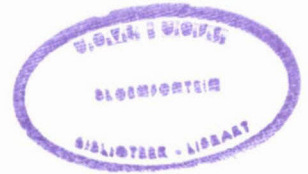


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SALINITY IN THE STRUISBAAI AQUIFER

by

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Thesis

Submitted in the fulfilment of the requirements for the degree of

Magister Scientiae

in the

**Faculty of Science
Department of Geohydrology
University of the Orange Free State
Bloemfontein**

Supervisor: Prof G van Tonder MSc., PhD.

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Siep Talma, my partner in the research project of which this is a part of.

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SUMMARY

SALINITY IN THE STRUISBAAI AQUIFER

The water-supply for Struisbaai has a historical reputation for its high salinity. Like most of the coastal holiday resorts along the Cape South Coast there are a number of permanent residents. For Struisbaai these comprise owners of small businesses servicing the holiday trade, fishermen and their families and retired folk. However, unlike other coastal resort-towns, Struisbaai is notable for the lack of houses with attractive gardens. This is a direct reflection of the relatively high salinity of the water-supply which in the past was not suitable for irrigation, having salinities of over 100 mS/m and sometimes over 500 mS/m. For example a sample of town water-supply was collected in June 1990 from a tap at Struisbaai Hotel and the EC was found to be 658 mS/m (4150 mg/L of dissolved salts). In 1990 a replacement wellfield was developed which has an EC of about 90 mS/m. With this relatively low salinity attractive gardens may become a feature of the future for Struisbaai.

Three previous groundwater investigations have taken place, and in all of these the high salinities have been ascribed to over-pumping with resulting seawater intrusion. However, none of these authors gave any conclusive evidence for their theories. All of these reports gave field observations and then formulated theories for the origin of the salinity but in none of these reports were the two linked by logical arguments. This thesis thus considered the various possible sources of salinity and made conclusions as to the most likely source.

The three sources of salinity that were considered are:

- ◆ Salinity derived from sea-spray causing high salinity recharge.
- ◆ Geological factors which yield high salinity groundwater.
- ◆ Hydrogeological factors which result in sea-water intrusion.

Field work consisted of drilling of four new boreholes, geophysical down-hole logging of six boreholes, establishing rainwater sampling points, collecting of groundwater samples and processing water samples for isotopic analysis.

The methodology used to analyse the data was to closely consider the water quality of rainwater and groundwater samples as well as the isotopic composition of the groundwater. By considering ratios of the chemical composition, ratios of isotopic composition and using graphical plots the conclusion made was that the source of salinity is due to sea-spray which causes rain recharging to the aquifer to have a high salinity. This rain was measured to have a salinity of 10.5 and 12.5 mS/m respectively for the two rain collector stations. When a recharge to the aquifer of about 10% is allowed the resultant salinity is similar to that measured for groundwater at that site.

Using the same methodology it was concluded, except for two individual boreholes, that geological and hydrogeological factors are not the source of salinity. For these two individual boreholes it was shown that over-pumping and seawater intrusion was the probable cause of salinity.

The decision to replace the old wellfield with the new wellfield has been a fortuitous decision. By doing so two positive effects have occurred. Firstly the wellfield is now in an area where the local recharge is less saline due to it being further away from the sea and thus receiving less sea-spray. Secondly the possibility of over-pumping and inducing seawater intrusion is minimal.

This thesis has contributed to South African hydrogeology in that as far as can be ascertained this is the first documentation of the contribution that sea-spray makes towards causing salinity in South African coastal aquifers.

OPSOMMING

SOUTGEHALTE VAN DIE STRUISBAAI AKWIFEER

Struisbaai se watervoorsiening is histories van n hoë soutgehalte. Soos die meeste vakansie oorde langs die Kaapse Suid Kus, is daar 'n aantal permanente inwoners. Struisbaai se permanente inwoners is eienaars van klein besighede, vissemanne en afgetredenes. In teenstelling met die ander vakansie dorpie langs die Suid Kus is daar nie erwe met mooi tuine nie. Die rede hiervoor is die relatiewe hoë soutgehalte van die dorpswater. In die verlede was die water se soutgehalte meer as 100 mS/m en in sommige gevalle was die soutgehalte selfs hoër as 500 mS/m. 'n Monster wat in Junie 1990 in die Struisbaai Hotel geneem is, het 'n elektriese geleiding van meer as 658 mS/m gehad (dit is gelykstaande aan 4150 mg/L se opgeloste soute). In 1990 is 'n nuwe grondwaterbron ontwikkel. Die water van hierdie bron het 'n elektriese geleiding van ongeveer 90 mS/m. Hierdie verbetering in die soutgehalte van die watervoorsiening mag dalk daartoe lei dat mooi tuine in Struisbaai nog 'n algemene verskynsel sal word.

In die verlede is drie onafhanklike geohidrologiese ondersoeke op Struisbaai uitgevoer. In al drie die ondersoeke is die hoë soutgehalte van die grondwater toegeskryf aan seewater indringing as gevolg van te hoë pomptempos. Nie een van hierdie skrywers het oortuigende bewyse gelewer van hierdie teorie nie. Al drie verslae het veldwaarnemings voorgelê, waarvandaan gevolgtrekkings gemaak is. Geeneen kon die twee logies verbind nie. Hierdie tesis kyk na al die moontlike bronne van versouting en verwys daarvolgens na die mees waarskynlikste bron.

Die drie moontlike oorsake van versouting wat in ag geneem is:

- Versouting as gevolg van seesproei wat daartoe lei dat afloopwater wat die grondwaterbron aanvul 'n hoë soutgehalte het.
- Geologiese faktore wat grondwater van 'n hoë soutgehalte lewer.
- Hidrogeologiese faktore wat gelei het tot seewater indringing.

Vir die ondersoek is vier addisionele boorgate geboor, geofisiese waarnemings is uitgevoer in ses boorgate, reënwater monsterneming punte is opgestel en grondwater monsters is ingesamel vir chemiese en radio-isotoop analiese.

Die metodiek vir hierdie ondersoek was om die watergehalte van die reën met die van die grondwater te vergelyk en te kyk na die isotoop samestelling van die grondwater. Deur die verhoudings van die chemiese samestelling asook die verhoudings van die isotoop samestellings grafies te vergelyk kon die gevolgtrekking gemaak word dat die seesproei die bron van versouting is deurdat die reënval afloopwater aanvullingswater met n hoë soutgehalte lewer. Die chemiese analiese van die reënwatermonsters het bewys dat die soutgehalte van die reën by die monsterpunte wissel van 10.5 mS/m tot 12.5 mS/m. As 'n 10% aanvullingsyfer in ag geneem word is die soutgehalte van die grondwater dus gelykstaande aan die gekonsentreerde soutgehalte van die reënwater.

Deur van dieselfde metodiek gebruik te maak, kon die gevolgtrekking gemaak word dat behalwe vir twee van die boorgate, die geologiese en geohidrologiese faktore nie die bron van versouting is nie. In die geval van die twee boorgate is seewater indringing as gevolg van 'n te hoë pomptrekkings tempo waarskynlik die bron van versouting.

Die besluit om die produksieveld met 'n nuwe een te vervang het gely tot twee goeie resultate. Eerstens is die watervoorsieningsbron verder van die see geleë in 'n area waar die soutgehalte van die afloopwater wat as aanvullingswater dien baie laer is. Tweedens is die waarskynlikheid van seewater indringing as gevolg van verhoogde pomptempo minimaal.

Hierdie tesis het 'n bydrae gelewer tot die Suid Afrikaanse hidrologie in die sin dat sover moontlik vasgestel kon word is dit die eerste skrywe wat die rol van seesproei verbind met 'n verhoogde soutgehalte in Suid Afrikaanse kusakwifere.

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CHAPTER 1

STRUISBAAI: INTRODUCTION, WATER-SUPPLY AND PROBLEMS OF HIGH SALINITY

1.1 PREAMBLE

Struisbaai is 170 kilometres east of Cape Town (Fig. 1.1). The name Struisbaai is derived from the Dutch name Vogelstruijsbaai recorded in 1672, meaning bay of ostriches. The bay provides the only protected harbour for 60 km to the west and 25 km to the east. In addition to the holiday resort population there is also a small commercial handline fishery.

The permanent population is 1700 of whom about half are fisher-folk. The summer population is estimated at about 9,000. This population variation is reflected in the water consumption as shown in Figure 1.2. This data was supplied by the municipality.

The water-supply for Struisbaai has a historical reputation for its high salinity. Like most of the coastal holiday resorts along the Cape South Coast there are a number of permanent residents. For Struisbaai these comprise owners of small businesses servicing the holiday trade, fishermen and their families and retired folk. However, unlike other coastal resort-towns, Struisbaai is notable for the lack of houses with attractive gardens. This is a direct reflection of the relatively high salinity of the water-supply which in the past was not suitable for irrigation, having salinities of over 100 mS/m and sometimes over 500 mS/m. For example a sample of town water-supply was collected by McLea (1990) from a tap at Struisbaai Hotel and the EC was found to be 658 mS/m (4150 mg/L of dissolved solids). In 1990 a replacement well field was developed which has EC of about 90 mS/m so attractive gardens may become a feature of the future for Struisbaai.

1.2 OBSERVATIONS BY PREVIOUS WORKERS REGARDING THE ORIGIN OF THE SALINITY OF STRUISBAAI GROUNDWATER

Figure 1.3 shows the study area and the positions of the various monitoring points.

Previous workers Meyer (1986a and 1986b), Levin (1988) and Toens (1991) have ascribed the salinity to various factors including seawater intrusion.

Meyer (1986a) was surprised by the high observed TDS values (870 - 1000 mg/L) for the boreholes drilled into the Table Mountain Group (TMG) quartzites. He would have been more familiar with values of 50 - 200 mg/L as is obtained from boreholes elsewhere (inland) in the TMG. He said (1986) that "one possible explanation is that water from the overlying Bredasdorp Formation in one or another manner mixes with water in the sandstones". This is a theme also followed by Toens (1991). Also mentioned by Meyer (1986a) was borehole 9A which was drilled into Bokkeveld shales and which had poor quality (high salinity) water.

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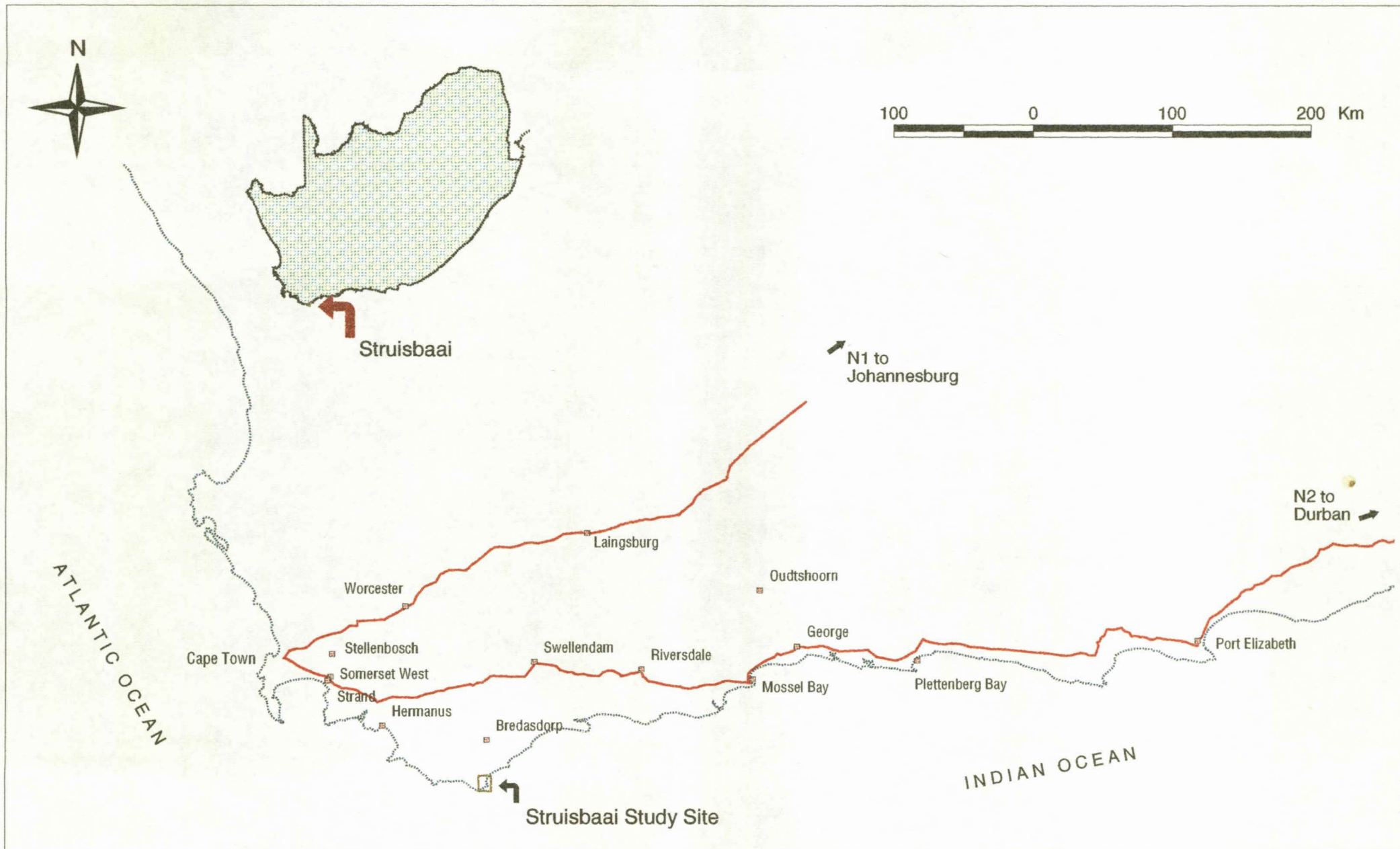


FIGURE 1-1: Struisbaai locality map

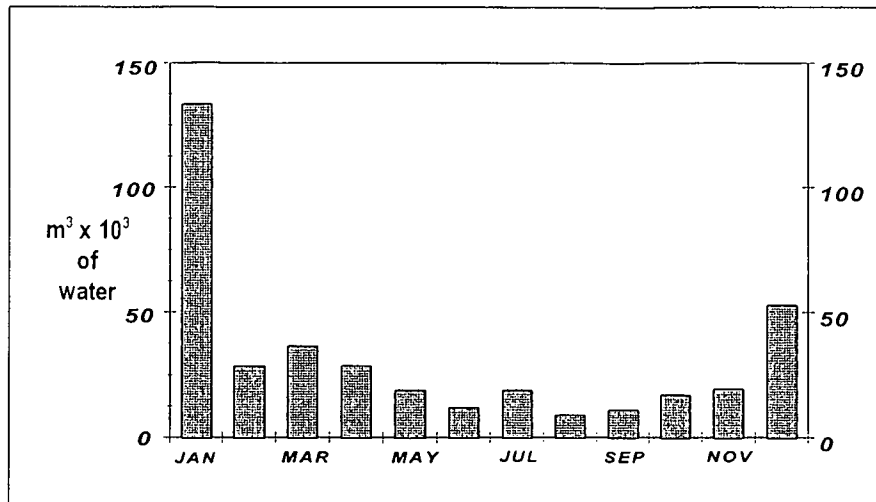


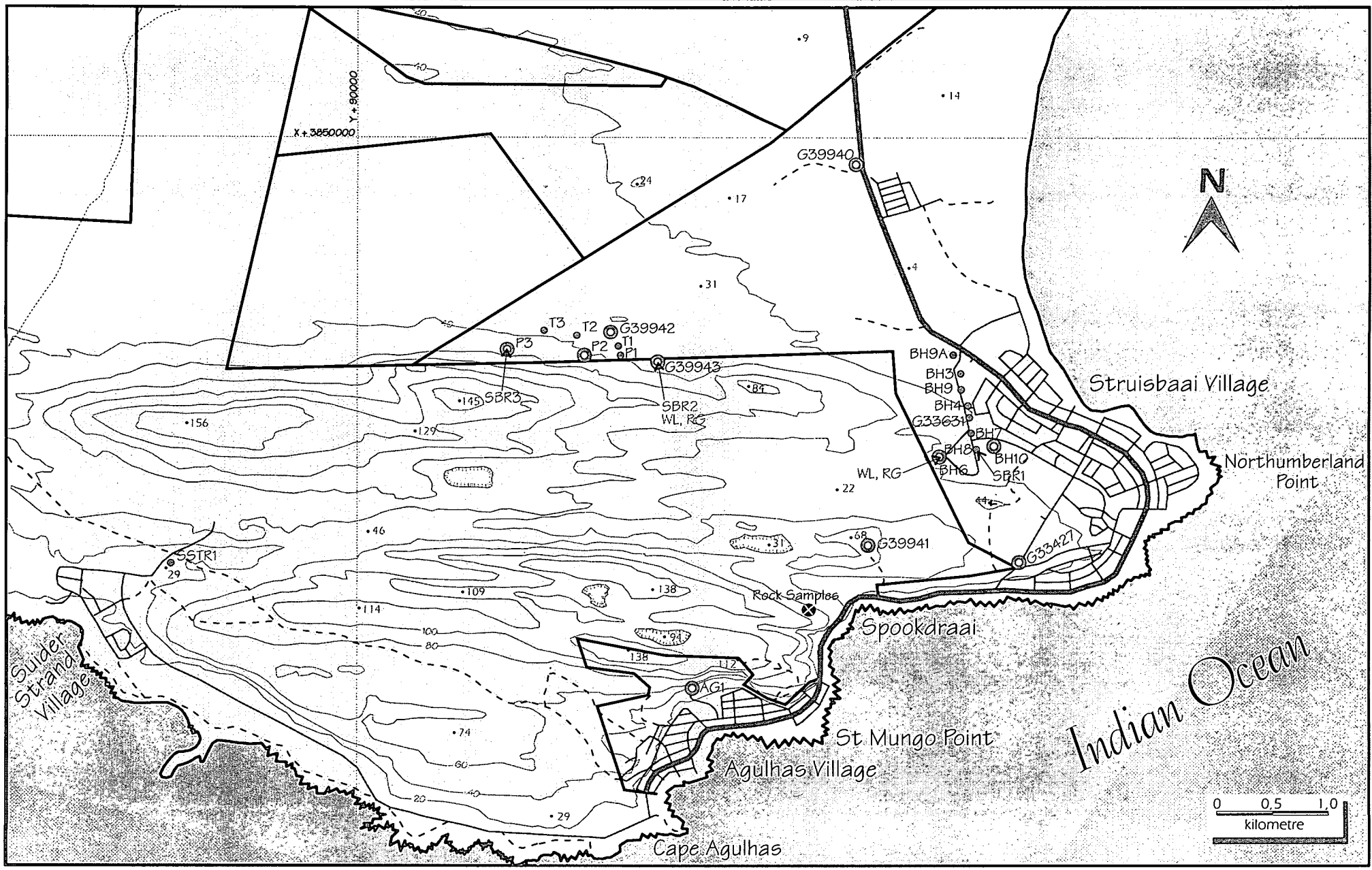
Figure 1.2 Struisbaai water consumption for 1996. The metering period is 15 to 15 of following month, thus the 133560 m³ consumption of January is for the peak holiday season of December/January (Data from Municipal Records)

Meyer (1992 pers comm) later developed the theme that the high salinity is due to sea water intrusion during periods of high pumpage. This is based on two sets of data. The first data-set used for developing the theme is the TDS measured in borehole G33427 during a test-pumping exercise (Figure 1.4). This borehole was sited by Meyer in 1986 on a NNE striking fracture which was mapped in the quartzites below the high water mark. The borehole is about 400 metres inland. Seven hours after pumping (rate not known) started the salinity increased rapidly and continued to increase at a lower rate. He regarded this as seawater intrusion. The second data-set used is the hydrograph (Figure 1.5) of G33631 which is located in the original well field. This shows a steep drop of water-levels by some 8 - 12 metres every summer season when the water demand is very high due to the holiday-maker influx. The graph indicates the water level drops up to 14 m below sea-level. Also shown on Figure 1.5 is the measured conductivities of 3 water-supply boreholes.

Levin (1988) concluded that the TMG holds the best potential as a groundwater source and that boreholes should be drilled to 150 metres. This would place the water-strikes below sea-level. He reports a deterioration of water quality with increasing depth which he ascribed to factors such as:

- ▣ salt concentration due to the flat groundwater gradient
- ▣ effect of Bokkeveld shales
- ▣ possible seawater intrusion

Toens (1991) carried out a regional assessment of groundwater potential. A total of 53 groundwater analyses were collated (23 collected and 30 from previous work). He notes that strata underlying the Bredasdorp are characterised by high salinities, which is particularly evident in the low lying areas near the coast. Analyses from boreholes and springs south of the Sandberg have EC's more than 130 mS/m which he ascribes to the water occurring at the base of the Bredasdorp.



GEOCHEMISTRY & ISOTOPES

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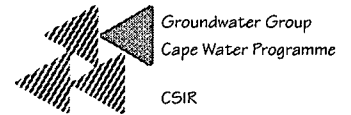
Figure 1-3

Struisbaai study site locality and positions of monitoring points

Legend

- Tracks
- Farm Boundaries
- Spot Elevation
- Contours (20m interval)
- Borehole
- Sampled Boreholes

- SBR1 = Rain sampler
- WL = Water level recorder
- RG = Automatic Rain gauge



TDS values: G33427

46 hr Constant discharge test

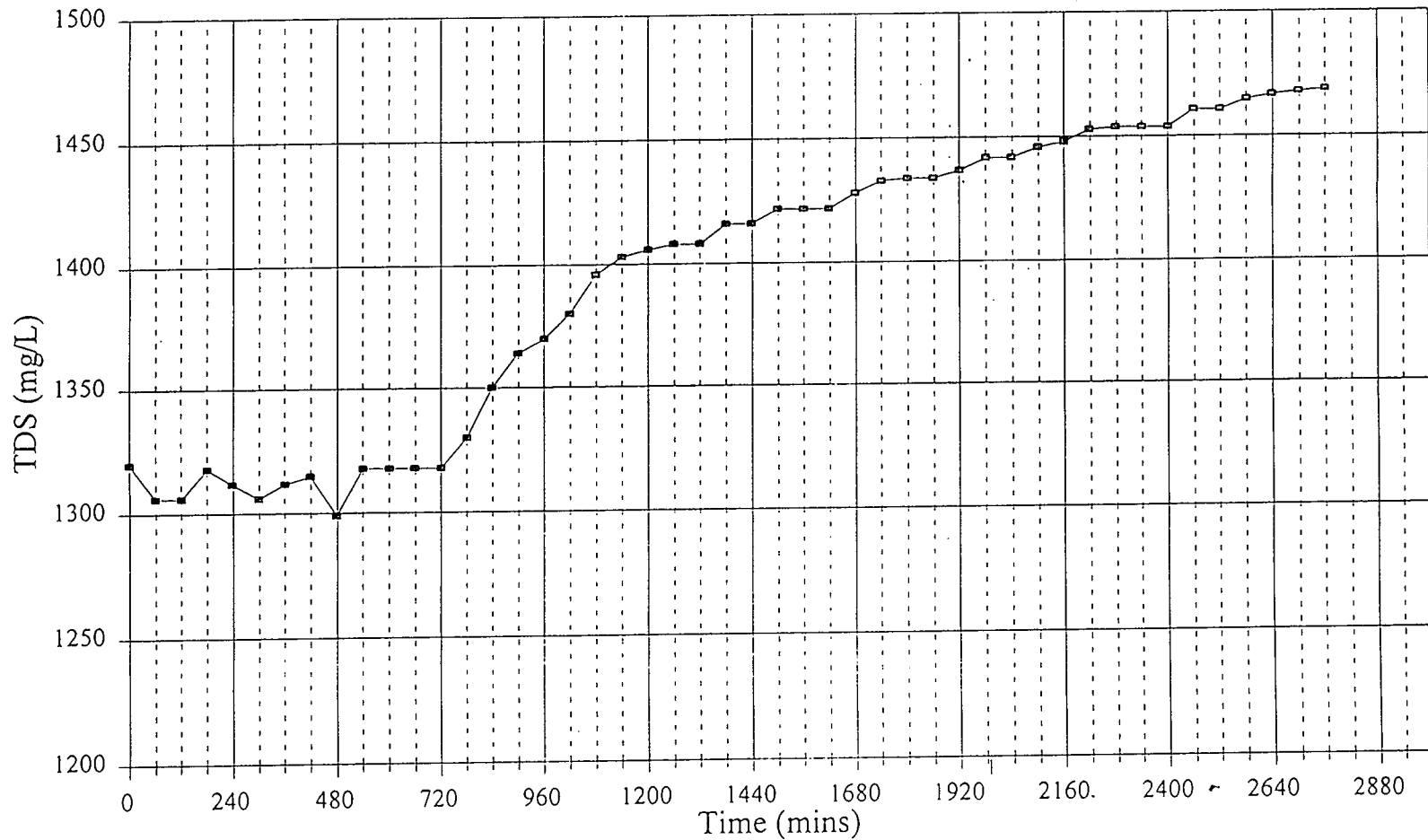


Figure 1-4 Struisbaai : Graph showing the increase of salinity observed in borehole G33427 during a 46-hour constant discharge test (from Meyer 1992)

STRUISBAAI

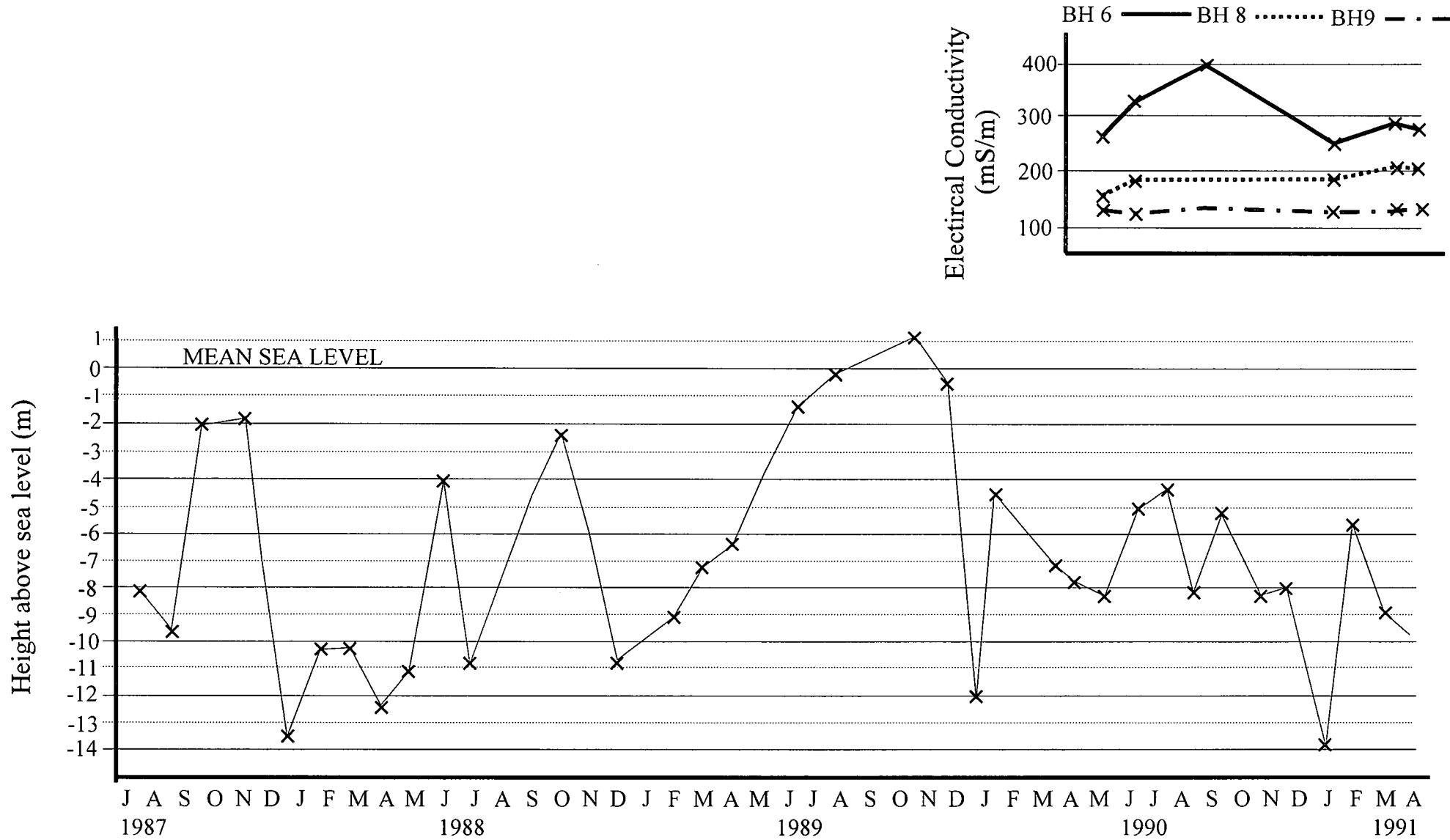


FIGURE 1-5 Struisbaai: Observed water-level fluctuations in monitoring borehole G33631 which is in the "old wellfield" (from Meyer, 1992). The water quality graph shows the EC for the corresponding dots.

For boreholes in the TMG where there is no Bredasdorp cover Toens (1990) found EC's of 80 mS/m and ascribes the increased EC of 100 mS/m for P₁, P₂ and P₃ (new water supply boreholes for Struisbaai as due to the Bredasdorp cover. He ascribes the high EC's encountered in the old Struisbaai boreholes to be a result of seawater intrusion drilled into the TMG.

None of these authors gave any conclusive evidence for their theories. All of these reports gave field observations and then made theories but in none of these reports were the two linked by logical arguments.

1.3 THE AIM OF THIS THESIS

The investigation of the hydrogeology at Struisbaai was carried out as part of a Water Research Commission research project titled "Geochemistry and Isotopes for Resource Evaluation in the Fractured Rock Aquifers of the Table Mountain Group" (Weaver *et al.*, 1997). After drilling of additional sampling boreholes and completion of the final few sampling runs the project team realised that this site was not suitable as a research site for the objectives of that research project and further work was discontinued.

It was, however, recognised that the information could be used towards solving the source of salinity in the groundwater supply. This would then constitute a useful case-study, because as far as the author has been able to ascertain no similar work has been carried out in South Africa. There are three sources of salinity which are considered to possibly be the cause of groundwater at Struisbaai having a higher than expected dissolved salt content. These are:

- ▣ Salinity derived from sea-spray causing high salinity recharge.
- ▣ Geological factors which yield high salinity groundwater.
- ▣ Hydrogeological factors which result in seawater intrusion.

Salt fallout from sea-spray is a phenomenon experienced by all inhabitants along the coast. House windows that need regular cleaning and motorcars that rust faster than do inland cars are two examples of this phenomenon. This sea-spray also affects groundwater quality (Martin and Harris, 1982). The effect is most marked along the coastal strip and lessens the further inland one goes.

There are two geological factors which are possible contributors of salinity. The first is connate salinity, which is seawater trapped in rock-pores from periods of marine transgression when groundwater was replaced by seawater. The second is salinity derived from shales of marine origin. In the Western Cape shales from the Malmesbury Supergroup and from the Bokkeveld Group are well known for having saline groundwater.

