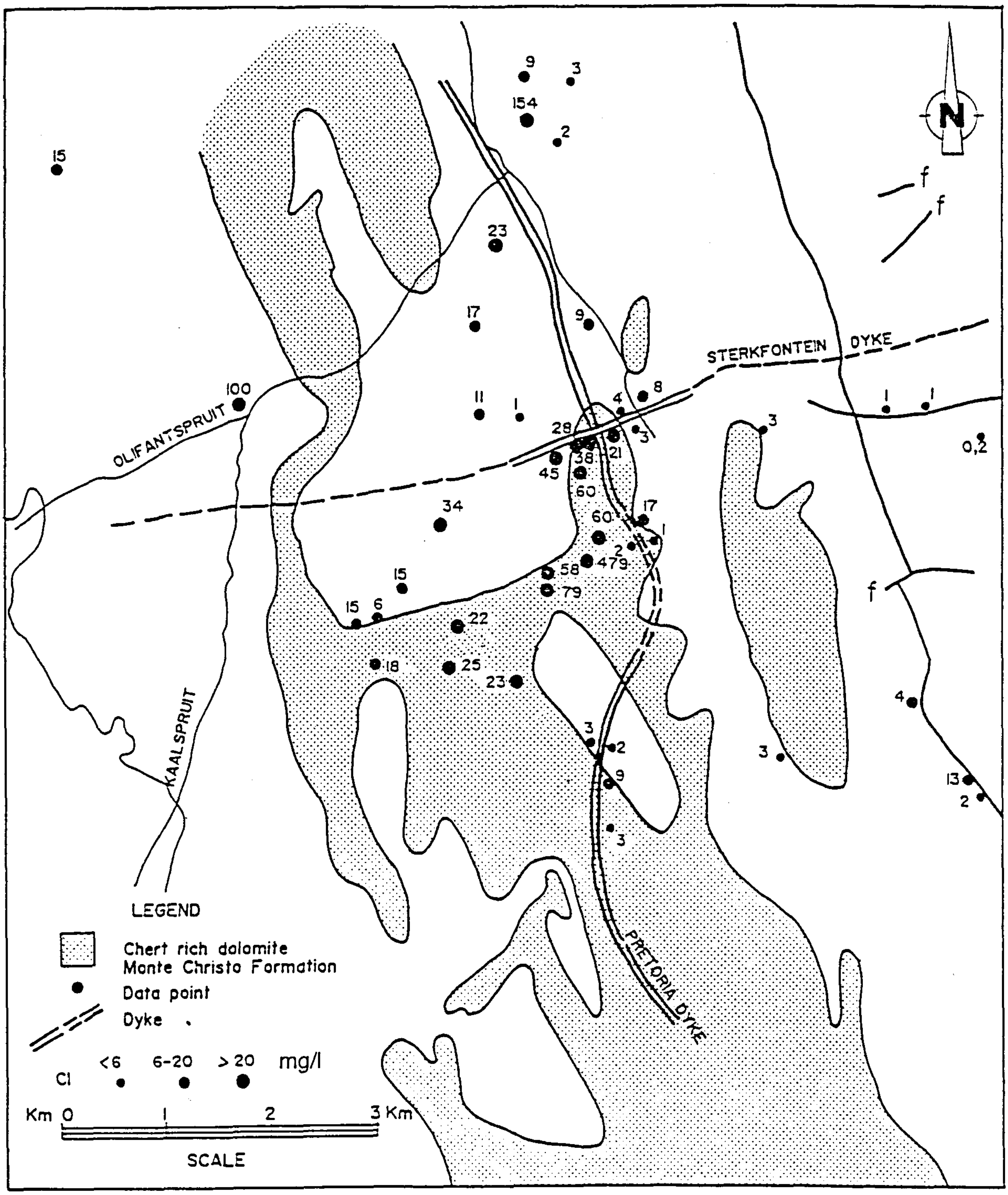


Figure 7.5 Cl values 1990 - 1994 (mg/ℓ)

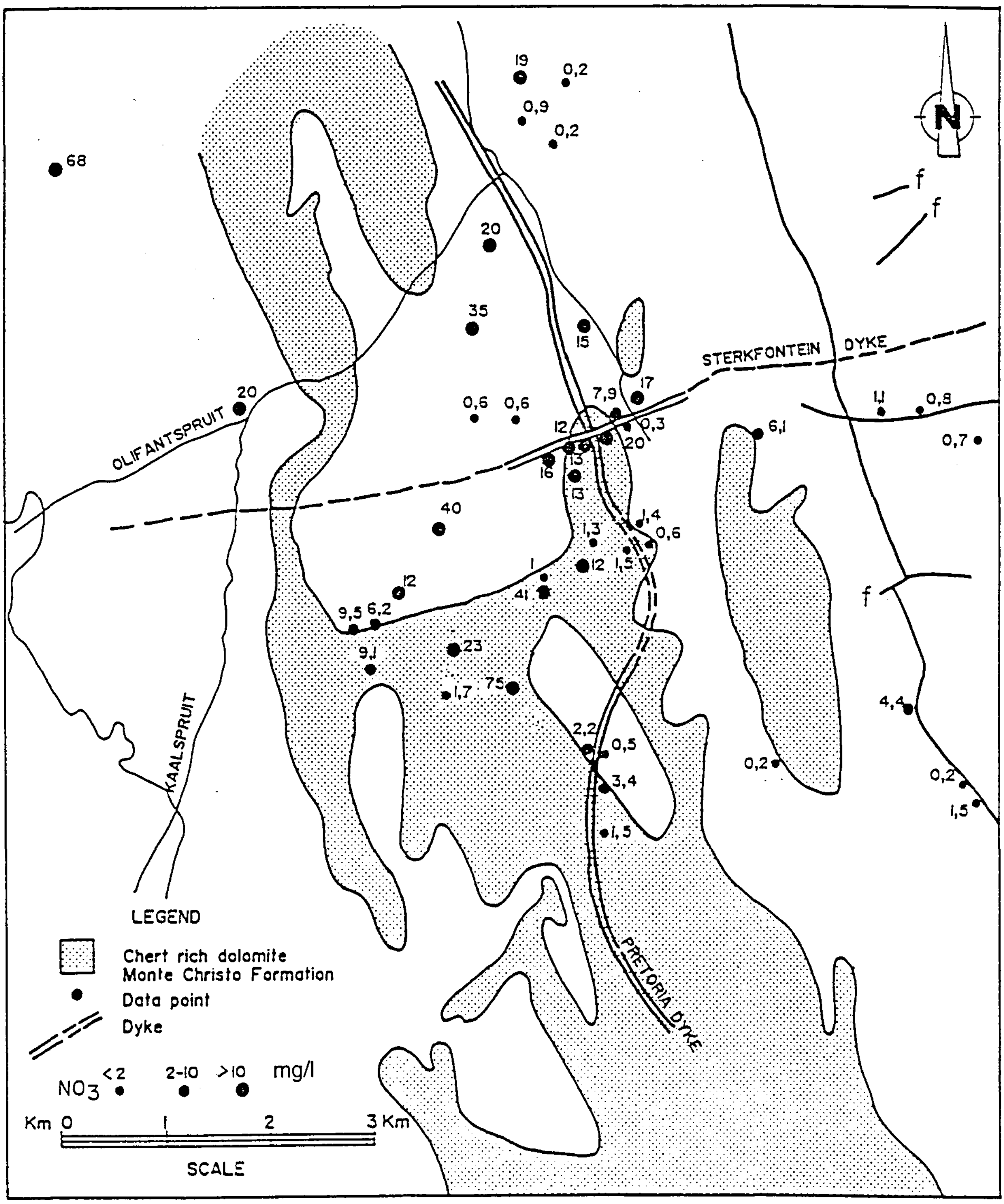


Figure 7.6 NO_3 values 1990 - 1994 (mg/ℓ)

facility. The areal extent of the high concentration is difficult to assess due to the lack of sampling points.

The extremely elevated values of all ions in boreholes CC 46 and CC 11 in fact represent only the standing water in the boreholes. CC 46 had not been in operation for over a year and during sampling was not pumped long enough to be considered a representative sample. CC 11 was one of the monitoring holes around the waste disposal facility. This borehole had collapsed just below the water table, allowing only a small amount of stagnant water to be removed from the borehole. This water could have entered the borehole from surface, or represents residual water sitting in the borehole after its collapse. These areas could be highlighted as point source pollution if the inadequacies of their sampling were not known. Care should therefore be taken in such surveys in regard to consistent sampling technique.

Figure 7.7 shows the characteristics of the ground water within the dolomitic formation in the Clayville area. Approximately 50% of the analyses are similarly located on the Piper diagram as for the control area and can be considered relatively pure dolomitic water. The remaining 50% have migrated into the upper section of the diamond field, indicating a relatively higher proportion of SO_4 and Cl or NO_3 as opposed to the normal dominant HCO_3 cation. Figures 7.8 and 7.9 respectively show the position of ground water samples associated with the dolomitic and Karoo formations and Karoo Formation only. These samples are also located further into the upper section of the diamond field. The shift of the dolomitic water could then be attributed to mixing with the ground water associated with the overlying Karoo Formation. The alternative reason for the ionic shift, is the introduction of pollutants into the ground water regime via point or diffuse source pollution associated with general urban development, including urban water supply and sanitation, industrialisation past and present, waste disposal and intensive crop cultivation. In order to investigate these alternatives, environmental isotopes were incorporated into this aspect of the investigation.

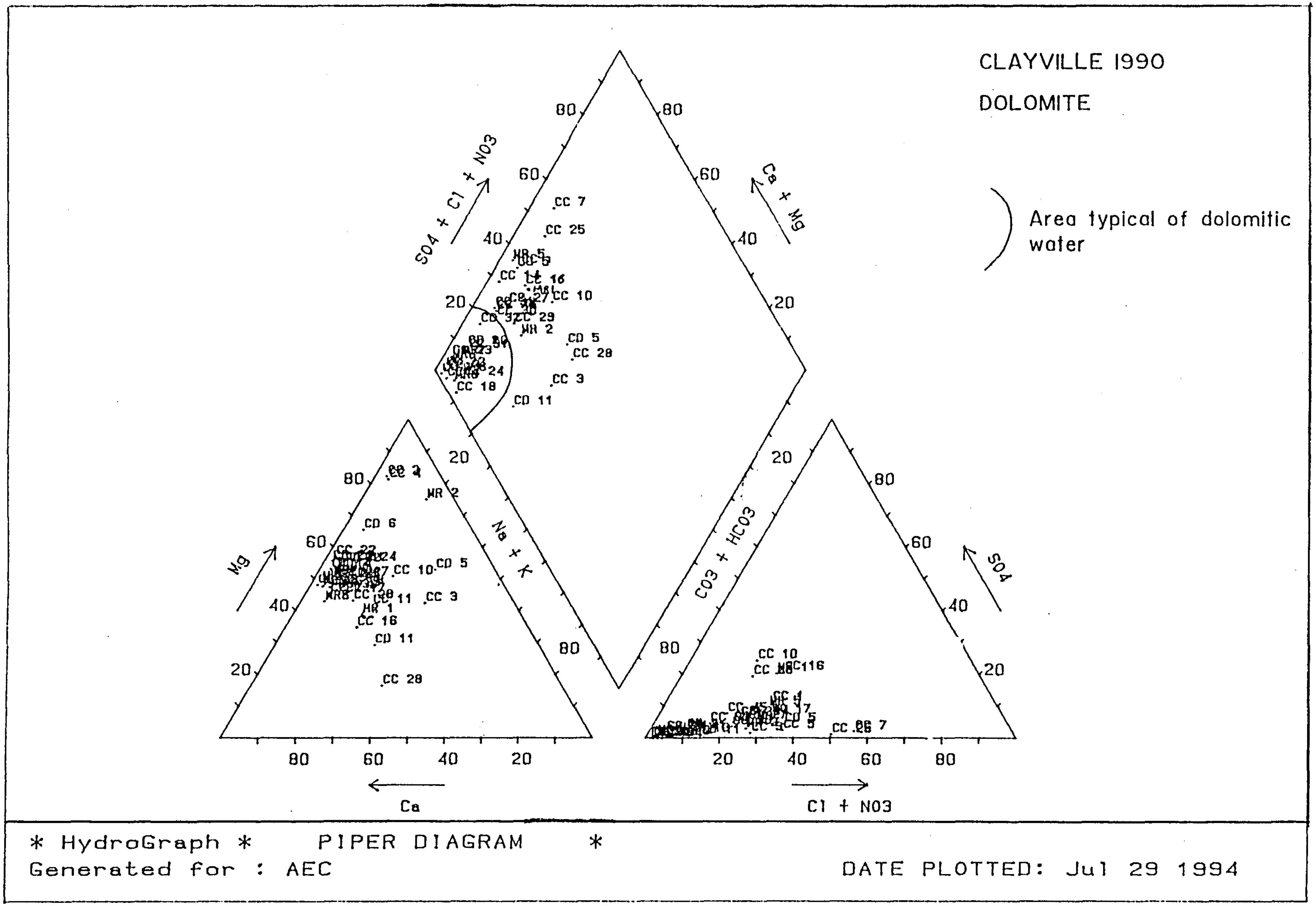


Figure 7.7 **Piper diagram - Clayville 1990 - Dolomite**

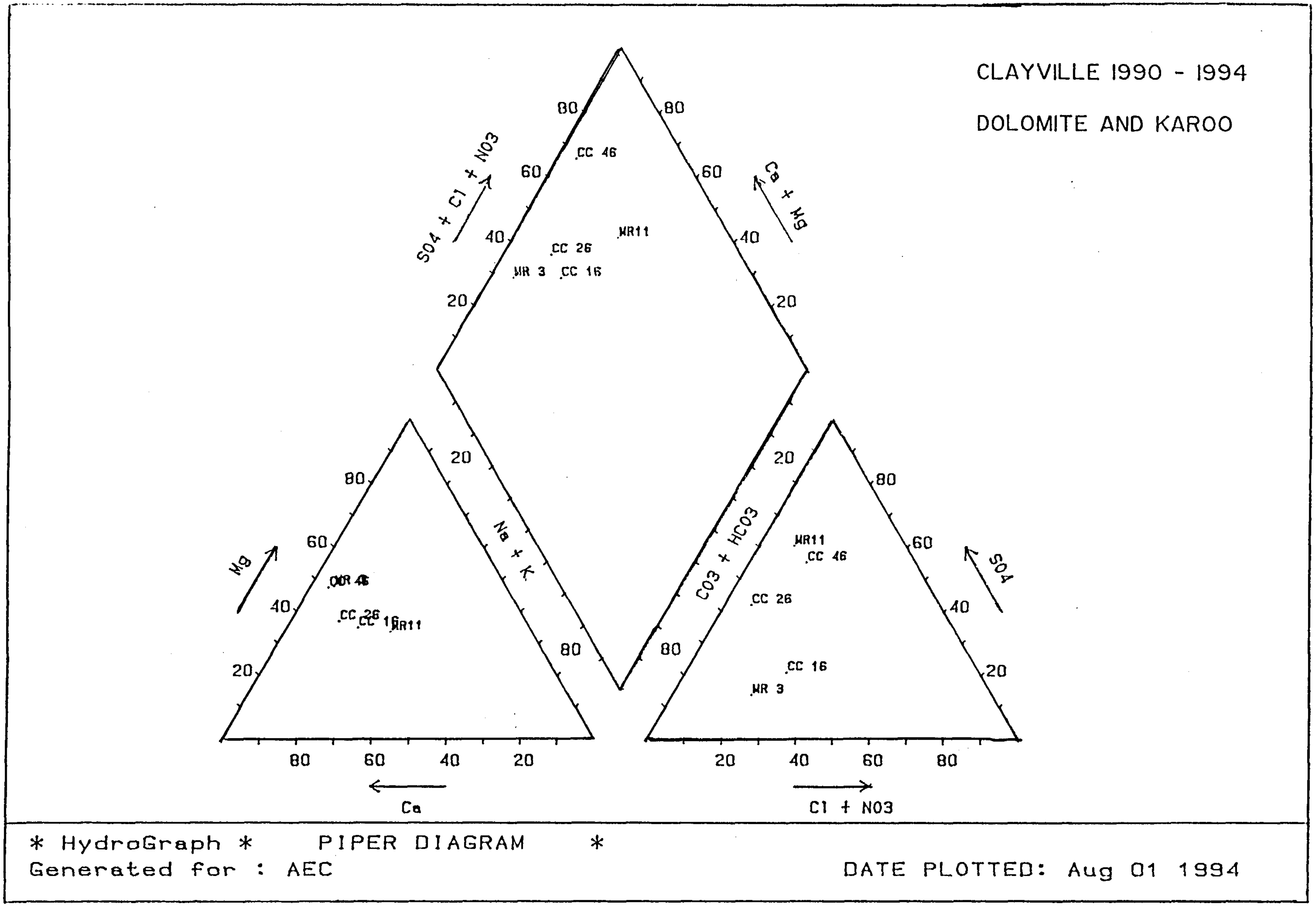


Figure 7.8 Piper diagram Clayville 1990 - 1994 - Dolomite and Karoo

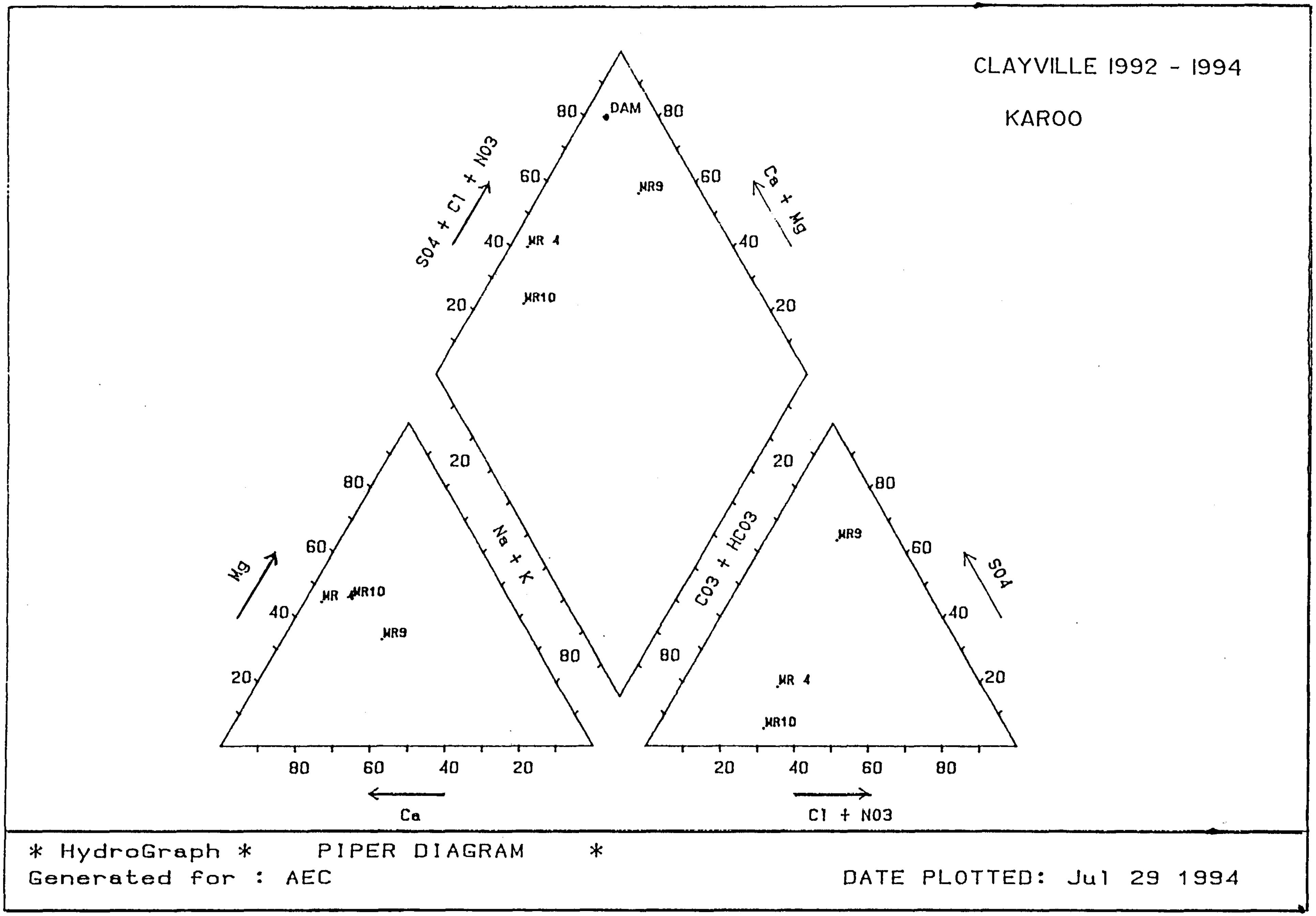


Figure 7.9 Piper diagram - Clayville 1992 - 1994 - Karoo

7.4 Temporal Variation in Water Quality

Resampling has indicated that generally, change in ground water quality has been insignificant both in the control and Clayville area over the duration of the project. However it has highlighted in fact that local point source pollution does occur and enters the ground water system rapidly. This clearly indicates the vulnerability of the aquifer to pollution. Figure 7.10 shows the selected boreholes that were resampled at Clayville. Only four have shown significant change, two of which associated with waste disposal facilities show a marked deterioration. CC 2 is located in a valley down-gradient from an old waste dump located directly on dolomitic formation. Over a two year period it has shown a marked increase in nearly all constituents with the exception of fluoride. A cement processing factory is located near the borehole and may be a contributing factor. CC 10 was located just to the west of a waste disposal facility within an old mined out Karoo outlier (Figure 2a). Again the ground water quality has significantly deteriorated with a marked increase in all major cations and anions with the exception of Ca and Mg. The Piper and Schoeller diagrams in Figures 7.11 to 7.14 show the changes in chemical characteristics of the ground water.

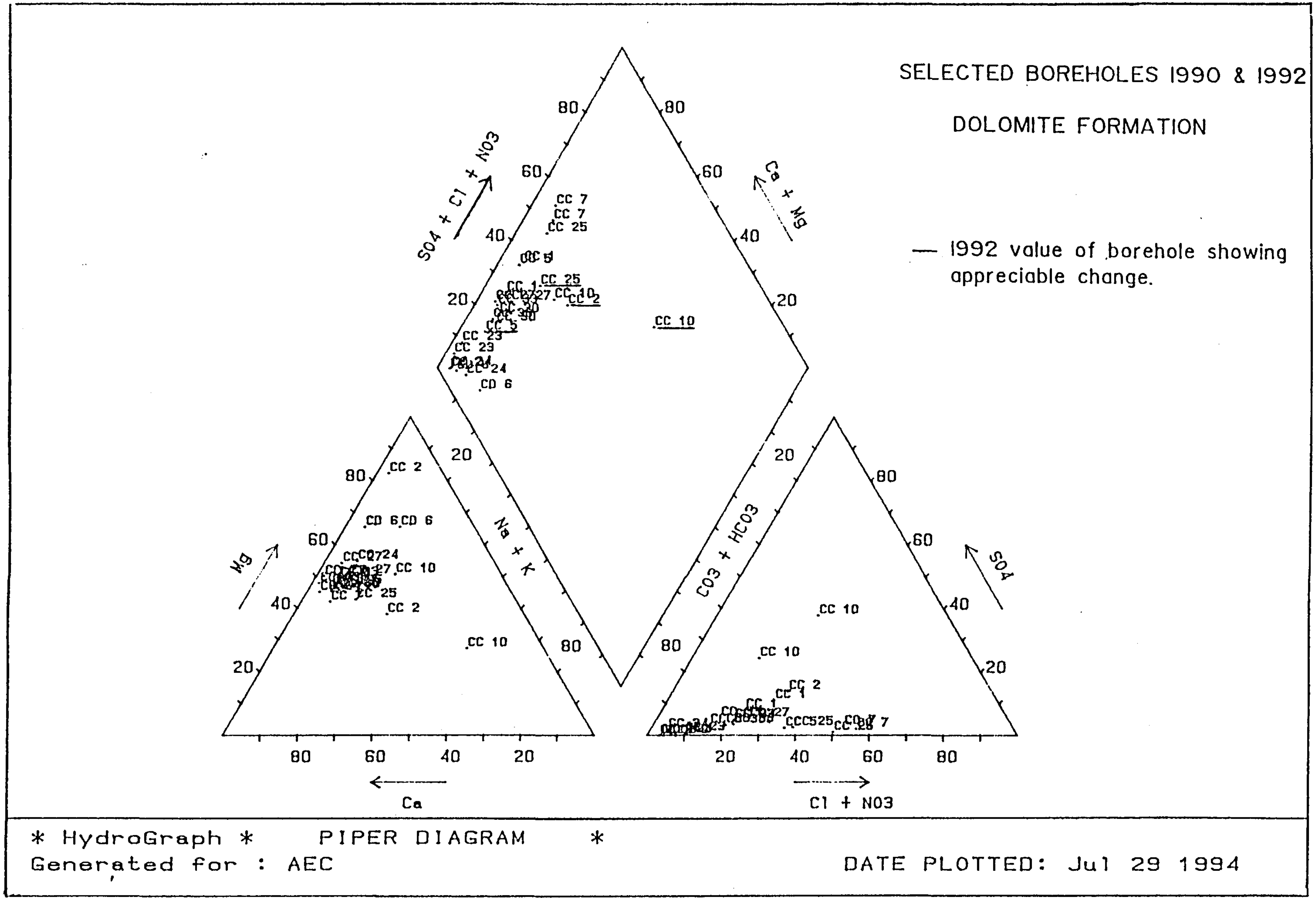


Figure 7.10 Piper diagram - selected boreholes 1990 - 1992 - Dolomite

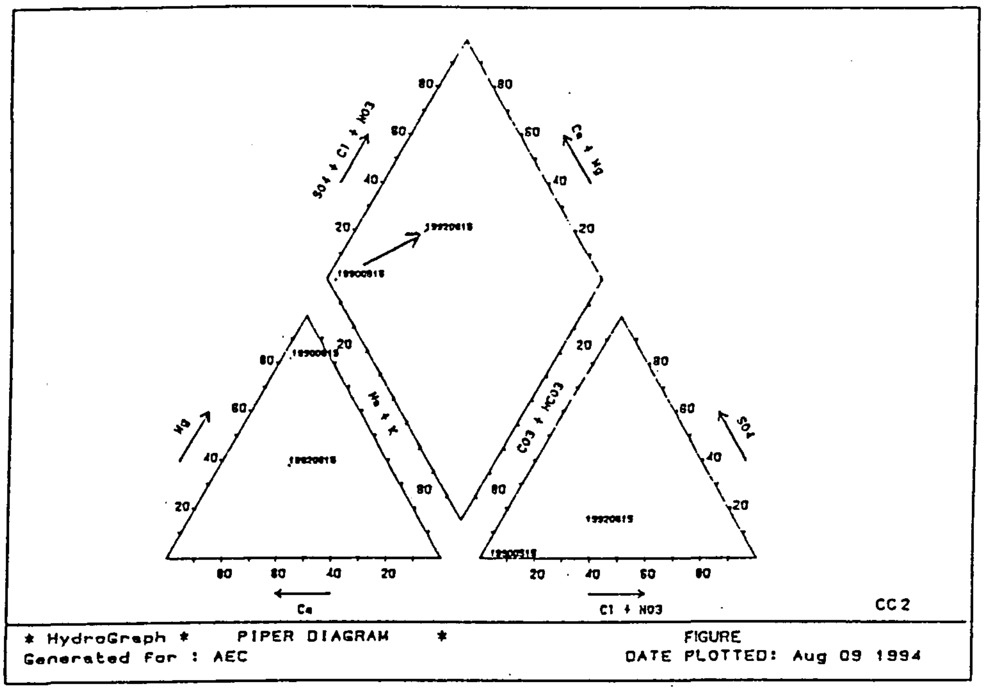


Figure 7.11 Piper diagram - CC 2 1992

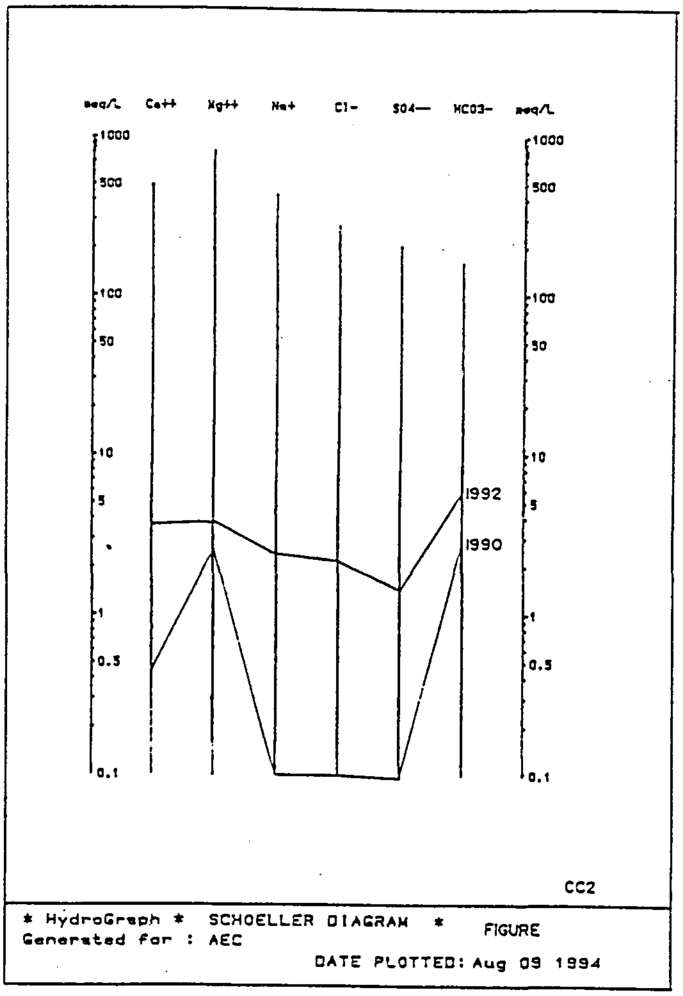


Figure 7.12 Schoeller diagram - CC 2 1992

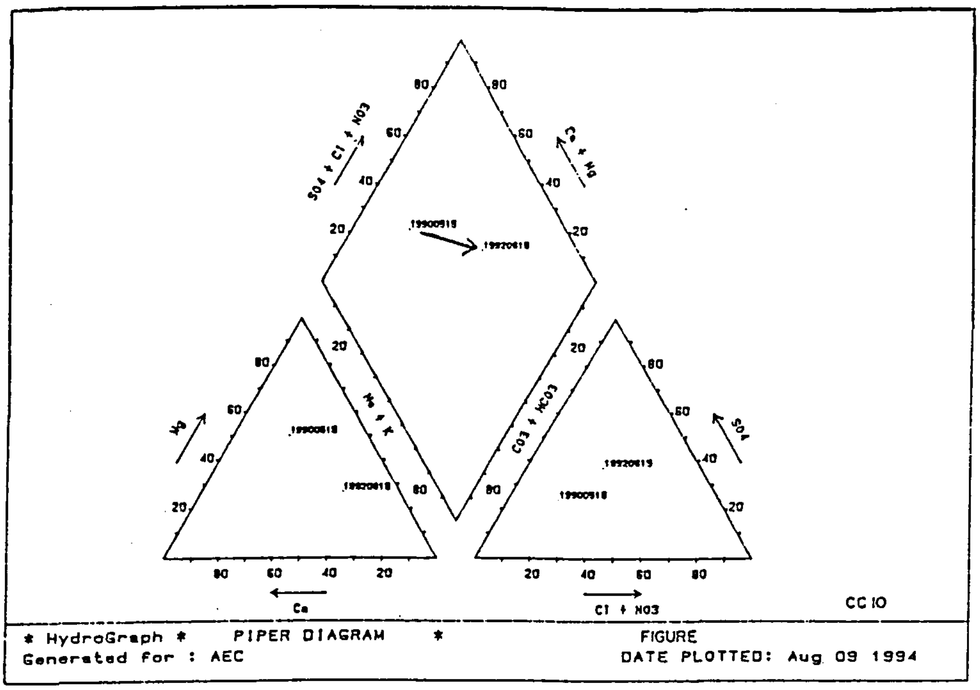


Figure 7.13 Piper diagram - CC 10 1992

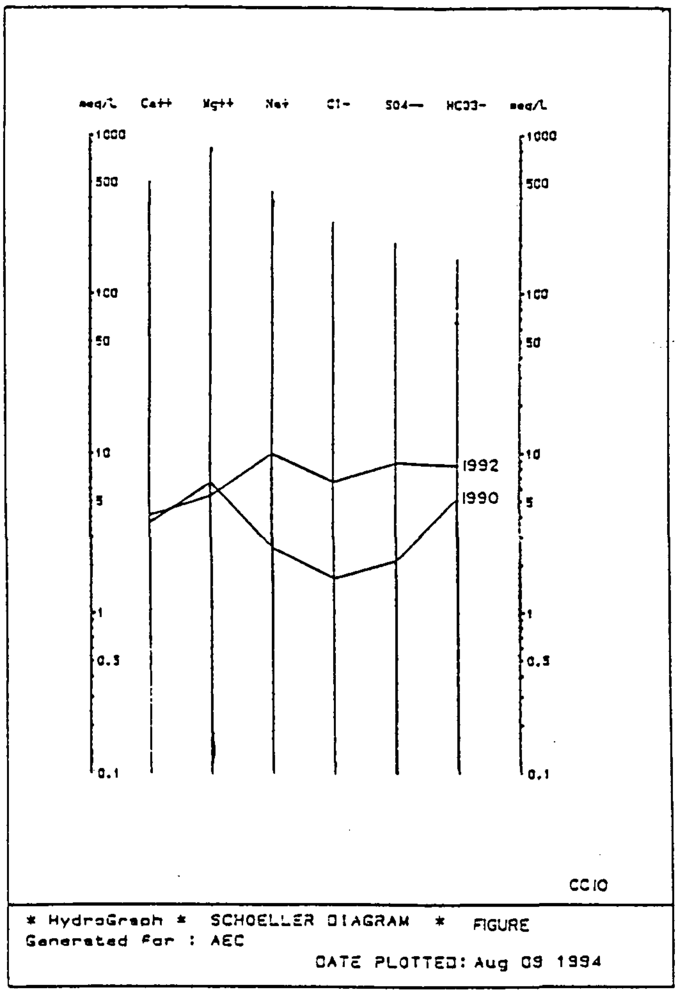


Figure 7.14 Schoeller diagram - CC 10 1992

8 WATER QUALITY ASSESSMENT USING ENVIRONMENTAL ISOTOPES

The earliest industrial activity in the Olifantsfontein area has been brickmaking, involving the quarrying of clay. Carbonaceous material in the clay contains pyrite which, when oxidised on exposure to the atmosphere, produces sulphate. Open water standing in these quarries would have been subject to kinetic evaporation, resulting in the water assuming a stable isotopic composition lying on an evaporation line (Section 6.3.1). A possible early source of pollution could have been characterised by its sulphate dominance, associated with an evaporative stable isotope signal. As was discussed in Section 6.10, no *significant* evaporation isotope signal was encountered in any of the dolomite ground water occurrences sampled during the borehole survey, or subsequently in this project. Therefore, significant SO_4 at present observed in ground water was probably not introduced via standing water bodies in the old clay quarries. Any subsequent leachate formation from landfill sites is not expected to carry a distinctive isotope signal, as the mobilising liquid would probably be rain infiltration without evaporative modification. Other processes connected with this, and subsequent industrial and domestic development, might be responsible for sulphate, and any other pollutants in the dolomitic ground water.

In the original borehole survey, environmental isotope measurements and hydrochemical analyses were undertaken to establish a baseline for the area against which pollution from the waste disposal site could be investigated (Section 7.3). It was not expected to obtain much additional information about regional water characteristics, or the state of general pollution in the Clayville area. In the event, isotope correlations with major ions provided clues as to how pollutants are at present entering the ground water system. This approach shows great potential in similar studies, especially when ongoing pollution is suspected.

Having established the basis for environmental isotopic tracing in this environment (Sections 6.8 and 6.9), the major anions in ground water (SO_4, Cl, NO_3), taken to be proxy ions of pollution, were plotted against both ^3H and $\delta^{18}O$ (Figures 8.1 to 8.6).

8.1 Isotopic correlations with sulphate

High SO_4 concentrations (>10 mg/l) are all associated with ^3H values >1.5 TU (Figure 8.1), i.e. recent recharge. As all the borehole survey observation points for which data were available have been plotted, it is clear that all recharge sources introduce significant SO_4 into the ground water. Water with higher residence time (underflow; $\leq$ 1 TU) contains <10 mg/l SO_4. When sulphate is plotted against $\delta^{18}O$ (Figure 8.2) higher values ($\geq$10mg/l) are seen to lie in the range between the limits of mains water and the weighted mean in rain, ($\delta^{18}O \sim$ - 3,5‰).

8.2 Isotopic correlations with chloride

A very similar distribution is seen for chloride vs. ^3H (Figure 8.3), except that significant chloride values are seen to be associated with a wider spread of tritium values. Older, deeper ground water has Cl values < 10 mg/l. Again, the higher chloride values are mainly associated (Figure 8.4) with sources of recharge ranging between direct rain infiltration, to isotopically heavier values.

8.3 Isotopic correlations with nitrate

Significant nitrate concentrations are more ubiquitous than either of the two other anions measured, showing a wider spread of surface sources. There is an even more marked positive association with higher tritium concentrations (Figure 8.5).

The dependence on $\delta^{18}O$ (Figure 8.6) is however quite different from those of the other two anions. The water with which the high NO_3 concentrations cluster in a range of isotopic values much closer to the weighted mean for precipitation. This suggests that much of the nitrate is a pollutant derived from a different source than the other anions.

8.4 Conclusions

The above correlations show that, amongst the possible ground water pollutants in the area, SO_4 and Cl can be regarded as proxy ions for pollution derived mainly from urban/industrial sources. These ions correlate reasonably with "heavier" isotopic signals in the water, which have been ascribed to significant additions of RW mains.

Nitrate correlates with isotopically "lighter" water, closer to the stable isotope signature for rain water, or for local dolomitic ground water. It is concluded that part of the nitrate content may be natural and may partly be due to agriculture where ground water irrigation is widely employed, and which has been practised in the area for many decades, before more intensive urban and industrial development.

The geographic distribution of these ions (Figures 7.4 to 7.6) supports these conclusions. Higher levels of SO_4^{2-} and Cl^- are largely confined to the western compartment, whilst NO_3 is more widely spread over the study area.

