GEOLOGICAL CONTROL OF AQUIFER PROPERTIES OF THE CHUNIESPOORT GROUP IN THE KLIP RIVER VALLEY AND NATALSPRUIT BASIN, TRANSVAAL

BY

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ABSTRACT

The aquifer of the study area occupies an escarpment and low lying limestone plain, and exhibits a Vaal River type karst. The four dolomitic formations present fall into two distinct aquifer forming types; chert poor units and chert rich units. The chert poor units of the Oaktree and Lyttelton Formations were deposited in a subtidal environment and were probably dolomitised in a migrating schizohaline environment during basin subsidence and shoreline trangression. The chert rich units of the Monte Christo and Eccles Formations were deposited in the shallow subtidal to supratidal zones and the interbedded chert and dolomites may result from minor cyclical marine trangressions and regressions or be a geochemical response to the periodic flooding of freshwater carbonate and flats and tidal deltas.

These fundamental geological differences are reflected in correspondingly different development of karst. Transmissive zones in the chert poor units are generally discrete solution features in massive dolomite, 1 m to 2 m thick. Transmissive zones in the chert rich units comprise thick (up to 60 m) and extremely weathered chert with a high void content resulting from the dissolution of carbonate material. The relative importance of various geological features to the development of the karst was assessed using information from two extensive hydrogeological investigations of the area. From the results it has been concluded that lithostratigraphy, including the occurrence of palaeokarstic horizons, is the major control of aquifer properties. All other geological features are of lesser importance but may nevertheless be associated with enhanced transmissivities in any given unit. Faults and lineaments are the structural features most widely associated with

highly transmissive zones. The knowledge gained in this study is applicable elsewhere as the principal hydrogeological characteristics of the study area are common to many of the Chuniespoort Group aquifers in the Pretoria - Witwatersrand - Vereeniging Region.

CONTENTS

PAGE

LIST OF FIGURES IV

LIST OF TABLES VIII

LIST OF PLATES X

1. INTRODUCTION 1

1.1 Background 1

1.2 Previous work 2

1.3 Aims and objectives 5

1.4 Location of the study area 5

1.5 Physiography 6

2. INVESTIGATION PROCEDURES AND CONSTRAINTS 8

2.1 Desk study 8

2.2 Geohydrological census 9

2.3 Geological mapping 10

2.4 Drilling and aquifer tests 12

2.4.1 General 12

2.4.2 Drilling 12

2.4.3 Pumping tests 14

2.5 Geophysics 16

2.5.1 General 16

2.5.2 Magnetics 16

2.5.3 Gravity 18

2.6 Hypotheses 21

3. GEOLOGY 24

3.1 Introduction 24

3.2 Lithostratigraphy 25

3.2.1 General 25

3.2.2 Pre Transvaal Sequence 26

Witwatersrand Supergroup 26

Ventersdorp Supergroup 26

3.2.3 Transvaal Sequence 27

Black Reef Formation 27

Chuniespoort Group 27

Pretoria Group 32

3.2.4 Karoo Sequence 32

3.2.5 Quaternary and Recent 34

3.3 Intrusives 35

3.3.1 Dykes 35

3.3.2 Sills 36

3.4 Sedimentology 37

3.4.1 General 37

3.4.2 Carbonates and stromatolites 37

3.4.3 Dolomitisation 40

3.4.4 Silicification 43

3.5 Structure 47

3.5.1 Regional 47

3.5.2 Folding 48

3.5.3 Faulting 49

3.5.4 Lineaments 50

4. KARST HYDROGEOLOGY 51

4.1 Introduction 51
4.2 Principles of Karst formation 55
4.2.1 General 55
4.2.2 Structure 56
4.2.3 Decrease of permeability with depth 59
4.2.4 Base levels 61
4.2.5 Paleaokarst 61
4.3 Transvaal Karst 62
4.3.1 General 62
4.3.2 History of the Transvaal Karst 66
4.4 Karst of the study area 68
4.4.1 Surface karst 68
4.4.2 Subsurface karst 70
4.4.3 Base levels 72

5. RESULTS 77

5.1 Introduction 77
5.2 Descriptive analysis of geohydrological census ... 79
5.3 Stratigraphic control of aquifer properties 80
5.4 Palaeokarstic control of aquifer properties 91
5.5 Hydrogeological role of linear features 93
5.5.1 Geohydrological census 93
5.5.2 Exploration boreholes 102
5.6 Hypothesis testing and discussion 114

6. CONCLUSIONS AND RECOMMENDATIONS 120

7. REFERENCES 123

APPENDIX 134

LIST OF FIGURES

FIGURES PAGE

1. Location map of the study area. 4

2. Schematic block diagram of the Klip River Valley. 6

3. Typical magnetic signature of East-West trending dykes in the study area. 17

4. Geological profile across gravity low in the Far West Rand. 20

5. Diagrammatic representation of working hypotheses. 23

6. Generalised lithostratigraphic column. 25

7. Typical succession of the Karoo Sequence at Vereeniging. 34

8. Idealised profile of the Chuniespoort Group environment of deposition. 40

9. Depiction of hypothetical solubility relationships of calcite, dolomite and silica for mixing of meteoric and marine waters. 45

10. Deposition of dolomite and chert in a schizohaline environment. 46

11. Regional geological map showing major fold axes. 47

12. Diagrammatic geological cross section across the nose of the Potchefstroom synclinorium in the Klip River Valley. 50

13. Trend analysis of structural features in the study area. 51

14. Experimental rate curves comparing the solution of a cavernous limestone with a non cavernous dolomite. 54

15. The development of large solution openings in carbonate rock. 54

16. Relationship between hydrogeological characteristics and depth. 60

17. 'Escarpment and low lying limestone plain' type karst. 65

18. Geological age plotted against permeability for open or obstructed fissures in calcium carbonate rocks. 65

19. Karst types of the Transvaal. 68

20. Disappearance of streams on the Chuniespoort Group outcrop. 69

21. Ground water level map of the study area. 73

22. Ground water occurrence in the Natalspruit Basin relative to the rest water level. 75

23. Ground water occurrence in the Klip River Valley relative to the rest water level. 76

24. Graphical analysis of the geohydrological census in the Natalspruit Basin. 80

25. Distribution of reported borehole yields in relation to stratigraphic height in the Upper Klip River area. 82

26. Distribution of reported borehole yields in relation to stratigraphic height in the Middle and Lower Klip River area. 84

27. Exploration borehole transmissivities in relation to stratigraphy. 85

28. Geological log of borehole penetrating chert rich aquifer. 88

29. Borehole log showing gradual increase in air-lift yield with depth. 89

30. Typical geological log of water yielding borehole in chert poor dolomite. 90

31. Reported borehole yields in relation to distance from various hydrogeological features for the Oaktree Formation. 95

32. Reported borehole yields in relation to distance from various hydrogeological features for the Oaktree and Lyttelton Formations. 96

33. Reported borehole yields in relation to distance from various hydrogeological features for the Lyttelton and Monte Christo Formations. 97

34. Reported borehole yields in relation to distance from various hydrogeological features for the Monte Christo and Eccles Formations. 98

35. Reported borehole yields in relation to distance from various hydrogeological features for the Eccles Formations. 99

LIST OF TABLES

TABLES PAGE

1. Summary of previous geohydrological reports in the Klip River Valley and Natalspruit Basin. 2

2. Average density values for bedrock and overburden occurring in areas underlain by the Chuniespoort Group. 20

3. Evidence for mechanisms of dolomitisation. 42

4. Types of carbonate aquifer systems in regions of low to moderate relief. 63

5. Drainage densities for different lithologies. 70

6. Summary of reported yields in the Upper Klip River Valley. 82

7. Summary of reported borehole yields in the Middle and Lower Klip River Valley. 83

8. Borehole transmissivities according to stratigraphy. 85

9. Borehole transmissivities on the pre-Karoo Sequence palaeokarst. 91

10. Aquifer properties on the pre-Karoo Sequence palaeokarst. 92

11. Occurrence of yields on palaeokarsts. 93

12. Summary of hypothesis tests for the effect of hydrogeological features on borehole yields. 101

13. Aquifer properties along faults. 103

14. Borehole transmissivities along lineaments. 104

15. Aquifer properties along lineaments. 105

16. Borehole yields and transmissivities on fold axes. 108

17. Aquifer properties on fold axes. 109

18. Aquifer properties in exploration boreholes adjacent to perennial streams. 110

19. Aquifer properties in exploration boreholes near dykes. 112

20. Exploration borehole yields at sill margins. 112

21. Summary of all results. 113

LIST OF PLATES

PLATES		PAGE
I	Bevet's Conglomerate Member of the Rooihoogte Formation.	11
II	Quartzite ridge of the Timeball Hill Formation.	11
III	Square notch weir.	15
IV	Piezometer used for yield measurements.	15
V	Large domal stromatolites.	29
VI	Domical stromatolite in the Monte Christo Formation.	30

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1. INTRODUCTION

1.1 Background

The Klip River Valley and Natalspruit Basin is one of six dolomitic areas proposed to provide an emergency water supply to the Pretoria-Witwatersrand-Vereeniging (PWV) Region. As a result of prolonged drought conditions prevailing in 1983 a drilling programme was started by the Department of Water Affairs to provide production boreholes for emergency water supply. At this stage borehole siting methods and the conceptual aquifer model were derived from the numerous investigations concerning mine dewatering and ground stability in the dolomites of the Far West Rand reported to the State Technical Committee on Sinkholes and Subsidences. The Klip River Valley and Natalspruit Basin was selected as an area for more detailed hydrogeological investigation in order to assess the geological control of the aquifer properties and improve the conceptual aquifer model. The benefits of this more detailed study would be improved drilling target selection and more appropriate aquifer management methods.

Although the study area is estimated to have a once off exploitable storage of 30 x 10^6 m^3 only 8% of the total storage of the six areas (Vegter, 1986) it is believed that the results should have a bearing on the aquifer characteristics of the Chuniespoort Group elsewhere.

1.2 Previous work

A summary of all published work on the geohydrology of the study area is presented in Table 1. The investigation of the study area by the Department of Water Affairs was carried out in two phases.

TABLE 1: Summary of previous geohydrological reports in the Klip River Valley and Natalspruit Basin

Date	Author	Synopsis
1905	Struben, A.M.A.	A record of personal accounts of the flow of the springs and streams in the Klip River Valley.
1910	Union of South Africa	Report on the occurrence of groundwater and springs and the effect of Rand Water Board groundwater extraction on surrounding farms.
1919	Union of South Africa	Hydrocensus of water sources and abstraction; description of dolomite hydrogeology and an analysis of the management of the Klip River catchment water resources.
1921	Du Toit, A.L.	Description of the occurrence of dolomitic groundwater and the abstraction of groundwater by the Rand Water Board.
1937	Frommurze, H.F.	Analysis of drilling results in dolomitic areas including the Klip River.
1986	Kafri, U. et al	Extensive geohydrological investigation of the Klip River Valley and Natalspruit Basin.

In the first phase Kafri et al (1986) postulated a set of geological controls which were tested in the drilling programme. The results largely supported the major hypotheses that the chert rich formations of the Chuniespoort Group were better aquifers compared to the chert poor formations. However highly transmissive zones are encountered in boreholes penetrating the chert poor formations and not all exploration boreholes penetrating the favourable chert rich formations encountered productive aquifer zones.

The report of Kafri et al (1986) contains a large volume of reliable geohydrological data which were not fully analysed.

The present author, a co-worker on the first investigation, supervised the second phase investigation and drilling programme concentrating in the southern part of the area (Reynders, 1988). The results of this investigation enabled a reassessment, reinterpretation and further study of the results of the earlier work.

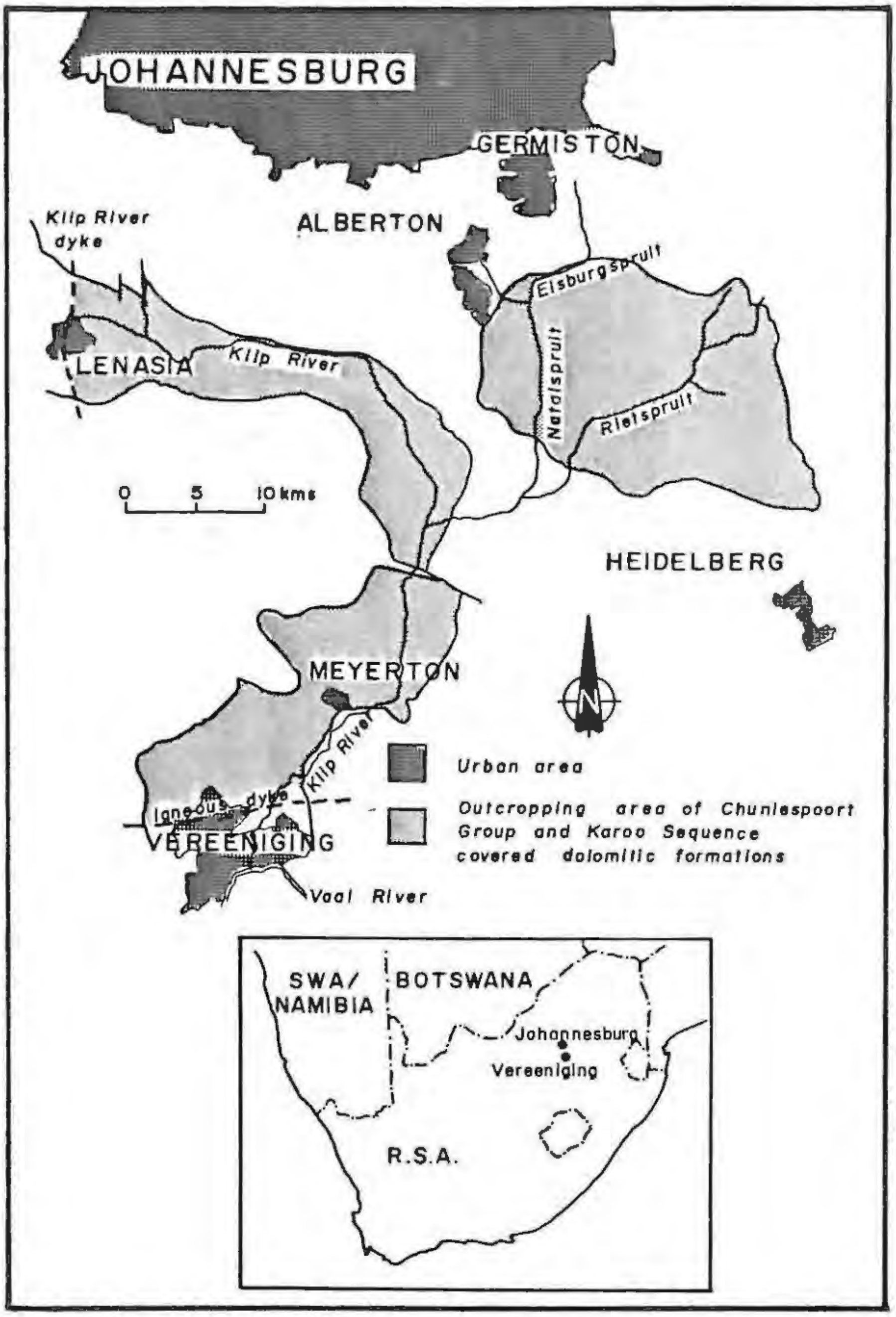


FIGURE 1: Location map of the study area

1.3 Aims and Objectives

The objective of this study is to determine the relative importance of individual geological features in the development of highly transmissive zones in the dolomite aquifer and thereby derive a reliable and realistic conceptual aquifer model.

The specific aims are:

(i) to collect detailed geological information on lithology, structural geology, intrusive rocks and karst in the study area;

(ii) to analyse geohydrological information regarding the nature of the aquifer and the performance of wells and boreholes;

(iii) to investigate the relationship between the geology and geohydrology;

(iv) to investigate the vertical and lateral variation of aquifer properties.

1.4 Location of the Study Area

The study area covers approximately 800 km^2 at an elevation of between 1 500 and 1 700 m above mean sea level. It is situated within the catchments of the Klip River and the Natalspruit, Elsburgspruit and Rietspruit streams lying to the south of Johannesburg (see Figure 1). The area can be divided into a western and eastern area defined by the valley of the Klip River and the Natalspruit basin respectively.

1.5 Physiography

The Klip River area occupies a broad flat-bottomed valley which follows the arcuate outcropping area of the Chuniespoort Group. It is bounded to the north and east by higher ground occupied by the Black Reef quartzite and pre-Transvaal Sequence formations and to the south and southwest by the ridge and valley topography of the Pretoria Group. The outcropping area of the Chuniespoort Group is generally flat, but the upper chert rich unit forms a noticeably elevated morphological step (Figure 2).

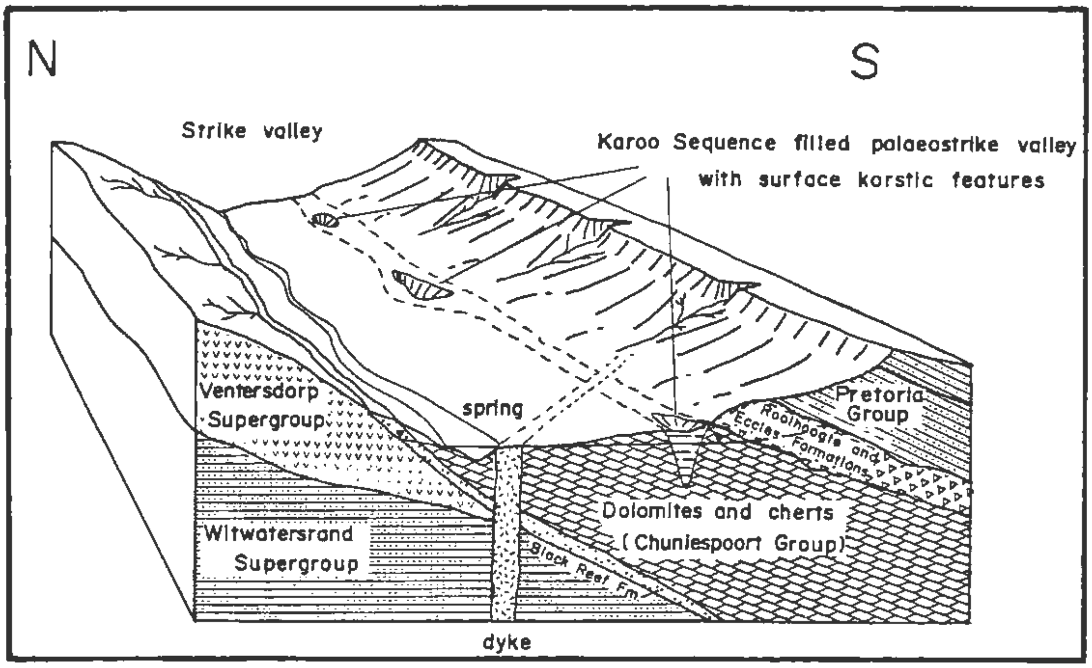


FIGURE 2: Schematic block diagram of the Klip River Valley (approximate valley width, 7 kms)

The dolomitic formations of the Natalspruit Basin form an outlier surrounded by higher ground of the pre-Chuniespoort Group formations. The topography of this basin is relatively subdued. The higher ground in the eastern half of the basin is associated with the outcrop of dolerite sills, whilst in the western half, high ground coincides with the occurrence of chert rich units.

The entire region experiences a moist, temperate climate (cwb type, Köppen classification) characterised by cool, dry winters and hot, wet summers. Average annual rainfall for the region is about 700 mm with higher rainfall occurring on the high ground surrounding the area.

The natural vegetation is the central variation of the Bankenveld, a false grassveld type. Rocky hills and ridges carry a bushveld vegetation dominated by <u>Protea caffra</u>, <u>Acacia caffra</u> and <u>Celtis africana</u>. <u>Xerophyta retinervis</u> is also typical on hilly ground (Acocks, 1975). Stands of Eucalyptus (blue gums) are found throughout the area with an increased concentration found in the vicinity of the Klip River.

Between the major urban concentrations land is mainly occupied by small agricultural holdings. The larger part form a low density residential area. Some of the properties cultivate market gardening produce, particularly the riparian farms and those farms able to irrigate using ground water. The larger farms practice extensive cultivation of maize, sorghum and sunflower as well as arable farming.

2. INVESTIGATION PROCEDURES AND CONSTRAINTS

2.1 Desk study

The desk study provided a full familiarisation with the known details of the subject under investigation. Duplication of work was prevented and the investigation was able to start from the furthest point of advancement of previous workers. It entailed the compilation, analysis and interpretation of relevant literature regarding:

(i) the geology and hydrogeology of the study area;

(ii) the hydrogeology of the Chuniespoort Group at other localities and;

(iii) carbonate hydrogeology worldwide.

A photo-geological interpretation from 1:30 000 contact scale stereo pairs, was carried out prior to fieldwork to rapidly and accurately delineate the major geological features, identification of areas requiring field geological mapping and location of areas of possible karst and geological interest. During the compilation of the final geological interpretation the stereo photo pairs were again used for further refinement of the field map.

1:50 000 Aeromagnetic maps were also studied prior to fieldwork to delineate the approximate position and trend of dykes crossing the study area. These dykes were more accurately located with ground magnetic surveys during the field work.

2.2 Geohydrological census

The collection of information from existing boreholes in the study area provided vital hydrogeological information only otherwise obtained by the drilling of new boreholes. The geohydrological census conducted between November 1984 and March 1985 by the Department of Water Affairs (Kafri et al, 1986) provided information from approximately 1 300 private boreholes. There is no public use of the ground water at present. All the information was reported verbally by the owners of the boreholes, usually from memory, at best from a brief driller's report.

The boreholes are used for domestic water supply, stock watering or crop irrigation. The greater portion of these boreholes have either 6" (150 mm) of 4½" (110 mm) cased internal diameters and were drilled with similar equipment, by drillers with approximately the same level of expertise. The reported or observed yields in the census are therefore considered comparable, as long as results are viewed with a degree of circumspection.

Water levels and borehole yields were measured where borehole equipment permitted the use of an electronic dip meter. Static water levels recorded in residential areas were not considered reliable. These areas normally have a dense network of boreholes and water levels may represent dynamic head conditions induced by nearby pumping. Borehole collar elevations were interpolated from 1:10 000 scale orthographic aerial photographs (orthophoto's) and reduced water levels are quoted to the nearest metre.

Water samples taken during the census were analysed for major anions and cations by standard spectrophotometric, titrametric and turbidimetric methods.

2.3 Geological Mapping

All geological exposures were mapped in the field and details recorded on 1:10 000 scale orthophoto's. Where extensive soil cover obscured geological contacts interpretation was made between exposures with the aid of the stereo aerial photographs. A conglomeratic member of the Rooihoogte Formation and the Timeball Hill quartzite were used as marker horizons (see Plates I and II and page 32). This aided the detection and delineation of faults displacing Pretoria Group formations in contact with the Chuniespoort Group. Only the uppermost formation of the Chuniespoort Group (the chert rich Eccles formation) is consistently well exposed. The remainder of the group is poorly exposed, and prevented identification of the dolomitic formations by stromatolic type as achieved by Eriksson and Truswell (1974) north west of Johannesburg. Formation contacts in the Chuniespoort Group are largely conjectural and their position inferred by field relationships only.

PLATE I - Chert pebble conglomerate of the Bevet's Conglomerate Member of the Rooihoogte Formation

PLATE II - View of the prominent quartzite ridge in the Timeball Hill Formation used as a photo geological marker

2.4 Drilling and aquifer tests

2.4.1 General

In order to maintain consistency throughout the study the drilling and pump testing of the boreholes in both phases of the investigation were conducted using the same equipment, techniques and level of expertise. Differences between drilling contractors in borehole construction were further reduced by the overall supervision and standards required by the Department of Water Affairs. Final cased internal diameters are 250 mm in almost all the holes and the design of perforated casing lengths was standard for all boreholes. The information from these will therefore be assessed assuming controlled conditions to the extent that circumstances allowed.

2.4.2 Drilling

The drilling of boreholes was conducted to obtain sub-surface geological information for the refinement of the geological interpretation and to investigate aquifer conditions at specific target localities and depths. Boreholes were drilled using air percussion drilling equipment. This drilling method is rapid, provides almost immediate return of samples, and allows for estimating borehole yield during the drilling operation by measuring the "blow out" (air lift) yield using a 90° V-notch weir.

The method has the serious disadvantage of suffering great difficulty in penetrating loose, unconsolidated or very fractured formations especially when the unstable material is of coarse gravel size (crucially, typical of good aquifer zones). Such a situation normally demands installation of casing and drilling at a reduced diameter. Any reduction in diameter is particularly undesirable in the aquifer zone where retaining the largest possible diameter assures lower well losses and better well performance (Driscoll, 1986). To compound the problem strong water strikes encountered below approximately 100 m below ground surface often caused the air compressors to cut out, or reduce air pressure at the hammer preventing its action. This prevented drilling from penetrating the full thickness of the aquifer in many boreholes. High yielding boreholes were normally cased to the bottom of the borehole with perforated casing being positioned at the aquifer zones.

Drill cuttings were taken at 1 m intervals or wherever a change in lithology was noted. Penetration rates were recorded by the driller as well as the details of any water strikes encountered. Drill cuttings were described in the field by geologist and on completion the borehole was logged using a down the hole geophysical logging unit.

2.4.3 Pumping tests

All boreholes drilled in the two investigations were tested using either a vertical line shaft turbine or a positive displacement type pump. Previous drilling programmes in the Chuniespoort Group have shown boreholes with no blow out yield to have significant yields when pumped (Bredenkamp et al, 1986). High costs prevented the drilling of observation boreholes, so a programme of step drawdown and constant yield tests was carried out to provide values for borehole efficiency, transmissivity and specific drawdown.

Water levels were measured in the pumping borehole with an electrical conductor probe, in a conduit introduced into the borehole after emplacement of the pump.

Discharge (yield) was measured by one of three techniques:

(i) Low yields (0-30 ℓ/s) were calculated by measuring the time to fill a 220 litre steel tank.

(ii) High yields (25 + ℓ/s) were measured from calibrated discharge curve for a 90° square notch weir (see Plate III).

(iii) All yields (0-100 ℓ/s) were calculated from piezometer readings for water discharging through a circular orifice (see Plate IV).

PLATE III: Square notch weir

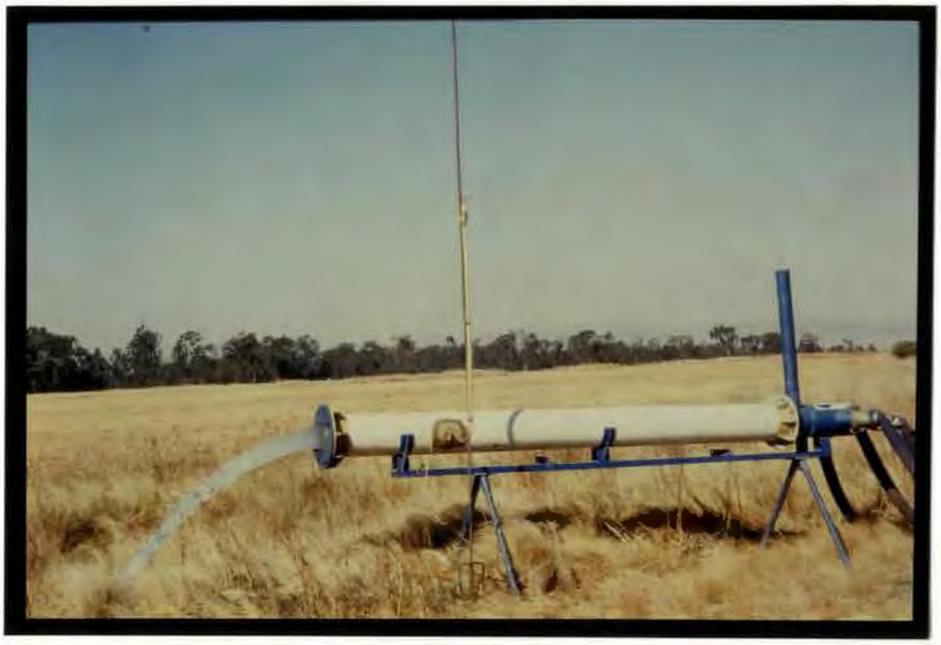


PLATE IV: Piezometer used for yield measurement

2.5 Geophysics

2.5.1 General

Geophysical surveying techniques were used to complement the geological mapping in areas where bedrock is not exposed and to investigate the subsurface bedrock profile.

2.5.2 Magnetics

Ground magnetic traversing was carried out to accurately locate igneous dykes indicated on aeromagnetic maps. The aeromagnetic flight line separation was approximately 1 km for north-south flight lines and 10 km for east-west flight lines. As a result of the large E-W flight line separation there is only poor control on the position of north-south striking magnetic features. This was resolved by ground magnetic traversing along east-west lines.

East-west striking dykes may be delineated with more confidence from aeromagnetic maps, but the position of the interpreted vertical dyke is to the north of the peak of field intensity because of the inclination of the earth's magnetic field (see Figure 3).