The third possible source of salinity is hydrogeological and is man-induced. This is saline intrusion which is caused by over-pumping of boreholes. This lowers the water-table to below sea-level, thus inducing seawater to flow towards the pumping borehole which then pumps a mixture of seawater and groundwater.

This thesis will examine the field data in terms of these possible sources of salinity and makes conclusions as to which of these factors is responsible.

The aim of the thesis is to identify the cause of the high salinity of the groundwater at Struisbaai.



CHAPTER 2

FIELD INVESTIGATION: METHODS AND PROCEDURES

The original project was directed towards an examination of variations of chemical and isotopic composition of groundwater with time as an aid to estimating groundwater reservoir capacity. Only after research work was stopped at Struisbaai was it realised that the data could be used to identify the sources of the high salinity in the groundwater. Some minor additional field work was done.

2.1 PREVIOUS INVESTIGATIONS

Previous investigations at Struisbaai and Agulhas were directed towards water supply. Meyer (1986a and 1986b) summarized previous drilling at Agulhas, a total of 9 boreholes, and at Struisbaai, a total of 9 boreholes. At Agulhas boreholes 1 and 2 of Meyer (1986b) are still in use for water-supply. This borehole 1 is marked AG1 on Figure 1.3. The Struisbaai boreholes (Meyer 1986a) have been replaced by a well field located further from the sea. Figure 1.3 shows the old Struisbaai well field BH3 to BH10 located adjacent to the village and the replacement well field boreholes P1, P2 and P3 which are 4 kilometres west of Struisbaai. This well field was established by the Engineering Consultants VKE (McLea, 1990) to supply water for a township development north of Struisbaai. Due to the good quality of the water from this well field all Struisbaai's water is obtained from this well field, with the old well field now being used as a standby to supply peak summer holiday season demand.

Other workers, Joubert (1973), Levin (1988) and Toens (1991) carried out investigations and made recommendations for water-supply but did not carry out any drilling.

2.2 PRELIMINARY FIELD WORK

On 3rd and 4th March 1993 an initial field visit was made in order to establish which of the boreholes described in the various reports were available for sampling. The boreholes were AG1, BH8, BH10, P2 and P3 (Figure 1.3). Other boreholes were located but were not available for sampling, either because of blockages or they were collapsed or they were sufficiently close to the chosen boreholes and were thus considered to be duplicates.

2.3 DRILLING OF ADDITIONAL BOREHOLES

In order to obtain a sampling network with a wider areal coverage an additional four boreholes were drilled (G39940, G39941, G39942 and G39943). Borehole G39940 was drilled in order to obtain water samples from the Uitenhage Formation (Jurassic age). G39941 in order to obtain a sample further from the old well field. G39942 and G39943 in order to obtain water samples from

the upper zone of the quartzites, as the production boreholes P1, P2 and P3 were deep boreholes obtaining water from fractures deeper than 70 m. Access to the central zone was impossible as the calcrete forms a very rugged topography with many cavernous weathering features on surface. Note the internal drainage feature 1.5 kilometres to the south of borehole P3. In addition the existing but damaged borehole G39427 was reconditioned. Borehole logs of existing boreholes and of the new boreholes are presented in Appendix 1.

The drilling method was air-percussion with a drill-foam being used to reduce side-wall collapse. Where collapsing conditions were particularly severe, mud-rotary drilling was used.

Collapsing conditions were encountered at the calcrete/quartzite contact where the calcrete was cavernous and weathered. For the boreholes drilled during this investigation a steel casing was inserted and seated into the quartzite below this contact, thus sealing off any water intersected in the calcretes. This was done as the water quality in the quartzites was being investigated. Drilling then continued until the first water strike with a yield sufficient for sampling was encountered. The positions of these boreholes plus all existing known boreholes is shown in Figure 1.3.

Down-the-hole geophysical logging of these boreholes was carried out by Mr Barry Venter of DWA&F. The logs and the interpretations are contained in Appendix 4.

Test pumping data is available only for existing boreholes P1, P2 and P3 (McLea, 1990 and 1991). These are presented in Appendix 2.

2.4 RAIN GAUGES

Rainwater samples were collected in order to compare chemistry and isotopes of recharge and groundwater. Three rainwater collectors were erected, namely at Bh10 - SBR1, at BhG3943 - SBR2 and at BhP3-SBR3. These rainwater collectors have a collecting funnel attached to a tube leading down into a sealed container. The other end of the tube is placed inside a sample bottle which stands upright in the bottom of the container. The water from each rainstorm collects in the inner sample bottle from which a chemistry sample is taken during each (monthly) field visit. The data for these samplers thus represents the cumulative rainfall composition since the preceding sampling date. With knowledge of the rainfall quantities of the same period, an estimate of the annual isotope and chemical input at each site can be made.

2.5 GROUNDWATER SAMPLING

Five sampling runs were carried out. The first in March 1993 was for the existing boreholes and for the full network of ten monitoring boreholes was in October 1993, April 1994, August 1994 and December 1994. The results are contained in Appendix 3. The sampling equipment was either the existing production pump or an electric submersible which has a yield of ~ 0.8 L/sec.

For the geochemistry and isotopes study, the following determinants were required:

Table 2.1 Physical and chemical determinants measured

Group	Determinants
Physical determinants	EC, pH, temperature
Major cations	K, Na, Ca, Mg
Major anions	Cl, SO ₄
Aggregate determinants	Alkalinity, DOC, TIC
Other elements	P, Si, NO ₂ , NH ₄
Metals	Cu, Fe, Mn, Zn
Micro constituents	Sr, Rb, Ba, Li
Isotopes	¹³ C, ¹⁸ O ¹⁴ C, (radioactive) ⁸⁷ Sr/ ⁸⁶ Sr (radiogenic)

Field data sheets were prepared before each sampling exercise. Standard sampling and sample handling procedures as set out in Weaver (1992) were followed. Some of the environmental isotopes and chemical constituents required specialised sampling mechanisms or preservation measures. ¹⁴C, for example required the processing of 20 litres of water.

Before collecting a sample, the static water level at each borehole was measured. The borehole was then pumped for a period long enough to purge the hole of stagnant water. This allows representative samples of the *in-situ* groundwater to be taken. During pumping the electrical conductivity was monitored continuously and sampling begun once the reading had stabilised, but after three times the volume of water standing in the borehole column had been removed.

Temperature, EC and pH were measured in the field for the following reasons:

- ☛ These are parameters which can change after removal of water from the sampling point and are best measured as soon as possible. EC and pH are temperature-dependent parameters and are influenced by precipitation of salts out of solution or sample degassing.
- ☛ These parameters provide a preliminary overview of the water quality which can be used to decide the extent of sample collection necessary.
- ☛ They provide a check on laboratory data. (Lloyd and Heathcote, 1985).

Water samples were collected in PVC plastic bottles which were acid washed prior to sampling to remove all leachable materials. Unfiltered samples were collected for major cations and anions, alkalinity, hardness and DOC. Each bottle was rinsed at least twice with the sampled water before filling.

For filtered samples a hand-held syringe was fitted with a 0.45 micron filter membrane and the

collected sample filtered into a sample bottle containing enough nitric acid to adjust the pH to less than 2. These preservation measures are necessary to prevent the metal ions precipitating or forming complexes with organic or other ligands in the water before reaching the laboratory. The syringe and filter holder was also rinsed with the sample water before collecting filtered samples for metal analyses.

For environmental isotopes, two 250 ml samples in glass bottles were collected for ^{18}O and D, and one sample preserved with 1 ml HgCl_2 for ^{13}C . Tritium samples required at least a litre of water. The sampling procedure for ^{14}C was more complex. Because the isotope occurs at very low concentrations, suitable samples for transport and laboratory analysis require a large volume of sample and specialised treatment. Approximately 20 litres had to be acidified and the formed CO_2 expelled with air in a closed system. The CO_2 was trapped in an absorber filled with caustic soda solution in the field for later analysis of the precipitated carbonate in the laboratory (Vogel, 1967).

All samples were delivered to the laboratories as soon as possible after collection to minimise the possibility of sample deterioration.

2.6 LABORATORY ANALYSIS

Chemical analysis of water samples was undertaken by the CSIR laboratories in Stellenbosch. Methods used conformed to guidelines set out in *Standard methods for the examination of water and wastewater* (APHA, 1989). Ion balances were checked to be within 5% for data quality control. Isotope analyses were carried out at the Environmentek laboratories in Pretoria.

Selected samples were also sent for ICPMS analysis. The first batch were tested at the Anglo-American Research Laboratories and the later samples at the Pretoria laboratories of the Institute of Soil, Climate and Water (Agricultural Research Council). It was hoped that these low-concentration metals could provide additional or supporting information to that derived from the major ion chemistry. At this stage, however, no useful correlations have been found. The results of the exercise are nevertheless presented as a part of Appendix 3. ICPMS is a relatively inexpensive analytical method which can generate large amounts of data on microchemistry. The usefulness and applicability of this method to groundwater studies needs to be assessed in relation to traditional methods.

2.7 GENERAL DISCUSSION ON THE ANALYTICAL DATA

Detailed examination of the analytical data reveals some anomalous results. The analytical laboratory of the CSIR in Stellenbosch is in high repute for producing results with both high accuracy and precision. In the annual inter-laboratory comparison this laboratory is always placed in the first five out of 30-odd participating laboratories. In the light of the confidence in the quality of the analyses these anomalies are commented on.

- ➡ DOC (Dissolved Organic Carbon). Inspection of the results for the production boreholes AG1, P2 and P3 an apparent instrumentation calibration problem was observed. These boreholes are regularly pumped thus ensuring representative groundwater samples. AG1 is 3 kilometres from P2 and P3 and its overall chemistry is different to P2 and P3 which

are 700 metres apart and have similar chemistry. The DOC analyses for each sample run are similar to each other, but different between each sampling run. Table 2.2 shows the DOC results as well as alkalinity and nitrate.

Table 2.2 Struisbaai. DOC, alkalinity and nitrate results for the production boreholes AG1, P2 and P3

Date	4/3/93	28/10/93	14/4/94	28/8/94	7/12/94
DOC					
AG1	4.4	6.9	3.0	1.7	0.79
P2	4.7	7.0	2.9	1.6	0.79
P3	4.1	7.2	2.9	1.4	0.79
ALKALINITY					
AG1	215	228	216	217	212
P2	222	230	213	213	211
P3	208	220	209	238	208
NITRATE					
AG1	2.35	4.74	3.12	2.34	2.32
P2	0.1	0.26	<0.1	0.28	<0.1
P3	0.05	0.1	<0.1	0.13	<0.1

There is no correlation between alkalinity and DOC. For nitrate and DOC there is some correlation for borehole AG1 in that the highest DOC result corresponds to the highest nitrate result, but no correlation between nitrate and DOC for P2 and P3. AG1 receives groundwater from a different stratigraphic elevation than do P2 and P3 but if this were the reason for the DOC/Nitrate partial correlation for AG1 and not P2 and P3 then the DOC for P2 and P3 should be different to AG1 and not virtually identical. From ¹⁴C results AG1 is much older water than P2 and P3, thus should be well buffered from seasonal changes and also chemically (DOC) different to P2 and P3. Geologically and hydrologically there is not an explanation.

These results were discussed with the analytical staff and in the time period of sampling and analysis there was neither an instrument nor an analytical method change which could have influenced the DOC results. The graphs from the auto-analyser were retrieved and re-examined. For all of these analyses standards of 20, 10 and 5 mg/L DOC were used, plus a control sample of groundwater from the Atlantis aquifer which has a similar, but less saline water. The standards and the control sample were consistent and the DOC's measured for these samples are correct in relation to the standards and control.

The mystery of the sampling run correlation and the trend for the period of sampling remains a mystery.

- ➡ The first set of analyses for the two newly drilled boreholes G39942 and G39943 appear to have residual effects from either the drilling mud used during the tricone rotary drilling of the calcretes or from drilling foam used with the air percussion used for drilling the quartzites. For example G39942 calcium increases from 57 mg/L to 74 mg/L, sulphate decreases from 61 mg/L to 21 mg/L and alkalinity increases from 72 mg/L to 172 mg/L. These two samples are not discarded, but in the ensuing discussions regarding the chemical and isotopic evaluation of the groundwater the influence of drilling mud is taken into account.
- ➡ The isotopes were analysed in a different laboratory from that which analysed the chemistry. These results show only two anomalies. The first samples from G39942 and G39943 which have TIC (total inorganic carbon) less than half of the subsequent samples which also resulted in a carbon-14 content not being able to be measured for G39943. This would appear to support the cause of the anomalies to be due to the organic drilling mud used.
- ➡ $\delta^{18}\text{O}$ of borehole P3 for 15/04/94 is -4.0‰ whereas the other samples for this borehole range from -4.8 to -5.1‰ which is the same range as for all the other boreholes (except G39940). This value is considered incorrect.



CHAPTER 3

MARITIME INFLUENCE ON RAINFALL AND RECHARGE QUALITY

3.1 GENERAL

Struisbaai falls in the winter rainfall region receiving most rain in winter, nevertheless there is substantial summer rain. The rain varies between 400 and 500 mm per annum, the long term average being 458 mm. The prevailing winds are west to southwest in winter and southeast in summer, reaching gale force from either direction. The average maximum temperature in summer is 28 °C and winter is 17 °C.

3.2 STRUISBAAI RAINFALL AND SALINITY

The South African Weather Bureau, Information Section was contacted for information regarding rainfall figures. The two closest weather stations are Agulhas lighthouse and Bredasdorp Police Station. For Agulhas lighthouse monthly rainfall is available from 1894 to 1997 and daily rainfall from 1902 to 1997. For Bredasdorp Police Station the same period but monitoring stopped in 1991.

Graphs of the long-term rainfall and the monthly average are shown in figure 3.1, 3.2, 3.3 and 3.4. The bulk of the rain is in winter with 67% of Agulhas' rain and 61% of Bredasdorps rain falling in winter. However, it is also obvious that there is an appreciable amount of rain that falls during the summer period. The winter rains are from cold frontal systems passing over the coast and the rain is from the west. During summer the low pressure fronts pass further to the south, but as they pass, south-west to south onshore winds are generated which produces the relatively high summer rains.

Rainfall collectors SBR1 and SBR2 were installed 12 October 1993 and a third SBR3 on 15 April 1994. A veld-fire on 10-11 January 1995 destroyed SBR1 and SBR2. Lack of co-operation in sample collecting resulted in the samples being collected at long intervals rather than after each rainfall. Consequently combining the rain analyses with the historical rainfall data (figure 3.1) to produce a weighted average rainfall chemistry figure must be regarded as an indicator of rain chemistry rather than the actual rain chemistry. For each sample analysed this is taken to represent the chemistry of the total rain between the date of collection and the previous sampling run. Thus SBR1 of 16 April 1994 is taken to be the chemistry of all the rain between 23 Nov 1993 and 16 April 1994.

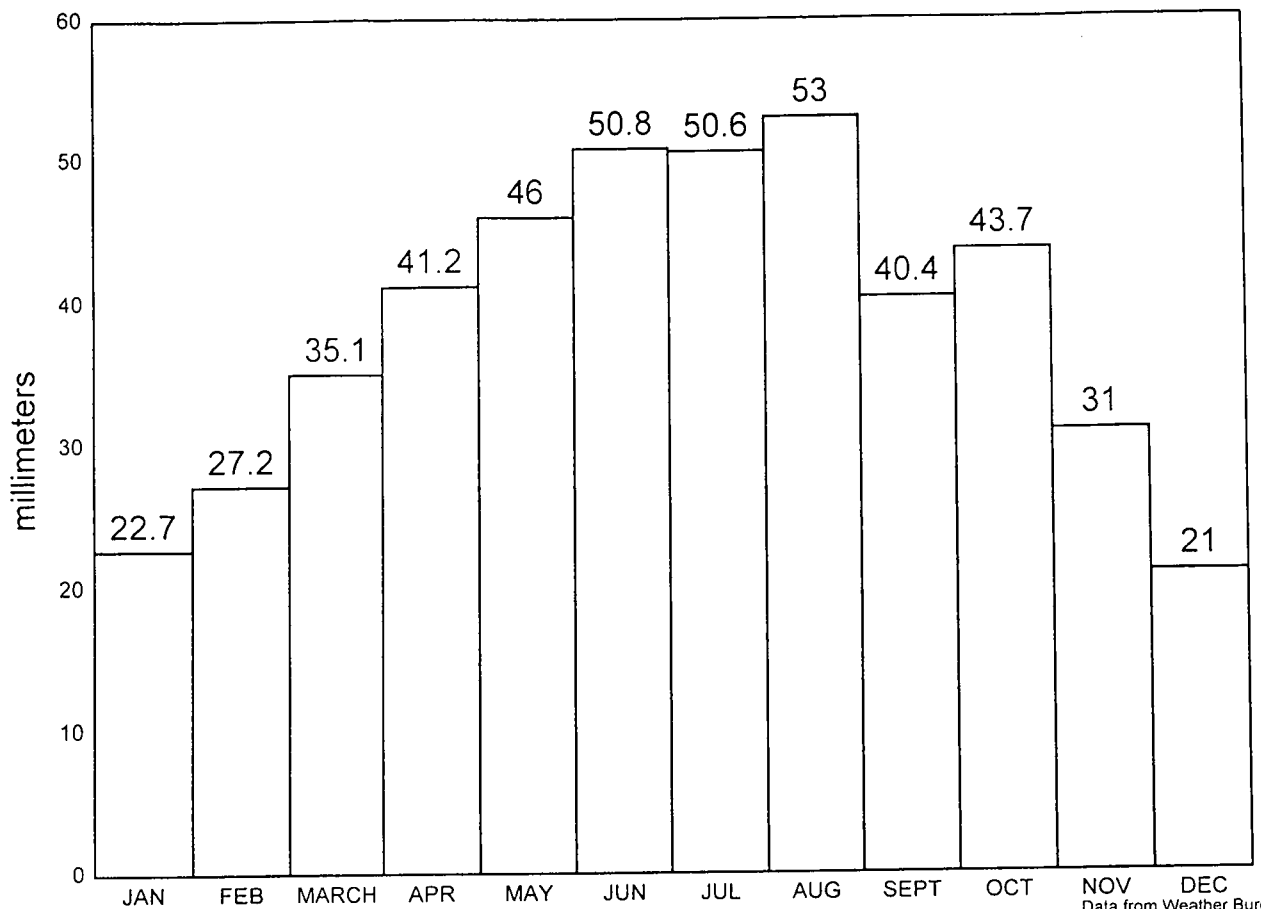


Figure 3.1 Monthly average rainfall for Bredasdorp. Note that the maximum rain is during the winter months nevertheless there is appreciable summer rain

Data from Weather Bureau
Department of Environmental affairs

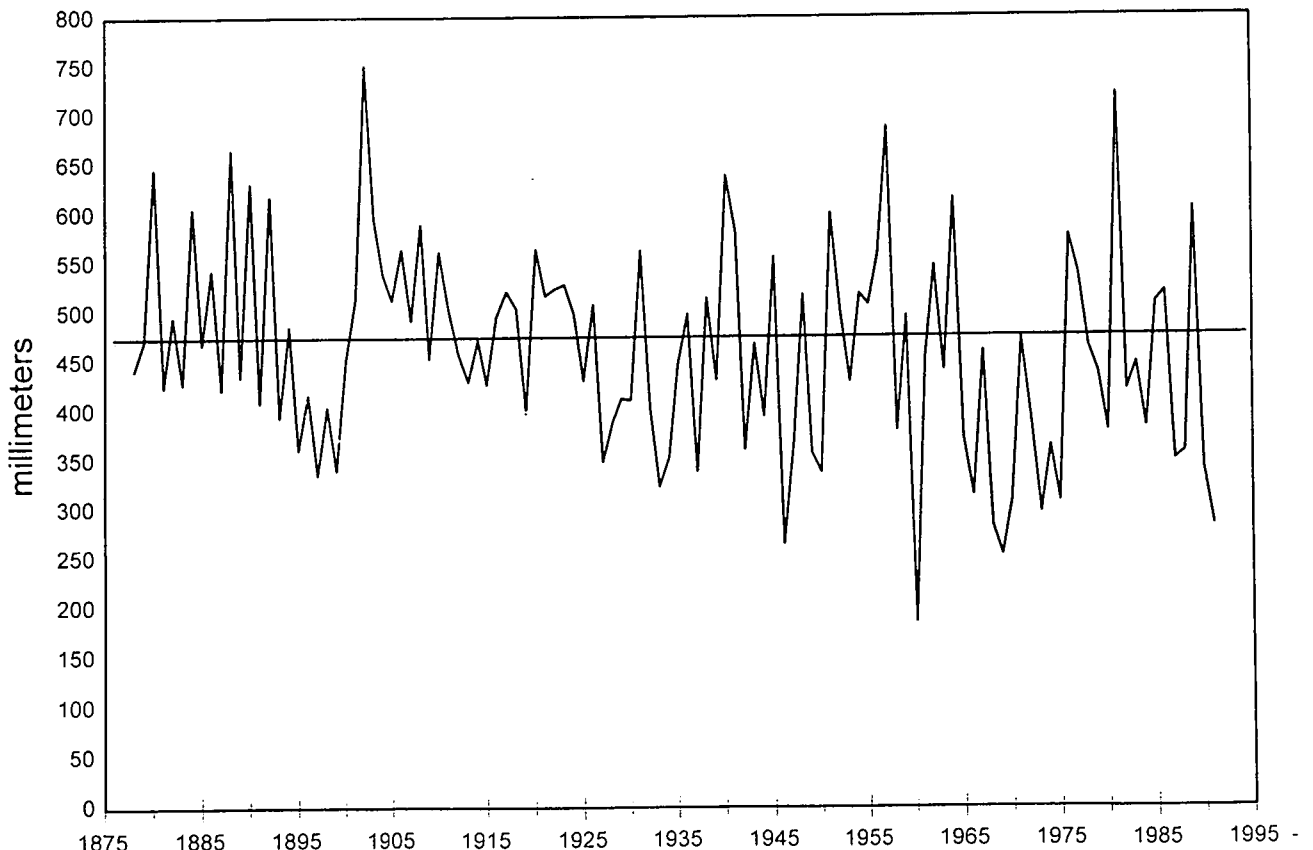


Figure 3.2 Annual Rainfall at Bredasdorp for the years 1878 to 1991
Average is 462.3mm

Data from Weather Bureau
Department of Environmental Affairs

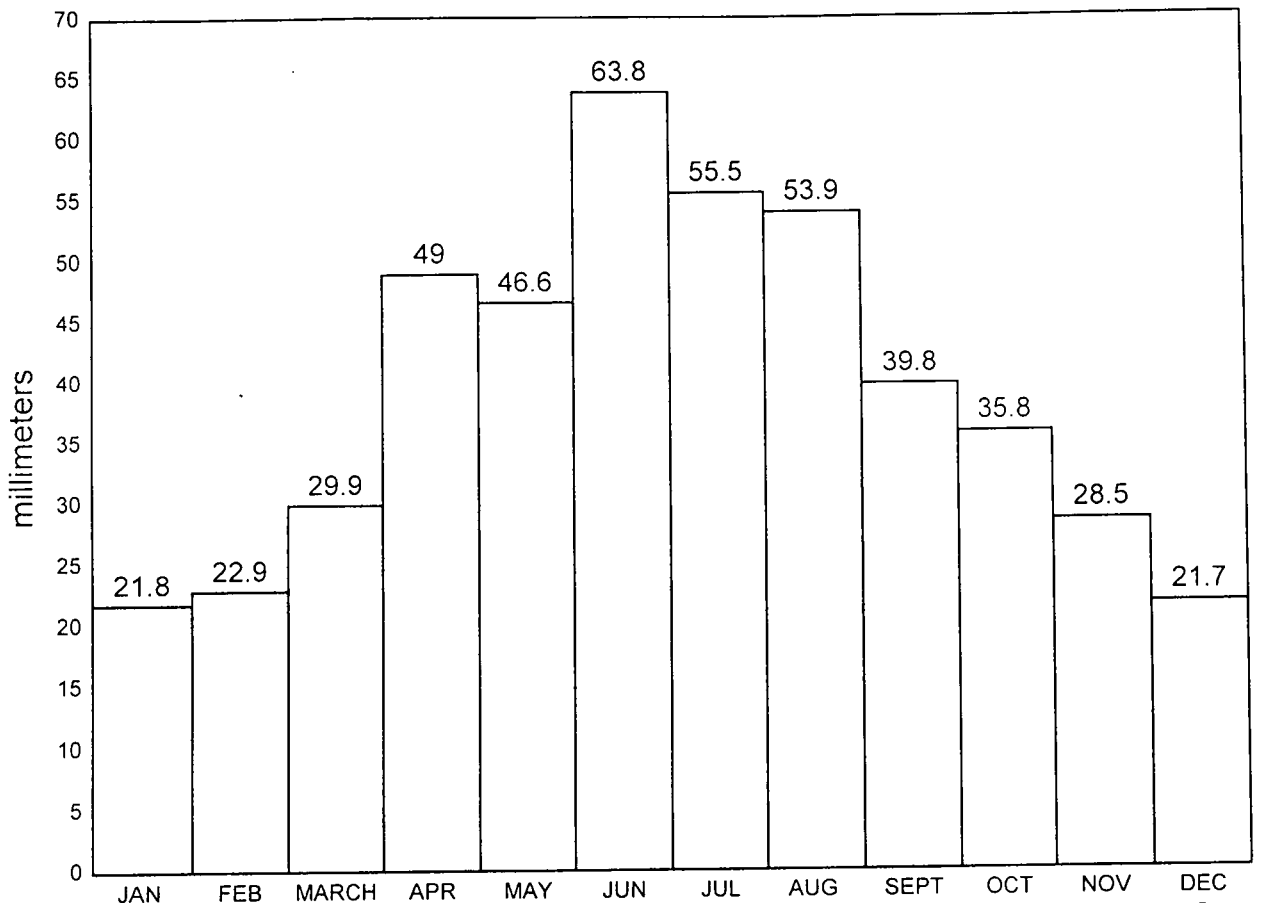


Figure 3.3 Monthly average rainfall for Agulhas Note that the maximum rain is during the winter months nevertheless there is appreciable summer rain

Data from Weather Bureau
Department of Environmental affairs

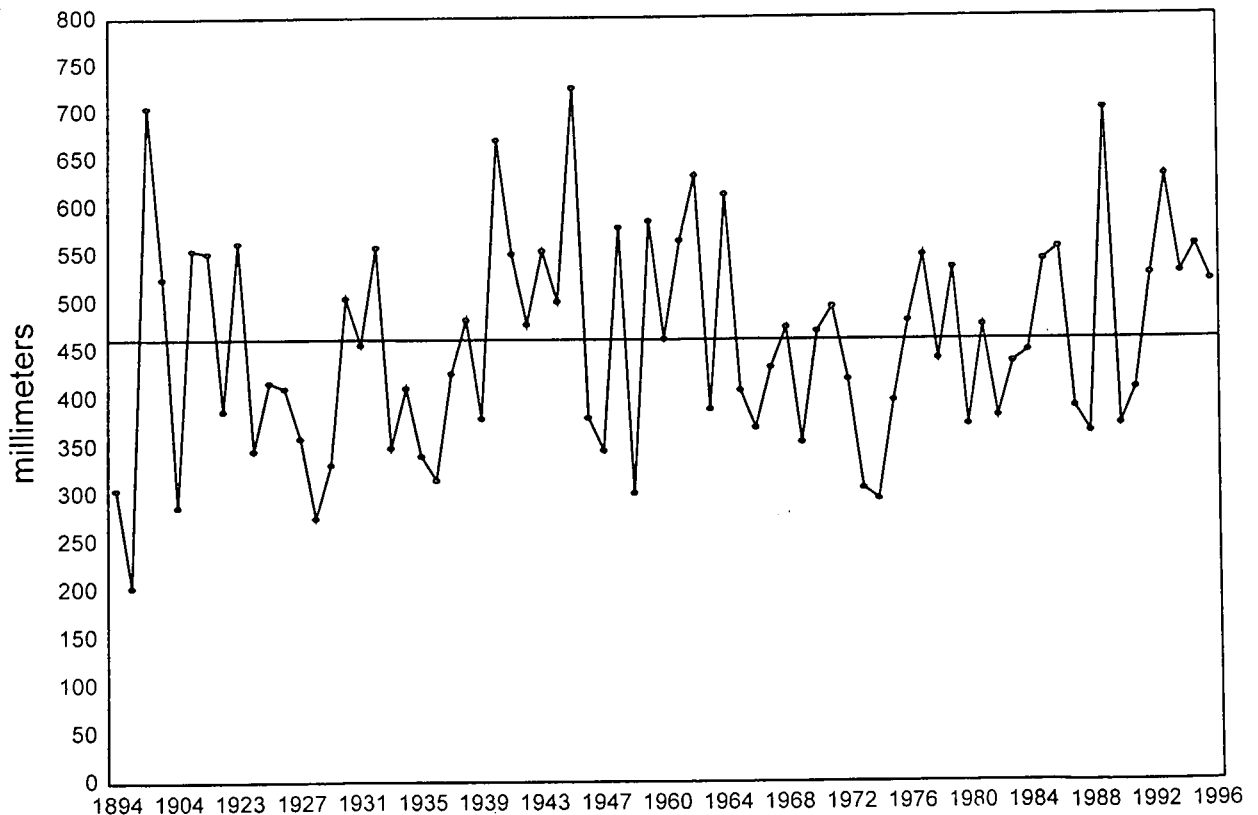


Figure 3.4 Annual Rainfall at Agulhas for years 1875 to 1996
Average is 457.6 mm

Data from Weather Bureau
Department of Environmental affairs

The weighted average rain quality was calculated by the following equation:

$$\text{weighted average rain quality} = \frac{\sum_{i=1}^n EC_i x_i}{\sum_{i=1}^n x_i}$$

where EC_i (mS/m) is the measured rain quality for the i^{th} sample period
 X_i is the rainfall (mm) for the i^{th} sampling period as measured at Agulhas

The daily rainfall figures from Agulhas lighthouse were used to determine the total rain for the period that water quality samples were collected. The data is summarized in Table 3.1 below.

Table 3.1 Struisbaai. Amount of rainfall, rainfall quality and weighted average quality of rain during period 12/10/93 to 30/08/94.

Period	Rainfall (mm)	SBR1		SBR2	
		EC for period (mS/m)	Weighted average EC (mS/m)	EC for period (mS/m)	Weighted average EC (mS/m)
12/10/93	1.0	56	12.5	45	10.5
29/10/93	4.4	59		37	
23/11/93	53.6	34		24	
16/04/94	372.4	9		8.4	
30/08/94					
Total Rain	439.4				

Similarly the weighted average for all the determinants can be calculated and are presented in Table 3.2. There is insufficient data for SBR3 so no calculations are made.

Table 3.2 Struisbaai: Weighted average quality for Struisbaai rainfall as determined for rainfall collectors SBR1 and SBR2 for period 12/10/93 to 30/08/94. EC is in mS/m the rest in mg/L.