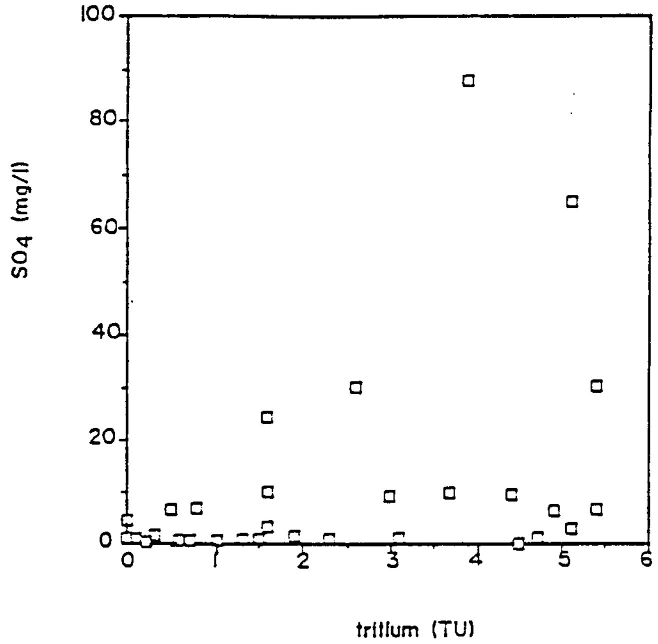


Figure 8.1 SO_4 vs ^3H

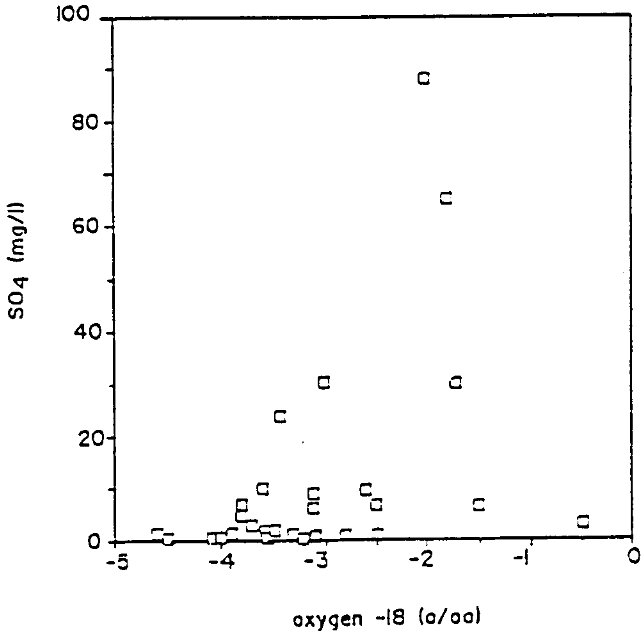


Figure 8.2 SO_4 vs $\delta\ ^{18}O$

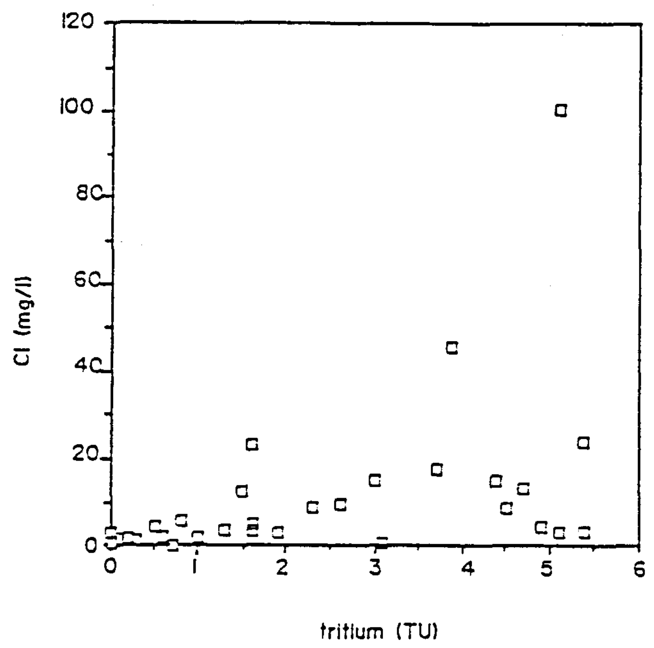


Figure 8.3 Cl vs ^3H

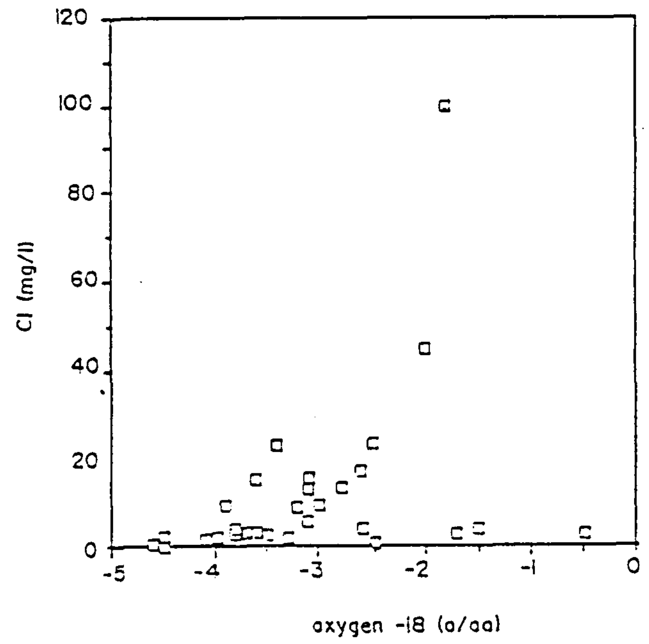


Figure 8.4 Cl vs δ ^{18}O

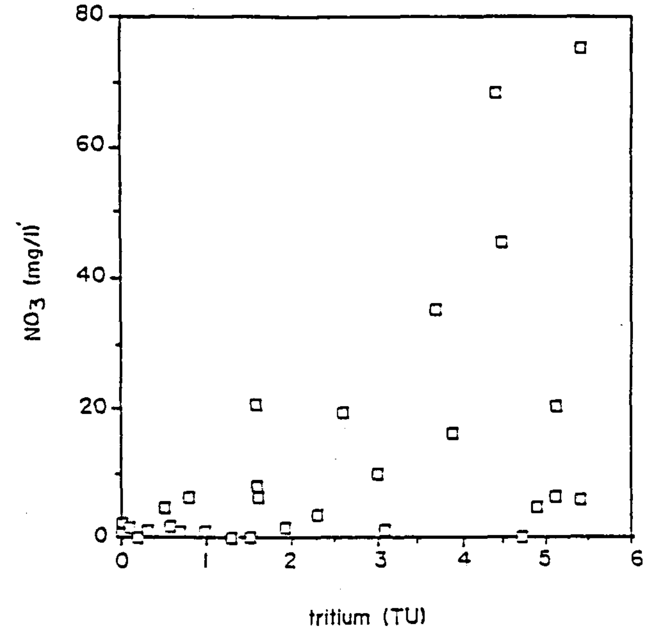


Figure 8.5 NO$_3$ vs ^{3}H

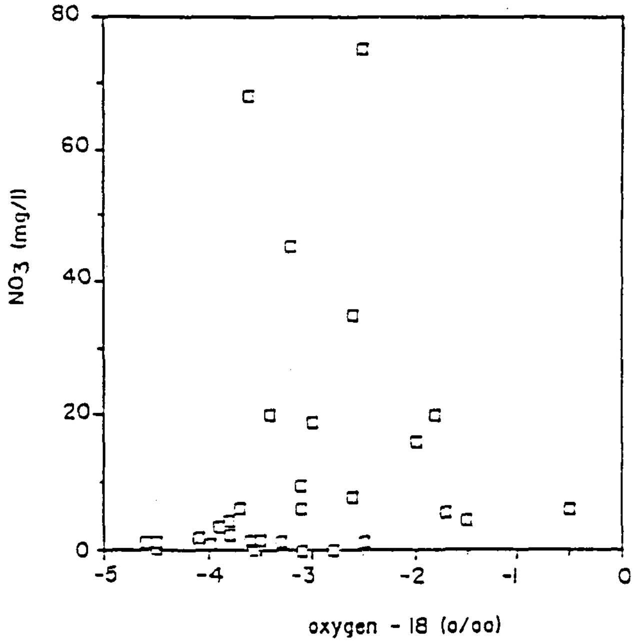


Figure 8.6 NO$_3$ vs δ ^{18}O

9 ISOTOPE STUDY OF THE COMPETENCE OF KAROO DEPOSITS

9.1 Background

The primary focus of the present study at Midrand was the Olifantsfontein waste disposal site, which was closed in 1992 (Section 1.3). The aim was to assess the influence of the site on the underlying surrounding dolomite ground water, using environmental isotope and hydrochemical techniques. In the event, the existing monitoring boreholes were found to be deficient in their ability to reliably reflect the movement of leachate in or below the Karoo. The two observation boreholes to the east and west of the site were obliterated when the disposal facility was closed by the operators.

Following extensive negotiations, it was subsequently agreed that the operating firm would have three new monitoring boreholes drilled. On the basis of geophysical observations, sites were suggested to the north-west and north-east of the site, where conductive zones, and therefore possible ground water flow, were indicated during the present study (Figure 3.12). Proceeding on competing and divergent advice, the firm had the boreholes drilled immediately to the north of the site, where geophysics had indicated the presence of solid dolomite. All three boreholes encountered only solid dolomite and were found to be almost dry.

The study was therefore left in a position where no specific information could be obtained on the relationship between water in contact with the contents of a sanitary landfill in an excavation and ground water in the underlying dolomite. In any event, the approach to such an investigation remained problematic as:

a) the isotopic composition of any leachate forming would be unlikely to contrast sufficiently with the underlying dolomitic ground water to act as a reliable tracer, and

b) the expected very large difference in permeability between the Karoo and conductive dolomite placed severe constraints on identifying transport through the former to the latter.

The only remaining approach therefore appeared to be to search for an analogue situation, which could be extrapolated to cases such as the Olifantsfontein site. Such a situation was identified in Karoo deposit 1, to the north-west of the waste site (Figure 2b). A quarry, worked-out some 20 years ago, receives waste water from i.a. a tile factory. The suspended solid load largely settles in the resulting dam and more or less clear water leaves the excavation across a shallow weir to the north. The stable isotopic composition of the water in the dam, some 100 m across, showed that the water originates almost entirely from Rand Water mains. Any movement of this water in or through the Karoo deposits which remained after cessation of quarrying, would therefore be readily traceable through its oxygen -18 composition (Section 6.7). An additional tracer, although not unique to the water in the dam, is tritium.

9.2 Drilling operations

Three boreholes were sunk to obtain samples of the Karoo from which moisture could be extracted for isotope measurement. The boreholes were all sited in close proximity (20 - 30 m) to the east and south of the dam (Figure 2b). It was first mooted to drill with a flight auger, as water would have to be extracted from the drilling material, in particular in the unsaturated zone. As the material at certain levels was anticipated to present difficulties for drilling with an auger, it was decided to use a down-the-hole airflush hammer drill. The ejected cuttings were collected at various depths as drilling progressed, and immediately packed into airtight containers.

The borehole logs are given in Appendix 2.

MR 9 was drilled in an area recently cleared of quarry waste. The first two metres were disturbed material. Then followed a sequence of material of variable consistency to 16 m where very moist carbonaceous mudstone was encountered which became saturated from 20 m. Drilling was stopped at about 33 m. The borehole was cased down to 32 m and subsequently pumped to obtain an integrated water sample.

MR 10 was drilled some 200 m south-westwards. The material encountered was quite different from that found in MR 9. Rather moist clayey material was found at 6 - 10 m. Carbonaceous clay was found from 7 -11 m, but this was followed by considerable thicknesses of good quality clay, sometimes with chert fragments. At 33 m gravelly sand was encountered. Saturated conditions were struck abruptly at 42 m where the hole was stopped. As the overlying material was competent, good quality clay all the way down, the hole was not cased. It was subsequently pumped to obtain a representative water sample from that depth.

MR 11 was drilled some 12 m to the south of MR 9. The upper 14 meters resembled that of MR 9, but carbonaceous material was then encountered, more argillaceous than that of the nearby hole. Saturated conditions were only encountered near 30 m. Drilling was continued until extremely weathered dolomite with chert fragments was encountered at about 50 m. This continued until igneous material was found around 65 m, where drilling stopped. It therefore appears that the dolomite is here (partially) underlain by an intrusion. The site lying as it does near the northern edge of the outlier, is possibly associated with an intrusion parallel to, or an offshoot from, the Sterkfontein dyke. The hole was cased using unslotted casing and subsequently pumped to obtain an integrated water sample.

9.3 Experimental procedure

Drilling cuttings were collected, the integrated samples from successive depth ranges filled into 2 litre preserve jars, which had previously been oven-dried, capped airtight and labelled. In the laboratory, the jars were inserted into heated metal containers attached to Liebig condensers and collection vessels. The apparatus was evacuated through capillary tubes to limit the loss of moisture. Moisture was distilled into the collection vessels to effective dryness of the drilling material. The moisture content of, and percentage moisture recovery from, individual samples was established by weighing. Stable isotope, and in some cases tritium, measurements were performed on the water samples thus obtained. Full isotope analyses were performed on water samples obtained when the boreholes were subsequently pumped. The results are shown in Appendix 5 and Figures 9.1 to 9.3. Because of the possible isotope shift caused by non-quantitative recovery of moisture, the isotope data was ignored in cases where the moisture recovery was less than 90% by weight. Water was decanted from samples taken from the saturated zone, and distilled.

9.4 Discussion

The striking difference in lithology between MR 9 and MR 11 on the one hand, and MR 10 on the other, is clearly reflected in the moisture content profiles, and in particular also in the $\delta^{18}O$ profiles, of the three holes.

In the cases of MR 9 and MR 11, the $\delta^{18}O$ values for the unsaturated zone are highly variable with depth. Some lie in the range of mean precipitation (~-3.5‰) whilst others are closer to the value found in the dam. In the saturated zone, however, values are closer to dam values, as are the pumped samples, which can be assumed to be a mixture of water yielded by the saturated zone. These profiles can be interpreted as follows: following the rather positive values in the first three metres or so of disturbed material, the highly variable $\delta^{18}O$ values can be taken as evidence that different layers conduct either dam water or rain water, depending on the conductivities and interconnections between the layers. The saturated zone, in the carbonaceous material, carries almost exclusively dam water.

In the case of MR 10, $\delta^{18}O$ values in both the unsaturated and saturated zones, although variable, are all < -3.4‰, i.e. in the range of rain water or deep dolomitic ground water. The pumped sample yielded a value of -4.5‰. There is therefore no evidence of dam water penetrating the Karoo material at this position. It should be noted that MR 10 is situated between an active quarry some 20 m deep, fairly close to the south-east and the dam, establishing a very steep hydraulic gradient (some 20%) from the surface of the dam, at 3 - 4 m, to the water level at the bottom of the quarry.

It should be noted also that the shallower of the three boreholes (MR 9) has a rest water level considerably higher than that of the deeper holes. MR 9 may be more influenced by the level in the dam, whilst the water levels in the deeper holes seem to be influenced mainly by hydraulic pressure in the underlying ground water. There is definite indication of flow, considering that the water level in the dam is 3 - 4 m, at a distance of some 30 m from boreholes MR 9 (6 m) and MR 11 (14 m), which are separated laterally by only 12 m.

In the case of MR 11, the isotopic values undergo considerable variations with depth. Although tending towards the dam values at greater depth, lighter values are interspersed. In view of the lithology revealed by the borehole, it is possible that the lighter values encountered at depth may be due to interfingering of dolomite water, which at this location has a phreatic level of some 30 m, and dam water.

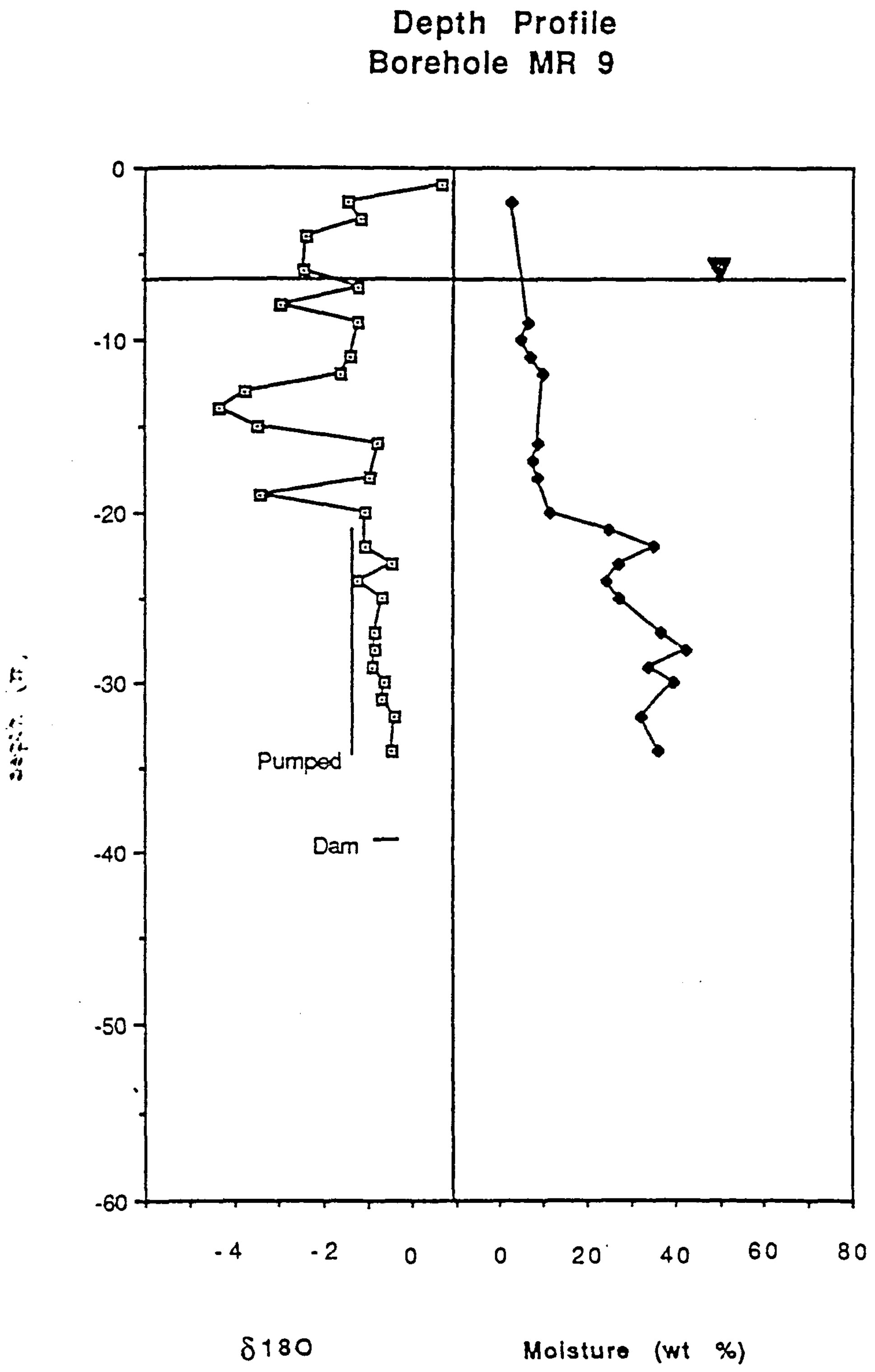


Figure 9.1 Depth profile - borehole MR 9

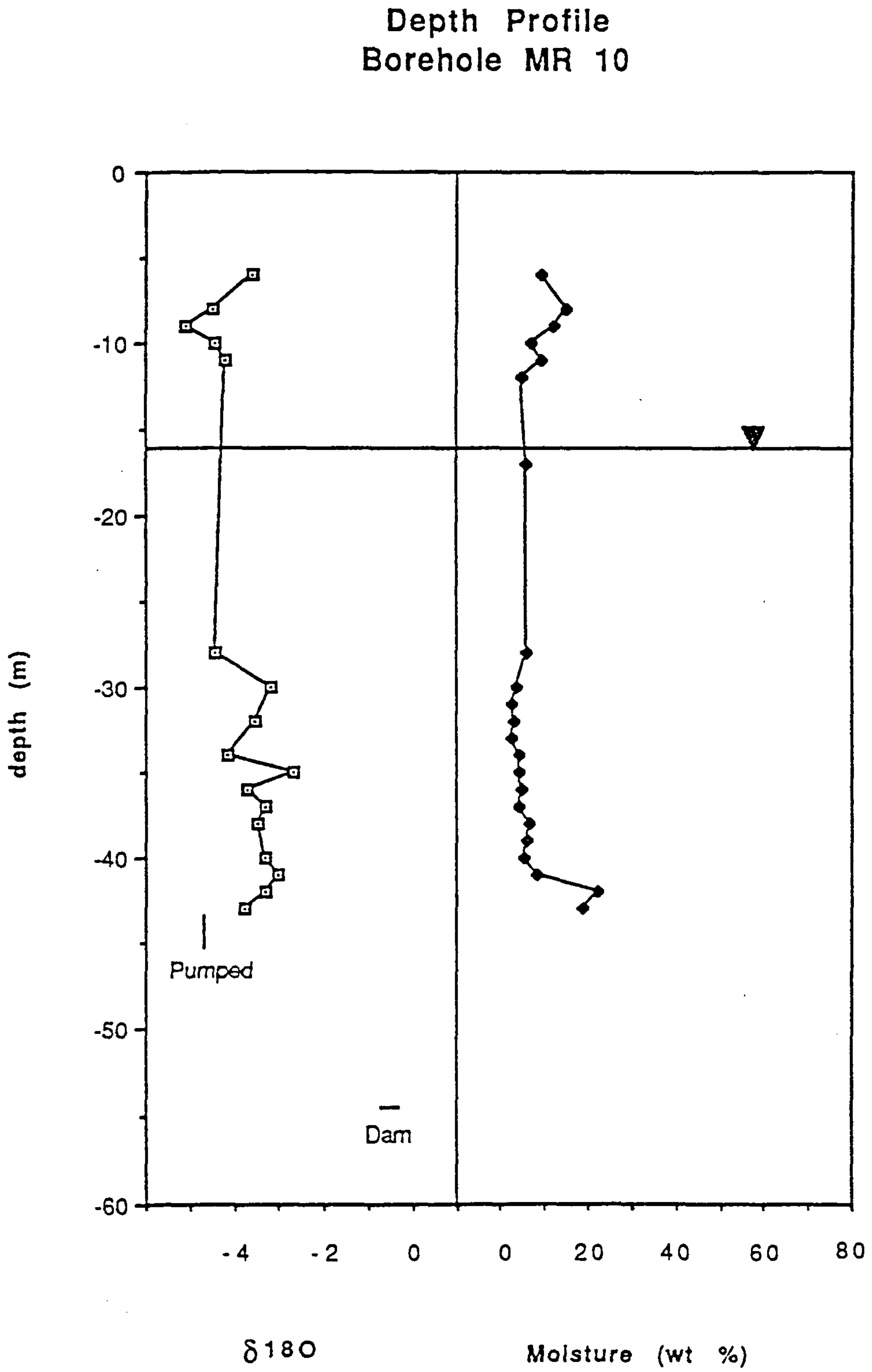


Figure 9.2 Depth profile - borehole MR 10

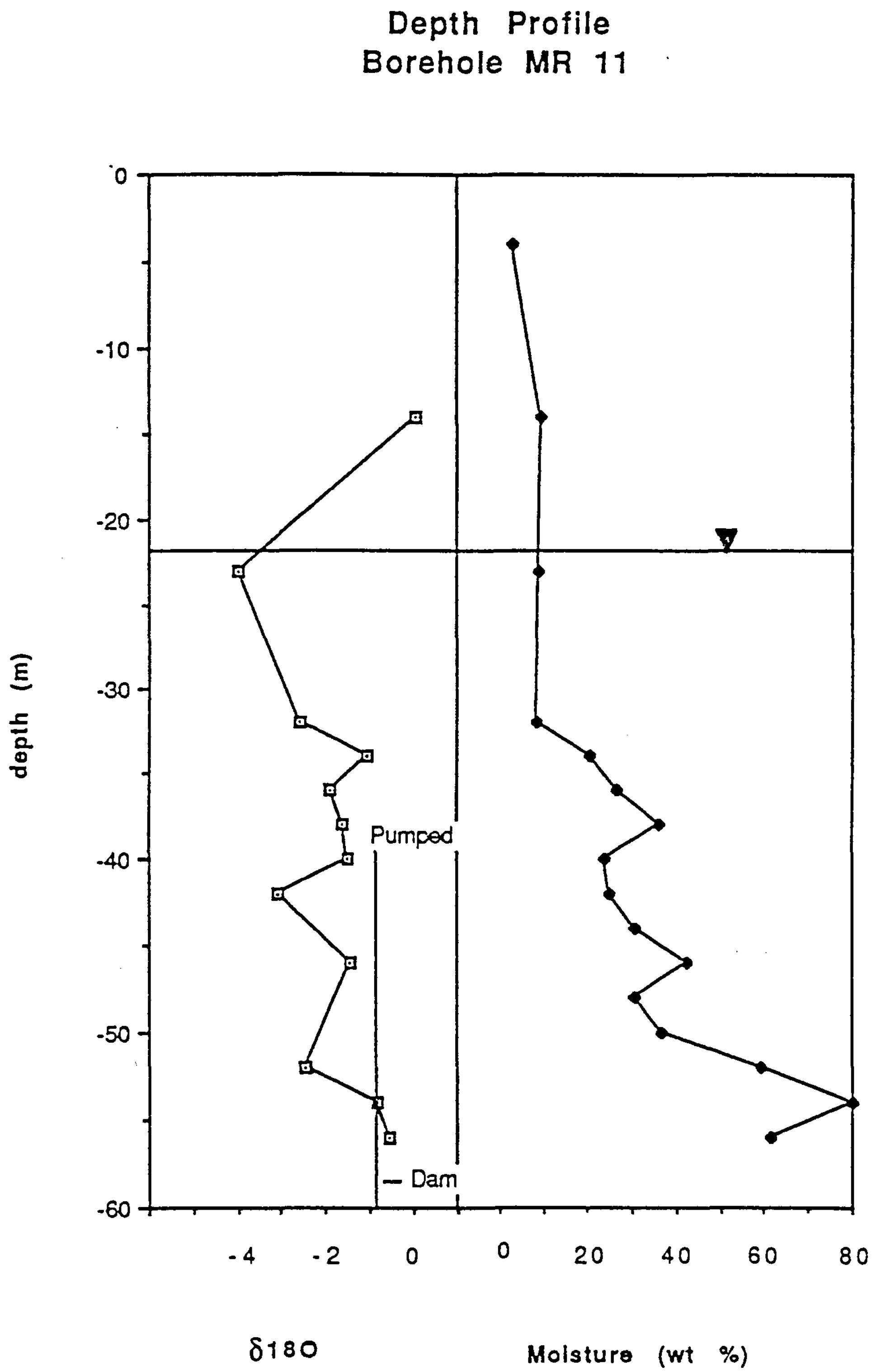


Figure 9.3 Depth profile - borehole MR 11

The isotope data from the pumped water samples is given in Table 9.3.

Table 9.1 Isotope data for water pumped from boreholes MR 9, MR 10 and MR 11 after completion

	Carbon-14 (pMC)	Tritium (TU)	$\delta^{18}O$ (‰)
MR 9	47.5 ± 0.8	2.9 ± 0.3	-1.17
MR 10	61.4 ± 1.0	0.4 ± 0.3	-4.33
MR 11	53.1 ± 1.2	2.8 ± 0.3	-0.59

These results can be interpreted as follows. The $\delta^{18}O$ value for water pumped from a depth of 42 m in MR 10, is within the range of deep dolomite water. This conclusion is supported by the ^{14}C and vanishing tritium values. It is possible that some of the lighter $\delta^{18}O$ values encountered at lesser depths in the profile may be due to interfingering of such water into certain levels of the clay profile.

The $\delta^{18}O$ value for MR 11 is compatible with, if isotopically somewhat lighter than, dam water. The associated tritium value supports this conclusion. The $\delta^{18}O$ value for MR 9 is more negative than dam water, but much more positive than either mean rain or deep dolomite water. It therefore is interpreted as a mixture of dam and dolomite water. The ^{14}C values for water pumped from these two boreholes are much lower than could accompany the observed tritium values, which represent recently recharged water, compatible with the value of dam water. This supports the concept of mixed water. Water from the dam is at low alkalinity, whilst the dolomite water, at several meq/l, will have the major influence on the ^{14}C contents of the TDIC of the mixture.

9.5 Conclusions

The overall conclusion which can be derived from this exercise is that the Karoo at this site is highly heterogeneous, both vertically and laterally. At a site such as MR 10, stable isotopic values are encountered which are compatible with rain and deep dolomite water. There is no evidence of any dam water in this profile. The clay is therefore largely competent against dam water penetration into, or through the matrix, in spite of the steep hydraulic gradient. The owners of the property expressed surprise at this considerable thickness of good quality clay, missed in their exploratory drilling, in an area previously regarded by them as beyond the edge of the Karoo outlier. A substantial thickness of such material could indeed be regarded as effectively impermeable to lateral, and therefore probably also vertical, leachate movement from any waste repository operated in a worked-out pit, such as the one now turned into a dam. It should be noted, however, that even in the profile of MR 10, the competence of the material reduces significantly at depths greater than 30 m.

At equal distance from the dam the two closely adjacent boreholes MR 9 and MR 11, on the other hand, have revealed a completely different lithology, with highly incompetent carbonaceous material encountered from fairly shallow depths. Here, there is clear evidence of significant penetration of dam water. Moreover, there is a substantial difference in lithologies over the small distance between them, further highlighting the extreme heterogeneity of the Karoo. The fact that these boreholes have different rest levels, which in turn lie considerably below the surface of the open water in the dam, suggest that these water levels indicate a pressure gradient associated with significant flow into the sub-surface from the dam in this direction along preferential pathways such as joints and sandy layers.

It may be argued that this aspect of the investigation dealt with a worse-case scenario: a situation resembling a waste disposal pit which had become completely flooded with (rain) water. The landfill site in deposit 1, has been furnished with access shafts, from which it is possible to remove any leachate before it could exert any significant hydrostatic pressure on the bottom or sides of the containing pit. On the other hand it can be argued that the worse-case scenario is the one which should be taken as the norm in assessing waste disposal sites. Preventing the build-up of leachate would be a responsibility burdening future generations for possibly centuries. Unless rigorously circumscribed by long-term, enforced legislation, the responsibility could lapse and surface evidence of such a closed site obliterated.

Results from the borehole survey have established that dolomite exposures such as at Midrand are generally vulnerable to surface pollution. Intact Karoo outliers are the obvious choice for the siting of sanitary landfill sites in such areas. These should however be established on surface, providing the full Karoo profile as a barrier between the waste and the underlying dolomite ground water. In this way, the waste remains accessible, allowing it to be much more readily managed and any leachate forming disposed of. The most competent material has usually been removed from worked-out quarries, leaving a relatively thin layer which in many instances consists of much less competent material, such as the poorly cemented sandstone found at the bottom of the adjacent pit next to the waste disposal facility. Parallel tension cracks infilled with ferruginous material emphasise the incompetency of the material. Any compaction, or even lining, of the bottom of such a quarry can at best be regarded as of temporary value, as ongoing karstification at such sites will inevitably produce movement and thus disruption of the compacted layer or lining.

The unnatural acid environment produced at the base of the waste disposal facility if released via cracks produced by slumping, could remobilise the ferruginous material, opening the tension cracks and allowing leachate to flow into the underlying dolomite. This in turn would also be vulnerable to dissolution leading to increased sinkhole development and slumping.

10 THE LINBRO PARK LANDFILL SITE

10.1 Introduction

The Linbro Park landfill site is located on the north-eastern boundary of the Johannesburg municipal area, within the Sandton municipal district (Figure 10.1). It is situated in a borrow pit from the construction of the N3 highway, which borders the site to the west. The refuse is mainly urban wastes. Toxic, hazardous and liquid wastes are not accepted at the site, which is classified as a Class 2 site (Hojem, 1988).

A broad shallow valley separates the northern and southern section of the landfill, sloping from Third Road, in a westerly direction, down to the N3 highway (Figure 10.2). The northern section of the site slopes in a south-westerly direction with a slope of about 2.5°, while the southern section slopes in a north-westerly direction with a slope of 4.0°.

10.2 Geology

The Linbro Park landfill is situated on weathered granites of the Grey Granodiorite Suite of the Johannesburg-Pretoria granite dome. Geological outcrops are not exposed in the landfill site, although large, round boulders of granite are present. These granites display narrow jointing and cracks.

The residual granite ranges in thickness from 2 m near the stream up to 12 m in the north-western section of the site. Fissures and joints were found to be closed in this residual granite. Most of the site is covered by a 1 metre layer of orange-red hillwash material, except where it has been replaced by alluvium along the river (Williams *et al.*, 1983).

10.3 Hydrology

The granites of the Linbro Park area generally have low water yields, but the water is fairly pure and suitable for most uses (Davis *et al.*, 1966). The residual granite has a low permeability, it is fairly compact, transmitting water primarily by fissure flow. Measurements of the rest levels of both the up-gradient and down-gradient boreholes are shown in Table 10.1.

Rest level measurements for boreholes GL 3 and GL 4 were not obtained in 1994 because of obstructions. The data shows that the boreholes, with the exception of GL 3 which is probably an erroneous result due to the obstruction, have lower rest levels after the initial sampling exercise by pumping in June of 1992, possibly an indication of the length of time these boreholes in the granites take to recover. A general decrease in the standing water level is seen in the measurements taken in 1994 in the middle of the rainy season, suggesting low transmissivity. GL 6 shows a 2 m rise in water level, possibly due to more rapid recharge as a result of its proximity to the river.

From Table 10.1 it is apparent that borehole GL 3 had already partially collapsed by mid-1992, and GL 4 and GL 6 had noticeable decreases in their depths, most likely due to

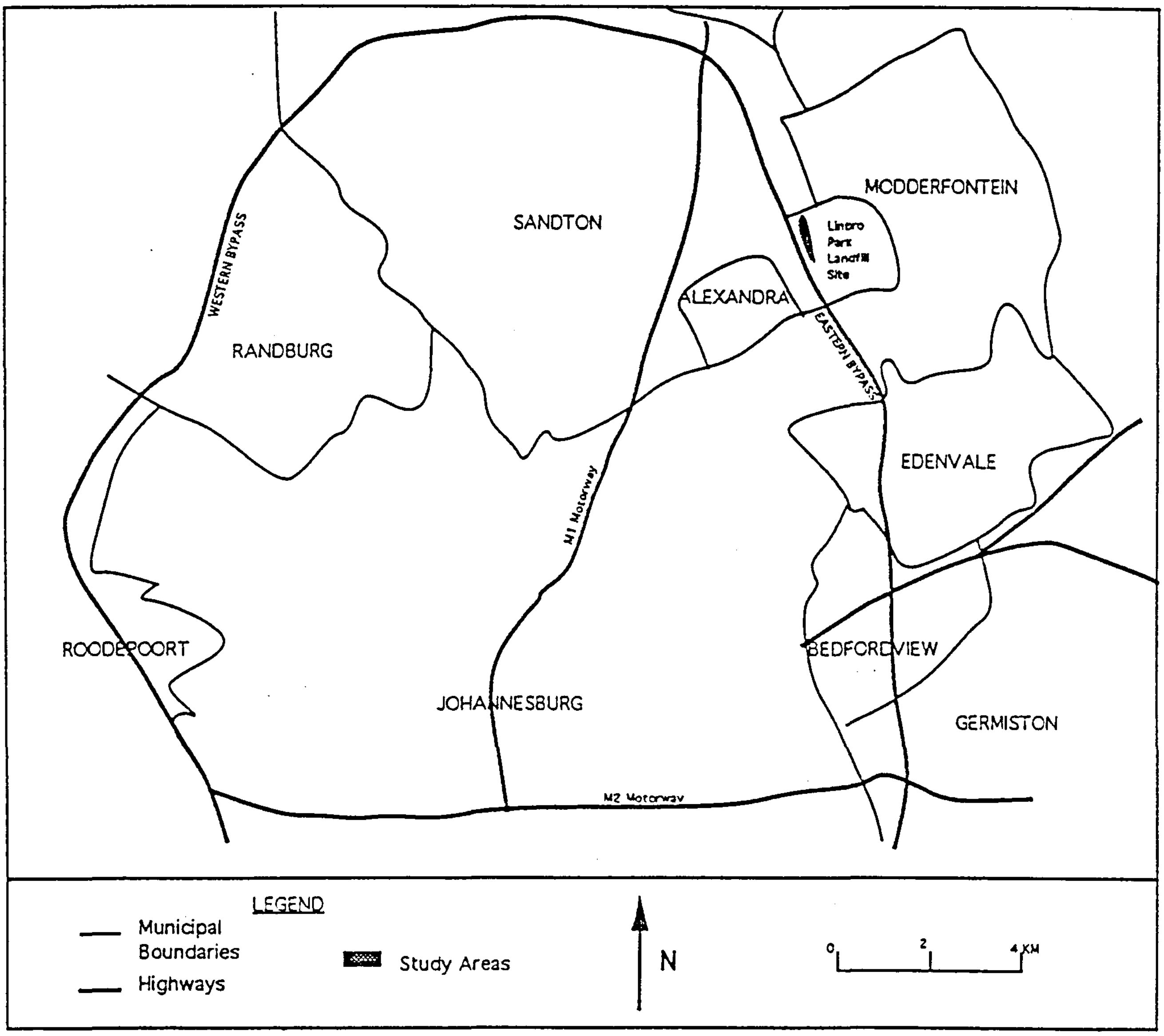


Figure 10.1 Map showing the location of the Linbro Park landfill site

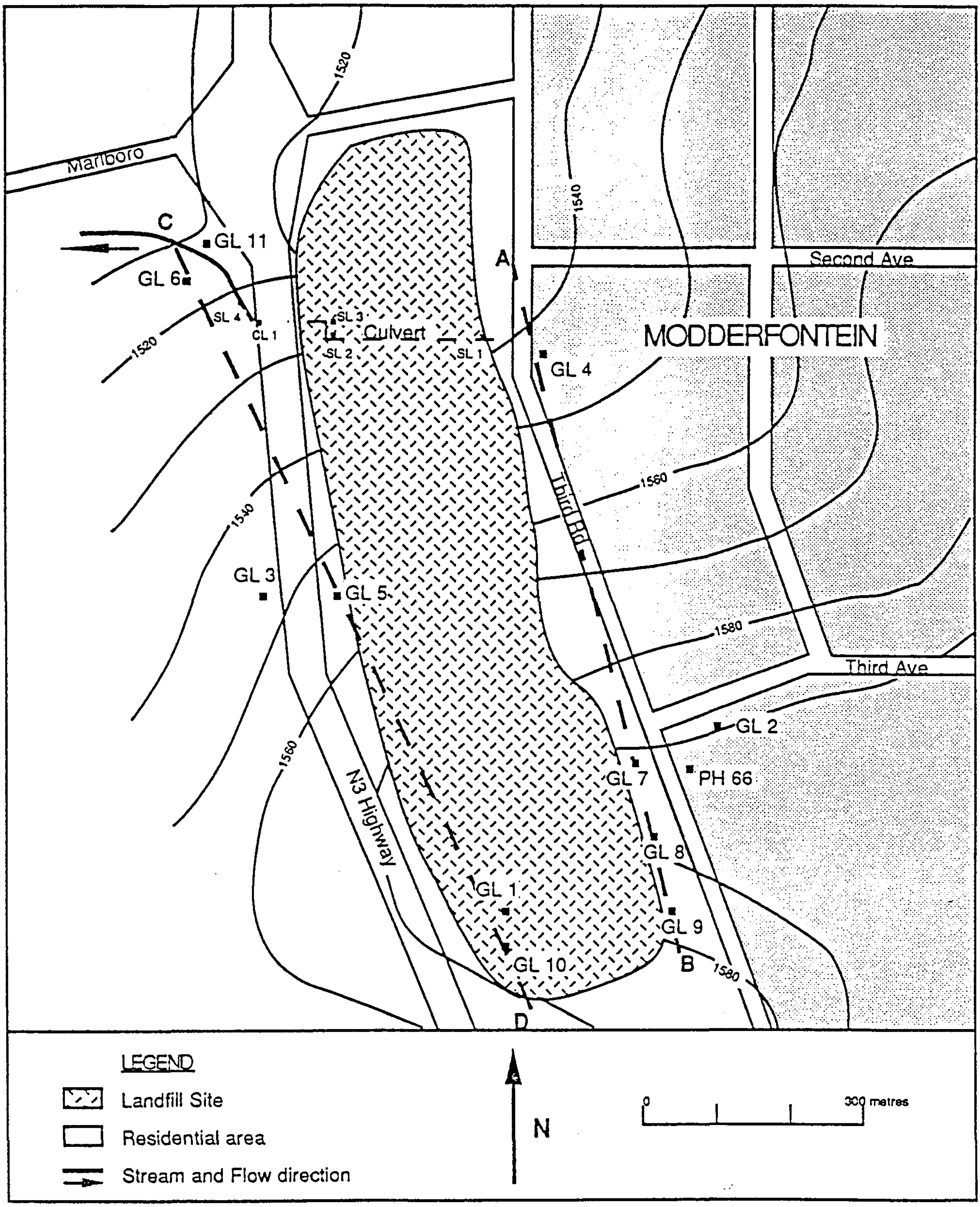


Figure 10.2 Location of the ground and surface water pollution monitoring points for past and present studies at the Linbro Park landfill site. Shown also are sections A-B and C-D from Figure 3. Surface contours in metres above sea level

silting. The eventual blockage of GL 4 is believed to be due to vandalism as the borehole was inappropriately covered.