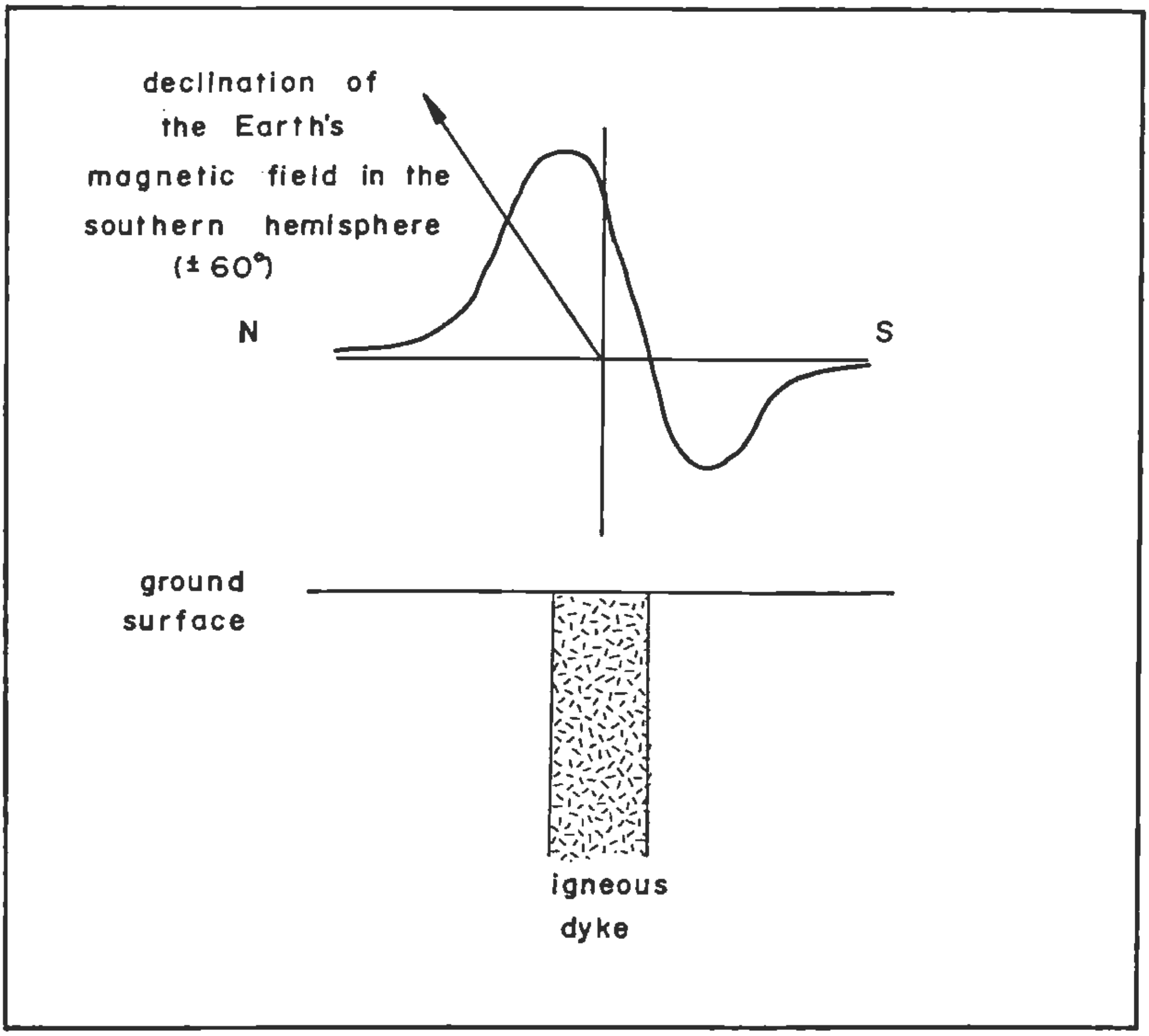


FIGURE 3: Typical magnetic signature of east-west trending dykes in the study area

Ground magnetic traversing was carried out using a proton total field magnetometer with 10 m station intervals. Traverses were conducted normal to the expected strike of the feature. When tracing dykes widely spaced traverses were carried out followed up by closer traverse spacing in areas of faulting or changes of strike. Traverses across dykes were generally less than 2 km long with a duration of about one hour. No drift corrections were made.

2.5.3 Gravity

Gravity surveying was undertaken to delineate zones of weathering in the Chuniespoort Group in areas where it is covered by Karoo Sequence or superficial deposits.

The unit measured in the field is not the earth, total gravitational attraction but its variation between points in part due to subsurface changes in density. Gravity would be constant across the surface of an homogeneous, isotropic sphere, but as the Earth rotates, centrifugal forces are imposed upon gravitational attractions. The earth also bulges at the equator as a result of the rotation and is flattened at the poles. The difference in the Earth's radius between the poles and the equator gives rise to a general variation of gravity according to latitude. The relationship is represented by the International Gravity Formula as follows:

$g = 978{,}049\ (1 + 0{,}0052884 \sin^2 \emptyset - 0{,}0000052 \sin^2 2\emptyset)$

(units cm/s^2 in c.g.s. units).

(Dobrin, 1976).

In addition to the lateral changes in density distribution, the feature being investigated, gravity values observed in the field depend on latitude, elevation, topography, tidal changes. After correcting the field readings for elevation (free air correction) as well as instrument drift and earth tides, corrected observed values are compared to theoretical values of the earth's field. The variation is called the Bouguer anomaly.

In the Klip River area Bouguer anomaly contour maps were drawn up. These show regional gravity trends which reflect regional bedrock variations and smaller local anomalies showing local and near surface variations of overburden and bedrock. These smaller anomalies are of most interest in hydrogeological studies and are best interpreted from residual Bouguer anomaly maps where the regional trend has been removed (see Map 2, back pocket).

In the Chuniespoort Group the gravity method is widely used for mapping near surface solution weathering profiles and palaeo-valleys filled with Karoo Sequence or superficial deposits (Kleywegt and Enslin, 1973 and Enslin et al, 1976). These features are associated with Bouguer anomalies as a result of the variation in average density values of sediments found in the area (Table 2 and Figure 4).

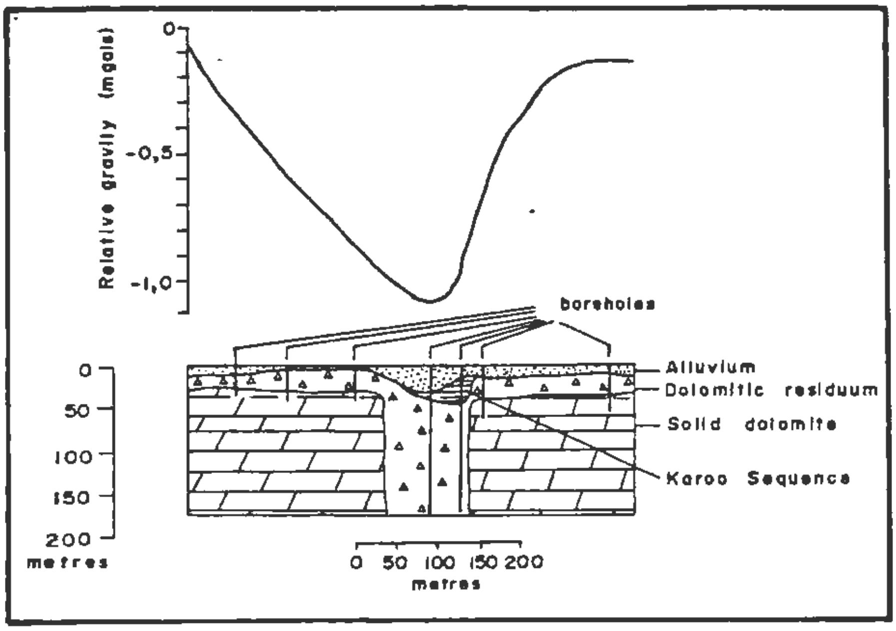


FIGURE 4: Geological profile across gravity low in the Far West Rand (after Kleywegt and Enslin, 1973)

TABLE 2: Average density values for bedrock and overburden occurring in areas underlain by the Chuniespoort Group (after Enslin et al, 1976).

Lithology	Average Density Value (g/cm^3)
Fresh dolomite	2,85
Incompletely leached dolomitic bedrock	2,6
Overburden material (surface deposits wad and incompletely leached dolomitic bedrock	2,35
Karoo Sequence sediments	2,0-2,4
Surface deposits	1,6
In-situ completely leached zone (inverse density variation with depth, compact cemented chert breccia with density of 2,6 g/cm^3 over horizon of porous of wad of 1,0 to 1,2 g/cm^3	2,1

The anomalies seen on the residual Bouguer maps are usually either negative linear lows associated with the weathering of igneous dykes and linear solution channels, or extensive gravity lows associated with widespread weathering of the dolomitic formations, in filled wide palaeovalleys or weathered outcrops of sills.

Results of gravity surveys carried out by the Geological Survey were available for large areas in the vicinity of the Klip River dyke at Lenasia and for the whole of the farm Zwartkopjes. Further gravimetric surveys were undertaken for the Department of Water Affairs: along roads and fences between Lenasia and Zwartkopjes; an extensive gravity grid south of Zwartkopjes farm (Steffen, Robertson and Kirsten, 1986) and in the lower Klip River area between Daleside and Vereeniging (Terrabro, 1986) as shown in Map 2.

2.6 Hypotheses

From results obtained in previous hydrogeological investigations of the Chuniespoort Group (Bredenkamp et al, 1986; Orpen and Leskiewicz, 1985; Steffen, Robertson and Kirsten, 1985 and studies shown in Table 1) and from basic principles of karst hydrogeology the following hypotheses are put forward to explain the distribution of highly transmissive zones in the Chuniespoort Group aquifer (see Figure 5):

1. The different mass sedimentological, petrological and mechanical rock characteristics of the four Chuniespoort Group formations are reflected in differing development and degree of karstic erosion (Figure 5A).

2. The pre-Karoo Sequence unconformity is an erosional surface where the dolomitic formations were exposed in pre-Karoo Sequence times to meteoric waters, dissolution and karstification (Figure 5B).

3. In addition to near surface karstification of recent and pre-Karoo Sequence times there are deeper levels of palaeokarst associated with ancient palaeo-base levels and erosional cycles (Figure 5A).

4. Structural features such as faults, joints, lineaments and intrusive dykes are associated with greater openness, weathering and density of rock discontinuities and are thus more susceptible to karst weathering processes (Figures A and D).

5. The concentration of surface flow along modern drainage courses results in greater infiltration and thus more extensive karstification (Figure 5E).

6. Increased run-off from impermeable dolerite sills enhances dissolution near sill margins (Figure 5C).

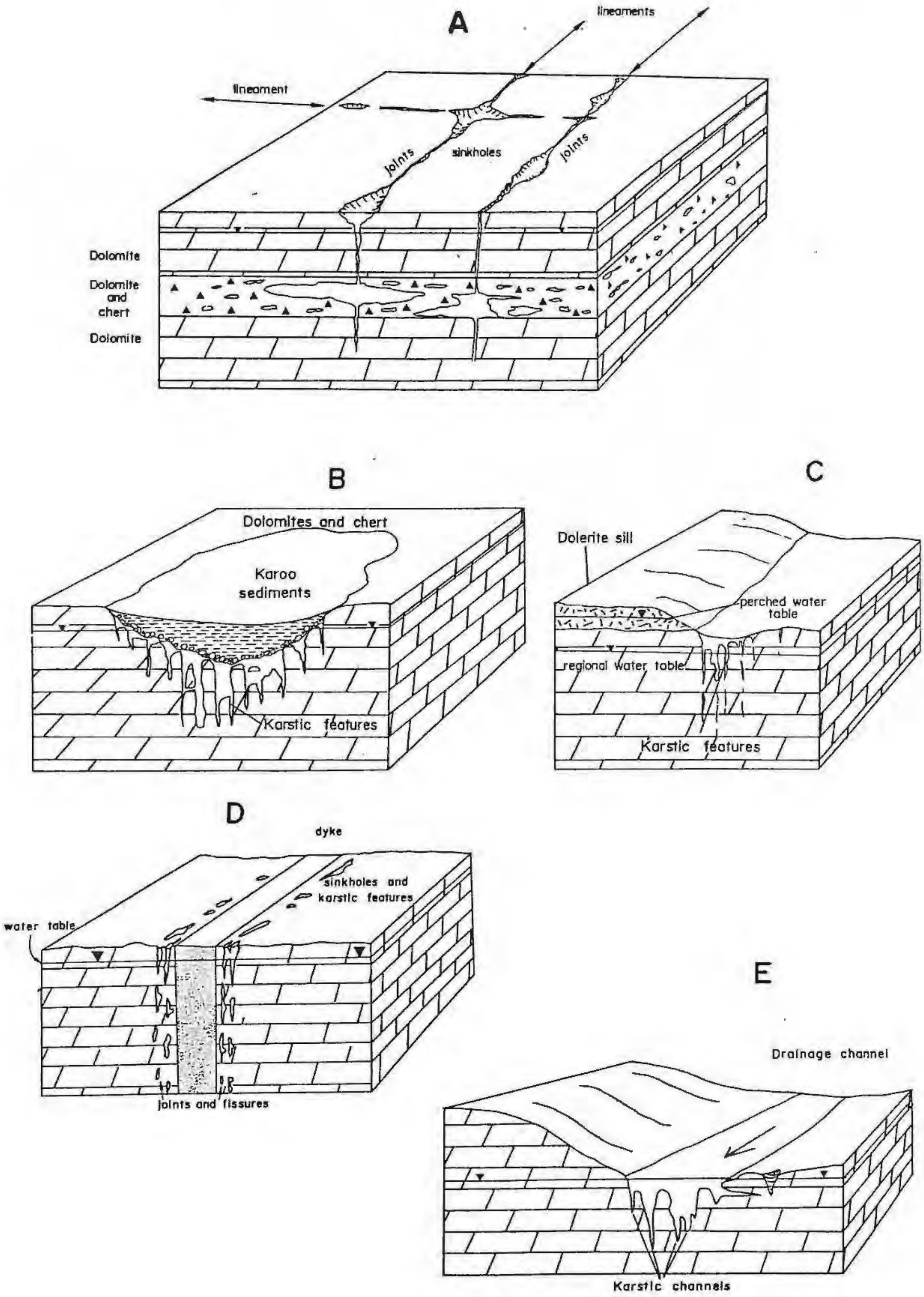


FIGURE 5: Diagrammatic representation of working hypotheses

3. GEOLOGY

3.1 Introduction

Compact ancient carbonate rocks such as the dolomites of the Chuniespoort Group are characterised by very low porosity and primary permeability. The development of secondary permeability takes place by solution weathering along discontinuities. The rate at which this occurs as well as the extent and distribution of weathering is dependent, amongst other things, on the:

(i) mineralogy/petrology/geochemistry: these govern the actual chemical reaction of carbonate dissolution as well as the nature of the weathering products, whether they are soluble or insoluble, permeable or impermeable;

(ii) sedimentology; this governs the carbonate facies type, bed thicknesses and the nature of the interbedded strata;

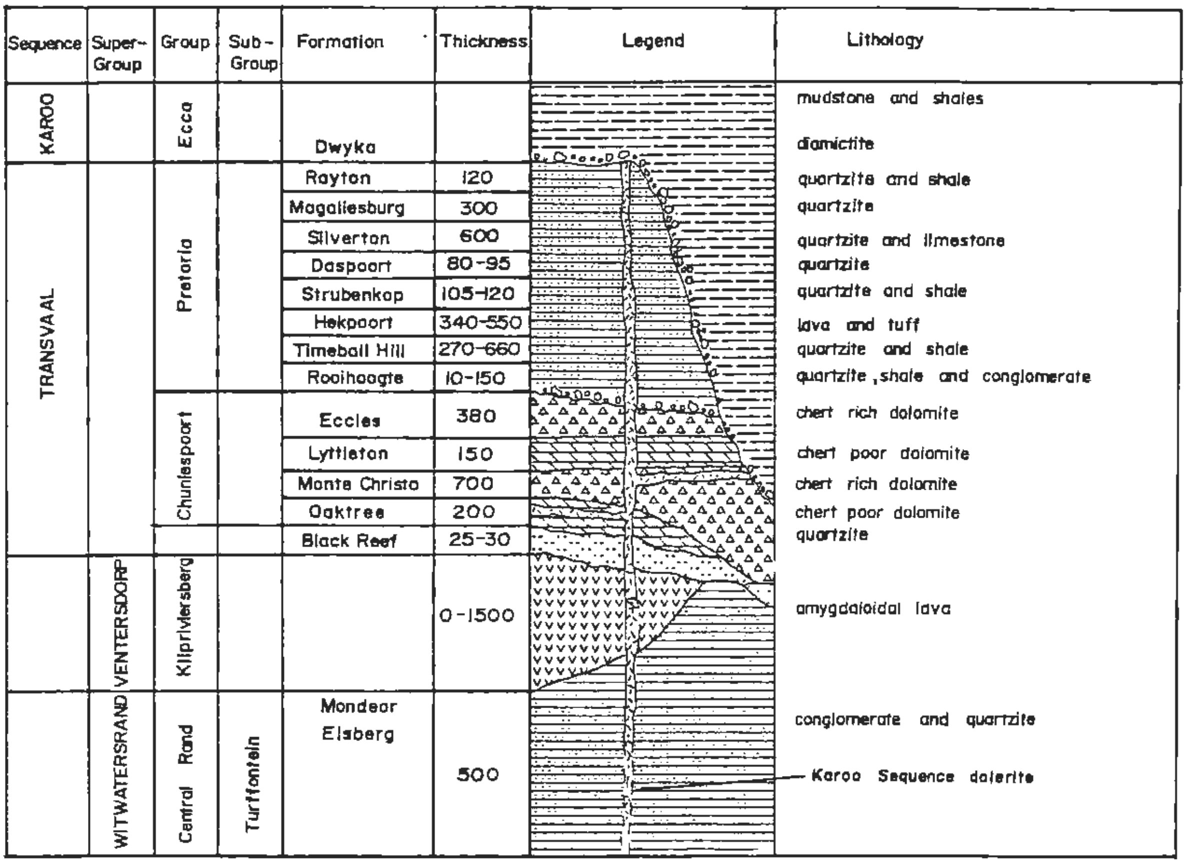
(iii) structural geology; the general tectonic setting plays a part in the size and distribution of facies; folding, faulting and other structural features can determine the degree of openness of discontinuities and thus the penetration of chemically aggressive ground waters.

It can be seen from the above that many aspects of geology may have a bearing on carbonate hydrogeology. An extensive study of the subject, in the context of the dolomites of the Chuniespoort Group has therefore been carried out.

3.2 Lithostratigraphy

3.2.1 General

The dolomitic formations of the Chuniespoort Group were deposited in the large Transvaal Basin during the Vaalian Erathem of the Proterozoic. The Chuniespoort Group forms part of a tectono-sedimentary phase of the clastic, volcanic and chemical sediments which form the Transvaal Sequence (Tankard et al, 1982). General lithostratigraphic relations are represented in Figure 6 and the geology is presented in Map 1 (see back pocket). The formations outcropping in the study area are described below from oldest to youngest.



Sequence	Super-Group	Group	Sub-Group	Formation	Thickness	Legend	Lithology
KAROO		Ecca					mudstone and shales
				Dwyka			diamictite
TRANSVAAL		Pretoria		Rayton	120		quartzite and shale
				Magaliesburg	300		quartzite
				Silverton	600		quartzite and limestone
				Daspoort	80-95		quartzite
				Strubenkop	105-120		quartzite and shale
				Hekpoort	340-550		lava and tuff
				Timeball Hill	270-660		quartzite and shale
				Rooihoogte	10-150		quartzite ,shale and conglomerate
		Chuniespoort		Eccles	380		chert rich dolomite
				Lyttleton	150		chert poor dolomite
				Monte Christo	700		chert rich dolomite
				Oaktree	200		chert poor dolomite
				Black Reef	25-30		quartzite
	VENTERSDORP	Klipriviersberg			0-1500		amygdaloidal lava
	WITWATERSRAND	Central Rand	Turffontein	Mondeor Elsberg	500		conglomerate and quartzite

FIGURE 6: Generalised lithostratigraphic column (after SACS, 1980)

3.2.2 Pre-Transvaal Sequence

Witwatersrand Supergroup

This thick succession of arenaceous and argillaceous rocks outcrops only in a very small area of the Natalspruit Basin near Brakpan. The formation exposed comprises coarse grained cross-bedded quartzites and conglomerates of the Elsburg Formation. This is the only location in the study area where the Witwatersrand Supergroup underlies the Black Reef Formation directly.

Ventersdorp Supergroup

On a regional scale the formations of the Ventersdorp Supergroup lie unconformably on the upper surface of the Witwatersrand Supergroup. In the Central and Eastern Rand as well as in the Heidelberg area the relationship with the underlying Witwatersrand Supergroup may be conformable (SACS, 1980). Rocks of this supergroup outcrop in the hills of the Klipriviersberg that form the northern border of the study area and occupy the high ground surrounding the Natalspruit Basin. The Klipriviersberg Group has an estimated maximum thickness of 1 500 m (Du Toit, 1954) and consists of lavas, tuffs and agglomerates (SACS, 1980).

3.2.3 Transvaal Sequence

Black Reef Formation

This formation was deposited on a regional unconformity overlying rocks of the Ventersdorp and Witwatersrand Supergroup. It is the basal clastic formation of the first transgression of the sea across the Transvaal Basin. Conglomerates and coarse grained, cross bedded sandstones occur at the base; finer sandstones and quartzites then pass upwards into shale units in the upper part of the formation. 13,1 m of Black Reef Formation has been recorded in gold exploration boreholes on the West Rand, about 20 km west of the Klip River Valley (Cousins, 1962). Its upper contact with the dolomitic formations is transitional and conformable. Interbedded shale, dolomite and quartzite commonly occurs in this zone.

Chuniespoort Group

General

Only the four lowest formations of this group are present in the study area; the Oaktree, Monte Christo, Lyttelton and Eccles Formations (see Figure 6). The contact between the top of the Chuniespoort Group and the base of the Pretoria Group is formed by an erosion surface. This surface truncates the stratigraphy progressively from north to south across the Transvaal Basin (Tankard et al, 1982). As a result the Frisco, Penge and Duitschland Formations of the Eastern Transvaal are not represented here and the Pretoria Group was deposited with angular unconformity on the Eccles Formation.

The outcrop width of the Chuniespoort Group in the Upper Klip River Valley narrows from west to east (see Map 1). This narrowing can be explained by either regional dip steepening or reduced formation thickness. There is no significant change in regional dip in the overlying Pretoria Group. So it is assumed that the total thickness of the Chuniespoort Group in the Klip River Valley is less than 1 246 m measured in boreholes at Western Areas Gold Mine (Cousins, 1962). SACS (1980) reports an estimated thickness of 1 430 m for the central Transvaal whereas exploration boreholes in the Springs-Delmas area lying immediately east of the Natalspruit Basin indicate as little as 900 m of Chuniespoort Group (Leskiewicz, 1986, pers. comm.). If a thickness of 1 200 m is assumed, the dip would be 21° at the point of narrowest outcrop of the Chuniespoort Group (3,4 km). A dip of 10° westwards was measured in the Glen Douglas dolomite quarry at Daleside (See Map 1). It is possible that unconformities within the Chuniespoort Group are responsible for the reduced sequence thickness.

Oaktree Formation

The Oaktree Formation comprises blueish grey to grey dolomicrite or recrystallised dolomite. It has a distinctive wrinkled grey or brown appearance when weathered that is reminiscent of elephant's skin (Oliphantsklip in Afrikaans). The sedimentology of the formation is characterised by large domal stromatolites with an amplitude reaching 1 m and a plan width of up to 3 m (see Plate V).

PLATE V: Large domal stromatolites in the Oaktree Formation

The formation commonly has thin shale bands and may have thin beds of quartzite towards its base. The Oaktree Formation is almost devoid of chert, however silica (SiO_2) contents up to 30% have been noted from X-ray fluorescence studies for this formation in the Springs-Delmas area (Orpen, 1987, pers. comm.). A high silica content was also reported for the Oaktree Formation in borehole logs by Kafri et al (1986) particularly in the Natalspruit Basin. Disseminated pyrites was noted in all formations throughout the study area (Kafri et al, 1986)

Monte Christo Formation

This is the thickest formation of the Chuniespoort Group (761 m, SACS, 1980) and in general terms may be called a chert rich dolomite formation. It is poorly exposed in the study area and the following description is based on borehole information from the study area (Kafri et al, 1986, and Reynders, 1988) and observations in other areas.

The dolomite itself can be micritic or recrystalline and a variety of colours; brown grey, cream, pink or blueish grey. Interbedding of chert with the dolomite occurs on all scales, from fine alternating laminations to beds, bands and whole units several metres thick (Button, 1973). Sedimentary structures commonly found in the Monte Christo Formation are ripple marks, interference ripples and oolites. Algal sedimentary features include, laminations, crinkled laminations, domical stromatolites, columnar stromatolites and spheroidal oncolites, all normally less than 1 m in relief (see Plate VI).

PLATE VI: Domical stromatolite in chert banded dolomite of the Monte Christo Formation

A minor unconformity separates the Monte Christo Formation from the overlying Lyttelton Formation (Tankard et al, 1982). This horizon is marked by the occurrence of a chert in shale breccia (Eriksson and Truswell, 1974 and Button, 1973). In the study area boreholes commonly penetrated very weathered or fractured chert with clay and oxidized material at this horizon.

Lyttelton Formation

This formation is lithologically similar to the Oaktree Formation. It is a dark grey/blue dolomicrite or recrystallised dolomite which weathers to a chocolate brown or grey brown colour. It is almost completely chert free and large elongate stromatolite domes are the characteristic algal sedimentary feature. The top few metres of the formation are lighter in colour and a little chert may be present. Its junction with the Eccles Formation above is marked by a brecciated chert horizon (Eriksson and Truswell, 1974).

Eccles Formation

This is the only well exposed formation of the Chuniespoort Group in the study area.

The Eccles Formation resembles the Monte Christo Formation to a large degree. It is a chert rich dolomitic formation with columnar and domical stromatolites, algal laminations and abundant ripple marks. In the study area the exposed formation was represented by massive in-situ chert or extremely weathered chert, where the carbonate had dissolved leaving an open, void filled, chert honeycomb structure.

Pretoria Group

The deposition of the Pretoria Group was separated from Chuniespoort Group sedimentation by a period of erosion. Uplift and consequent erosion took place on the south-eastern Transvaal basin margin and the upper formations of the Chuniespoort Group were removed.

The Rooihoogte Formation is the basal clastic formation of the Pretoria Group. The formation consists of chert cemented chert breccias, quartzites and conglomerates; with shales and quartzites in the upper part of the unit. The chert breccia is thinnest where the Pretoria Group rests on a chert poor unit and thickest when deposited on a chert rich unit, indicating that the chert was deposited very close to its point of erosion (Button, 1973). The formation contains a very distinctive chert pebble conglomerate called the Bevet's Conglomerate Member which enabled a clear distinction to be made between the chert rich units of the Eccles Formation and those of the Rooihoogte Formation.

The Rooihoogte Formation is overlain by the Timeball Hill Formation which comprises a lower unit of shale and an upper quartzite unit. The latter forms a prominent ridge in the study area and provides a useful photo-geological marker.

3.2.4 Karoo Sequence

Extensive outcrop of the Karoo Sequence in the study area, reaches as far north as the Springfield Collieries between Meyerton and Vereeniging and also occurs north of the Natalspruit Basin near Brakpan (see Map 1).

The first sediments of this sequence were poorly sorted rudaceous fluvio-glacial deposits of the Dwyka Formation. These were deposited on the surface of the exposed Palaeozoic rocks which were deeply scoured and dissected by glaciation in the Carboniferous. Dwyka Formation has been found at the base of ice scoured caverns on the West Rand (Brink, 1979) as well as underlying the coal measures of the Vereeniging-Sasolburg area (Coetzee, 1976).

South of Vereeniging the Dwyka (tillite) Formation is up to 45 m thick. It is more poorly developed north of Vereeniging. The Dwyka Formation in filled the major pre-Karoo Sequence topographic depressions and may be absent over the palaeotopographic highs. The South Rand coalfield (Springfield Collieries, Meyerton) comprises 120 m of the coal measures of the Vryheid Formation of the Ecca Group. The coals are interbedded with sandstone and subordinate shale, sandy shale, shaley sandstone with occasional conglomerate and grit (see Figure 7) (Coetzee, 1976). In quarries and boreholes elsewhere in the study area the Ecca Group consisted of light yellow, cream, white or grey clays or weathered shale, as well as weak yellow siltstone or silty sandstone. Chert and quartzite and syenite pebbles and cobbles are common.