	EC	K	Na	Ca	Mg	SO ₄	Cl	Alkalinity	Na:Cl
SBR1	12.5	0.7	16.1	3.1	2.0	4.9	31.0	2.0	0.52
SBR2	10.5	0.7	9.8	5.6	1.2	3.4	23.1	6.3	0.42

Examining these data it is seen that SBR1 has higher EC, Na, Mg, SO₄ and Cl whereas SBR2 has higher Ca and alkalinity. This is interpreted to be a reflection of their localities relative to the sea. The south-east wind blows strongly in summer and also in winter after a cold-front has passed by. This wind blows sea-spray (aerosols) and SBR1 being the closest to the sea receives more aerosols than does SBR2 and thus has higher levels of EC, Na, Mg, SO₄ and Cl. The higher Ca and alkalinity for the SBR2 which is inland is explained by this rain collector receiving more dust than SBR1. As the surface soils are calcrete and quartz sand this dust gives the higher Ca and alkalinity. This effect of distance from the sea leading to a relatively higher calcium and alkalinity for the collectors further from the sea has also been observed by Meyer *et al.* (1993) in the Zululand coastal plain.

Nitrate and ammonia are not processed as these are mostly related to insect or bird dropping contamination.

These relatively high salinities for the rainfall will have a marked effect on groundwater quality. For the Struisbaai area there is very little evidence of surface runoff. The calcrete surface has numerous solution cavities. Topographic features are the internal drainage features which can be seen between the ridges of the fossil dunes. In figure 1.3 one of these can be seen 1,5 kilometres south of borehole P3 and another is 500 metres north-northwest of borehole AG1.

Using scenarios of 0% and 20% loss of rainfall due to runoff and evapotranspiration varying between 90% and 70% the quality of recharge water is calculated. Chloride being conservative is used for these calculations. The calculated results are presented in Table 3.3.

Table 3.3 Struisbaai rainfall and recharge water quality simulations

	Runoff %	Evapotranspiration %	Recharge as a % of rainfall	Resulting chloride content mg/L of Cl
SBR1 Weighted average chloride content is 31 mg/L	0	95	5	620
	0	90	10	310
	0	80	20	155
	0	70	30	103
	20	90	8	310
	20	80	16	155
	20	70	24	103
SBR2 Weighted average chloride content is 23.1 mg/L	0	90	10	231
	0	80	20	115
	0	70	30	77
	20	90	8	231
	20	80	16	115
	20	70	24	77

SBR1 was installed at BH10 which has an average chloride content of 532 mg/L. Comparing this value to Table 3.3 it is seen that for the 0% runoff option this value lies between the recharge value of 5% and 10% of rain. Working backwards 532 mg/L implies a recharge of 5.8%. For the 20% runoff option the implied recharge is 4.7% of rainfall.

Similarly for SBR2 the nearest borehole is Bh P₃ with an average chloride content of 141 mg/L the implied recharge at 0% runoff is 16.4% of rainfall and at 20% runoff it is 13.1% of rainfall.

These values of recharge are quite feasible considering the porous nature of the calcrete cover.

Relatively little work has been done on estimating recharge through Bredasdorp Formation calcretes. This is probably due to these aquifers being of local importance to coastal regions in the southern Cape. For the Langebaan limestone aquifer using borehole hydrographs Weaver and Du Toit (1995) determined that groundwater recharge was 8% of annual rainfall.

Salt input to the ground is called cyclic salting (Lloyd and Heathcote, 1985). Cyclic salting has been recognized as a major contributor to the salinity of small islands, coastal aquifers and areas which have low or intermittent recharge (arid zone).

3.3 RECHARGE AND SALINITY

In chapter 3.2 it was shown that the salinity as measured for the rain could quite feasibly be the source of the high salinities recorded for the groundwater. It is however, noted that these are the salinities recorded for all rainfall and include any windblown dust and salts. An argument can be advanced that groundwater recharge occurs only after significant falls of rain and that light rains do not contribute to recharge. Consequently the argument says that only the water quality for the heavy winter rains should be considered. The consequence is that when recharge does take place after heavy rainfall then all salts that have accumulated on surface will dissolve in the rainwater and be flushed and recharged into the groundwater system.

In order to test the proposition that air-borne salts originating from the sea is the primary source of salinity in the groundwater a leaching test of the calcrete was conducted. Two samples of calcrete were collected from a newly developed road approximately 300 metres from the coast and inland from Spookdraai (see figure 1.3). The first sample was from an exposed and weathered rock-face and the second was from a freshly exposed surface, both being collected close to each other in order to have similar exposures to the elements. In hand-specimen the difference between the samples was that the weathered sample was more porous due to calcrete having been weathered. The samples were crushed and split. Fifty grams of crushed sample was mixed and thoroughly stirred with 500 ml of de-ionized water. A water-sample of each was decanted after 24 hours and analysed for cations and anions. The data is presented in Table 3.4 below.

Table 3.4 Analysis of leachable salts from Struisbaai calcrete

Two air dried samples of finely crushed rock was analysed. 50 g of sample was weighed into flasks and deionised water (EC 0.1 mS/m) was added to 500 ml mark.		
The slurry was magnetically stirred for 3 hours, (constant EC) and allowed to settle overnight. The supernatant was filtered (0.45 micron) and analysed.		
Sample ID:	Fresh	Exposed
Potassium as K mg/L	2.1	5.4
Sodium as Na mg/L	9	185
Calcium as Ca mg/L	12.5	21
Magnesium as Mg mg/L	1.9	19
Ammonia as N mg/L	0.1	<0.1
Sulphate as SO ₄ mg/L	3	24
Chloride as Cl mg/L	6	336
Alkalinity as CaCO ₃ mg/L	43	25
Nitrate plus Nitrite as N mg/L	0.1	0.3
Ortho phosphate as P mg/L	0.8	<0.1
Conductivity mS/m @ 25 °C	11.6	122
pH (Lab)	8.3	8.8
Analysed by the CSIR Analytical Laboratory, Stellenbosch		

Some observations are made on these results. The EC was continuously measured during stirring. For both samples the EC rose to the final EC within ten minutes. This is a reflection of the solubility of the various salts, being mainly Na and Cl.

To gain an idea of what minerals could contribute to these results the mineral speciation model MINTEQ was applied to these two analyses.

MINTEQ allows one to model which minerals are likely to precipitate from a given solution, or in this case an analysis of the dissolved ions. Being a modelling package it does not prove that this will occur, but makes a prediction. In addition there is modelling routine which allows one to not allow precipitation, thus enabling one to determine which minerals are supersaturated. The following are the modelling results of applying MINTEQ to the "fresh" and "exposed" analytical results.

For the fresh rock sample, model run standard

☛ hydroxyapatite ($\text{Ca}_5(\text{PO}_4)_3\text{OH}$) precipitated

when precipitation was not allowed

☛ hydroxyapatite was supersaturated

☛ aragonite (CaCO_3) and calcite (CaCO_3) were just below saturation

☛ dolomite (Ca MgCO_3) was well below saturation

For the exposed rock sample model run standard (phosphate taken as equal to 0.1)

☛ hydroxyapatite and dolomite precipitated

when precipitation was not allowed

☛ hydroxyapatite and dolomite supersaturated

☛ calcite just above saturation

☛ aragonite and magnesite (MgCO_3) just below saturation

The conclusion made is that the relatively high presence of magnesium in the exposed rock promotes the formation (potential) of dolomite (and magnesite). This magnesium is from sea-spray. Seawater intrusion promotes dolomitization (Meyer (1991), Fidelibus and Tulipano (1991)). The absence of (potential) dolomite in the fresh sample and the presence of (potential) dolomite in the exposed sample indicates that seawater intrusion has not taken place but that (potential) dolomitization is via sea-spray contact with the calcrete. If the (potential) dolomitization had been caused by seawater intrusion then both samples would have (potential) dolomite.

The ratio of Na to Cl for the exposed sample is 0.551 which is almost exactly that for ocean water. The Indian Ocean off the south coast of Africa is well mixed, has little fresh water influence from major rivers or ice-caps and is not subject to concentration due to limited circulation such as the Arabian Gulf. Table 3.5 gives the concentration of the major ions and ratios of various salts, and Table 3.6 compares these to the ratios for the two rock samples.

Table 3.5 Average seawater concentration of major ions (Goldberg, 1963)

Ion	Concentration mg/L
	Goldberg (1963)
Chloride	19000
Sodium	10500
Sulphate	2700
Magnesium	1350
Calcium	400
Potassium	380
Bicarbonate	142
Bromide	65
Strontium	8
Na ⁺ /Cl ⁻	0.553
K ⁺ /Cl ⁻	0.020
Ca ²⁺ /Cl ⁻	0.021
Mg ²⁺ /Cl ⁻	0.071

Table 3.6 Ratios of various ions to chloride for leachate from two rock samples from Struisbaai for the two rainfall collectors and for seawater

	Na/Cl	K/Cl	Ca/Cl	Mg/Cl	SO ₄ /Cl
Rock sample - fresh	1.5	0.35	2.08	0.317	0.5
Rock sample - exposed	0.552	0.016	0.063	0.057	0.07
Rainfall collector: SBR1	0.52	0.023	0.10	0.065	0.158
Rainfall collector: SBR2	0.42	0.03	0.24	0.052	0.147
Seawater	0.553	0.020	0.021	0.071	0.140

From this table comparing these ratios to the seawater ratios it appears that the rock sample - exposed, SBR1 and SBR2 all have Na, K and Mg approximately in proportion to seawater. Calcium for all three is elevated, which is probably due to dust. SO₄ for the two rain collectors is in proportion, but for the rock sample - exposed is low. The rock sample - fresh ratios have no resemblance to the others.

These results support the argument that windblown sea-spray is a major contributor to groundwater salinity with the three samples, being the two rainfall collectors and the rock sample - exposed, which are exposed to sea-spray having similar ratios of ions as seawater. The rock sample - fresh has no similar ratios. Thus the conclusion is made that the salinity is derived from sea-spray and not from dissolution of the calcrete.

Martin and Harris (1982) working in the Perth area of Western Australia found similar results with the Na and K with rainfall and groundwater having Na, K and Mg to Cl ratios similar to seawater while Ca to Cl was enriched in Ca. Table 3.7 below shows these results.

Table 3.7 Ratios of cation to chloride ion from Perth area, Western Australia (Martin and Harris, 1982)

	Na/Cl	K/Cl	Ca/Cl	Mg/Cl
Rainfall	0.548	0.032	0.075	0.071
Groundwater	0.560	0.050	0.450	0.093
Seawater	0.556	0.020	0.021	0.067

3.4 CONCLUSIONS

Rainfall samples that have been collected and weighted to the average annual rainfall show that rain (plus sea-spray and dry fallout) contributes a high salt load to the area.

Relating the rainfall salinities at each of two rain collectors to local groundwater salinities the implied recharge is 4.7% and 13.1% for the two collectors. These are quite feasible figures.

Leaching of two rock samples shows that the exposed calcrete yields a high salinity and the fresh calcrete low salinity. Mineral speciation modelling of the leachate shows (potential) dolomite is present in the exposed sample and not the fresh sample. Both these results show that sea-spray is the likely origin for the salt and not seawater intrusion or connate water.

Ionic ratios for the two rainfall collectors and the exposed calcrete sample are very similar to those of seawater while the ratios for the fresh rock sample are very different. These results support sea-spray being the origin of salinity.



CHAPTER 4

GEOLOGICAL CONTROL OF GROUNDWATER SALINITY

4.1 GEOLOGY OF THE STRUISBAAI AREA

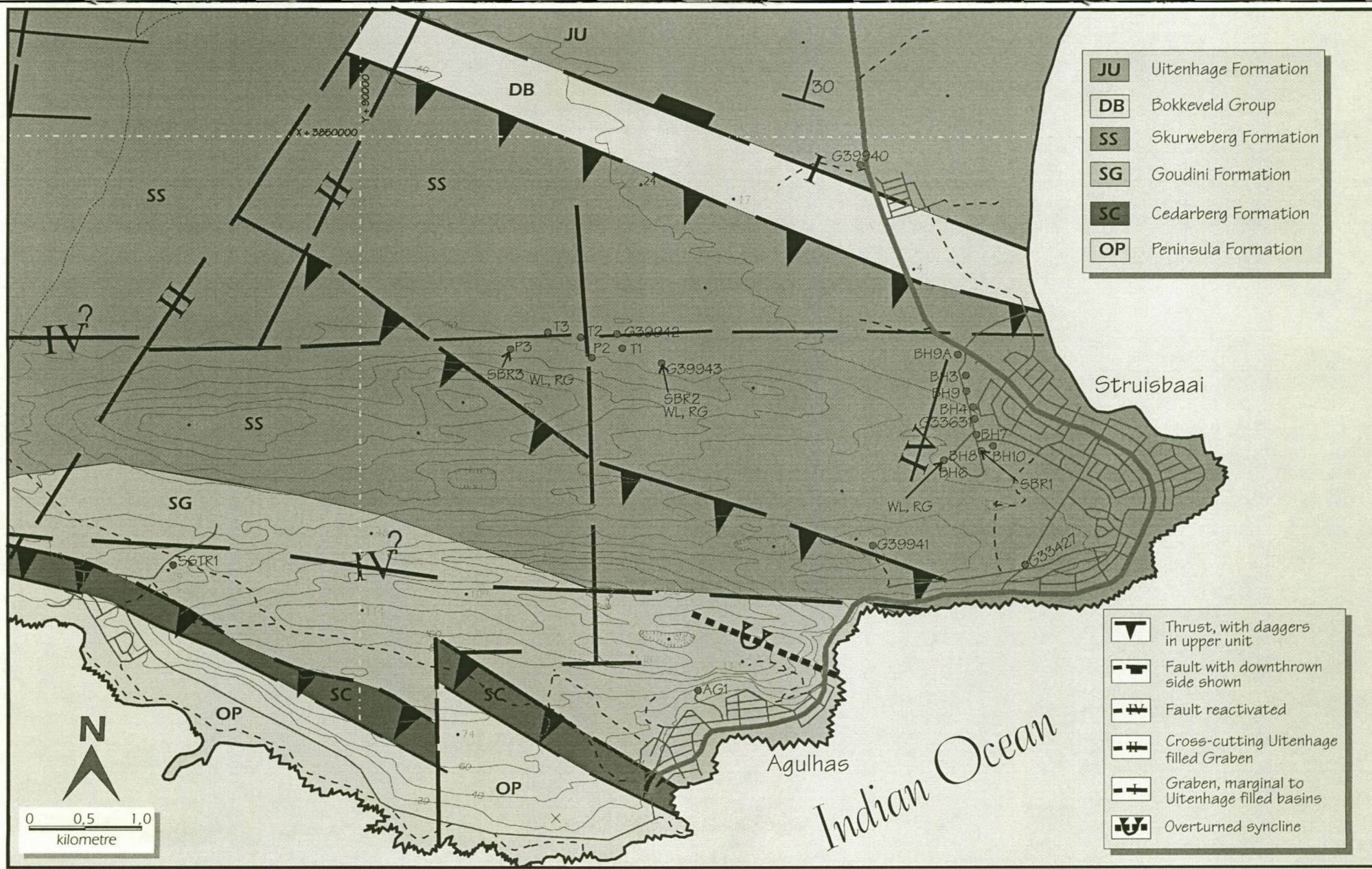
4.1.1 Regional Geology

The first detailed description of the area was by Spies *et al.* (1963) a product of which was the 1:125000 geological map number 235. In the late 1980's the Atomic Energy Corporation on behalf of Eskom conducted an intensive survey of the geology and groundwater from Gansbaai in the west to Waenuiskrans in the east. This was part of their assessment for the location of a future nuclear power plant. The survey results have been published in map form (Andreoli *et al.*, 1989). This map has been used to compile Figure 4.1 which superimposes contours, borehole positions and the road network over the geology.

The regional geology is best illustrated by the schematic stratigraphic profile developed by Malan and Viljoen (1990) and shown in Figure 4.2. Of the sequences shown in this Figure, at Struisbaai are exposed the Table Mountain Group, the Uitenhage Group and the Bredasdorp Group. Encountered but not exposed in outcrop is the Bokkeveld Group. The stratigraphic column for the regional geology is shown in Table 4.1.

Table 4.1 Struisbaai. Stratigraphic column for regional geology

Period	Group	Formation	Member	Thickness
Quaternary Tertiary		Bredasdorp	Wankoe De Hoopvlei	50 - 290 0.2 - 17
Cretaceous Jurassic	Uitenhage	Enon		
Devonian	Bokkeveld			
Silurian		Rietvlei Skurweberg Goudini Cedarberg		
Ordovician	Table Mountain	Pakhuis Peninsula		

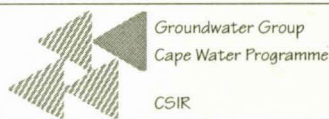


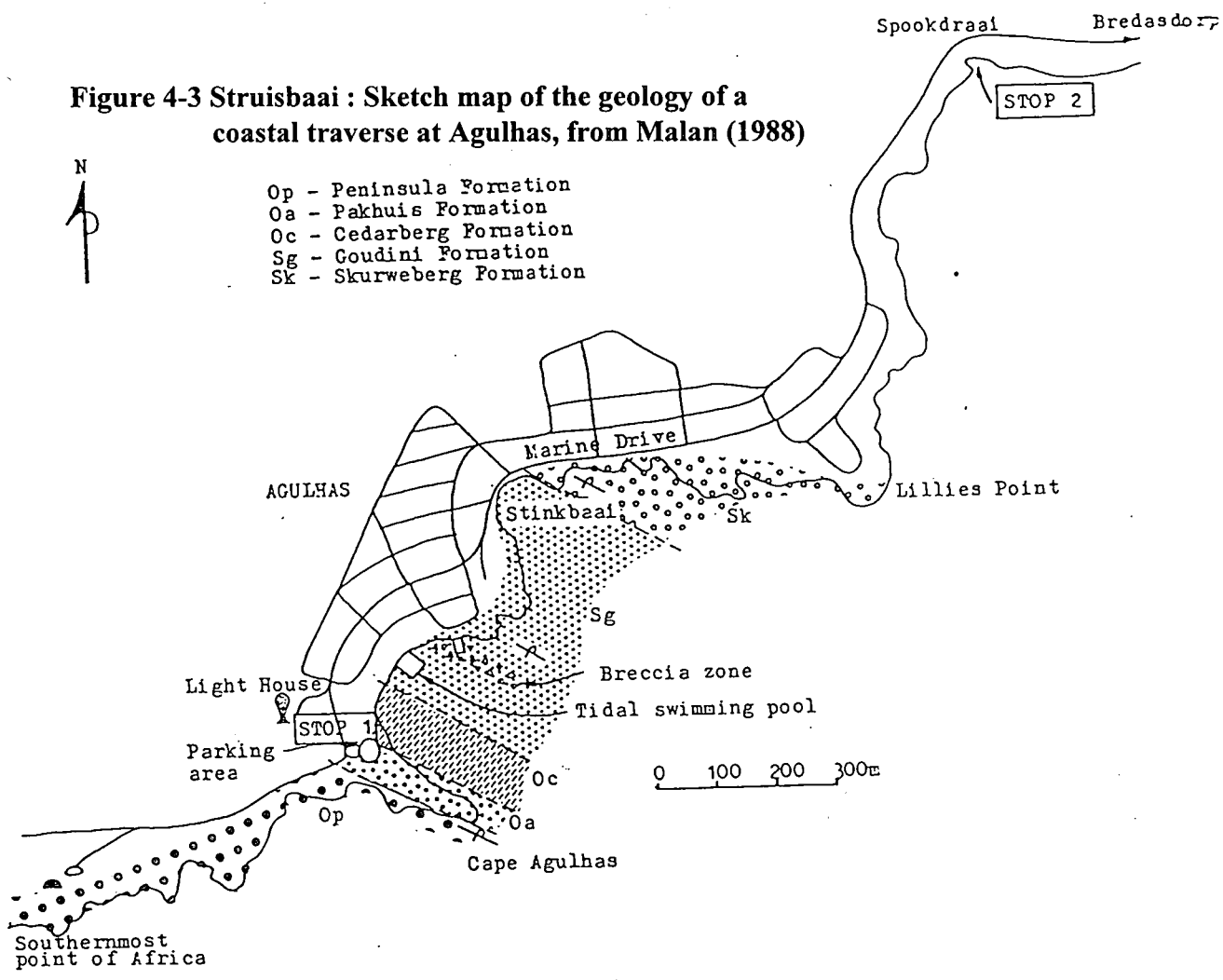
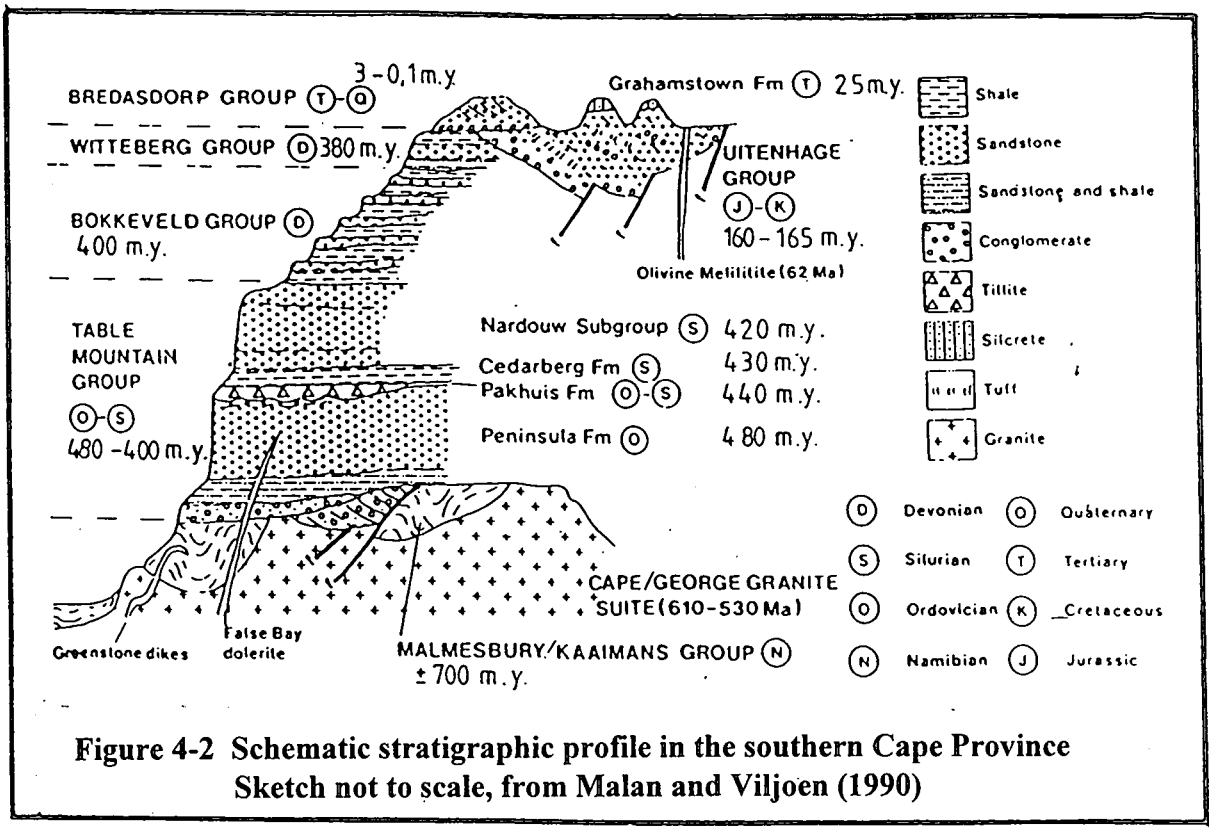
GEOCHEMISTRY & ISOTOPES **WRC K5/481/0/1**
Figure 4-1
Geology of Struisbaai area . Bredasdorp cover removed
 (Geology from AEC Report PIN 1133 (B/R) - GEA (July 1989))

Legend

- Tracks
- Contours (20m interval)
- 74 Spot Elevation
- BHB Borehole

SBR1 = Rain sampler
 WL = Water level recorder
 RG = Automatic Raingauge





4.1.2 Local Geology

The Struisbaai Peninsula is almost completely covered by Bredasdorp Group sediments. Examination of the surface contours of Figure 2.1 shows two parallel ridges running east-west with elevations of up to 156 metres compared to the surrounding countryside to the north which is at 20 metres. These two ridges are calcretised fossil dunes. The east-west direction reflects the prevailing wind direction which is still experienced today, namely west winds in winter bringing the main rain and east winds in summer which also produce rain, but less. Also evident on this figure are some inter-dune slacks. These are hollows from which there is no surface drainage. Field inspection of one of the slacks to the west of borehole G39941 showed solution features which will have a strong influence on recharge.

A traverse along the coast at low tide from Cape Agulhas eastwards to Spookdraai and further east to Struisbaai Point encounters a large part of the stratigraphy of the Table Mountain Group. This is due to the near vertical to overturned attitudes of the stratigraphy. This is shown in more detail in Figure 4.3 which is from the 1988 Agulhas Infanta Excursion Guide (Malan *et al.*, 1988).

The stratigraphic column of the TMG is shown in Table 4.2.

Table 4.2 Stratigraphic column of the Table Mountain Group outcropping in the Struisbaai area (after Levin, 1988 and Malan *et al.*, 1988).

Formation	Lithology
Rietvlei	Does not outcrop.
Skurweberg	White-grey thick-bedded quartzites.
Goudini	White to brown fine grained quartzites with subordinate siltstones and shales, interbedded bioturbated horizons.
Cedarberg	Highly tectonised greenish shales, siltstones and phyllite.
Pakhuis	Dark grey diamictite (tillite) with many small pebbles with overlying massive to cross bedded white quartzites (oskop member).
Peninsula	Medium to coarse grained white quartzite.

The only TMG formation which does not outcrop along the coast is the Rietvlei Formation. The Rietvlei Formation has a distinct magnetic characteristic and consequently has been identified from aeromagnetic surveys. On the AEC geological map (Andreoli *et al.*, 1989) this is shown and appears to the north-east of Figure 4.1. The nearest outcrop of Rietvlei Formation is at the Soetanytsberg which is about 20 km westwards along the coast from Agulhas.

Bokkeveld Group rocks are not exposed in outcrop in the Struisbaai area. They have been intersected in boreholes and postulated (Andreoli *et al.*, 1989) to form a narrow strip along the north of the Struisbaai Peninsula as shown in Figure 4.1.

Further to the north (Figure 4.1) is a downthrown graben which has been filled with Enon conglomerates of the Uitenhage Formation. Being relatively soft rocks compared to the TMG quartzite they have been extensively eroded and form a rather flat featureless plain which one crosses when travelling to Struisbaai. There are isolated mounds which are overlying calcretes of the Bredasdorp Formation. Struisbaai Bay owes its presence to the protection provided by the TMG to the soft erodible Enon. About 10 km inland (NNE) of Struisbaai is Jubilee Hill which is an outcrop of Enon Formation exposed in the road cutting and the adjacent quarry. The author visited the site with the 1988 field trip and the notes provided for this trip have the following to say.

"At this hill in the vicinity of Soetendalsvlei, outcrops of conglomerate interbedded with clay are exposed in a road cutting and adjacent quarry. The deposit itself is capped by surface-cemented gravels on a Tertiary erosion surface but the conglomerates appeared to resemble Enon deposits rather than basal conglomerates of the Table Mountain Group as they had previously been described. Outcrops in the quarry of rock similar to the diamictites of the Pakhuis Formation, TMG, led to further speculation. However, the clasts appeared to be derived from the Skurweberg and Rietvlei Formations of the TMG which outcrop extensively in the immediate vicinity.

A borehole drilled to a depth of about 40 m (log attached) indicated mainly conglomerates with about 5 m of mudstone at 25 m depth and some layers of sandstone and gritstone. From 37.05 m to 37.9 m, the grit and conglomerates contained tuffaceous material. Thin section examination by R G Cawthorn of the Department of Geology of the University of Witwatersrand revealed a few shards of volcanic glass. Fragments of carbonised wood were identified as Gymnosperm by M Zavoda of the Botany Department at the same University.

Air photo interpretation and field mapping were used to extend the occurrence of similar outcrops to a narrow trough of about 3 km in length and 1 km in width to the southeast of Jubilee Hill. This trough appears to be bounded by a fault on its northern side and by a sedimentary contact with rocks of the Table Mountain Group to the south.

A gravimetric survey along the Struisbaai-Bredasdorp road indicates a graben or half-graben type of fault-trough about 2 km wide, to the north of Struisbaai and striking slightly north of west. This trough is likely to be related or connected to that at Jubilee Hill (Malan *et al.*, 1988)."

4.2 GEOMORPHOLOGY

The overall shape of the South African coastline is controlled by geological processes. The outline of the coast was formed by the splitting of Gondwanaland (Du Toit, 1922). The pre-Gondwana

rocks are mostly hard and resistant to erosion, especially the quartzites of the TMG and thus readily forms rocky coastlines. By the end of the Cretaceous the present configuration of the coastline was established and the actual position of coastlines was determined by tectonic uplift and flexuring of the subcontinent and eustatic sea level movements caused by changes of the ice masses (Dardis and Grindley, 1988).

The local geomorphology at Struisbaai is characterized by an extensive wave-cut platform of post-Cretaceous age mostly covered by a veneer of tertiary sediments. This wave-cut platform is about 20 km wide and has a NE-SW trend which is parallel to the coastline eastwards of Cape Agulhas. The inland border of this wave-cut platform stretches from the Soetnysberg, which is on the coast 14 km west of Struisbaai, and in a NE direction past the village of Bredasdorp towards Potberg. The wave-cut platform is about 1200 km² in areal extent and the elevation is between 10 m and 30 m above present sea-level. For the Struisbaai peninsula the elevation has been measured in a number of boreholes and is shown in Figure 4.4. As can be seen this contact has an elevation varying from 8.7 mamsl to 16.5 mamsl.