Table 10.1 Rest levels and borehole depths of the pollution monitoring boreholes

Borehole Number	Borehole Depths (m)		Rest Levels (m)				
	initial	02.06.92	initial	02.06.92	24.09.92	14.10.92	14.01.94
GL 3	30	19.0	9.8	13.0	10.4	14.7	
GL 4	60	55.0	6	7.0	7.9	8.0	
GL 5	71	69.8	8	15.5	16.2	16.3	17.3
GL 6	90	85	1	3.0	3.1	3.0	1.1
GL 7	44	44.0	22	25.0	28.8	29.0	27.9
GL 8	23	23.2	18	11.7	13.1	13.2	14.3
GL 9	23	23.4	5	6.9	8.3	8.2	8.9

Ground water flows in a westerly direction from the landfill towards the Jukskei River. There is also a possibility that a certain proportion of the ground water flows from the site in an easterly direction towards some of the privately owned boreholes along Third Road (Williams *et al.*, 1983). A large drawdown is inferred at the highest elevation on the eastern side of the landfill site, in the vicinity of borehole GL 7 is depicted in Figure 10.3a. This is most likely the result of the pumping of private boreholes to the east of borehole GL 7, lowering the ground water level below the site. In Figure 10.3b, the water table follows the surface topography.

As the site originally straddled a stream, a culvert was constructed along the length of the channel, which is now beneath the landfill. This stream flows westwards, from the site, into the Jukskei River. The general direction of the surface water runoff is in a north-westerly direction, obliquely across the site towards the stream. This stream also channels water flowing down Third Road from both the north and south.

10.4 Previous studies

Monthly surface water sampling and analysis was undertaken at Linbro Park in 1978 by the Johannesburg Municipality (Theron, 1986). These sampling points, marked SL 1 to SL 4 and CL 1, are shown in Figure 10.2. Discharge from weepholes in the culvert suggested mineralised leachate from the landfill.

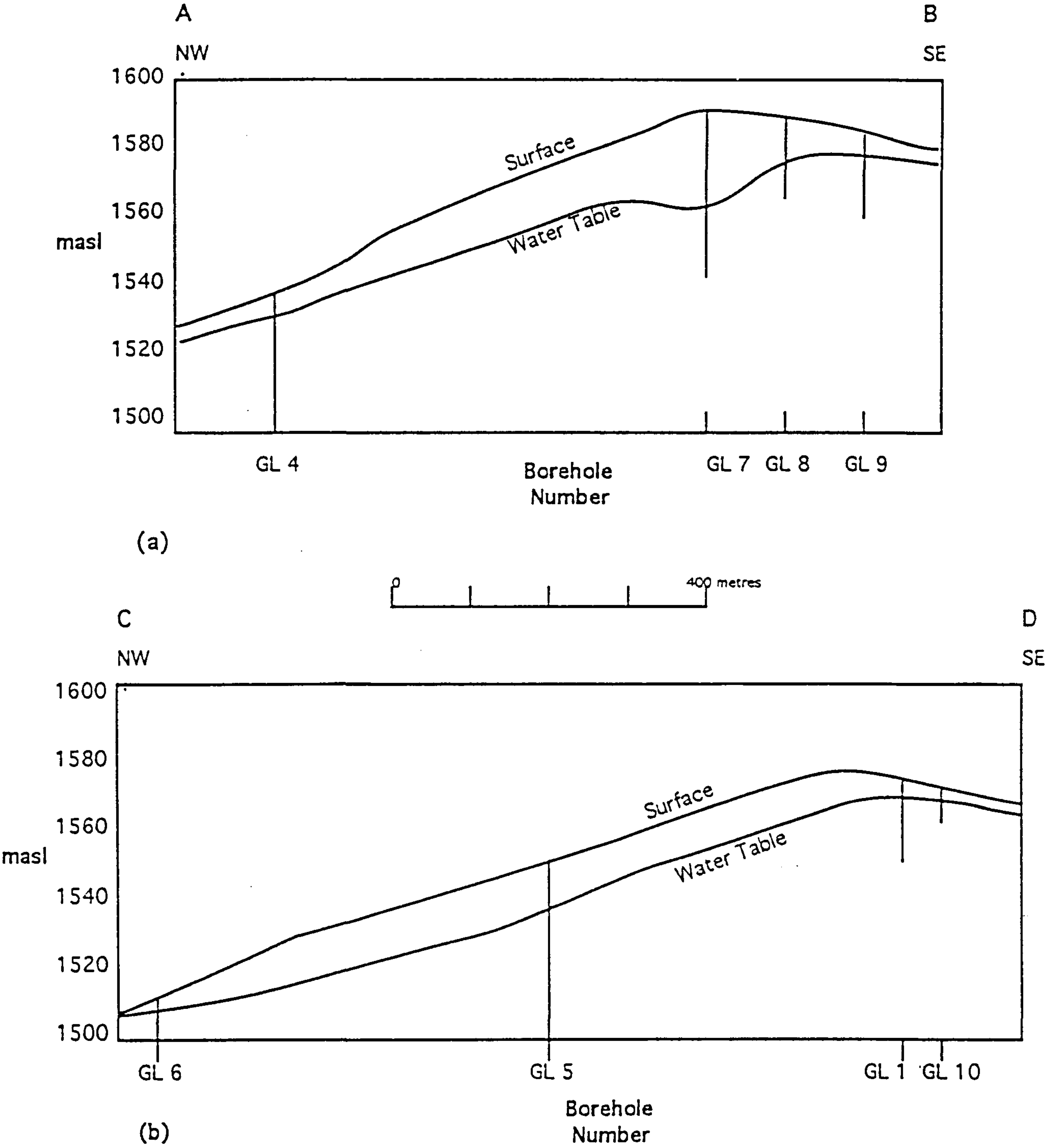


Figure 10.3 Water table transects, using initial rest levels, for
a) the eastern section A-B and
b) the western section C-D.
Sections are shown in Figure 10.2. Note inferred depression cone at borehole GL 7 in section A-B.

The pollution monitoring boreholes, GL 1 to GL 11 have been drilled through alluvium and decomposed granite, and have been cased with UPVC casing. They are summarised in Table 10.2, and their locations are shown in Figure 10.2.

Table 10.2 Summary of the pollution monitoring boreholes (Theron, 1986)

Borehole Number	Date Drilled	Initial Depth (m)	Initial Rest Level (m)	Current Status
GL 1	1982	11	7.8	Destroyed
GL 2	1982	30	25.7	Dry
GL 3	1982	30	9.8	Collapsed
GL 4	1987	60	6	Collapsed
GL 5	1987	71	8	Functional
GL 6	1987	90	1	Functional
GL 7	1989	44	22	Functional
GL 8	1989	23	18	Functional
GL 9	1989	23	5	Functional
GL 10	1989	9	2	Collapsed

Williams *et al.* (1983) of the City Engineers Department claim that, because of the low permeability of the underlying granite and the high evaporation rates in the area, leachate should not pollute the ground water, provided sanitary landfill standards have been followed. Beaumont *et al.* (1987), Hojem (1988), and Blight (1992) concluded from various studies on the landfill, that no chemical pollution of the ground water was occurring. Hojem (1988) estimated that the landfill would start producing leachate from about the year 2001.

At present, borehole and surface water is monitored every three months by the site staff. Sampling of the boreholes is carried out using the open-bailer method, where only a small portion of the standing water column is sampled. Up to 1992, analysis of these samples had not shown any indication of the presence of leachates. In the context of the present study this sampling technique is regarded as questionable, and the analytical results are not considered meaningful.

10.5 Results of the present study

10.5.1 Introduction

The monitoring boreholes GL 3 to GL 9 were sampled twice in 1992, first in the dry season in early June, and later after considerable rain had fallen in October. Boreholes GL 7, GL 8 and GL 9 are considered to be up-gradient of the landfill site, while boreholes GL 5 and GL 6 are down-gradient. Boreholes GL 3 and GL 4 appear to be in an intermediate position (Figure 10.2). The diameter of the casing was too small for a standard submersible pump. A special small diameter submersible pump therefore had to be employed.

A private borehole PH 66, situated about 300 m east of borehole GL 7 was sampled as a test of the quality of the water within the residential areas (Figure 10.2). It is claimed by the owner to have been drilled to a depth of 115 m into the granites.

The volume of water standing in the boreholes was purged and the samples were taken, believed to be the most representative samples of the ground water possible under poor conditions. During sampling, the pumping speed had to be drastically reduced as water levels were rapidly drawn down, either due to poor borehole design, the low permeability of the residual granite, or obstructed slots in the casing. It was often the case that barely sufficient water was available for the carbon-14 samples.

However, in spite of the poor sampling conditions, the samples were analysed for the major ions and for the stable and radioactive isotopes. Well-head measurements of temperature, pH, conductivity and alkalinity were taken at each borehole during both sampling exercises.

10.5.2 Hydrochemistry

Well-head measurements are given in Table 10.3. Generally, the down-gradient boreholes (D) have higher alkalinity, conductivity, pH and temperature values than the up-gradient boreholes (U).

The up-gradient boreholes are generally sodium bicarbonate dominant ground water, while the down-gradient tend to be calcium bicarbonate dominant.

The up-gradient boreholes, including GL 3, tend to have relatively low TDI concentrations, ranging between 2 and 4 meq/l, while the down-gradient boreholes including GL 4, have TDI concentrations ranging between 5 and 8 meq/l (Table 10.4c).

The basic differences between the up-gradient and down-gradient boreholes are the higher calcium concentrations, and to a lesser extent, the sodium and bicarbonate concentrations in the down-gradient boreholes. This is illustrated in Figures 10.4a (June 1992) and 10.4b (October 1992). These are referred to as Schoeller diagrams, although the sequence of ions is somewhat modified in order to clearly represent the primary tracers assumed to represent potential pollution. The modified form of the Schoeller diagram has also been employed in the following chapters.

Table 10.3 Well-head measurements for the two sampling periods (1992)

Borehole Number	Alkalinity (meq/l)		E.C. (mS/m)		pH		Temp (°C)	
	2 Jun	14 Oct	2 Jun	14 Oct	2 Jun	14 Oct	2 Jun	14 Oct
GL 3	1.0		8		6.1		19.0	
GL 4	1.7	1.5	16	22	6.4	6.0	20.0	19.8
GL 5 (D)	2.6	2.1		22	7.4	6.5	20.0	20.6
GL 6 (D)	2.6	2.4	32	32	6.6	6.0	18.5	20.9
GL 7 (U)	1.1	0.7	14	14	5.5	4.2	18.2	19.8
GL 8 (U)	1.2	0.9	9	12	6.3	5.2	19.0	19.9
GL 9 (U)	1.5	1.1	8	11	6.6	5.5	18.9	18.9
PH 66 (U)	1.2		16		6.2		17.0	

(D) = Down-gradient boreholes
(U) = Up-gradient boreholes

Table 10.4a Cation concentrations in meq/l for the two sampling periods (1992)

Borehole Number	K (meq/l)		Mg (meq/l)		Na (meq/l)		Ca (meq/l)	
	2 Jun	14 Oct	2 Jun	14 Oct	2 Jun	14 Oct	2 Jun	14 Oct
GL 3	0.03		0.08		0.70		0.2	
GL 4	0.04	0.04	0.51	0.51	0.78	0.78	1.1	1.1
GL 5 (D)	0.01	0.01	0.31	0.31	0.91	0.96	1.4	1.4
GL 6 (D)	<0.002	0.004	0.50	0.54	0.83	0.91	1.9	2.1
GL 7 (U)	0.14	0.12	0.32	0.25	0.87	0.78	0.5	0.3
GL 8 (U)	0.12	0.10	0.23	0.19	0.57	0.52	0.6	0.4
GL 9 (U)	0.06	0.11	0.20	0.33	0.61	0.65	0.4	0.9
PH 66(U)	0.10		0.27		0.65		0.7	

Table 10.4b Anion concentrations in meq/l for the two sampling periods (1992)

Borehole Number	HCO_3 (meq/l)		SO_4 (meq/l)		Cl (meq/l)		NO_3 (meq/l)	
	2 Jun	14 Oct	2 Jun	14 Oct	2 Jun	14 Oct	2 Jun	14 Oct
GL 3	1.0		0.05		0.09		0.02	
GL 4	1.6	1.7	0.25	0.25	0.54	0.51	0.29	0.31
GL 5 (D)	2.4	2.3	0.15	0.15	0.11	0.11	0.27	0.29
GL 6 (D)	2.6	2.8	0.12	0.12	0.85	0.99	0.06	0.06
GL 7 (U)	1.3	0.8	0.03	0.01	0.17	0.16	0.69	0.73
GL 8 (U)	1.3	0.9	0.16	0.13	0.11	0.09	0.02	0.13
GL 9 (U)	1.5	1.5	0.01	0.02	0.05	0.04	<0.01	<0.01
PH 66 (U)	1.1		0.03		0.15		0.48	

Table 10.4c Total dissolved ion concentrations in meq/l for the 2 sampling periods (1992)

Borehole Number	TDI (meq/l)	
	2 Jun	14 Oct
GL 3	2.2	
GL 4	5.1	5.2
GL 5 (D)	5.6	5.6
GL 6 (D)	6.8	7.5
GL 7 (U)	3.9	3.2
GL 8 (U)	3.1	2.6
GL 9 (U)	2.9	3.6
PH 66 (U)	3.5	

(D) = Down-gradient boreholes
(U) = Up-gradient boreholes

Table 10.5 Drinking water standards as proposed for application in South Africa (Weaver, 1992)

Determinant	Recommended Limit	Maximum Permissible	Crisis Limit
K (mg/l)	200	400	800
Mg (mg/l)	70	100	200
Na (mg/l)	100	400	800
Ca (mg/l)	150	200	400
Cl (mg/l)	250	600	1 200
NO_3(N) (mg/l)	6.0	10.0	20.0
SO_4 (mg/l)	200	600	1 200
F (mg/l)	1.0	1.5	3.0
Fe (mg/l)	0.1	1.0	2.0
Al (mg/l)	0.15	0.5	1.0
E.C. (mS/m)	70	300	400
pH	6.0 - 9.0	5.5 - 9.5	<4.0 - >11.0
Temp (°C)	<25	<30	<40

Borehole GL 6 generally has higher major ion concentrations. Due to its proximity to the stream, it is possible that leachates, seeping through weepholes in the culvert into the stream, are entering the ground water in the vicinity of this borehole. Boreholes GL 7 and PH 66 have significant high nitrate concentrations of 44 mg/l and 30 mg/l respectively, higher than the recommended limit for drinking water (Table 10.5). This is attributed to leakage from septic tanks. The October sample of borehole GL 9 has an iron concentration of 21.0 mg/l, and an aluminium concentration of 6.9 mg/l. This is the only instance of the appearance of these pollutants observed during this study, the concentrations greatly exceeding the crisis limit specified in Table 10.5.

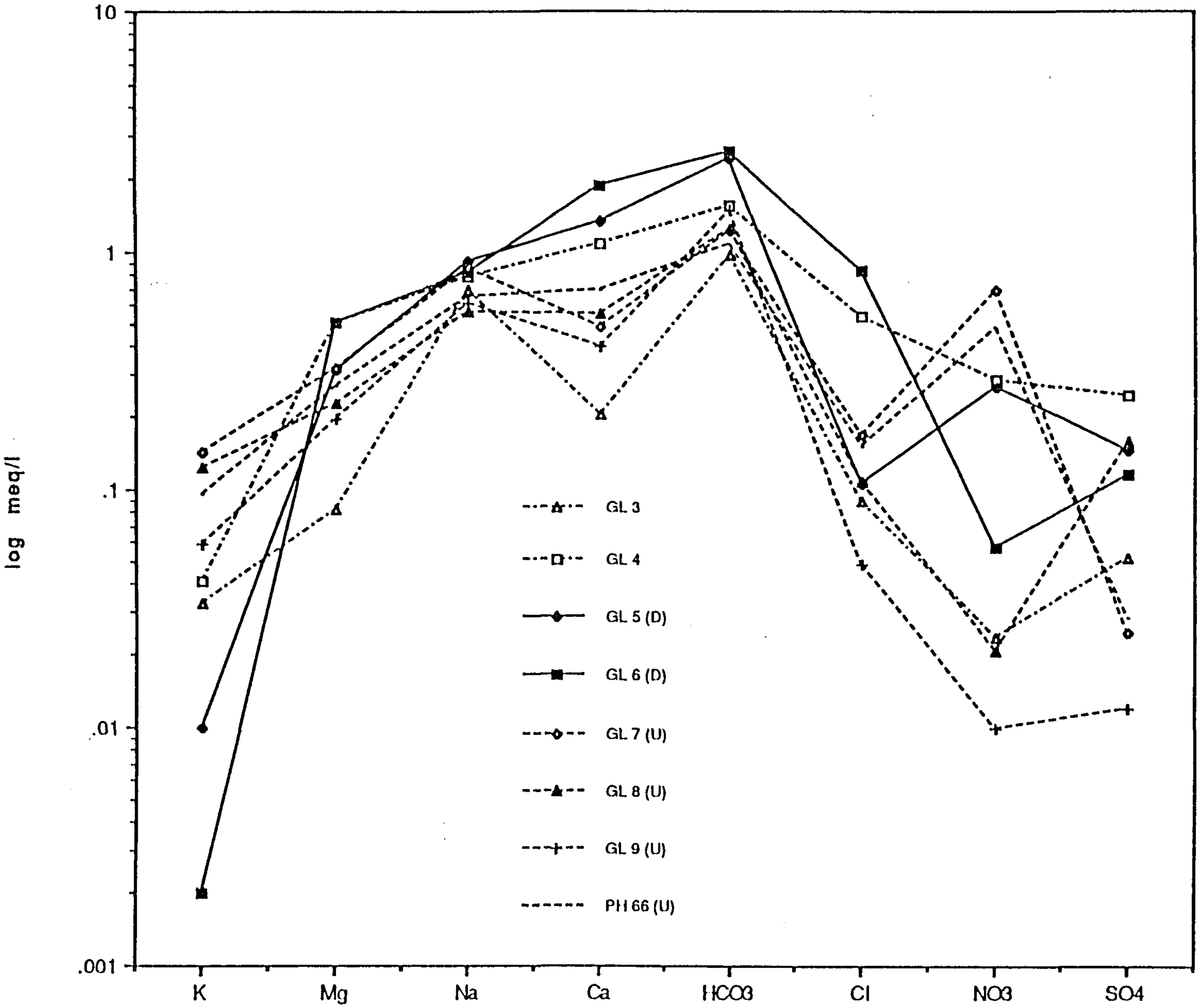


Figure 10.4a Modified Schoeller diagram for Linbro Park boreholes : June 1992

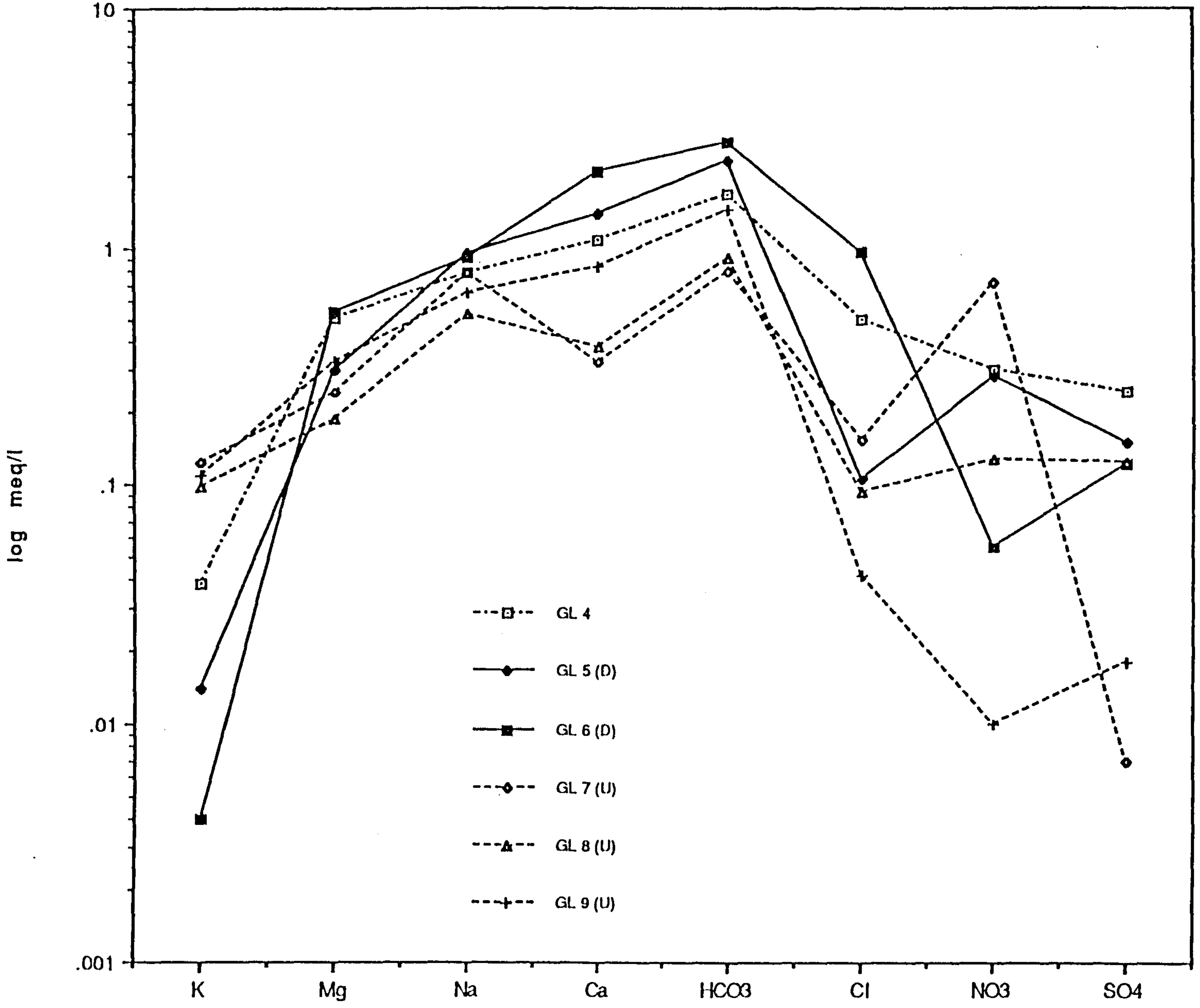


Figure 10.4b Modified Schoeller diagram for Linbro Park boreholes: October 1992

10.5.3 Stable isotopes

Table 10.6 Mean δD and mean $\delta^{18}O$ for the two sampling periods (1992)

Borehole Number	δD (‰)	$\delta^{18}O$ (‰)
GL 3	- 21.3	- 3.95
GL 4	- 25.4	- 4.45
GL 5 (D)	- 24.0	- 4.63
GL 6 (D)	- 20.2	- 4.07
GL 7 (U)	- 25.0	- 4.50
GL 8 (U)	- 25.1	- 4.58
GL 9 (U)	- 28.3	- 4.86
PH 66 (U)	- 26.4	- 4.50

(D) = Down-gradient boreholes
(U) = Up-gradient boreholes

The range of δD and $\delta^{18}O$ values is fairly small for both the up-gradient and down-gradient boreholes (Table 10.6). The somewhat heavier stable isotope composition of GL 6 is probably due to local infiltration of the stream water (Figure 10.5).

10.5.4 Tritium and Carbon-14

Generally, the radiocarbon and tritium concentrations are within the normal environmental range, and indicate a fairly rapid turnover, more apparent in the up-gradient boreholes. Borehole GL 7 has a carbon-14 concentration over 100 pMC, and a tritium concentration less than 1 TU (Table 10.7). A similar situation is observed in GL 9. A possible explanation for this combination is the introduction of CO_2 into the ground water through root respiration by the well developed vegetation (trees) in the vicinity. Such combinations have been observed in other granitic areas (Verhagen, unpublished data).

An overall increase between 4 and 11 pMC is evident in the carbon-14 concentrations over the sampling period (Table 10.7). This may possibly indicate poor contact of the boreholes with the aquifer, or relatively low ground water mobility.

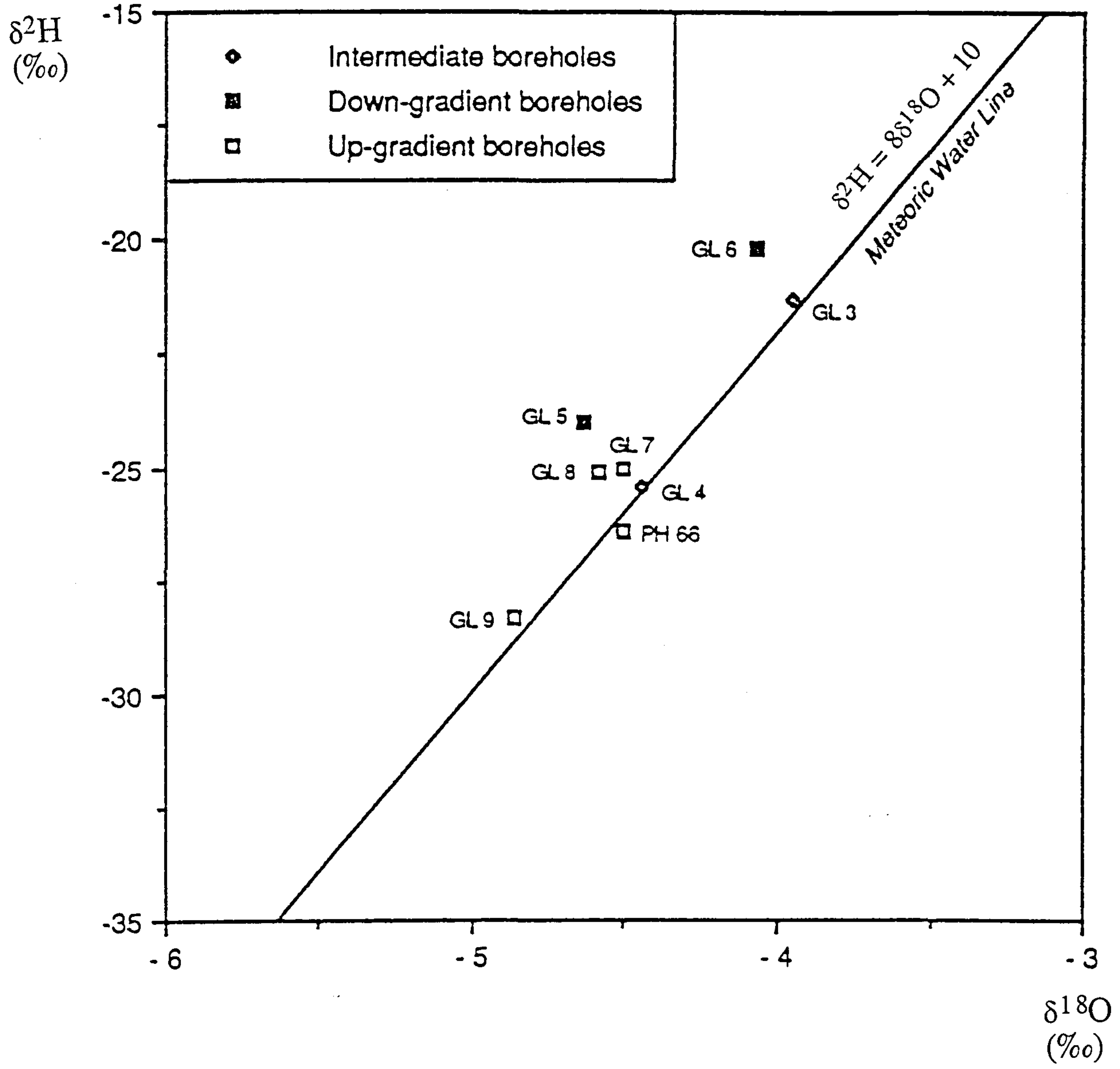


Figure 10.5 Plot of ∂ ^{2}H against ∂ ^{18}O. Also shown in the world meteoric water line (WMWL)

Table 10.7 Radioactive isotopes for the two sampling periods (1992)

Borehole Number	^{3}H (TU)		^{14}C (pMC)		δ ^{13}C (‰)	
	2 Jun	14 Oct	2 Jun	14 Oct	2 Jun	14 Oct
GL 3	4.6±0.4					
GL 4	1.2±0.2	1.4±0.3	86.2±0.8	91.3±1.6	-10.5	-10.8
GL 5 (D)	0.6±0.2	0.4±0.2	69.4±0.8	73.8±0.6	-9.1	-9.0
GL 6 (D)	3.4±0.3	2.2±0.3	94.4±0.8	104.9±1.0	-10.9	-10.3
GL 7 (U)	0.8±0.2	0.9±0.2	117.2±0.5	123.8±1.4	-8.5	-8.3
GL 8 (U)	5.8±0.4	4.8±0.4		110.9±0.9	-11.6	-11.5
GL 9 (U)	0.4±0.2	0.4±0.2	97.7±0.2	101.6±2.4	-10.7	-10.0
PH 66 (U)	0.4±0.1		84.0±0.9		-10.2	

(D) = Down-gradient boreholes
(U) = Up-gradient boreholes

10.6 Summary and Discussion

Generally, the ground water is very recent, with a turnover time in the order of decades, and should therefore reflect any leachate entering the subsurface. On average, the up-gradient boreholes tend to have a shorter turnover time than the down-gradient boreholes. With the exception of the up-gradient boreholes GL 7, GL 8 and GL 9, there is no clear evidence of pollution. The pollution found in these up-gradient boreholes could possibly be derived from the neighbouring small holdings. The higher overall mineralisation in the down-gradient samples relative to the up-gradient samples could be due to a more mature hydrochemistry. The increased Ca concentration might be evidence of the effect of acid leachate.

Within the constraints of the poor sampling conditions, it can therefore be concluded that no significant leachate is entering the down-gradient ground water at present. The consistent increase in the carbon-14 concentrations of the resampled boreholes is a possible indication of the poor sampling conditions which, in turn, suggests that the pollution monitoring boreholes poorly reflect any temporal changes in the hydrochemistry.

10.7 Recommendations

It is recommended that several properly tested boreholes are installed with slotted, durable casings of standard size, which will provide samples representative of the ground water. A suitable sampling programme of both the surface and ground water is also necessary, with the boreholes being sampled by pumping on a regular basis.

11 WATERVAL LANDFILL SITE

11.1 Introduction

The Waterval landfill site is situated approximately 15 kilometres west-northwest of central Johannesburg within the north-western suburbs (Figure 11.1). It is positioned in the centre of a residential area, with a school bordering the north-west corner of the site (Figure 11.2).

The Waterval landfill site is the oldest and largest in Johannesburg. It was established in 1928 and covers an area of approximately 28 hectares. Operations at the site were completed by 1978, 50 years after landfilling commenced. Initial dumping took place into marshy land (Ball, 1984). The site received predominantly urban domestic refuse from the north-western suburbs of Johannesburg, as well as garden refuse and minor amounts of business and industrial refuse. In 1973, a culvert was constructed to contain the natural stream course through, and originating below, the landfill site. Although the culvert was insulated by a metre of clay, ground water seeps through weepholes and joints below the water table (Ball, 1984).

11.2 Geology

The Waterval landfill site is situated on the south-southwest margin of the Johannesburg-Pretoria Granite Dome. The rock types on this contact zone are dioritic gneisses and hybrid granites of the dome, and ultrabasic schists from the ancient Swaziland Supergroup (Ball, 1984). The landfill is situated in the Waterval Valley which trends in a NE/SW direction, bounded on either side by quartzites, forming a catchment area which drains to the north-east.

Profiles of the monitoring boreholes indicate that the valley fill generally comprises a 1.5 metre surface layer of hillwash, followed by a 1.5 metre layer of alluvium, which overlies decomposed residual diorite.

11.3 Previous studies

In September 1976, the Johannesburg City Council initiated monitoring of the Waterval landfill site. Water samples from pollution monitoring boreholes, streams and the culvert were taken during both dry and wet seasons. The locations of the pollution monitoring boreholes are depicted in Figure 10.2. However, as for the Linbro Park monitoring boreholes (Section 10.4), these boreholes were sampled using the open bailer method, where only the uppermost portion of the standing water column is sampled. It is questionable whether these samples were representative of the ground water at that time.

An MSc dissertation by Ball in 1984, gives a fairly extensive report of both the surface and ground water situations at the Waterval site. His project involved the assessment of the pollution status and any variation in pollution with time and distance from the landfill. It was shown, using conductivity and chlorinity as proxy indicators, that significant pollution could be observed in some of the observation boreholes down-gradient of the landfill. A 1.2 metre diameter hole was augured through the landfill which was then sampled and profiled.