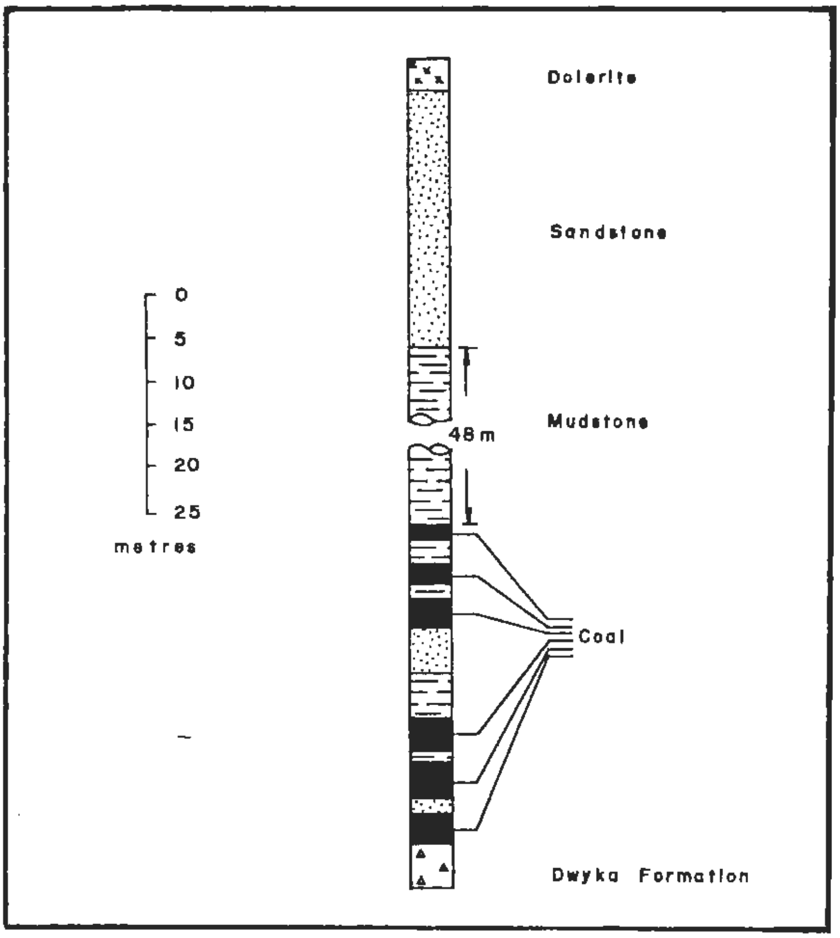


FIGURE 7: Typical succession of the Karoo Sequence at Vereeniging (after Coetzee, 1976)

3.2.5 Quaternary and Recent

Various post-Karoo Sequence cycles of erosion were responsible for several episodes of planation and the formation of an extensive pediment. Coarse grained colluvium may be present where concentrated surface flow has transported eroded material from the Pretoria Group ridges. Most of the study area is covered with sandy soils of a mixed origin. These soils are in general, red ferrisiallitic sand, loams and clays. They have undergone advanced pedogenesis by the process of bioturbation, pedogenesis and possibly redistribution by wind during an arid climatic period (Brink, 1985).

The pedogenesis of these soils has progressed to an advanced stage by virtue of their preservation on a remnant of the African erosion surface. The transported soils are normally between 1 m and 6 m thick and overlie the pebble marker defining the boundary between the upper transported surface soils and residual soils below (Brink, 1985). Their widespread development is largely responsible for the poor rock exposure and flat terrain of the study area.

Alluvial soils occur along the flood plains of the major streams and thin black hydromorphic clays have developed on areas underlain by dolerite sills and become thicker in the valleys.

3.3 Intrusives

3.3.1 Dykes

Only two dykes were observed to outcrop at surface in the study area. A syenite dyke passing through Vosloorus in the Natalspruit Basin and a dolerite dyke in the Klip River Valley. Both of these dykes have strong, negative magnetic anomalies. Published 1:50 000 aeromagnetic maps show that these dykes extend across the whole Chuniespoort Group outcrop. Several additional prominent dykes were interpreted from the aeromagnetic maps and ground magnetic surveys (see Map 1).

The two eastern-most dykes in the study area have strong positive magnetic anomalies and are known as East Rand type dykes. The age of these dykes is uncertain but is at least 1 120 ± 45 Ma. Two E-W trending dykes pass through the Vereeniging area (see Figure 3, p. 17). These are thought to be of post-Karoo Sequence age. The remainder of the prominent dykes crossing the study area are of the Pilanesberg dyke system (1 310 ± 60 Ma). These dykes are recognised by their negative magnetic anomalies resulting from remanent magnetism (Day, 1980).

3.3.2 Sills

Sills outcrop most extensively in the eastern part of the Natalspruit Basin (see Map 1). The sills are generally doleritic and flat lying. The maximum thickness of dolerite proven was 84 m in exploration borehole G36566 in the south eastern portion of the Natalspruit Basin (Kafri et al, 1986).

A dolerite sill outcrops on the eastern side of the Klip River on Zwartkopjes farm. This is the only extensive outcrop of dolerite in the Klip River Valley. A poorly defined aeromagnetic anomaly extends from the sill and follows the course of the Klip River upstream. This may represent a concealed extension of the sill.

West of Zwartkopjes farm a thin syenite sill was intercepted in an exploration borehole between the Timeball Hill shales and the Eccles Formation. Numerous intrusive bodies, 1 m to 2 m thick, were penetrated in boreholes throughout the study area.

3.4 Sedimentology

3.4.1 General

Mineralogy, sedimentology and diagenesis are the principal factors, together with metamorphism, governing the geological characteristics of a fully indurated sediment. The effects of these rock characteristics and processes on the present day hydrogeology of the Klip River Valley dolomites can only be assessed with a thorough understanding of the early geological history of the Chuniespoort Group. In the following sections the primary deposition of the original carbonate sediment is discussed together with the formation and environmental significance of stromatolites. This is followed by a discussion of possible modes of dolomitisation and deposition of chert.

3.4.2 Carbonates and stromatolites

Geochemical analyses of the carbonate portion of the Chuniespoort Group have been carried out by Button (1975) in the Eastern Transvaal and Eriksson et al (1975) in the Far Western Transvaal. In the Eastern Transvaal most of the samples were of almost pure dolomite, with an MgO content approaching the theoretical 22% for $CaMg(CO_3)_2$, however several horizons of primary limestone were noted. In the Western Transvaal the subtidal chert poor units were found to consist of pure dolomite whilst the intertidal chert rich units are composed of primary limestones and dolomitic limestone.

Electron microscope studies of micritic carbonates have shown them to be an accumulation of tiny needles and platelets of silt and clay size (±/15 μ). It is now generally accepted that these crystals are derived from the bodies of filamentous algae such as Codiacean and Penicillus sp. which grow tiny aragonite crystals in their sheathes (Friedman and Sanders, 1978). Filamentous algae has been described from dolomites in the Chuniespoort Group (MacGregor et al, 1974). When the algae die, they release the needles to accumulate as an autocthonous lime mud.

In contrast, stromatolites are evidence of constructive algal sedimentation. There are several documented processes by which stromatolites grow in modern environments. In Hamelin Pool, Shark Bay in Western Australia exposure of algal colonies in the intertidal zone at low tide is accompanied by the precipitation of intergranular aragonite. This forms a protective lithified crust which provides an ideal site for new algal growth (Hoffman, 1976). On the eastern Bahama Bank between the Exuma Islands large sub-tidal stromatolites have a sticky mucilagenous surface which traps ooid sand washed past by tidal currents. Further algal growth then takes advantage of the fresh sediment as a new site for growth (Dill et al, 1986). Stromatolite growth has also been described from the tidal and freshwater marshes of the Everglades, Florida and Andros Island in the Bahamas. Algal mats on carbonate mud flats grow as much as three centimetres thick within two months of flooding by rain, or inundation by the sea (Monty and Hardy, 1976). The study of modern stromatolite growing environments (op cit) particularly those from Hamelin Pool allows palaeoenvironmental interpretations to be made from stromatolite morphology (Logan et al, 1964).

Stratiform algal sheets are found on fresh water and tidal marshes as well as coastal locations where wave and tidal scour are weak (Hoffman, 1976; Monty and Hardy, 1976). Columnar structures occur where tidal scour is strong, their relief increasing with wave intensity (Hoffman, 1976). The more extensive stromatolite colonies are found in the subtidal zone as are the 'giant' modern stromatolites recently discovered off the eastern Bahama Bank (Dill et al, 1986).

Abundant evidence of stromatolites indicates their prolific growth in the Transvaal Basin. From the above discussion the chert poor Oaktree and Lyttelton Formations are interpreted to have formed in the subtidal zone. The growth of large stromatolites occurred in water depths of several metres and was accompanied by the accumulation of fine aragonite filaments to form a carbonate mud.

The great variety of stromatolite morphology observed in the Monte Christo and Eccles Formations and the occurrence of oolitic beds, ripple marks and columnar stromatolites are diagnostic of an intertidal environment of deposition. Shifting tidal channels and intertidal pools impart rapid lateral changes in the distribution of sedimentological facies, allowing various sedimentary and algal sedimentary forms to exist contemporaneously (see Figure 8). Supratidal forms would also be expected to be closely associated.

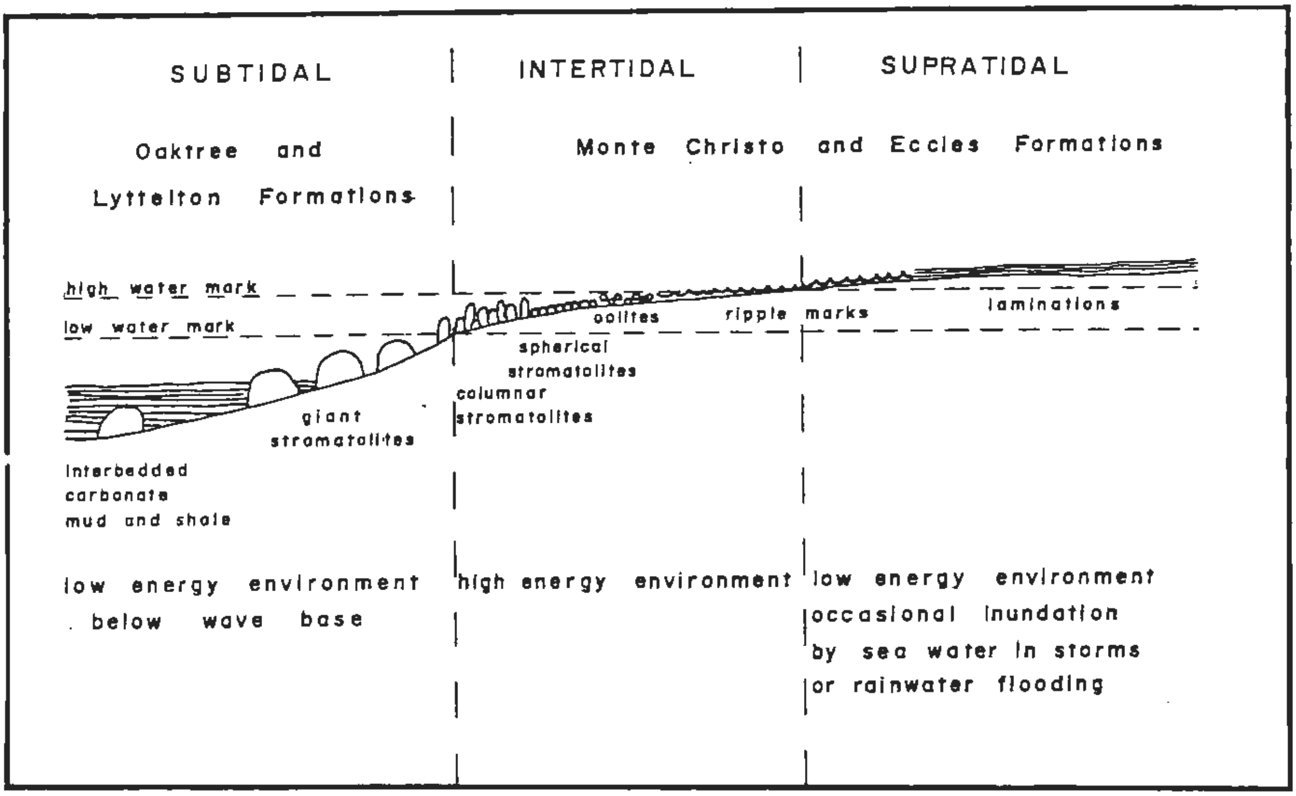


FIGURE 8: Idealised profile of the Chuniespoort Group environment of deposition.

3.4.3 Dolomitisation

Almost all researchers (with the exception of a large number of Russian geologists) now agree that dolomite is a replacement product and not a primary precipitate (Zenger et al, 1980). The conditions required for dolomitisation to take place are:

(i) an Mg/Ca ratio sufficient for the reaction to occur;

(ii) a suitable mechanism to flush dolomitising fluid through the rock;

(iii) enough time to allow the process to go to completion;

(iv) a large enough source of magnesium

(Hanshaw, Back and Deike, 1971; Blatt, Middleton and Murray, 1972).

There are currently two main theories of dolomitisation:

The Sabkha type model; relies upon raising the Mg/Ca ratio by the evaporation of sea water in restricted basins to generate gravity driven seepage refluxion (Adams and Rhodes, 1960), capillary concentration (Friedman and Sanders, 1967) or evaporative pumping (Hsü and Siegenthaler, 1969).

The Dorag type models: supports that dolomitisation takes place in the zone of mixing of freshwater and sea water (the schizohaline zone).

Laboratory work by Badiozamani (1973) showed that on mixing increasing quantities of sea water with ground water the solution gradually becomes less saturated with respect to calcite but more saturated with respect to dolomite (see Figure 9). With a mixture of 5-30% sea water in ground water the solution is undersaturated with respect to calcite and supersaturated with respect to dolomite. In this condition replacement of calcite by dolomite can occur.

$2\ CaCO_3 + Mg^{2+} =$ $CaMg\ (CO_3)_2 + Ca^{2+}$

calcite dolomite

There is firm evidence of dolomites having formed according to both mechanisms (Land, 1973 and Friedman, 1980). Observations used to suggest the mechanism of dolomitisation are given in Table 3.

TABLE 3: Evidence for mechanism of dolomitisation (after Blatt, Middleton and Murray, 1972)

	Sabkha/Evaporative	Dorag/Mixing
1.	Dolomite beneath evaporites or evidence of past evaporites	Absence of evidence of past evaporites
2.	Dolomite bodies bounded by disconformity on top and terminated downward against limestone	Dolomitisation unrelated to evaporitic facies, such as Sabkha, desert playa or standing body of water evaporites
3.	Heavy ∇O^{18} values	Light ∇O^{18} values
4.	Porosity increases downward	High strontium values
5.	High sodium content in dolomite	Low sodium content in dolomite

NOTE

None of the last three chemical properties have been investigated in the dolomites of the Chuniespoort Group.

3.4.4 Silicification

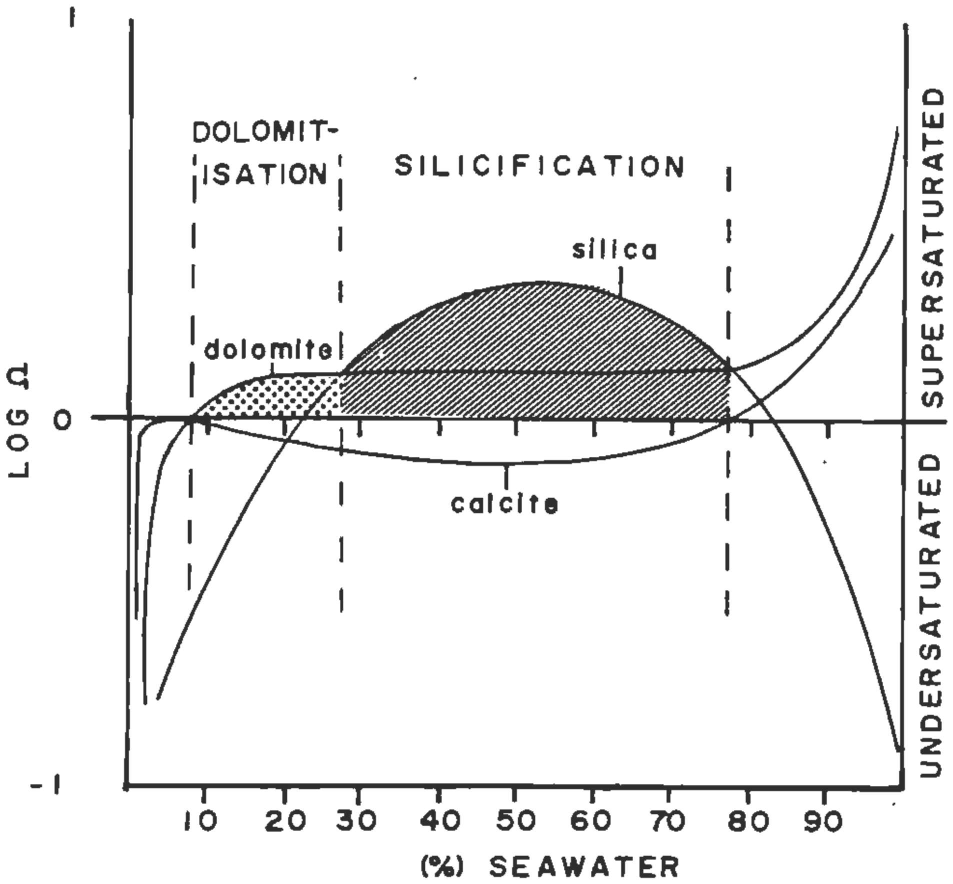
The replacement of limestone by chert requires that diagenetic waters are simultaneously supersaturated with respect to crystalline silica and undersaturated with respect to calcite (Knauth, 1979). These conditions may be met in two situations.

(i) Where a solution has a pH in excess of 9 the solution is undersaturated with respect to silica but saturated with respect to calcite. If the pH is then reduced to below 9 the calcite can dissolve and the silica precipitate (Correns, 1969);

(ii) for the range of seawater - groundwater mixtures where the solutions are undersaturated with respect to calcite but supersaturated with respect to silica as proposed by Knauth (1979). The shape of the solubility curves depend on many variables and can be strongly assymetric with respect to the degree of mixing as shown in Figure 9 (Wigley and Plummer, 1976).

The extensive development of chert units described on pages 30 and 31 may be the result of a near horizontal mixing zone extending many kilometres inland as on the Yucatan Peninsula of Mexico. Here the mixing zone occurs at a depth of 70 m over an area of several thousands of square kilometres (Back and Hanshaw, 1970). Alternatively chert may develop extensively during transgressive or regressive episodes where the zone of mixing will advance or retreat with the shoreline (Figures 10A-D).

It is clearly of some significance to sequences of interbedded dolomites and chert that the same hydrogeochemical environment is proposed for the formation of both lithologies. If the precipitation of the minerals is assumed to take place at the concentrations suggested by Badiozamani (1973) and Knauth (1979) (see pages 41 and 43) then both dolomite and chert could precipitate simultaneously at different levels in the zone of mixing. During a marine transgression the mixing zone would move shoreward and dolomitisation would take place before chertification (see Figure 10). This would be consistent with the chert poor units being associated with subtidal facies following marine transgressions. It is assumed that silica would not replace dolomite in the same manner as it does calcite. This may be a reasonable assumption if the mixture is saturated with respect to dolomite or if the speed of transgression prevents the chertification process. Conversely silicification would occur in preference to dolomitisation during a regression (see Figure 10D). The Dorag model may thus be applicable to thicker chert poor or chert rich units, but explaining interlaminated and thinly interbedded chert by this process is very difficult. It is possible that these thinly bedded sediments of the intertidal to supratidal zones are dolomitised by one of the evaporative mechanisms. Alternatively if algal photosynthesis in a brackish tidal marsh raises pH's to above 9, precipitation of silica results from a pH drop due to either inundation by fresh water following rain, or sea water (pH 8,3) due to a storm or exceptional high tide. The incomplete dolomitization of these carbonates in the Western Transvaal (Eriksson et al, 1975) would lend credence to a different mechanism acting in the intertidal sedimentary facies.



NOTE: Saturation state expressed in terms of log Ω where Ω = the ratio of the ion activity to the mineral equilibruim constant

FIGURE 9: Depiction of hypothetical solubility relationships of calcite, dolomite and silica for mixing of meteoric and marine waters (after Knauth, 1979).

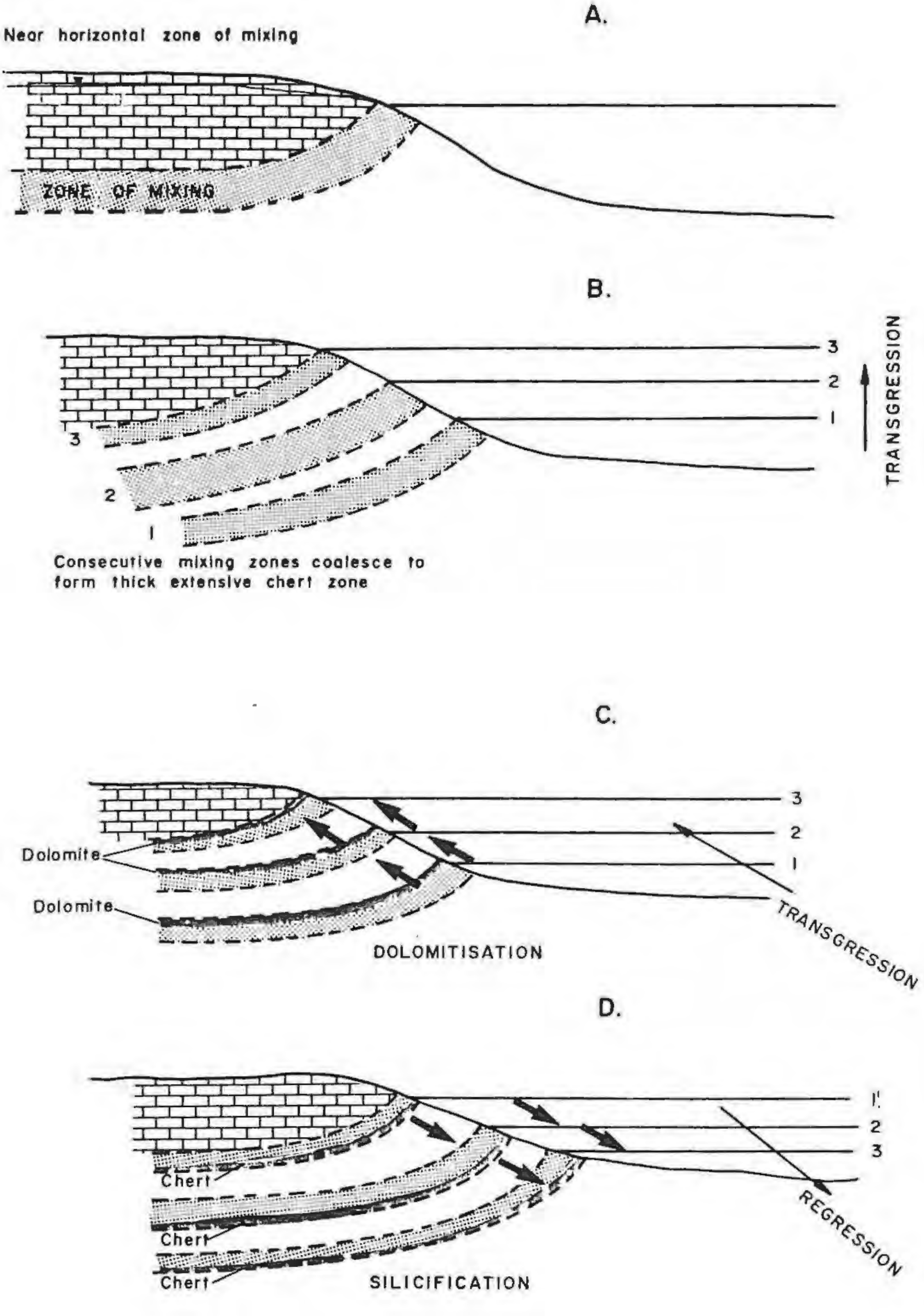


FIGURE 10: Deposition of dolomite and chert in a schizohaline environment.

3.5 Structure

3.5.1 Regional

The Chuniespoort Group of the study area is situated in a large westward plunging synform known as the Potchefstroom Synclinorium. Pre-Transvaal Sequence strata lie to the north in the hills of the Klipriviersberg; to the east, thus separating the study area from the dolomites of the East Rand, and to the south in the hills of the Suikerbosrand and the Vredefort Dome (Figure 11). Limb dips of approximately 10° were the norm in the Black Reef Formation and 15° in the Pretoria Group. Steeper dips were recorded in the Pretoria Group between Daleside and Vereeniging (see Map 1).

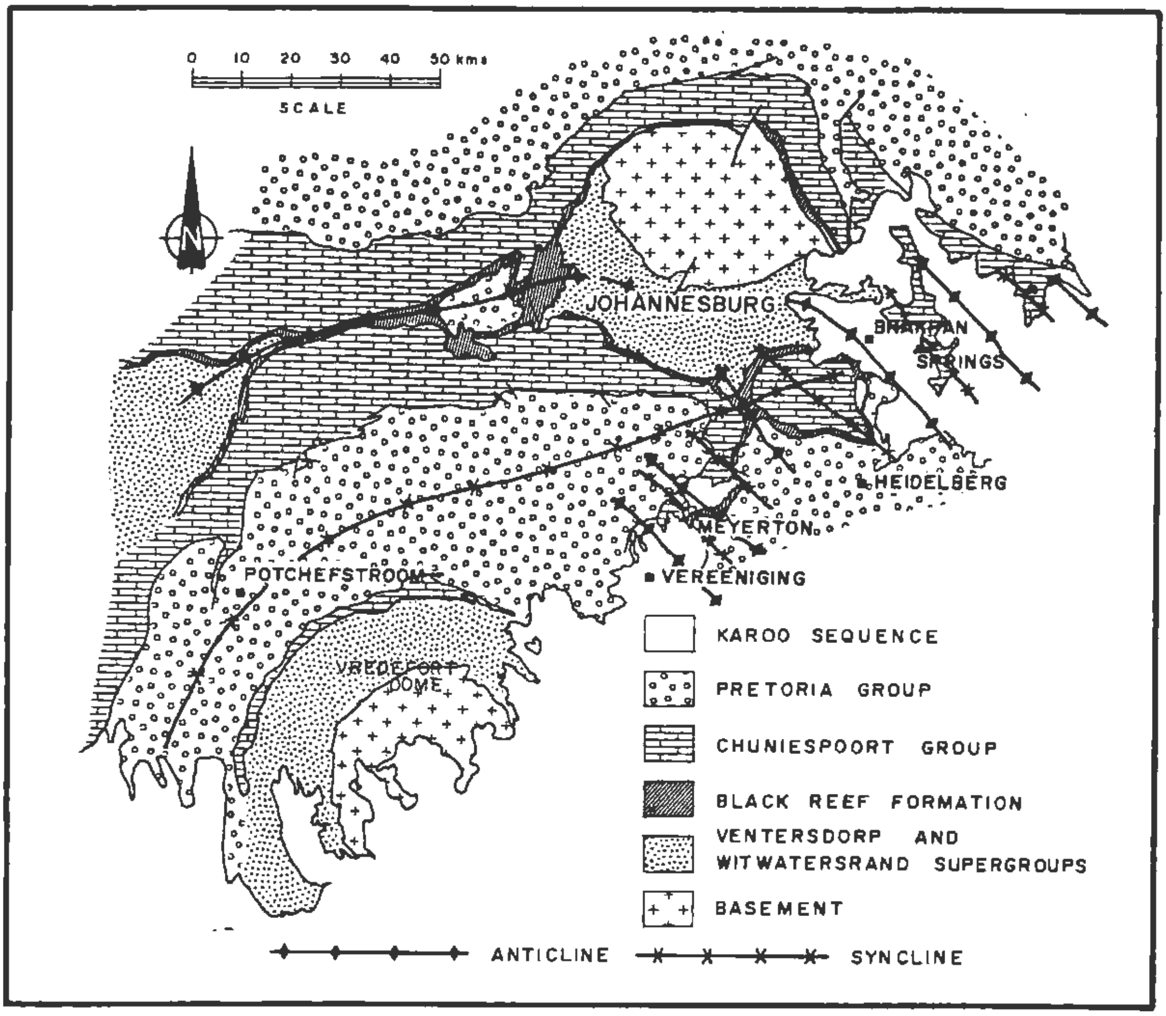


FIGURE 11: Regional geological map showing major fold axes in the study area

On the southeastern limb of the Potchefstroom Synclinorium the Chuniespoort Group outcrop width varies from an estimated 2 km at Meyerton and Daleside to 11 km between Meyerton and Vereeniging. Published geological maps depict the Pretoria Group faulted against the Black Reef Formation in the vicinity of Daleside. Detailed geological mapping of the Rooihoogte and Timeball Hill Formations as part of this study has shown that these 'intruding' Pretoria Group features are synforms. The lines of greatest outcrop width may therefore be interpreted as antiforms.