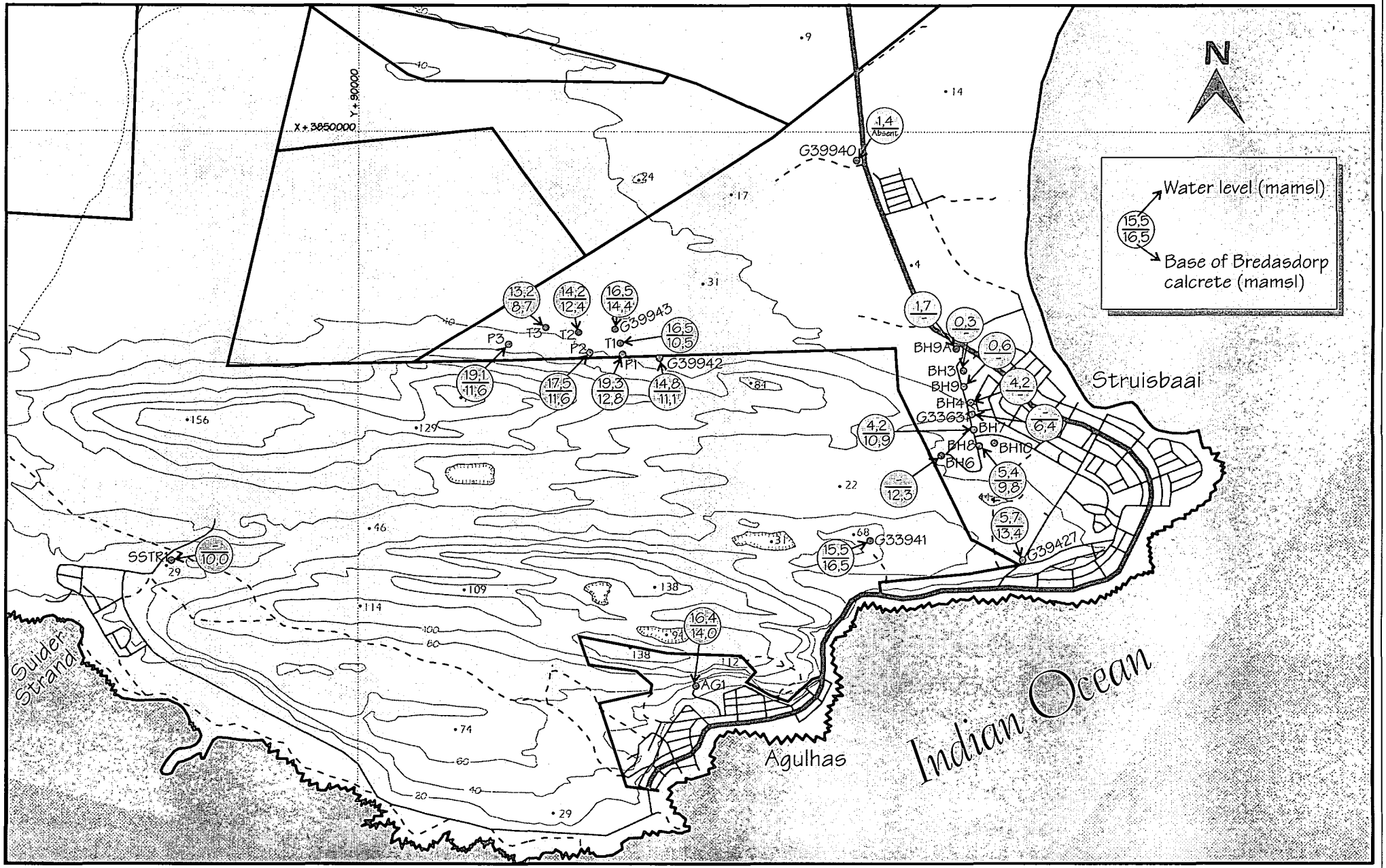
Unconformably overlying this wave-cut platform are the local marine and upper aeolian units of the Bredasdorp Group. The local marine De Hoopvlei Formation varies between 0.2 and 17 m and the aeolian Wankoe Formation is 50 to 290 m thick (Malan, 1988). The De Hoopvlei Formation is a shelly limestone with a local calcirudite and overlying calcarenite. The Wankoe Formation comprised of back shore aeolian sand dunes which lie parallel to the coastline. Examination of Figure 1.3 shows two of these east-west oriented sand dunes. Subsequent to deposition calcretization took place resulting in the present-day strong topographic highs which are resistant to weathering. Nevertheless chemical weathering has occurred and there are a number of surface karst features. Interconnected solution pathways have resulted in caves at the basal contact being common along the coastline. These also result in the numerous springs encountered along the coast, eg at Die Kelders and Stilbaai these springs form the main water-supply for these coastal resorts.

Inland of the Agulhas peninsula the Bredasdorp forms a thin veneer over the underlying geology. This has resulted in very flat topography with vleis, salt-pans and wetlands being common.

4.3 SEA-LEVEL TRANSGRESSIONS AND CONNATE SEAWATER

A sometimes used explanation for groundwater salinities, especially when high salinities are encountered is to ascribe it to rock-bound residual seawater. This is explained either as being from when the rock was deposited as a marine deposit (connate salinity) or from a period of marine transgression when the groundwater was replaced by seawater. The high salinities encountered in shales of the Malmesbury Formation and of the Bokkeveld Formation are usually explained as being derived from connate salinity.

An example of this explanation is from the Breede River Valley. The high and increasing salinities encountered from agricultural return-flow drains are explained as due to farmers developing new fields or ploughing deeper, thus exposing fresh rock-faces to percolating water and thus allowing connate salts to be dissolved (Greef 1991, 1994). Similarly if one collects fresh drill cuttings from a borehole in either of these formations and soak them in water, the salinity of the water increases due to salts being leached from the fresh rock faces exposed on these drill chips.



GEOCHEMISTRY & ISOTOPES

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Figure 4-4
 Map showing the relationship of the calcrete/quartzite contact to water levels of August (Both in MAMSL)

Legend

- Tracks
- Contours (20m interval)
- Spot Elevation
- Borehole
- Farm Boundaries
- Contours (20m interval)
- Borehole

0 0,5 1,0
 kilometre

Groundwater Group
 Cape Water Programme
 CSIR

The calcretes of the Bredasdorp Group have been exposed to seawater both during deposition and during subsequent marine transgressions. An argument for the salinities of the groundwater could be that it is derived from residual seawater. It is not doubted that leaching of the Bredasdorp does occur during rain infiltration as the groundwater has high calcium and alkalinity which is not obtained from the quartzites.

However, over the last 50 000 years the sea-level around the southern African coast has been below its present level, as is shown in Figure 4.5.

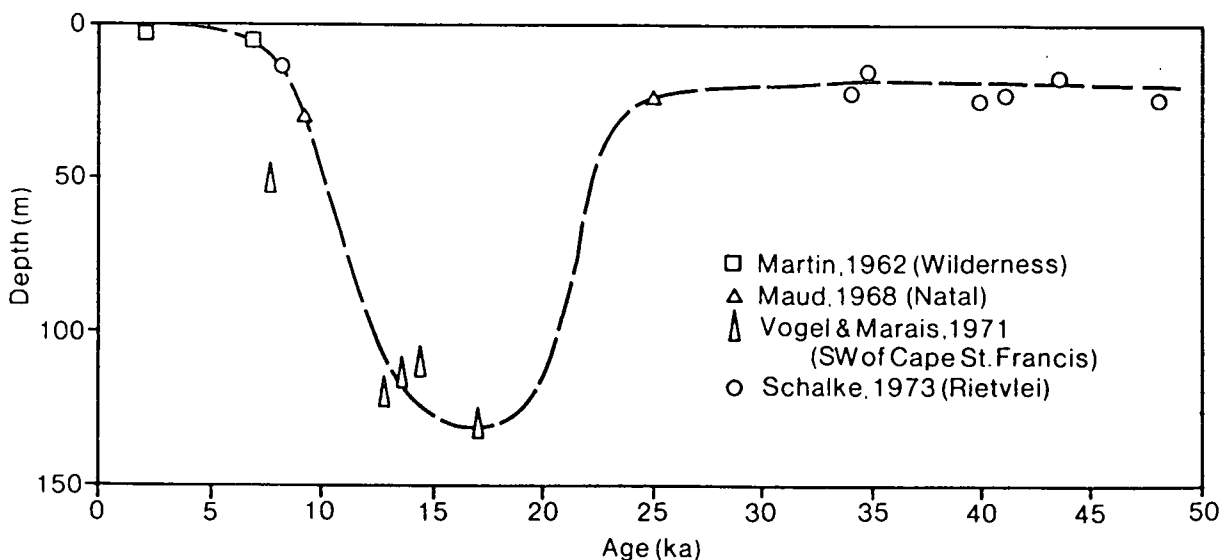


Figure 4-5 Late Quaternary southern African sea-level changes (after Tankard (1976) and Dardis and Grindley (1988))

Figure 4.5 shows that historic sea-levels have always been below current sea-levels. However, there is evidence that for a brief period between 6000 and 5000 B.P. sea-levels were up to 3 metres above present levels (Yates *et al.*, 1986; Miller, 1990; Miller *et al.*, 1993). This sea-level nevertheless is lower than the wave-cut platform which is at + 8.7 to + 16.5 mamsl.

Now if sea-level has been mostly below the present sea-level it has also been below the base of Bredasdorp in the Agulhas Peninsula and the coastal plain. With the relatively high permeability encountered for calcrete it is improbable that after 50 000 years that connate seawater is still encountered in sufficient quantities as to be a cause of the high salinities encountered.

Toens (1991) carried out a hydrocensus of the area up to the Heuningnes River which is 14 km north of Struisbaai and found high salinities of up to 1200 mS/m. This was associated with Bokkeveld Formation shales and these salinities could very well be connate salinity.

4.4 CONCLUSIONS REGARDING CONNATE SEAWATER

In the Agulhas peninsula there is a wave-cut platform at an elevation of 8.7 to 16.5 mamsl. The basal rocks are quartzites of the TMG and unconformably overlying this wave-cut platform are calcretes of the Bredasdorp Formation.

For the last 50 000 years sea-levels were mostly below the current sea-level. For a brief period 6000 to 5000 B.P. sea-level was + 3 mamsl. This is below the wave-cut platform which is + 8.7 m to + 16.5 mamsl. As the calcretes have some permeability it is highly unlikely that there is sufficient residual connate seawater which could give rise to the salinities encountered in the Struisbaai water-supply.

The conclusion is thus that connate seawater is not the source of salinity in Struisbaai water-supply.



CHAPTER 5

HYDROGEOLOGY OF THE STRUISBAAI AREA

5.1 OVERVIEW

In the Struisbaai Peninsula there are two geological formations which each have an important role to play in controlling the hydrogeology. The TMG quartzites which have been wave-cut to form a flat topped unit and the overlying calcretes of the Bredasdorp are the role players.

Minor other aquifers lie to the north of the NW-SE trending thrust fault, these are the Bokkeveld shales and north of the NW-SE trending graben fault are the Uitenhage Formation sediments.

5.2 QUARTZITES OF THE TMG

Geological mapping shows three quartzite formations, Skurweberg, Goudini and Peninsula (Figure 4.1). In terms of groundwater hydraulics these can be lumped together as one aquifer. They are all quartzites which effectively have no primary porosity as lithification has remobilized quartz which has filled the voids between the original sand grains. Secondary porosity associated with weathering and micro-fracturing forms the storage which is exploited by boreholes which intersect the larger and more open fractures. The quartzites are very competent thus during deformation the fractures that form tend to stay open and to stay open to great depths. Elsewhere in the Cape Province are found numbers of hot springs all of which are associated with TMG quartzites. This confirms that these fractures remain open at great depth. Examination of the geology map (Figure 4.1) shows that a number of faults have been recorded. These are a variety of types and are of different ages. In the bottom right corner of Figure 4.1 are listed the various structural features. It is seen on this map that both the old and the new wellfield have faults recorded in the vicinity.

Drilling and test-pumping records for the old wellfield boreholes do not exist. The only available data is from Meyer's (1986a and 1986b) reports on Struisbaai and Agulhas. The data for Struisbaai is shown in Table 5.1 below.

Detailed borehole logs as well as test-pumping data are available for the three production boreholes P1, P2 and P3 from the new wellfield. Also available are drill records but no test pumping for the boreholes G39940 to G39943. These are presented in Appendix 1 (drilling logs) and Appendix 2 (test-pumping data). Down hole geophysics is presented in Appendix 4.

From these data the elevation of the calcrete/quartzite contact can be determined as well as the depth of the main water strikes below this contact. This is numerized in Table 5.2. The calcrete/quartzite contact and water-level data is also depicted in Figure 4.4.



Table 5.1 Struisbaai. Borehole details for the old wellfield (from Meyer, 1986a)

Borehole No.	Depth (m)	Tested delivery (L/s)	Water-level (mbd)	Water-strike (m)	EC (mS/m)	Water-levels (1994) (mbd)	Remarks
3	?	6.3	?	?	?	4.5	Abandoned. Collapsed.
4	85	11.3	9.10	?	?	-	Pump not working.
5	90	8.6	?	?	?	10.3	Not in use, equipment blocking borehole.
6	117	7.5	9.14	35-85	153	4.76	Pumping @ 5 L/s. Production borehole.
7	153	13.9	10.67	137-139	148	9.0	Pumping @ 7.6 L/s. Production borehole.
8	130	13.3	12.19	56-107	145	10.6	Pumping @ 7.6 L/s. Production borehole.
9	123	8.8	8.00	?	167	-	Pumping @ 8.8 L/s. Production borehole.
9A	*	*	*	*	*	2.3	Abandoned due to poor quality water. Position approximated.
10	88	8.8	?	?	?	-	Pumping @ 8.8 L/s. Production borehole.

*No details. Poor quality water. Possibly drilled into Bokkeveld shales.

Table 5.2 Struisbaai. Table showing the calcrete/quartzite contact elevation, water-strike position and water-levels.

Borehole No.	Calcrete/quartzite contact elevation (mamsl)	Main water-strike (mamsl)	Water-level (mamsl)
AG1	14.0	13 to 14	16.4
BH6	12.3	-20 to -70	11.3
BH7	10.9	-120 to -124	4.2
BH8	9.8	-38 to -90	5.4
BH9	-	-	0.6
G39927	13.4	-28 to -36**	5.7
G39941	16.5	-4*	15.5
G39942	11.1	-25*	14.8
G39943	14.4	-16*	16.5
P1	12.8	-13 to -46	19.3
P2	11.6	-30 to -60	17.5
P3	11.6	-55 to -71	19.1
T1	10.5	-	16.5
T2	12.4	-	14.2
T3	8.7	-	13.2
**	From down hole log		
*	First water-strike		

Examination of Table 5.2 shows that the calcrete/quartzite contact varies from 8.7 to 16.5 mamsl and excluding the lowest and highest there are 12 records of contacts which are between 9.8 and 14.4 mamsl. The water-level in the old wellfield area is mostly a few metres below this contact and for AG1 and the new wellfield it is a few metres above this level. This shows how uniform was the wave-cut platform.

Most notable, however, is that the water-strikes in the quartzites are all well below this contact and thus is also well below sea-level. Two cross-sections have been drawn, Figure 5.1 being north-south and Figure 5.2 east-west. These two figures show these water-strikes and the "zone of water-strike" which has been assigned a relatively high permeability factor. This could be a bit misleading in that the impression is given that there is only this single water-bearing zone. However, if a very deep borehole were to be drilled there will quite likely be more water intersections at greater depths.

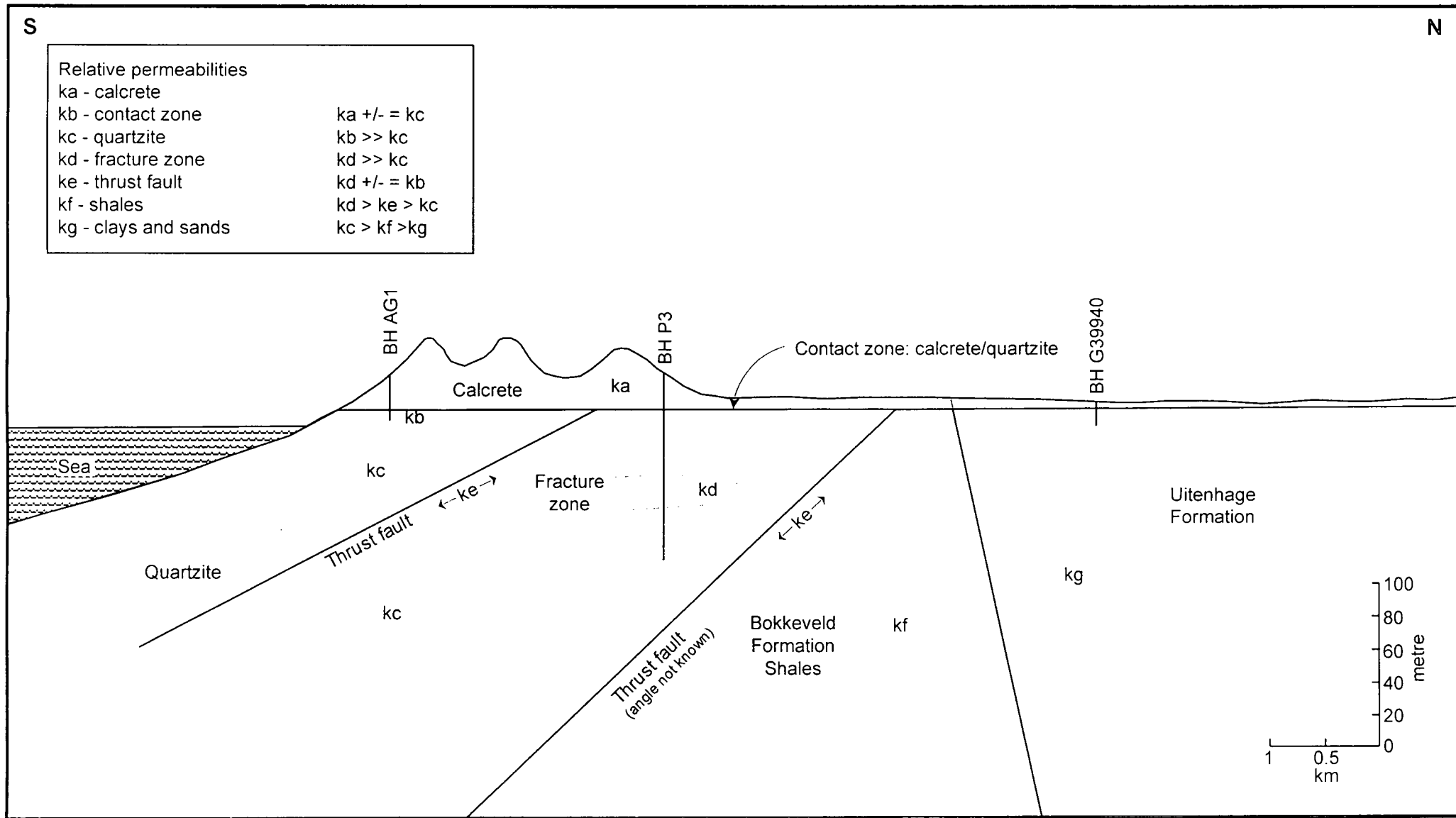


Figure 5-1: Struisbaai N-S geological sketch section (not to scale with vertical exaggeration of about 12 times)

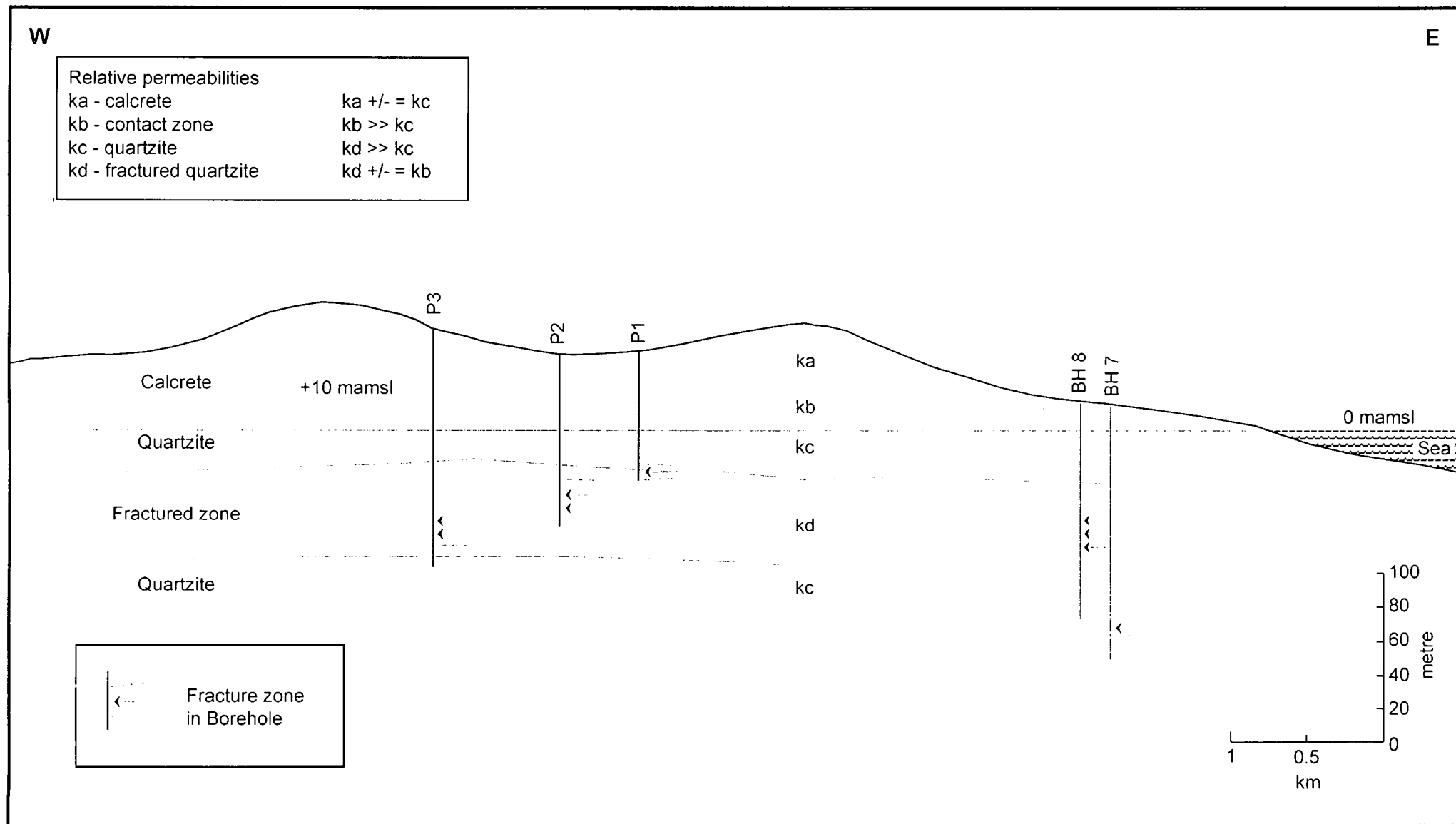


Figure 5-2: Struisbaai E-W section (roughly to scale)

Examining the data for the old "wellfield" it is seen that the water-levels are about 4 to 5 m above sea-level, with water-strikes up to 124 m below sea-level. Using the Ghyben-Herzberg relationship of 1:40 this would indicate that the saline interface is 160 to 200 m below surface. With the high hydraulic conductivities associated with fracture flow it is quite feasible that this interface could be drawn into the boreholes zone of influence. Up-coning would be a mechanism which would pose considerable danger of inducing salinity.

5.2.1 Test-pumping of boreholes in TMG quartzites

There are three boreholes for which proper test-pumping has taken place. The test pumping exercises for each borehole has been:

- ▣ multiple rate test comprising four to five steps of one hour each
- ▣ recovery test for multiple rate test
- ▣ constant discharge test of 72 hours
- ▣ recovery test of 70 minutes for P1, 200 minutes for P2 and for P3

The various test pumping curves are presented in Appendix 2. Also shown on these curves are the hand drawn straight lines which have been used to calculate transmissivity according to the Jacob Straight Line Method (Kruseman and De Ridder, 1991, Hazel, 1975).

From the McLea (1990, 1991) reports no data has been given for drawdowns measured in the observation boreholes. The only information given is the following:

"A drawdown of 2.2 m occurred in borehole P1 after 72 hours of pumping in P2, a distance of 280 m away" (McLea, 1990) and

"Monitoring of the existing borehole No. P2 was carried out during the 72 hour constant delivery test. The existing borehole No. P2 was monitored for the duration of the 72 hour test and showed only very slight fluctuations of less than 0.03 m over the period and returned to the static water level, at the end of the recovery period" (McLea, 1991). The distance of P3 to P2 is 710 metres. Thus no other analytical method can be used to determine transmissivity other than using Jacob Straight Line. The test pumping data and results are summarized in Table 5.3.

5.2.2 Analysis of test-pumping data

The test-pumping curves show two stages of reaction of the aquifer to pumping. The first stage (early curve) is the reaction of the fracture to pumping and the second stage (late curve) is that of the micro fractures and weathered quartzite. This is the double porosity model for fractured rock. The curve has a similar shape to that of a primary aquifer with leakage, except that for a fractured rock environment the second stage can continue indefinitely. Transmissivity has been calculated for both stages and presented in Table 5.3. It must be appreciated that although the transmissivity of the fracture is lower than that of the matrix the hydraulic conductivity of the fracture will be much higher. The hydraulic conductivity is not calculated as the thickness of the fracture is not known. For modelling purposes and long-term prediction of aquifer behaviour the late curve (second

stage) transmissivity is used.

Storativity is calculated using formula 3.10 on page 66 of Kruseman and De Ridder (1991).

$$S = \frac{2.25kDt}{r^2}$$

where k D = transmissivity = 100 m²/d
t = time = 3 days
r = radius P1 to P2 = 280 m

$$\frac{2.25 \times 100 \times 3}{280 \times 280}$$

$$8.6 \times 10^{-3}$$

This value is in the range that is generally observed and accepted for fractured rock aquifers.

Table 5.3 Struisbaai. Test-pumping data for new wellfield boreholes P1, P2 and P3 (from McLea, 1990; 1991)

Borehole No	P1	P2	P1 (OBS)	P3
Elevation of water strike (mamsl)	-13 to -38	-29 to -59	P2 (Pumping)	-55 to -67
Test rate m ³ /hr	25.2	46.0	46.0	34.8
Drawdown at end of constant rate CD (m)	11.7	21.3	2.2	24.7
Residual drawdown after 3.3 hour recovery (m)	0.7	1.2	?	0.2
Elevation of drawdown at end of CD test (mamsl)	+7.6	-3.9	15.2	-5.6
EARLY CURVE T from Jacob Str. Line				
Pumping	25	29	No data	17
Recovery	35	30		13
LATE CURVE T from Jacob Str. Line				
Pumping	205	145	No data	182
Storativity	-	-	8.6 x 10 ⁻³	-
Transmissivity and storativity calculated by Weaver (the author) from the McLea test-pump data.				

5.3 CALCRETES OF THE BREDASDORP GROUP

The calcretes have an important role in influencing recharge. On surface are observed many solution features. Internal drainage features can be seen between the ridges of the fossil dunes.

The second important feature of the calcretes is found at the basal contact with the underlying quartzites. At this contact is often found a cavernous solution cavity. This feature possibly has a strong control on the hydrogeology in that the hydraulic conductivity is very high and this acts as a drainage feature providing an upper limit to the water-table. High-yielding springs at this basal contact are a feature of the South Cape coast, eg. at Stilbaai and the Kelders.

Borehole AG1 is exploiting groundwater from this contact zone. This borehole intersected the cavity at 21 m below surface and drilling was stopped at 22 metres. The water-level is at 18.6 m which means that there is 2.6 metres of available drawdown. A pumping rate of 31.5 L/sec for 48 hours was sustained which indicates the very high hydraulic conductivity of this contact zone. Unfortunately no drawdown data is available and thus transmissivities cannot be calculated.

5.4 SHALES OF THE BOKKEVELD GROUP

No outcrop is exposed and no information is available for the strip of shales to the north of the quartzites. Further north from the Enon infilled graben, Toens (1991) in a hydrocensus identified boreholes drilled into the Bokkeveld shales. He did not note any hydraulic information, merely ascribing the high measured salinity to being derived from the shales.

5.5 ENON GROUP

No hydraulic information is known for this formation.



CHAPTER 6

HYDROGEOCHEMISTRY AND ISOTOPES

6.1 OVERVIEW

As mentioned in Chapter 1.3 the original investigation was aimed at determining variations of groundwater chemical and isotopic content with time and relating these variations to groundwater reservoir capacity. No variations of any significance were observed and after one year monitoring was discontinued. The data are presented in Appendix 3.

Considering two of the production boreholes, AG1 which supplies Agulhas and P3 supplying Struisbaai, if one examines the data then this reasoning for stopping the monitoring is illustrated. AG1 has C^{14} of 45% which is taken to be old water, while P3 has C^{14} of 83% making this water old but younger than AG1. Table 6.1 below shows selected determinants and the observed consistent results over a period of about two years.

Table 6.1 Struisbaai. Selected determinants from two production boreholes illustrating the consistent results.

Date of sampling		4/3/93	27/10/93	15/4/94	28/8/94	6/12/94
AG1 Agulhas						
Chloride	mg/L	347	359	356	364	367
Silica	mg/L	4.4	3.8	3.8	3.9	3.9
Alkalinity	mg/L	215	228	216	217	212
C^{14}	PMC	45.5	46.3	45.1	45.3	44.7
$\delta^{18}O$	‰	-4.8	-4.7	-4.7	-	-5.0
P3 Struisbaai						
Chloride	mg/L	139	142	138	140	147
Silica	mg/L	4.8	4.1	4.3	4.4	4.2
Alkalinity	mg/L	208	220	209	238	208
C^{14}	PMC	84.1	83.2	82.6	84.1	82.3
$\delta^{18}O$	‰	-4.9	-4.8	-4.0	-	-5.1

6.2 DISCUSSION OF HYDROCHEMICAL DATA

As the results show little variation with time an average of the results has been calculated and is presented in the data sheets of Appendix 3 in the final column of data for each borehole. This data has been used to prepare the tri-linear plot or Piper diagram of Figure 6.1.

Piper Diagram

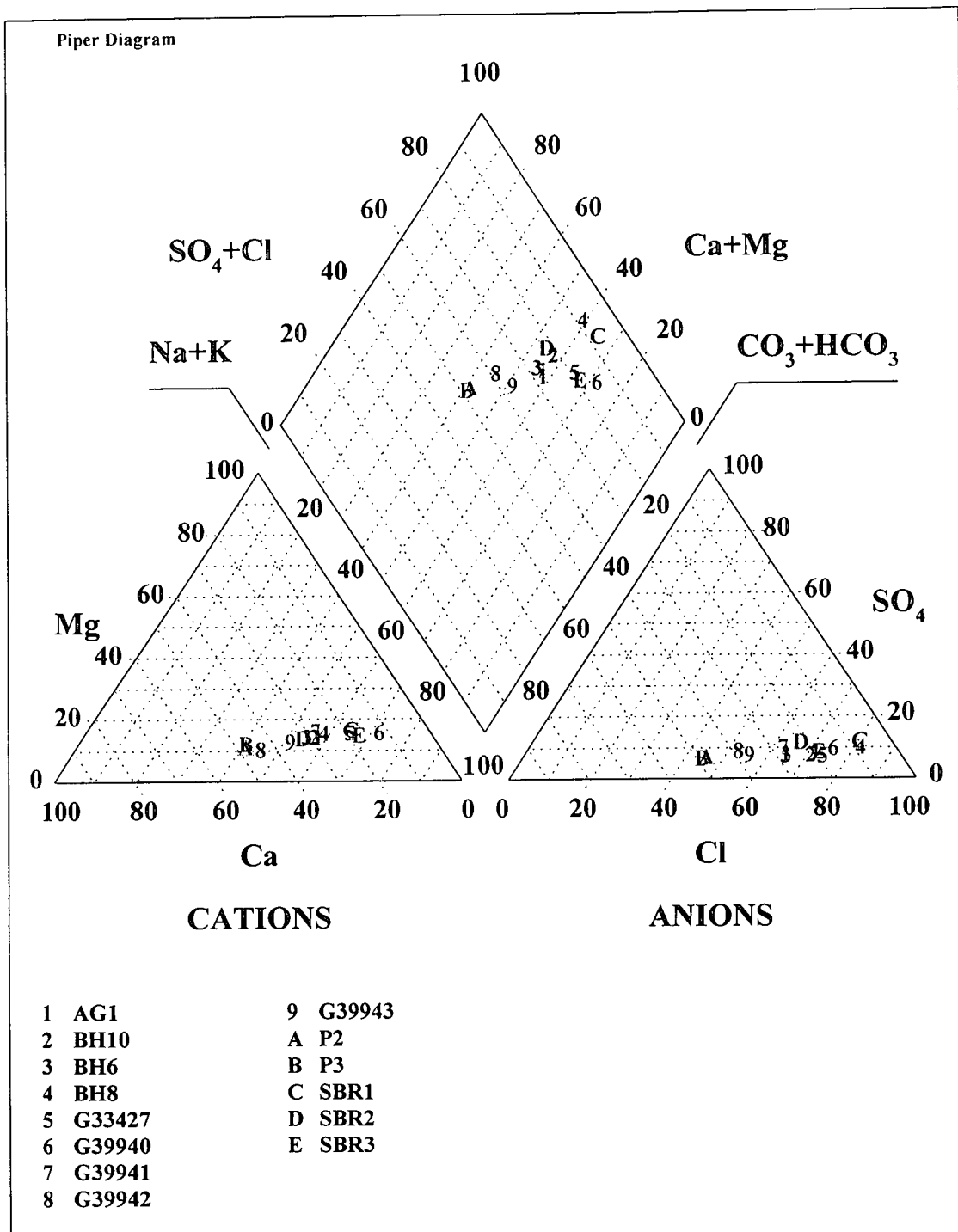


Figure 6-1 Struisbaai : Piper diagram of groundwater from sampled boreholes and rainwater from rain-collectors

For the Piper diagram the left corner represents newly recharged water which is relatively high in calcium magnesium and alkalinity, and low in sodium, and chloride. The right hand corner is regarded as stagnant water or old water from the discharge zone of an aquifer. Also the right hand corner represents sea water (Johnson, 1975; Mazor, 1991; Lloyd and Heathcoate, 1985).