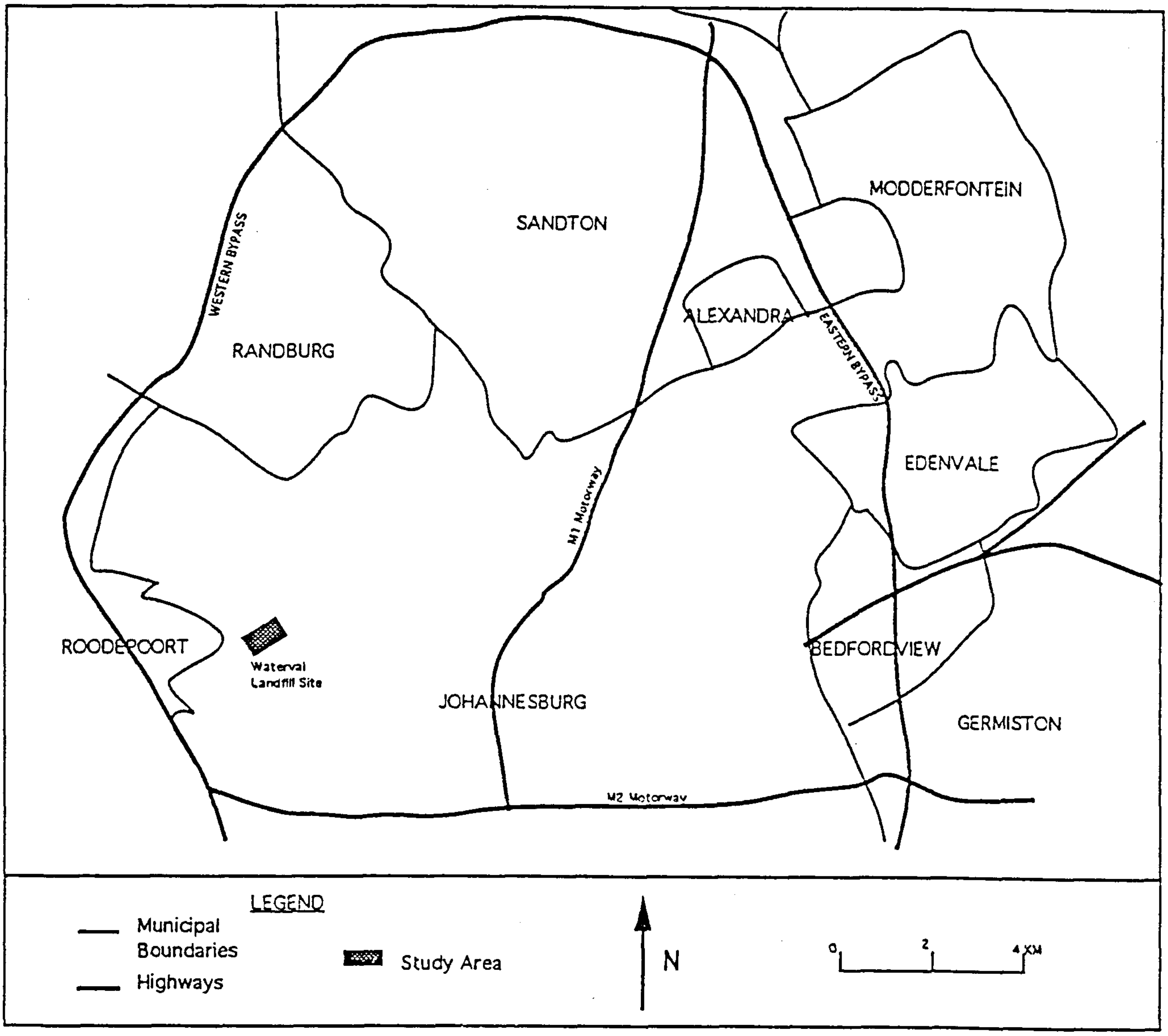


Figure 11.1 Map showing the location of the Waterval landfill site

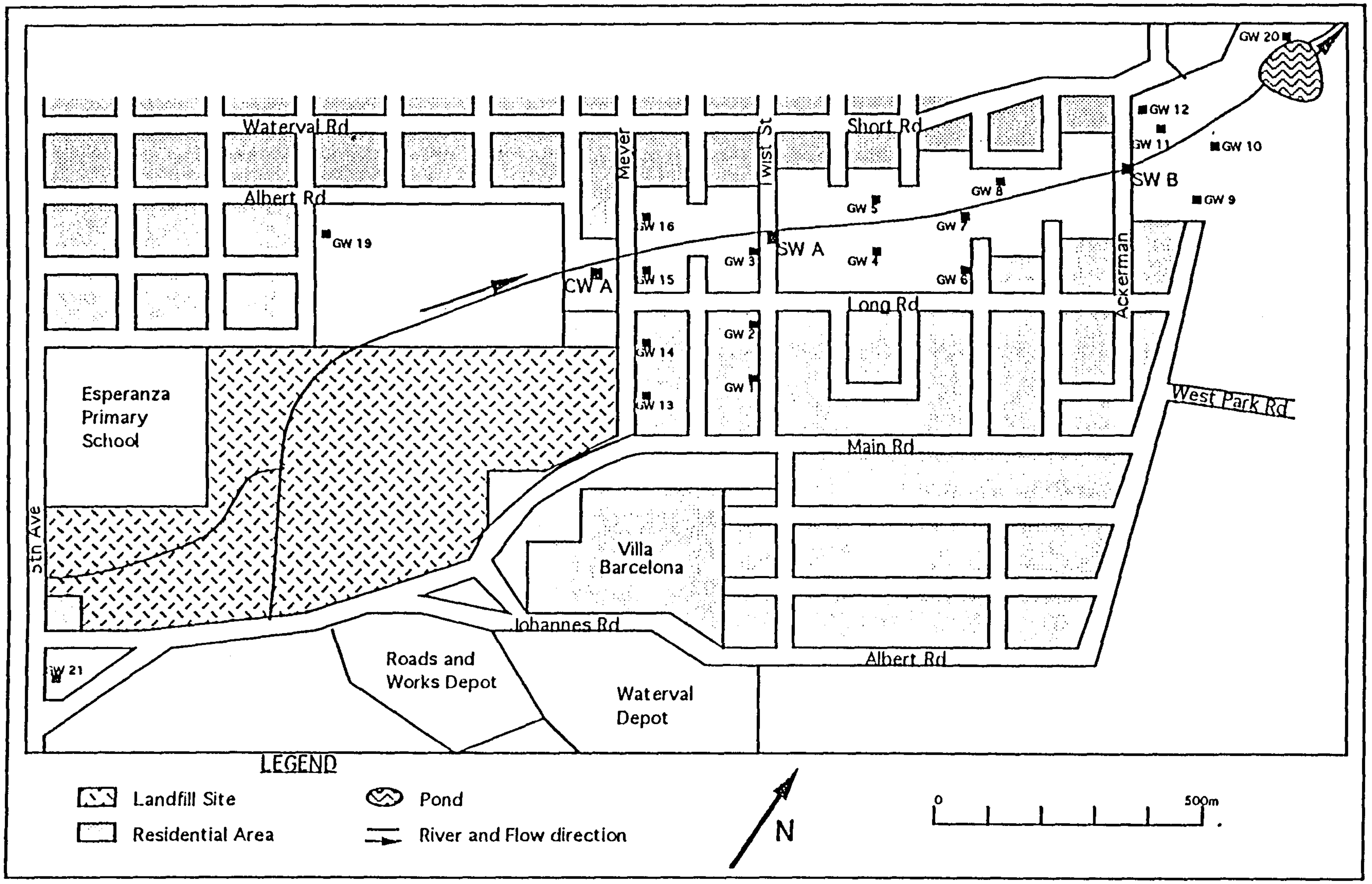


Figure 11.2 Location of ground and surface water pollution monitoring points

It was concluded that, if any ground water pollution was occurring, it would be the result of direct contact between the refuse and the ground water.

11.4 Results

11.4.1 Introduction

Several private boreholes were sampled for stable isotopes and tritium in February 1992. No well-head measurements were recorded for any of these boreholes. The localities of these boreholes are shown in Figures 10.3 and 10.4. An initial attempt to sample the pollution monitoring boreholes early in 1992 proved to be futile as almost all these boreholes were secured with manhole covers, which were impossible to remove without the correct tool. The boreholes that were accessible were dry, and appeared to be filled-in with soil, assumed to be the result of vandalism.

In April 1992, the correct tool was obtained, and most of the manhole covers were removed, some with great difficulty. However, all but one of the boreholes were found to be dry and filled-in with soil, which could only have resulted from the casing collapsing, as vandalism would not have been possible. The only pollution monitoring borehole that could be sampled was GW 21, which is situated up-gradient of the landfill site (Figure 11.2). This borehole had an extremely low yield.

Three surface water samples, for both the stable isotopes and tritium, were also taken. One sample was taken from the culvert beneath the landfill slightly downstream of the landfill, namely CW A, and two more from the stream, namely SW A and SW B (Figure 11.2). At the time, no field measurements were taken. However, in December of 1994, these sampling points were analysed for the various field parameters in order to clarify certain features observed in the environmental isotope data.

11.4.2 Field measurements

The conductivity of the surface water samples was found to be higher in the stream water sample, SW A (Table 11.1) than in the culvert water, CW A, which is predominantly seepage from below the landfill site. This suggests that additional contamination enters the stream from a source situated between the culvert and the SW A sampling point. The estimated flow rate roughly doubles between the culvert and this sampling point, indicating an influx of water, which is also evident in the higher alkalinity value, and the lower pH.

Further downstream, at sample point SW B, the conductivity is lower, the pH returns to the previous value found at CW A, and the alkalinity drops considerably. The estimated flow rate once again increases to roughly double that seen at the SW A sample point, indicating further influx of water into the river, but dissimilar to that seen at SW A. Between SW B and the pond sample, the field chemistry begins to return to the initial values seen in the CW A sample. In all four samples, a fairly high nitrate concentration is evident.

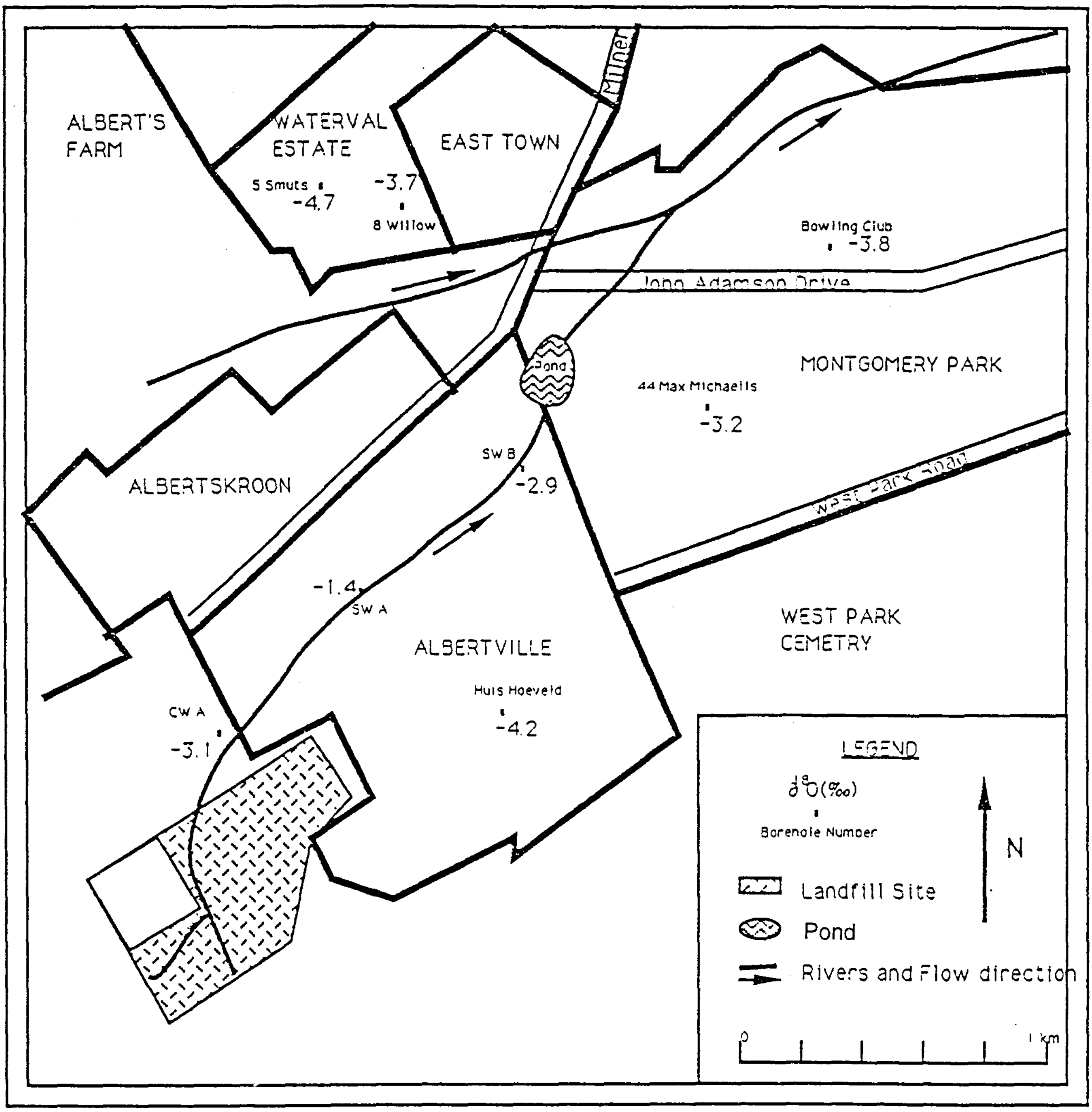


Figure 11.3 Ground water δ ^{18}O values down-gradient of the Waterval landfill site

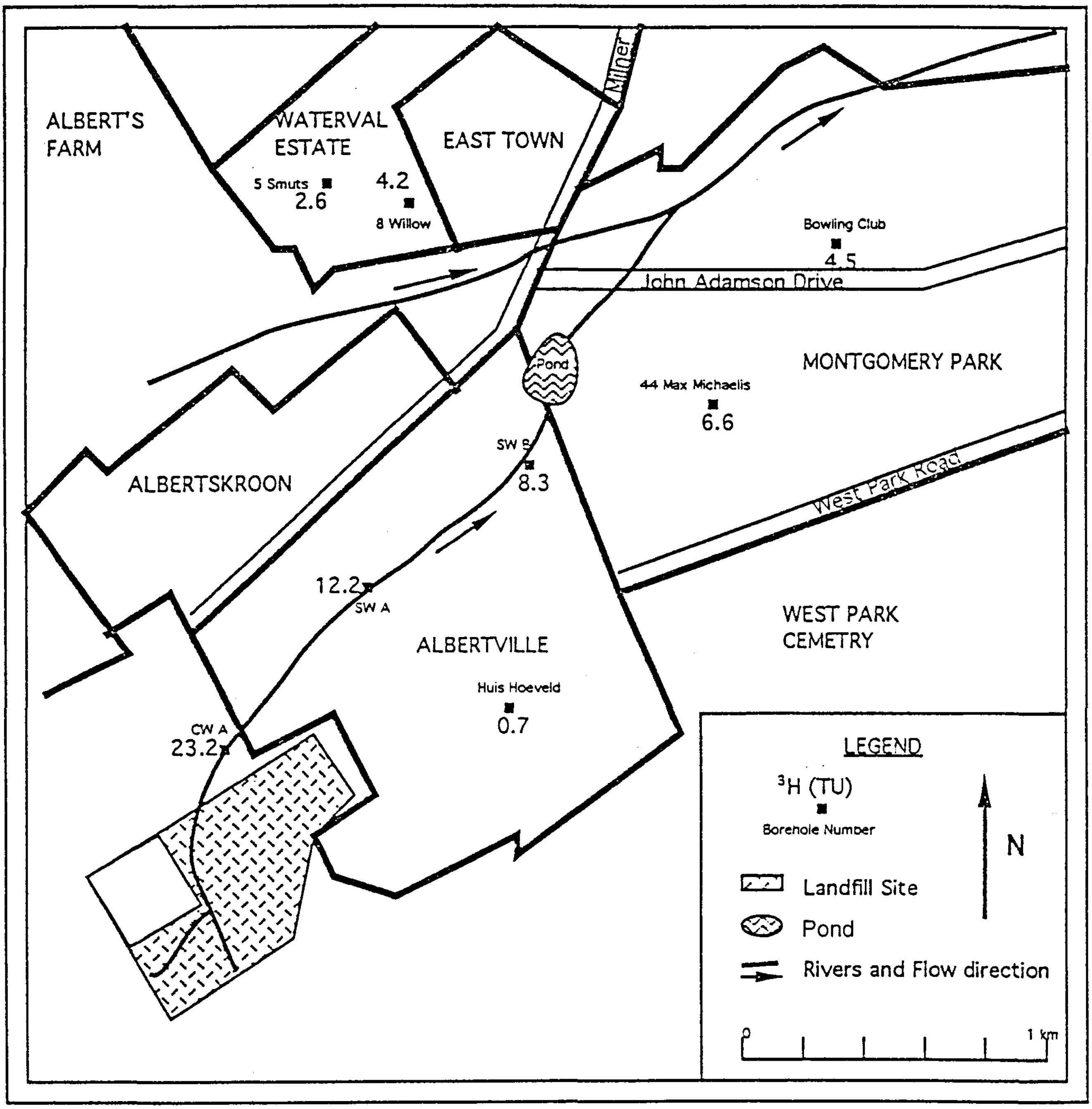


Figure 11.4 Ground water tritium values in TU down-gradient of the Waterval landfill site

Table 11.1 Field measurements for surface water samples (1992)

Sample Number	E.C. (mS/m)	Alkalinity (meq/l)	pH	Estimated Flow Rate (l/sec)	Estimated Nitrate (mg/l)
CW A	68.0	4.0	8.15	~ 1	~ 20
SW A	83.5	4.3	7.80	~ 2	~ 20
SW B	58.0	2.8	8.15	~ 4	~ 20
Pond Entry	65.0	3.4	8.30	~ 4	~ 20

11.5 Isotopes

11.5.1 Stable isotopes

The samples from the culvert and stream have heavier stable isotopic compositions than found in private boreholes in the area, and in GW 21. SW A is significantly heavier than the other two surface water samples, further suggesting the introduction of water from a source other than ground water (Table 11.2). The decrease in the $\delta^{18}O$ value at the SW B sampling point is an indication that isotopically lighter water, probably ground water, has entered the river, substantially diluting the isotopically heavier stream water. Moisture above the water line along the banks of the stream during low flow conditions, supports the assumption that the isotopically lighter water is ground water. All the private boreholes have lower $\delta^{18}O$ values than found in the stream (Figure 11.3). The ground water elevations are higher than the stream bed, with the exception of 44 Max Michealis, where the stable isotope and tritium levels both suggest influence from the river.

Table 11.2 Stable and radioactive isotope values.

Borehole Number	δD (‰)	$\delta^{18}O$ (‰)	^{3}H (TU)
Huis Hoëveld	-24.5	-4.21	0.7±0.2
CW A	-13.2	-3.05	23.2±1.1
SW A	-5.0	-1.41	12.2±0.6
SW B	-16.4	-2.90	8.3±0.5
5 Smuts	-25.3	-4.73	2.6±0.3
Bowling Club	-22.7	-3.75	4.5±0.3
8 Willow	-21.1	-3.74	4.2±0.4
44 Max Michealis	-18.2	-3.21	6.6±0.4

The sample from the culvert, CW A, plots on the MWL, but significantly heavier than the ground water samples, probably due to contributions of RW mains water from the higher lying residences and schools. The stream water sample, SW A, plots considerably heavier than the other samples, along a mixing line between the local ground water and Rand Water mains (Figure 11.5). This suggests a large percentage of RW mains combined with the stream water, and is most probably a leakage in the sewer system which runs along the length of, and below, the stream bed. It is clear that the SW A sample plots between this average value and the value of uncontaminated ground and surface water in the area, indicative of mixing.

11.5.2 Tritium

A significantly high tritium concentration of 23.2 TU is found in the culvert water sample CW A. This is much higher than the normal environmental range, indicating an artificial tritium source within the landfill. The tritium concentration decreases considerably downstream (Figure 11.4). This is probably the result of dilution by two inflows previously identified:

a) channel water, assumed to be Rand Water mains-derived, with an expected value of almost 5 TU;
b) local ground water, with at most 4.5 TU.

The tritium concentrations in the stream are higher than the ground water concentrations encountered in all the private boreholes which, with the exception of Huis Hoëveld, show a turnover time of less than 30 years.

11.6 Summary and Discussion

The study on this landfill site confirms that the UPVC casing, used by the Johannesburg Municipality in the pollution monitoring boreholes, is not sufficiently durable for the extensive period of time required to monitor the landfill during its operation, and after the closure of the site, particularly in loose sediments.

A strong case for the continued monitoring of this landfill site is the fact that private boreholes down-gradient of the landfill, may be directly recharged by the stream, as is suggested by both the $\delta^{18}O$ and tritium values at 44 Max Michaelis. The work of Ball (1984) indicates that pollution could be observed in the (now defunct) network of pollution monitoring boreholes. Downstream private boreholes are potentially susceptible to any pollution within the steam, which, in turn, is partially derived from leachate seeping through weepholes in the culvert. The $\delta^{18}O$ values, together with field chemistry, clearly show that further pollution is occurring to the river downstream of the landfill site. This may be attributed to leakages in the sewage system, which runs along the river bed. It is also evident that this water is diluted further downstream, probably by influent ground water. The University of the Orange Free State recommended a monitoring period of 20 years after the closure of the two Bloemfontein landfill sites (Bekker, 1992). The Waterval site has been closed for less than that suggested time.

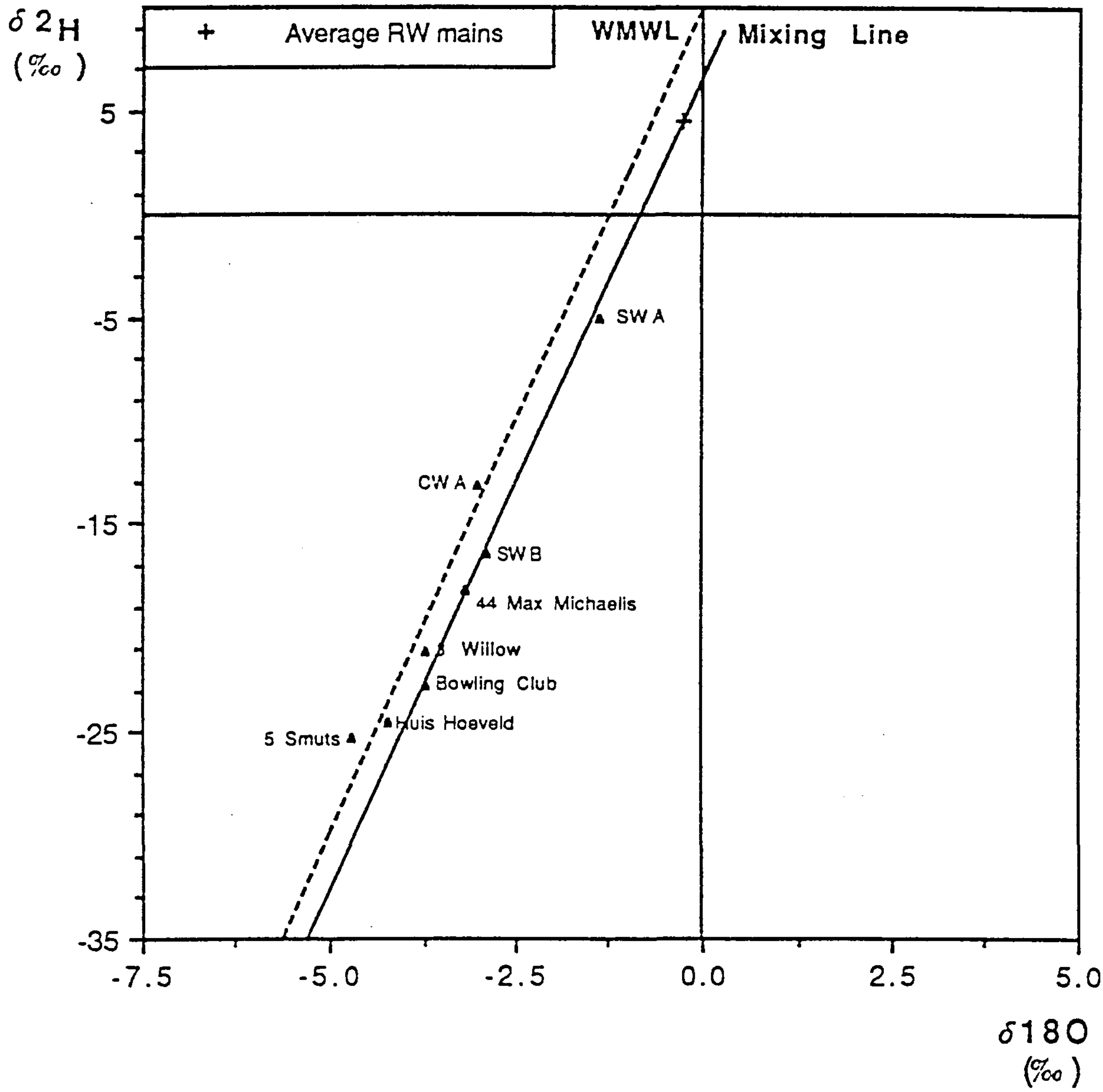


Figure 11.5 Plot of δD against $\delta\ ^{18}$O. Also shown is the meteoric water line, as well as the mixing line between local ground water and RW water.

The significantly high tritium concentration in the culvert water sample, apparently due to artificial tritium within the landfill, is evidence of the continued pollution of the stream, most likely resulting from leachates emanating through the weepholes in the culvert. The source of this artificial tritium is, as yet, unidentified tritium-containing domestic/industrial refuse which was previously deposited at this site. This tritium concentration is considerably diluted as it moves downstream by, what appears to be, both Rand Water mains and ground water. Leachate from this site is therefore uniquely labelled and the artificial tritium can be used as a convenient surface and ground water tracer for pollution from the site. It should be stressed that although several times higher than environmental levels, these tritium concentrations are many orders of magnitude below biologically hazardous levels.

Possible influence of the stream water is seen in the ground water downstream at 44 Max Michaelis. There is also evidence of influent conditions from the ground water in the lower reaches of the stream, up to the dam. However, boreholes situated close to the stream bed might well reflect as much the stream water as they may reflect the ground water, carrying contamination from the landfill.

11.7 Recommendations

At least some of the monitoring boreholes at the Waterval site should be rehabilitated, durably cased, and regularly sampled by pumping. Measurement of certain proxy ions should suffice. Occasional tritium measurements could clearly identify the source of these ions for some years to come.

12 THE BLOEMFONTEIN NORTHERN LANDFILL SITE

12.1 Introduction

The Northern landfill is a Class 2 site, located to the north of Bloemfontein, covering an area of about 35 hectares (Figure 12.1). The slope of the area is to the south-east, ranging from a 40° hill slope in the north-west (Petra Groef), to a 2° in the south-east (Farmer's dam). The landfill itself has a fairly steep slope to the north and north-east, and is situated on a slightly higher elevation due to the high resistance to weathering of the underlying dolerite.

Water from the dolerite mine, Petra Groef, located on the north-western boundary and upgradient of the northern landfill site (Figure 12.1), may affect the chemistry of the ground and surface water, as a large percentage of run-off from the mine drains through a portion of the landfill. A catchment dam is situated virtually on the eastern boundary of the landfill site, and a farmer's dam is positioned about 100 metres further downstream (Figure 12.1).

Three boreholes have been drilled to monitor pollution from the landfill. Borehole N 0001 is situated approximately in the middle of the site, while boreholes N 0002 and N 0003 are down-gradient of the landfill site, along its eastern boundary (Figure 12.1). All three boreholes were drilled into dolerite to a depth of about 35 m (Table 12.1) (Bekker, 1992).

12.2 Hydrogeology

The landfill site is underlain by 3 - 4 m of very coarse and crystalline, weathered dolerite, followed by fresh dolerite, which is estimated to be about 38 m thick forming a solid base for the flow of ground water (Bekker, 1992). The yield of the monitoring boreholes in the weathered dolerite ranges from 0.2 to 0.5 l/s, and the permeability of this dolerite, measured by slug tests, was found to be fairly high, with a K-value of between 0.4 and 0.6 m/d for boreholes N 0002 and N 0003. The expected ground water flow in the valley is in a south-easterly direction, following the topography, towards the two dams. However, ground water within and below the site will flow in a northerly to easterly direction.

The run-off water from the upper reaches of the area is captured in the catchment dam, and includes drainage from the Petra Groef mine. A large portion of the surface drainage from the mine is diverted along a channel situated to the north of the site to prevent it from flowing through the site (Figure 12.1). A pond is situated on the landfill site, north of, and down-gradient from, borehole N 0001, designated P 0001.

The water levels of the pollution monitoring boreholes at the time of drilling were between 2 and 3 m below the surface (Bekker, 1992). Borehole N 0003, which was the only rest level measurement recorded during the sampling in August of 1993, dropped slightly to 3.5 m (Table 12.1), which is still very shallow.

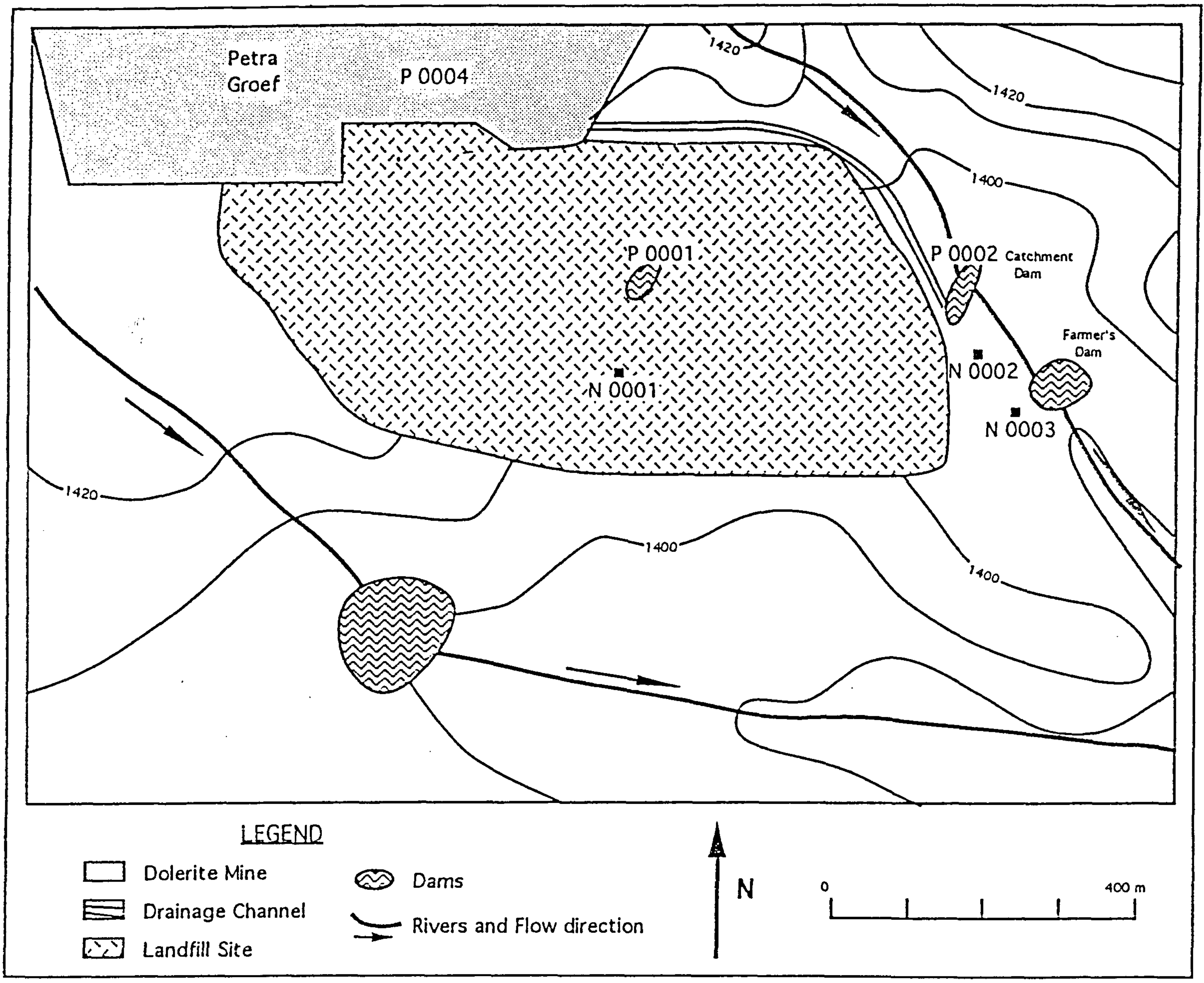


Figure 12.1 Map of the Bloemfontein North landfill site, showing the location of the pollution monitoring boreholes, as well as the Petra Groef dolerite mine

Table 12.1 **Rest levels and borehole depths of the pollution monitoring boreholes**

Borehole Number	Borehole Depths (m)	Rest Levels 21/02/92 (Bekker, 1992) (m below surface)	Rest Levels 30/08/93 (m below surface)
N 0001	31.5	3.0	
N 0002	38.5	2.0	
N 0003	31.5	2.0	3.5

12.3 Previous Studies

A study is being conducted by the Institute for Ground Water Studies at the University of the Orange Free State on this landfill site, initiated by the Bloemfontein Health Department. It has involved the sinking of boreholes down-gradient of the landfill, an interpretation of the local geology, as well as sampling and chemical analyses of the ground and surface water.

In 1992, borehole N 0001 was found to be significantly polluted, with high concentrations of organics, calcium, magnesium, chloride (Table 12.3) and a manganese concentration of 8.0 mg/l. Borehole N 0002, although considerably less polluted than N 0001, had significantly high iron and lead concentrations of 2.37 and 0.63 mg/l respectively.

12.4 Results of the present study

12.4.1 Introduction

An environmental isotope and hydrochemistry survey of the three pollution monitoring boreholes was conducted in January, 1992, and in August, 1993. The volume of water standing in each hole was purged, using a mobile submersible pump, and a constant conductivity reading was obtained prior to the collection of each sample. A carbon-14 sample was not taken at N 0001 as it is believed that the chemistry would be too complex due to significant pollution, including organics.

12.4.2 Hydrochemistry

Well-head observations are given in Table 12.2, and the major ion concentrations for the various sampling dates is given in Table 12.3. The conductivity of borehole N 0001 in 1993 had an initial value 190 mS/m with much scum, but stabilised at 550 mS/m once the hole had been sufficiently purged. This was considerably lower than the value of 620 mS/m obtained during sampling in 1992. An initial value of 80 mS/m was measured in borehole N 0003, but increased to between 115 and 120 mS/m once a sufficient volume of water had been extracted.

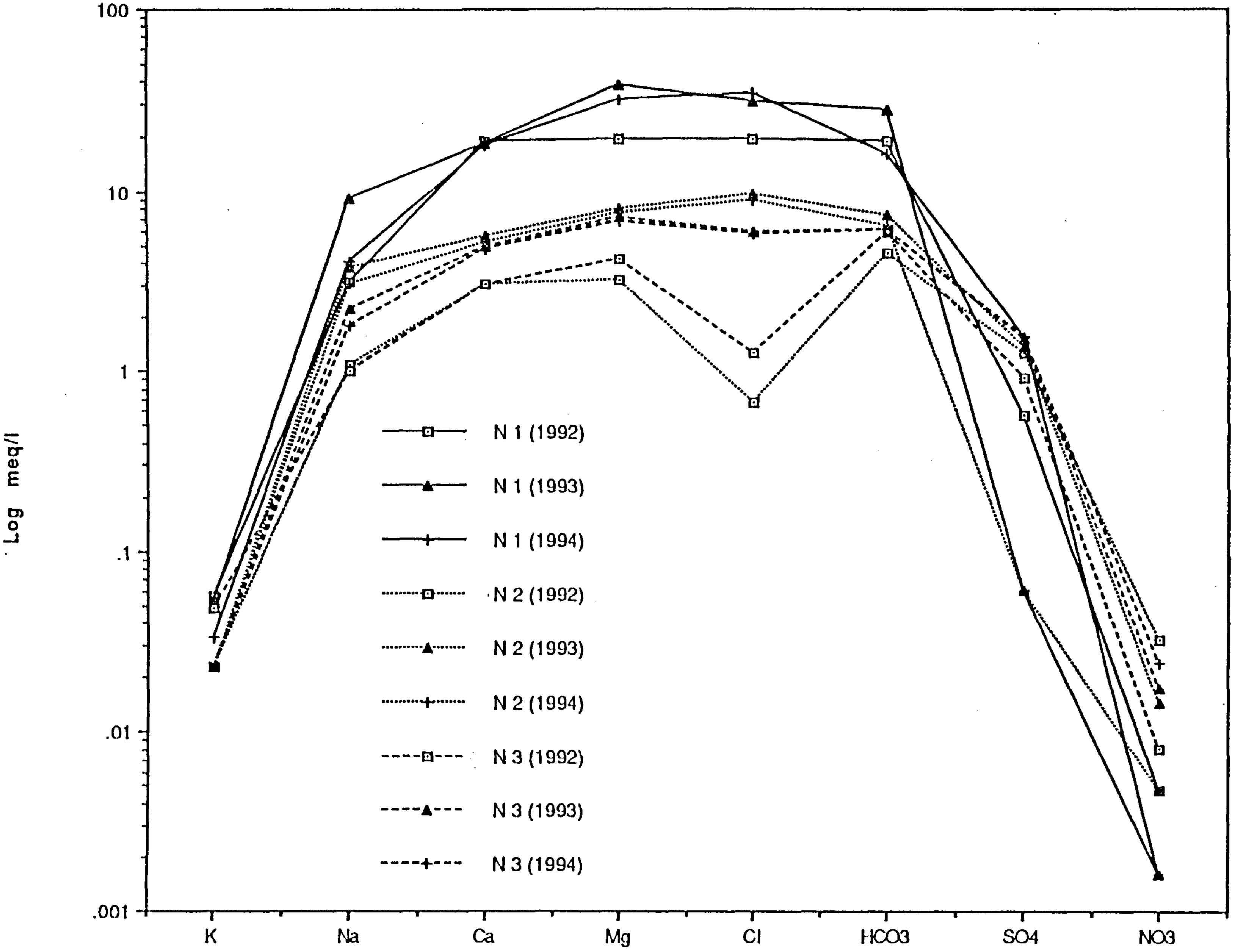


Figure 12.2 Modified Schoeller diagram for Bloemfontein North boreholes

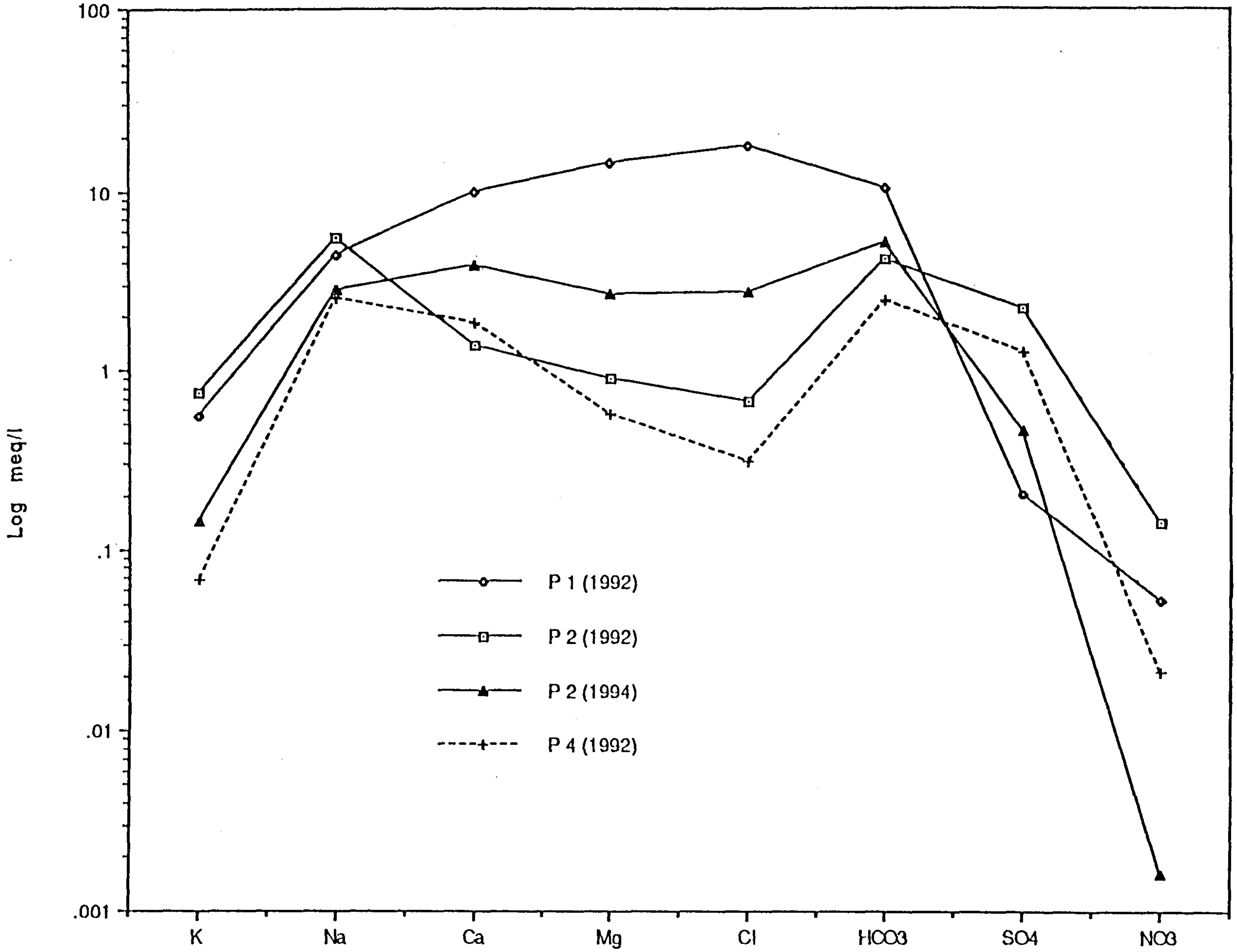


Figure 12.3 Modified Schoeller diagram for Bloemfontein North surface water

Table 12.2 Well-head measurements for the pollution monitoring boreholes 1993

Borehole Number	Alkalinity (meq/l)	Conductivity (mS/m)	pH	Temperature (°C)
N 0001		550		
N 0002	7.1	120	7.35	19.0
N 0003	6.4	115	7.00	19.0

The major differences between the boreholes are in the calcium, magnesium and chloride concentrations, and to a lesser extent, sodium and alkalinity. However, it is suspected that the alkalinity value is not purely due to HCO_3, but from other compounds resulting from pollution. The occurrence of higher concentrations of chloride, as well as sodium, calcium and magnesium, in boreholes N 0002 and N 0003 subsequent to the 1992 sample, suggests incipient pollution down-gradient of the landfill (Figure 12.1).