The extension of this interpretation to the rest of the study area explains the occurrence of the dolomitic outlier of the Natalspruit Basin as the result of two crossing synclinal axes. An anticlinal saddle separates the basin from the Klip River Valley.

This geological interpretation is supported by the parallel folding of pre-Karoo Sequence strata in the East Rand dolomitic area deduced from the results of deep exploration boreholes (Button, 1968) and the study of axial trends of folds in the northern portion of the Witwatersrand Basin by McCarthy et al (1986). The NW-SE trend is consistent with compressive forces that would have been generated by the development of the Vredefort dome. The fold wavelengths between Vereeniging to Delmas vary between 13 km and 26 km (see Figure 11).

3.5.2 Folding

In the Natalspruit Basin folds with small amplitudes and wavelengths have been postulated in order to provide a geological interpretation consistent with the results of the geological mapping and available borehole logs (Map 3, see back pocket). The folds are parallel to the NW-SE trend of the large scale folding.

3.5.3 Faulting

Numerous small faults have been mapped in the Black Reef Formation and Pretoria Group sediments by virtue of their good exposure and clear expression on aerial photo's. The faults probably extend into the Chuniespoort Group strata but the poor exposure of the dolomitic formations largely prevents their mapping. Most of these faults appear to be of normal type.

Strike slip (transverse) faulting is associated with the axial regions of the NW-SE trending folds near Meyerton and Daleside.

Long normal faults with a curved surface expression cross the Klip River Valley between Zwartkopjes farm and Daleside. It is interpreted that these faults are associated with synclinal arching (see Figure 12). Similar faulting has been interpreted on the south western margin of the Natalspruit Basin, in order to explain the outcrop of Monte Christo Formation directly in contact with the Black Reef Formation.

Two transverse faults are associated with the Panvlakte dyke striking WNW-ESE in the western part of the Klip River Valley.

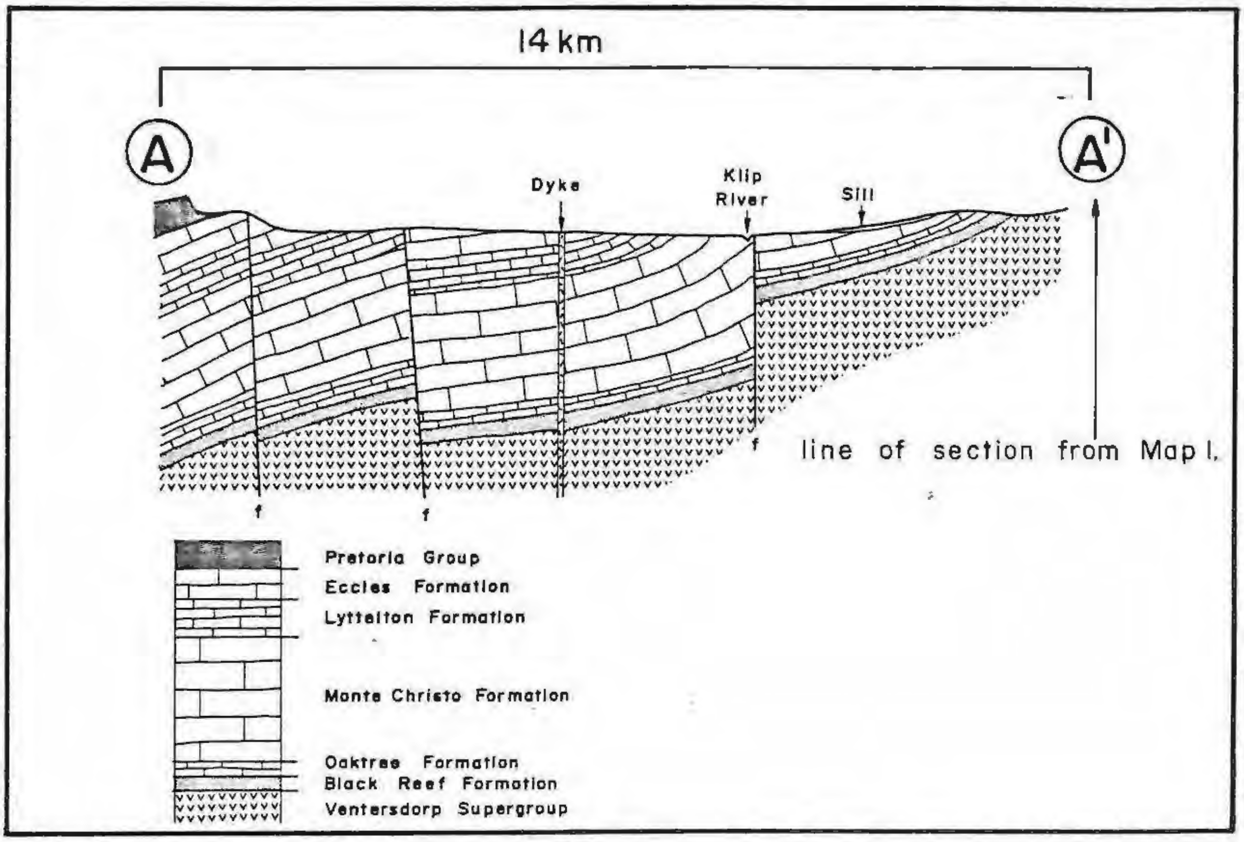


FIGURE 12: Diagrammatic geological cross - section across the nose of the Potchefstroom Synclinorium in the Klip River Valley.

3.5.4 Lineaments

Major joint sets in the Witwatersrand and Ventersdorp Supergroups are clearly expressed on aerial photographs of the Suikerbosrand Hills and as straight stream segments on 1:50 000 topographical maps. A trend analysis is shown in Figure 13. All lineaments in the Chuniespoort Group of the Natalspruit Basin, ran parallel or sub-parallel with the long dykes crossing the study area.

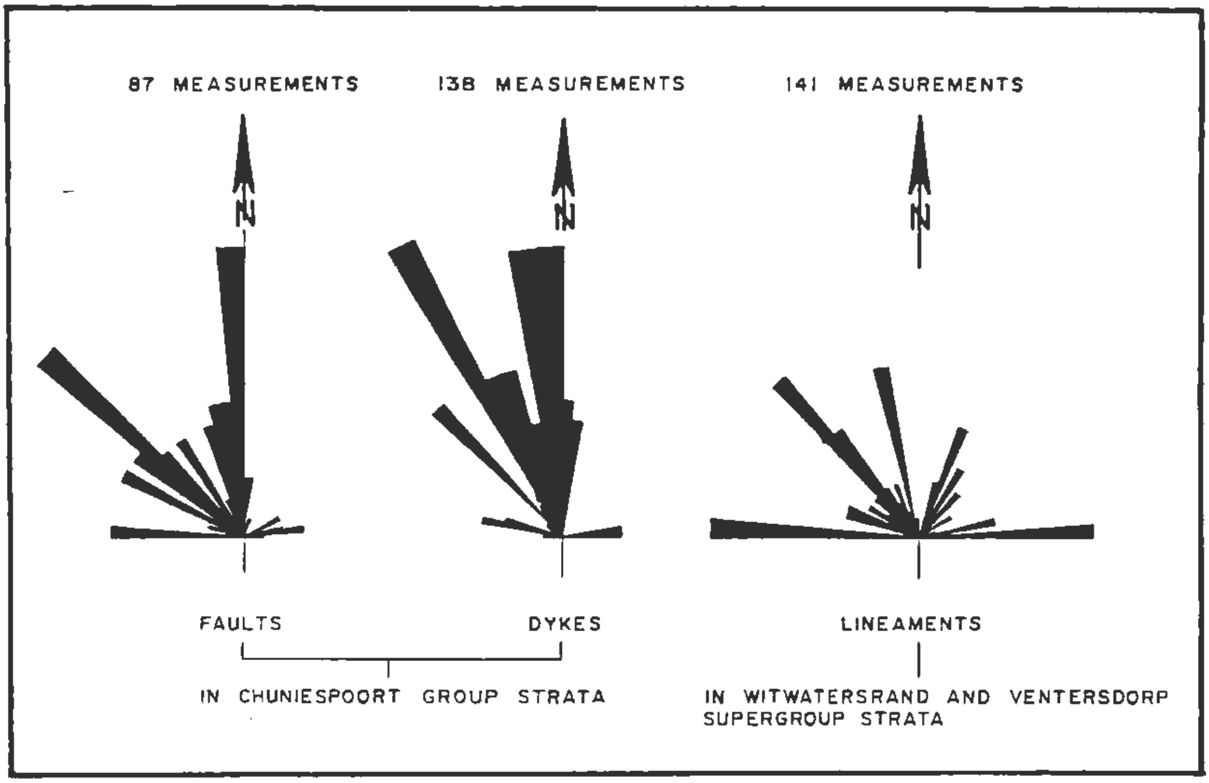


FIGURE 13: Trend analysis of structural features in the study area.

4. KARST HYDROGEOLOGY

4.1 Introduction

"Karst denotes any terrain underlain by carbonate rocks in which circulating water has dissolved the rock creating such physical features as enclosed depressions, sinkholes, swallow holes and long dry valleys, scarcity of surface streams and subterranean drainage through solution openings" (La Moreaux et al, 1986).

Calcite and dolomite are only moderately soluble in pure water. The presence of carbon dioxide in ground water greatly increases its solvent ability. Rainwater is already slightly acidic when it reaches the ground surface due to atmospheric pollution. It then becomes enriched with carbon dioxide as it percolates through the soil. CO_2 pressure is considered to be the most important factor in the solution process. The pressure of CO_2 gas in soil and in cracks in the bedrock is many times greater than in the atmosphere (Sweeting, 1972). The increase in CO_2 pressure is the result of vegetational and microbial activity. Further contribution of CO_2 may be made by organic acids from decomposing vegetable matter. The ground water may thus be regarded as weak carbonic acid.

$$\underset{\text{water}}{H_2O} + \underset{\text{carbon dioxide}}{CO_2} = \underset{\text{carbonic acid}}{H_2 CO_3}$$

Acidity may be further increased by the presence of sulphuric acid derived from the oxidation of any pyrites present (see page 29).

The dissolution of dolomite may be simply represented by the following equation:

$$\underset{\text{Dolomite}}{3CaCO_3.2\,MgCO_3} + \underset{\text{carbonic acid}}{5H_2CO_3} = \underset{\text{calcium bicarbonate}}{3Ca\,(HCO_3)_2} + \underset{\text{magnesium bicarbonate}}{2Mg(HCO_3)_2}.$$

In detail the dissolution of carbonate rocks is not a simple reaction but a series of reversible reactions and dissociations, the reader is referred to Sweeting (1972, chapter 3) and White (1977).

Three types of carbonate aquifer porosity have been described by White (1969):

(i) Primary or intergranular porosity.

(ii) Secondary porosity consisting of a multitude of joints, faults, fractures and bedding plane partings.

(iii) Secondary porosity in solution openings from centimetre size to the size of large caverns.

The last type of porosity is reported to be rare in dolomites. White (1977) attributes this to the difference in solution kinetics between calcite and dolomite. Laboratory experiments on the solution process of limestone showed that the initial dissolution of calcite by a typical ground water would be very high. It would then drop after a short period of time to continue at a low rate. In the case of dolomite the initial rate of dissolution is high but drops to a lower level at a much earlier point than calcite (see Figure 14). In an aquifer context the ground water would enter the carbonate formation along the many small openings of relatively dispersed secondary porosity. The ground water would only travel a short distance before critical undersaturation would be reached, dissolution would then continue at a slow rate along all path-ways as the ground water migrated. The first path that allows water to emerge from the aquifer still below the critical level of undersaturation will then experience a significantly more rapid solution rate. This pathway will then develop preferentially to form a large solution opening (see Figure 15). It is thought that because of dolomite's earlier drop in dissolution rate this critical triggering for conduit development rarely takes place.

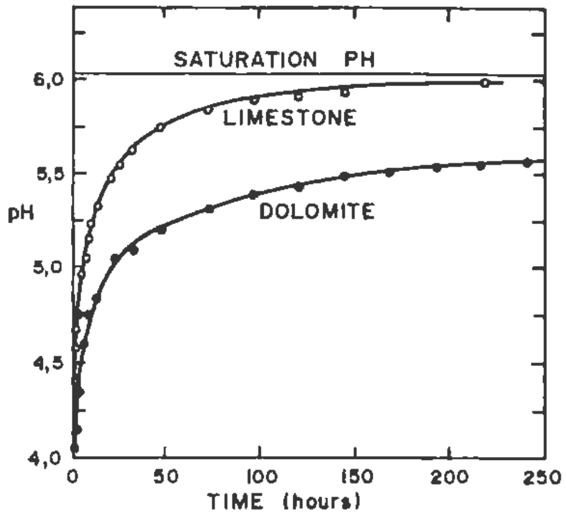


FIGURE 14: Experimental rate curves comparing the solution of a cavernous limestone with a non cavernous dolomite (after White, 1977)

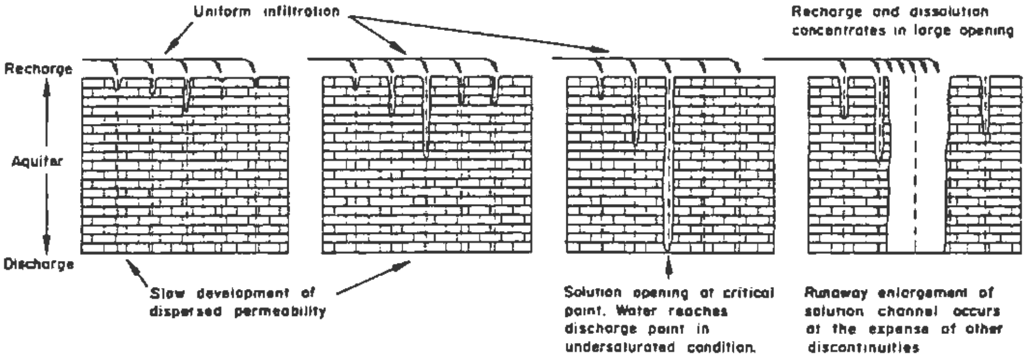


FIGURE 15: The development of large solution openings in carbonate rock

4.2 Principles of Karst Formation

4.2.1 General

In order for the dissolution of carbonate rock and the development of a karst aquifer to occur the strata must be able to:

(i) receive fresh water at an intake area

(ii) allow passage of water through the area

(iii) permit the water to leave the system.

These conditions are not possible in the marine environment of carbonate deposition. Tectonic or eustatic activity is therefore a pre-requisite for karstification. For karst to form, marine carbonate deposits must be moved to an environment of fresh water circulation, (Stringfield, Rapp and Anders, 1979).

The principle characteristics of karst aquifers are:

(i) a wide range of permeability, and storage characteristics;

(ii) the occurrence and movement of ground water are related to geological structures but not according to set rules i.e. faults may act as conduits or barriers to ground water movement (La Moreaux, Wilson and Memon, 1984);

(iii) the zone of greatest permeability tends to develop at the water table (Le Grand and Stringfield, 1971);

(iv) erosional base levels play an important role in karst development by governing the elevation of the water table;

(v) erosional unconformities may form palaeokarsts and their occurrence may be unrelated to present base levels (Le Grand and La Moreaux, 1975).

Influence of stratification

Horizontal and vertical changes in lithology will be reflected in physical, chemical and mechanical characteristics. Metasomatic, metamorphic and tectonic forces will tend to affect different lithologies in different ways or to different degrees, (La Moreaux, Wilson and Memon, 1984).

4.2.2 Structure

General

The large number of interdependent and independent factors contributing to the development of the aquifer mean that no two carbonate aquifers are identical. The influence of structural geology is so variable that there are no simple rules governing the effect of joints, faults or folds on the development of an aquifer.

On the regional scale the tectonically induced position of the body of carbonate rocks governs the potential recharge/discharge relationship.

Faults, fractures and joints

There is a great wealth of evidence supporting the relationship between the development of solution porosity and the presence of fractures in Palaeozoic and Mesozoic limestones. The subject is reviewed by Stringfield, Rapp and Anders (1979).

Faults associated with tensional forces, such as normal faults are normally accompanied by joint and fracture opening and an increase in permeability. Reverse and thrust faults may have a negative effect as a result of recrystallisation or mylonitisation along the fault plane. In such cases the faults act as barriers to ground water flow and hence impair the development of karst. Faults that exert no influence on ground water movement in carbonate aquifers are rare, (La Moreaux, Wilson and Memon, 1984).

It should not be assumed that the orientation of joint sets, fracture traces and fault zones are all related. In the Edwards Limestone Aquifer in Texas there is no correlation between the orientation of short faults and fractures and the strike of major Balcones fault zone. The major fault zone is middle to late Tertiary in age, the short fractures correlate with the tectonics of the basement metamorphic system. (Wermund and Cepeda, 1977).

Valleys and fracture traces

In compact carbonate rocks with no intergranular permeability, joints and fractures are essential for the initiation of downward water percolation (Stringfield, Rapp and Anders, 1979). The more compact the rock the more important is the effect of planes of weakness (La Moreaux, Wilson and Memon, 1984). Water will flow over the surface of the rock until a plane of weakness is encountered. Infiltration will be controlled by the frequency, openness and continuity of the planes of weakness.

Tributary patterns of surface drainage systems on all rock types have been shown to be governed by the orientation of rock discontinuities, joints and fractures (Parizek, 1976). Erosional agents are more effective along these discontinuities where joints are commonly more open, or filled with weak weathered material. This is particularly so in the case of carbonate rocks where the rock solubility in natural water is so much greater than elsewhere. As erosion continues, surface drainage is progressively concentrated in these zones and leads to increased infiltration and recharge of ground water. This in turn fosters more rapid solution of the carbonate bedrock.

Just as surface drainage develops along structural weaknesses, so does the solution of the rock by ground water. Flow will be greatest along the most open most direct path which will be associated with the distribution of the planes of weakness. Small valleys in particular are affected by zones of fracture concentration. As valleys gradually widen due to erosion the original drainage control by a fracture zone may become obscured (Parizek, 1976).

Folds and dips

The dip of bedding planes should control the direction of ground water movement in much the same way as joints and faults. The point of discharge will however ultimately govern the net direction of flow.

The axial regions of anticlines and synclines are often associated with zones of intense fracturing. There are many examples where these zones are intensely karstified or form excellent aquifers. (La Moreaux, and Powell, 1963)

4.2.3 Decrease of permeability with depth

In carbonate aquifers the effective porosity, storage coefficient and permeability generally decrease with depth from the low seasonal water table (see Figure 16). At this horizon the dynamic and chemical action of ground water is greatest (Le Grand and Stringfield 1971). Because of longer lines of flow the volume of ground water flow per unit area decreases with depth. Master conduits develop preferentially towards the top of the zone of saturation and limit flow and solution at deeper levels (Rhoades and Sinacoari, 1941: Bedinger, 1967).

Where artesian conditions exist the piezometric surface does not represent a critical zone of circulaton. Zones of greater circulation and solution may develop at the upper part of the aquifer as a result of shorter flow lines there. Artesian limestone aquifers may once have been in a water table circulation system.

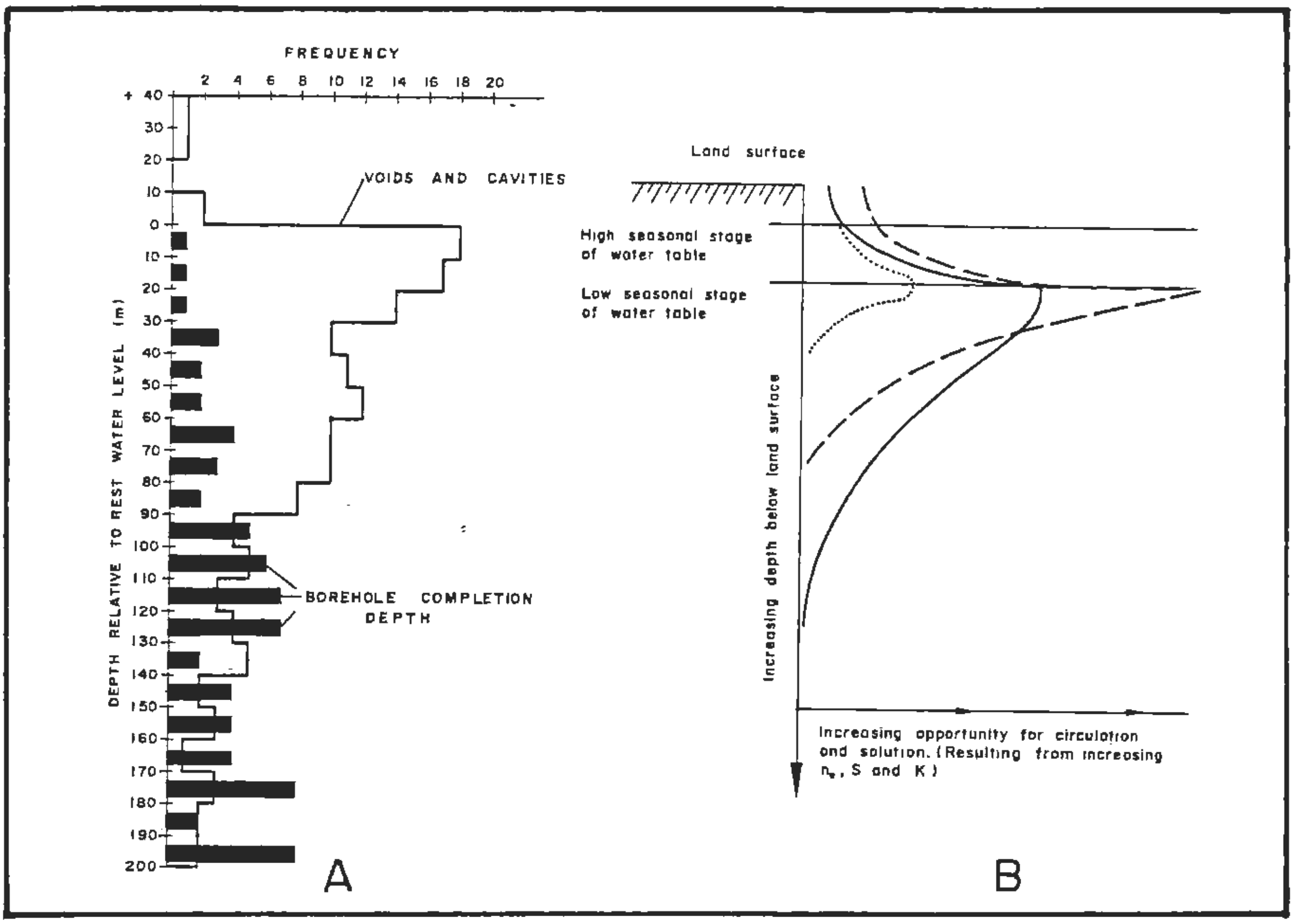


FIGURE 16: Relationship between hydrogeological characteristics and depth for A; Klip River Valley and the Natalspruit Basin and B; general case (the solid line represents a common condition, the dashed and dotted lines represent less common, but not unusual conditions; adapted from Le Grand and Stringfield, 1966).

At springs, flow lines are concentrated both spatially as well as in the water table plane. This concentration of flow maximises the development of permeability and porosity by solution.

4.2.4 Base levels

The elevation of the water table (and in turn the zone of greatest circulation and solution) is governed by the erosional base level. The base level controls the gradient of the movement of water above and below the ground surface. The base level may be represented by:

(i) sea level;
(ii) perennial gaining streams;
(iii) underlying impervious formations.

If a base level remains relatively static, the water table in a limestone aquifer will gradually lower until a point of equilibrium is reached between the recharge and discharge of the system at the base level. This water table will develop as a zone of higher permeability and porosity as discussed previously (see page 59). In the long term these zones are not static. Perennial streams will progressively lower their beds and with them the water table and the zone of greatest circulation. In coastal areas where the aquifer discharges directly into the sea, base levels change with the sea level.

4.2.5 Palaeokarst

When a carbonate sediment is raised above sea level as a result of tectonic uplift or drop in sea level it is exposed to weathering and karst processes. At any stage in the development of the karst the sediment may be submerged again by a transgressive sea. There the karst surface may suffer further erosion in a high energy environment or it may be modified by the deposition of sand, clay or newly precipitated carbonate. Some of the karst features may still survive until the sediment is once again raised above sea level. If the interval between the submergence of the first karst and development of the new karst is too short there may not be sufficient thickness of deposits separating the two karst cycles to make them distinct from one another.

4.3 Transvaal Karst

4.3.1 General

Fresh dolomite of the Chuniespoort Group is essentially impermeable with an effective porosity of 0,3% (Brink, 1979). Secondary permeability and porosity has developed by ground water circulating through joints, discontinuities and bedding planes.

A general guide to the type of carbonate aquifer system to be expected in the study area is provided by White's classification (1969) subsequently modified in La Moreaux, Memon and Wilson (1984) as presented in Table 4. On the basis of this classification the Chuniespoort Group aquifer in the study area could be expected to belong to the "Free Flow" type where "thick, massive soluble rocks" with a coarse textured permeability would have an integrated conduit cave system. In addition the aquifer would be of the "deep" type where the "karst system extends to considerable depth below base level", where flow is through submerged conduits.

TABLE 4: Types of carbonate aquifer systems in regions of low to moderate relief (from La Moreaux, Wilson and Memon, 1984 p39)

Flow type	Hydrological control	Associated cave type
I. DIFFUSE FLOW (fine-textured permeability)	SHALEY LIMESTONE; CRYSTALLINE DOLOMITES High primary porosity or uniformly distributed fractures	Caves rare, small, have irregular patterns.
II. FREE FLOW (coarse-textured permeability)	THICK, MASSIVE SOLUBLE ROCKS Conduits develop along bedding, joints, fractures, or fold axes.	Integrated conduit cave systems.
A. PERCHED	Karst system underlain by impervious rocks near or above base level.	Cave streams perched - often have free air
1. Open	Soluble rocks extend upward to land surface.	Sinkhole inputs; heavy sediment load; short channel morphology caves.
2. Capped	Aquifer overlain by impervious rock.	Vertical shaft inputs; lateral flow under capping beds; long integrated caves.
B. DEEP	Karst system extends to considerable depth below base level.	Flow is through submerged conduits.
1. Open	Soluble rocks extend to land surface.	Short tubular abandoned caves likely to be sediment-choked.
2. Capped	Aquifer overlain by impervious rocks.	Long, integrated conduits under caprock. Active level of system inundated
III. CONFINED FLOW	DIFFUSE FLOW OR FREE FLOW SYSTEMS STRATIGRAPHICALLY BOUND BETWEEN BEDS OF LOW PERMEABILITY	
A. ARTESIAN	Impervious beds which force flows below regional base level.	Rare, small irregular caves (diffuse flow). Inclined 3-D network caves (free flow).
B. SANDWICH	Thin beds of soluble rock between impervious beds.	Rare, small irregular caves (diffuse flow). Horizontal 2-D network caves (free flow).

Within the study area the aquifer may be further classified locally as "open" or "capped". In the former case where soluble rocks extend to the ground surface, short tubular abandoned caves are likely to be sediment choked. In the latter case the aquifer is overlain by impervious rocks and "long, integrated conduits" occur under the caprock, the "active level of the system being inundated".

According to Le Grand and Stringfield's classification of karst by landform (1971) the karst of the Klip River Valley is an "Escarpment and low lying limestone plain".

Comparable areas would be the Nashville Basin - Highland Rim of Tennessee, the Dougherty Plain - Tifton Upland of southern Georgia, the Salem Plateau - Springfield Plateau of Missouri and the Dripping Springs - Chester Escarpment of Kentucky and Alabama (La Moreaux, Wilson and Memon, 1984) (see Figure 17).

Jakuc's (1977) demonstrated that open fissure density and permeability for calcium carbonate rocks is greatest in Tertiary and Quarternary Formations and decreases with age. The actual fissure density was shown to increase with age but in Palaeozoic (and presumably Pre-Cambrian) rocks microfissures are infilled with secondary calcite or healed by recrystallisation (see Figure 18).