Mazor (1991) further shows that the straight line joining these two end points represents mixing of waters from these two end points. This is shown in Figure 6.2.

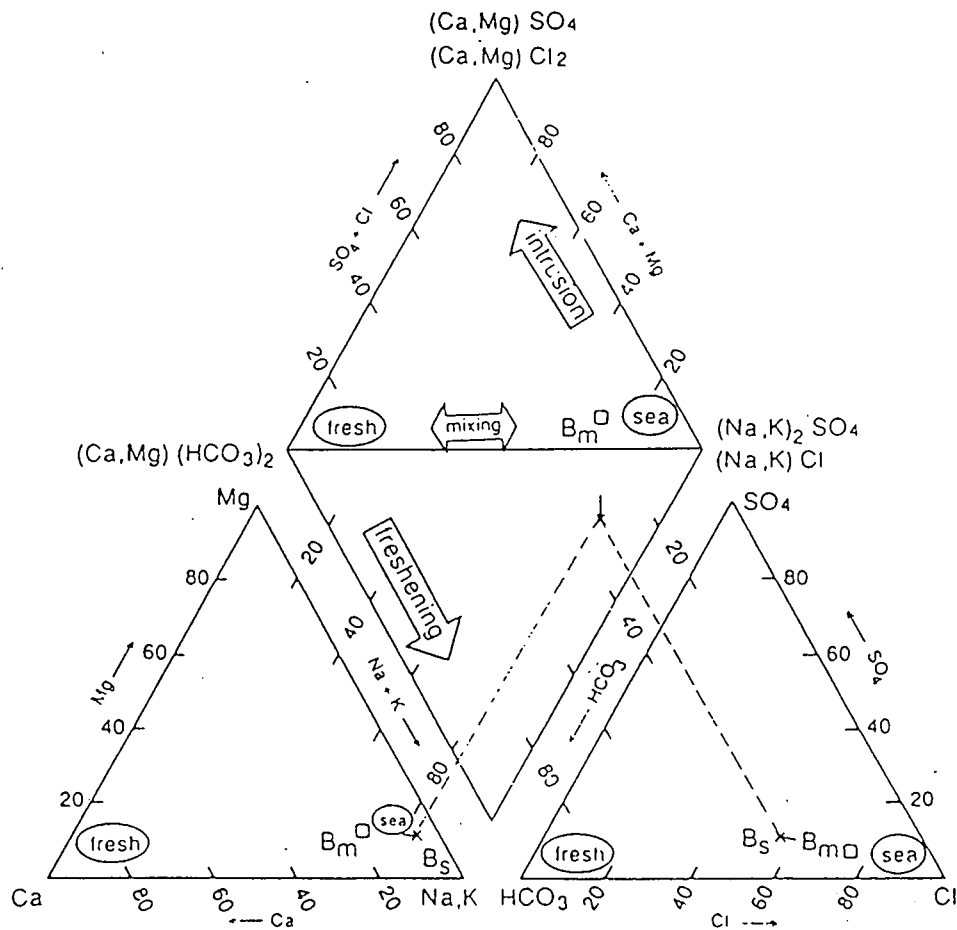


Figure 6-2 Piper diagram showing average compositions of fresh water and seawater (from Mazor 1991)

Also shown in Figure 6.2 are the two directions in which chemistry will plot for an aquifer which is either in the process of flushing out, saline water "freshening", or is being subject to saline intrusion. Comparing Figure 6.1 to Figure 6.2 it is seen that all these boreholes plot in the mixing zone except perhaps for borehole BH8. Note also that SBR1 the rain sampler with the more salty (Na and Cl) water also plots along this line. This would support the saline rainwater theory. The connate water theory for the origin of salinity would plot on the freshening area of the piper plot, while seawater intrusion would plot on the intrusion part of the diagram. BH8 could be considered to be in the intrusion area of this graph. This is discussed further in Chapter 6.5.2.

A number of graphical plots of one chemical determinant versus another have been prepared and presented as Figures 6.3 to 6.9. Also plotted on these Figures is the seawater mixing line which has been derived from Table 3.5.

Figure 6.3 is chloride versus sodium. Notable on this figure is the very close correlation of the boreholes with the seawater mixing line. This indicates that the salinity of these boreholes is derived from either seawater intrusion or sea-spray and not from connate salts. Also plotted is the crystalline sodium chloride ratio. This would represent solution of crystallised sea salt. It is noted that G39940 plots between these two mixing lines. This could mean that the salinity encountered in G39940 is a mixture of seawater/sea spray and residual crystalline salt from previous seawater transgressions.

Figure 6.4 is chloride versus potassium. There is a reasonable correlation with the seawater mixing line supporting seawater intrusion or salt spray.

Figure 6.5, chloride versus calcium, shows that all samples are enriched in calcium compared to the seawater mixing line. This represents calcium dissolved from the limestone during rainwater recharge.

Figure 6.6 shows chloride versus magnesium. This shows a very good correlation with the seawater mixing line showing that the magnesium is derived from either seawater intrusion or salt-spray. During salt water intrusion dolomitization processes which characteristically accompany saline intrusion (Fidelibus and Tulipano, 1991; Mazor, 1991) tends to reduce the magnesium concentration in the mixed water. This is, however, a slow process.

It is noted that G39940 and BH8 do plot slightly below the seawater mixing line indicating that there could be some dolomitization effect. All the waters are regarded as salt spray mixing or young salt water intrusion.

Figure 6.7 shows chloride versus sulphate. There is a good correlation to the seawater mixing line.

Figure 6.8 shows chloride to strontium. All analyses show enrichment of strontium. This strontium is derived from dissolution by percolating rainwater of the calcretes which were derived from seashells. The strontium levels are thus enhanced similar to calcium.

Figure 6.9 shows chloride versus iodine. Iodine levels are enriched versus the seawater mixing line. It is thought that this iodine, similar to strontium, is derived by percolation of rainwater. No literature could be obtained mentioning this phenomenon.

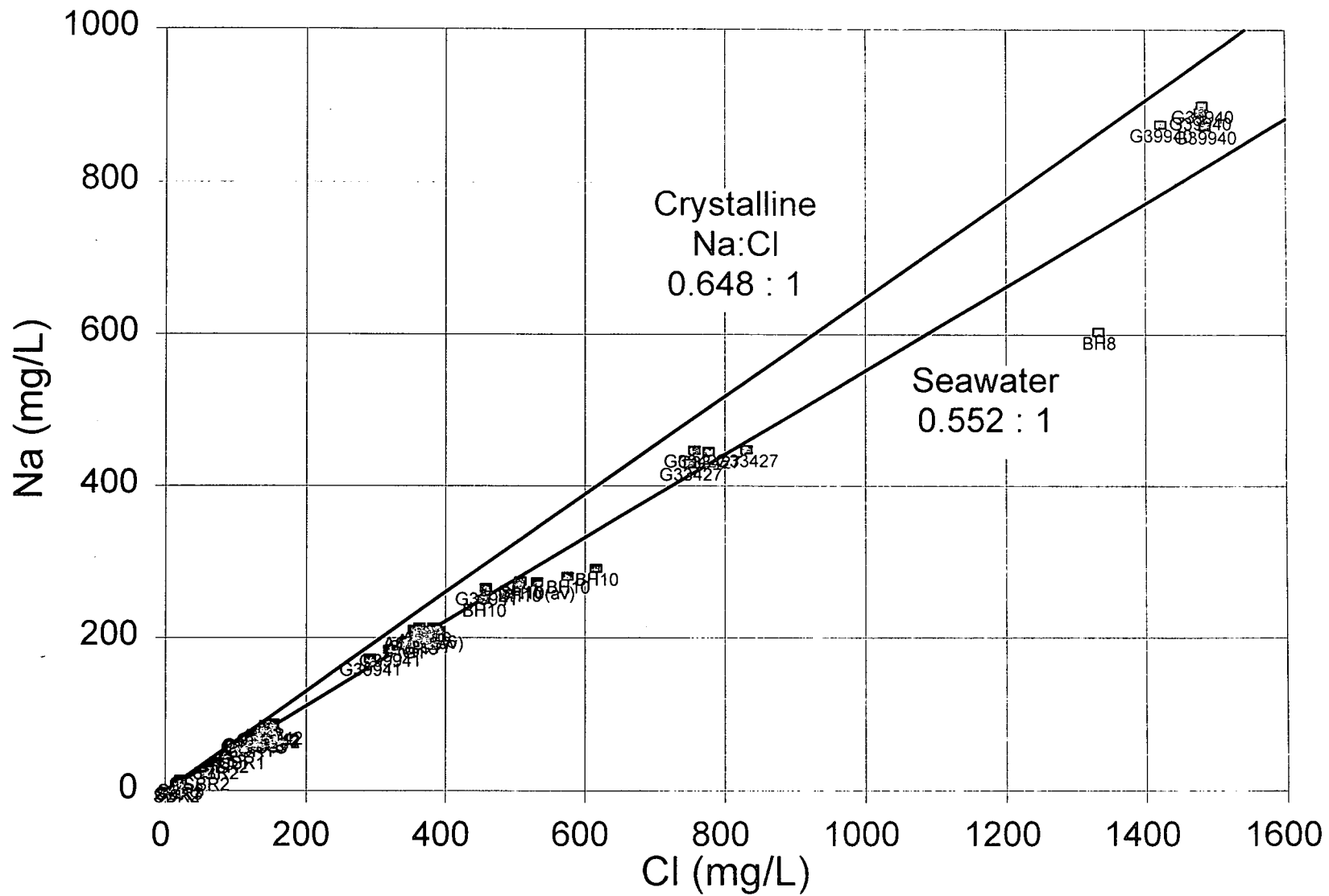


Figure 6.3: Struisbaai. Chloride versus Sodium

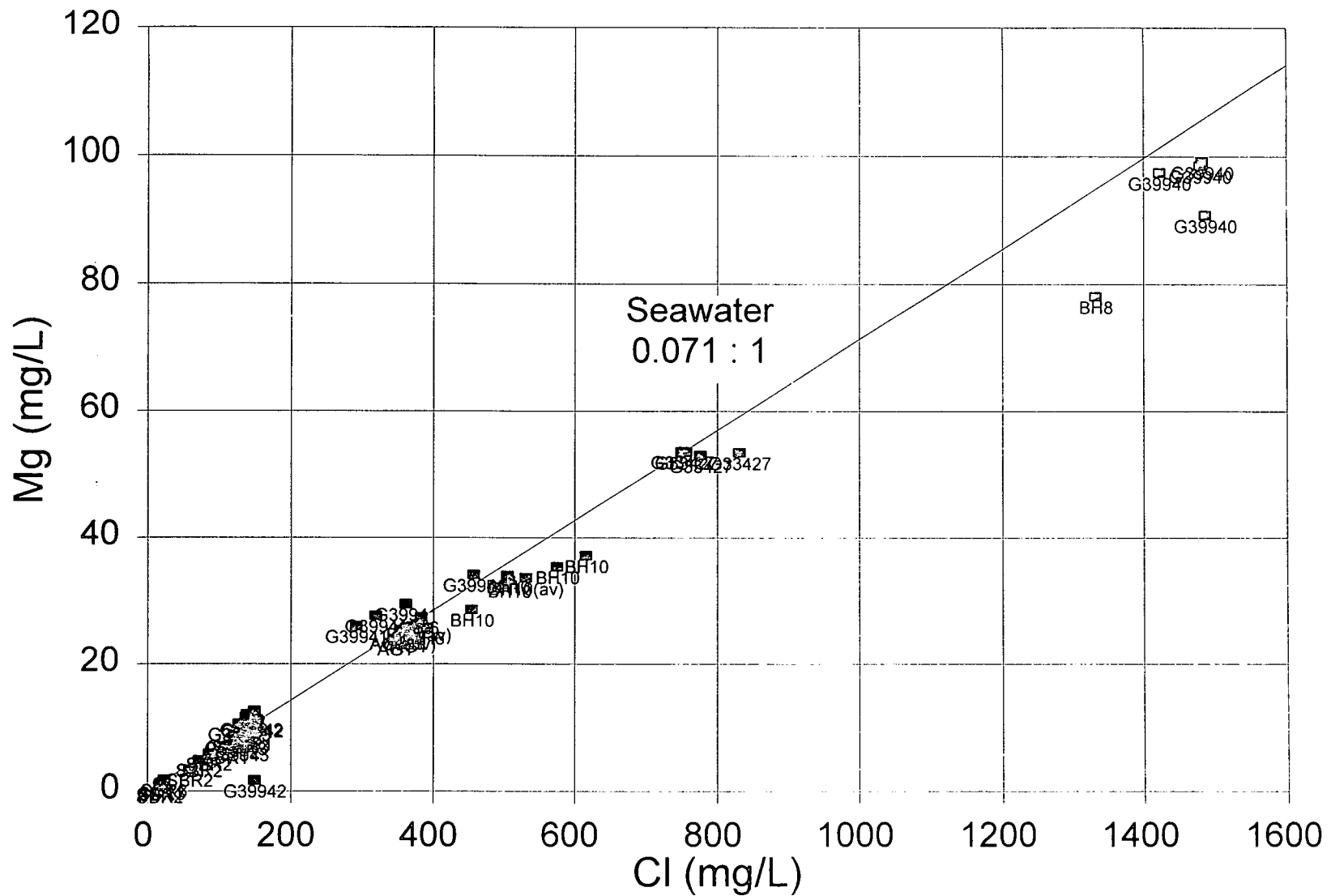


Figure 6.6: Struisbaai. Chloride versus Magnesium

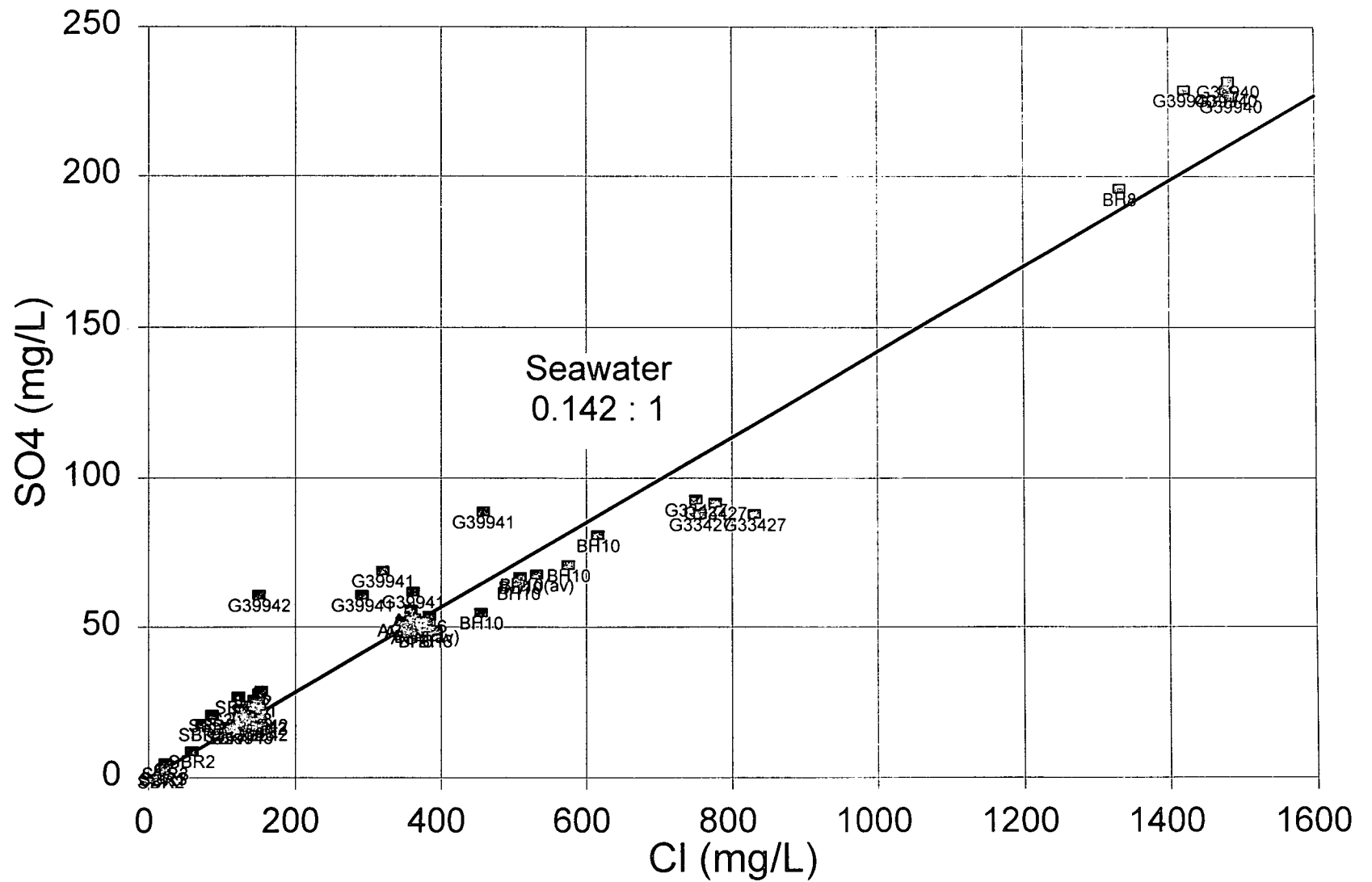


Figure 6.7: Struisbaai. Chloride versus Sulphate

x 9 057 871 I

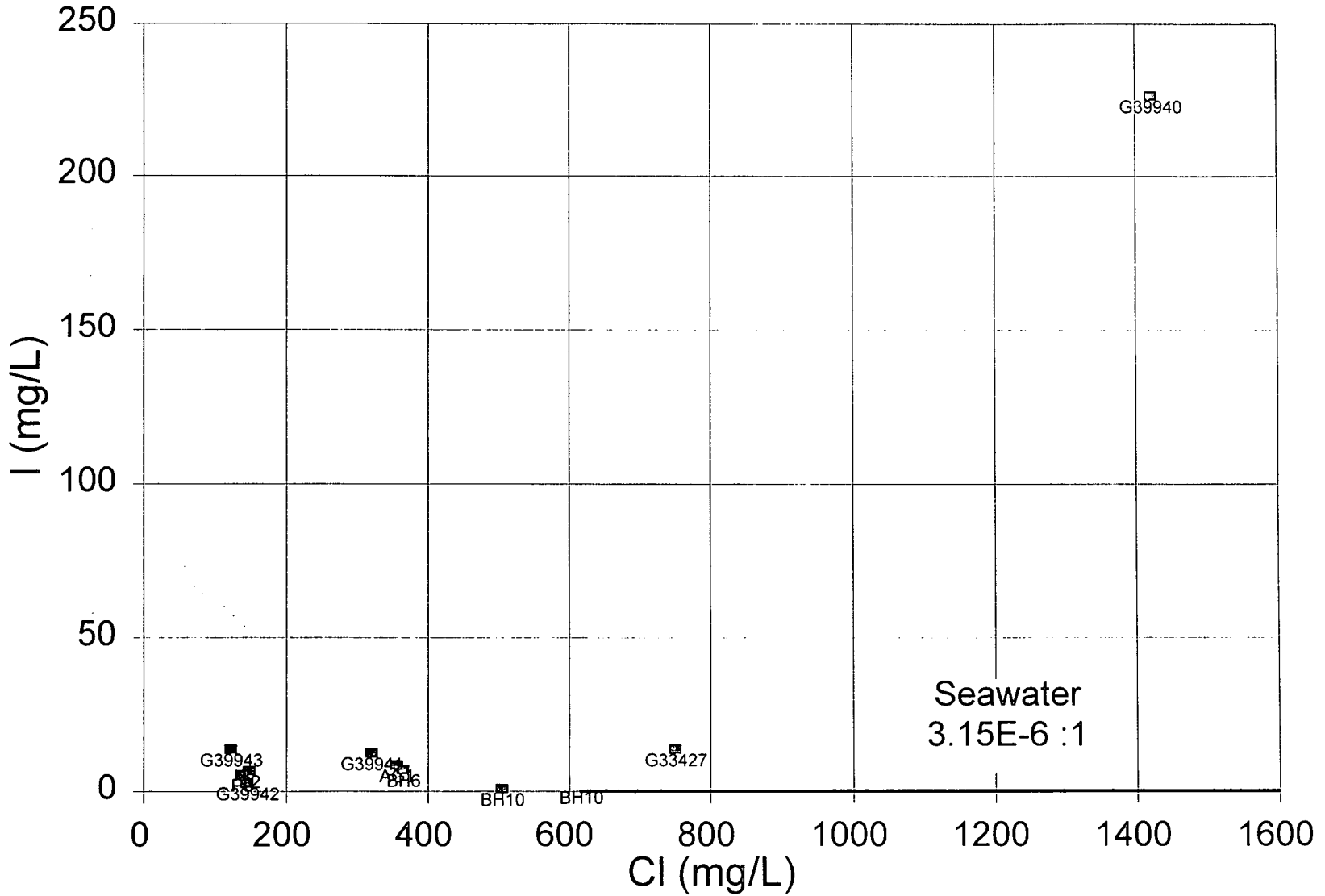


Figure 6.9: Struisbaai. Chloride versus Iodine

6.2.1 Conclusions from Chemistry Overview

- The Piper diagram shows that all boreholes fall on a mixing line between the left and right corners of the triangle. BH8 appears to be on the saline intrusion mixing line extending towards the top corner.
- Calcium and strontium are enriched by solution of calcretes during recharge.
- Sodium, chloride, potassium, magnesium and sulphate all fall on the seawater/sea spray mixing line thus indicating that there is no other source for these ions. This precludes the shales of the Bokkeveld being a source of salinity. Calcrete being composed of quartz, sand and calcium carbonate can only contribute calcium and strontium. Quartzites of the TMG being inert will not contribute any ions.

6.3 USES OF ENVIRONMENTAL ISOTOPE HYDROLOGY IN GEOHYDROLOGY

The naturally occurring stable isotopes, hydrogen (H), deuterium (D), oxygen-16 (^{16}O), oxygen-18 (^{18}O), carbon-12 (^{12}C) and carbon-13 (^{13}C) and the radioactive forms, tritium (T) and radiocarbon (^{14}C), have become useful tools in groundwater studies. The main hydrogeological use of environmental isotopes can be summarised as follows:

- to provide a signature to a particular water type;
- to identify the occurrence of mixing two or more water types;
- to provide residence time information about groundwater;
- to provide information concerning travel times and groundwater velocities;
- to provide information on water-rock interaction (Lloyd and Heathcote, 1985).

As it is not useful to present the absolute concentration of a single isotope, stable isotopic abundances are reported as a ratio to some abundant isotope of the same element or as positive or negative deviations of these isotope ratios (R) away from a standard. The relative difference is designated by δ (normally expressed in parts per thousand, permil ‰).

$$\delta_x = \frac{R_x R_{std}}{R_{std}} \times 1000$$

R is the particular isotopic ratio (for example $^{18}\text{O}/^{16}\text{O}$ or $^{13}\text{C}/^{12}\text{C}$) for the sample and standard. The standard used for carbon is PDB (Pee Dee Belemnite) and for oxygen and hydrogen SMOW (Standard Mean Ocean Water).

The isotope ratios of natural compounds may change as a consequence of the history and processes to which such compounds have been submitted in the environment. The mass differences between isotopes of the same element produces small differences in their chemical and physical behaviour which in turn establish slightly different isotopic compositions (isotope fractionations), among co-existing chemical compounds or phases (Unesco, 1973).

6.4 CARBON ISOTOPES

6.4.1 Introduction

Three isotopes of carbon occur naturally: stable ^{12}C and ^{13}C and radioactive ^{14}C .

The behaviour of ^{13}C in groundwater is studied in the context of the carbonate system. This system is complex in the subsurface and the most important application of $\delta^{13}\text{C}$ data is in process identification (Domenico and Schwartz, 1990).

The ^{13}C content of groundwater is controlled by dissolution, precipitation and fractionation processes. Initially the ^{13}C chemistry is controlled by the $\delta^{13}\text{C}(\text{CO}_2)_{\text{gas}}$ in the atmosphere, which falls in a range from -7 to -10%.... with respect to the carbonate PDB standard (Domenico and Schwartz, 1990). Changes in $\delta^{13}\text{C}$ occur when carbon is added to, or removed from, the water during its transit through the aquifer. Possible sources of carbon are:

- Dissolution of calcite, aragonite, or dolomite from limestone, which introduces relatively heavy carbon.
- Oxidation of organic matter, which introduces relatively light carbon.
- Transport of CO_2 gas from a soil atmosphere, which also introduces relatively light carbon.

Carbon may be lost from the water by precipitation of a carbonate mineral or by loss of CO_2 gas. In general ^{13}C is used to identify sources of carbon and is particularly valuable for distinguishing between carbon derived from organic matter (light) and carbon derived from carbonate minerals (heavy) (Drever, 1988).

Radiocarbon (^{14}C) is produced in the atmosphere by interaction of cosmic rays with nitrogen and was introduced in large amounts by nuclear weapons testing. ^{14}C has a half-life of 5730 years, making it a useful tool for dating waters as old as 50 000 years. The ^{14}C generated in the atmosphere is carried down to the earth's surface by precipitation, and becomes incorporated into the biomass or transported into water bodies such as lakes, the ocean and groundwater (Drever, 1988).

Measurements of ^{14}C are reported in terms of per cent modern carbon (pmc) where:

$$A \frac{(^{14}\text{C}/^{12}\text{C})_{\text{SAMPLE}}}{(^{14}\text{C}/^{12}\text{C})_{\text{MODERN}}} \times 100 \text{pmc}$$

There are some complications in the behaviour of ^{14}C during recharge, so the "absolute" age of a groundwater cannot be determined reliably. However, if the ^{14}C concentration is measured at several points along a flow line within an aquifer, the differences in age between the points and hence the flow velocity can be determined (Vogel, 1967). One complication is that dissolution of organic matter or carbonate minerals within the aquifer may add "old" or "dead" (no detectable ^{14}C) carbon to the water, giving an erroneously old age. The contribution of carbon from these sources

can sometimes be estimated from the $^{13}\text{C}/^{12}\text{C}$ measurements and chemical arguments, so corrections can be made (Talma *et al.*, 1984). Another complication is mixing. A low ^{14}C concentration may mean that we are looking at relatively "old" water, or it may mean that we are looking at a mixture of relatively "young" water and "dead" water. ^{14}C measurements can be interpreted as ages only where mixing is insignificant (Drever, 1988).

6.4.2 Discussion of Carbon Isotope Results

These processes and methods of quantitative treatment of these processes in order to develop a full interpretation of the isotopic composition of dissolved carbon is extensively discussed in Mook (1983) and Lloyd and Heathcote (1985). Using these descriptions, the carbon isotope results from Struisbaai are discussed. As the analytical data was found to be constant with time the average of the sets of analyses for each borehole is used and is shown in Table 6.2 below, arranged in descending order of ^{14}C content.

Table 6.2 Struisbaai. Carbon and oxygen isotope data. The values shown are average valued for the various sampling runs and arranged in descending Carbon-14 content within wellfield groupings.

Borehole No	Carbon-13 (‰ PDB)	Total Inorganic Carbon (TIC) mM/L	Carbon-14 (PMC)	Oxygen-18 $\delta^{18}\text{O}$ (‰ SMOW)	Model Age (years)
G39940	-11.4	8.8	86.1	-4.2	recent
G39942	-11.2	3.6	90.4	-4.8	recent
G39943	-11.4	2.8	89.3	-4.8	recent
P3	-11.2	4.3	83.3	-4.9	50 - 400
P2	-11.2	4.5	80.8	-5.0	50 - 400
BH10	-12.7	4.9	84.7	-4.8	50 - 400
BH6	-12.3	4.8	81.9	-4.9	50 - 400
BH8	-12.5	4.5	81.0	-4.6	50 - 400
G39427	-12.3	6.0	68.0	-4.8	1800
G39941	-11.4	4.3	65.2	-4.9	2200
AG1	-10.6	4.4	45.4	-4.8	3800
Modern Seawater	+2.0	2.2	120	+0.3	

Depending on the various processes that take place young recharge water can have a ^{14}C content varying between 114 pmc and as low as 65 pmc. At Agter Witzenberg (Weaver *et al.*, 1997) there are no soil carbonates and the TIC (total inorganic carbon) comprises virtually entirely of CO_2 derived from the decay of plant material. Vogel (1970) found recent waters with ^{14}C content of 85 ± 5 pmc and explained this by isotopic exchange between inorganic carbon and gaseous CO_2 in the unsaturated zone. Lloyd and Heathcote (1985) present data from the Chalk aquifer in England where recent recharge water samples have a ^{14}C of 65 pmc.

The four boreholes in the new wellfield are G39942 and G39943 which have been drilled to the first water intersection at about 33 m and stopped and P_3 and P_2 which have been drilled much deeper to intersect higher yielding fractures. The two shallow boreholes show ^{14}C of 90.4 pmc and 89.3 pmc which shows good agreement with Vogels (1970) observation. The production boreholes which have the main water yielding intersections at about 100 m both have slightly lower ^{14}C at 83.3 pmc and 80.8 pmc which indicates slightly older water.

As the water strikes in the shallow boreholes and the deep boreholes are all in the quartzites there can be no isotope exchange reactions which could explain these differences. The difference is a hydrogeologic difference - the deeper water is the older water.

The old wellfield data from BH6, BH8 and BH10 show similar ^{14}C content as the new wellfield production boreholes P_2 and P_3 .

If one argues that the discharge zone for the regional groundwater flow is along the coast, then G39427, G39941 and AG1 can be regarded as sampling discharge water which would be the oldest water.