It is possible to compare the 1992 catchment dam sample, P 0002, with the sample from the dolerite mine, P 0004, as well as with the 1992 samples of N 0002 and N 0003 (Figure 12.2). However, the 1994 P 0002 sample is more characteristic of P 0001, the pond sample alongside N 0001, and reasonably similar to N 0002 and N 0003. The higher concentrations of the major ions in the two down-gradient boreholes is either due to the enrichment of the ions in the pond as a result of evaporation, or due to the encroachment of the polluted ground water from the site.

12.5 Isotopes

12.5.1 Stable isotopes

The changes in the stable isotope compositions in the three monitoring boreholes (Table 12.4) are interpreted as follows:

The samples from borehole N 0001 plot slightly to the left of the world meteoric water line (Figure 12.4), possibly due to hydrogen isotopic exchange with organics within the landfill. The values of both borehole N 0002 and N 0003 indicate significant, but widely different evaporation, suggesting recharge from evaporating surface water. During the sampling in 1992, the catchment dam was almost dry, probably resulting in the significantly heavy isotopic composition of N 0002. During 1993, this dam was completely dry. It appears as if the farm dam became the main source of recharge for these two boreholes, resulting in the closely similar stable isotope compositions, along the evaporation line (Figure 12.4).

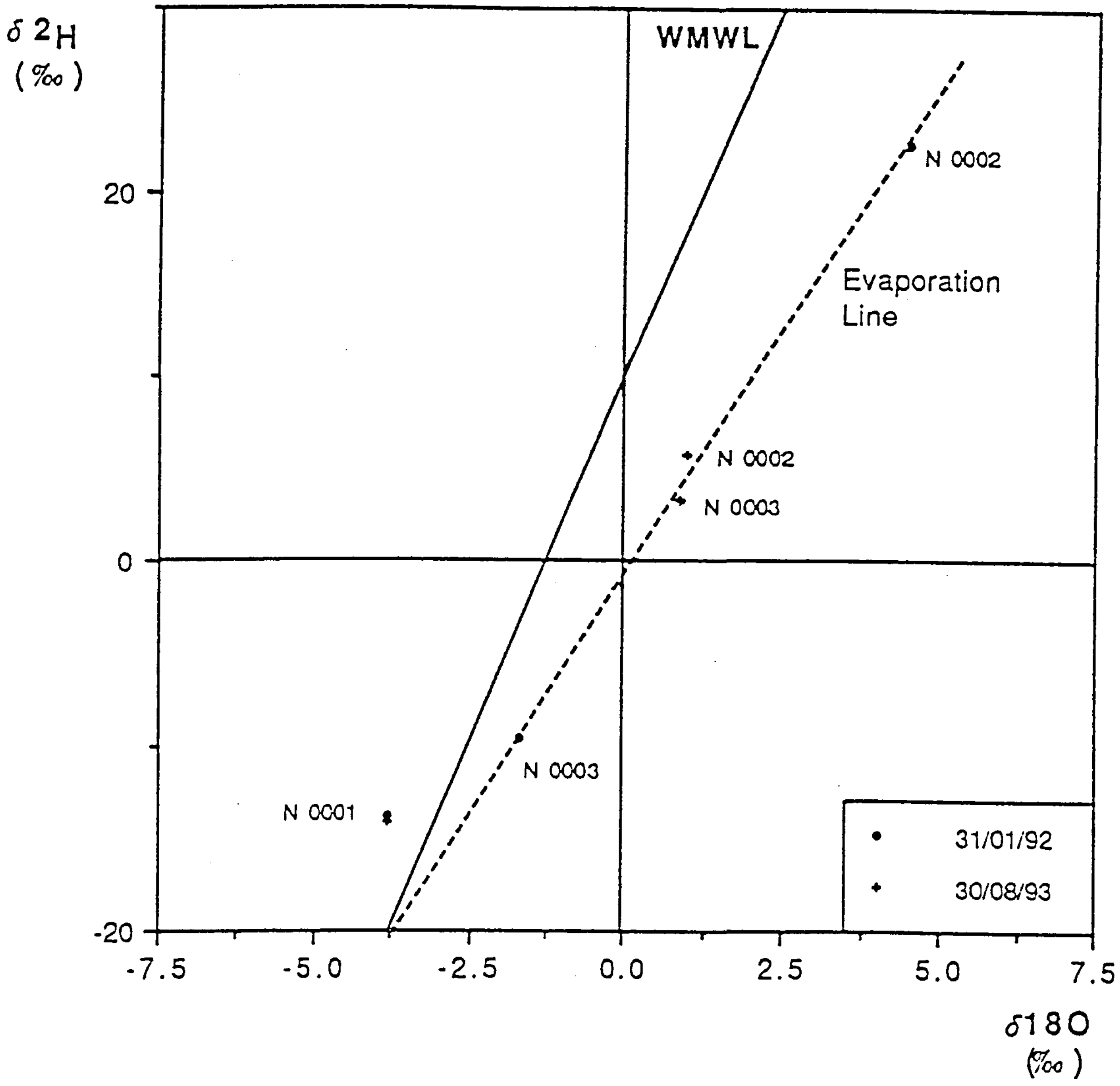


Figure 12.4 Plot of δD against δ ^{18}O. Also shown is the world meteoric water line

Table 12.3 Major ion concentrations in meq/ℓ for different sampling dates - Bloemfontein North

Borehole Number	Dated Sampled	Potassium (meq/ℓ)	Sodium (meq/ℓ)	Calcium (meq/ℓ)	Magnesium (meq/ℓ)	Chloride (meq/ℓ)	Bicarbonate (meq/ℓ)	Sulphate (meq/ℓ)	Nitrate (meq/ℓ)
N 0001	Jul 92	0.06	3.2	18.9	10.0	19.10	18.6	0.6	0.0
N 0001	Aug 93	0.05	9.1	18.5	38.2	31.3	27.8	0.1	0.002
N 0001	Apr 94	0.03	4.1	17.6	31.7	34.60	16.1	1.6	0.0
N 0002	Jul 92	0.02	1.1	3.0	3.2	0.70	4.6	1.3	0.0
N 0002	Aug 93	0.02	3.8	5.6	8.1	9.70	7.3	1.4	0.0
N 0002	Apr 94	0.02	3.1	5.2	7.7	9.00	6.5	0.1	0.0
N 0003	Jul 92	0.05	1.9	3.0	4.2	1.30	6.0	1.0	0.0
N 0003	Aug 93	0.02	2.2	4.9	7.2	6.00	6.1	1.5	0.0
N 0003	Apr 94	0.02	1.8	4.8	6.8	5.80	6.2	1.6	0.0
P 0001	Jul 92	0.56	4.4	10.0	14.2	17.70	10.5	0.2	0.1
P 0001	Apr 94	0.08	6.7	2.9	10.6	7.3	7.3	1.3	0.0
P 0002	Jul 92	0.74	5.5	1.4	0.9	4.3	4.3	2.2	0.1
P 0002	Apr 94	0.14	2.9	3.9	2.7	5.3	5.3	0.5	0.0
P 0004	Jul 92	0.07	2.6	1.9	0.6	2.5	2.5	1.3	0.0

Table 12.4 **Stable isotope values for the pollution monitoring boreholes for the 1992 and 1993 sampling periods**

Borehole Number	δD (‰)		$\delta^{18}O$ (‰)	
	Jan 1992	**Aug 1993**	**Jan 1992**	**Aug 1993**
N 0001	-13.7	-14.1	-3.83	-3.79
N 0002	+22.6	+5.7	+4.44	+0.98
N 0003	-9.5	+3.2	-1.72	+0.88

12.5.2 Tritium

The tritium concentrations in the three pollution monitoring boreholes (Table 12.5) exceed the present day environmental range in the southern African continental environment (≤ 5 TU). The significantly high tritium concentration found in borehole N 0001 indicates a source of artificial tritium within the landfill (Table 12.4). The only significant increase in tritium concentration between the two sampling periods is seen in the N 0002 samples, possibly indicating the encroachment of the polluted ground water from the landfill. The relative amounts will depend on rainfall and level of the dams.

Table 12.5 **Radioactive isotope values for the pollution monitoring boreholes for the 1992 and 1993 sampling periods**

Borehole Number	^{3}H (TU)		^{14}C (pMC)		$\delta\,^{13}C$ (‰)	
	Jan 1992	**Aug 1993**	**Jan 1992**	**Aug 1993**	**Jan 1992**	**Aug 1993**
N 0001	26.5±1.5	27.7±1.4				
N 0002	8.0±0.5	11.8±0.8	108.2±0.9	111.4±0.7	-7.9	-10.0
N 0003	8.1±0.6	8.8±0.7	113.8±0.8	111.8±0.7	-8.1	-10.0

12.5.3 Carbon-14

A carbon-14 sample was not taken from borehole N 0001 due to the complexity of the ground water chemistry within the actual landfill. A slight increase in the carbon-14 concentration of borehole N 0002, which is possibly related to the higher tritium concentration also found in this borehole, indicates leachate encroachment (Table 12.5). The values lie within the range of present day environmental values for southern Africa, and indicate ground water mean residence times of less than 30 years, confirming the tritium observations.

12.6 Summary and discussion

The increase in the conductivity of the 1993 samples of borehole N 0001 and N 0003 once sufficient water had been removed from the borehole, is further evidence of the need to sufficiently purge a borehole before sampling.

In both the environmental isotope and hydrochemical data, boreholes N 0002 and N 0003 are seen to respond quite rapidly to surface water in the catchment and farm dams. In 1992, the catchment dam was drying and the farm dam water stood close to the two boreholes. At that stage, the stable isotope contrast between them was greatest, with N 0002 showing a strong evaporation signal. In 1993, with the catchment dam dry, and the farm dam level considerably lower, the two boreholes have closely similar stable isotope signals, albeit with an evaporation signal. At this stage too, the carbon-14 values have become identical, as are the $\delta\ ^{13}C$ values, considerably lighter than in 1992. These values suggest more uniform ground water in the vicinity of these two boreholes.

12.7 Recommendations

The isotope study has shown the profound influence of surface water on the two monitoring boreholes N 0002 and N 0003. It is therefore recommended that additional monitoring boreholes be sited well away from surface drainage.

13 THE BLOEMFONTEIN SOUTHERN LANDFILL SITE

13.1 Introduction

The Southern landfill site, situated to the south of Bloemfontein, covers an area of approximately 44 hectares, sloping slightly to the south-west at approximately 4° (Bekker, 1992). The site is mainly a Class 2 site, with a small area on the east side of the site designated as a Class 1 site.

Three pollution monitoring boreholes, S 0003 to S 0005, were drilled down-gradient of the Class 2 site within 15 m of the western boundary, between the highway and the landfill site (Figure 13.1). Two more boreholes, S 0001 and S 0002, intended to monitor the Class 1 site are situated to the east of these (Seymour *et al.*, 1991). The nearest private boreholes in the area are at a distance of 600 to 800 m in a south-westerly direction from the site.

13.2 Hydrogeology

The landfill site is underlain by Karoo sediments of the Beaufort Group, mainly siltstone with lenses of shale and sandstone. A thin dolerite dyke is situated about 15 m east of the landfill and slopes about 25° to the west (Figure 13.1).

Borehole S 0001 was drilled almost entirely through horizontally bedded siltstones interbedded with thin layers of clay, sandstone and shale (Seymour *et al.*, 1991). A 5 m layer of dolerite is located above these siltstones in borehole S 0002. In borehole S 0003, weathered dolerite is located at a depth of 5 m, while boreholes S 0004 and S 0005 made contact with the weathered dolerite at a depth of about 35 m (Bekker, 1992).

Boreholes S 0001 to S 0003 were dry during the drilling operations, although water did seep into the holes subsequent to drilling and rest levels were measured (Table 13.1). The expected direction of ground water flow is in a south-westerly direction, following the surface gradient, towards the Van der Walt farm, as well as several other farms. Slug tests, established that the permeability of the underlying siltstones and shales. The K-value determined at borehole S 0005 is about 3 x 10^{-2} m/d (Bekker, 1992). This indicates that the shale and siltstone formation is fairly well fractured if the recommended hydraulic conductivities after Davis, 1969, Dunn and Leopold, 1978; Freeze and Cherry, 1979 are taken into consideration.

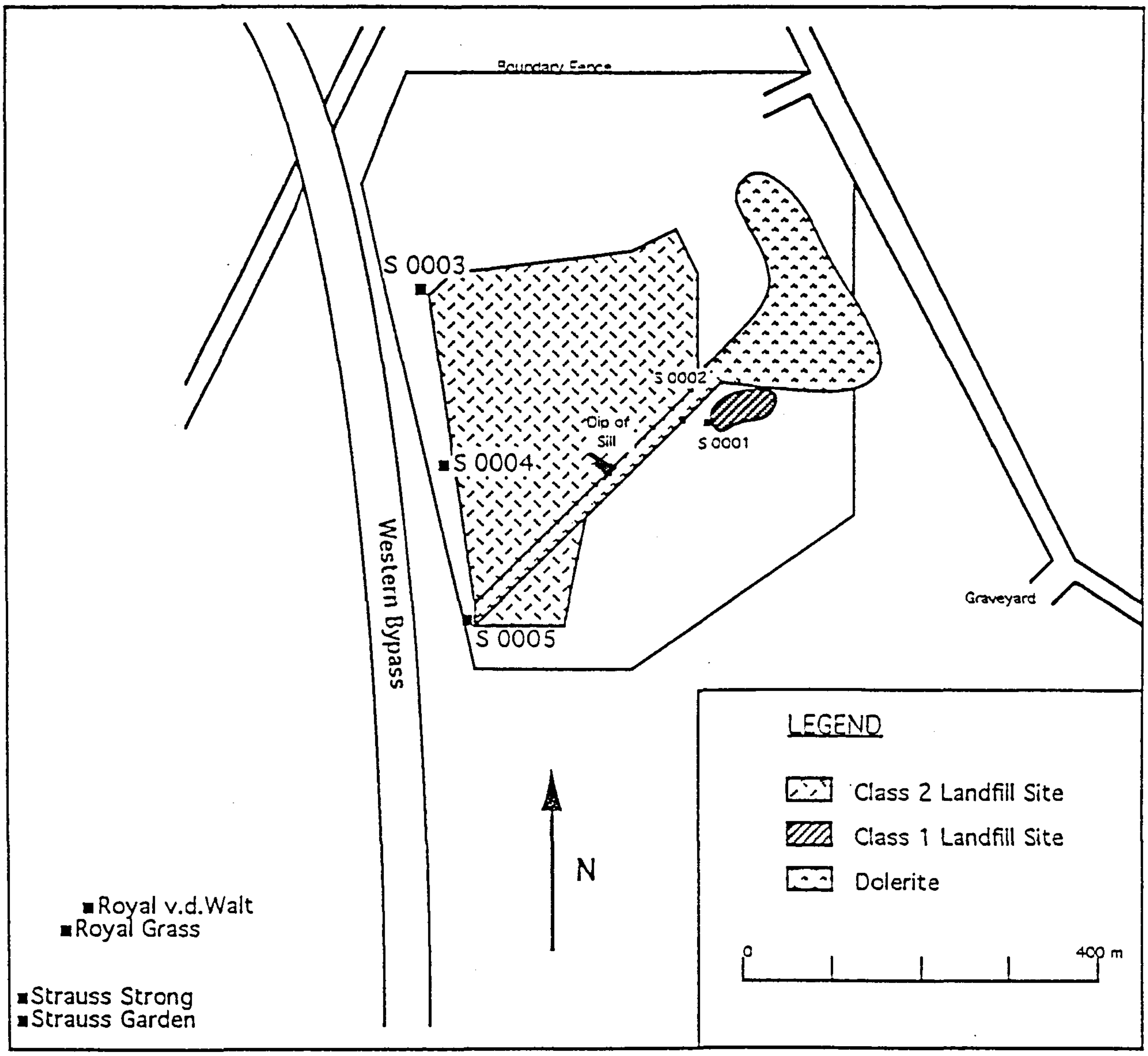


Figure 13.1 Map of the Bloemfontein Southern landfill site, showing the location of the pollution monitoring boreholes, as well as the farm boreholes

Table 13.1 Rest levels and borehole depths of the pollution monitoring boreholes and farm boreholes

Borehole Number	Borehole Depths (m)	Rest Levels 31/02/92 (Bekker, 1992) (m below surface)	Rest Levels 30/08/93 (m below surface)
S 0001	46.0	28.5	
S 0002	35.0	28.5	
S 0003	17.0	14.8	
S 0004	40.0	18.1	22.3
S 0005	38.0	21.4	24.7
Royal Grass	36.0	22.0	
Royal v.d. Walt		22.0	

13.3 Previous studies

The Bloemfontein Health Department initiated a study on this landfill site, which is being carried out by the Institute for Ground Water Studies at the University of the Orange Free State. The study included the sinking of the pollution monitoring boreholes down-gradient of the site, as well as an interpretation of the local geology (Bekker, 1992). These boreholes, as well as two farm boreholes, Royal van der Walt and Royal Grass, were sampled for chemical analyses.

13.4 Results of the Present Study

13.4.1 Introduction

An environmental isotope and hydrochemical survey of monitoring and farm boreholes was conducted in January, 1992, and again in August, 1993. Borehole S 0001 had a very low yield, and boreholes S 0002 and S 0003 were dry. During the 1992 sampling period, it was observed that a large part of south section of the landfill had been eroded away due to heavy rains. A substantial amount of run-off had occurred, flowing in a south-westerly direction towards borehole S 0005, as well as through a culvert under the highway, in the direction of the farms. The damage to the landfill had been repaired by the time the 1993 samples were taken.

13.4.2 Hydrochemistry

The well-head observations are given in Table 13.2, and the major ion concentrations for the different sampling dates in Table 13.3. It is interesting to note that the differences between the boreholes are mainly in the concentrations of calcium, magnesium and chloride, and significantly less in alkalinity. The other ionic concentrations are comparatively invariant. Calcium, magnesium and chloride also show the greatest variability at the northern landfill site. These three ions are therefore taken as characterising leachate formed in these landfill sites. Circumstantial evidence points to borehole S 0005 as most prominently reflecting pollution from the landfill (Figure 13.2). Borehole S 0001, upstream from the landfill, and at low mineralisation, is a Na-HCO_3 dominant ground water and is, for the purpose of comparison, taken as "natural" ground water (Figure 13.3). Taking these two cases as end-members, the Schoeller diagram in Figure 13.2 suggests that the farm boreholes Van der Walt, Grass and Strauss show the (inferred) influence of the polluted end-member in decreasing proportion with their distance from the landfill. This same sequence is seen in the Piper diagram (Figure 13.4).

Table 13.2 Well-head measurements for the pollution monitoring boreholes and farm boreholes

Borehole Number	Alkalinity (meq/l)	Conductivity (mS/m)	pH	Temperature (°C)
S 0004	10	100	6.60	20.5
S 0005	15.5	400	6.80	22.5
Royal v.d. Walt	10.2	200	7.15	18.5
Royal Grass	8.9	145	6.80	19.6
Strauss Garden	6.3	100	6.85	19.4
Strauss Strong	6.6	97	7.05	19.3

13.5 Isotopes

13.5.1 Stable isotopes

Three separate groups plot along the meteoric water line (Figure 13.5). The samples from the most polluted monitoring borehole S 0005, are the isotopically heaviest, followed by S 0004 and the Royal van der Walt sample. The third group, which has the lightest isotopic composition, consists of the Royal Grass and the Strauss samples, and show some local evaporation (farm dam infiltration?). This same trend was found in the well-head measurements, the heavier stable isotope compositions corresponding to the higher alkalinity and conductivity values. There is no clear evidence of evaporation in any of the samples at this landfill site.

Table 13.3 Major ion concentrations in meq/ℓ for different sampling dates - Bloemfontein South

Borehole Number	Dated Sampled	Potassium (meq/ℓ)	Sodium (meq/ℓ)	Calcium (meq/ℓ)	Magnesium (meq/ℓ)	Chloride (meq/ℓ)	Bicarbonate (meq/ℓ)	Sulphate (meq/ℓ)	Nitrate (meq/ℓ)
S 0001	Jul 91	0.02	3.0	0.7	0.2	0.5	2.2	0.31	0.01
S 0001	Sep 93	0.02	4.9	3.1	0.6	0.4	8.5	0.37	0.002
S 0001	Apr 94	0.02	6.6	3.0	0.6	0.4	9.5	0.14	0.002
S 0003	Jan 92	0.25	9.4	4.8	4.7	3.1	10.2	5.79	0.10
S 0003	Sep 93	0.15	5.6	1.1	5.3	2.1	5.3	4.47	0.002
S 0003	Apr 94	0.15	7.1	5.3	5.4	2.1	11.1	4.38	0.002
S 0004	Jan 92	0.09	2.0	3.0	2.1	1.4	5.3	0.61	0.01
S 0004	Sep 93	0.05	2.2	5.1	3.7	1.6	9.8	0.08	0.00
S 0004	Apr 94	0.06	2.1	4.3	3.1	1.4	8.3	0.14	0.002
S 0005	Jan 92	0.21	4.1	24.4	14.8	27.1	11.2	0.37	0.01
S 0005	Sep 93	0.08	3.7	23.2	18.0	27.4	15.4	0.69	0.002
S 0005	Apr 94	0.08	3.6	20.3	14.8	20.6	17.5	0.29	0.002
Royal Grass	Jul 91	0.05	2.9	6.2	4.4	4.6	8.4	0.43	0.01
Royal Grass	Oct 93	0.07	2.9	7.9	6.3	7.5	8.2	0.49	0.01
Royal Grass	Apr 94	0.07	3.0	5.4	6.4	8.2	6.0	0.51	0.002
v/d Walt	Jun 92	0.10	3.1	9.8	8.6	12.8	10.5	0.51	0.01
v/d Walt	Sep 93	0.07	2.8	10.2	9.2	11.2	10.0	0.71	0.002
v/d Walt	Apr 94	0.08	2.8	12.1	9.5	13.8	10.2	0.73	0.002
Strauss	Sep 93	0.06	2.7	4.5	3.5	2.9	6.7	0.88	0.04
Strauss	Apr 94	0.07	2.4	4.4	3.7	3.3	6.6	0.71	0.04

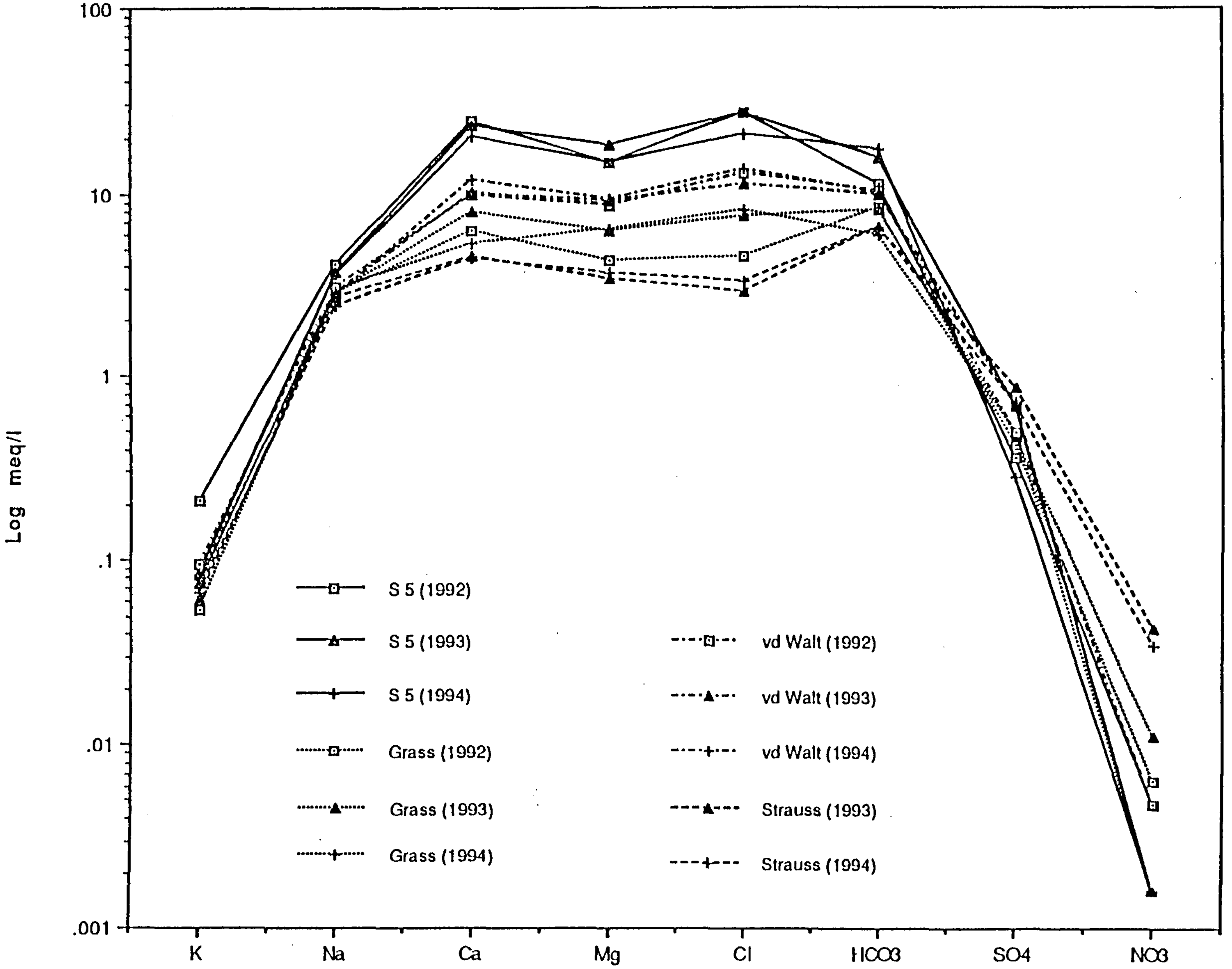


Figure 13.2 Modified Schoeller diagram for "downstream" boreholes at Bloemfontein South

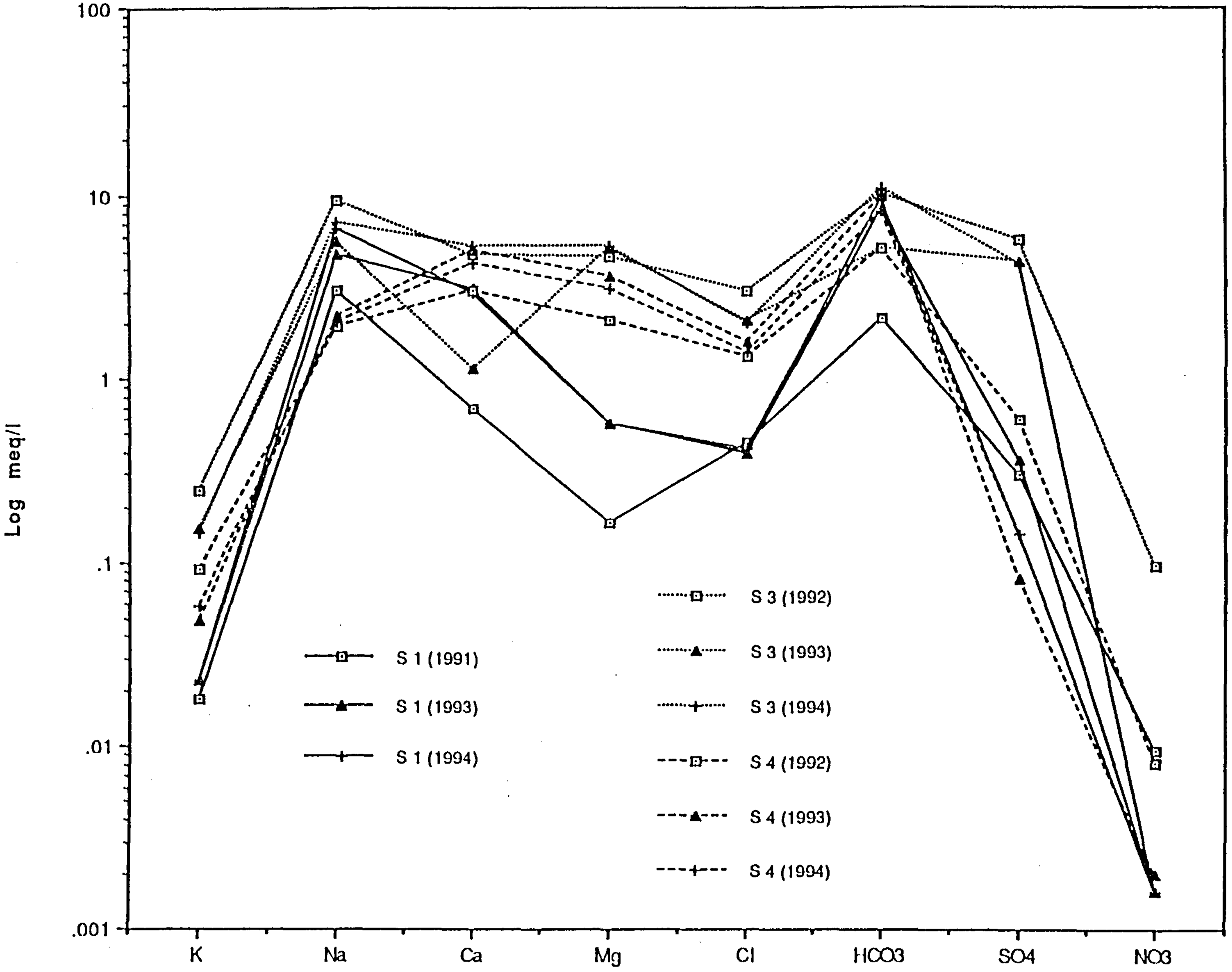


Figure 13.3 Modified Schoeller diagram for "upstream" boreholes at Bloemfontein South

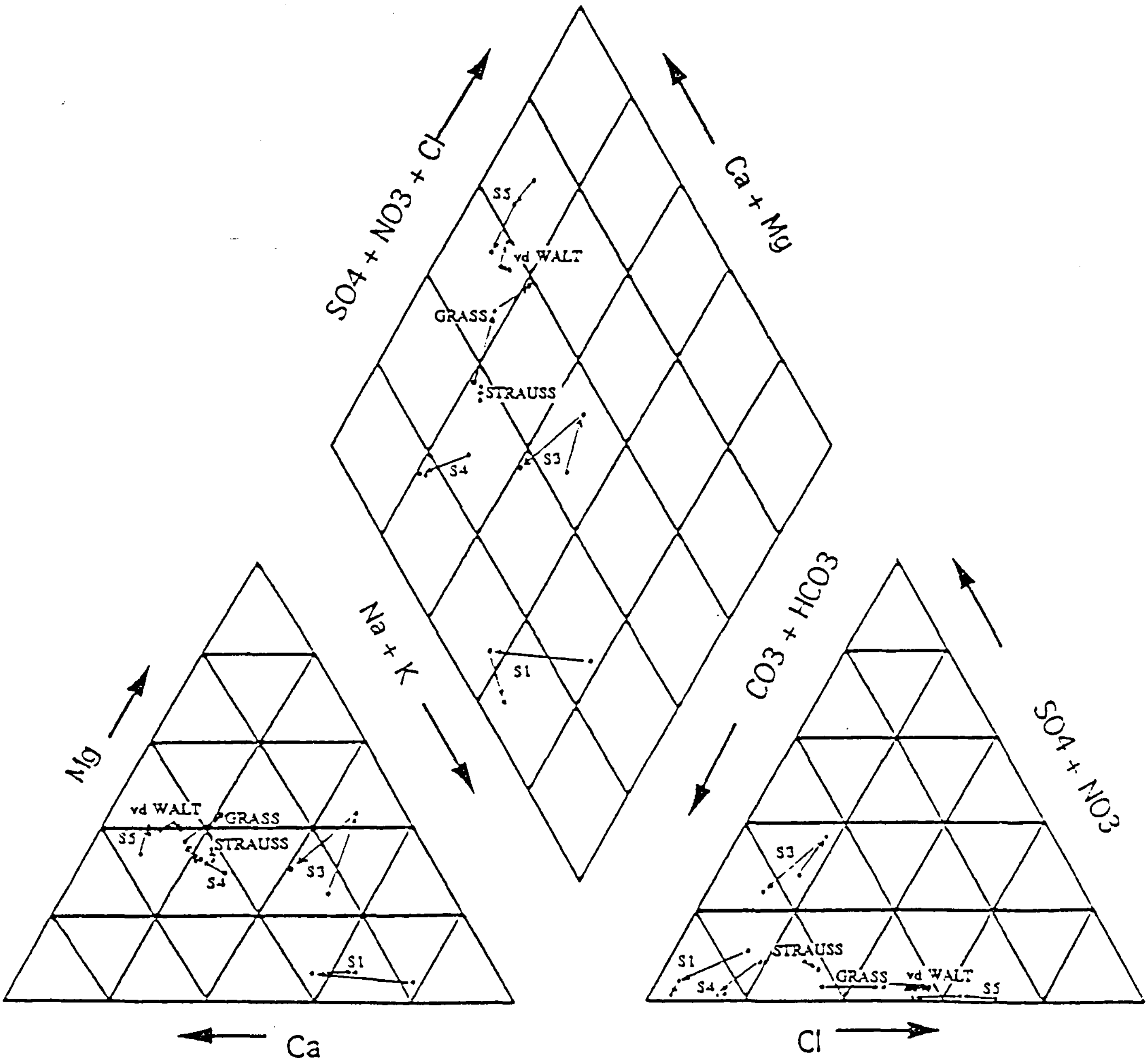


Figure 13.4 Piper diagram for Bloemfontein South

Table 13.4 **Stable isotope values for the pollution monitoring boreholes and farm boreholes for 1992 and 1993**

Borehole Number	δD (‰)		$\delta^{18}O$(‰)	
	Jan 92	**Aug 93**	**Jan 92**	**Aug 93**
S 0004	-36.9	-36.8	-5.87	-5.73
S 0005	-31.2	-31.5	-5.08	-4.90
Royal v.d. Walt	-36.1	-35.8	-5.88	-5.65
Royal Grass	-41.0	-43.7	-6.24	-5.95
Strauss Garden		-42.0		-6.02
Strauss Strong		-41.8		-6.10
S 0001	-37.1		-5.21	

13.5.2 Tritium

Borehole S 0005, which has a tritium concentration considerably higher than the normal environmental values expected in the southern African environment, increases between 1992 and 1993 by 12 TU, indicating the continued influx of artificial tritium into the ground water. The tritium values of the other boreholes remain virtually unchanged. Borehole S 0004, the Strauss boreholes, and the Royal Grass sample, have tritium concentrations less than 2 TU, indicating mean residence times of less than 30 years. However, the Royal van der Walt sample has a tritium content at the upper limit of the normal environmental range, suggesting incipient contamination by the landfill.

13.5.3 Carbon-14

The highest carbon-14 concentration is found in the polluted borehole S 0005. The value of 125 pMC is out of normal environmental range, and could be ascribed to artificial carbon-14 leached from the landfill. The positive $\delta\ ^{13}C$ and high alkalinity of the ground water supports this interpretation.

The increase of some 20 pMC over 18 months observed in the nearby borehole S 0004, appears to occur due to a quite different mechanism. It is accompanied by a decrease in the $\delta\ ^{13}C$ value by some 11‰, which suggests a biogenic source. It is not accompanied by any chemical indication of pollution. As with other monitoring boreholes, S 0004 is only pumped for an hour or so during infrequent sampling. This does not induce much displacement of the surrounding ground water. It is possible that ground water in the area was only gradually drawn into the borehole during brief and widely spaced pumping periods. As the ground water is being fairly rapidly recharged at this site (mean residence time < 30 years), it would appear that no significant leachate from the landfill is entering the ground water.