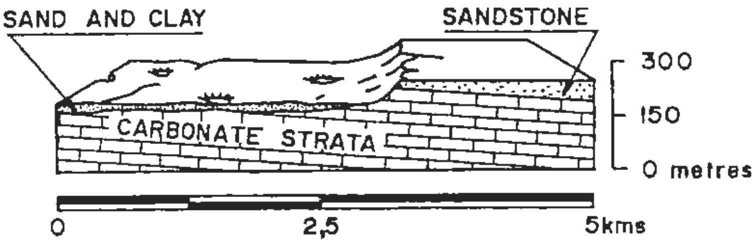


FIGURE 17: Escarpment and low lying limestone plain type karst (after La Moreaux, Wilson and Memon, 1984)

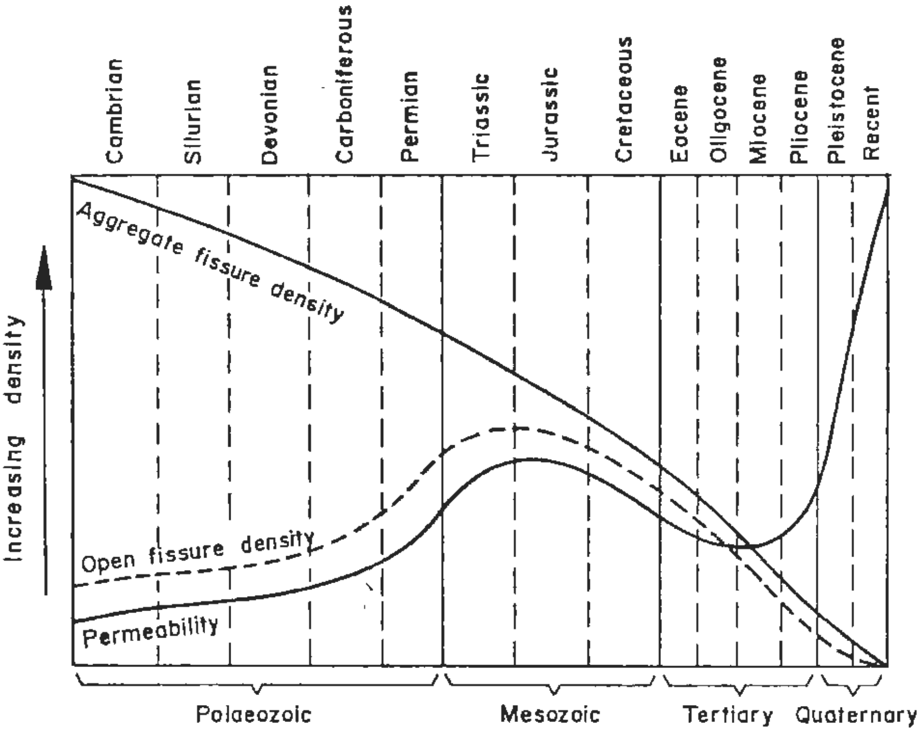


FIGURE 18: Geological age plotted against permeability for open or obstructed fissures in calcium carbonate rocks (from Jakucs, 1977, p 284)

4.3.2 History of the Transvaal karst

The Chuniespoort Group has experienced at least four karst episodes each corresponding to major breaks in deposition such as at present (Martini and Kavalieris, 1976).

The four episodes are:

1. Pre-Pretoria Group Karst Period - occurring at the erosional unconformity separating the Chuniespoort Group and the Pretoria Group. Products of the erosion of the dolomitic formations were deposited as chert breccias in the Rooihoogte Formation.

2. Pre-Waterberg Group Karst Period - supported by the occurrence of red sandstone in dissolution cavities near Lobatsi, Botswana.

3. Pre-Karoo Sequence Karst Period - believed to be a long period of erosion lasting approximately 1 000 Ma. It spanned the Carboniferous glacial period when the Transvaal region was subjected to the effects of an ice sheet covering this area. This glacial episode came to an end with the depositional conditions of the Karoo Sequence. Fluvio and peri-glacial sediments were deposited on the karst surface as the tillites and diamictites of the Dwyka Formation. These were followed by clays and carbonaceous sediments. The occurrence of coal in outliers of Karoo Sequence on the dolomites of the West Rand suggest that the organic sedimentation was contemporaneous with karst subsidence and that karst formation was a feature of both pre and post-Dwyka Formation times.

4. Tertiary to Recent Karstic Period - the Cenozoic was characterized by epeirogenesis, and widespread erosion (Tankard et al, 1982). Martini and Kavalieris (op cit) postulate that by the end of the Tertiary Era enough Karoo Sequence deposits had been removed to allow a karst landscape to evolve in the Transvaal. The present karst of the study area is described by Martini and Kavalieris as "Vaal River" type which is basically the same as their "Plateau" type, but weakly incised by perennial drainage. The Plateau type is characteristic of the West Rand and the flat, featureless plains between Johannesburg and Botswana (see Figure 19). The dolomitic plateau has an average elevation of 1 500 m but is covered by a thick blanket of superficial deposits over large areas. This plateau represents the African erosion surface of King (1962). The plateau surface coincides approximately with the level of the pre-Karoo Sequence karst surface and it appears likely that the present karst is active on the resurrected pre-Karoo Sequence karst.

Martini and Kavalieris suggest that the flat topographic character of the Transvaal dolomitic plateau indicates an advanced stage of karst evolution.

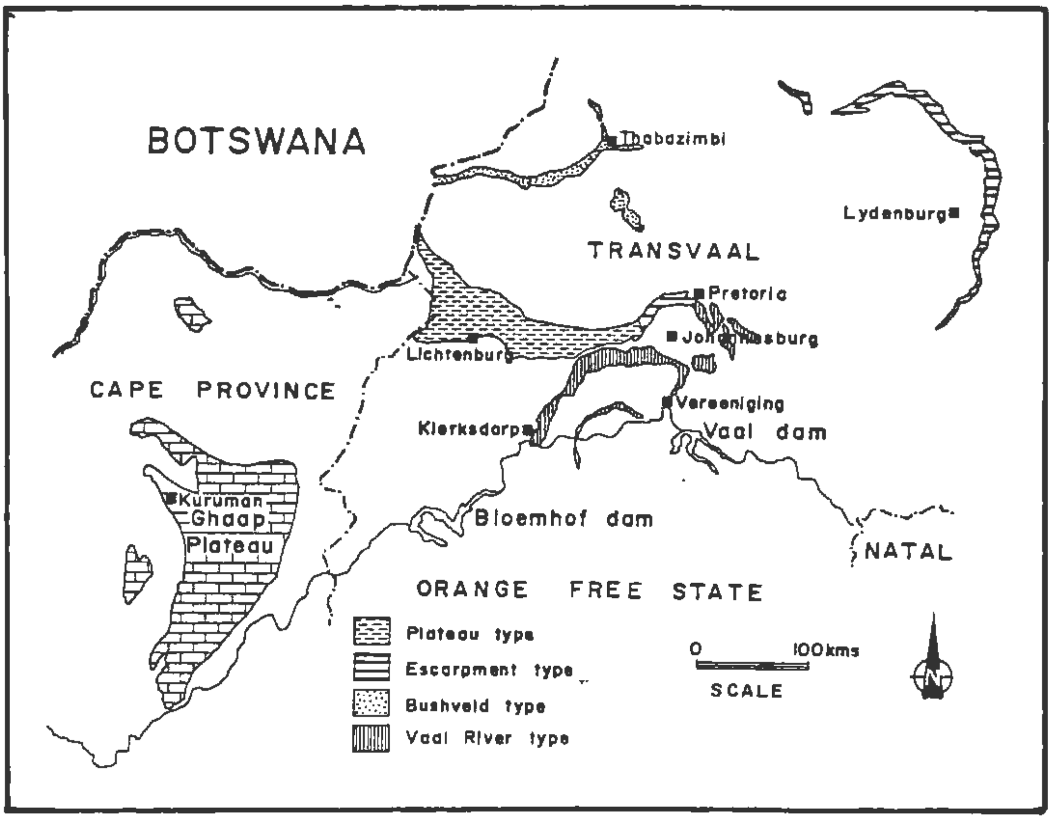


FIGURE 19: Karst types of the Transvaal (after Martini and Kavalieris, 1974)

4.4 Karst of the Study Area

4.4.1 Surface karst features

Drainage densities are lower on areas underlain by Chuniespoort Group than the other strata occurring in the study area. Typical drainage densities are shown in Table 5. Stream courses on the Pretoria Group outcrop disappear after crossing onto the outcrop of the dolomitic formations (Figure 20).

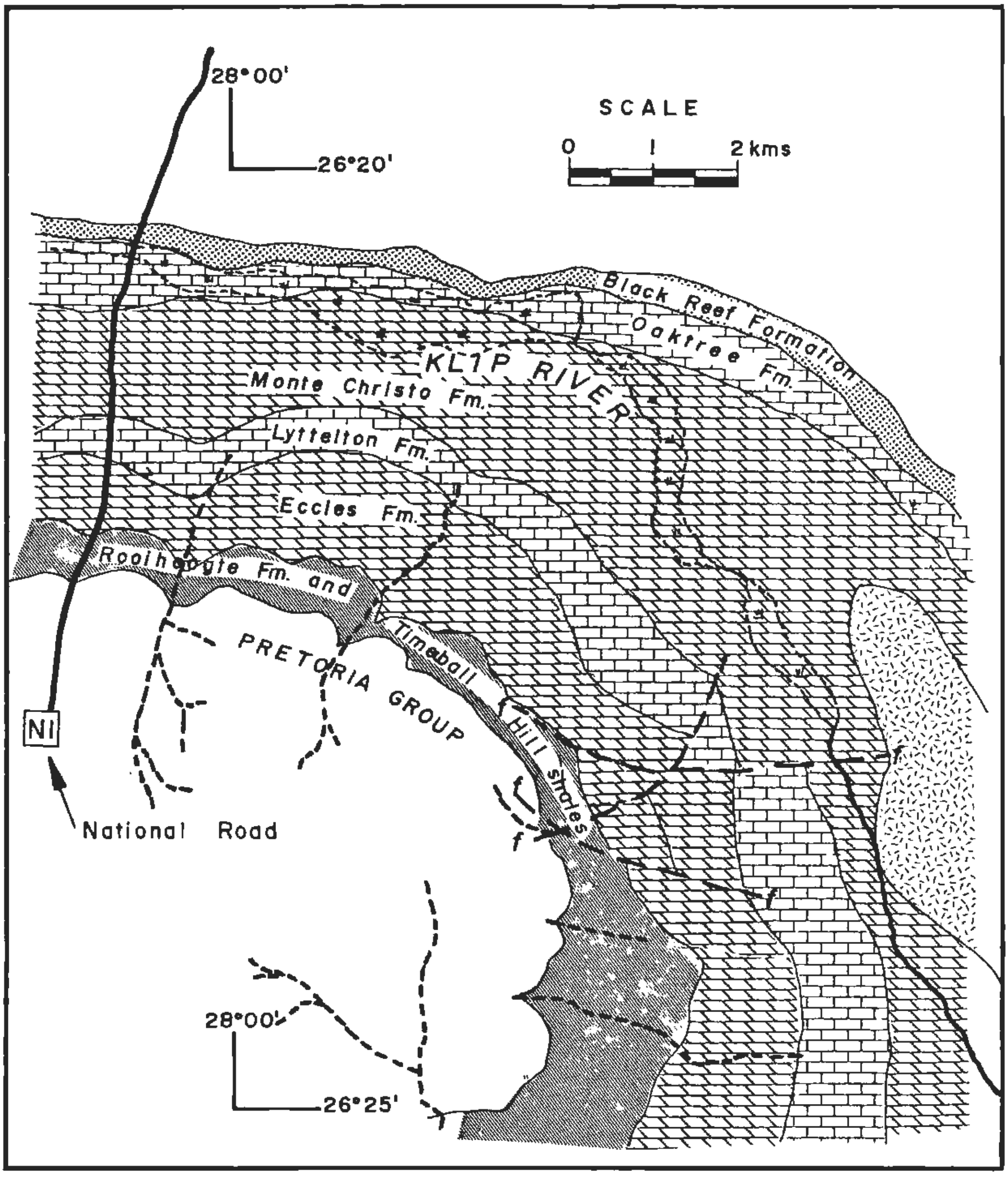


FIGURE 20: Disappearance of streams on the Chuniespoort Group outcrop

TABLE 5: Drainage densities for different lithologies (from Kafri et al, 1986, p 30)

	Drainage densities (km/km^2)				
Formation	Ventersdorp	Black Reef	Dolomite	Rooi-hoogte	Pretoria Group
Area					
Western Klip River	0,84	0,88	0,58	0,66	0,91
Eastern Basin	0,58		0,42		

Only three dolines were noted in the Klip River Valley and they all occur near the base of the Eccles Formation. The distribution of dolines across the whole study area is shown in Map 3. In the Natalspruit Basin Kafri et al, (1986) interpreted a structural lineament underlying dolines showing an apparent linear trend. Two large dolines occur at the base of the Oaktree Formation on the western margin of the basin. A number of small dolines lie in the drainage course coincident with an interpreted anticlinal axis.

4.4.2 Subsurface karst features

Gravity information

Gravity information compiled from various public and private sources by Kafri et al, (1986) and Reynders (1988) show extensive areas of Bouguer gravity lows associated with outliers of Karoo Sequence. Numerous linear gravity lows are also apparent and are probably the result of enhanced karstic weathering along lines of weakness in the underlying dolomite (Map 2).

At the western extreme of the study area, in the vicinity of the Klip River Dyke there is a large Karoo Sequence outlier with an associated regional gravity low (see Map 2). A series of subparallel linear gravity lows is imposed on this regional field trending approximately NW, these are interpreted as pre-Karoo Sequence solution channels (see page 19). One lineament runs parallel with the Klip River Dyke giving the impression of solution channels converging on the now dry Klip River Spring. The other N-S linear gravity low, occurring on the north and south side of the river appears to be associated with the N-S faulting crossing the river in this area.

The gravity information indicates that karstic weathering has been more effective north of the Panvlakte Dyke. A gravity low runs between the dyke and the sub-parallel quartz vein.

In the area between Zwartkopjes farm and Daleside the gravity information indicates that the zone of deepest dolomite weathering is noticeably strike governed. The gravity low coincides with the outcrop of the Eccles Formation, disturbed only slightly by faults. The exceptions to this are two crossed NE-SW striking features on the farm Zwartkopjes and a gravity low on the eastern side of the river associated with weathering of the dolerite sill and dyke.

In the Natalspruit Basin limited gravity information shows two linear gravity lows running strike parallel and flanking a minor anticlinal axis. The other extensive gravity low appears to be strike controlled.

4.4.3 Base levels

The ground water level map of the study area indicates that base levels may be established at numerous sites where ground water flow is hindered by impermeable barriers (see Figure 21). These barriers are formed by impermeable igneous dykes, except at the southwestern margin of the Natalspruit Basin where the Natalspruit stream crosses onto impermeable Ventersdorp Supergroup. Ground water generally flows towards the points of discharge over the dykes. These occur along the rivers where the dykes are most deeply eroded.

The streams of the Natalspruit Basin and the upper section of the Klip River are in hydrological connection with the Chuniespoort Group aquifer, which discharge over the dykes at the surface. South of Zwartkopjes farm, the Klip River flow is separated from ground water flow by impermeable Karoo Sequence and alluvial deposits. The ground water discharge from this section is subsurface over the E-W dyke passing north of Vereeniging.

The northern most sub-aquifer in the Klip River Valley discharges both westwards across the Klip River Dyke and eastwards down the Klip River. The extensive karstification on the eastern side of the Klip River Dyke, indicated by the Bouguer gravity anomaly map (see Map 2), suggests that at one time the main ground water flow was in an east-west direction across the Klip River Dyke. The present discharge of ground water in this direction is however due solely extraction of ground water for public water supply on the western side of the dyke at Zuurbekom. Prior to Rand Water Board pumping, the Zuurbekom aquifer discharged ground water into the Klip River.

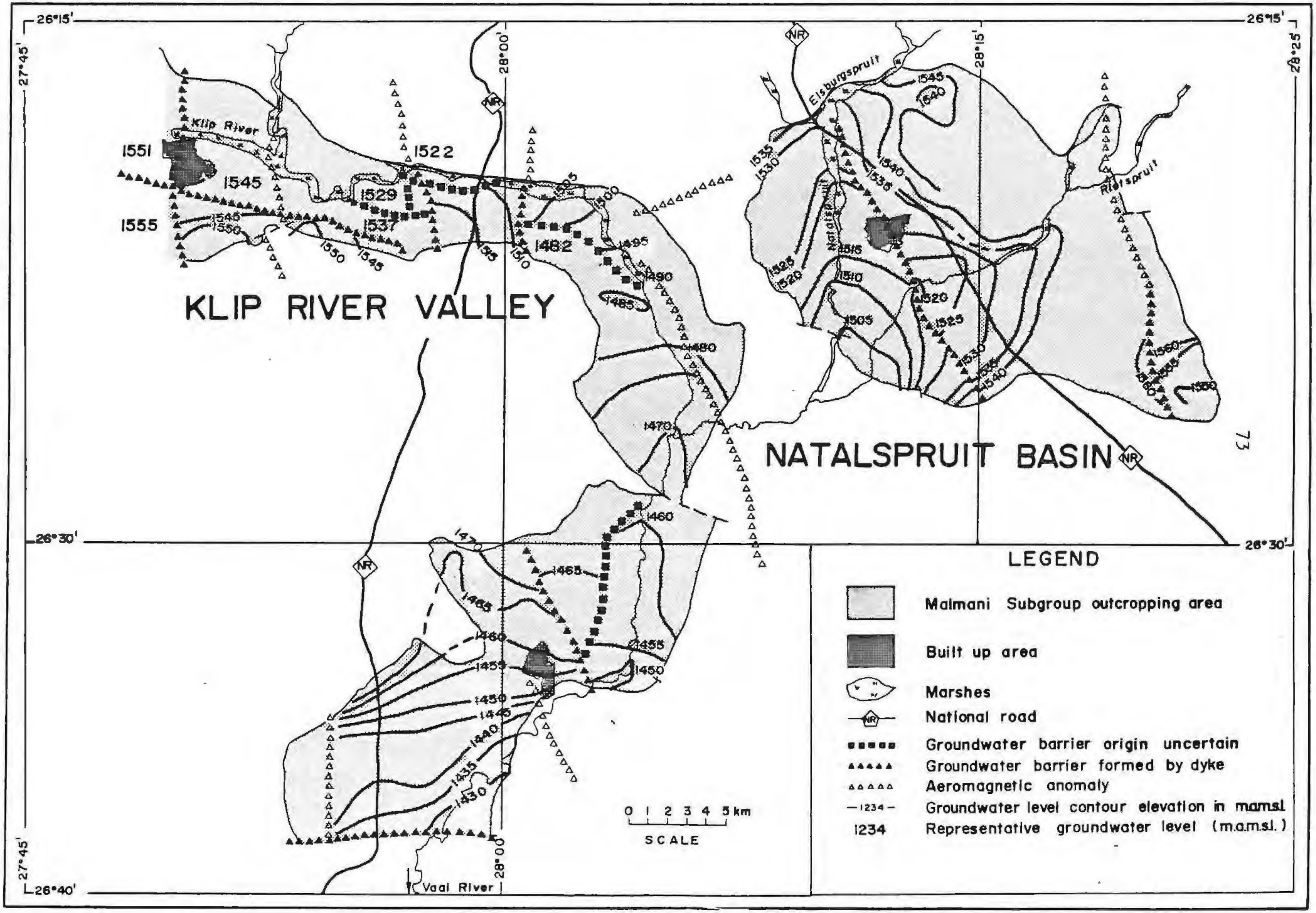


FIGURE 21: Groundwater level map of the study area (after Kafri et al, 1986)

To determine the relative importance of recent karst activity and the predicted base levels, all permeable zones encountered in the exploration boreholes were plotted relative to the rest water level and distance from ground water barriers formed by dykes. The results are depicted in Figures 22 and 23.

Natalspruit Basin - With the exception of the two boreholes nearest the outlet point of the basin, the highest level of karst solution occurs between 10 m and 20 m below the rest water level (see Figure 21). The aquifer is therefore assumed to be in a confined or semiconfined condition. The permeable zone may then represent recent karstic activity at the base of the confining strata or a recent fresh water circulation system acting on a reactivated palaeokarst i.e. the Karoo Sequence - Chuniespoort Group contact. Where permeable zones were encountered in excess of 100 m from the rest water level the control of geological structure or a more ancient, deeper palaeokarst in suspected.

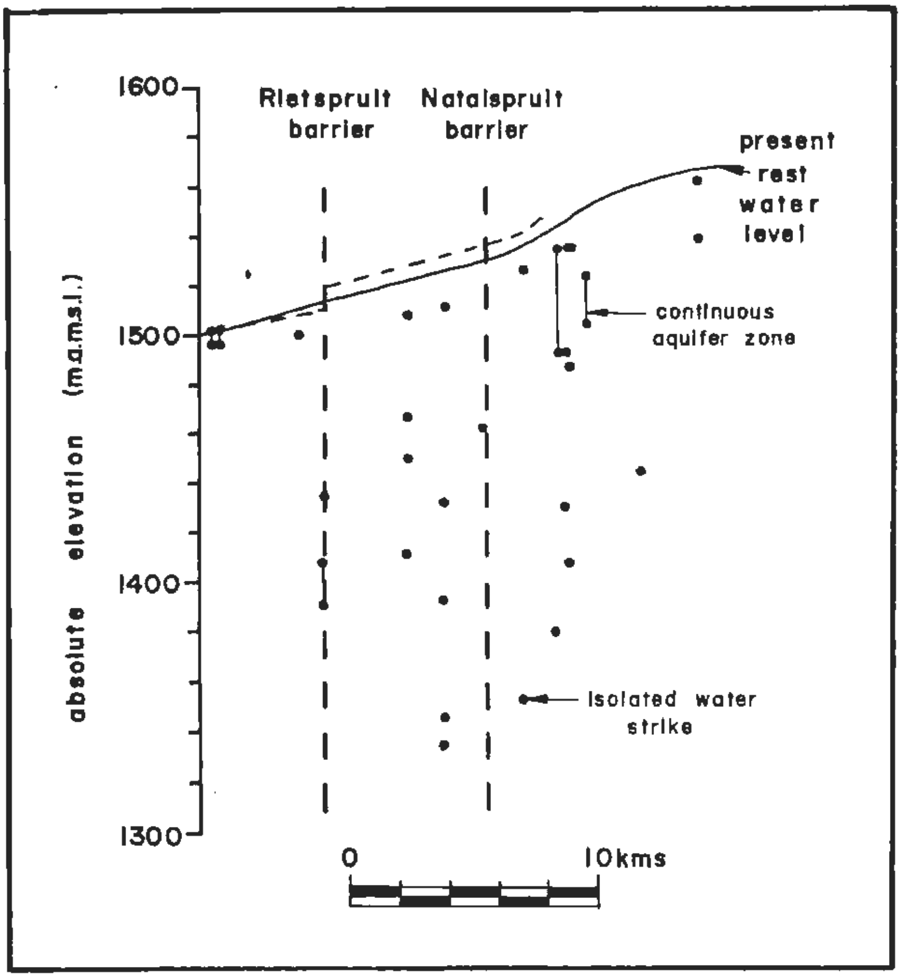


FIGURE 22: Ground water occurrence in the Natalspruit Basin relative to the rest water level

Klip River Valley - Permeable zones are developed at the water table in compartments 1, 2 and 3 of the Upper Klip River Valley as well as in the Middle Klip River Valley just south of Zwartkopjes (see Figure 23). Here extensive weathering was commonly encountered continuously to 80 m below rest water level (Kafri et al, 1986). This development of solution porosity may be a result of modern karst activity or as in the Natalspruit Basin may be a modern circulation system superimposed on a palaeokarst. In the Upper Klip River this would be the pre-Karoo Sequence palaeokarst, in the Middle Klip River, the pre-Pretoria Group or pre-Lyttleton Formation palaeokarst.

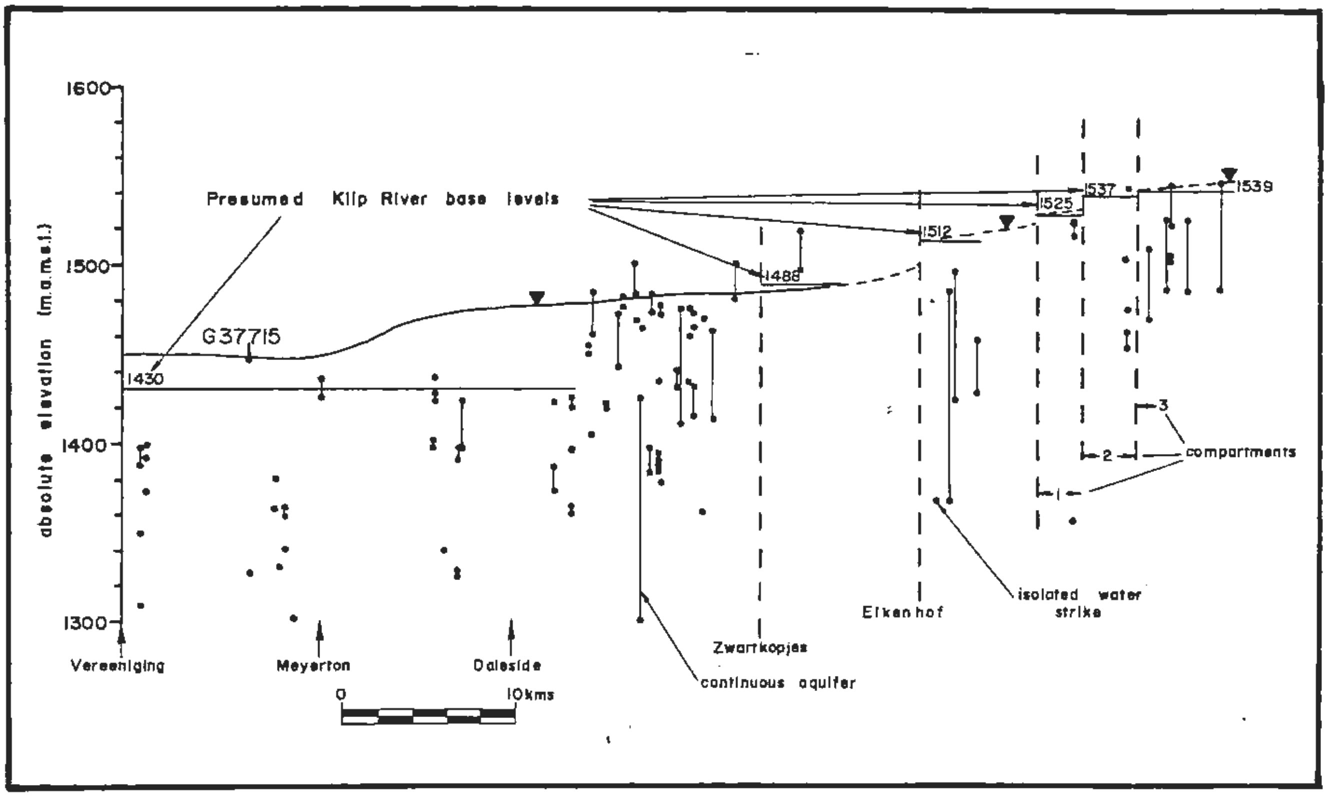


FIGURE 23: Ground water occurrence in the Klip River Valley relative to the rest water level

The occurrence of permeable zones in the remainder of the Klip River Valley is similar to that of the Natalspruit Basin. The upper level of solution features is in excess of 10 m below rest water level with the exception of borehole G37715 (Reynders, 1988). At this borehole the Eccles Formation was extensively exposed at the surface and aquifer conditions locally appear to be unconfined. All the other boreholes encountered the Chuniespoort Group beneath Karoo Sequence and below rest water level.

Results from the borehole logs presented by Kafri et al, (1986) in Figure 16 show that the development of solutional porosity in relation to the rest water level in the Chuniespoort Group aquifer conforms to the general case of the carbonate aquifer. The occurrence of voids, cavities and permeable zones is most likely at the water table or at the base of confining strata. The diagram clearly indicates that permeable zones may still be achieved at depths well in excess of 100 m below the water table.

Locally and regionally the absolute height of the water table is governed by the deepest point of weathering of the ground water barriers formed by dykes, where leakage of ground water occurs.

5. RESULTS

5.1 Introduction

In the previous two chapters, the geology and the karstic features of the study area were discussed in some detail. In order to fulfil the objectives of this research it now remains to analyse the relationship between these two and determine to what extent the one impinges on the other. The results of both the geological census and the exploration drilling are presented dealing with each hypothesis, from section 2.6 in turn.

For the reasons outlined on page 9. Individual borehole records from the census are of very limited value in this study. The large number of datapoints permits useful results to be gained through the benefits of averaging. For each borehole with a reported yield the following information was recorded and tabulated.

(i) Geological formation in which water strike occurred according to the compiled geological map i.e. stratigraphy.

(ii) Distance from lineament or surface drainage feature.

(iii) Distance from an igneous dyke.

(v) Distance from a perennial stream;

(vi) and where applicable distance from a fold axis or sill margin. Distances in excess of 2,0 km were ignored.

Detailed hydrogeological information was recorded for each exploration borehole drilled by the Department of Water Affairs. This information is highly reliable and justifies more detailed study, analysis and discussion. Pumping test results and borehole siting are presented in the Appendix and Map 4.