The ^{14}C values for these boreholes confirm this proposition by having the lowest ^{14}C values. Taking these ^{14}C values borehole AG1 apparently has the oldest water of all the boreholes. This, however, may be a result of solution - precipitation exchange processes. This occurs when the aquifer water which contains ^{14}C is in contact with the calcrete which has zero ^{14}C . In other words the C of the aquifer water moves into the calcrete which is exchanged for C from the calcrete which has no ^{14}C thus reducing the ^{14}C content of the groundwater and increasing the ^{13}C content. This borehole is the only production borehole where the aquifer water is in direct contact with the calcretes. The production zone is the solution cavity at the quartzite - calcrete contact. All other boreholes have the high yielding fractures in the quartzites which being pure quartz are not subject to aquifer carbonate solution-exchange processes. Supporting this theory that the ^{14}C has been lowered by solution-exchange processes is that the ^{13}C for AG1 is also lower than for any other borehole. Nevertheless the amount of exchange that has occurred is low, with ^{13}C only decreasing from -12.5 to -10.6 ‰. The ^{14}C thus indicates this water is old.

6.4.3 Conclusions from carbon isotopes

The carbon isotopes show variations according to sampling position in the regional aquifer.

- ➡ At the same site deeper water has lower ^{14}C than shallower water thus confirming that deeper water is older water.

- ➡ Water from discharge zone sample sites have lower ^{14}C than boreholes up-gradient confirming that regional groundwater flow is from the interior towards the sea.
- ➡ Where aquifer water is in contact with calcretes then solution-precipitation processes occur increasing the heavier carbon-13 and reducing the ^{14}C content of the groundwater giving an apparently older age to the water.

6.5 STABLE ISOTOPES OF OXYGEN AND HYDROGEN IN THE HYDROLOGICAL CYCLE

6.5.1 Introduction

The most important physical process causing variation of isotopic composition in natural waters is vapour-liquid fractionation during evaporation and condensation. The vapour pressure of water containing the light isotopes (^1H and ^{16}O) is greater than that of water containing the heavier isotopes (D and ^{18}O). When liquid water and water vapour are in equilibrium, the vapour is isotopically lighter with respect to both D/H and $^{18}\text{O}/^{16}\text{O}$ than the liquid, and hence water vapour in the atmosphere is isotopically lighter than water in the ocean (Drever, 1988).

Water vapour which evaporates from the ocean is depleted by 10 - 15 ‰ in ^{18}O and by 80 - 120 ‰ in D with respect to SMOW (Standard Mean Ocean Water) (Unesco, 1973; Drever, 1988).

When water vapour condenses to form rain, fractionation takes place in the reverse direction, with the liquid being isotopically heavier than the vapour. The fractionation during evaporation is thus largely reversed during condensation and the first rain to fall from water vapour over the ocean would have an isotopic composition of about -3 ‰ (Drever, 1988). If this rain again forms a vapour, ^{18}O will be selectively removed from the vapour phase and the $\delta^{18}\text{O}$ of the vapour will become progressively more negative as the rain continues to fall. By this process of *Rayleigh fractionation*, rainfall becomes progressively lighter in both δD and $\delta^{18}\text{O}$ as it occurs further from the ocean source. The δD and $\delta^{18}\text{O}$ values in precipitation generally plot close to a straight line (the *meteoric water line*) with equation:

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

The slope (8) is a general determined by the physical properties of the isotopes. The intercept (10), also called the d-excess, is a general one applicable to the world's composite set of samples (Dansgaard, 1964). Locally d-excess values ranging from 0 to +25 have been observed (IAEA, 1922; Gat and Carmi, 1970).

Water with an isotopic composition falling on the meteoric water line is assumed to have originated from the atmosphere and to be unaffected by other isotopic processes. Evaporation from open water and exchange with rock minerals are two of the more commonly observed processes causing deviations from the meteoric water line (Domenico and Schwartz, 1990).

As temperature has a dominant effect on isotopic fractionation, variations in isotopic concentrations in precipitation can relate to climate and altitude (Lloyd and Heathcote, 1985). This dependency on temperature produces seasonal isotope variations (winter precipitation is depleted in heavy isotopes with respect to summer precipitation); latitude variations (high latitude

precipitation is depleted with respect to low latitude precipitation) altitude effects (the heavy isotope content of precipitation decreases with increasing altitude) and amount effects (larger rainstorms tend to have lower heavy isotope content). In regional hydrological studies, the altitude effect can be used to differentiate groundwaters derived from recharge areas at different elevations. In general there is about a 0.3 ‰ decrease in $\delta^{18}\text{O}$ and 2.5 ‰ decrease in δD per 100 metres increase in elevation (Unesco, 1973; Midgley and Scott, 1944).

Isotopes of oxygen and hydrogen are, in a certain sense, ideal geochemical tracers of underground water because their concentrations are not subject to changes by interaction with the aquifer material (Unesco, 1973). Once underground and removed from zones of evaporation, the isotope ratios are conservative and only affected by mixing. When precipitation infiltrates to feed groundwater, mixing in the unsaturated zone smoothes the isotopic variations, so water in the saturated zone has a composition corresponding to the mean isotopic composition of infiltration in the area. This may differ slightly from the mean isotopic composition of precipitation due to the fact that not all precipitation during the year infiltrates in the same proportion (Unesco, 1973).

Analyses of δD and $\delta^{18}\text{O}$ can be used to identify the probable source of an underground water. If the isotopic composition of an underground water plots close to the meteoric water line in a position similar to that of present-day precipitation in the same region, the water is almost certainly meteoric. Although the isotopic composition of precipitation at a particular location is approximately constant, it varies from season to season and from one rainstorm to another. The variations can be used to identify the season at which most of the recharge takes place (Drever, 1988).

Groundwater recharged by seepage from surface waters such as rivers or lakes should reflect the isotopic signature of the surface water body eg. a river may collect water which originates at higher altitudes and is depleted in heavy isotopes while seepage from lake waters which have been evaporated will be enriched in heavy isotopes. Isotopic imaging of surface water/groundwater interactions is a useful application of δD and $\delta^{18}\text{O}$ data. Groundwater isotope data across the Sacramento Valley, California has been used to establish groundwater mining of ancient groundwater and to identify regions of limited recharge by surface water and areas of rapid recharge by irrigation water (Criss and Davisson, 1996). Such information can now be used to design an aquifer management scheme for the region.

In some areas palaeowaters may be present with different isotope ratios, often lower than those of modern age (Heaton *et al.*, 1986). These were recharged under different climatic conditions from those prevailing now, and are generally of great age.

6.5.2 Discussion of results

6.5.2.1 Overall results

The results are tabled in the last column of Table 6.2. Figure 6.10 shows chloride versus $\delta^{18}\text{O}$. This figure shows that $\delta^{18}\text{O}$ is independent of chloride. Examining the average results, except for G39940, the variation is minimal, ranging from -4.6 ‰ to -5.0 ‰. Examining the individual analyses for each sampling run it is seen that the range is from -4.6 ‰ to -5.1 ‰ which if one

considers that the analytical error is ± 0.2 ‰ indicates a uniform and localized direct recharge. The calculated average of all the analyses excepting those for G39940 and the incorrect analysis for P3 is -4.86 ‰ for a total of 32 analyses.

6.5.2.2 Borehole G39940

Borehole G39940, however, shows a significant increase of $\delta^{18}\text{O}$. This increase can be one of two factors, mixing with seawater or evaporation effects. This borehole has a higher salinity than any other sample which supports either of these two scenarios.

Accepting that the average rainfall salinity, as discussed in chapter 3, is 62 mg/L of chloride and that there is 10% recharge then the recharge water will have 620 mg/L of chloride. Seawater has 19000 mg/L of chloride. This borehole has an average of 1467 mg/L of chloride.

This mixing percentage is calculated as follows:

$$X\% \times 620 \text{ mg/L} + (100 - X)\% \times 19000 = 100\% \times 1467$$

thus $X = 95.4\%$

Thus the mixing ratio of recharge water to seawater would be 95.4% to 4.6%. Ocean water has a $\delta^{18}\text{O}$ of zero, so mixing seawater with the local recharge water which has a $\delta^{18}\text{O}$ of -4.86 in the ratio of 95.6 : 4.6 gives an end product of -4.65 ‰ which is above that of the measured value of -4.2 ‰. Thus mixing with seawater is not seen as a mechanism.

Looking at Figure 1.3 it is seen that the area inland of borehole G39940 is very flat. The 1 : 50 000 topographic map shows a number of wetlands confirming that pools of standing water is common. Thus recharge via open pan is to be expected in this area and the $\delta^{18}\text{O}$ enriched groundwater sample from G39940 confirms this.

6.5.2.3 Borehole BH8

BH8 has an anomalously high chloride content of 1333 mg/L, considering it is situated between BH6 with 380 mg/L chloride and BH10 with 532 mg/L chloride, and that BH10 is closer to the sea than BH8 (Figure 1.3). The $\delta^{18}\text{O}$ for BH8 may be the clue. BH8 has a $\delta^{18}\text{O}$ of -4.6 ‰ which at first glance does not seem out of line with the other samples. However, following the seawater intrusion mixing model for chloride the mixing ratio would be 96.1% to 3.9%. This would result in a $\delta^{18}\text{O}$ of -4.67 . It is thus concluded that it is quite possible that BH8 has been subjected to seawater intrusion. This would have to be discrete fracture related because the adjacent boreholes are apparently not affected. Referring back to the Piper diagram discussion for Figure 6.1 and 6.2 it is seen that BH8 is the only borehole which plots on the seawater intrusion line of Mazar (1991) further supporting the theory that this borehole has been subjected to seawater intrusion.

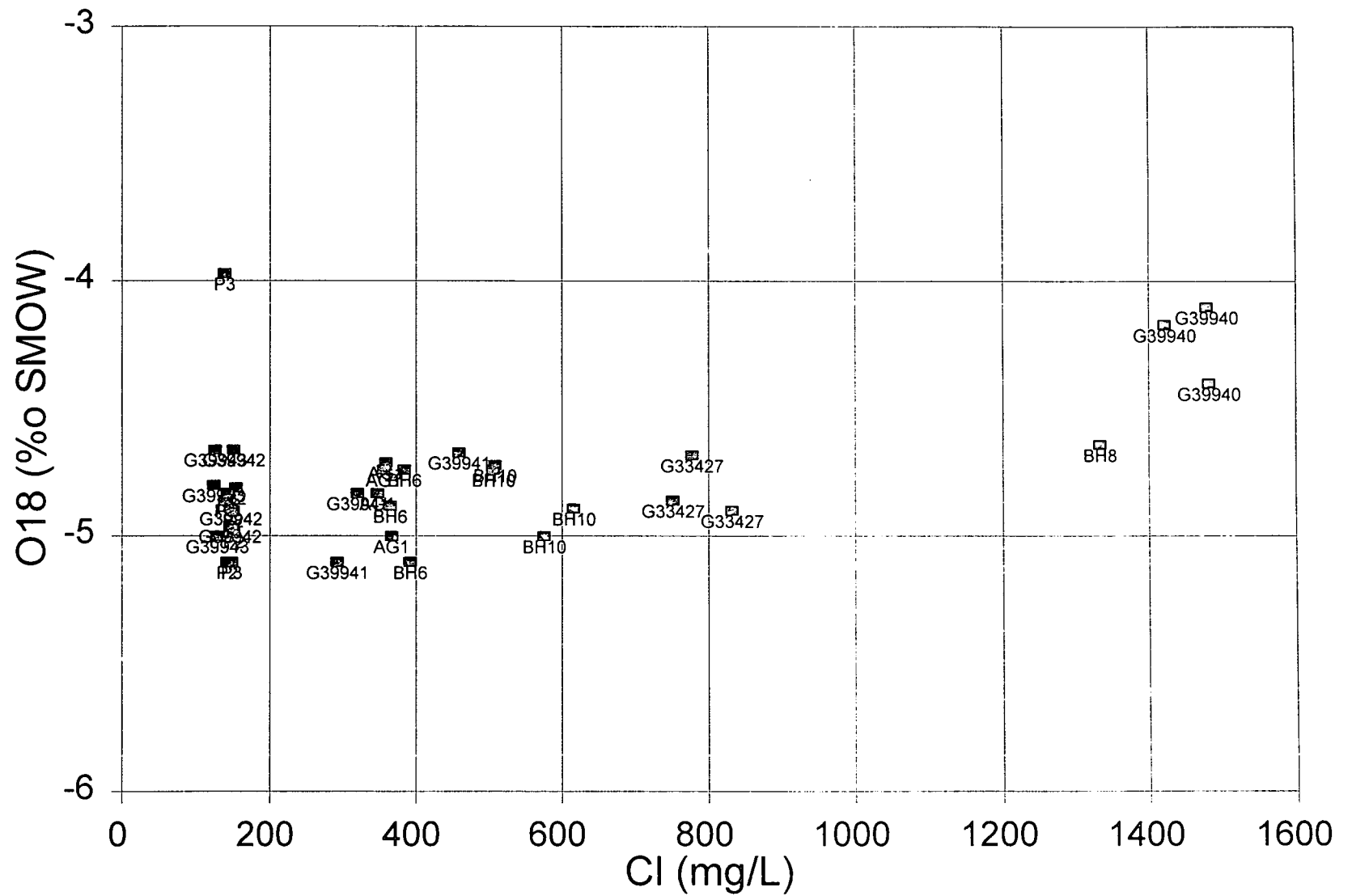


Figure 6.10: Struisbaai. Chloride versus Oxygen-18

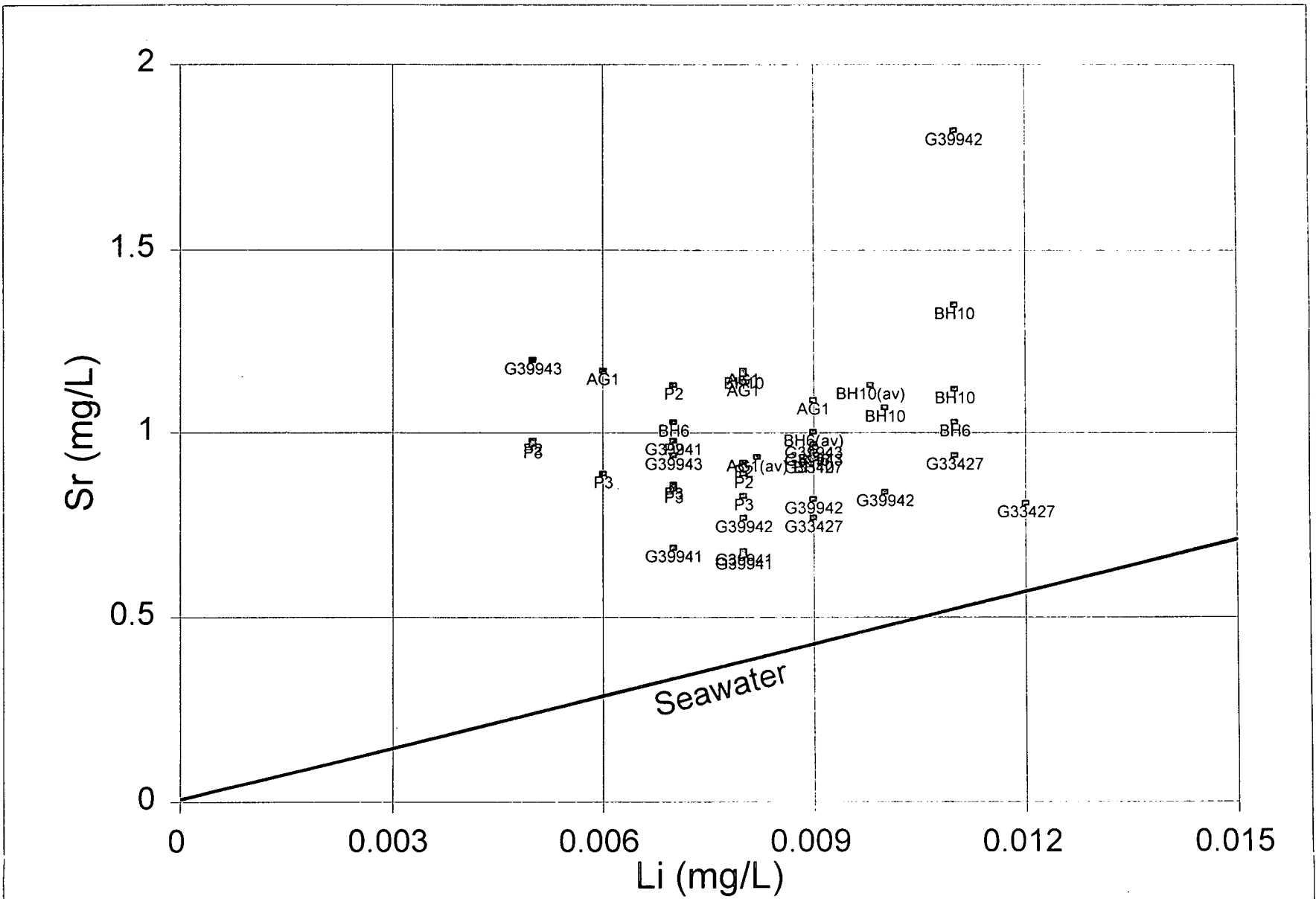


Figure 6.11: Struisbaai. Strontium versus Lithium

6.5.3 Conclusions

- ➡ The boreholes related to the main aquifer show a uniform $\delta^{18}\text{O}$ of -4.86 ‰ with a variation less than the analytical error of ± 0.2 ‰. This indicates uniform and localized direct recharge.
- ➡ Borehole G39940 shows a significantly different $\delta^{18}\text{O}$ of -4.2 ‰. This enrichment is due to recharge from open pan.
- ➡ Borehole BH8 shows a slight enrichment at $\delta^{18}\text{O}$ of -4.6 ‰. This borehole also has anomalously high salinity which is $2\frac{1}{2}$ to $3\frac{1}{2}$ times that of surrounding boreholes. Both these can be explained by mixing with 3.0% of seawater. The plotting position of BH8 on the piper diagram (Figure 6.1) supports the theory that this borehole has been subjected to seawater intrusion. This will have taken place along discrete high permeability fractures.

6.6 STRONTIUM ISOTOPES AND LITHIUM : STRONTIUM RATIOS

6.6.1 Introduction

The source of salinity for Struisbaai as discussed in Chapter 1.3 is one of the following:

- ➡ sea-spray
- ➡ connate water
- ➡ seawater intrusion

Considering strontium and its isotopes, any of these will and can contribute strontium according to the seawater mixing line. However, when one adds the aquifer material then dissolution of this rock will change isotopic ratios and move the sample plotting point away from the mixing line. The sampling data for the various boreholes are presented in Table 6.3 below. The boreholes are presented in the same order as in Table 6.2. Both lithium and strontium are useful ions to consider because they both have high solubility in water and similar to chloride are conservative. Hence these are good tracers to consider when investigating groundwater problems.

Figures 6.11 and 6.12 plot total strontium versus lithium and calcium and Figure 6.18 which is chloride versus strontium it is seen that all the samples except the rain samples plot above the mixing line. The strontium levels are independent of chloride. It was shown earlier, Figure 6.3 chloride versus sodium, that all samples plot on the seawater mixing line, thus for Figure 6.8 there is excess strontium indicating an additional source of strontium, probably from the aquifer material, probably calcrete.

Examining the $^{87}\text{Sr} / ^{86}\text{Sr}$ ratios it is seen that there is no difference between the groundwater values, seawater and shells, both modern and fossil. The Sr ratios can thus not be used to identify the source of salinity for any of these. However, the Sr ratios do exclude solution of either the Bokkeveld shales or TMG quartzites as being the source of salinity.

Table 6.3 Struisbaai. Strontium and lithium concentration and strontium isotope ratios. The values shown are average values for the various sampling runs. Lithium is included.

Borehole No	Strontium concentration (mg/L)	$^{87}\text{Sr} / ^{86}\text{Sr}$ ratio	Lithium concentration (mg/L)	Li/Sr
G39940	2.62	.709298	.023	0.009
G39942	0.81	.709302	0.009	0.011
G39943	1.02	.709402	0.008	
P3	0.88	.709204	0.007	
P2	0.98	.709215	0.007	
BH10	1.12	.709241	0.010	0.009
BH6	1.00	.709234	0.009	
BH8	2.35	.709260	0.016	
G39427	0.86	.709286	0.010	0.012
G39941	0.68	.709224	0.008	0.012
AG1	1.14	.709185	0.008	0.007
Seawater	8.0	.7092	0.17	0.021
Sea shells ¹ (modern)	-	.709197	-	
Fossil ¹ quaternary	-	.70920	-	
Fossil ¹ tertiary	-	no data available	-	
TMG ² Quartzite	<0.05	.712900	<0.005	
Bokkeveld ² shale (Agter Witzenberg)	0.2	.718	0.03	0.15
Bokkeveld ³ shale (Breede)	0.17	.717674	0.026	0.15
¹ Data from Eglington (1997) ² Data from Agter Witzenberg (Weaver <i>et al.</i> , 1997) ³ Data from Kirchner (1995) No data is available for cretaceous rocks. Average for all boreholes is 0.709259.				

Figure 6.11 shows total strontium versus lithium. Excepting for the two anomalous boreholes BH8 and G39940, there is a general scatter around lithium 0.008 mg/L and strontium 0.9 mg/L. This indicates a uniform source the most likely origin being solution of aquifer rock. Common to all of this grouping is calcrete and quartzite. During the investigation at Agter Witzenberg, Weaver *et al.* (1997) analysed for lithium and strontium in groundwater from quartzites of the Table Mountain Group and in groundwater from shales of the Bokkeveld Group. The results are shown in Table 6.3. The strontium and lithium for the quartzites for the total of 16 samples was always below detection limit. There is no reason to assume that the Struisbaai quartzites are any different from those of Agter Witzenberg, thus the quartzites cannot be the source of either lithium or strontium. There is a possibility that the strip of Bokkeveld shales to the north could provide/be the source of strontium and lithium. For Struisbaai the Li : Sr ratio is 0.009 while for Agter Witzenberg it is 0.153, a 17x difference. Thus the Bokkeveld shale is ruled out as a source rock. By the process of elimination the source of the strontium and lithium is from solution of the calcretes. This also shows that the source of salinity is unlikely to be from the Bokkeveld shales as postulated by Meyer (1986a).

Figure 6.12 shows strontium versus calcium. Also plotted on this graph is the seawater mixing line and the sea shell (modern) solution line. All the samples plot between these two lines. From the Sr vs Cl graph it has been shown that the Sr cannot be derived from seawater/sea-spray alone. It is thus concluded that the strontium and lithium is derived from solution of calcretes possibly with some additional input from seawater/sea-spray. Figure 6.5 which is chloride versus calcium shows enrichment of calcium from solution of calcretes. The sample from G39942 and G39943 plotting above the seawater mixing line plot anomalously due to drilling fluid effect (chapter 3.6.4).

Examining the $^{87}\text{Sr} / ^{86}\text{Sr}$ isotope data it is seen that TMG quartzites and Bokkeveld shales give significantly different values while whole rock analyses for sea shells, both modern and tertiary, show very good agreement to the groundwater samples.

The consistent $^{87}\text{Sr} / ^{86}\text{Sr}$ ratio for groundwater from the Bokkeveld shales for Agter Witzenberg and Breede River indicates that one could expect a similar value from this area which is not found in any of the Struisbaai boreholes.

Examining the variation of the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio for all the boreholes it is seen that the values are very consistent. The $^{87}\text{Sr}/^{86}\text{Sr}$ ratios unfortunately does not allow one to distinguish between seawater and calcrete as the origin. Sea shells both modern and fossil grow in the sea and thus the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio is identical to that of seawater. The calcium carbonate for the calcretes of the Bredasdorp is derived from solution/dissolution of calcareous material within the formation and thus has the same signature as the sea shells have and thus of seawater. Thus there would be no difference of $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of groundwater whose salinity is derived 100% from seawater/sea-spray, from 100% solution of calcretes or from a 50 : 50 mix of the two.

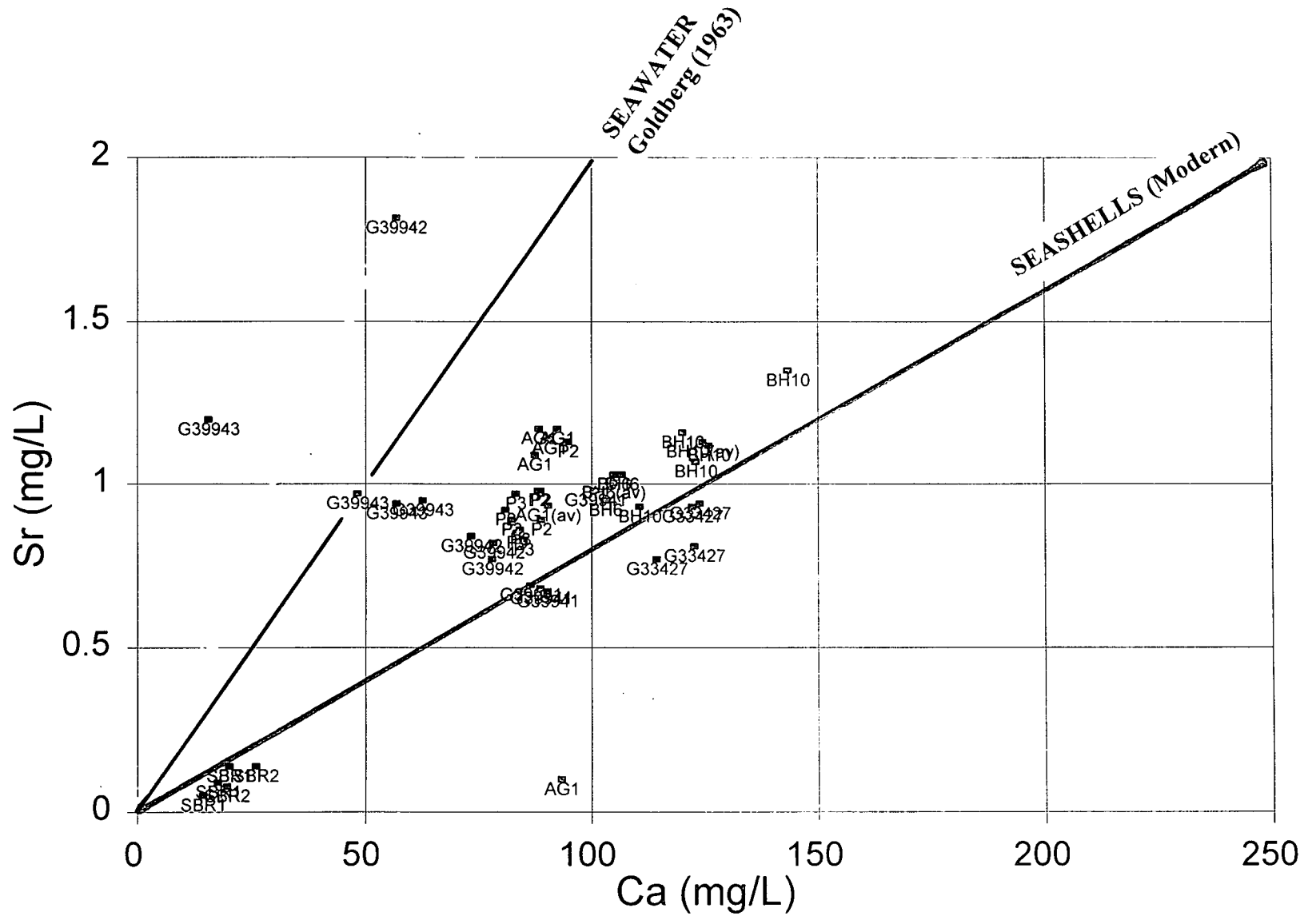


Figure 6.12: Struisbaai. Strontium versus Calcium

6.6.2 Conclusions from strontium data

Except for borehole G39940 and BH8 strontium and lithium group quite closely around strontium values of 0.9 mg/L and lithium of 0.008 mg/L. The $^{87}\text{Sr}/^{86}\text{Sr}$ ratio show very similar values with the average being .709259.

Conclusions are that:

- ▣▣▣▣ the strontium and lithium detected in groundwater is derived from solution of calcretes
- ▣▣▣▣ $^{87}\text{Sr}/^{86}\text{Sr}$ ratios as well as strontium and lithium content show that there is no contribution from solution of either Bokkeveld shales or from TMG quartzites
- ▣▣▣▣ $^{87}\text{Sr}/^{86}\text{Sr}$ ratios for the groundwater is virtually identical to sea shells both modern and tertiary which in turn is virtually identical to seawater. The groundwater $^{87}\text{Sr}/^{86}\text{Sr}$ is thus derived via solution of calcrete formed from fossil sea shells which grew in the sea.



CHAPTER 7

MODELLING THE POTENTIAL FOR SEA-WATER INTRUSION AT STRUISBAAI

7.1 SEAWATER INTRUSION

Around the turn of the century the two scientists Ghyben (1888) and Herzberg (1901) working independently along the coastline of the North Sea first described the relationship between fresh water and salt water in the underground environment. They found that salt water occurs not at sea-level but at a depth of about 40 times the height at which the water-table is above mean sea-level. They analysed this relationship and attributed it to the relative densities of the two waters. Seawater has a density of 1.025 g/cm^3 and freshwater has a density of 1.000 g/cm^3 . Under simple hydrostatic conditions this yields the 1:40 relationship which is generally referred to as the Ghyben-Herzberg relation.

Under real conditions there is some variation to this relation. Where freshwater flow towards the sea occurs then the interface between the fresh and salt water is displaced seawards. At the coastline the water-table is usually assumed to be at mean sea-level. If there is abundant wave action or significant tidal variation then the water-table will tend to be above mean sea-level. The net effect of these phenomena is to shift the interface both deeper than the 1:40 relation would predict and also extends the freshwater discharge zone seawards so that undersea freshwater springs can be encountered.

Seawater intrusion occurs when pumping of boreholes which are situated close to the interface cause the interface to either migrate inland or to cause upconing of the underlying interface. Typically seawater intrusion occurs when boreholes are sited too close to the coastline or when boreholes are closely concentrated and local overpumping occurs.

Todd (1980) describes five methods for controlling seawater intrusion:

- (1) Modification of pumping pattern: Changing the location of pumping wells, typically by dispersing them in inland areas.
- (2) Artificial recharge: Which raises groundwater levels.
- (3) Injection barrier: Similar to artificial recharge except the freshwater is recharged by injection boreholes.
- (4) Extraction barrier: Which is a line of coastal boreholes which captures the saline water, preventing it from moving further inland.
- (5) Subsurface barrier: Construction of an impermeable subsurface barrier parallel to the coast and through the vertical extent of the aquifer.

The method most commonly and effectively used is the first one. By calculating the drawdowns created by a pumping wellfield and developing contours of the resulting cone of depression one

can measure the effect on the natural watertable contours. By ensuring that the watertable or piezometric surface is always a few metres above sea-level then seawater intrusion can be prevented.