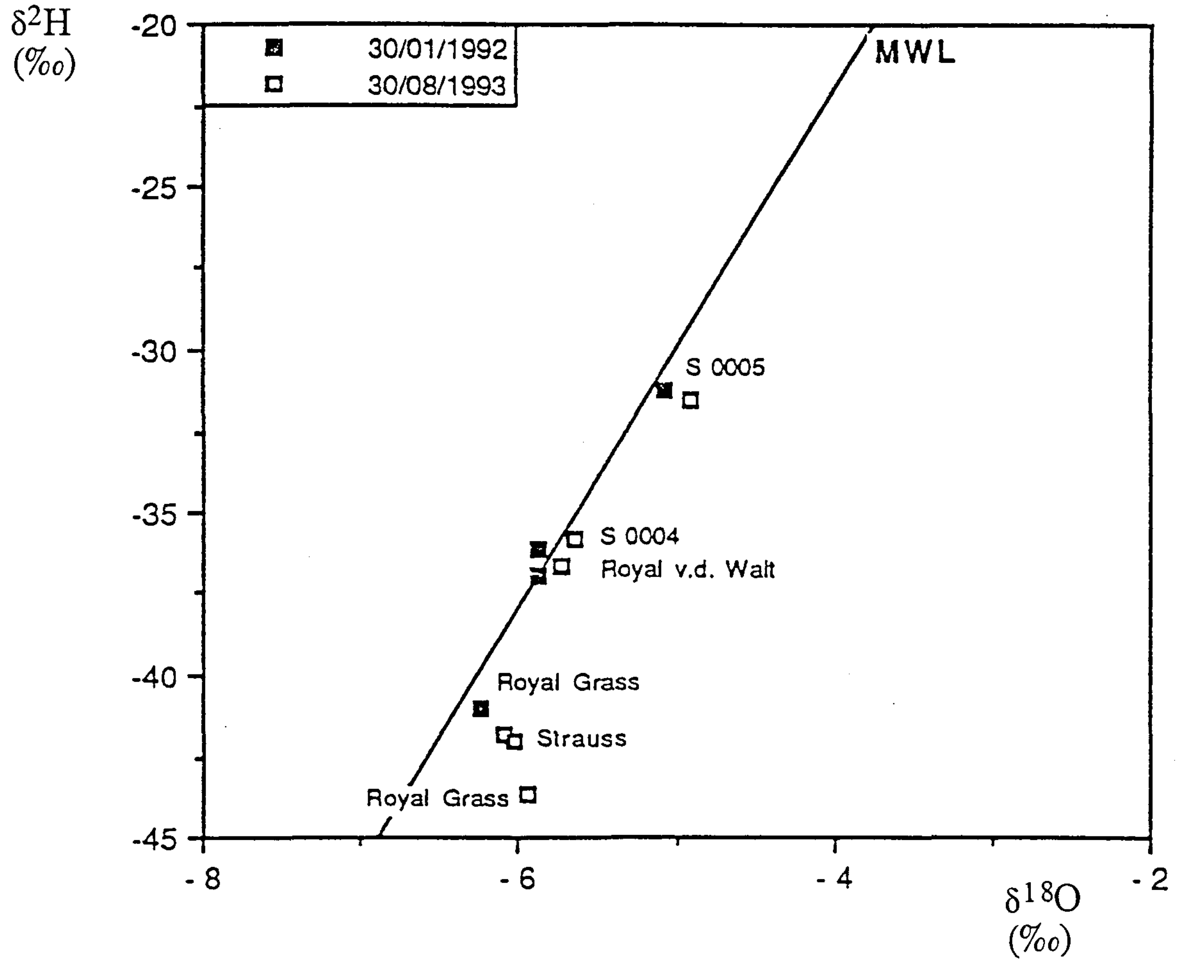


Figure 13.5 Plot of δD against $\delta\ ^{18}O$. Also shown is the world meteoric water line

The Van der Walt borehole results remained unchanged. The high ^{14}C, ^{3}H and relatively positive $\delta\ ^{13}C$ values, all suggest an influence from the landfill.

Table 13.5 Radioactive isotope values for the pollution monitoring boreholes and farm boreholes for 1992 and 1993

Borehole Number	^{3}H (TU)		^{14}C (pMC)		$\delta\ ^{13}C$ (‰)	
	Jan 92	**Aug 93**	**Jan 92**	**Aug 93**	**Jan 92**	**Aug 93**
S 0004	0.9±0.2	1.2±0.3	92.8±1.1	112.2±0.7	-6.0	-17.4
S 0005	28.1±1.5	40.1±1.9	123.5±1.0	125.5±0.7	+0.9	+0.1
Royal v.d. Walt	5.7±0.6	5.8±0.5	117.3±1.1	118.2±0.7	-2.5	-2.3
Royal Grass	1.9±0.3		107.7±0.8		-4.2	
Strauss Garden		0.8±0.3				
Strauss Strong		1.0±0.2				
S 0001	1.2±0.2					

13.6 Summary and discussion

Borehole S 0005 is the most polluted borehole at the Southern landfill site, with the highest alkalinity, conductivity and temperature of all the boreholes. This borehole is significantly more polluted than the other boreholes. It is situated at a point where substantial run-off from the site, due to erosion, seeped through drying cracks in the surface clay material.

The three separate groups of stable isotope values which plot along the meteoric water line appear to correspond to the level of pollution found in each borehole. Borehole S 0005, which has the heaviest isotopic composition, is the most polluted, followed by S 0004 and Royal van der Walt. The other farm boreholes, namely Royal Grass, Strauss Strong and Strauss Garden, have lighter isotopic compositions, and appear to have much lower levels of pollution.

The extremely high tritium concentration measured in S 0005 is more than likely the result of artificial tritium within the landfill site, and is a helpful tracer when following the movement of any pollution from the site. The Royal van der Walt borehole has a significantly higher tritium concentration than the neighbouring farm boreholes, and could either indicate the encroachment of the pollution from the landfill, or could be an indication of a very localised recharge source. The ionic ratios of this borehole show similarities with S 0005. Should these elevated values be due to pollution from the landfill, the polluted water would have to be transported on the surface. It is estimated, taking into account the distance, hydraulic gradient, and estimated permeability of the underlying siltstones, that a pollution front in ground water would take about 100 years or more to cover this distance. Fracture flow could be more rapid.

The highest carbon-14 value is found in S 0005, and suggests a source of artificial carbon-14, as well as tritium, in the landfill.

13.7 Recommendations

A suitable control borehole, well away from the influence of the landfill site is required in order to facilitate hydrochemical and isotopic interpretation. At least one or two more monitoring boreholes are required to replace the dry boreholes. In both the southern and northern sites, more frequent sampling, and longer pumping periods are advisable.

14 SUMMARY AND DISCUSSION

14.1 Development of the project

It was foreseen from the beginning of this research that the Clayville area was going to be an extremely difficult geohydrological environment. As work progressed this became more apparent. Research work therefore developed along the lines of:

a) assessing the baseline situation and vulnerability of the dolomite ground water,

b) defining the condition of the Karoo deposits and more importantly of the worked-out pits into which the waste is deposited,

c) elucidating the hydrogeology of both the Karoo and the surrounding dolomitic formations, and their inter-relationship,

d) extending the studies to waste disposal sites in other geological environments.

In the initial borehole survey at Clayville, tritium and radiocarbon clearly indicated the widespread presence of local recharge in the dolomitic ground water. This led to the conclusion that the entire area is prone, and vulnerable, to surface pollution. The correlation of these radioactive isotopes with stable isotope values led to the elucidation of the flow regime in the dolomites, and the realisation that some local recharge was of different origin than that which generates the regional underflow. This in turn led to the identification of the different sources of ground water in the area and the importance of Rand Water mains as a contributory recharge source. The potential of this water to carry pollutants into the ground water was realised when the source of various ions in a highly polluted borehole with high tritium and radiocarbon values was traced to spillage from an irrigation canal carrying sewage disposal effluent, borne by mains water. It was then appreciated that mains water in the Gauteng area has a unique stable isotope composition: much "heavier" than average rain and ground water, but on or close to, the world meteoric water line. This allows for tracing mains water through ground water systems and for the distinction between mains water and infiltration from evaporating surface water bodies.

These studies, and the conclusions which could be drawn from them, had initially not included the Karoo outliers, which house various quarries, some of which are worked out, and one at the time being operated as a commercial class 2 landfill. Although it was realised that the primary focus of the study was this particular site, the lack of suitable observation boreholes initially precluded a coherent study of this, and similar sites. In order to overcome this continuing obstacle, a worked-out quarry receiving waste water was later investigated as a worse-case scenario of the waste disposal site.

Whilst the investigations at Clayville continued, parallel studies were undertaken at the Linbro Park and Waterfall landfill sites in Johannesburg and the northern and southern landfill sites at Bloemfontein. The results from the latter three first drew attention to the presence of tritium containing material in South African waste disposal sites.

14.2 Geophysics and drilling

The project budget did not allow for a significant amount of borehole drilling. Some drilling capacity was pledged by the Department of Water Affairs. As the karstic dolomite is complex, it was necessary to conduct a geophysical survey in order to obtain more detailed information on its structure. Resistivity, magnetic, electromagnetic and gravity surveys were conducted by EMATEK (CSIR) and the Department of Water Affairs and Forestry.

Geophysics became an integral and vital component of the investigation: in siting exploration holes, identification of dykes and patches of decomposed dolomite, together with an indication of the vertical extent of weathering. Geophysical modelling proved useful when investigating known geological features. The trend of the Pretoria dyke was questioned as a result of modelling. This feature has a major, but as yet poorly quantified effect on the geohydrology of the region.

Geological information was obtained from existing Department of Water Affairs boreholes for which detailed geological logs were available. Geophysical techniques could therefore be calibrated over the whole region, indicating the existence, and prompting further investigation, of subsurface geological features.

On the basis of these surveys, and on other considerations, 11 boreholes were sunk at different sites and different phases of the project. The aim was (1) to confirm the areas of high conductivity indicated by geophysics as areas of significant ground water flow (2) to establish areas of leakage across the Pretoria dyke (3) to investigate the characteristics of Karoo ground water as compared with the dolomite and (4) to establish the competence of the Karoo as a barrier against the movement of leachate.

The outcome of these different approaches can be summed up as follows:

a) The boreholes drilled in apparently conductive zones encountered highly weathered material, but rather stagnant ground water. It is possible that higher yields might have been encountered at greater depths, but the limited budget of borehole meterage did not allow for extending the investigation to greater depths.

b) Two pairs of boreholes MR 4 and MR 5, and MR 6 and MR 8, straddled the Pretoria dyke. The isotopic signature of the first pair was sufficiently similar to allow for the conclusion of ground water transport eastwards near the Sterkfontein dyke. The second pair, drilled further south in chert-rich, decomposed but low-yielding dolomite, differed in isotopic signature to the extent that no clear evidence of transport was obtained. In neither of the two pairs of boreholes could clear hydraulic continuity across the Pretoria dyke be established by test pumping.

c) Neither the chemical nor isotopic signal of ground water encountered in the Karoo could clearly distinguish this water from dolomitic ground water, except in cases where the Karoo Formation is rich in carbonaceous material. The variable characteristics of dolomite ground water in the area added to the lack of distinction between the ground water in the two formations. This confirmed expectations that it might prove impossible to trace ground water, recharged through the Karoo, and the solutes it carries, in the dolomite aquifer.

d) Depth-related isotopic information on boreholes MR 9, 10 and 11, purposely drilled close to a mains water-fed dam, proved to be extremely useful in assessing the competence of the Karoo. This study leads to the conclusion that worked-out clay pits are not suitable for using as sanitary landfill sites in karstic dolomite terrain.

A further three boreholes which the waste site contractor had drilled immediately to the north of the landfill were predictably almost dry, and therefore did not contribute to the study of the Karoo outliers, nor to future monitoring of the site.

The regional geohydrological investigation, involving geophysics and project-specific borehole drilling was undertaken in order to better understand the ground water flow regime and the movement of existing and potential pollutants. In particular, the movement of ground water across or through the Pretoria dyke and the possible influence on the Sterkfontein spring was targeted. The results of this investigation have added substantially to the knowledge of the structure, ground water dynamics and extent of the Karoo in the area. The hydrochemical and isotope information has constrained certain hypotheses regarding the geohydrology. However, this investigation has fallen short of defining with any precision the geohydrological relationship between the different dolomitic compartments. To achieve this would require a more intensive drilling and geohydrological investigation, which was not foreseen in, and certainly lay well outside the scope of the present project. In the light of the importance of this area to existing and future ground water supply, it is strongly recommended that such an investigation, involving the integrated or holistic approach illustrated in this study, be undertaken.

14.3 Rietvlei control area

The concept of a control area as an unpolluted analogue of the area under investigation, was evaluated in this study. Such an area should, when available, as closely as possible resemble the area of interest, but be devoid of any known pollution such as intensive cultivation and urban and industrial development. The characteristic hydrochemical type of the control area could be said to represent the area under investigation. Deviations from this would then help to indicate incipient and point source pollution within the aquifer.

In the present study, the Rietvlei area was conveniently placed and contained some boreholes which could be sampled. The results proved that in an area devoid of significant urban development a more defined dolomitic type water is seen. However, instances of clearly identifiable ground water pollution were encountered.

The overall conclusion in connection with future studies is that a) it may be very difficult to find comparable areas which are truly unpolluted and b) it is questionable whether the information obtained warrants the extra time and expense required to incorporate such an area.

14.4 Isotopic observations

14.4.1 Environmental isotopes as geohydrological tools

This study has shown the intrinsic power of environmental isotope techniques in analysing various geohydrological aspects of waste disposal. Conventional geohydrological techniques deal with the pressure relationships which induce the movement of water. Environmental isotopes, as tracers of water, enable the investigation of the transport of ground water and the contaminants it carries. When applied during the initial stage of an investigation environmental isotope measurements can quite rapidly assess aspects of the geohydrology, such as recharge areas, ground water flow in relation to depth, discharge points and turnover time. Using conventional methods, this type of information could only be obtained after lengthy observations and with detailed information on the existing boreholes. This is not usually available, especially when private boreholes have to be incorporated into a study. The alternative is expensive exploratory drilling.

For the information obtainable, environmental isotope data is highly cost effective. The costs involved in the analysis in a water sample of the full suite of five isotopic parameters, as discussed in this report, may be compared with the costs of a full ionic plus microbiological analysis in a pollution study.

In each of the aspects of the study in the Midrand areas as well as in each of the four other studies undertaken in different geological environments, environmental isotope data provided unique information in understanding basic aspects of pollutant transport. The influence of nearby surface drainages on monitoring boreholes was highlighted. In addition, the various studies have produced unexpected possibilities in the use of isotopic techniques which can be of great practical importance in studying leachate movement as well as of the influence of mains water in the sub-surface.

Although environmental isotope techniques provide unique information and thus are powerful in themselves, their full power can only be realised when used in a multidisciplinary or holistic context. The behaviour of ground water can be fully described only when the complimentary techniques of stable and radioactive isotopes, hydrochemistry and conventional geohydrology are combined in a single, integrated investigation.

Environmental isotope hydrology is appropriate technology. Isotope techniques are state of the art, are employed worldwide, in particular in geohydrology, and wide experience and expertise have been developed in both their application and interpretation. The specifications for many ground water development and evaluation projects internationally stipulate an environmental isotope input, along with geophysical and hydrochemical studies. South Africa has available local analytical facilities of world standard and internationally recognised expertise in the application of environmental isotope hydrology and is therefore favourably placed to conform to international practice.

14.4.2 Tritium

The use of tritium highlighted the fact that the aquifer is being actively recharged, to some extent identifying local areas of recharge. The success and comprehensiveness of this would depend on the density of sampling. The areal variability of the tritium values also indicates that the process of recharge is complex within the study area. In this particular study tritium proved more useful in the identification of recharge areas than HCO_3 ion dominance. HCO_3 is dominant throughout the whole system, producing a buffering effect (i.e. suppressing contrast). The presence of a more dynamic upper ground water regime overlying an older system was not identified using only hydrogeochemistry. This was highlighted by the correlation between tritium and $\delta^{18}O$ values. Isotope values were however found to be affected by variations in sampling routines. Further studies in regard to this aspect should be done and more rigorous standards for sampling conditions developed.

14.4.3 Radiocarbon

The inherent shortcomings of ^{14}C, most costly and most time consuming in measurement, are the need to infer initial activity and the difficulty in assessing exchange with aquifer rock in dolomitic terrain. These shortcomings have been overcome by:

(a) residence time modelling, using tritium

(b) using radiocarbon as a tracer as well as a dating tool

(c) correlations with other isotopes.

These correlations are important, in that radiocarbon labels a solute, whereas the other isotopes label the solvent. The correlation of $\delta^{18}O$ with ^3H could be neatly confirmed with ^{14}C.

Modelling indicates that extensive dilution of ^{14}C concentrations is occurring. Recharge may also occur at a relatively low alkalinity (channelled recharge). Karstic dolomite is a difficult geological environment in which to assess mean residence time using ^{14}C. Using a variety of isotopes, these shortcomings can be largely overcome.

14.4.4 Stable isotopes

When $\delta^{18}O$ is correlated with deuterium, sources of recharge could be identified. Correlations between $\delta^{18}O$ and ^3H values and major anions provided clues as to how pollutants were entering the system. This becomes particularly important in the presence of existing pollution (background). In this particular study it is apparent that sulphates and chlorides are entering the ground water system mainly via recent recharge water i.e. associated with ^3H values in excess of 1.5 TU. When plotted against $\delta^{18}O$ these anions are seen to be associated with water having an isotopic label ranging between the limits of mains water and the weighted mean of rain. Nitrate however is associated with a range of $\delta^{18}O$ values much closer to the weighted mean for precipitation. It therefore appears that sulphates and chlorides are entering the system via ways other than direct rain infiltration, and may be entering via leakage from the Rand Water mains system. Other possible routes of entry include runoff water from factories using mains water to wash floors etc., french drain systems and sewage effluent disposal.

14.5 The Sterkfontein spring

The geohydrology of the Olifantsfontein area is obviously complex and the source of the Sterkfontein spring remains unclear. The chemistry of its water indicates it to be as yet unaffected by the general diffuse urban pollution taking place around the town of Clayville. The elevation of the spring is anomalous in relation to the surrounding water levels, and its lower topographic position in a natural surface drainage which extends south of the Sterkfontein dyke, suggests the spring to be a solution channel which has been exposed by natural weathering and dissolution by surface water. The high ^{3}H value accompanying the observed radiocarbon in the spring water suggests a mixture of low alkalinity, recent water with a deeper underflow component. The carbon-13 value is one of the highest found in the area indicating closed system dissolution of dolomite. Its stable isotope signal does not clearly identify its origins from either east or west of the Pretoria dyke. The indications that the spring water originates from a closed system suggests it to be associated with the Lyttelton Formation. The Monte Christo Formation, or more appropriately, the upper portion thereof, proves to be more of an open system susceptible to surface infiltration.

14.6 Existing pollution

In each of the individual studies reported here, environmental isotopes were able to make a contribution to an understanding of the processes of the transport of pollutants. Combining isotope and hydrochemical data, widespread incipient pollution was shown to be present in the Midrand dolomite ground water. The levels of the proxy ions are as yet so low that they would not have been identified as pollution, had not the accompanying isotope signal suggested them as such. Pollution identified in the Rietvlei control area could be traced to a surface stream. First indications of pollution in a single borehole at Linbro Park could be shown to be localised input as most boreholes show active recharge. The presence of leachate in surface and possibly ground water could be demonstrated by the presence of artificial tritium at the Waterval site. Stable and (artificial) radioactive isotopes could be employed at both the Bloemfontein landfill sites to show the influence of surface water transport in the spreading of leachate to neighbouring boreholes. The results of these brief surveys in different ways demonstrated the important role of environmental isotopes in understanding pollution transport studies.

The isotopic identification waste water derived from the Gauteng mains supply identified it as a major carrier of pollution and has opened up possibilities for the tracing of leakages from urban reticulation systems.

14.7 Worked-out Karoo quarries as potential waste disposal sites

The condition of the pit containing the sanitary landfill at Olifantsfontein could not be studied because it was in operation before the start of this research project. Existing monitoring boreholes were found to be inadequate.

Observations of nearby excavations revealed prominent slumping and faulting of the Karoo. Poorly cemented sandstone was encountered at the base of an adjoining pit, with well defined parallel tension cracks formed as a result of slumping into the underlying dolomite. There is no evidence to suggest that subsidence is still taking place due to the ferruginous nature of the fractures. However, the highly decomposed nature of the underlying dolomitic material does not discount the possibility that subsidence might still occur. Acid leachate from sanitary landfill could mobilise the fracture filling and reactivate karstification.

The heterogeneity of the Karoo deposits themselves has cast serious doubt on the generalisation that they are "safe" media in which to dispose waste. Perched water tables indicate complicated geohydrological conditions. In one case there was completely saturated material at the base of the deposit. The isotopic and chemical label of this particular water indicated it to be infiltrated water from a nearby surface water body. Both the surface water and ground water have high sulphate values. However, there is a possibility that the high sulphate in the ground water is associated with the saturated carbonaceous deposits. This indicates that ground water infiltrates into the Karoo, most probably along preferential pathways determined by faulting within the deposits. Should such a situation exist in a landfill, the waste would in effect become part of the saturated environment, and capping would not stop an influx of water.

The variation in thickness of the Karoo deposits over very short distances has also been highlighted during this research. Extremely steep sided deep pockets of Karoo are separated by dolomite or sandstone "hardbanks". It is these deeper pockets which are generally used for waste disposal. Their steep sides support very little "barrier" medium on the sides of the facility. Should the pockets become saturated from infiltrated water away from site, there is concern at the lack of constraint of lateral movement of leachate into the more dynamic upper sections of the surrounding dolomitic aquifer. This scenario is not suggested specifically at the Olifantsfontein site. However, research has identified the possibility of deeper pockets becoming saturated over a relatively short time scale from surface water bodies, obviously putting the surrounding aquifer at risk.

The heterogeneity of the Karoo lithology and its competence in acting as a barrier against the inflow of leachate was fully demonstrated by investigating the movement of isotopically distinct water from a worked-out quarry, now a mains water waste dam, into various sections of the surrounding Karoo deposits. Isotopic observations proved that no dam water at all could be observed in one of the boreholes, with an extensive sequence of good quality clay. Dam water intrusion in two other closely spaced boreholes with carbonaceous deposits was shown by isotopes to be extensive, and highly significant.

14.8 Minimum requirements for site placement

There are various measures that should be taken when considering such an environment for waste disposal. The local geology must be studied very critically, and the relationship between the Karoo and dolomitic formations both vertically and laterally, must be investigated thoroughly. Ground water sampling must include environmental isotopes to adequately appraise the dynamics of the local and regional geohydrological regime. Ample lining should be left around the pit to ensure a natural barrier, and careful consideration should be given to the possibility of ongoing karstification and subsequent slumping. Much more preferable would be to establish a well designed and controlled landfill site above intact Karoo deposits, with adequate peripheral surface drainage and leachate collection systems.

The regional investigation has highlighted that conventional methodologies including environmental isotopes, when used together, can provide a wealth of background information in relation to aquifer vulnerability, aquifer dynamics, background water quality, incipient and point source pollution, and the origin of that pollution. The combination of all the methodologies can also be used in more site specific and detailed investigations concerning the competence of the medium in which the waste is to be deposited. All this information is required when assessing the influence that potential waste site will have on the existing ground water environment. Establishing the water quality baseline along with a good knowledge of aquifer dynamics makes environmental impact assessment accurate, and subsequent monitoring programmes meaningful.

14.9 Monitoring systems

It was not in the original brief of this research work to evaluate existing monitoring systems. However, it is felt that comment should be made on the condition and usefulness of the monitoring systems encountered during this investigation.

Boreholes at several waste disposal sites investigated either gave insufficient coverage, were not constructed properly, or were not maintained. In the particular instance of the waste disposal facility at Olifantsfontein, monitoring holes were placed ignoring complex local geological and geohydrological conditions. In cases such as Bloemfontein North and Waterval, the proximity of monitoring boreholes to surface drainages should be considered.

Routine sampling techniques are often ineffectual. Clearly, adequate monitoring systems should be installed. Guidelines are available on the planning, initiation and operating procedures of a monitoring programme e.g. - ('Minimum requirements for monitoring of waste management facilities' - Department of Water Affairs and Forestry 1994), and Weaver (1992), and the principles will therefore not be discussed here.

The investigation also highlighted the problem of employing domestic private boreholes. Invariably such boreholes are used with varying frequency. These variations become apparent on repeat sampling. Provision should be made to minimise such variations in pumping schedules; there should at least be an awareness of the problem in assessing the data.

15 RECOMMENDATIONS

The conclusions arrived at this study firmly establish the combined methodologies in terms of their potential in investigating pollution-related ground water problems. It is important to note that the approach to their application depends on the individual system investigated. Apart from enumerating the overall principles underlying the various methods, only general guidelines as to their application can be derived. As each area of investigation is different, each investigation will require an individual research approach in order to creatively employ the methods and obtain the maximum benefit from them. It is therefore advisable, and ultimately most economical, to engage the various specialists in the study from the outset.

- Environmental isotope studies should be incorporated in the geohydrological evaluation of areas associated with waste disposal operations. Such isotope studies should be conducted taking a holistic approach, as part of a comprehensive geohydrological and hydrochemical investigation of ground water vulnerability and leachate transport.

- A comprehensive environmental isotope survey should be undertaken as a relatively rapid, highly cost effective means of obtaining a preliminary assessment of the geohydrology of areas where little *a priori* information is available. As the geohydrological and hydrochemical framework of an area becomes more firmly established, it should become possible to evaluate the isotope data on a more sophisticated and quantitative basis.

- Particular attention has to be given in dolomitic terrain to the design and maintenance of reticulation and sewage systems, to land usage and to the release of all waste water into natural drainage systems and the environment in general.

- Where no more suitable areas can be identified near dolomitic terrain, landfill sites may be established on Karoo outliers. Such sites should however be designed on surface rather than in worked-out quarries, to utilise the full profile of the undisturbed deposits as a barrier against contamination of the dolomitic ground water.

- Before establishing a landfill site on such outliers, a detailed study of the Karoo should first be conducted, in order to establish the competence and thickness of the argillaceous deposits.

- In spite of the fact that environmental tritium concentrations in southern African rain have dropped to near-natural values since the bomb peak in the mid-sixties, it remains a recommended and practical tool in the semi-quantitative assessment of recharge to, and thus the vulnerability of, ground water. Artificial tritium found to be present in some waste disposal sites, provides a very sensitive tracer for leachate transport from such sites.

- Incipient pollution to Clayville dolomites poses a potential threat to existing and future ground water supplies. The transport of ground water to the eastern compartment and the Sterkfontein spring from the western compartment, tentatively demonstrated in this study, should be firmly established by a more intensive, integrated geohydrological investigation.

- Sanitary landfills should all have properly designed, equipped, and operated ground water monitoring systems, based on production-standard boreholes. Siting, drilling and testing of such boreholes should be done professionally, to adequately cover possible leachate transport. Sampling and analysis to be done according to recognised procedures, and should where possible at least include isotopes to confirm their adequacy.

16 REFERENCES

Anhaeusser, (1973). The Geology and Geochemistry of the Archean Granites and gneisses of the Johannesburg-Pretoria Dome. In Symposium on Granites, Gneisses and related rocks, Ed: L.A. Lister.

Ball, J.M. (1984). Degradation of Ground and Surface Water Quality in Relation to a Sanitary Landfill. M.Sc Thesis, University of the Witwatersrand, Johannesburg.

Ball, J.M. and Blight, G.E. (1986). Ground water Pollution Downstream of a Long Established Sanitary Landfill. Int. Symp. on Env. Technology. Vol. 1 Hsai-Yang Fang (ed.).

Beaumont, R.D., Carter, N.G. and Dold, M.B. (1987). Linbro Park, Report on Ground water Pollution, Hill Kaplan Scott Inc, Johannesburg, CED File: 13/8/6/3, Report No. DC0118-01-00-0887.

Bekker, S. (1992). Verslag oor Waterkwaliteit Ondersoeke by die Noordelike Munisipale Klas 2 Afval Stortingsterrein. Bloemfontein. Instituut vir Grondwaterstudies, Universiteit van die Oranje Vrystaat.

Bekker, S. (1992). Verslag oor Waterkwaliteit Ondersoeke by die Suidelike Munisipale Klas 2 Afval Stortingsterrein. Bloemfontein. Instituut vir Grondwaterstudies, Universiteit van die Oranje Vrystaat.

Blight, J.J. (1992). The Influence of Landfill Covers on the Generation of Leachate. MSc Dissertation, University of the Witwatersand, Johannesburg.

De Klerk, M., Smit, P., Brink, D. and Anke, F.C. (1992). Gravity Investigation Around the Clayville Waste Disposal Site. Technical report no. GH 3774.

Davis, S.N., DeWiest, R.J.M. (1966). Hydrogeology. John Wiley & Sons, United States of America. p. 463.

Hertelendi, E. and Veres, M. (1992). Isotope Techniques in the Hydrogeological Assessment of Potential Sites for the Disposal of Chemical and Communal Waste in Eastern Hungary. Institute of Nuclear Research, Hungarian Academy of Sciences.

Hobbs, P.J. (1988). Geohydrology of the Verwoerdburg Dolomite Aquifer. Department of Water Affairs - Technical Report. Number GH 3013. Vol. 2.

Hojem, D.J. (1988). Water Balance and the Migration of Leachate into the Unsaturated Zone Beneath a Sanitary Landfill. MSc Dissertation, University of the Witwatersrand, Johannesburg.

IAEA (1983b). Technical reports series No. 81 - Guidebook on Nuclear Techniques in Hydrology. Vienna, IAEA.

IAEA (1983a). Technical reports series No. 228 - Isotope Techniques in the Hydrogeological Assessment of Potential Sites for the Disposal of High-level Radioactive Wastes.
IAEA (1992). Statistical Treatment of Data on Environmental Isotopes in Precipitation. Techn. Rep. Series No. 331, Vienna, IAEA.

Jansen, H. (1977). The Geology of the Country Around Pretoria. An explanation of sheet 2527 DA, DB, DC, DD, and 2528 CA, CB and CD. Geological Survey of South Africa, Government Printer, Pretoria.

Johnson, J.H. (1975). Hydrochemistry in Ground Water Exploration. Bulawayo, 1975.

Jones, D.H. (1984). Unstable Ground Conditions Associated with Karoo Outliers in the Dolomite Environment in the West Rand.

Kok, T.S., Wiegmans, F.E and Fayazi, M. (1985). Results of Exploration Drilling in Dolomite on Rietvallei 377, and at Erasmia and Valhalla, Pretoria. Technical Report GH 3379.

Le R. Cilliers, J.J. (1953). The geology of the Fountains Valley area south of Pretoria. M.Sc. thesis (unpubl.) Univ. Pretoria.

Levin, M., Walton, D., Verhagen, B. Th. and Sandilands, F. (1990). Development and Evaluation of Geohydrological and Isotope Hydrological Methodologies for the Identification of Areas Potentially Suitable for Waste Disposal. Progress Report No.1 for the Water Research Commission.

Marton, L., Miko, L., Rank, D. and Hertelendi, E. (1991). Istopenhydrogelogische Untersuchungen in der Großen Ungarishen Tiefebene. 20th Anniversary of Geol. Soc., Austria.

Piper, A.M. (1944). A graphic Procedure in the Geochemical Interpretation of Water Analysis. Trans. Am. Geoph. Union., p 914-928.

Seymour, A., Nel. G., van Tonder, G. and Cogho, V. (1991). Report on Water Quality Investigations at the Southern Municipal Class I Waste Disposal Site, Bloemfontein, Institute for Ground-water Studies, Univ. of the Orange Free State.

South African Committee for Stratigraphy (SACS) (1980). Stratigraphy of South Africa. Part 1 (comp. L.E. Kent). Lithostratigraphy of the Republic of South Africa, South West Africa/Namibia, and the Republics of Bophuthatswana, Transkei and Venda, Handb. geol. Surv. S. Afr., 8.

Temperley, B.N. (1987). Ground water in Pretoria and Surrounding Areas. Department of Water Affairs - Technical Report. Number GH 3013. Vol 2.

Theron, P.F. (1986). Monitoring History of the Water Regime at the Linbro Park Sanitary Landfill Site from 1979 to 1986.

Verhagen, B. Th., Geyh, M. A., Froehlich, K. and Wirth, K. 1991. Isotope Hydrological Methods for the Quantitative Evaluation of Ground Water Resources in Arid and Semi Arid Areas, Development of a Methodology. Federal Ministry for Economic Cooperation. Federal Republic of Germany.

Weather Bureau publication W.B. 28.

Weather Bureau publication W.B. 40. Climate of South Africa - Climate statistics up to 1984.

Weaver, J.M.C. (1992). Ground water Sampling : A Comprehensive Guide for Sampling Methods. Prepared for the Water Research Commission, WRC Project No. 339, TT 54/92, Pretoria.

Wiid, B.L. (1985). Report on the Geohydrology at the Proposed Quarry Site for Solid Waste Disposal - Clayville. Confidential report for Waste Tech, Bedfordview.

Williams, D.J., Cross, A.L. and Biggs, D.C. (1983). Hydrogeological investigation, Linbro Park: Proposed Southerly Extension of the Existing Sanitary Landfill Site. Unpub. Rep. DR 0093-01-00-0283, Jhb. Mun.

Wilkens, C.B., Eriksson, P.G. and van Schalkwyk, A. (1987). Two Generations of Karst-fill Sedimentary Rocks within Chuniespoort Group Dolomites South of Pretoria. S. Afr. J. Geol, 90, p 155-167.

Zuber, A. (1986). In: Handbook of Environmental Isotope Geochemistry, pp. 1-59. (Fritz and Fontes, Eds.), Elsevier.