Analysis of the census information was further subdivided into results from the Natalspruit Basin, the Upper Klip River Valley and the Middle and Lower Klip River Valley. The three areas were grouped by geological and geomorphological criteria into areas likely to reveal any local variations in hydrogeological characteristics on the basin of the following:

(i) The Natalspruit Basin is a distinct, separate geologic and geographic entity whose characteristics may differ from the remainder of the study area;

(ii) The Upper Klip River Valley was easier to interpret geologically and formation contacts are likely to be more accurate than for the middle and lower section of the valley, with its more extensive cover of Karoo Sequence deposits;

(iii) The persistent E-W lithological and topographical trend of the Upper Klip River Valley is crossed at right angles by dykes, faults and drainage features. This is in contrast with the Middle and Lower Klip River Valley where the strike of the Chuniespoort Group is sub-parallel to the N-S trending linear structural features (see Figure 13) and is broken by the large scale folding. Valley profiles are correspondingly more varied.

5.2 Descriptive analysis of geohydrological census

(Refer to Map 2)

Natalspruit Basin - The majority of strong boreholes are situated in Monte Christo Formation with a high density of boreholes in the flood plain of the Elsburgspruit stream and in the vicinity of the Karoo Sequence outliers. Other concentrations of boreholes occur along synclinal fold axis two (Map 3), east of Vosloorus, at the southern basin margin by Tamboekiesfontein and along stream courses.

Upper Klip River - The highest density of high yielding boreholes occurs in the vicinity of the north trending dykes and particularly towards the top of the Monte Christo Formation.

Middle and Lower Klip River boreholes in this area are fairly evenly distributed with the exception of the cluster of boreholes in the Klip River settlement lying halfway between Zwartkopjes and Daleside where strong boreholes occur nearer to the river course.

5.3 Stratigraphic control of aquifer properties

The results of the geohydrological census for this geological criterion in the Natalspruit Basin are shown in Figure 23. Because a much larger number of boreholes were recorded occurring in the Monte Christo Formation the results for the other formations have been weighted to allow a comparison of the formations properties.

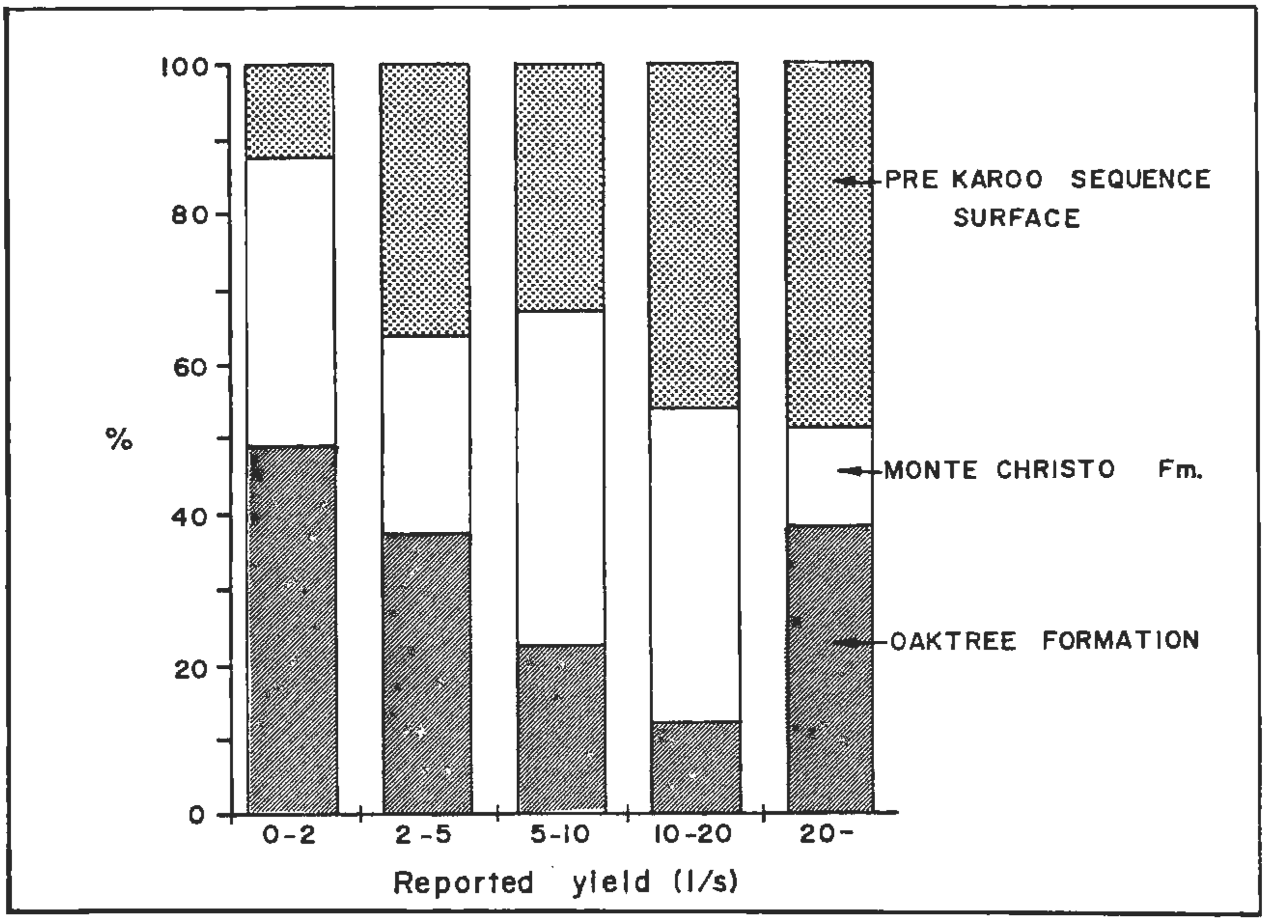


FIGURE 24: Graphical analysis of the geohydrological census in the Natalspruit Basin

The bar graph shows that boreholes penetrating the Monte Christo Formation predominate over those from the Oaktree Formation in the three yield classes from 2 to 20 ℓ/s. The trend is reversed in the highest yield class where the Oaktree Formation boreholes are more strongly represented.

Included in this analysis were boreholes where the water strike is known to have occurred at the contact between the Karoo Sequence and the dolomitic formations. Figure 23 shows that relatively few boreholes penetrating this horizon are of the weakest yield group and that there is good reason to expect strong yielding boreholes at this horizon (see results for palaeokarst, page 91).

The results of the geohydrological census in the Upper Klip River area are summarized in Table 6 and shown in Figure 24. The diagram shows that the highest reported yields for all subdivisions of the Oaktree Formation are lower than 6 ℓ/s and that the average formation yield is the lowest of all four formations. The average yield for the Monte Christo Formation is 6,5 ℓ/s and the highest reported yields in each subdivision are between 8 ℓ/s and 59 ℓ/s. The Lyttelton Formation shows the highest average formation yield (8,5 ℓ/s) but also the greatest variation in yield. The value for the average formation yield is highly distorted by extremely high reported yields in subdivision one. In particular one reported yield of 63,6 ℓ/s. It is interesting to note the high average reported yields in the adjacent subdivision at the top of the Monte Christo Formation (Monte Christo 4), and the base of the Lyttelton Formation (Lyttelton 1). The Eccles Formation has a relatively high average formation yield of 7,2 ℓ/s. The lowest average yields in its subdivisions are 3,8 and 3,5 ℓ/s, similar to that for the Monte Christo Formation (3,7 and 3,5 ℓ/s). These are both higher than the corresponding values for the Oaktree Formation (1,2 ℓ/s) and the Lyttelton Formation (2,6 and 3,0 ℓ/s).

TABLE 6: Summary of reported yields in the Upper Klip River Valley

FORMATION	SUBDIVISION	NUMBER OF DATA POINTS	AVERAGE YIELD ℓ/s	HIGHEST YIELD ℓ/s	AVERAGE YIELD FOR FORMATION ℓ/s
	1	1	6	6)	
Oaktree	2	1	1,2	1,2)	4,5
	3	4	4,9	5,9)	
	1	9	3,7	8,3)	
Monte	2	11	3,5	12)	
Christo	3	17	5,3	14,3)	6,5
	4	15	11,9	59)	
	1	11	13,3	63,6)	
Lyttelton	2	6	2,6	4,7)	8,5
	3	3	3,0	5,4)	
	1	6	3,8	12)	
Eccles	2	14	10,2	29)	7,2
	3	6	3,5	10)	

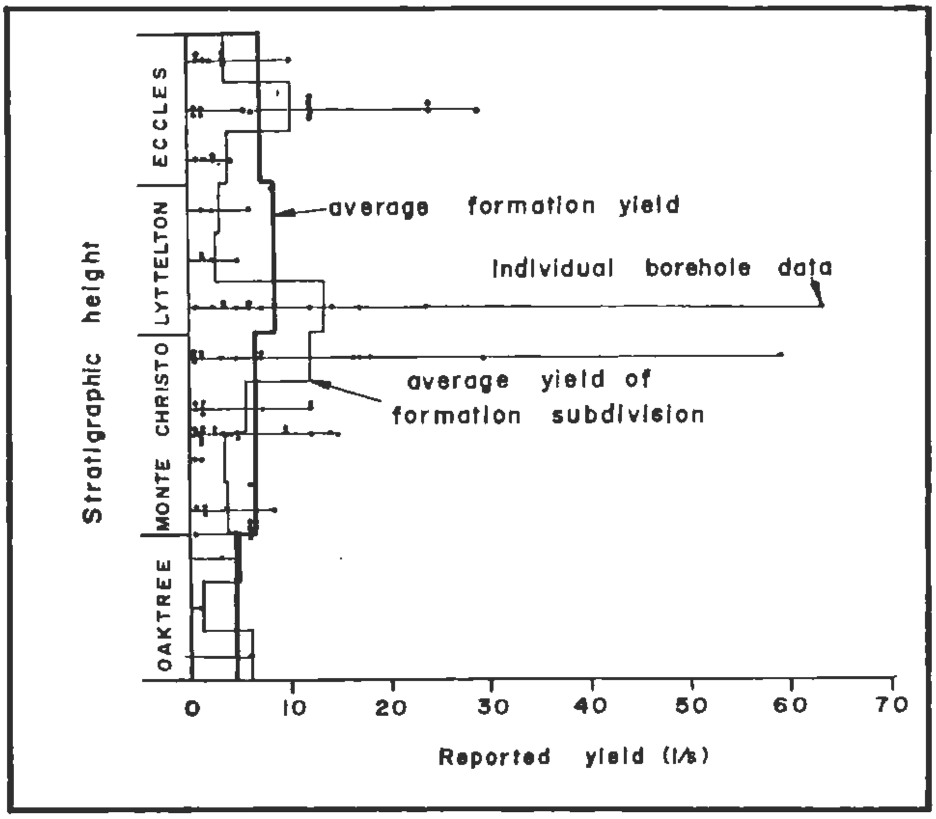


FIGURE 25: Distribution of reported borehole yields in relation to stratigraphic height in the Upper Klip River area.

The results of the geohydrological census in the middle and lower sections of the Klip River Valley (see Table 7 and Figure 25) show some similarities with those of the upper section (see above). As a result of the wider outcrop in this area it was possible to split the data into more groups. By doing this, boreholes penetrating formation contacts fall into a specific group. These values were then omitted when calculating average formation yields and thereby reduced the effects of a few yielding boreholes on an assessment of true formation characteristics.

The high reported yields occurring at the contacts between the Oaktree and Monte Christo Formations and the Lyttelton and Monte Christo Formations are clearly seen in the figure.

TABLE 7: Summary of reported borehole yields in the Middle and Lower Klip River Valley

Formation	Subdivision	Number of data	Highest yield (ℓ/s)	Average yield (ℓ/s)	Average formation yield (ℓ/s)
Oaktree	1	6	4,2	1,53	3,77
	2	8	10	4,42	
	3	3	3,1	2,17	
	Contact zone	9	38	9,76	
Monte Christo	1	1	0,1	0,1	5,31
	2	12	25	7	
	3	13	12	4,83	
	4	5	3,3	1,8	
	5	9	29,7	7,72	
	6	6	8,9	3,93	
	7	1	0,6	0,6	
	Contact zone	2	25	13,25	
Lyttelton	1	1	2,3	2,3	3,84
	2	1	10	10	
	3	2	2,5	1,45	
	4	3	10	3,9	
	Contact zone	6	12,5	3,67	
Eccles	1	3	12,6	6,63	4,36
	2	12	25	3,67	
	3	23	11	2,14	
	4	2	7,5	5,7	
	5	13	19	8,2	
	Contact zone	11	32	5,9	
Rooihoogte	1	13	19	4,4	4,44

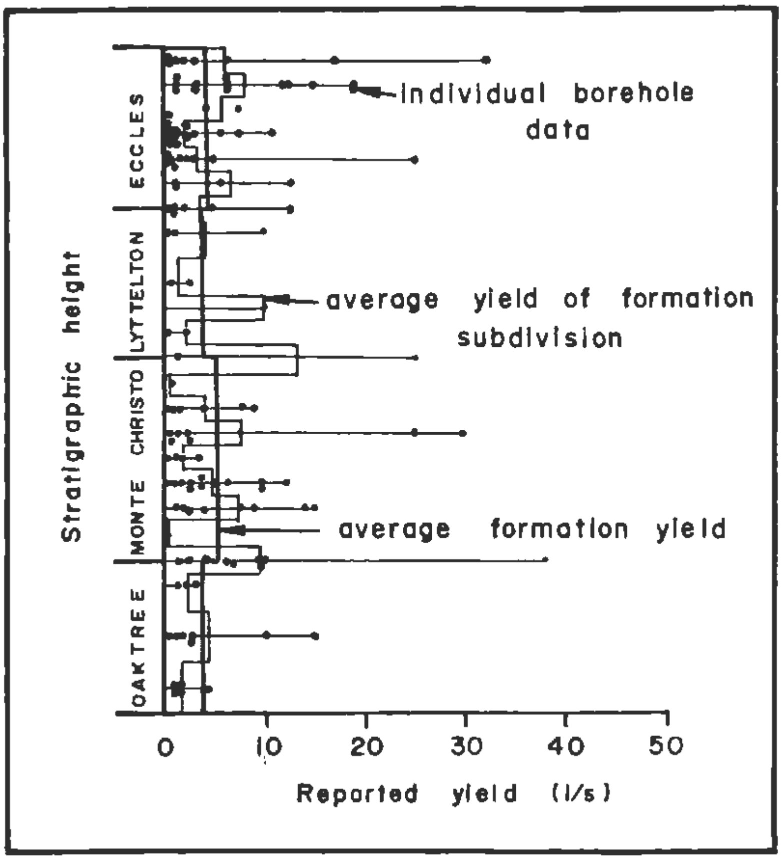


FIGURE 26: Distribution of reported borehole yields in relation to stratigraphic height in the Middle and Lower Klip River area

The overall differences in average formation yields in this area are smaller than for the Upper Klip River. Nevertheless the Oaktree Formation again is seen to have the lowest average formation yield (3,8 ℓ/s), the same as the Lyttelton Formation. Average formation yields for the Monte Christo and Eccles Formations are 5,4 ℓ/s and 4,36 ℓ/s respectively.

Figure 26 is a summary of the transmissivities obtained from all the exploration boreholes. Frequency values for each formation were weighted so that each formation was equally represented (see Table 8).

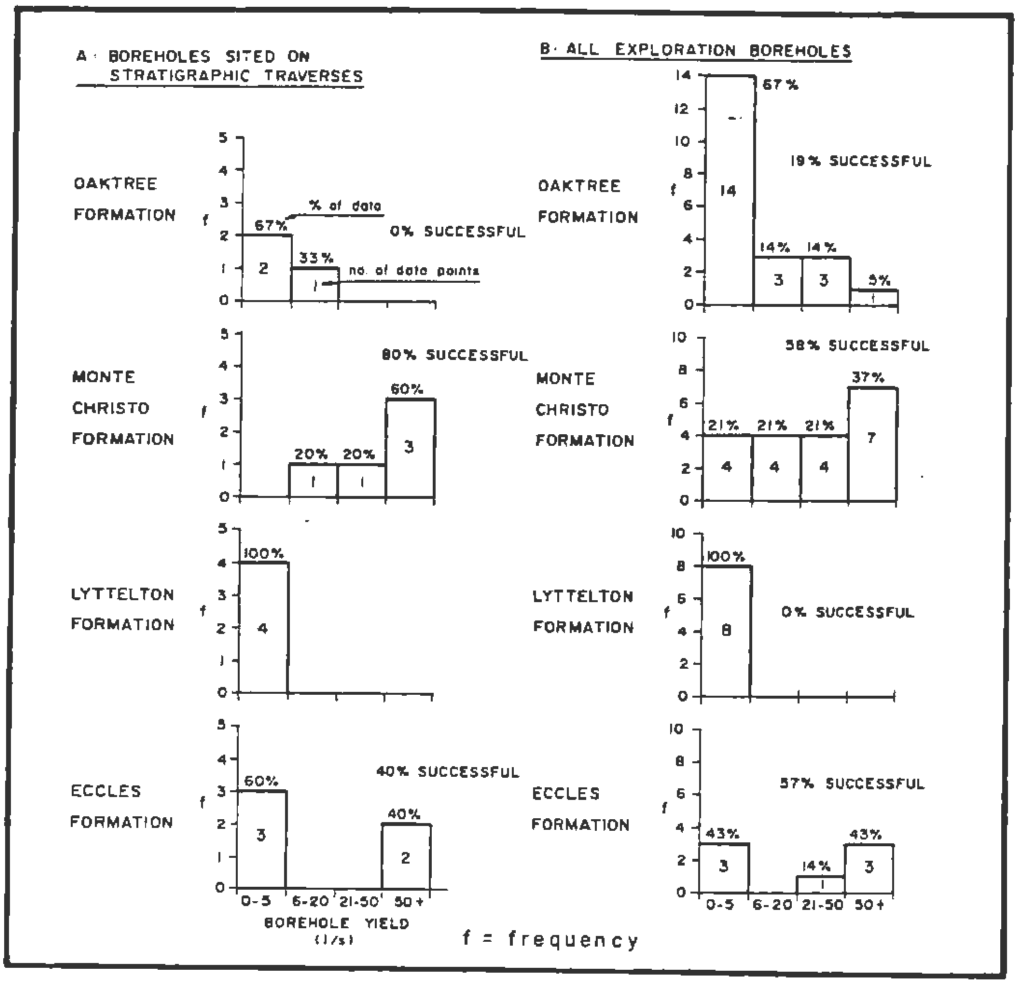


FIGURE 27: Exploration borehole transmissivities in relation to stratigraphy

TABLE 8: Borehole transmissivities according to stratigraphy

Formation a = actual w = weighted	Transmissivity (m^2/day)							
	0-20		20-100		100-500		500+	
	a	w	a	w	a	w	a	w
Eccles	9	9	3	3	9	9	9	9
Lyttelton	9	13,5	3	4,5	5	7,5	3	4,5
Monte Christo	8	12	5	7,5	3	4,5	4	6
Oaktree	14	26	1	2	0	0	1	2

It can be seen that the 0-20 m^2/day group was the modal class for all four formations although the Eccles Formation recorded the same frequency for the two highest groups.

Out of the 16 boreholes where the Oaktree Formation was penetrated below water level only two had transmissivities greater than 20 m^2/day. The graph shows that this formation represents only a small proportion of the boreholes with higher transmissivities.

Borehole transmissivities for the Monte Christo and Eccles Formations are both more evenly distributed than the Oaktree Formation. The Monte Christo Formation is more strongly represented in the highest transmissivity class.

The Eccles Formation is the most strongly represented formation in the two highest transmissivity classes. 18 out of the total of 30 boreholes drilled in this formation have transmissivities in excess of 100 m^2/day.

When studying the results of the exploration drilling it should be noted that the boreholes were not drilled on randomly selected sites. Although an analysis of a large number of randomly drilled holes would be statistically unbiased the economics of drilling large diameter boreholes do not permit this. Of the forty four boreholes drilled by Kafri et al, (1986) fifteen of them were sited with the sole criterion of penetrating a specific formation of the Chuniespoort Group below water level. The results of this drilling not intentionally on any known structural feature are presented in Figure 26. Data are limited but show higher transmissivities for the Monte Christo and Eccles Formations than the Oaktree and Lyttelton Formations and are in general agreement with other results.

The borehole logs of the exploration boreholes reveal a fundamental difference in the nature of the aquifers in the chert rich formations compared with the chert poor formations. In the Eccles and Monte Christo Formations water bearing zones reached thicknesses of up to 60 m. The best aquifer material is described as very fractured and weathered chert, or similar, and often with little evidence of any dolomite material (see Figure 28.) Where zones of extremely weathered formation were not encountered some boreholes such as G36552 (see Figure 29) reported gradual increases of yield on continued penetration of chert banded dolomite.

In the Oaktree and Lyttelton Formations all water strikes occurred on discrete zones of weathering. Although never reported thicker than 3 m continuation of the borehole past the initial water strike was often not possible. Above and below the zone of water strike was normally fresh dolomite. A band of shale and chert often coincide with the water strike zone. (See Figure 30).

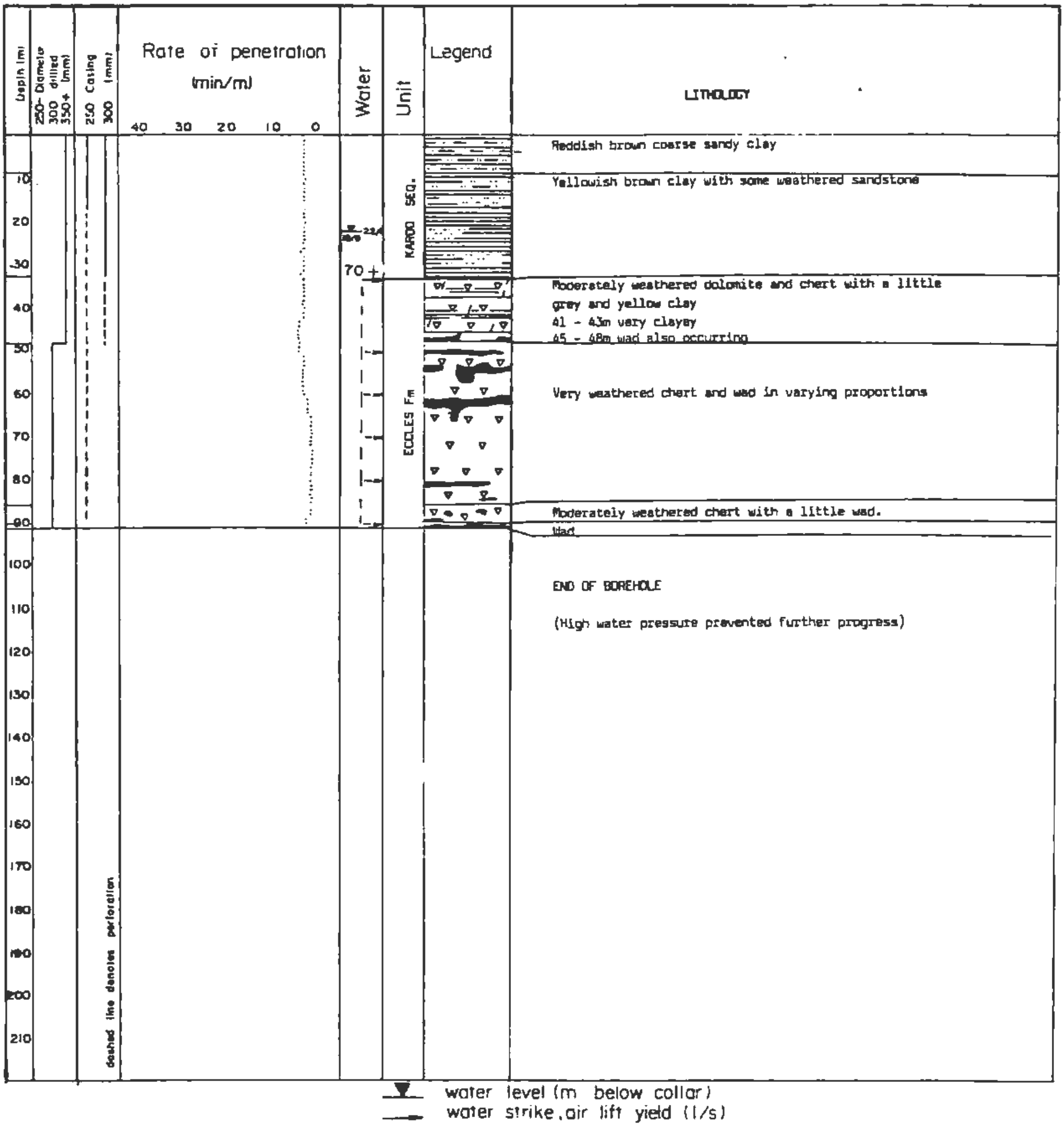


FIGURE 28: Geological log of borehole G36549 penetrating chert rich aquifer (after Kafri et al, 1986)

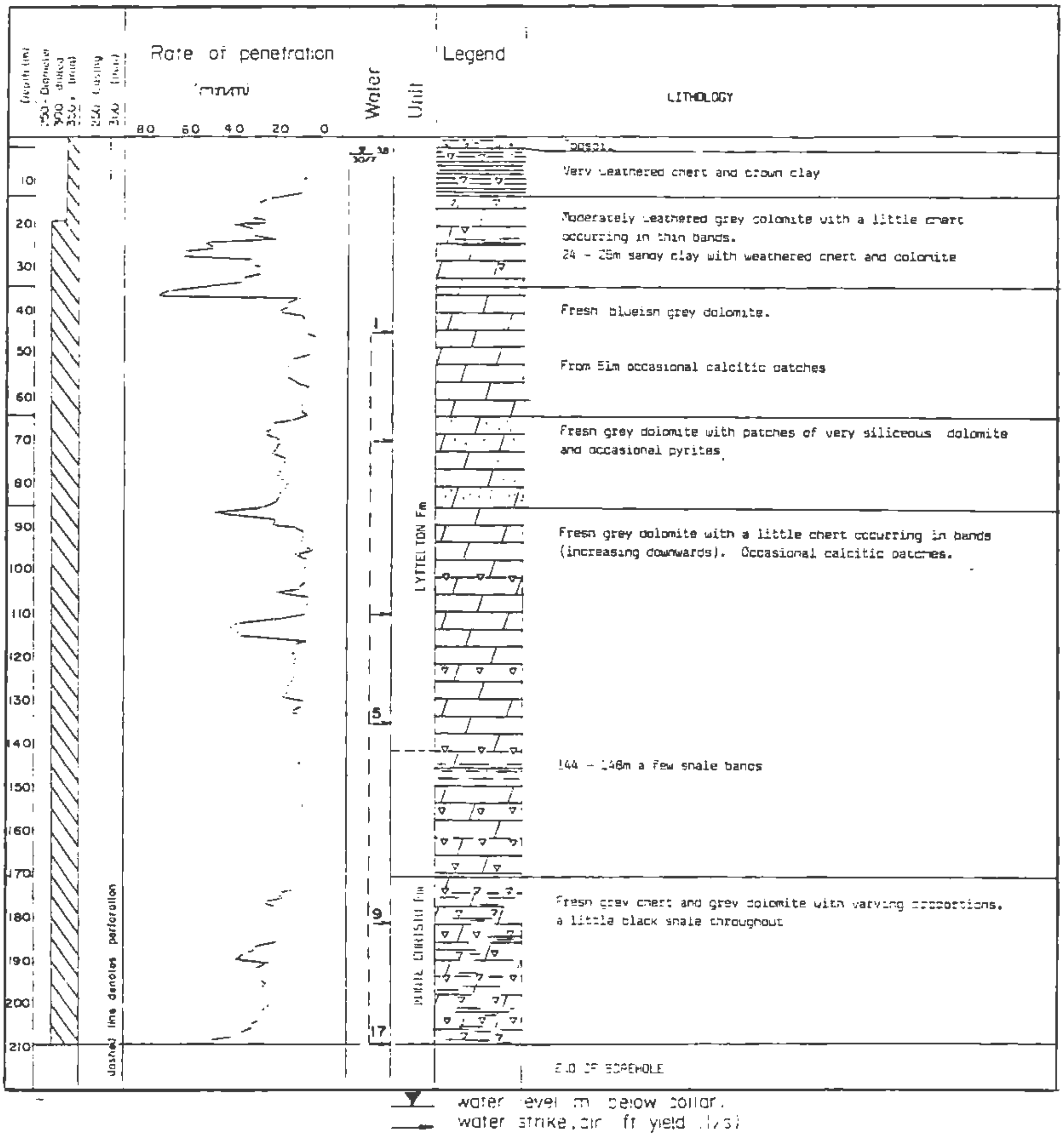
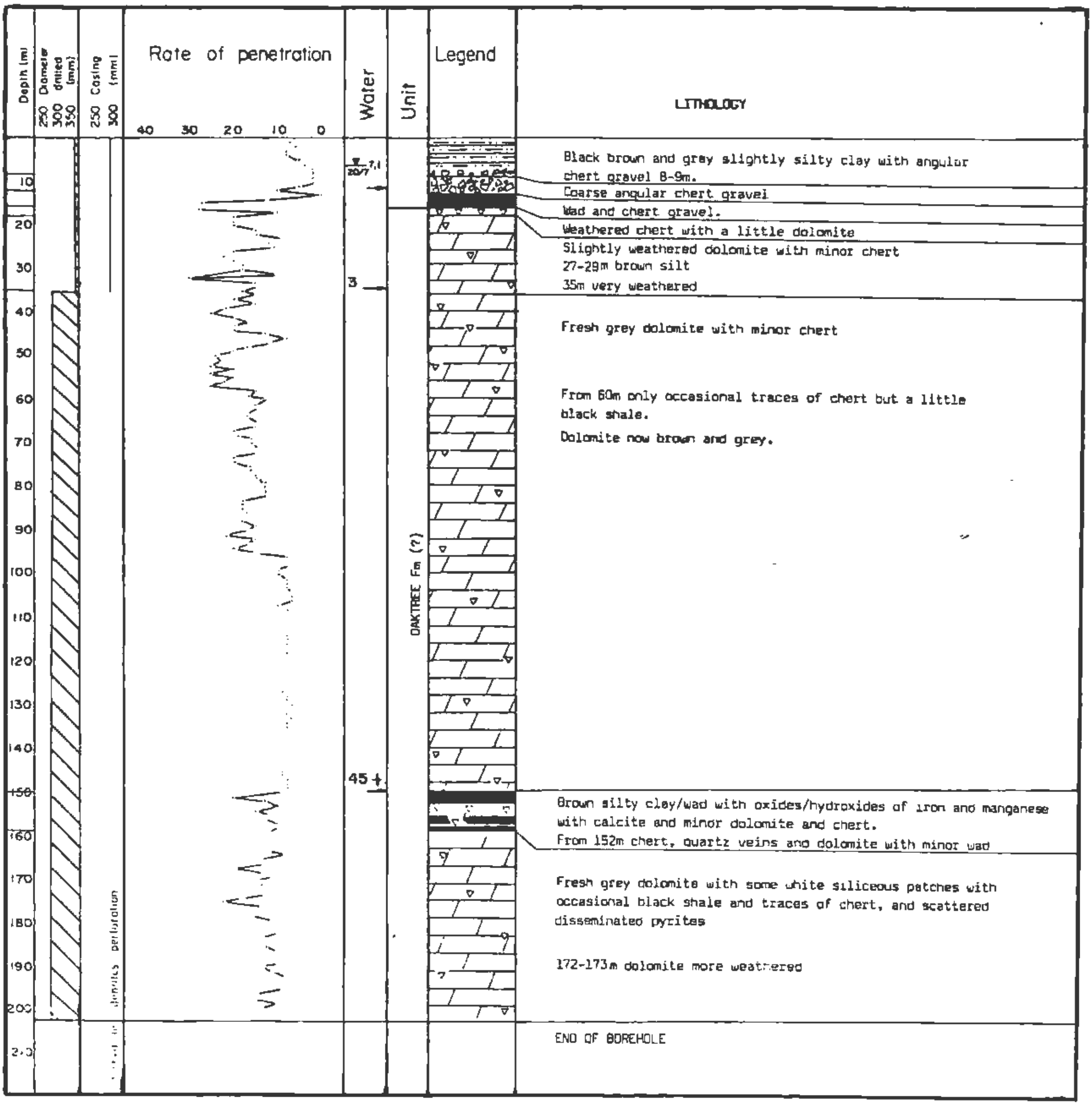


FIGURE 29: Borehole log of G36586 showing gradual increase in air-lift yield with depth (after Kafri et al, 1986)



Black brown and grey slightly silty clay with angular chert gravel 8-9m.