7.2 APPLICABILITY OF MODELLING TO THE STRUISBAAI SITUATION

The new wellfield at Struisbaai is more than 3000 m from the coastline. This distance affords good protection against seawater intrusion. The water-levels in these boreholes at the time of test-pumping were between 17 m and 19 m above mean sea-level. Applying the Ghyben-Herzberg principle this means the interface is 680 m to 760 m below the watertable at this point. This is well below the water-strikes and also below the base of the boreholes which is 78 m, 100 m and 133 m for the three production boreholes. When these boreholes are in production the dynamic water-levels will be +7 m, -4 m and 0 m above sea-level respectively. Although the water-levels for P2 and P3 are below and at sea-level, which is potentially harmful, the water-levels between the boreholes and the sea will be well above sea-level, thus maintaining a barrier to seawater intrusion.

However, the question arises as to what will happen in the future when water demand increases, and more boreholes are drilled.

To test scenarios such as this where the behaviour of aquifers in time and space is investigated, it is necessary to employ a mathematical model.

In recent years, numerous groundwater models have been used to simulate the behaviour of groundwater systems. The models are flexible and powerful, but the construction of a site model, can be time consuming because of the large amounts of data required, especially for three dimensional models. Models accurately reflecting actuality require large amounts of accurate input data. Unfortunately it is seldom that large amounts of data are available. Consequently when using available data (less than desired) as is the case for Struisbaai the model results must be viewed as an indication of what is probable rather than a faultless reflection of reality.

For Struisbaai the aquifer was assumed to be homogeneous in the vertical direction. Hence, a two dimensional flow model was used during the investigation. The aim of the model was to examine the effect of pumping at various discharge rates on the regional water-levels and hence to deduce, using the Ghyben-Herzberg principle the potential for seawater intrusion of the new wellfield

7.3 MODEL SOFTWARE AND INPUT DATA

7.3.1 Model software

MODFLOW was the software used during the investigation (McDonald and Harbough, 1988). It is an internationally accepted modelling package, which calculates the solution of the groundwater flow equation using the finite difference approach. The software package MODIME (Zhang *et al.*, 1996), was used as a pre and post processor for MODFLOW. MODIME allows the user to graphically specify model parameters. It then automatically generates input files in the right format for MODFLOW, PATH3D and MT3D. The user can also zoom into a subregion of the model for the

execution of high resolution equations.

7.3.2 Discretization

MODFLOW is a finite difference code that makes use of quadrilateral/block network. A regular mesh size was chosen. The mesh consisted of 93 x 98 cells in the x and y directions with the dimensions 120 x 75 m. Figure 7.1 is a schematic representation of the mesh.

In the simulations, the fault to the north of the aquifer was taken as a no flow boundary (refer to Figure 4.1).

7.3.3 Model Input Parameters

The aquifer thickness was taken to be 500 m. The thickness of the Peninsula Formation is ~ 1500 m in this area, but because of the numerous reverse overthrust faults and other faults this was reduced to 500 m. Initial water level data was obtained from the boreholes present in the area. These values were then extrapolated over the whole network.

Two parameters are used to describe the physical properties of an aquifer, namely hydraulic conductivity and aquifer storage. The first of these two quantifies the rate at which water moves through the aquifer and the latter quantifies the aquifer's ability to store water. The hydraulic conductivity was taken as 3 m/d and the storage coefficient as 0.009. These values were obtained from pumping tests performed on boreholes P1, P2 and P3. The average annual recharge was taken as 15 % of the rainfall. The average rainfall is 469.2 mm/annum (refer to Figure 3.3).



Figure 7.1 : Modelling network for the Struisbaai aquifer

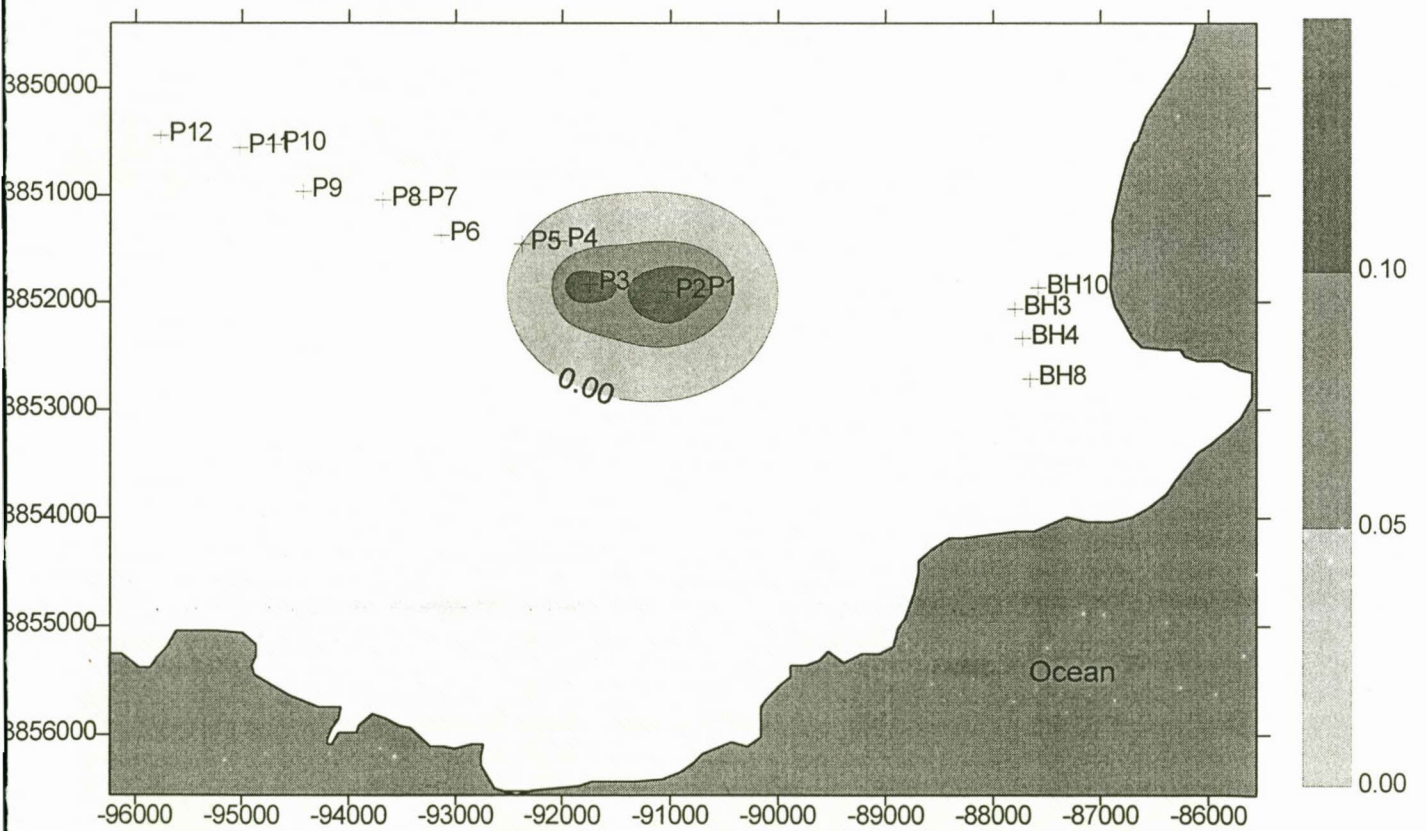


Figure 7.2 : Modelled decrease in waterlevels after 5 years of pumping at current pumping rates of 1350 m³/d for the existing boreholes P1, P2 and P3

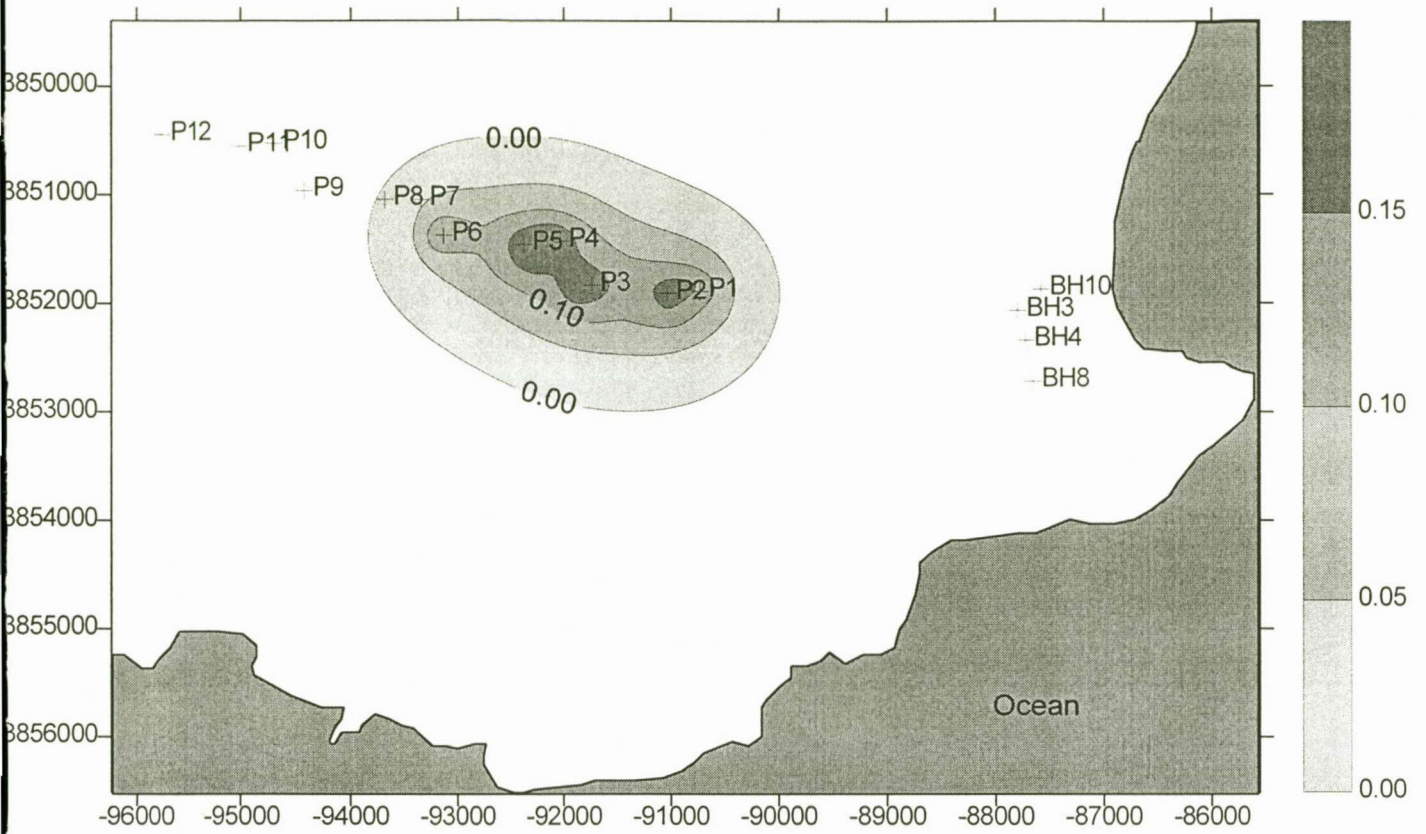


Figure 7.3 : Modelled decrease in waterlevels after 5 years of pumping at twice the current pumping rate (ie at 2700 m³/d)

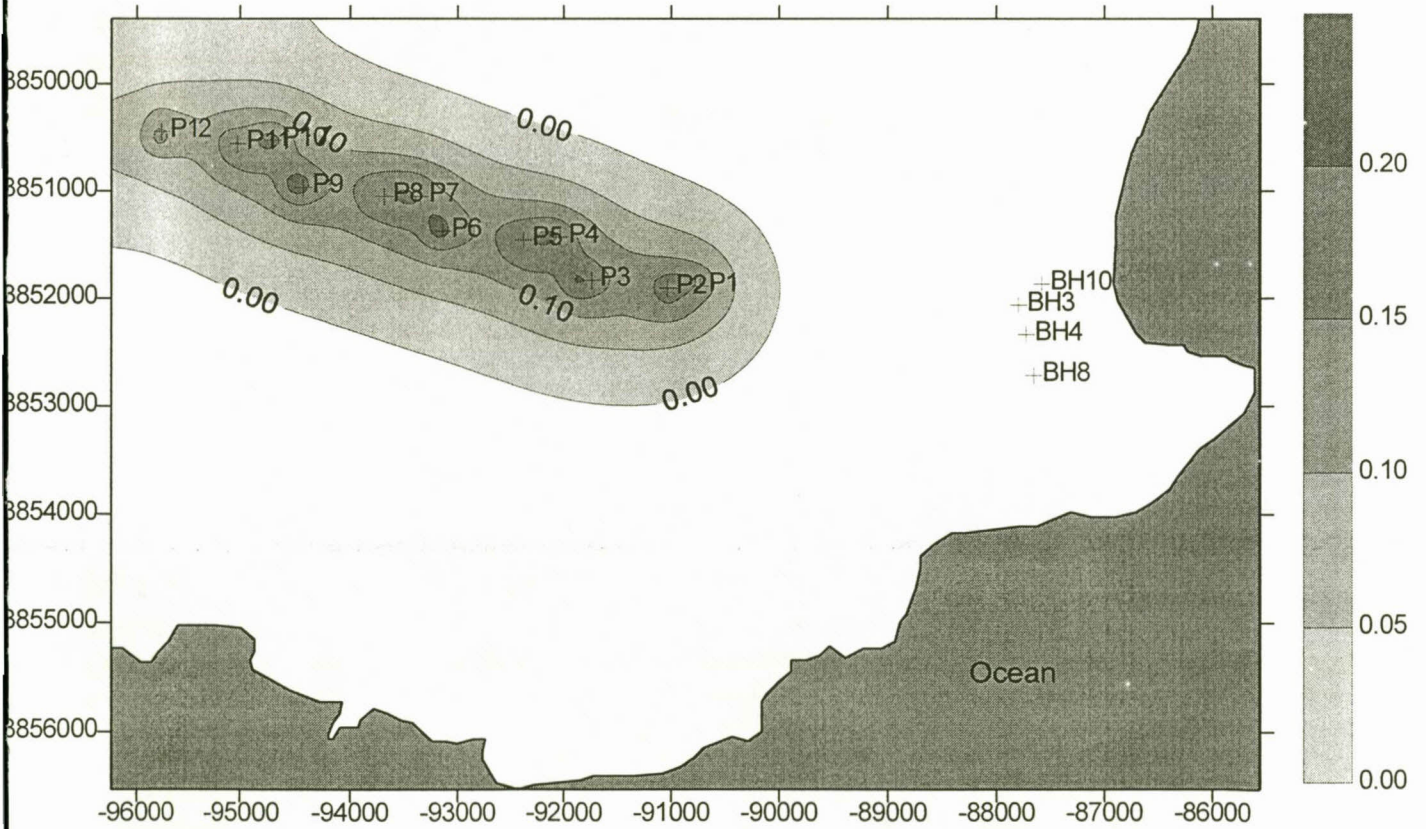


Figure 7.4 : Modelled decrease in waterlevels after 5 years of pumping at four times the current pumping rates (ie at 5400 m³/d)

7.4 SCENARIO'S TESTED

Once all data has been entered a steady state model was run. A transient flow model was then run for a period of 5 years, allowing the model to once again reach steady state conditions. Three scenarios were tested.

Scenario 1:

P1 and P2 were pumped at 500 m³/d and P3 at 350 m³/d for the whole simulation period. These are the current production rates of discharge. The difference between the initial water levels and those simulated after 5 years is shown in Figure 7.2.

Scenario 2:

A doubling of the current rate of discharge to 2700 m³/day is simulated by adding an extra three boreholes pumping at the same rates as P1, P2 and P3. The difference between the initial water-levels and those simulated after 5 years of pumping is shown in Figure 7.3.

Scenario 3:

A four-fold increase of the current rate of discharge to 5400 m³/day is simulated by adding an extra 9 boreholes pumping at the same rates as P1, P2 and P3. The difference between initial and those simulated after 5 years of pumping is shown in Figure 7.4.

7.5 DISCUSSIONS

Figure 7.2, 7.3 and 7.4 all show that water-levels between the pumping wellfield and the sea remain positive, i.e. above sea-level. This positive water-level barrier will reduce, if not prevent, the potential for landward migration of the interface. This is Todd's (1980) first recommended method.

With the limited data available it appears that moving the wellfield inland has reduced the probability of seawater intrusion affecting the quality of groundwater being pumped.

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CHAPTER 8

CONCLUSIONS

The water-supply for Struisbaai has a historical reputation for high salinity. Previous groundwater investigators have ascribed this salinity mainly to seawater intrusion but including other factors. None of these investigators gave any conclusive evidence for their theories.

This investigation identified three possible sources of salinity.

- ▣ Salinity derived from sea-spray causing high salinity recharge
- ▣ Geological factors which yield high salinity groundwater
- ▣ Hydrogeological factors which result in seawater intrusion

8.1 SALINITY DERIVED FROM SEA-SPRAY CAUSING HIGH SALINITY RECHARGE

Three rain collectors were installed and samples collected at intervals. Relating the rainfall recorded to the quality of the rain samples collected showed that the rain has an EC of 12.5 mS/m for the collector closer to the sea and 10.5 mS/m for the collector further from the sea. This is the first indicator of the groundwater salinity being derived from sea-spray.

Relating the chloride content of rain from these collectors to the chloride content of groundwater from the closest boreholes indicates a recharge of between 4.7 % and 5.8 % for the collector closer to the sea and between 13.1 % and 16.4 % for the collector further from the sea. These values are quite feasible further supporting the premise that the groundwater salinity is derived from sea-spray.

Two samples of calcrete were collected from a newly developed road-cutting which is approximately 300 metres from the sea. The samples were fine crushed and leached with deionised water. The leachate from the weathered rock produced an EC of 122 mS/m whereas the leachate from the freshly exposed rock produced an EC of 11.6 mS/m. This showed the sea-spray does contribute significantly to the inland salinity. Most if not all of this sea-spray will wash down into the aquifer. Examination of various ionic ratios show that the leachate from the exposed rock has similar ratios to that of seawater, whereas the ratios from the fresh rock-sample are dissimilar. For example, the ratio Na/Cl for seawater is 0.553, for the exposed sample is 0.552, for the fresh sample is 1.5, and for the rain collector close to the sea is 0.52 and for the rain collector further away is 0.42. These results and similar results for other ionic ratios strongly support the premise that the salinity is derived from sea-spray and not from dissolution of the calcrete.

Five sampling runs of existing and newly drilled boreholes were carried. The first sampling run was of existing boreholes and the next four were of a total of 10 boreholes. Plotting the results on a Piper plot shows that all the results lie on the mixing zone except for the result from one borehole

BH8 which is in the seawater intrusion portion of the diagram. The addition of sea-spray is the same as mixing.

A number of graphical plots of one chemical determinant shows that chloride, sodium, potassium, magnesium and sulphate all correlate closely to the seawater mixing line indicating they are derived from seawater. Conversely strontium, calcium and iodine appear to be derived from dissolution of calcrete.

$\delta^{18}\text{O}$ versus chloride showed that all but two of the boreholes plotted on the seawater mixing line. BH8 showed slightly higher $\delta^{18}\text{O}$ than the rest and this could be due to seawater intrusion. Borehole G39940 shows significant enrichment and this is due to recharge from open pans where evaporation has occurred.

Graphical plots of strontium versus calcium, strontium versus lithium and also $^{87}\text{Sr}/^{86}\text{Sr}$ ratios show that strontium and lithium are derived from dissolution of the calcrete and that there is no contribution from solution of either the Bokkeveld shales or of the TMG quartzites.

8.2 GEOLOGICAL FACTORS WHICH YIELD HIGH SALINITY GROUNDWATER

Connate seawater originating either from previous sea-level transgressions or from deposition of the formation is often invoked as the source of salinity. The last transgression which could have affected the area is over 50 000 years B.P. The calcretes have high permeability so it is improbable that salinity is still encountered in sufficient quantities as to be the cause of the high salinities encountered.

As described above the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios show that the excess strontium found in the groundwater is derived from calcrete dissolution and not from the Bokkeveld shales. Thus the Bokkeveld shales, which elsewhere do give high salinities to groundwater, in the case of Struisbaai are not a contributing factor.

8.3 HYDROGEOLOGICAL FACTORS WHICH RESULT IN SEAWATER INTRUSION

Except for the Agulhas borehole, AG1, all the boreholes have their water-strike well below sea-level. The water-levels vary from a few metres above sea-level for the old wellfield to nearly 20 m above sea-level for the new wellfield. For the old wellfield the water-strikes have been recorded at 124 m below sea-level. According to the Ghyben-Herzberg principle the interface is 160 m to 200 m below surface, thus when these boreholes were pumping it is quite conceivable that upconing of the interface would result in seawater intrusion and thus high salinities.

As mentioned earlier in section 8.1, for BH8 which is in the old wellfield, evidence from both the Piper plot and the $\delta^{18}\text{O}$ data indicates it was subjected to seawater intrusion.

The new wellfield has been moved 3 kilometres inland and the risk of seawater intrusion has been reduced.

8.4 CONCLUSION

The overall conclusion that is made is:

- ➡ that salinity in the old wellfield was quite probably due to a degree of seawater intrusion;
- ➡ that the salinity observed in the new wellfield and the Agulhas borehole is due to sea-spray.

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APPENDICES

Appendix 1

Drill and Geological Logs from all available Boreholes at Struisbaai

- ▣▣▣▣ Survey co-ordinates for 15 boreholes
- ▣▣▣▣ Summary of geology intersected
- ▣▣▣▣ Detailed descriptive geological logs G39940, G39941, G39942, G39943
- ▣▣▣▣ Detailed construction data for G39940 - G39943
- ▣▣▣▣ Schematic borehole logs for G39940 - G39943
- ▣▣▣▣ Drill logs borehole P1, P2, P3, T1, T2 and T3 (McClea, 1991)

	ID-NO	EW-COORD	NS-COORD	COL-ELEV
1	P3	91745.500	3851831.500	46.92
2	P2	91035.000	3851905.000	40.41
3	G39942	90818.898	3851697.500	25.17
4	G39943	90425.703	3851951.500	26.13
5	BH9	87793.898	3852201.250	8.62
6	BH3	87798.898	3852063.500	4.84
7	BH4	87729.602	3852336.250	15.3
8	BH7	87705.898	3852574.000	14.91
9	G39940	88615.500	3850225.500	7.39
10	G39941	88598.398	3853529.500	64.52
11	G33427	87286.500	3853704.000	28.94
12	BH6	87960.430	3852784.750	?
13	BH10	87584.055	3852716.250	?
14	BH9A	87809.719	3851866.250	?
15	BH8	87656.898	3852713.750	18.01
16	P1	90753.35	3851886.96	32.41
17	T1	90773.14	3857823.93	28.77
18	T2	91173.17	3851719.67	24.30
19	T3	91422.97	3857676.60	26.12

SUMMARY OF GEOLOGY AND GEOLOGICAL FORMATIONS INTERSECTED BY VARIOUS BOREHOLES IN STRUISBAAI

Borehole No	Depths	Geological Formation	Rock Type
G39940	0-12	Uitenhage Formation	Shelly sand and calcrete
G39941	0-47 47-70	Bredasdorp Formation Skurweberg Formation	Calcrete Quartzite and phyllite
G30042	0-12	Bredasdorp Formation Skurweberg Formation	Calcrete Quartzite and phyllite
G30043	0-15 15-42	Bredasdorp Formation Skurweberg Formation	Calcrete Quartzite and phyllite
P1	0-19 19-78	Bredasdorp Formation Skurweberg Formation	Calcrete Quartzite and phyllite
P2	0-28.5 28.5-100	Bredasdorp Formation Skurweberg Formation	Calcrete Quartzite and phyllite
P3	0-35 35-133	Bredasdorp Formation Skurweberg Formation	Calcrete Quartzite and phyllite
T1	0-17.9 17.9-18.3	Bredasdorp Formation Skurweberg Formation	Calcrete Quartzite
T2	0-11.5 11.5-12.5	Bredasdorp Formation Skurweberg Formation	Calcrete Quartzite
T3	0-17 17-18.3	Bredasdorp Formation Skurweberg Formation	Calcrete Quartzite
AG1	0-21 21-22	Bredasdorp Formation Goudini Formation	Calcrete Quartzite
BH3	Not known		
BH4	Not known, depth 85 m		
BH6	0-3.7 3.7-11.7	Bredasdorp Formation Skurweberg Formation	Calcrete Quartzite
BH7	0-4 4-153	Bredasdorp Formation Skurweberg Formation	Calcrete Quartzite
BH8	0-8.2 8.2-130	Bredasdorp Formation Skurweberg Formation	Calcrete Quartzite
BH9	Not known, depth 123 m		
BH9A	Not known, reported to be in Bokkeveld shale		
BH10	Not known, depth 88 m		

DRILLING LOG OF BOREHOLE G39940 AT STRUISBAAI

DRILLED DATE 20/08/93
DRILLING COMPANY J.J. Myburgh and bros.
DRILLER J. van Zyl
DRILLING METHOD Mud Rotary with Tri cone bit

GEOLOGICAL FIELD LOG

0 - 1m	No Sample
1 - 2m	Fine to Medium Light brown angular Quartzose sand
2m	Hard layer
2m - 8m	Fine to Medium Quartzose sand with coarse shell fragments and small calcrete pebbles
8m	Softer layer
8m - 9m	Fine shelly layer
9m - 10m	Light yellow very coarse shelly layer
10m - 12m	Very coarse shelly layer with fine 3mm - 5mm angular Quartzose pebbles
Well losses	
12m	Very hard layer

Drilling stopped.

LOGGED BY A. J. HÖN

DRILLING LOG OF BOREHOLE G39941 AT STRUISBAAI

DRILLED DATE 2/9/93
DRILLING COMPANY J.J. Myburgh and bros.
DRILLER J. van Zyl
DRILLING METHOD Mud Rotary with Tri cone bit and Air percussion

GEOLOGICAL FIELD LOG

Hard cemented calcrete layer on surface

0 - 3m	Fine to coarse angular and sub angular poorly sorted Quartzose sand in Calcrete matrix
4 - 8m	Fine to coarse angular and subangular poorly sorted Quartzose sand in Calcrete matrix with coarse shelly fragments Hard cemented calcrete layer up to 13m
9 - 13m	Fine to coarse angular and subangular poorly sorted Quartzose sand in calcrete matrix with coarse shelly fragments
14 - 18m	Creamy calcrete with fine brown pebbles of cemented calcrete
18.8m	Water strike
19m	Creamy calcrete with fine brown pebbles of cemented calcrete
20 - 25m	Creamy calcrete with fine to coarse quartzose sand
26m	Water strike
27.2m	Very hard layer of cemented calcrete
28 - 30m	Creamy calcrete with fine to coarse quartzose sand
30m	Hard cemented calcrete layer
31.8m	Hard cemented calcrete layer
32 - 33m	Creamy calcrete with fine to coarse quartzose sand
33.5m	Extremely hard layer of brown cemented calcrete
34 - 38m	Creamy calcrete with fine to coarse quartzose sand with angular brown cemented calcrete pebbles
38.6m	Hard layer of brown cemented calcrete
39.2m	Hard layer of brown cemented calcrete
40 - 45m	Creamy calcrete with fine to coarse quartzose sand with angular brown cemented calcrete pebbles
45.2m	Hard layer of brown cemented calcrete
46 - 48m	Creamy calcrete with fine to coarse quartzose sand with angular brown cemented calcrete pebbles
48m	Extremely hard layer. T.M.S. Quartzite contact

BOREHOLE CASED OFF WITH STEEL. AIR PERCUSSION FURTHER

49 - 53m	Very fine to coarse angular grey and cream quartzite pebbles
53.2m	Water strike estimated 0.1 L/s
54 - 62m	Very fine to coarse angular grey and cream quartzite pebbles

63m Very fine to coarse angular grey and cream quartzite pebbles with
phyllitic particles
63m Water strike estimated 0.2 L/s
64 - 68m Very fine to coarse angular grey and cream quartzite pebbles
68.5m Water strike measured 0.3 L/s
69 - 70m Very fine to coarse angular grey and cream quartzite pebbles

STOPPED

LOGGED BY A.J. H6N

DRILLING LOG OF BOREHOLE G39942 AT STRUISBAAI

DRILLED DATE 8/9/93
DRILLING COMPANY J.J. Myburgh and bros.
DRILLER J. van Zyl
DRILLING METHOD Mud Rotary with Tri cone bit
and Air percussion

GEOLOGICAL FIELD LOG

0 - 2m No Sample
2.5m Hard layer. Cemented calcrete
2 - 7m Creamy calcrete with fine to coarse well rolled quartzose sand
7.5m Very hard layer Brown cemented calcrete
7.8m Well losses till 10m
7 - 10m Fine pebbles of brown cemented calcrete 10.8m Hard layer. T.M.S.
contact
11m Fine pebbles of brown cemented calcrete and fine pebbles of white
quartzite
12m Extremely hard layer.

BOREHOLE CASED OFF WITH STEEL. AIR PERCUSSION FURTHER

13 - 14m Very fine to coarse angular grey and cream quartzite pebbles
14.2m Water strike Not measured
15 - 18m Very fine to coarse angular grey and cream quartzite pebbles
18.2m Water strike estimated 0.1 L/s
19 - 32m Very fine to coarse angular grey and cream quartzite pebbles
32m Blow yield estimated 0.3 L/s
33 - 40m Very fine to coarse angular grey and cream quartzite pebbles
40m Blow yield Measured 0.59 L/s
41 - 46m Very fine to coarse angular grey and cream quartzite pebbles
46.3m Water strike not measured
47 - 49m Very fine to coarse angular grey and cream quartzite pebbles with
ferrous intrusions
49m Soft phyllitic layer
49 - 51m Very fine to coarse angular grey and cream quartzite pebbles with
phyllitic pebbles
Water strike Blow yield measured 0.814 L/s

STOPPED

LOGGED BY A.J. Hön

DRILLING LOG OF BOREHOLE G39943 AT STRUISBAAI

DRILLED DATE 16/9/93
DRILLING COMPANY J.J. Myburgh and bros.
DRILLER J. van Zyl
DRILLING METHOD Mud Rotary with Tri cone bit and Air percussion

GEOLOGICAL FIELD LOG

0 - 2m Dark brown fine well rolled and sorted quartzose sand
3 - 8m Light brown fine well rolled and sorted quartzose sand with coarse shell fragments
8.5m Very hard layer. Brown cemented calcrete
8 - 10m Fine pebbles of brown cemented calcrete in cream coloured calcrete
10.1m 50% well losses to 13m
11m - 14m Fine pebbles of brown cemented calcrete in cream coloured calcrete
15m Extremely hard layer. T.M.S. contact
15m Fine pebbles of brown cemented calcrete and fine pebbles of white quartzite

BOREHOLE CASED OFF WITH STEEL. AIR PERCUSSION FURTHER

15 - 23m Very fine to coarse angular grey and cream quartzite pebbles
23.2m Water strike not measured
23 - 25m Very fine to coarse angular grey and cream quartzite pebbles
25.2m - 25.5m Soft weathered zone
25 - 27m Very fine to coarse angular grey and cream quartzite pebbles
27.2m Water strike not measured
27 - 33m Very fine to coarse angular grey and cream quartzite pebbles. Weathered zone
33m Blow yield measured 0.53 L/s
33 - 42m Very fine to coarse angular grey and cream quartzite pebbles. Very weathered
42m Hole collapsing Blow yield measured 1 L/s

STOPPED

LOGGED BY A J HÖN

BOREHOLE CONSTRUCTION AT STRUISBAAI

Borehole no.