APPENDIX 1

BOREHOLE INFORMATION AND WATER LEVEL DATA OLIFANTSFONTEIN

BOREHOLE INFORMATION AND WATER LEVEL DATA

BOREHOLE NUMBER	COORDINATES		APPROXIMATE WATER LEVEL m.a.m.s.l.	DEPTH TO WATER TABLE	DATE
	X	Y			
2528 CC 1	2866454.00	76793.00	1444.64	10.36	07/05/90
2	2866389.00	76264.00	1456.00	30.00	15/05/90
3	2866916.00	76818.00	1443.70	9.30	07/05/90
4	2867067.00	76344.89	1445.00	30.00	07/05/90
5	2869000.00	77000.00			
6	2869700.00	79167.00	1459.30	9.70	07/05/90
7	2867063.00	80937.00	1483.55	13.45	07/05/90
8	2869875.00	82673.00	1533.00	13.00	07/05/90
9	2870564.00	79579.00	1474.55	10.45	07/05/90
10	2871270.00	76390.00	1490.67	28.33	09/05/90
11	2871314.00	76275.00			
12	2871155.00	76075.00	1492.82	28.18	09/05/90
14	2869435.00	75610.00	1468.07	10.93	09/05/90
15	2869730.00	75475.00	1479.00	2.60	09/05/90
16	2870035.00	76395.00	1479.00	≃15,00	09/05/90
17	2868000.00	77000.00	1456.00	≃6,00	09/05/90
18	2874739.00	79301.00			
19	2874763.00	81779.00			
20	2873659.00	82482.00	1575.66	14.34	10/05/90
21	2875251.00	75672.00	1528.70	12.80	14/05/90
22	2873711.00	75721.00	1531.50	12.50	14/05/90
23	2873126.00	75780.00	1525.00	≃16.0	14/05/90
24	2872696.00	75866.00			
25	2872023.00	76649.00	1492.50	≃36.00	14/05/90
26	2869594.00	76997.00	1475.57	15.43	15/05/90
27	2871626.00	77124.00			
28	2871880.00	77495.00			
29	2872124.00	78067.00			
30	2871663.00	78220.00			
31	2871630.00	75019.00	1490.00	≃27.00	16/05/90
32	2869685.00	75610.00	1482.00	0.00	21/05/90
33	2868825.00	76043.00	1474.20	≃1.80	26/06/90
34	2870569.65	75322.32	1445.00	55.00	15/11/85

BOREHOLE NUMBER	COORDINATES		APPROXIMATE WATER LEVEL m.a.m.s.l.	DEPTH TO WATER TABLE	DATE
	X	Y			
35	2870542.08	75879.02	1488.10	13.20	15/11/85
36	2870147.04	76743.97	1487.50	8.00	15/11/85
37	2872064.24	78290.89	1490.10	6.40	15/11/85
38	2871900.00	78040.48	1487.00	21.00	15/11/85
39	2871688.52	77207.97	1488.00	30.00	15/11/85
40	2871812.11	77290.71	1488.00	32.20	15/11/85
41	2873066.52	76031.34	1491.30	44.10	15/11/85
42	2873156.91	75696.96	1525.00	21.00	15/11/85
43	2872392.73	76591.71	1491.40	43.60	15/11/85
44	2872982.00	76890.00			
45	2871125.00	78000.00	1481.20	31.80	12/02/91
46	2870660.00	77388.00	1484.00	11.00	01/08/85
CD 1	2871484.00	73481.00	1475.88	82.12	08/05/90
2	2872440.00	72538.00	1487.00	≈95,00	08/05/90
3	2871317.00	72729.00	>1365	>100.00	08/05/90
4	2874953.00	72209.00			
5	2873548.00	71790.00	1557.50	30.50	08/05/90
6	2873479.00	73545.00	1525.00	53.00	08/05/90
7	2872602.00	74324.00	1496.10	57.90	08/05/90
8	2869856.00	72670.00	1495.00	17.00	08/05/90
9	2870157.00	71737.00			
10	2870072.00	74609.00	1493.00	15.70	09/05/90
11	2873724.00	71896.00	1528.80	58.20	16/05/90
12	2869935.00	72411.00			
MR 1(A)	2870265.00	76170.00	1486.35	11.055	27/06/91
2	2871030.00	76050.00	1486.25	28.25	26/07/91
3	2869902.00	76100.00	1485.73	6.07	08/09/91
4	2869900.00	76120.00	1485.70	5.90	11/09/91
5	2869803.00	75940.00	1476.67	13.23	16/09/91
6	2871075.00	75533.00	1486.50	27.10	30/11/93
7	2870739.00	75380.00	1476.58	31.00	01/12/93
8	2870998.00	75327.00	1483.03	28.10	02/12/93

BOREHOLE NUMBER	COORDINATES		APPROXIMATE WATER LEVEL m.a.m.s.l.	DEPTH TO WATER TABLE	DATE
	X	Y			
9	2869940.00	77229.00	1486.65	6.40	02/12/93
10	2870035.00	77330.00	1476.19	17.00	21/02/94
11	2869943.00	77230.00	1479.50	13.20	22/02/94
Control Area					
RTV 1	2868589.00	67763.00			
2	2869091.00	69514.00			
3	2869979.00	68730.00			
4	2867841.00	65819.00			
5	2866858.00	66214.00			
6II	2869953.00	69593.00			
G 37024	2868995.00	68958.00	1504.75	18.13	11/03/91
G 37025	2870080.00	68229.00	1506.66	36.50	05/12/85

APPENDIX 2

BOREHOLE GEOLOGICAL LOGS
OLIFANTSFONTEIN

BOREHOLE INFORMATION

Borehole No.: MR I (A)

Total depth drilled: 60 m

Measured blow-yield: 2 l/s

Rest water level: 11,055 m ( )

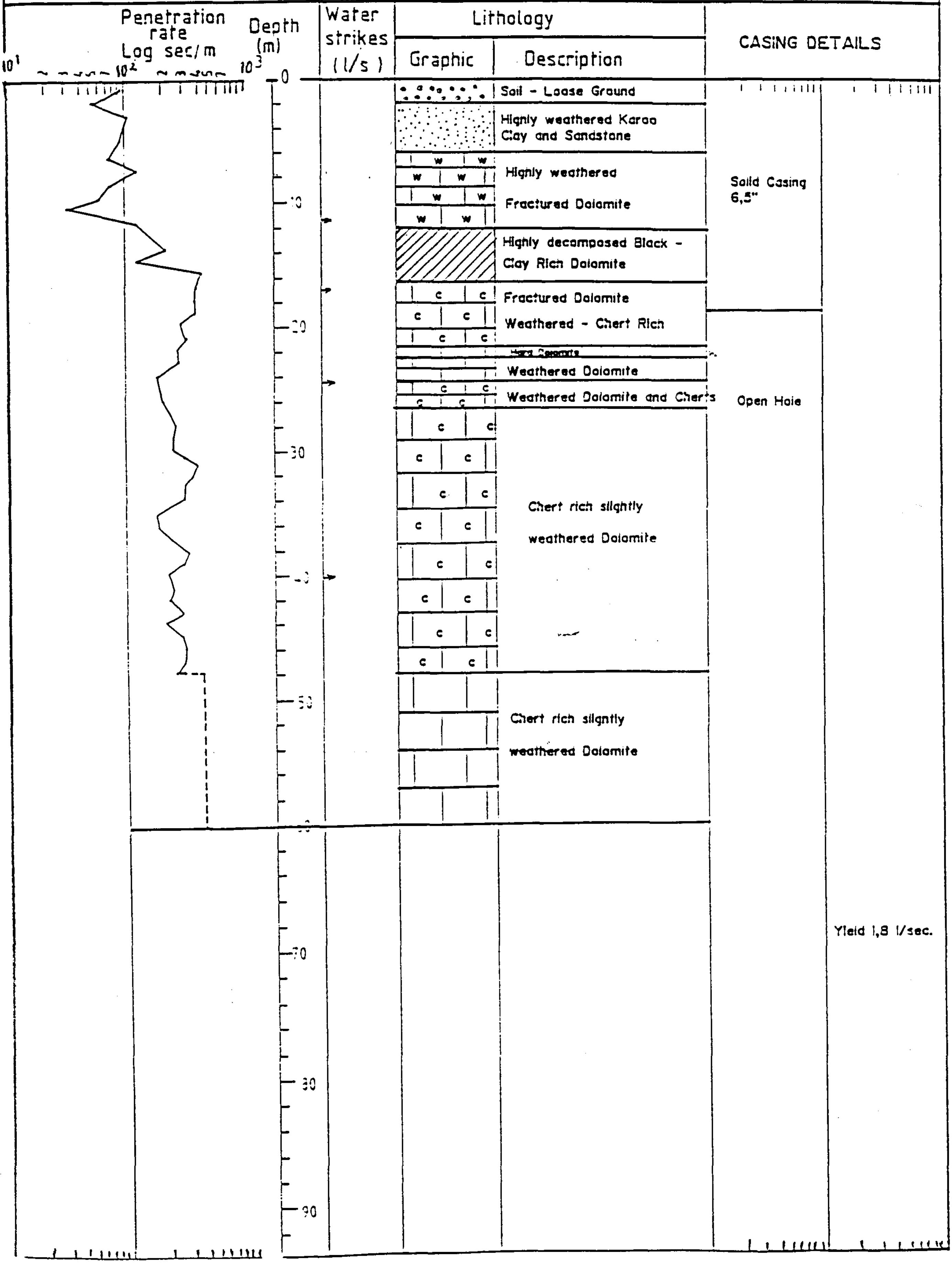
Date begin: 25/06/91 Date end: 27/06/91

Co-ordinates: X + 2878265

Y - 76170

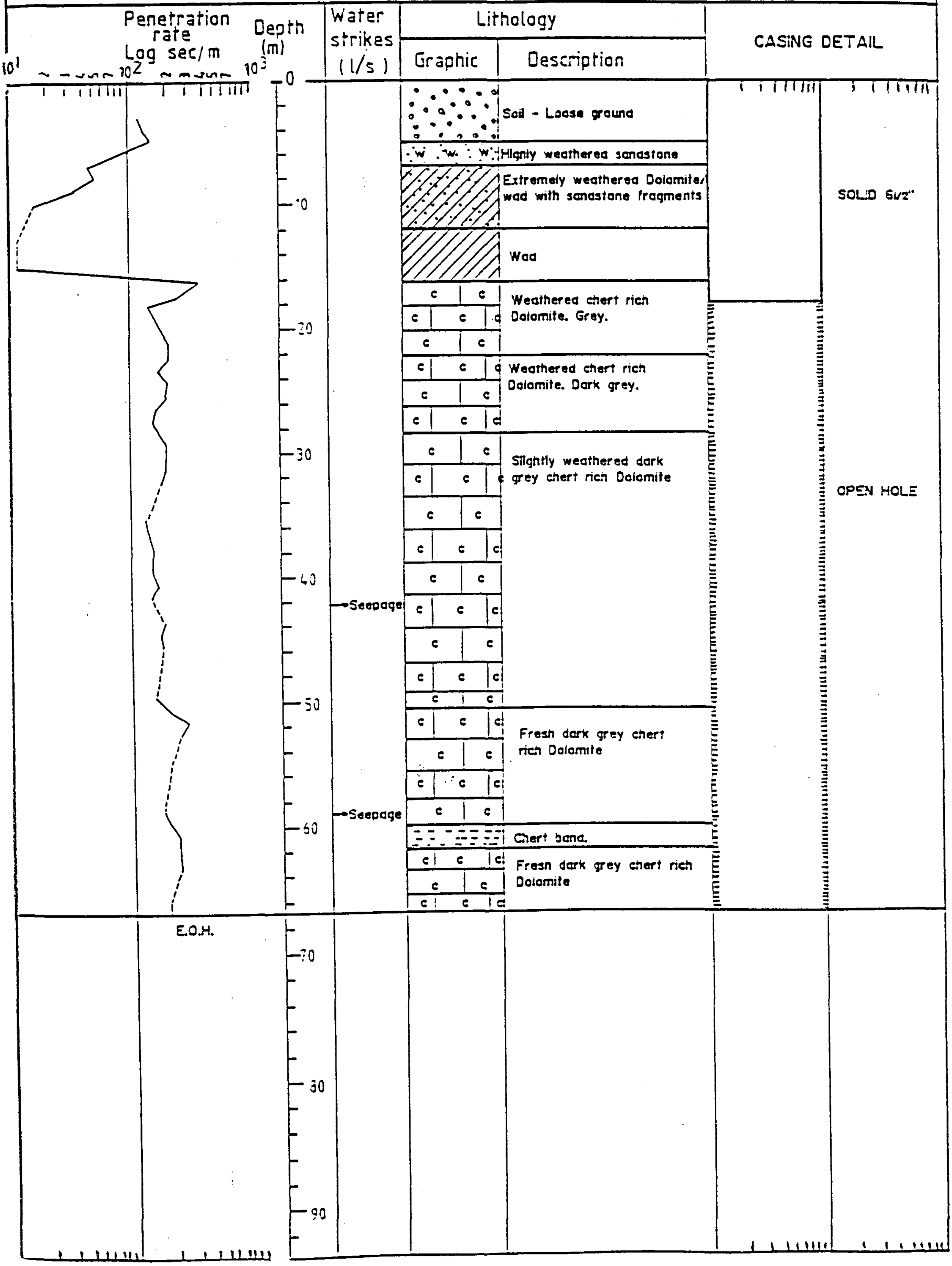
Collar elevation(a.m.s.l.) 1501,622 m

Casing diameter:



BOREHOLE INFORMATION

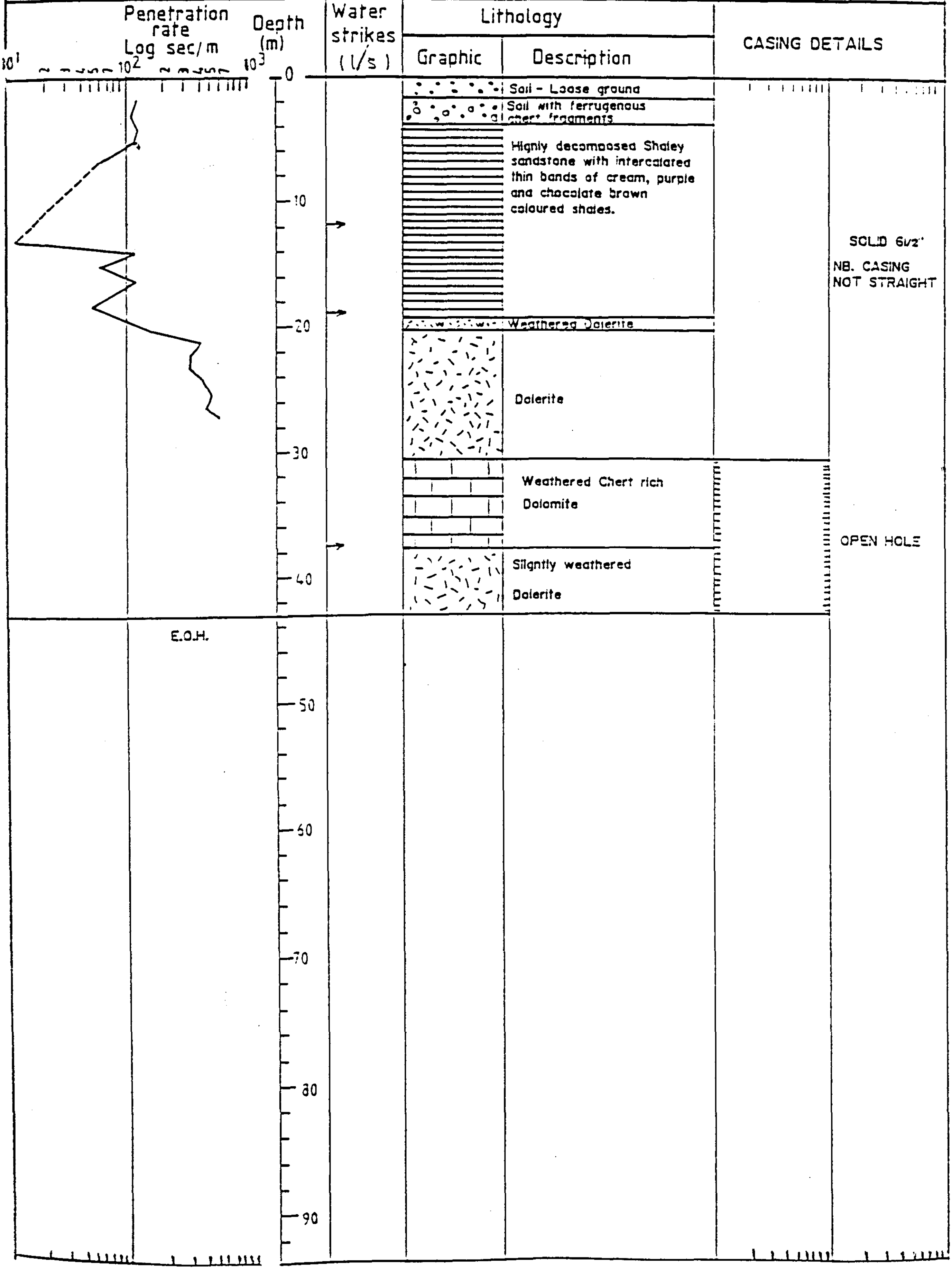
Borehole No.: MR 2
Date begin: 25/07/91 Date end: 26/07/91
Total depth drilled: 61 m
Co-ordinates: X + 2871030
Y - 76050
Measured blow-yield: l/s
Collar elevation (a.m.s.l.) 1514,50 m
Rest water level: 28,25 m ( )
Casing diameter: 6½"



BOREHOLE INFORMATION

Borehole No.: MR 3
Total depth drilled: 42 m
Measured blow-yield: 1,5 l/s
Rest water level: 6,07 m (   )

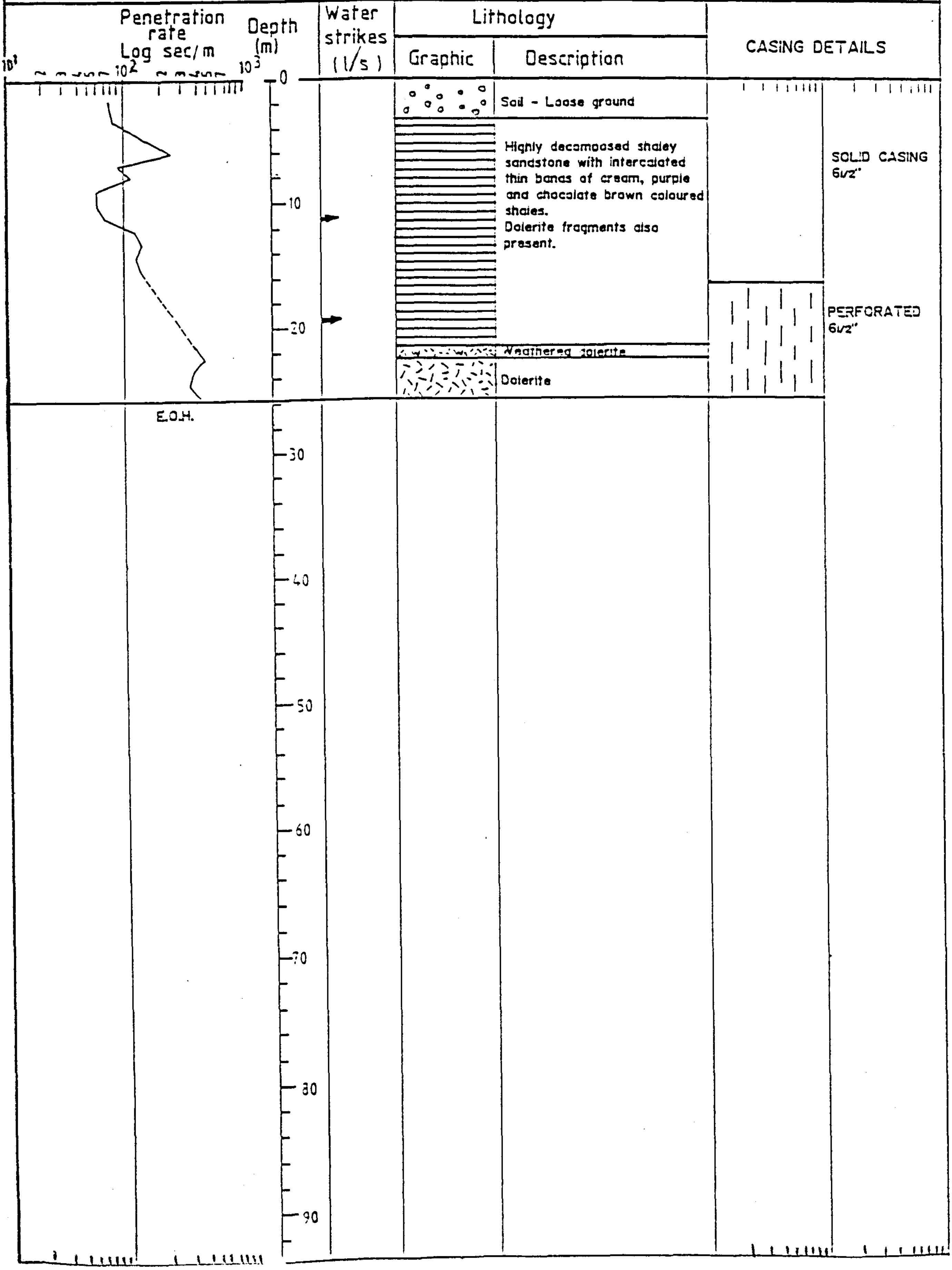
Date begin: 30/07/91 Date end: 08/09/91
Co-ordinates: X + 2869902
Y - 76100
Collar elevation(a.m.s.l.) 1491,80 m
Casing diameter: 6½"



Soil - Loose ground
Soil with ferrugenous chert fragments
Highly decomposed Shaley sandstone with intercalated thin bands of cream, purple and chocolate brown coloured shales.
Weathered Dolerite
Dolerite
Weathered Chert rich Dolomite
Slightly weathered Dolerite

BOREHOLE INFORMATION

Borehole No.: MR 4
Total depth drilled: 25 m
Measured blow-yield: 1,5 l/s
Rest water level: 5,90 m (   )
Date begin: 09/09/91 Date end: 11/09/91
Co-ordinates: X + 2869 902
Y- 76110
Collar elevation(a.m.s.l.) 1491,60 m
Casing diameter: 6 1/2"



Soil - Loose ground

Highly decomposed shaley sandstone with intercalated thin bands of cream, purple and chocolate brown coloured shales.
Dolerite fragments also present.

Weathered dolerite

Dolerite

SOLID CASING 6 1/2"

PERFORATED 6 1/2"

BOREHOLE INFORMATION

Borehole No.: MR 5

Total depth drilled: 30 m

Measured blow-yield: 6 l/s

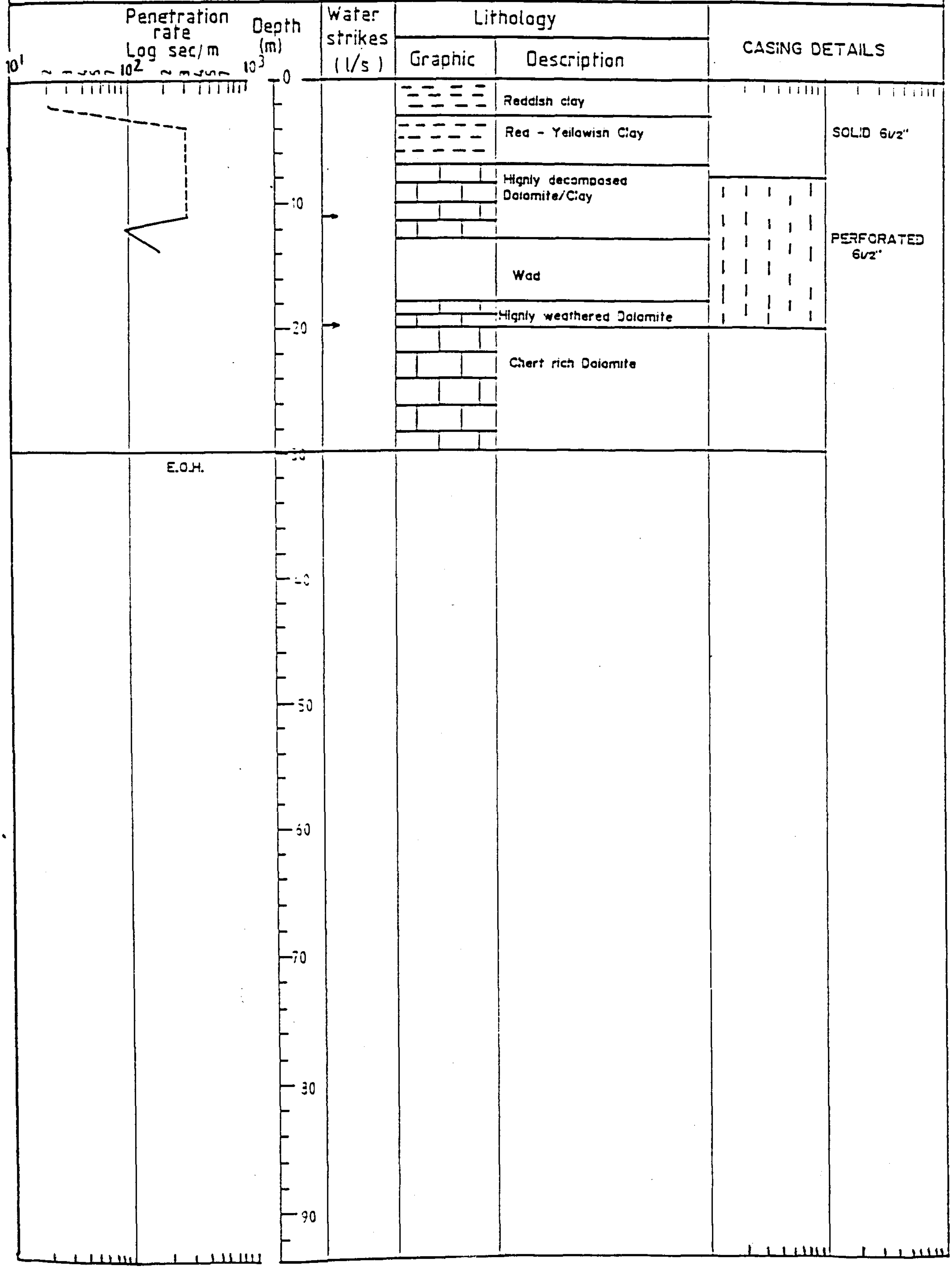
Rest water level: 13,23 m ( )

Date begin: 12/09/91 Date end: 16/09/91

Co-ordinates: X + 2869 804
Y - 75 940

Collar elevation (a.m.s.l.) 1489,90 m

Casing diameter: 6½" - open hole 8"

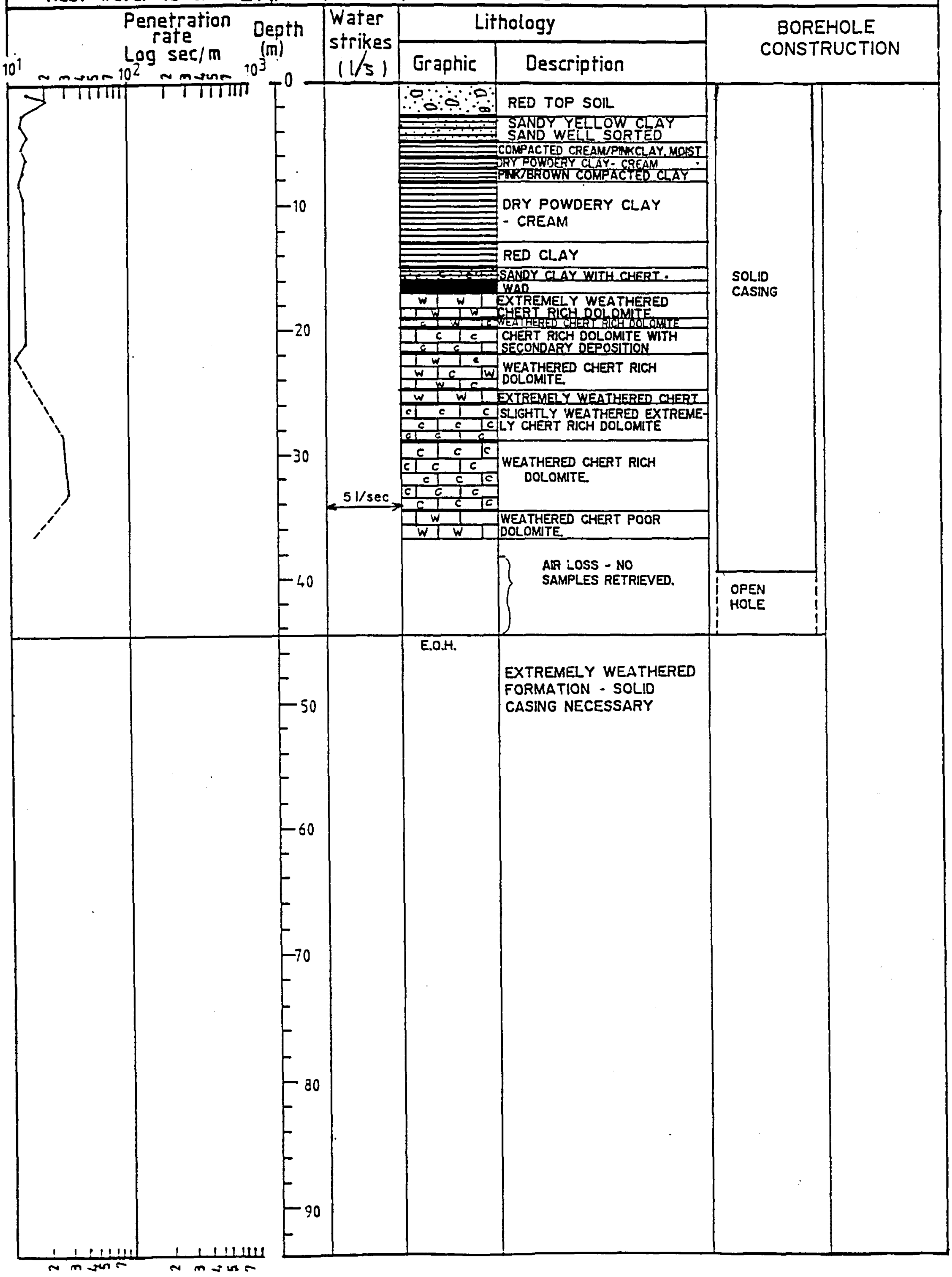


BOREHOLE INFORMATION

FIG.

Borehole No.: MR 6
Total depth drilled: 45 m
Measured blow-yield: 5 l/s
Rest water level: 27,1 m ( )

Date begin: 30/11/93 Date end: 30/11/93
Co-ordinates: X 2871075,00
Y 75533,54
Collar elevation(a.m.s.l.) 1513,16 m
Casing diameter: 150mm. Hole diameter 200mm



BOREHOLE INFORMATION

FIG.

Borehole No.: MR 7

Date begin: 01/12/93 Date end: 01/12/93

Total depth drilled: 40 m

Co-ordinates: X 2870739,12

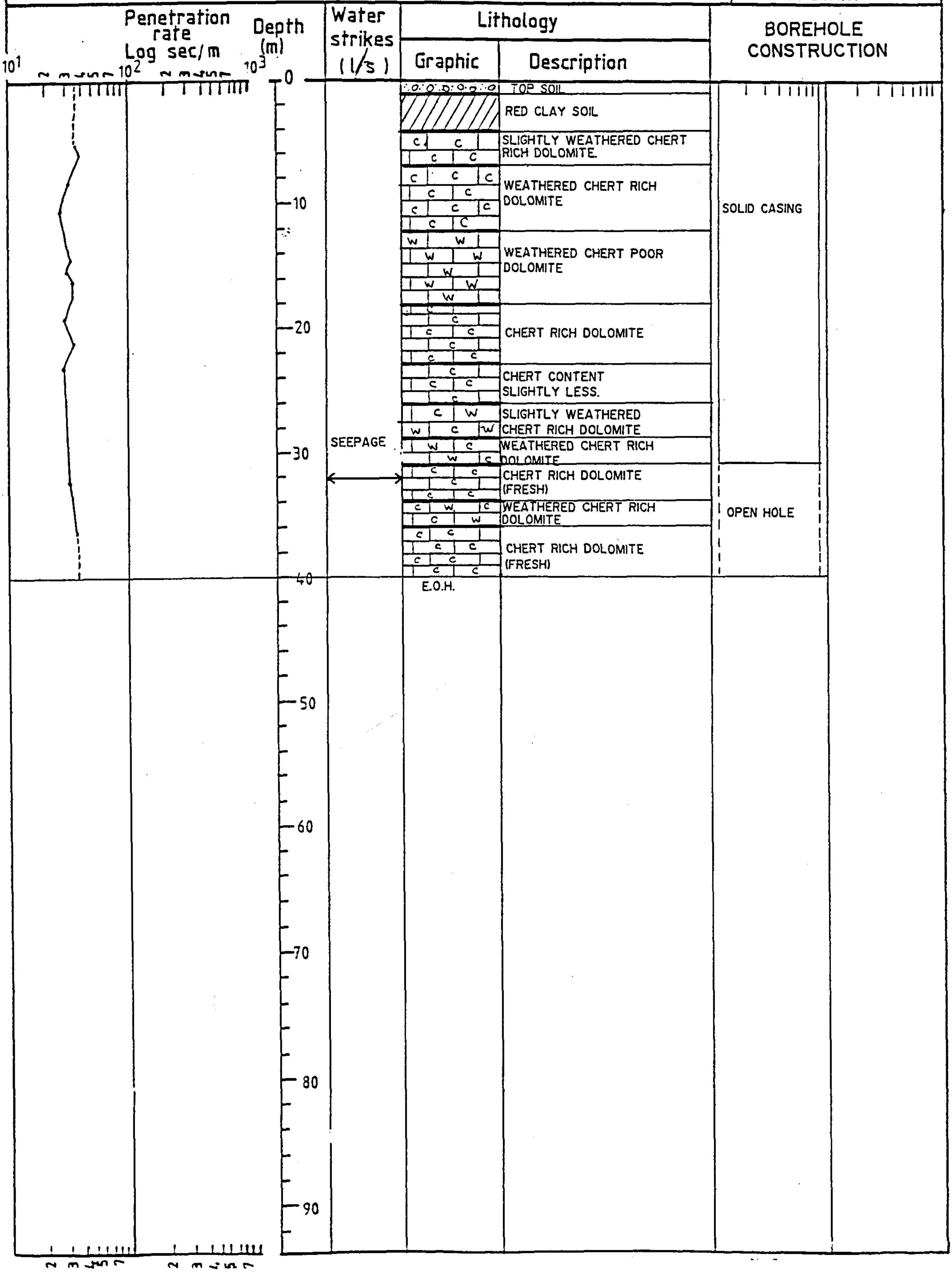
Y 75380,00

Measured blow-yield: l/s DRY

Collar elevation(a.m.s.l.) 1507,58 m

Rest water level: 31 m ( )

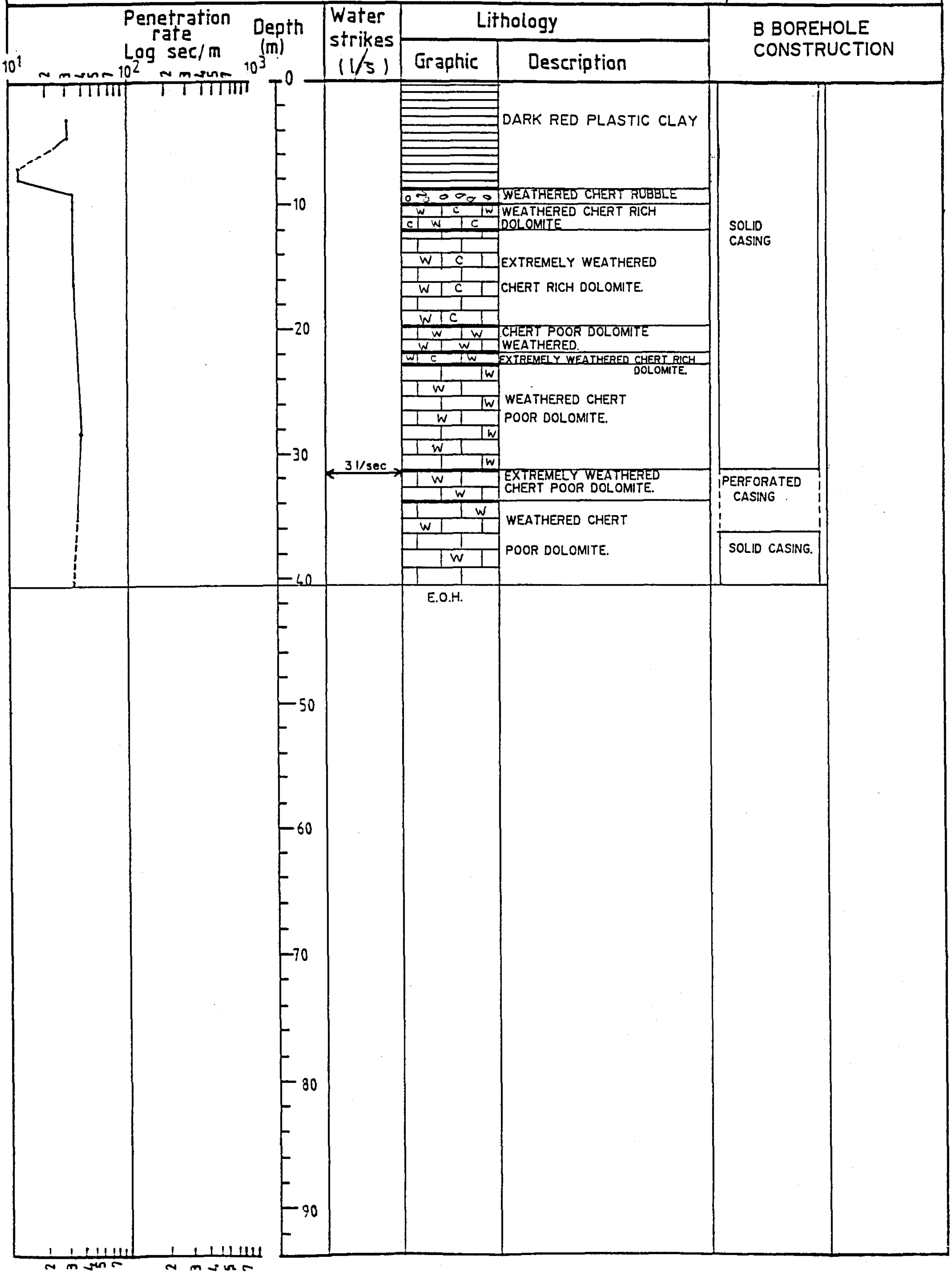
Casing diameter: 138mm ,hole=150mm



BOREHOLE INFORMATION

FIG.

Borehole No.: MR 8	Date begin: 01/12/93 Date end: 02/12/93
Total depth drilled: 41 m	Co-ordinates: X 2870998,62
	Y 75327,76
Measured blow-yield: 3 l/s	Collar elevation(a.m.s.l.) 1511,13 m
Rest water level: 28.1 m ( )	Casing diameter: 138mm, hole=150mm



BOREHOLE INFORMATION

FIG.

Borehole No.: MR 9

Total depth drilled: 33 m

Measured blow-yield: l/s

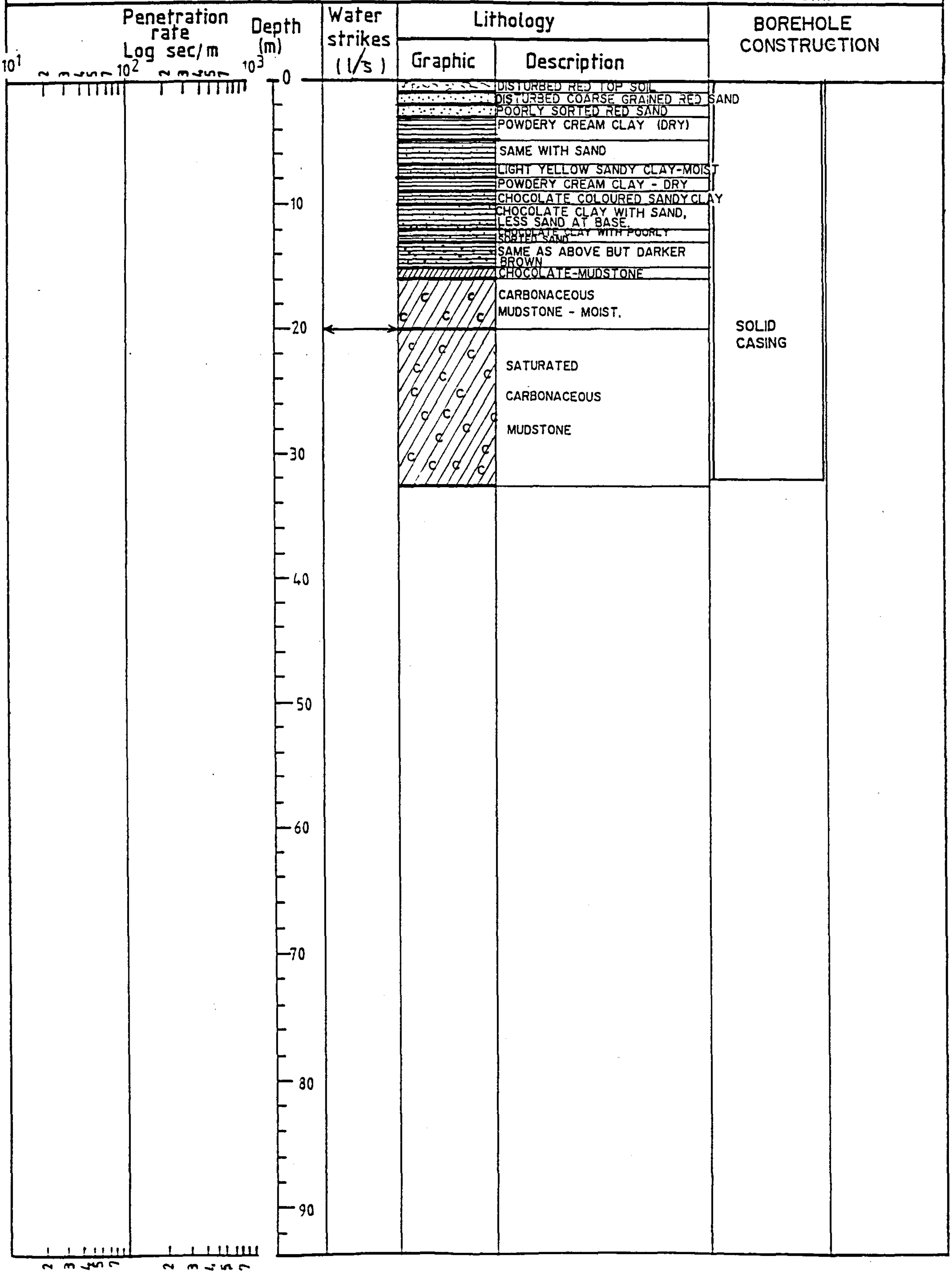
Rest water level: 6,4 m ( )

Date begin: 02/12/93 Date end: 02/12/93

Co-ordinates: X 2869940,60
Y 77229,00

Collar elevation(a.m.s.l.) 1493,05 m

Casing diameter: 138mm hole = 150mm



BOREHOLE INFORMATION

FIG.