Coarse angular chert gravel

Wad and chert gravel.

Weathered chert with a little dolomite

Slightly weathered dolomite with minor chert
27-29m brown silt
35m very weathered

Fresh grey dolomite with minor chert

From 60m only occasional traces of chert but a little black shale.

Dolomite now brown and grey.

Brown silty clay/wad with oxides/hydroxides of iron and manganese with calcite and minor dolomite and chert.
From 152m chert, quartz veins and dolomite with minor wad

Fresh grey dolomite with some white siliceous patches with occasional black shale and traces of chert, and scattered disseminated pyrites

172-173m dolomite more weathered

END OF BOREHOLE

FIGURE 30: Typical geological log of water yielding borehole (G36565) in chert poor dolomite (after Kafri et al, 1986)

5.4 Palaeokarstic control of aquifer properties

The geohydrological census records the occurrence of strong yielding boreholes at the base of Karoo Sequence outliers in the Natalspruit Basin (refer back to section and Figure 23).

Figures 24 and 25 both show the occurrence of high yielding boreholes at the contacts between the Rooihoogte and Eccles Formation and the Lyttelton and Monte Christo Formations. Both of these stratigraphic horizons are recognised as unconformities in the stratigraphic records (Tankard et al, 1984). The borehole logs of the exploration boreholes (Kafri et al, 1986 and Reynders, 1988) were studied and the nature of the aquifer at the postulated palaeokarstic horizons was noted together with water strike information. For the pre-Karoo Sequence surface six out of twenty five boreholes had transmissivities in excess of 100 m^2/day three of which were in excess of 500 m^2/day. Table 9 shows that greater transmissivities occur where the pre-Karoo Sequence surface penetrated either of the two chert rich formations.

TABLE 9: Borehole transmissivities on the pre-Karoo Sequence palaeokarst

Formation	T (m^2/day)			
	0-20	20-100	100-500	500+
Eccles	8	1	2	3
Lyttelton	4	0	0	0
Monte Christo	1	1	1	0
Oaktree	4	1	0	0

Every borehole description by Kafri et al, (1986) and Reynders (1988) showed signs of weathering at the Eccles Formation pre-Karoo Sequence erosion surface, a feature not characteristic of the other dolomitic formations. (See Table 10)

TABLE 10: Aquifer properties on the pre-Karoo Sequence palaeokarst

Borehole No.	Transmissivity (m^2/day)	Yield ℓ/s	Formation	Remarks
G36548	1 395	100	E	
G36549	9 755	100	E	
G36551	0	2	L	A
G36553	328	100	E	
G36554	207	85	M	
G36557	0	9	O	A
G36559	0	20	M	A
G36560	0	0	L	B
G36561	29,7	17	E	
G36562	1 930	43	E	
G36564	0	0	O	B
G36571	0	4	O	A
G36572	0	7	O	
G36573	49	50	M/O	
G36594	0	0	L	C
G37716	0	12,5	E	A
G37717	0	0	E	C
G37863	491	60	E	
G37864	0	0	E	C
G37866	0	0	E	C
G37871	0	0	L	C
G37875	0	0	E	C
G37877	0	0	E	C
G37882	0	0	E	C
G37878	0	0	E	C

A = Larger water strikes occur deeper
B = Intrusion at palaeokarst horizon
C = No water strike but signs of weathering
E = Eccles
L = Lyttelton
M = Monte Christo
O = Oaktree

The results in Table 11 show the results of the drilling into the palaeokarstic horizons at the contacts between:

(i) Rooihoogte and Eccles Formations;

Four out of seven boreholes have transmissivities greater than 100 m^2/day at this horizon with two boreholes in excess of 500 m^2/day.

(ii) Lyttelton and Monte Christo Formations;

One out of five boreholes have transmissivities greater than 100 m^2/day. The transmissivities in borehole G37718 was calculated from pump tests to be 11575 m^2/day. This was the only borehole with a final cased diameter of 380 mm.

TABLE 11: Occurrence of yields on palaeokarsts

Rooihoogte-Eccles palaeokarst			Lyttelton-Monte Christo palaeokarst		
Borehole No	Transmissivity (m^2/day)	Yield (ℓ/s)	Borehole No	Transmissivity (m^2/day)	Yield (ℓ/s)
G36547	4,6	6	G36551	73	53
G36555	0	0	G36586	4,5	19
G36585	1 626	75	G37715	71	12
G36595	36	8	G37718	11 575	100
G37337	214	55	G37721	0	0
G37862	550	50			
G37863	491	60			

NOTE: Yield of G37718 limited to 100 ℓ/s by pump capacity

5.5 Hydrogeological role of linear features

5.5.1 Geohydrological census

Figures 30-34 show graphs plotted in order to study the relation between reported borehole yields and their distance from various hydrogeological features. It was originally hoped that statistical methods could be applied to quantify the significance level of each hydrogeological feature. The graphs however reveal the limitations of the data available:

(i) Large spread of data resulting from a combination of factors such as inaccurate reporting and great variety in types of borehole construction.

(ii) Data is often sparse for the crucial interval nearest the feature (i.e. 0-0,2 km);

(iii) The distribution of the points is uneven, distance intervals with a high number of points would be expected to have proportionally more high yielding boreholes;

(iv) Where yields appear to decrease away from a feature "anomalous" high yields commonly occur at larger distance intervals. Where hydrogeological features are not widely spaced one feature's effect can be expected to impinge on the data of the adjacent feature.

Given the high degree of scatter and overall poor level of reliability of the individual data points and their scarcity in many of the cases, the application of statistical methods was not thought likely to be successful. It was therefore decided to judge the effect of the hydrogeological features by qualitative means as well.

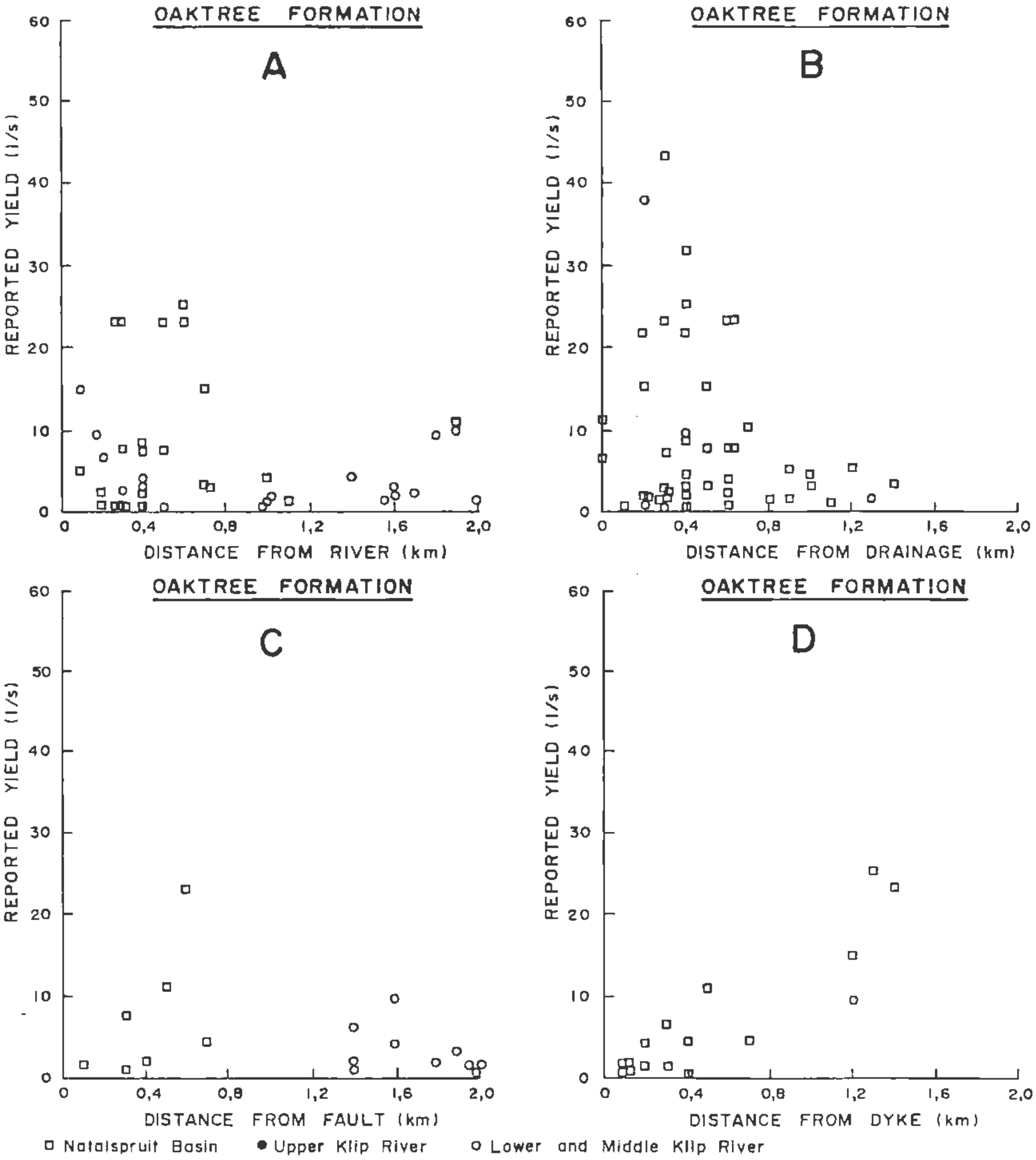


FIGURE 31: Reported borehole yields in relation to distance from various hydrogeological features for the Oaktree Formation.

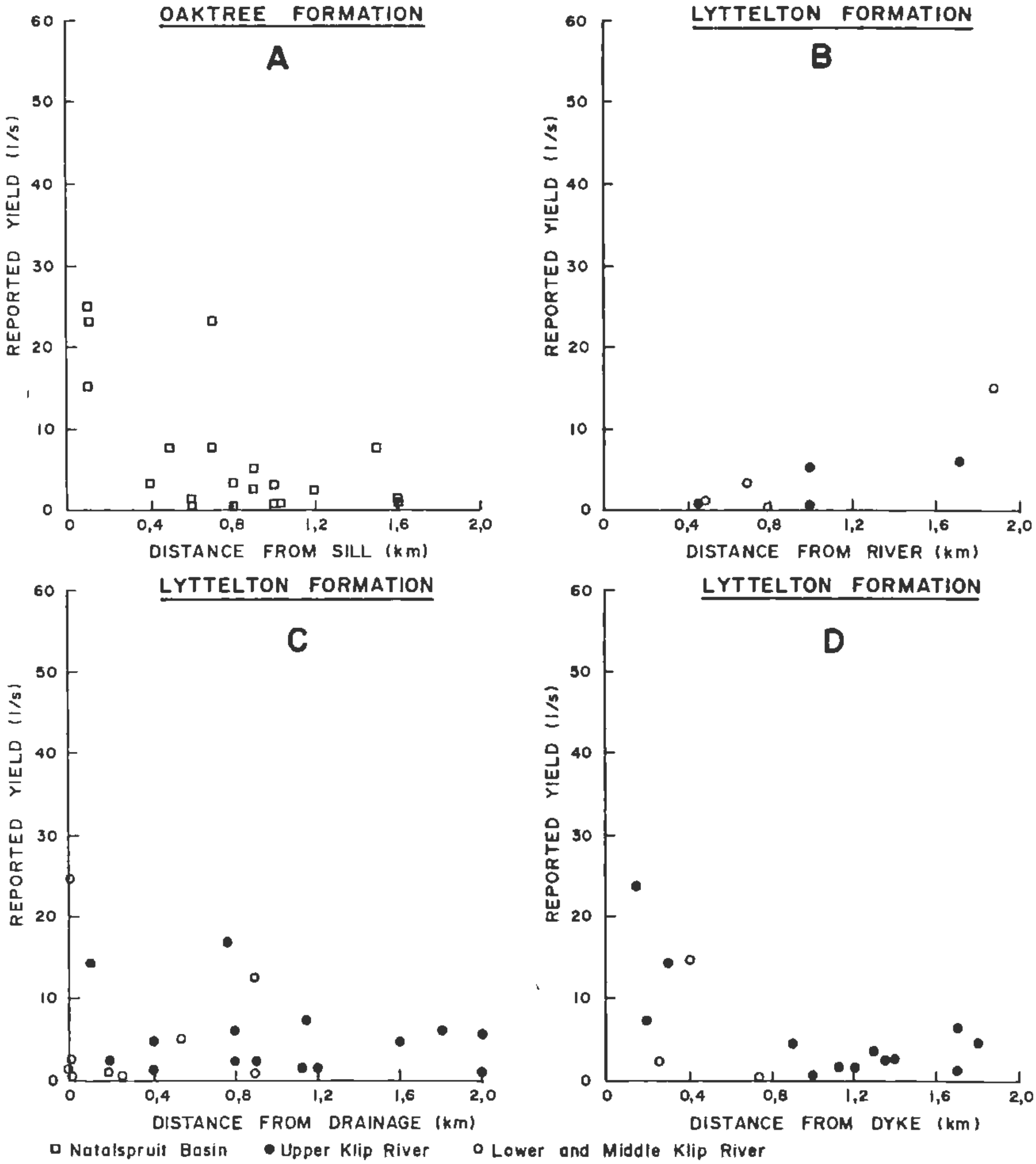


FIGURE 32: Reported borehole yields in relation to distance from various hydrogeological features for the Oaktree and Lyttelton Formations

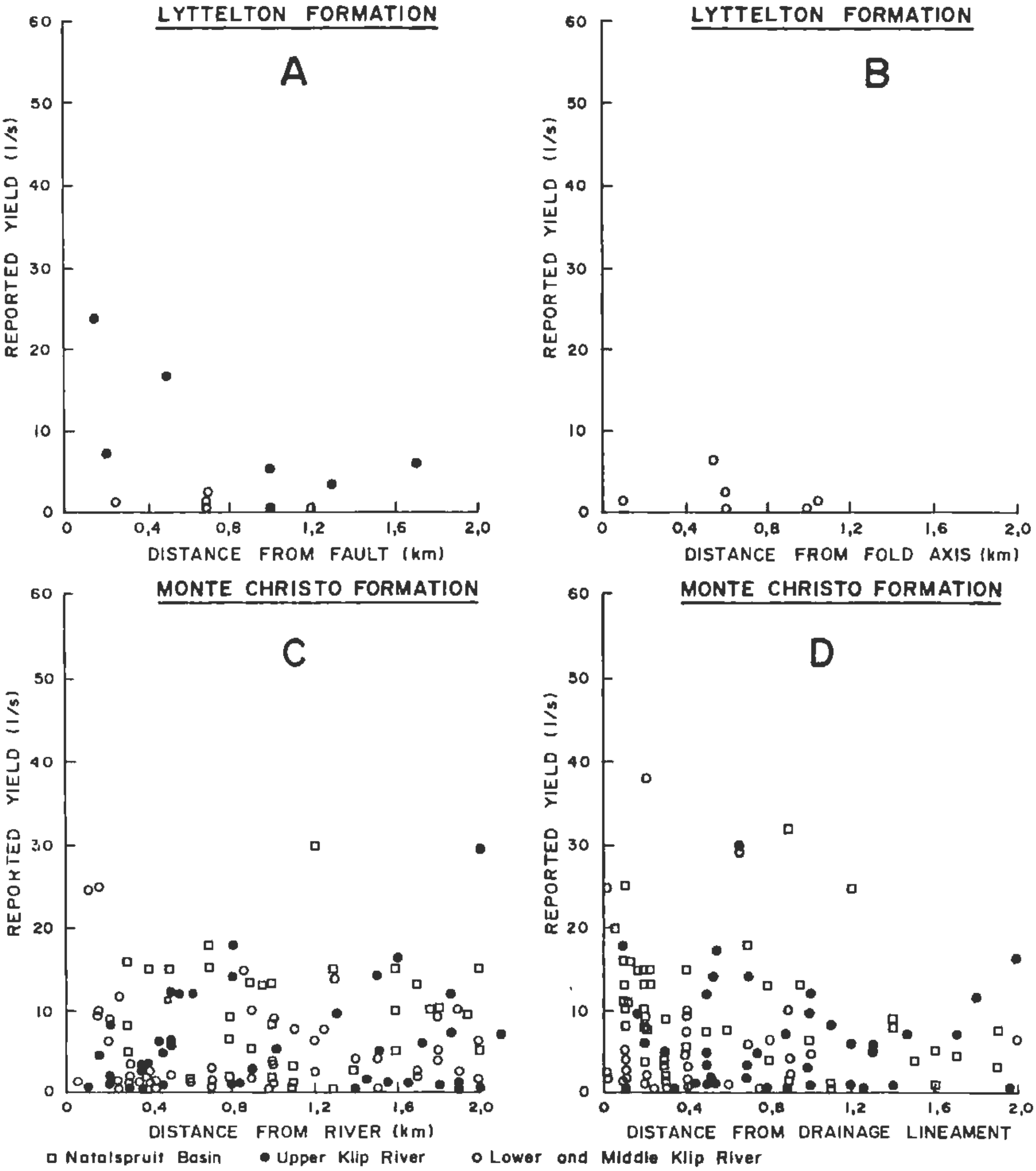


FIGURE 33: Reported borehole yields in relation to distance from various hydrogeological features for the Lyttelton and Monte Christo Formations

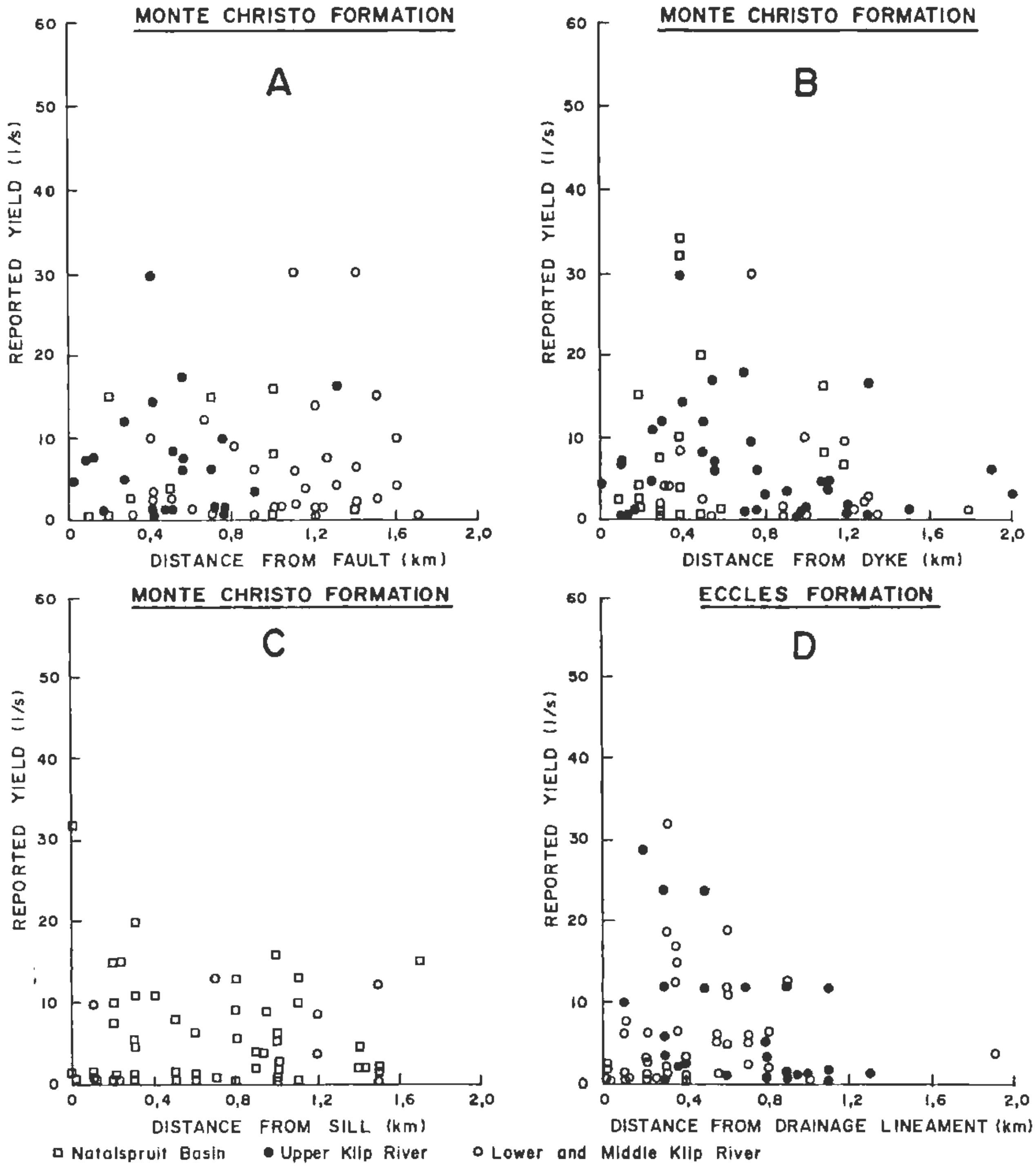


FIGURE 34: Reported borehole yields in relation to distance from various hydrogeological features for the Monte Christo and Eccles Formations

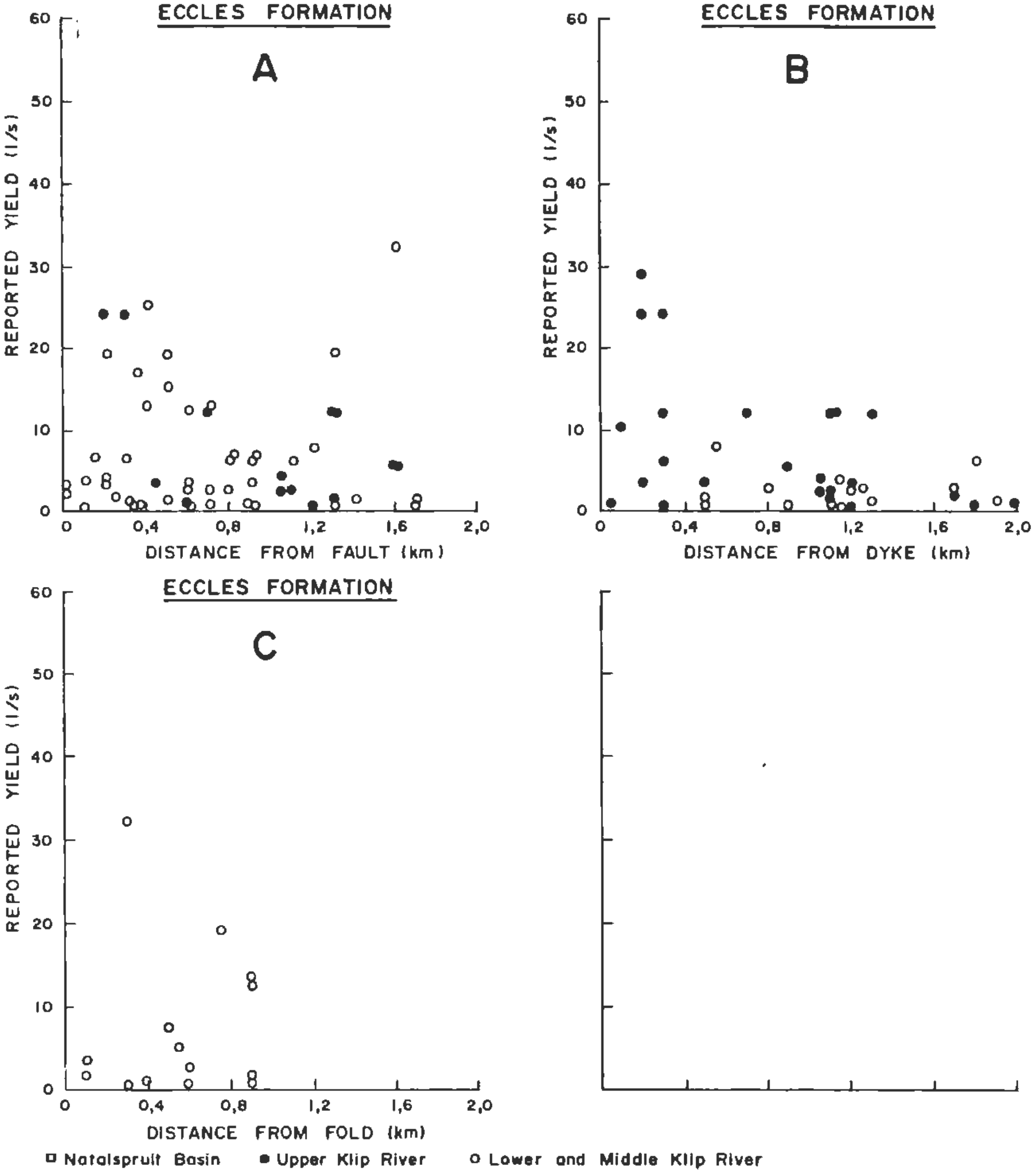


FIGURE 35: Reported borehole yields in relation to distance from various hydrogeological features for the Eccles Formation

Qualitative analysis

Each graph was studied and judged to either -

(i) support the hypothesis that the hydrogeological feature is associated with higher transmissivities and thus higher yielding boreholes;

(ii) oppose the hypothesis as stated above;

(iii) be inconclusive;

even where there were only a few data points, if the existing points supported the hypothesis then the hypothesis was accepted (see Figure 34A). A hypothesis was only rejected where well distributed points showed no support of the hypothesis suggesting that borehole yields were randomly distributed (see Figure 30D). Results were judged inconclusive if the data was sparse and unsupportive or if an addition of data points in a weakly populated interval near to the features could be expected to support the hypothesis (see Figure 30A). The results of the hypothesis testing is shown in Table 12.

TABLE 12: Summary of hypothesis tests for the effect of hydrogeological features on borehole yields

Feature	Formation											
	Oaktree			Monte Christo			Lyttelton			Eccles		
Perennial stream	1			-1			-1			–		
	0	–	1	-1	-1	0	–	0	0	–	–	–
Surface drainage lineament	1			1			1			1		
	1	–	1	0	0	1	–	0	1	–	1	0
Fault	0			-1			1			1		
	0	–	0	0	0	0	–	1	0	–	1	0
Dyke	-1			0			1			1		
	-1	–	0	0	0	0	–	1	0	–	1	0
Sill margin	1			1			–			–		
	1	–	–	1	–	0	–	–	–	–	–	–
Fold axis	A			–			0			0		
	B	C	D	–	–	–	–	–	0	–	–	0

1 = hypothesis accepted

0 = hypothesis neither accepted nor rejected

-1 = hypothesis rejected

– = insufficient data

A: Result for all data

B: Natalspruit Basin

C: Upper Klip River

D: Middle and Lower Klip River

Statistical analysis

The data were first analysed by step wise multiple regression. Correlation coefficients were found to be so low that no variable could be successfully taken into any regression equation. Data for the yield/distance-from-feature relationships were then tested using the runs test for randomness. Most data sets revealed a near random distribution. The results only supported with qualitative assessments in Table 12 for the following variables:

(i) Lyttelton Formation faults
(ii) Monte Christo Formation lineaments
(iii) Monte Christo Formation faults
(iv) Monte Christo Formation sills.

It is judged that the large spread of data resulting from non-geohydrological factors detailed on page renders the use of statistical analysis inappropriate in this instance.

5.5.2 Exploration boreholes

Faults

Of the eleven boreholes sited specifically on fault zones, nine (82%) had transmissivities in excess of 100 m^2/day and four (36%) in excess of 500 m^2/day. Table 13 shows that the boreholes were all drilled into either the Eccles or the Lyttelton Formations. The lack of data across the four formations is the result of only being able to trace faults in the well exposed Pretoria Group and Eccles Formation and interpreting their extension a short distance into the areas of poor outcrop.

TABLE 13: Aquifer properties along faults

Borehole No.	Transmissivity m^2/day	Yield ℓ/s	Formation
G36562	1 930	43	Eccles
G36563	26,8	13	Eccles
G36595	36	8	Rooihoogte/Eccles
G37337	214	55	Eccles
G37716	185	50	Eccles/Lyttelton
G37717	400	65	Eccles
G37862	550	50	Eccles
G37864	103	25	Eccles
G37866	185	65	Eccles
G37867	2 996	25	Eccles
G37873	673	60	Lyttelton

Lineaments

Thirty five boreholes were sited on surface drainage features, straight stream segments and linear structural features as delineated from gravity surveys, or the distribution of karstic features. Fifty-four per cent of these holes had transmissivities in excess of 100 m^2/day and 21% had transmissivities in excess of 500 m^2/day. The data from boreholes drilled along lineaments is presented in Table 15 and summarized in the data matrix of Table 14.

TABLE 14: Borehole transmissivities along lineaments

Formation	Transmissivity (m^2/day)			
	0 - 20	20 - 100	100 - 500	500+
Eccles	2	3	7	4
Lyttelton	3	0	5	2
Monte Christo	2	1	1	1
Oaktree	7	0	0	1

The high transmissivities found along lineaments in the Eccles and Lyttelton Formations contrast with the results for the Monte Christo and Oaktree Formations.

TABLE 15: Aquifer properties along lineaments

Borehole No.	Transmissivity m^2/day	Yield ℓ/s	Formation
G36549	9 755	100	E
G36550	0	0	O
G36561	29,7	17	E
G36562	1 930	43	E
G36563	26,8	13	E
G36564	0	0	E
G36567	0	3	O
G36568	0	5	O
G36569	128	100	M
G36570	17,9	19	M
G36574	2 651	100	M/O
G36575	0	1	O
G36578	3,7	6	M
G36581	81	30	M
G36582	0	0	O
G36584	0	0	O
G36585	1 626	75	E
G36592	0	0	O
G36595	36	8	R/E
G37336	0	0	L
G37337	214	55	E
G37713	310	45	L/M
G37714	688	50	L
G37716	185	50	E/L
G37717	400	65	E
G37718	11 575	100	L
G37720	359	70	L
G37863	491	60	E
G37864	103	25	E
G37868	227	45	E
G37869	0	0	E/L
G37870	1 912	80	E
G37871	0	0	L
G37872	245	50	L
G37874	224	20	L

O = Oaktree
M = Monte Christo
L = Lyttelton
E = Eccles
R = Rooihoogte

Fold Axes (Refer Figure 11 and Map 3)

The positions of the fold axes shown in Map 3 have been inferred taking due account of geological field relationships on both the regional and local scale.

The major Potchefstroom synclinal axis does not appear to have a great effect on the distribution of high yielding boreholes. It may be noted however that boreholes are more density distributed towards the centre of the Natalspruit Basin. Fold axis 5 does not cross the Chuniespoort Group but forms the anticlinal saddle that separates the Natalspruit Basin and the Klip River Valley.

Fold axis 1 - anticline; a dense cluster of boreholes occurs at the northern end of the axis which is associated with narrow linear gravity lows and Karoo Sequence outliers (see Map 2). High yielding boreholes extend southeastwards along the fold axis for several kilometres away from the river flood plain. Seven sinkholes or dolines are located within one kilometre of the axis along its length, four of them fall directly on the axis. At the southern end of the axis three strong boreholes occur on the fold axis along narrow valleys.

Fold axis 2 - syncline; boreholes are concentrated towards the centre of the basin. Three sinkholes occur within 1 km of the axis.

Fold axis 3 - anticline; the fold axis crosses a part of the basin occupied largely by open farmland and consequently few boreholes. The axis runs parallel with the aeromagnetic anomaly and coincident with the syenite dyke in the vicinity of Vosloorus township and northwards. Three sinkholes were observed close to the axis and two strong boreholes occur near to where the anticline crosses the major synclinal axis.

Fold axes 4 - syncline; the distribution of boreholes is concentrated at the southern end of the axis in the vicinity of Tamboekiesfontein farm. Strong boreholes are scattered throughout this area but not noticeably along the fold axis. Several faults have been interpreted crossing this area.

Fold axes 6 and 7 - syncline, anticline; the distance separating these two axes is in the order of two kilometres as a result of the tight folding. Although boreholes are not density clustered, eight strong boreholes occur within one kilometre either side of both axes.

Fold axes 8 - syncline; boreholes are fairly evenly distributed between fold axes 7 and 9. The synclinal axis 8 is not associated with any noticeable increase in borehole yields. This may reflect the weak development of this axis compared with the tight folding on either side.

Fold axis 9 - anticline; a few strong boreholes occur close to the fold axis. The geohydrological census reveals that most of the boreholes at the northwestern end of the axis do not penetrate to the depth of the dolomite rest water level (± 70 m from surface).

Fold axis 10 - syncline; no borehole information was obtainable for this area.

Fold axis 11 - anticline; several strong boreholes occur along the axis mostly in the vicinity of the river but also one in the Eccles Formation.

Sixteen of the exploration boreholes drilled for the Department of Water Affairs are located on fold axes (see Table 17) although none as a result of that specific siting criterion. The data matrices in Table 16A and B shows that from the limited transmissivity data 25% of the boreholes have T values greater than 100 m^2/day and 8% greater than 500 m^2/day. Using the yield figures; 6 boreholes (38%) yielded 20 ℓ/s or greater and 25% greater than or equal to 50 ℓ/s. The four strongest boreholes of the sixteen all occurred on anticlinal axes.

TABLE 16A: Exploration borehole transmissivities on fold axes

Formation	Transmissivity (m^2/day)			
	0 - 20	20 - 100	100 - 500	500+
Eccles	1	0	0	2
Lyttelton	2	0	0	1
Monte Christo	3	0	1	0
Oaktree	4	0	1	0

TABLE 16B: Exploration borehole yields on fold axes

Formation	Yield (ℓ/s)			
	0 - 10	10 - 20	20 - 50	50+
Eccles	2	0	1	2
Lyttelton	2	0	0	1
Monte Christo	4	1	0	1
Oaktree	4	0	1	1

TABLE 17: Aquifer properties on fold axes

Fold axis	Borehole no.	T(m^2/day)	Yield (ℓ/s)	Formation
1A	G36565	-	21	Oaktree
1A	G36567	0	0	Oaktree
2S	G36577	0	0	Monte Christo/Oaktree
2S	G36578	3,7	6	Monte Christo
3A	G36570	17,9	19	Monte Christo
3A	G36580	0	0	Monte Christo/Oaktree
3A	G36574	224	100	Monte Christo/Oaktree
4S	G36584	0	0	Monte Christo/Oaktree
6S	G37875	0	1	Eccles
6S	G37876	0	1	Lyttelton
9A	G37878	-	6	Eccles
9A	G37881	-	30	Eccles
9A	G37863	491	60	Eccles
9A	G37865	684	70	Eccles
11A	G37721	6,8	1	Lyttelton/Monte Christo
11A	G37718	11 575	100	Lyttelton

A = anticline   S = syncline

Perennial streams

Seven boreholes were drilled close to perennial streams, only the Oaktree, Monte Christo and Lyttelton Formations being penetrated below water level. The results are summarised in Table 18.

TABLE 18: Aquifer properties in exploration boreholes adjacent to perennial streams

Borehole No.	T (m^2/day)	Y (ℓ/s)	Formation
G36576	0	0	Sill/O
G36583	100	91	M
G36586	4,5	19	L/M
G36588	-	30	M
G36589	-	30	M
G36552	700	100	M
G36554	207	85	M

O = Oaktree
M = Monte Christo
L = Lyttelton

Borehole G36586 has a yield of 19 ℓ/s obtained from the Monte Christo Formation penetrated at 173 m. No water strike occurred in the Oaktree Formation. Boreholes G36588 and G36589 are 100 m apart and have similar geological conditions. Water strikes occurred in the weathered Monte Christo Formation between 10 m and 15 m. No further water strikes occured in the Oaktree Formation between 25 m and 116 m. Next to the Klip River in borehole G36552, water was struck just below the rest water level at 9 m in weathered chert and dolomite of the Monte Christo Formation and the yield gradually increased thereafter to a depth of 95 m. In borehole G36554 a yield 85 ℓ/s was struck in cavities in weathered chert of the Monte Christo Formation. This zone was overlain by 50 m of completely weathered chert and dolomite with a clayey sand matrix in turn overlain by clayey superficial deposits. In borehole G36583, next to the Natalspruit stream, a phreatic aquifer of very weathered Monte Christo Formation occurred from the surface to 50 m. Down to 40 m no dolomite was recorded in the log. The chert formation presumably supports a system of voids created by the dissolution of the dolomite.

Dykes

Nine of the exploration boreholes were sited within 100 m of dykes. Only G36570, G36580 and G37712 were sited with the specific purpose of striking karstic aquifer formation associated with tensional features at dyke margins. No yield was obtained in G36580. Monte Christo Formation was encountered to a depth of 158 m but the chert content was very small and thin layers of intrusive material occurred down to 50 m. On the edge of another branch of the same dyke G36570 revealed similar geology with the exception of a 2 m zone of abundant chert at 119 m. Water strikes occured above and below this zone. Table 19 shows that strong yielding holes all occurred where Eccles Formation was penetrated.

TABLE 19: Aquifer properties in exploration boreholes near dykes

Borehole No	T (m^2/day)	Y (ℓ/s)	Formation
G36546	0	0	Eccles (chert poor zone)
G36548	1 395	100	Eccles
G36558	0	0	Lyttelton/Monte Christo
G36560	0	0	Sill/Monte Christo
G36562	1 930	43	Eccles
G36570	17,9	19	Monte Christo/Oaktree
G37336	0	0	Lyttelton
G37712	1 393	25	Eccles

SILLS

Seven exploration boreholes penetrated sills. In only one borehole G36579 was water struck (2 ℓ/s) on the lower sill margin. Further water strikes were encountered in this borehole 90 m below the sill. Six exploration boreholes were drilled close to the outcropping margin of sills. The yields were as follows:

TABLE 20: Exploration borehole yields at sill margins

Borehole No.	Yields ℓ/s
G36565	20
G36567	2
G36571	0
G36575	0
G36578	6
G36592	0

TABLE 21: Summary of all results

<table>
<tr><th rowspan="3">Siting criterion</th><th colspan="4">Census results (ℓ/s)</th><th colspan="4">Exploration borehole results</th></tr>
<tr><th colspan="4"></th><th colspan="2">T (m^2/day)</th><th colspan="2">Yield (ℓ/s)</th></tr>
<tr><th>N</th><th>U</th><th colspan="2">M+L</th><th>% >100</th><th>% >500</th><th>% >20</th><th>% >50</th></tr>
<tr><td>Eccles)</td><td>-</td><td>7,2</td><td colspan="2">4,4</td><td>60</td><td>30</td><td></td><td></td></tr>
<tr><td>Lyttelton)</td><td>-</td><td>8,5</td><td colspan="2">3,8</td><td>40</td><td>15</td><td></td><td></td></tr>
<tr><td>Monte Christo)</td><td>-</td><td>6,5</td><td colspan="2">5,3</td><td>35</td><td>20</td><td></td><td></td></tr>
<tr><td>Oaktree)</td><td>-</td><td>4,5</td><td colspan="2">3,8</td><td>6</td><td>6</td><td></td><td></td></tr>
<tr><td>Pre-Karoo Sequence palaeokarst</td><td>Y</td><td>Y</td><td colspan="2">Y</td><td>19</td><td>12</td><td>31</td><td>19</td></tr>
<tr><td>Lyttelton-Monte Christo contact</td><td>-</td><td>Y</td><td colspan="2">Y</td><td>20</td><td>0</td><td>40</td><td>40(1)</td></tr>
<tr><td>Rooihoogte-Eccles contact</td><td>-</td><td>Y</td><td colspan="2">Y</td><td>57</td><td>29</td><td>57</td><td>57(1)</td></tr>
<tr><td></td><td>O</td><td>M</td><td>L</td><td>E</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Faults</td><td>?</td><td>N</td><td>Y</td><td>Y</td><td>82</td><td>36</td><td>82</td><td>55(2)</td></tr>
<tr><td>Lineaments/valleys</td><td>Y</td><td>Y</td><td>Y</td><td>Y</td><td>54</td><td>21</td><td>51</td><td>37</td></tr>
<tr><td>Fold axes</td><td>-</td><td>-</td><td>?</td><td>?</td><td>25</td><td>8</td><td>38</td><td>25</td></tr>
<tr><td>Perennial streams</td><td>Y</td><td>N</td><td>N</td><td>-</td><td>43</td><td>29</td><td>71</td><td>43(1)</td></tr>
<tr><td>Dykes</td><td>N</td><td>?</td><td>Y</td><td>Y</td><td>33</td><td>33</td><td>44</td><td>33(1)</td></tr>
<tr><td>Sills</td><td>Y</td><td>Y</td><td>-</td><td>-</td><td>0</td><td>0</td><td>17</td><td>0(3)</td></tr>
</table>

NOTES

Y - results show beneficial effect of the feature

N - results show no effect of the feature

? - results are inconclusive

(1) Limited data

(2) Eccles and Lyttelton Formations only

(3) Only one borehole of 20 ℓ/s

5.6 Hypothesis testing and discussion

1. The different mass sedimentological, petrological and mechanical rock characteristics of the four Chuniespoort Group Formations are reflected in differing development and degree of karstic erosion (Figure 5A).

   The results of both the geohydrological census and the exploration drilling show that in general, higher transmissivities occur in the chert rich Eccles and Monte Christo Formations than in the chert poor Oaktree and Lyttelton Formations. More importantly the exploration drilling revealed the fundamental differences between the nature of the water-bearing zones in the two types of dolomitic formation.

   The Oaktree and Lyttelton Formations exhibit typical aquifer characteristics of fairly pure carbonates. Well developed but normally quite widely spaced solution channels with high permeabilities separate large volumes of relatively impermeable fresh rock material.

   Extensive weathering of the Eccles and Monte Christo Formations has developed extensive permeable zones of porous coarse granular chert residue to the extent that its properties are similar to those of primary aquifers.

   The hypothesis is accepted.

2. The pre-Karoo Sequence unconformity is an erosional surface where the dolomitic formations were exposed in pre-Karoo Sequence times to meteoric waters, dissolution and karstification (Figure 5B).

   The results of the geohydrological census from the Natalspruit Basin strongly support the hypothesis. The overall success rate in the exploration boreholes for the occurrence of transmissive zones on this palaeokarst was low. However, high transmissivities were common where the palaeokarst surface lies directly on chert rich units.

   The discussion on base levels (page 72) raised the alternative that transmissive zones at this horizon may in part result from recent karst activity at the base of confining strata and not solely a reactivated karst surface.

   The hypothesis is partially accepted.

3. In addition to the near surface karstification of recent and pre-Karoo Sequence times there are deeper levels of palaeokarst associated with ancient palaeo-base levels and erosional cycles (Figures 5A).

   Information from the census in the Klip River Valley clearly showed higher reported borehole yields at the contacts between the Lyttelton and Monte Christo Formations as well as the Rooihoogte and Eccles Formations. The exploration drilling confirmed the results of the census for the Rooihoogte-Eccles palaeokarst. Although average transmissivities achieved on the Lyttelton-Monte Christo contact were poor, average borehole yields were good.

The hypothesis is accepted.

4. Structural features such as faults, lineaments, folds and intrusive dykes are associated with greater openness weathering and density of rock discontinuities and are thus more susceptible to karst processes (Figures 5A and D).

   (i) Faults - the geohydrological census showed higher borehole yields near faults in the Eccles and Lyttelton Formations. Faults showed no effect on the distribution of borehole yields in the Monte Christo Formation whilst results for the Oaktree Formation are inconclusive.

   Exploration boreholes drilled on faults had the best success rate of all the geological siting criteria. The results are only applicable to the Lyttelton and Eccles Formations. Faults could not be accurately delineated below the superficial deposits in the other two formations.

   The hypothesis is accepted for the Eccles and Lyttelton Formations only.

   (ii) Lineaments - Private borehole yields in all four dolomitic formations indicated a beneficial effect near to lineaments, surface drainage courses and dry valleys. This effect was apparent throughout the whole study area.

A good overall success rate for high transmissivities was achieved in the exploration boreholes, noticeably in the Eccles and Lyttelton Formations.

The hypothesis is accepted.

(iii) Folds - Due to the imprecise delineation of many of the fold axes, especially in the Natalspruit Basin, many of the census boreholes were not analysed in relation to the folding criterion. Those that were gave inconclusive results.

Limited exploration borehole data also made it difficult to assess the effect of fold axes on transmissivities. The percentage success rates on fold axes were not high.

The qualitative study of the effect of folding showed that borehole yields and the density of karst features increase towards fold axial regions. Anticlinal axes showed more favourable properties than synclinal axes.

The hypothesis is neither accepted nor rejected.

(iv) Dykes - Geohydrological census results showed that higher yields occurred near dykes in the Eccles and Lyttelton Formations. No association was noted for the Oaktree Formations and results for the Monte Christo Formation were inconclusive.

The overall success rate of the exploration drilling was moderate, but very high transmissivities were achieved in three of the four boreholes that penetrated the Eccles Formation. No highly transmissive zones occurred in any other formation.

The hypothesis is accepted for the Eccles Formation only. For the other formations the hypothesis is neither accepted nor rejected.

5. The concentration of surface flow along perennial streams results in greater infiltration and thus more extensive karstification (Figure 5E).

   Reported borehole yields from the census, showed increases in yields towards perennial streams only for the Oaktree Formation. The transmissivities of exploration boreholes sited close to these features were not significantly high. High yields were common largely as a result of shallow water levels. The exploration results are derived from only seven boreholes, five of which penetrate only the Monte Christo Formation.

   The hypothesis is neither accepted nor rejected due to insufficient data.

6. Increased run-off from impermeable dolerite sills enhances dissolution near sill margins (Figure 5C).

A qualitative analysis of borehole yields near sill margins supports the hypothesis for the Oaktree and Lyttelton Formations in the Natalspruit Basin. The success rate of the exploration boreholes were the lowest of all the siting criteria. The apparent effect of sill margins seen in the Natalspruit Basin could be attributed to other coincident hydrogeological features.

The hypothesis is rejected.

6. CONCLUSIONS AND RECOMMENDATIONS

The analyses in the results chapter permit the following conclusions to be drawn.

- Lithostratigraphy is the major geological control on the aquifer properties of the dolomitic formations in the study area. Varying depositional and diagenetic environments in the Pre-Cambrian have resulted in dolomitic formations with fundamentally different weathering characteristics. Unimpeded downward percolation of aggressive groundwaters in vertical joints, faults and fissures has caused the chert poor Oaktree and Lyttelton Formations to develop typical karstic solutional porosity along well spaced solution channels. Ubiquitous chert beds and laminations in the Eccles and Monte Christo Formations encourage horizontal development of carbonate dissolution. The transmissive zones in the chert rich units thereby comprise a much thicker and more extensive chert supported porous permeable zone.

- Transmissive zones occur on the Rooihoogte-Eccles and Lyttelton-Monte Christo Formations palaeokarstic horizons but not throughout the whole area. Just as transmissive zones in the modern karst are aerially restricted so palaeokarsts may be more transmissive along ancient structural features. These features may be ghosted by present day structures or have no modern surface expression.

- Over much of the study area the modern karst weathering processes act upon the shallow pre-Karoo Sequence surface which acts as a confining layer and/or a palaeokarstic horizon. In this environment aquifer transmissivities are significantly higher where the Karoo Sequence overlies chert rich formation.

- The effect of all the remaining hydrogeological features investigated by this study are of secondary importance. None of them control aquifer properties sufficiently to mask the influence of stratigraphy. The overriding importance of the lithostratigraphy was evident across the whole study area.

- Faults and lineaments are associated with zones of higher transmissivities in the Eccles and Lyttelton Formations. Highly transmissive zones also occur within 100 m of dykes in the Eccles Formation. Their effect in the other formations is not firmly established. Of all the structural features faults and lineaments are most widely associated with more transmissive zones.

- A general improvement in aquifer properties occurs towards the axial regions of anticlines. Sill margins and perennial streams exert little or no control on aquifer properties although high borehole yields can be expected due to shallow water levels.

The result of the summation of these geological controls is a more detailed conceptual model of transmissive zones in the aquifer. An improved model benefits the more precise delineation of drilling target areas and thus allows more intensive, detailed study of favourable areas rather than wasting costly exploration effort on areas with low potential. This should lead to improved drilling success rates thus lowering costs.

Although the study was restricted to the Klip River Valley and Natalspruit Basin much of the research is applicable to other aquifers of the Chuniespoort Group. Throughout the PWV region and most of the Transvaal the Chuniespoort Group aquifers would be similarly classified by White (1969), La Moreaux et al, (1984) and Le Grand and Stringfield (1971), (see pages 62 and 64). Geological controls on the development of the aquifers are therefore likely to have been the same. The hydrogeological similarities between the different areas may well be more significant than the differences.

Optimal conditions for karstic weathering are expected in an area where Eccles or Monte Christo Formation, crossed by tensional structural features especially faults and lineaments, is penetrated on the pre-Karoo Sequence palaeokarst below the water table in the axial zone of an anticline. It is therefore recommended that exploration of the dolomitic formations occurring in the fold nose concealed beneath Karoo Sequence deposits at Daleside is carried out (Map 1). If transmissive chert rich aquifer material can be identified it may extend to considerable depth as a result of the steep interpreted dips.

Detailed field geological mapping combined with thorough geological photo-interpretation can delineate the formations of the Chuniespoort Group as well as linear hydrogeological features likely to enhance aquifer transmissivities. These techniques should therefore be part of any geohydrological investigation of the dolomites of the Chuniespoort Group.

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APPENDIX

Summary of pumping test and siting criteria information for exploration boreholes (Kafri et al, 1986 and Reynders, 1988).

Borehole no.	T m^2/day	Yield ℓ/s	Water Strike formation	Borehole siting criteria
G36546	0	0	Eccles	Sinkholes at base of Eccles
G36547	4,6	6,1	Eccles	Stratigraphic traverse
G36548	1395	100+	Eccles	Pre-Karoo Sequence palaeokarst
G36549	9755	100+	Eccles	Stratigraphic traverse
G36550	0	0	Oaktree	Linear drainage feature
G36551	73	55	Lyttelton/ Monte Christo	Statigraphic traverse
G36552	700	100+	Monte Christo	" "
G36553	328	100+	Eccles	" "
G36554	207	85+	Monte Christo	" "
G36555	0	0	Eccles	" "
G36556	0	0	Oaktree	" "
G36557	29	17	Oaktree	" "
G36558	0	0	Monte Christo	" "
G36559	93	57	Monte Christo	" "
G36560	0	0	Monte Christo	" "
G36561	29,7	17	Eccles	Lineament (gravity)
G36562	1930	43	Eccles	" "
G36563	26,8	13	Eccles	Faulting
G36564	0	1	Eccles	Stratigraphic traverse
G36565	–	30	Oaktree	Drainage course/sill margin
G36566	0	0	Sill/Oaktree	Lower sill contact
G36567	0	3	Oaktree	Drainage course/sill margin
G36568	0	5	Oaktree	" " " "
G36569	128	100	Monte Christo	Lineament (sinkholes)
G36570	17,9	19	Monte Christo	Dyke parallel lineament
G36571	0	4	Oaktree	Lineament (gravity, sinkholes)
G36572	0	7	Oaktree	Pre-Karoo Sequence palaeokarst
G36573	49	50	Oaktree	Pre-Karoo Sequence palaeokarst
G36574	2651	100	Monte Christo/ Oaktree	Dyke parallel lineament
G36575	0	1	Sill/Oaktree	Drainage course/sill margin
G36576	0	1	Oaktree	" " " "
G36577	0	1	Monte Christo/ Oaktree	Stratigraphic traverse
G36578	3,7	6	Monte Christo	Lineament (sinkholes)
G36579	17,9	25	Monte Christo	Drainage course/sill margin
G36580	0	0	Monte Christo/ Oaktree	Dyke/vegetation anomaly
G36581	81	30	Monte Christo	Lineament (sinkholes)
G36582	0	0	Oaktree	Dyke parallel lineament
G36583	1193	100	Monte Christo	Perennial stream
G36584	0	0	Oaktree	Faulting
G36585	1626	75	Eccles	Faulting
G36586	4,5	18,5	Lyttelton/ Monte Christo	Perennial stream

Borehole no.	T m^2/day	Yield ℓ/s	Water Strike formation	Borehole siting criteria
G36587	0	0	Oaktree	Stratigraphic traverse
G36588	–	30	Monte Christo	Perennial stream
G36589	–	30	Monte Christo	" "
G36590	0	1	Lyttelton	Stratigraphy
G36591	12	12	Black Reef	Sinkhole
G36592	0	0	Eccles	Stratigraphy
G36593	8,9	22	Eccles	Stratigraphy
G36594	0	0	Lyttelton	"
G36595	36	8	Rooihoogte/ Eccles	Faulting
G37336	0	0	Lyttelton	Faulting/drainage course
G37337	214	55	Eccles	" " "
G37338	0	0	Eccles/Lyttelton	Stratigraphy
G37712	1393	25	Eccles	Faulting
G37713	310	45	Lyttelton/ Monte Christo	Lineament (gravity)
G37714	688	50	Lyttelton	Lineament (gravity)
G37715	71	12	Lyttelton	Faulting
G37716	185	50	Eccles/Lyttelton	Faulting/drainage course
G37717	400	65	Eccles	" " "
G37718	11575	100	Lyttelton	Drainage course
G37719	59	25	Lyttelton	Faulting
G37720	359	70	Lyttelton	Drainage course
G37721	6,8	1	Lyttelton/ Monte Christo	Lineament (gravity)
G37862	550	50	Eccles	Faulting
G37863	491	60	Eccles	Faulting/drainage course/ fold axis
G37864	103	25	Eccles	Faulting/drainage course
G37865	684	70	Eccles	Faulting/drainage course/ fold axis
G37866	185	65	Eccles	Faulting/drainage course/ fold axis
G37867	2996	25	Eccles	Faulting
G37868	227	45	Eccles	Drainage course
G37869	0	0	Eccles/Lyttelton	Drainage course/faulting
G37870	1912	80	Eccles	Drainage course
G37871	0	0	Lyttelton	Drainage course/faulting
G37872	245	50	Lyttelton	Faulting
G37873	673	60	Lyttelton	Faulting
G37874	224	20	Lyttelton	Faulting/drainage course
G37875	301	40	Eccles	Faulting/fold axis
G37876	34	25	Lyttelton	" " "
G37877	19,2	15	Eccles	Faulting
G37878	–	6	Eccles	Drainage course/fold axis
G37881	–	30	Eccles	" " " "
G37882	971	60	Eccles	Faulting/drainage course
G37883	–	–	Lyttelton/ Monte Christo	Faulting