Borehole No.: MR 10

Total depth drilled: 43 m

Measured blow-yield: l/s

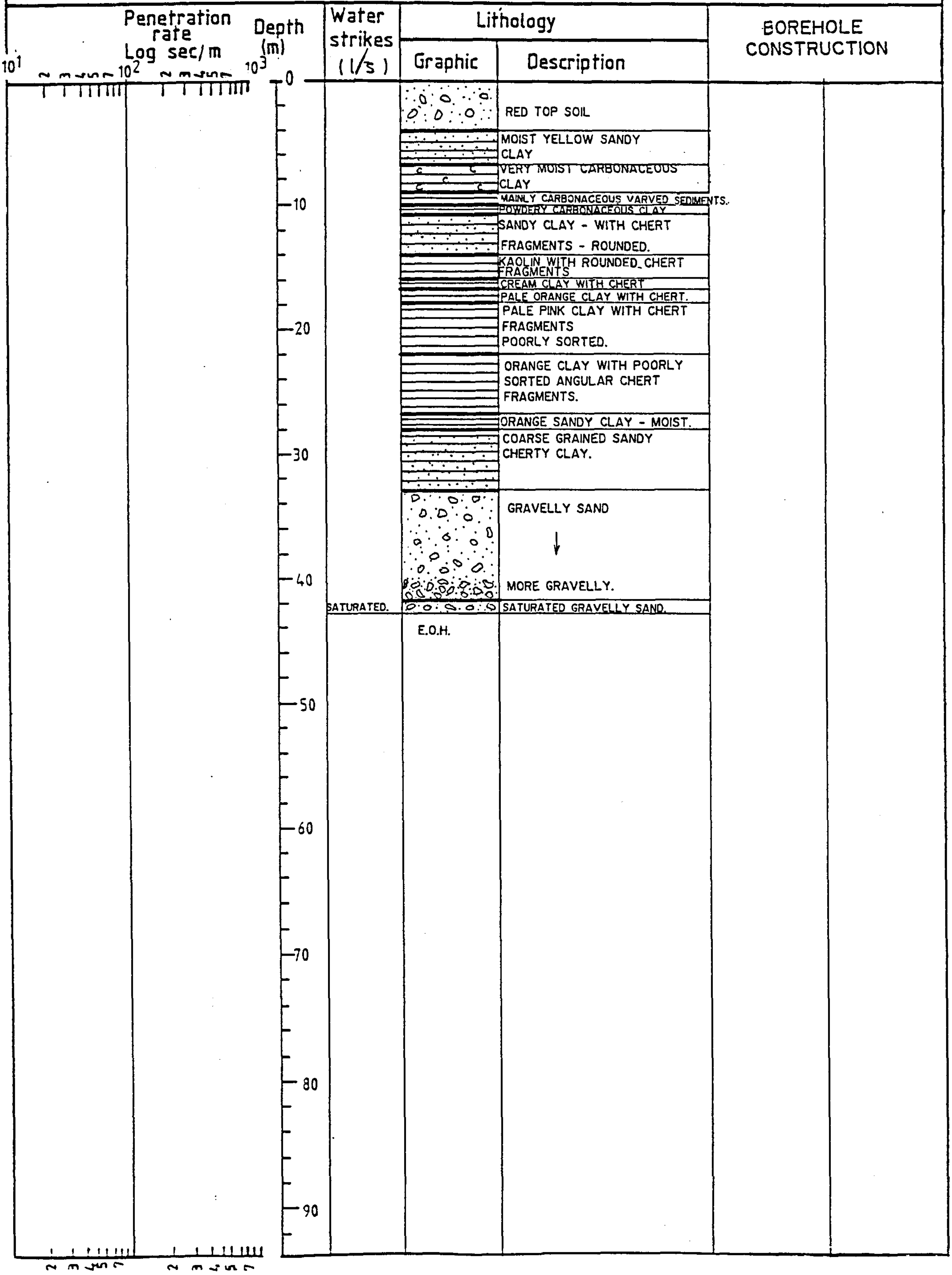
Rest water level: 17 m ( )

Date begin: 21/02/94 Date end: 21/02/94

Co-ordinates: X 2870035,00
Y 77330,00

Collar elevation(a.m.s.l.) 1493,19 m

Casing diameter: NO CASING



RED TOP SOIL

MOIST YELLOW SANDY CLAY

VERY MOIST CARBONACEOUS CLAY

MAINLY CARBONACEOUS VARVED SEDIMENTS.

POWDERY CARBONACEOUS CLAY

SANDY CLAY - WITH CHERT FRAGMENTS - ROUNDED.

KAOLIN WITH ROUNDED CHERT FRAGMENTS

CREAM CLAY WITH CHERT

PALE ORANGE CLAY WITH CHERT.

PALE PINK CLAY WITH CHERT FRAGMENTS POORLY SORTED.

ORANGE CLAY WITH POORLY SORTED ANGULAR CHERT FRAGMENTS.

ORANGE SANDY CLAY - MOIST.

COARSE GRAINED SANDY CHERTY CLAY.

GRAVELLY SAND

↓

MORE GRAVELLY.

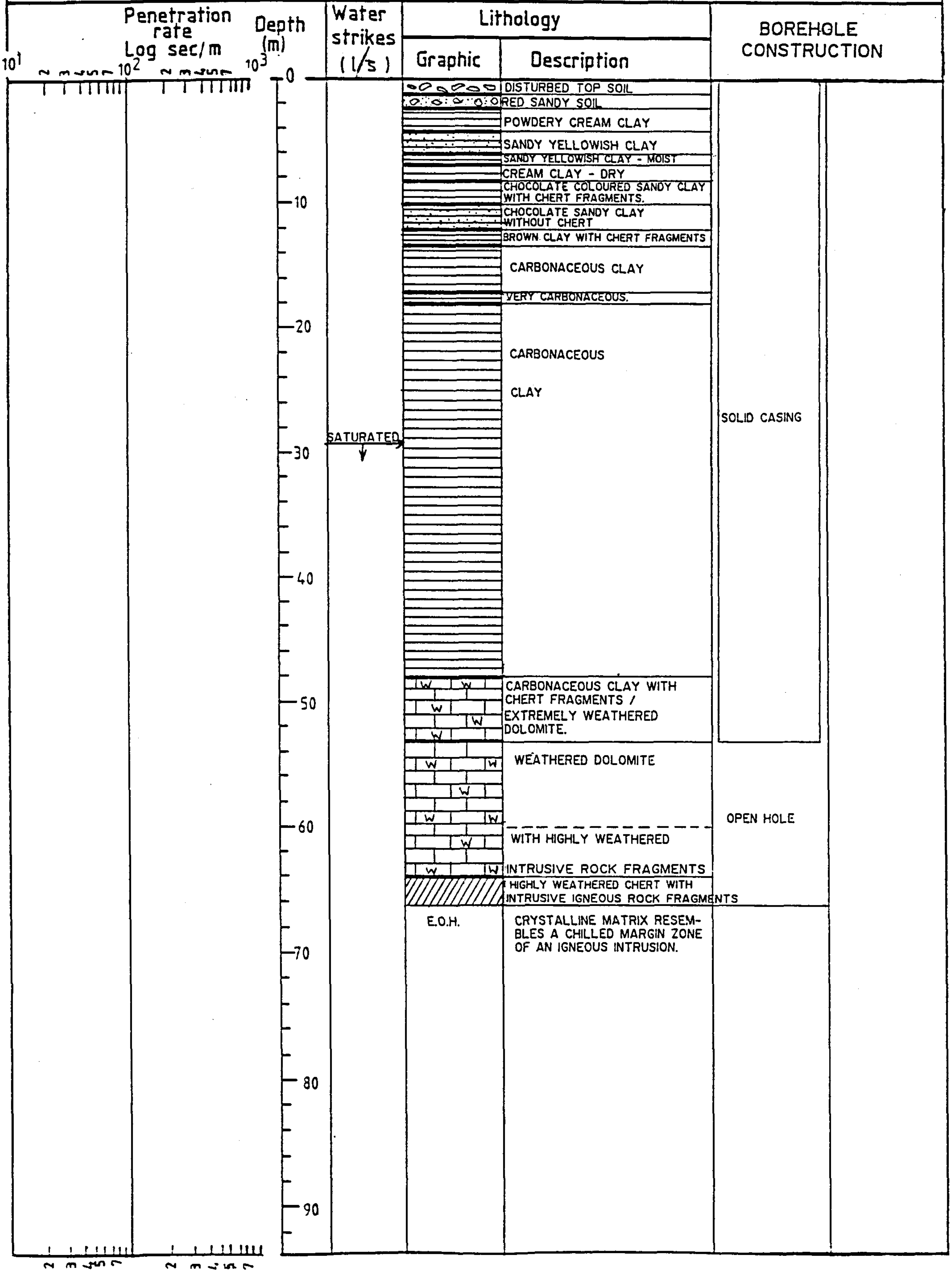
SATURATED GRAVELLY SAND.

BOREHOLE INFORMATION

FIG.

Borehole No.: MR 11
Total depth drilled: 66 m
Measured blow-yield: l/s
Rest water level: 13,2 m ( )

Date begin: 21/02/94 Date end: 22/02/94
Co-ordinates: X 2869943,00
Y 77230,00
Collar elevation (a.m.s.l.) 1492,70 m
Casing diameter:



APPENDIX 3

CHEMICAL DATA
OLIFANTSFONTEIN

CHEMICAL DATA

Borehole Number	Date	pH	E.C. mS/m	HCO_3 CO_3	SO_4	Cl	NO_3	F	PO_4	Ca	Mg	Na	K	Si	Fe	Cu	Ni
2528 CC 1	07/05/90	7.4	32.9	305	30	9	19	0.22	<0.10	54	37	9	0.3	10.9	<0.1	<0.1	<0.1
CC 1	24/04/92	7.1	49.9	331	31	9	21	0.05	<0.2	48	33	8	0.4	7.4	<0.1	-	-
CC 2	15/05/90	7.2	26.4	171	<0.5	3	<0.2	0.25	<0.10	9	31	2	0.5	1.4	2.3	<0.1	<0.1
CC 2	24/05/92	7.2	90.5	359	72	78	16	0.04	<0.2	73	46	55	3.6	8.5	<0.1	-	-
CC 3	07/05/90	7.7	30.0	683	12	154	0.93	0.10	<0.10	59	63	72	39.3	4.7	-	-	-
CC 4	07/05/90	8.2	26.3	195	<0.5	2	<0.20	0.25	<0.10	10	34	3	0.6	1.3	1.3	<0.10	<0.10
CC 5	07/05/90	7.2	49.7	311	10	17	35	0.22	<0.10	61	37	8	0.8	13.8	<0.10	<0.10	<0.10
CC 5	24/04/92	6.8	40.0	416	14	20	10	0.09	<0.2	60	37	10	0.8	8.5	0.24	-	-
CC 6	07/05/90	7.3	84.7	314	65	100	20	0.23	<0.10	68	27	81	3.7	15.9	0.4	<0.10	<0.10
CC 6	24/04/92	7.0	66.1	328	60	68	3.2	0.24	<0.2	46	24	79	9.4	8.2	<0.10	-	-
CC 7	07/05/90	6.4	48.0	244	10	15	68	0.26	<0.10	54	31	8	0.8	22.8	<0.10	<0.10	<0.10
CC 7	24/04/92	6.8	47.5	266	14	7	67	0.09	<0.2	51	26	9	0.7	12	1.3	-	-
CC 8	07/05/90	7.6	7.0	52	<0.5	2	1.6	0.16	<0.10	5	2.1	10	1.3	35.1	0.1	<0.10	<0.10
CC 10	09/05/90	7.4	60.0	323	108	58	<1.0	0.6	1.00	73	79	58	4.6	-	0.9	-	-
CC 10	24/04/92	7.4	205.0	514	440	235	<0,2	0.1	<0.2	82	66	230	11	6.9	5.7	-	-
CC 11	09/05/90	7.4	65.0	61	115	79	41	4.5	<0.10	85	56	49	1.8	-	0.15	-	-
CC 12	09/05/90	7.4	175.0	229	839	479	12	1.4	<0.10	168	167	377	21.1	-	0.85	-	-
*(SW) CC 13	09/05/90	8.1	0.10	214	30	3	5.5	0.30	<0.10	10	4	3	1.7	2.0	<0.1	<0.1	<0.1
CC 14	09/05/90	7.5	33.2	244	19	8	17	0.22	<0.10	41	30	3	0.5	13.2	<0.10	<0.10	<0.10
CC 15	09/05/90	7.6	40.3	262	37	3	0.3	0.32	<0.10	44	32	7	3.2	7.1	5.9	<0.10	<0.10
CC 16	09/05/90	7.1	65.9	281	88	45	16	0.17	<0.10	70	32	32	1.9	14.8	<0.10	<0.10	<0.10
CC 17	09/05/90	7.2	47.6	259	24	23	20	0.23	<0.10	45	28	12	0.9	14.2	<0.10	<0.10	<0.10
CC 18	10/05/90	7.1	33.6	287	1	1	0.9	0.22	<0.10	42	28	9	1.8	32.5	0.28	<0.10	<0.10
CC 19	10/05/90	6.8	16.1	67	<0.5	9	45	0.15	<0.10	14	4	20	3.6	27.1	0.26	<0.10	<0.10

Borehole Number	Date	pH	E.C. mS/m	HCO_3 CO_3	SO_4	Cl	NO_3	F	PO_4	Ca	Mg	Na	K	Si	Fe	Cu	Ni
CC 21	14/05/90	7.2	49.8	403	<0.5	2	0.5	0.14	<0.10	59	47	3	0.4	11.3	15	<0.10	<0.10
CC 22	14/05/90	6.9	48.0	397	1	3	1.5	0.13	<0.10	53	45	3	0.5	14.8	4	<0.10	<0.10
CC 23	14/05/90	7.0	56.0	433	1	9	3.4	0.24	<0.10	72	42	3	0.5	12.9	19	<0.10	<0.10
CC 23	21/04/92	7.2	36.1	459	4	4	10	0.04	<0.2	61	39	3	0.6	9.6	<0.10	-	-
CC 24	14/05/90	7.6	36.0	293	5	3	2.2	0.36	<0.10	35	32	9	0.8	14.5	<0.10	<0.10	<0.10
CC 24	21/04/92	7.2	34.1	384	1	1	3	0.05	<0.2	58	31	4	1	7.8	0.5	-	-
CC 25	14/05/90	7.1	63.8	360	7	23	75	0.22	<0.10	72	46	15	1.2	16.2	<0.10	<0.10	<0.10
CC 25	21/04/92	7.1	60.6	404	14	25	50	0.25	<0.2	61	37	23	1.2	7.9	<0.10	-	-
CC 26	15/05/90	7.8	10.1	31	20	1	0.6	0.27	<0.10	9	4	2	1.1	0.7	9.2	<0.10	<0.10
CC 27	16/05/90	7.3	47.4	384	24	22	23	0.2	<0.10	61	46	15	1.4	11.7	<0.10	<0.10	<0.10
CC 27	24/04/92	7.4	53.9	438	24	22	20	0.08	<0.2	57	46	7	1.2	7.0	<0.10	-	-
CC 28	16/05/90	8.0	23.4	159	40	25	1.7	0.3	<0.10	34	7	26	3.7	8	<0.10	<0.10	<0.10
CC 29	16/05/90	7.1	35.0	223	16	18	9.1	0.2	<0.10	38	23	13	1.7	18.3	0.3	<0.10	<0.10
CC 30	16/05/90	7.3	36.0	232	9	15	9.5	0.23	<0.10	39	24	7	1.3	18.9	<0.10	<0.10	<0.10
CC 30	21/04/92	7.2	41.3	283	10	14	11	0.07	<0.2	41	25	8	1.2	8.4	0.2	-	-
CC 31	16/05/90	7.4	33.2	323	6	6	6.2	0.24	<0.10	46	39	6	2.3	19.7	<0.10	<0.10	<0.10
CC 32	21/05/90	7.0	24.8	220	10	4	7.9	0.23	<0.10	33	27	4	0.5	11.9	<0.10	<0.10	<0.10
CC 33	26/06/91	6.5	56.0	281	15	9	15	0.5	-	41	28	6	0.9	11.2	0.08	<0.10	-
CC 33	24/04/92	7.0	48.7	337	20	10	13	0.10	<0.2	49	31	8	1.2	7.3	<0.10	-	-
CC 45	12/02/91	7.2	45.0	315	26	15	12	0	<0.2	59	41	10	1.5	-	<0.10	<0.10	<0.10
CC 46	12/02/91	7.4	160.0	451	667	34	40	0	-	248	149	27	2.2	-	5.7	<0.10	<0.10
CD 2	08/05/90	7.8	29.2	235	6	4	4.4	0.19	<0.10	34	26	4	0.4	10.6	1.0	<0.10	<0.10
CD 5	08/05/90	7.2	2.2	17	1	2	1.5	0.19	<0.10	1	2	2	0.4	6.6	<0.10	<0.10	<0.10
CD 6	08/05/90	8.3	14.2	101 9	<0.5	3	<0.2	0.19	<0.10	11	15	2	0.6	0.9	1.2	<0.10	<0.10

Borehole Number	Date	pH	E.C. mS/m	HCO_3 CO_3	SO_4	Cl	NO_3	F	PO_4	Ca	Mg	Na	K	Si	Fe	Cu	Ni
6	10/07/92	8.2	14.7	60 4	0.2	3	<0.2	0.07	<0.10	4	8	3	0.7	-	-	-	-
CD 8	08/05/90	7.4	21.7	168	1	1	1.1	0.24	<0.10	22	15	4	0.5	10.6	<0.10	<0.10	<0.10
8	22/04/92	7.2	34.8	264	6	4	7.9	0.07	<0.2	34	22	4	0.7	7.5	0.13	-	-
CD 9	08/05/90	7.6	7.0	43	1	0.2	0.7	0.22	<0.10	3	4	4	0.2	8.8	0.6	<0.10	<0.10
9	22/04/92	7.2	24.7	193	2	2	2.6	0.12	<0.2	21	16	6	0.6	6.6	<0.10	-	-
CD 10	09/05/90	6.8	29.9	244	3	3	6.1	0.27	<0.10	35	24	4	0.5	12.1	<0.10	<0.10	<0.10
CD 11	16/05/90	7.3	11.2	134	1	13	<0.2	0.23	<0.10	15	6	10	0.7	3	12	<0.10	<0.10
CD 12	26/06/90	6.0	18.8	110	2	1	0.8	0.3	<0.10	10	8	4	1.2	6.3	0.11	<0.10	<0.10
MR 1	13/01/92	7.1	33.4	340	100	60	13	0.05	<0.10	73	40	35	1.8	10	-	-	-
MR 2	02/09/91	7.7	71.0	300	10	60	1.3	0.02	<0.2	12	73	28	7.0	8.4	-	-	-
MR 3	02/09/91	8.0	55.4	308	51	28	12	0.02	-	70	44	9	3.0	14	-	-	-
MR 4/1	13/01/92	7.5	22.5	68	66	37	14	0.80	<0.10	74	40	8	1.3	9.6	-	-	-
MR 4/2	13/01/92	7.6	26.9	258	68	38	13	0.47	<0.10	73	39	7	1.3	6.4	-	-	-
MR 5/1	13/01/92	7.0	22.9	362	34	21	20	0.10	<0.10	54	33	4	0.9	6.4	-	-	-
MR 5/2	13/01/92	6.9	21.5	264	33	21	20	0.47	<0.10	56	33	4	1.1	3.8	-	-	-
MR 6	03/12/93	7.4	53.0	329	2	2	1.5	0.20		51	26	7	0.98	15.0	-	-	-
MR 7	03/12/93	7.3	64.0	395	5	17	1.4	0.20		65	45	7	1.60	8.1	-	-	-
MR 8	03/12/93	7.2	71.0	347	5	1	<0.6	0.20		57	39	3	0.46	7.8	-	-	-
MR 8a	03/12/93	7.2	73.0	402	1	1	5.3	0.10		65	40	4	0.20	11.0	-	-	-
MR 9	03/12/93	6.2	33.0	20	60	12	<0.6	0.10		14	7	9	2.7	8.9	-	-	-
MR 10	03/12/93	6.8	35.0	118	8	12	7.3	0.11		21	14	6	1.9	16.0	-	-	-
MR 11	03/12/93	7.9	43.0	71	111	11	<0.6	0.12		17	9	12	4.0	23.0	-	-	-
DAM	03/12/93	7.8	169.0	119	700	18	0.8	0.9		145	92	24	13.0	3.2	-	-	-

Borehole Number	Date	pH	E.C. mS/m	HCO_3 CO_3	SO_4	Cl	NO_3	F	PO_4	Ca	Mg	Na	K	Si	Fe	Cu	Ni
CONTROL AREA																	
RTV 1	16/04/91	7.3	12.5	92	1	1	4.8	0.08	<0.20	15	10	3	1.1	7.8	<0.10	<0.10	-
1	11/04/92	7.2	17.1	139	1	2	5	0.06	<0.20	16	11	3	1.2	7.2	<0.10	<0.10	-
RTV 2	16/04/91	6.8	4.9	238	44	36	29	0.09	<0.20	39	24	40	3.5	8.4	<0.10	<0.10	-
RTV 3	16/04/91	7.4	22.5	177	2	4	9.3	0.07	<0.20	30	18	4	0.5	8.4	<0.10	<0.10	-
3	23/04/92	7.0	25.6	183	2	5	8.7	0.06	<0.20	25	15	3	0.7	7.9	7.5	<0.10	-
RTV 4	16/04/91	8.1	19	171	1	1	1.4	0.05	<0.20	27	15	2	0.5	7.1	0.13	<0.10	-
4	24/04/92	8.0	21.7	174	1	2	1.2	0.04	<0.20	21	13	3	0.7	6	<0.10	-	-
RTV 5	16/04/91	7.4	20	173	2	4	9.7	0.06	<0.20	27	16	5	0.7	4.6	<0.10	<0.10	-
5	22/04/92	7.0	25	189	2	3	5.8	0.08	<0.20	23	17	4	0.8	6.2	<0.10	-	-
RTV 6II	16/04/91	7.1	16.7	44	2	6	8.7	0.10	<0.20	13	10	6	0.3	11	-	-	-
G 37024	16/04/91	7.7	25	222	1	1	9.9	0.07	<0.20	46	20	3	0.4	7.8	0.53	<0.10	-
G 37024	23/04/92	7.0	22	179	2	9	9.3	0.07	<0.20	24	15	5	0.8	7.1	0.23	-	-
G 37025	16/04/91	7.1	29	259	1	1	4	0.06	<0.20	40	22	3	0.6	12	6.0	<0.10	-

*(SW) = Surface Water

APPENDIX 4

ENVIRONMENTAL ISOTOPE DATA
OLIFANTSFONTEIN

ENVIRONMENTAL ISOTOPE ANALYSES

NUC No	WITS No	Date	Description/Location	Map Ref (258-)	^{14}C (pMC)	^{3}H (TU)	$\delta^{18}O$ (‰)	$\delta^{2}H$ (‰)	$\delta^{13}C$ (‰)
101		28.05.90		CC 1		2.6±0.3	-3.0	-20.0	
102		28.05.90		CC 2		1.3±0.2	-3.6	-20.2	
103		28.05.90		CC 4		0.2±0.2	-4.0	-26.4	
104		28.05.90		CC 5		3.7±0.3	-2.6	-13.8	
105		28.05.90		CC 6		5.1±0.4	-1.8	-5.4	
106		28.05.90		CC 7		4.4±0.4	-3.6	-23.5	
107		28.05.90		CC 8		0.6±0.2	-4.1	-26.3	
108		28.05.90		CC 10		2.0±0.4	-3.8	-24.6	
109		28.05.90		CC 11		3.8±0.4	-3.0	-16.5	
110		28.05.90		CC 12					
111		28.05.90		CC 13		5.4±0.5	-1.7	-0.3	
114		28.05.90		CC 16		3.9±0.4	-2.0	-10.9	
115		28.05.90		CC 17		1.6±0.3	-3.4	-20.2	
116		28.05.90		CC 18		0.3±0.2	-3.6	-23.3	
117		28.05.90		CC 19		4.5±0.4	-3.2	-19.6	
118		28.05.90		CC 21		1.0±0.2	-4.0	-25.0	
119		28.05.90				0.5±0.2	-3.8	-19.4	
131		28.05.90		CD 5		0.1±0.2	-3.3	-19.4	
133		28.05.90		CD 8		0.0±0.2	-4.6	-25.9	
134		28.05.90		CD 9		0.2±0.2	-4.5	-23.5	
135		28.05.90		CD 10		1.6±0.2	-3.7	-19.3	
136		28.05.90		CD 11		1.5±0.3	-3.1	-18.8	
137		06.06.90	Acromed Spanner St	CC 44		1.6±0.3	-3.4	-21.3	
138		06.06.90	Wocke 8 Meintje St			2.3±0.3	-2.5	-17.8	
139	1950	19.06.90	Reynders 8 Oribi St		98.5±0.6	1.3±0.3	-4.1	-23.1	-12.3
140	1965	19.06.90	Celliers 50 Impala St		96.8±0.6	1.7±0.3	-3.7	-22.7	-12.8
141	1966	19.06.90	Meyer 3 Becker St	CC 28	62.2±0.5	1.3±0.3	-3.8	-21.1	-9.0
142	1971	19.06.90	Havenga 86 Oribi St	CC 22	97.1±0.6	2.3±0.3	-3.3	-21.0	-13.2
143	1972	19.06.90	Bannink 75 Pearce Rd	CC 29	94.4±0.6	4.9±0.4	-2.8	-11.9	-9.6
144	1973	19.06.90	Wocke 8 Meintjies St		83.4±0.6	2.3±0.3	-3.4	-20.3	-11.0
145	1974	19.06.90	Acromed Spanner Rd	CC 44	81.8±0.6	1.6±0.3	-3.6	-20.3	-9.8
146	1975	19.06.90	Marais 30 Dan St	CC 30	85.1±0.6	2.7±0.4	-3.1	-21.6	-10.0
147	1976	19.06.90	van Zyl 13 Springbok	CC 24	53.0±0.5	0.0±0.2	-3.8	-25.6	-8.1

NUC No	WITS No	Date	Description/Location	Map Ref (258-)	^{14}C (pMC)	^{3}H (TU)	δ^{18}O (‰)	δ^{2}H (‰)	δ^{13}C (‰)
148	1954	26.06.90	Rosema Brick	CD 8	50.7±0.5	0.0±0.2	-4.6	-25.5	-11.3
149	1955	26.06.90	Sterkf. Brick	CD 10	76.1±0.8	1.6±0.2	-4.1	-24.3	-8.0
150	1956	26.06.90	Avenue Farm	CC 16	89.1±0.6	2.3±0.2	-3.5	-20.3	-8.4
151	1957	26.06.90	Salberg Concr.	CC 3	98.3±0.8	3.5±0.4	-3.9	-18.2	-7.8
152	1964	26.06.90	Timeball Farm		62.2±0.5	0.0±0.2	-4.8	-27.7	-14.5
153	1959	26.06.90	Sunlawns	CC 5	81.8±0.6	3.8±0.3	-2.8	-15.2	-12.2
154	1958	03.07.90	Markus Randjiesfntn	CC 8	89.3±0.6		-4.1	-26.3	-11.4
155	1960	03.07.90	Olifantsfontein	CC 18	76.7±0.5	0.3±0.2	-3.6	-23.3	-10.2
156	1961	03.07.90	Sterkfontein	CD 2	70.9±0.5	0.5±0.2	-3.8	-19.4	- 7.5
157	1963	09.07.90	Vermeulen 52 Glenton St	CC 25	97.9±0.6	4.9±0.6	-2.9	-15.1	-11.8
159	1970	25.07.90	# Gate Waste Tech	CC 10	38.7±0.4	3.2±0.3	-3.7	-24.8	-8.6
160		25.07.90	#3 Tar Road Waste Tech	CC 12		6.5±0.6		-20.4	
161	1969	25.07.90	#1 Office Waste Tech	CC 11	68.5±0.7				-9.9
162	1979	06.09.90	Rothman		106.7±0.8	5.8±0.5		-3.8	-7.2
164	1981	06.09.90	Ugerer 25 Blesbok		86.2±0.7			-23.3	-10.4
165	1980	06.09.90	Sterkfntn Spr.	CC 32	73.6±0.8	4.3±0.4		-21.7	-6.4
166		02.10.90	New Brick Factory No. 1/1	CC 26		4.3±0.4	-2.6	-7.0	
167		"	" #1			5.3±0.4	-2.4	-5.8	
168		"	" 12 m			4.8±0.4	-2.5	-5.2	
169		"	" 30 m				-2.5	-5.9	
170		11.90	Clayville Tap Water #1			4.7±0.4		+6.5	
171		11.90	" #2			5.8±0.6		+6.9	
180	2017	5.91	RTV 1		56.7±0.5			-24.1	-10.3
181	2016	"	RTV 2		103.2±0.6	4.8±0.4		-11.4	-7.9
182		"	RTV 3			1.2±0.4		-22.1	
183	2018	"	RTV 4		55.1 ±0.7	0.5±0.2		-24.1	-10.3
184	2019	"	RTV 5		78.0±0.8	0.6±0.2		20.1	-6.8
193	2026	"	G 37024		65.1±0.6	0.6±0.2		-36.2	-7.9
194	2027	"	G 37025		68.3±0.5	1.1±0.2		-25.5	-8.1
195			MR 1			4.1±0.3			
196	2028		RTV 6II		80.6 ±0.8	1.0±0.2		-23.0	-12.8
197	2029		RTV 7		60.8±0.7	0.2±0.2		-25.2	-11.2
206	2113		MR 1		83.7±0.8	3.3±0.2	-3.62	-22.3	-9.54
207	2114		MR 4/1		82.8±0.9	3.9±0.2	-3.62	-21.5	-9.65
208	2115		MR 4/2		82.1±1.7		-3.52	-21.8	-9.47
209	2116		MR 5/1		84.2±0.6		-3.61	-23.4	-8.90

NUC No	WITS No	Date	Description/Location	Map Ref (258-)	^{14}C (pMC)	^{3}H (TU)	$\delta^{18}O$ (‰)	$\delta^{2}H$ (‰)	$\delta^{13}C$ (‰)
210	2117		MR 5/2		85.8±0.7	3.3±0.3	-3.75	-25.3	-9.44
211	2118	30/01/92	Bfn S 00005		1235±1.0	28.1±1.5	-5.08	-31.2	+0.94
212	2119	30/01/92	Bfn S 00004		92.8±1.1	0.9±0.2	-5.87	-36.9	-6.01
213		30/01/92	Bfn S 00001		-	1.2±0.2	-5.21	-37.1	
214		30/01/92	Bfn N 00001		-	31.2±1.5	-3.83	-13.7	
215	2120	30/01/92	Bfn N 00002		108.2±0.9	7.9±0.5	+4.44	+22.6	-7.89
216	2121	30/01/92	Bfn N 00003		113.8±0.8	8.0±0.6	-1.72	-9.5	-8.14
217	2122	31/01/92	Bfn Royal vd Walt		117.3±1.1	5.7±0.4	-5.88	-36.1	-2.49
218	2123	31/01/92	Bfn Royal Grass		107.7±0.8	1.9±0.3	-6.24	-41.0	-4.20
219		17/02/92	Wfl Main St. Albertville		-	0.7±0.2	-4.21	-29.5	
220		19/02/92	Wfl CW A		-	23.2±1.1	-3.05	-16.7	
221		19/02/92	Wfl SW A		-	12.2±0.6	-14.1		
222		19/02/92	Wfl SW B		-	8.3±0.5	-2.90		
223		22/02/92	5 Smuts Ave		-	2.6±0.3	-4.73		
224		22/02/92	Bowling Club		-	4.5±0.3	-3.75		
225		22/02/92	8 Willow St		-	4.2±0.4	-3.74		
226		24/02/92	44 Max Michaelis		-	5.6±0.4	-3.21		
227	2179	14/05/92	Midrand	CC 10	71.2±0.7		-3.72	-9.97	
228	2177	14/05/92	Midrand	CC 11	60.4±0.5		-4.37		-9.81
229	2175	21/05/92	GL 4 Linbro Pk		86.2±0.8	1.2±0.2			
230	2176	21/05/092	GL 6 Linbro Pk		69.4±0.8	0.6±0.2			
231	2178	21/05/92	GL 6(A) Linbro Pk		94.4±0.8	3.4±0.3			
232	2180		MR 3		84.3±0.8				-9.90
233	2181		Midrand	CD 11	77.8±0.8		-4.39		-6.16
234	2182		A2N696		108.8±0.8				
235	2183		Midrand	CC 24	85.9±0.5		-5.06		-9.99
236	2184		Midrand	CD 4	64.6±1.1	0.4±0.2	-5.38		-8.26
237	2185	02/06/92	GL 7 Linbro Pk		117.2±0.5	0.8±0.2	-4.73		-8.47
238	2186	02/06/92	GL 8 Linbro Pk				-5.06		-11.55
239	2187	02/06/92	GL 9 Linbro Pk		97.7±2.2	0.4±0.2	-5.38		-10.73
240	2188	03/06/92	PH 66 Linbro Pk		84.0±0.9	0.4±0.2	-4.95		-10.19
241		03/06/92	GL 3 Linbro Pk			4.6±0.4	-4.40		
242	2189	04/06/92	Midrand	CD 6	92.2±1.2	2.3±0.2	-4.37		
243	2190	04/06/92	Midrand	CD 2	77.8±0.7	1.6±0.3	-4.61		

APPENDIX 5

DEPTH PROFILE DATA

Borehole MR 9 - Stable isotope analysis

NUC N°	DEPTH (m)	$\delta^{18}O$ (‰)	Sample Mass Before (kg)	Sample Mass After (kg)	Mass Water (kg)	Percent Recovery	Mass Percent Water
292	00-01	+0.68		2.83			
293	01-02	-1.46	3.55	3.48	0.063	91.3	2.3
294	02-03	-1.17		3.47	0.094		
295	03-04	-2.42		3.10	0.120		
296	04-05			3.55	0.028		
297	05-06	-2.45		3.67	0.071		
298	06-07	-1.21		3.24	0.046		
299	07-08	-2.99		3.03	0.273		
300	08-09	-1.20	3.46	3.28	0.169	91.1	6.4
301	09-10		3.20	3.06	0.119	87.6*	5.1
302	10-11	-1.37	3.57	3.37	0.194	96.0	7.1
303	11-12	-1.59	3.19	2.96	0.226	96.4	9.6
304	12-13	-3.73		3.33	0.219		
305	13-14	-4.33		3.29	0.232		
306	14-15	-3.49		2.08	0.195		
307	15-16	-0.79	3.62	3.37	0.243	95.1	8.7
308	16-17		3.31	3.11	0.183	92.5	7.4
309	17-18	-0.94	2.97	2.77	0.191	96.1	8.9
310	18-19	-3.41		3.00	0.181		
311	19-20	-1.04	2.88	2.63	0.238	96.2	11.6
312	20-21		3.76	2.88	0.739	83.4*	25.2
313	21-22	-1.05	3.96	2.83	1.098	96.7	35.1
314	22-23	-0.46	4.27	3.30	0.937	96.5	27.3
315	23-24	-1.22	4.07	3.23	0.798	95.0	24.7
316	24-25	-0.69	4.35	3.46	0.965	102.1	27.4
317	25-26	Broken					

318	26-27	-0.83	3.99	2.78	1.162	96.0	36.9
319	27-28	-0.85	2.42	1.72	0.674	96.5	42.6
320	28-29	-0.91	3.08	2.29	0.756	96.0	33.8
321	29-30	-0.63	3.55	2.51	1.077	102.9	39.6
322	30-31	-0.65		3.29	0.663		
323	31-32	-0.39	4.11	3.03	1.067	98.9	32.6
324	32-33	-0.46	3.89	2.73	1.104	95.3	36.1

Table 9.2 Borehole MR 10 - Stable isotope analysis

NUC N°	Depth (m)	$\delta^{18}O$ (‰)	Sample Mass Before (kg)	Sample Mass After (kg)	Mass Water (kg)	Percent Recovery	Mass Percent Water
331	05-06	-3.56	3.10	2.87	0.211	91.9	9.30
332	07-08	-4.50	2.82	2.49	0.300	91.4	15.14
333	08-09	-5.08	3.01	2.72	0.267	93.6	12.28
334	09-10	-4.45	3.99	3.76	0.216	93.2	6.85
335	10-11	-4.21	3.67	3.38	0.270	95.4	9.54
336	11-12		3.86	3.70	0.139	88.3*	4.60
337	16-17		3.35	3.18	0.142	86.4*	5.67
338	27-28	-4.44	3.50	3.32	0.161	91.3	6.05
339	29-30	-3.17	3.50	3.40	0.093	91.3	3.49
340	30-31		3.83	3.73	0.081	87.4*	2.71
341	31-32	-3.55	3.96	3.85	0.099	92.3	3.16
342	32-33		3.51	3.43	0.69	85.2*	2.59
343	33-34	-4.15	3.60	3.46	0.123	92.4	4.46
344	34-35	-2.71	3.29	3.18	0.106	91.5	4.31
345	35-36	-3.72	3.24	3.12	0.113	93.7	4.71
346	36-37	-3.28	3.42	3.30	0.115	92.2	4.45
347	37-38	-3.49	3.45	3.28	0.163	93.2	6.23
348	38-39		3.55	3.38	0.156	89.5*	5.74
349	39-40	-3.33	3.43	3.28	0.140	93.7	5.40
350	40-41	-3.04	3.42	3.20	0.211	92.7	8.15
351	41-42	-3.33	4.56	3.69	0.818	94.6	21.96
352	42-43	-3.78	4.90	4.12	0.757	97.1	18.62

Borehole MR 11 - Stable isotope analysis

NUC N°	Depth (m)	$\delta^{18}0$ (‰)	Sample Mass Before (kg)	Sample Mass After (kg)	Mass Water (kg)	Percent Recovery	Mass Percent Water
353	03-04		3.55	3.47	0.073	88.5*	2.68
354	13-14	-0.08	3.21	2.99	0.213	96.9	8.99
355	22-23	-3.96	3.40	3.17	0.224	93.5	8.73
356	31-32	-2.56	3.33	3.12	0.205	96.0	8.21
357	33-34	-1.06	3.23	2.73	0.492	98.2	20.57
358	35-36	-1.90	3.61	2.86	0.743	99.3	26.82
359	37-38	-1.62	3.94	2.78	1.125	96.9	36.28
360	39-40	-1.49	3.76	3.05	0.692	97.3	23.65
361	41-42	-3.08	3.95	3.15	0.783	98.4	25.15
362	43-44		3.99	2.81	0.972	82.0*	30.76
363	45-46	-1.45	3.82	2.45	1.263	92.1	42.26
364	47-48		4.15	3.01	1.015	89.0*	30.65
365	49-50		3.78	2.41	1.090	79.4*	37.01
366	51-52	-2.44	3.43	1.84	1.533	96.6	59.18
367	53-54	-0.86	2.84	1.22	1.606	98.8	80.03
368	55-56	-0.54	3.26	1.65	1.494	92.9	61.72