G39940 Drilled to 12m using 300mm Tri Cone bit
3m Screen at base with end cap

Screen supplied

3m Slotted P.V.C.
186mm outside diameter
166mm inside diameter
5 vertical rows of 0.8mm slotsize
5mm horizontal spacing
110 mm not slotted at top
170 mm not slotted at bottom

Casing supplied

P.V.C. solid casing
180mm O.D.
166mm I.D.

Construction

320 Litres of 7/16 Consol gravel pack
Level up to 7m below surface
10mm grit pack to surface
1m square concrete block with lockable steel cap on surface

Borehole no.

G39941 Drilled to 48m using Tri Cone bit
300mm Steel casing down to 48m
Drilled to 71m using 212.5mm Air percussion
3m Screen at base with end cap

Screen supplied

3m of Slotted P.V.C. Screen
186mm Outside diameter
166mm Inside diameter
5 vertical rows of 2mm Slotsize
75 to 80mm O.D. Slot length
50mm I.D. Slot length
10mm horizontal spacing
170mm not slotted at top
110mm not slotted at bottom

Casing supplied

High impact P.V.C.
 186mm Outside diameter
 166mm Inside diameter
 Casing fitted with wedges at 4m and 8m from base

Construction

200 Litres of 10mm Grit pack
 Level up to 50m below surface
 20 Litres of 7/16 Consol gravel pack level up to 49.5m below surface
 1.5 bags of cement for plug below steel casing
 1m Square concrete block with lockable steel cap on surface

Borehole no.

G39942

Drilled to 12m using 300mm Tri cone bit
 300mm Steel casing to 12m
 Drilled to 51m using 212.5mm air percussion
 3m of Screen at base.

Screen supplied

3m of 2mm slot High impact P.V.C.
 Same dimensions as G39941

Casing supplied

High impact P.V.C.
 Same dimensions as previous boreholes

Construction

210 Litres of 10mm grit pack
 Level up to 20m below surface
 90 Litres of 7/16 Consol gravel pack
 Level up to 14.2m below surface
 4 bags of cement for plug
 1m square concrete block with lockable steel cap on surface

Borehole no.

G39943

Drilled to 15m using 300mm Tri cone bit
300mm Steel casing to 15m
Drilled to 42m using 212.5mm air percussion
6m Screen at base with end cap

Screen supplied

3m of 0.8mm slotted P.V.C.
Same dimensions as G39940

Casing supplied

High impact P.V.C.
Same dimensions as previous boreholes

Construction

270 Litres of 7/16 Consol gravel pack
Level up to 21m below surface
30 Litres of 10mm grit pack
Level up to 20m below surface
4 bags of cement for plug
1m square concrete block with lockable steel cap on surface

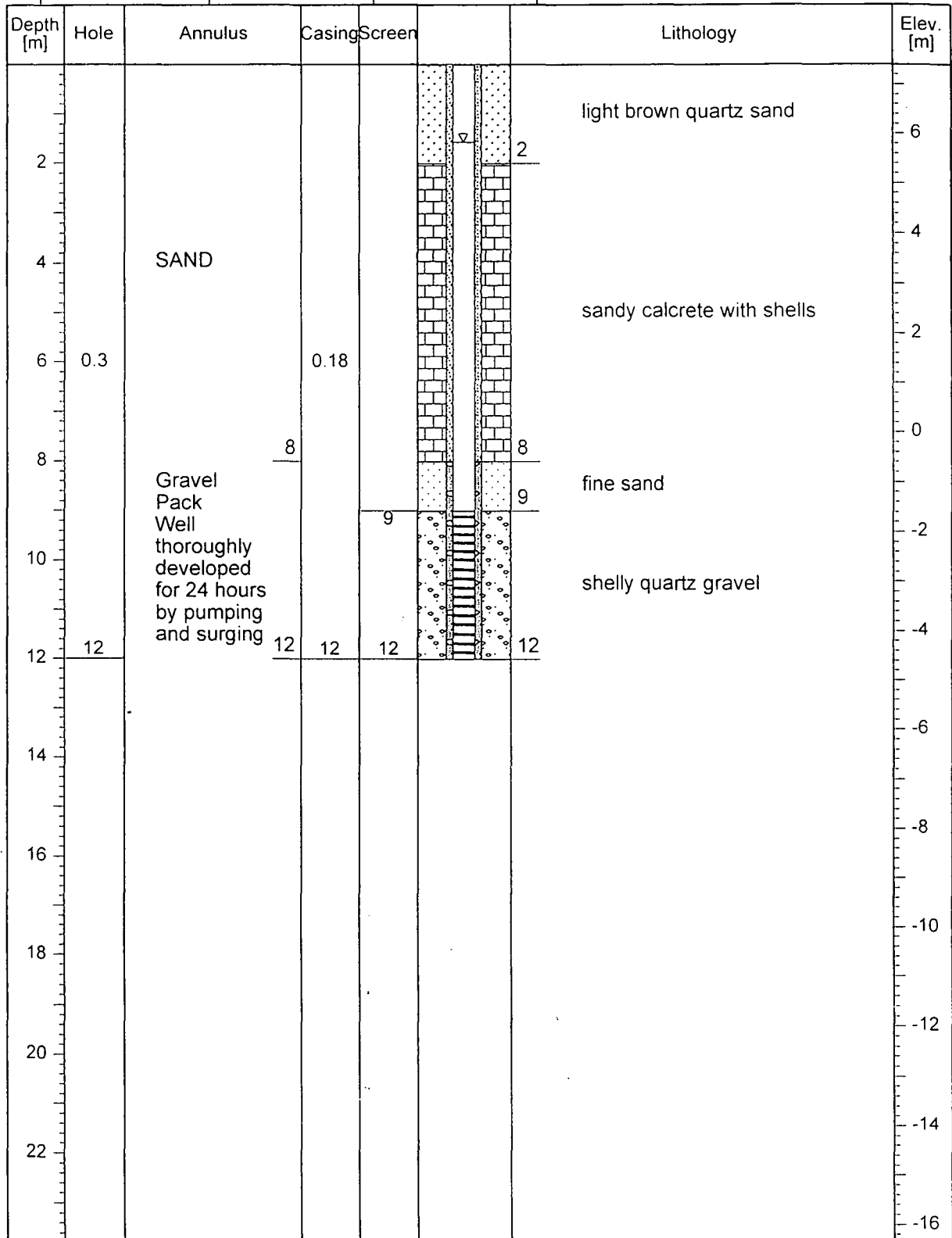
Struisbaai

Well Ident
G39940

Drilling Date 20 August 1993	SWL 5.83	Use Exploration
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Vert. Scale 120.0	Hor. Scale 50.0	Drilling Method Mud rotary with Tri cone bit
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X 50226	Y 88616	ZM
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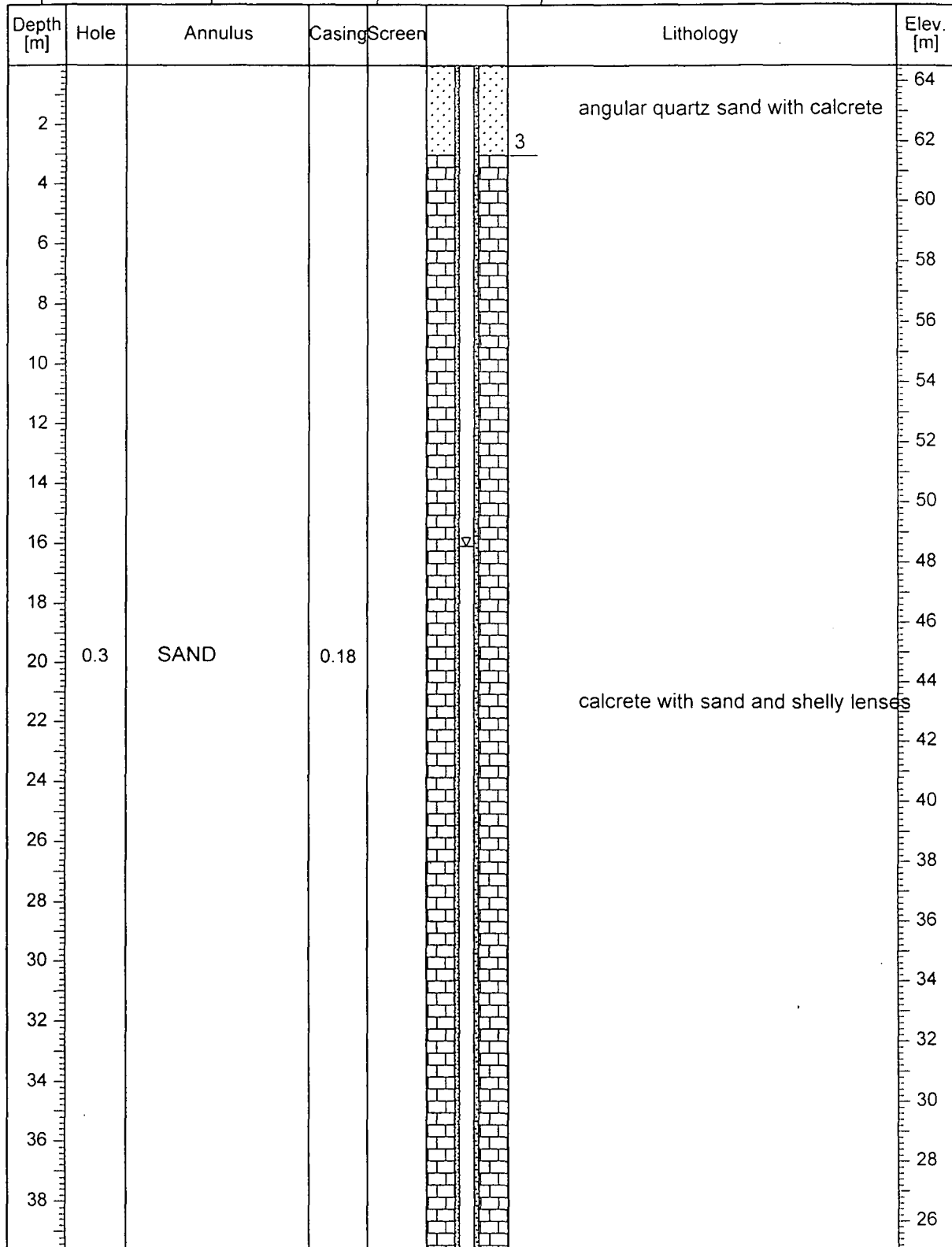
Struisbaai

Well Ident
G39941

Drilling Date 2 September 1999	SWL 48.50	Use Exploration
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Vert. Scale 200.0	Hor. Scale 75.0	Drilling Method Mud rotary and air percussion
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X 53529	Y 88598	Z 64.52
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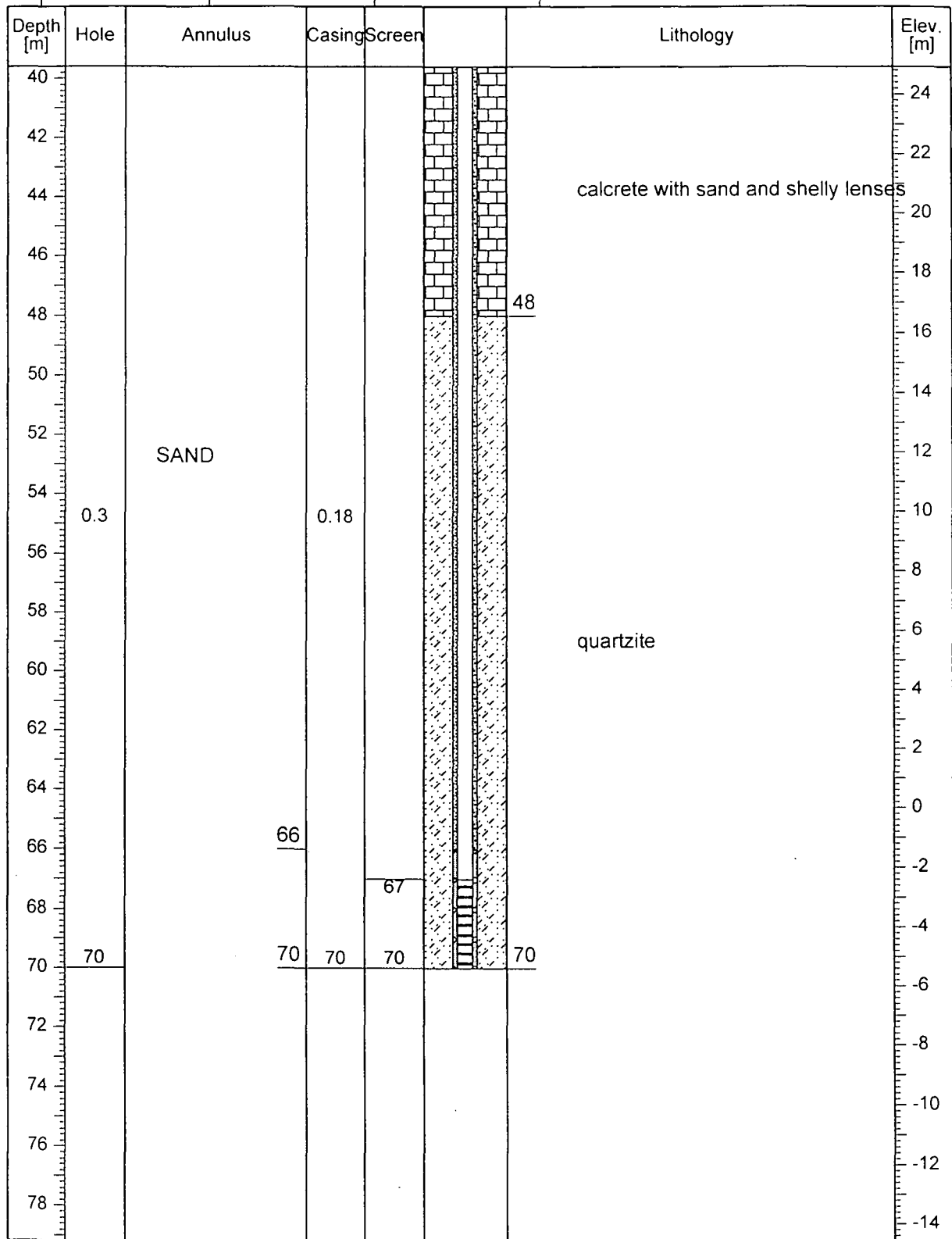
Struisbaai

Well Ident
G39941

Drilling Date 2 September 199	SWL 48.50	Use Exploration
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Vert. Scale 200.0	Hor. Scale 75.0	Drilling Method Mud rotary and air percussion
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X 53529	Y 88598	Z 64.52
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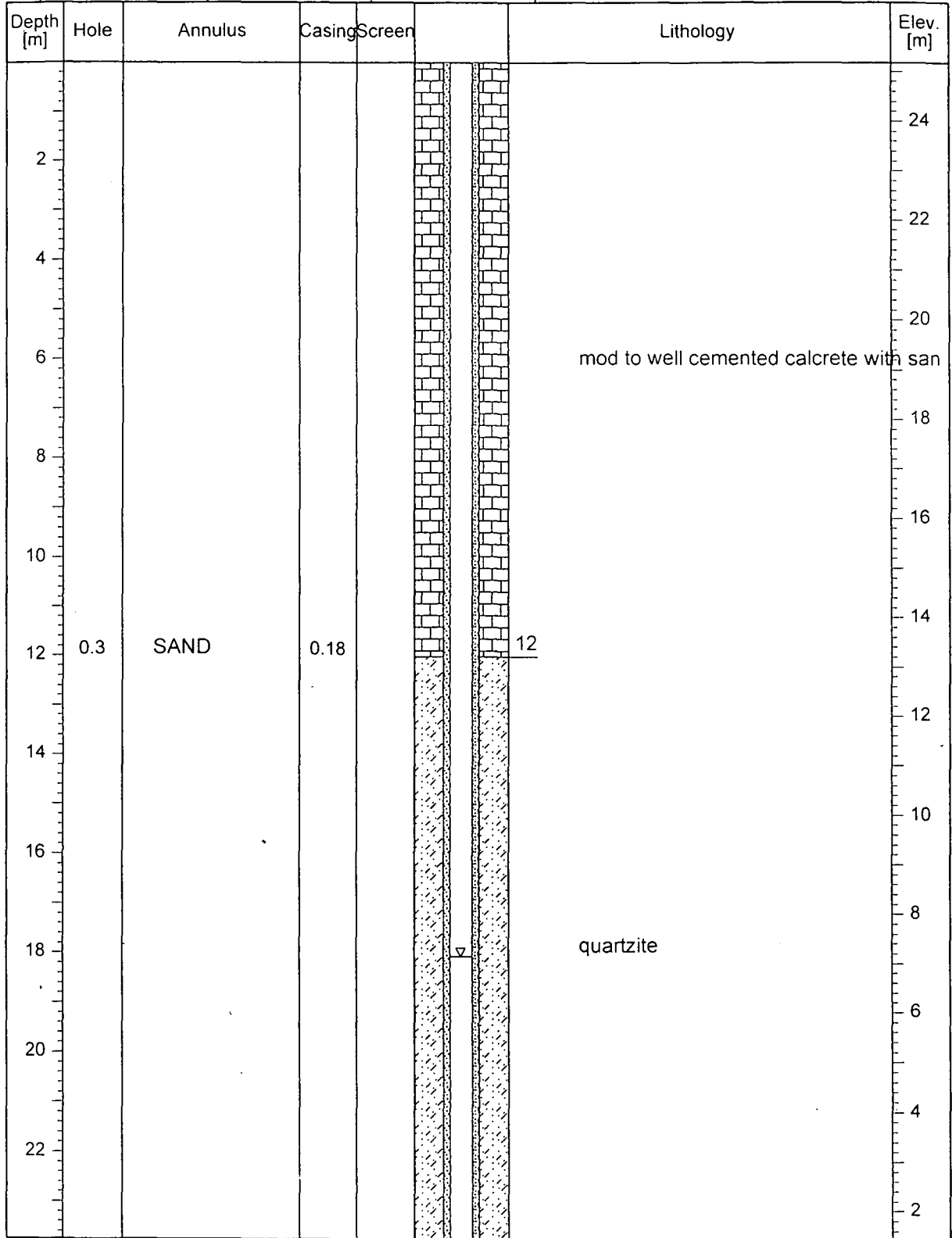
Struisbaai

Well Ident
G39942

Drilling Date: 8 September 1999
SWL: 7.10
Use: Exploration

Vert. Scale: 120.0
Hor. Scale: 50.0
Drilling Method: Mud rotary and air percussion

X: 51698
Y: 90819
Z: 25.17



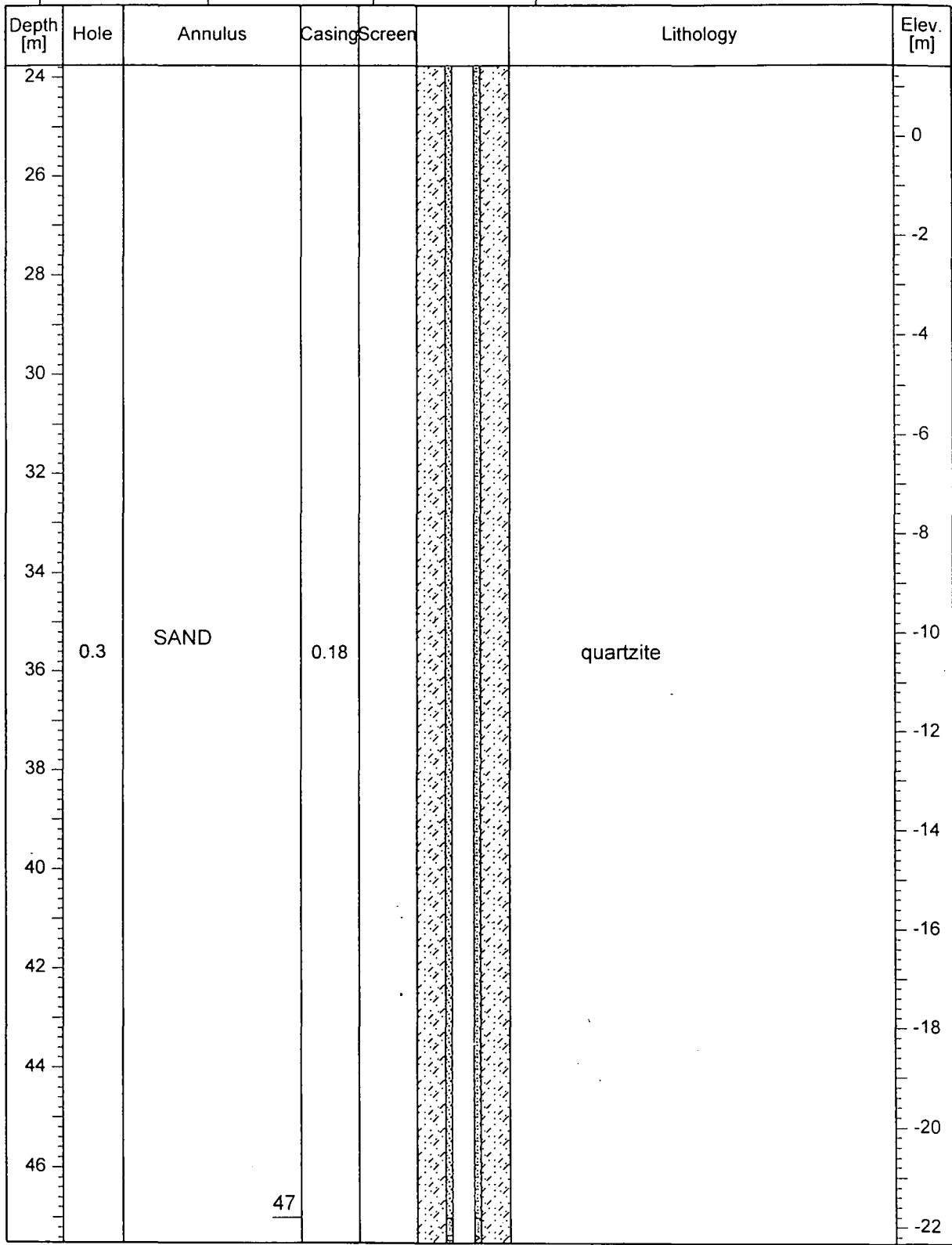
Struisbaai

Well Ident
G39942

Drilling Date 8 September 1999	SWL 7.10	Use Exploration
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Vert. Scale 120.0	Hor. Scale 50.0	Drilling Method Mud rotary and air percussion
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X 51698	Y 90819	Z 25.17
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Struisbaai

Well Ident
G39942

Drilling Date 8 September 199		SWL 7.10	Use Exploration
Vert. Scale 120.0	Hor. Scale 50.0	Drilling Method Mud rotary and air percussion	
X 51698	Y 90819	Z 25.17	

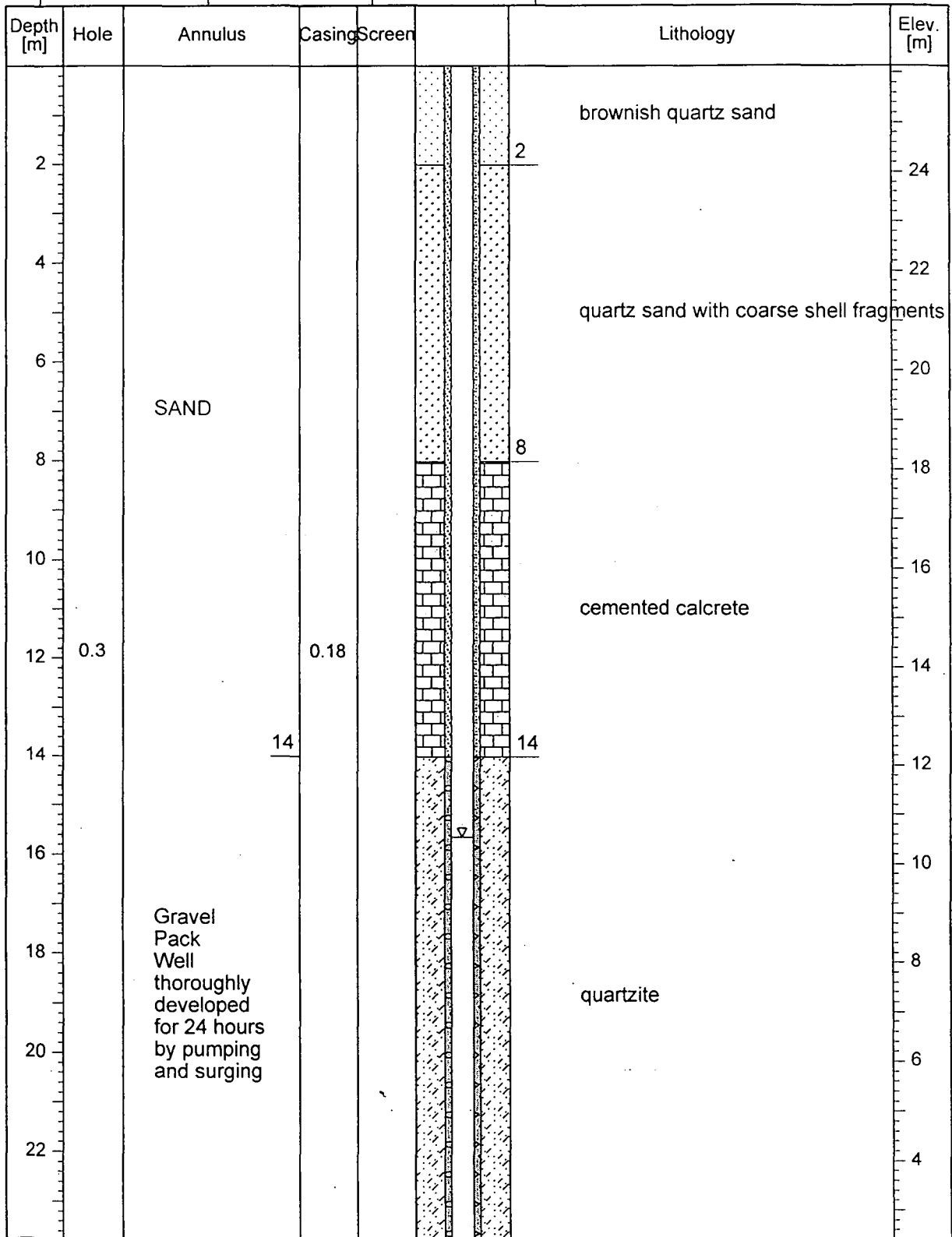
Depth [m]	Hole	Annulus	Casing	Screen	Lithology.	Elev. [m]
48					quartzite	
	0.3		0.18			-24
50					soft phyllitic layer with quartzite	
	51	51	51	51		-26
52						
						-28
54						
						-30
56						
						-32
58						
						-34
60						
						-36
62						
						-38
64						
						-40
66						
						-42
68						
						-44
70						

Struisbaai

Well Ident

G39943

Drilling Date 16 September 19		SWL 10.50	Use Exploration
Vert. Scale 120.0	Hor. Scale 50.0	Drilling Method Mud rotary and air percussion	
X 51951	Y 90426	Z 26.13	



Struisbaai

Well Ident
G39943

Drilling Date 16 September 19		SWL 10.50	Use Exploration
Vert. Scale 120.0	Hor. Scale 50.0	Drilling Method Mud rotary and air percussion	
X 51951	Y 90426	Z 26.13	

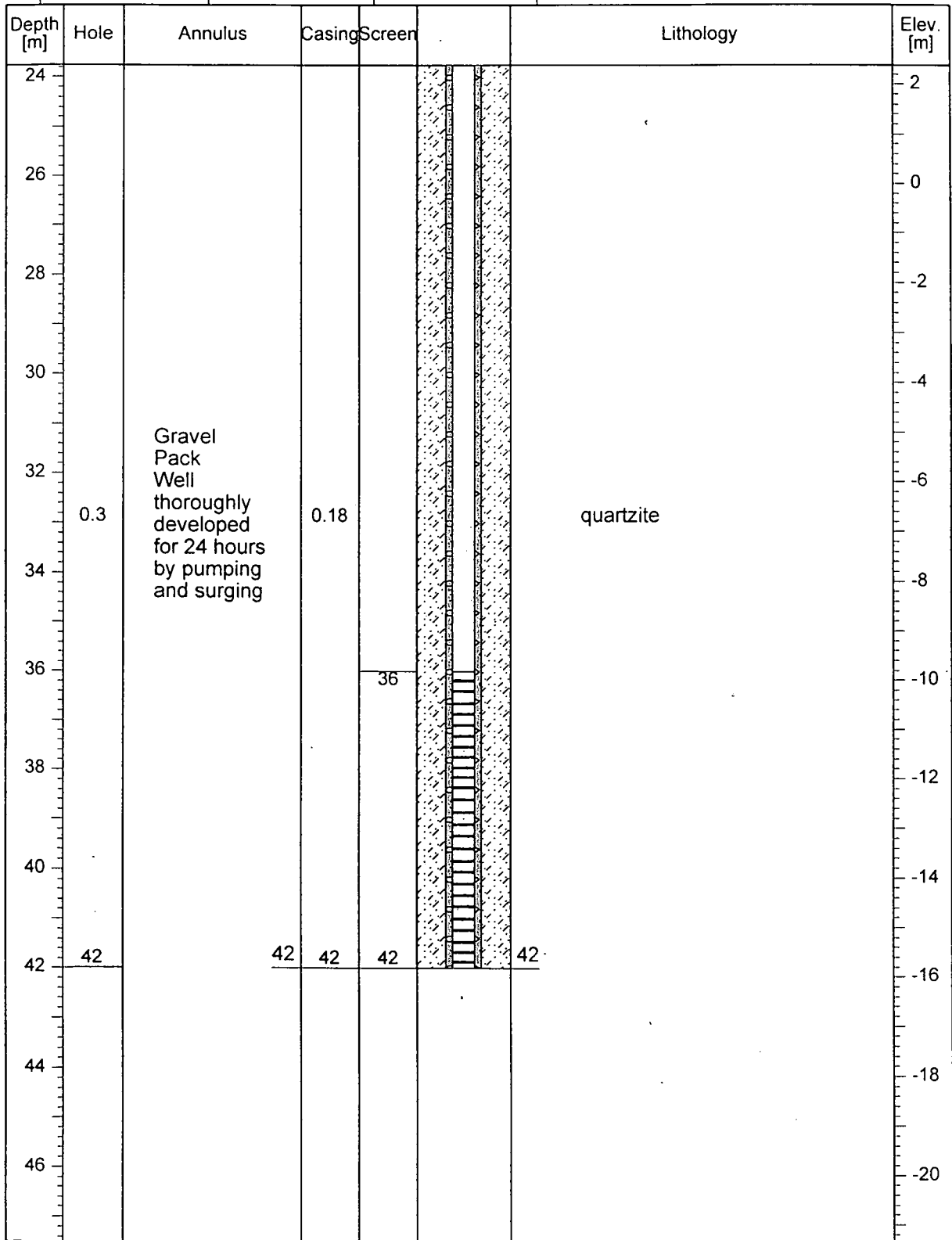


TABLE 1

STRUISBAAI - ERF 920

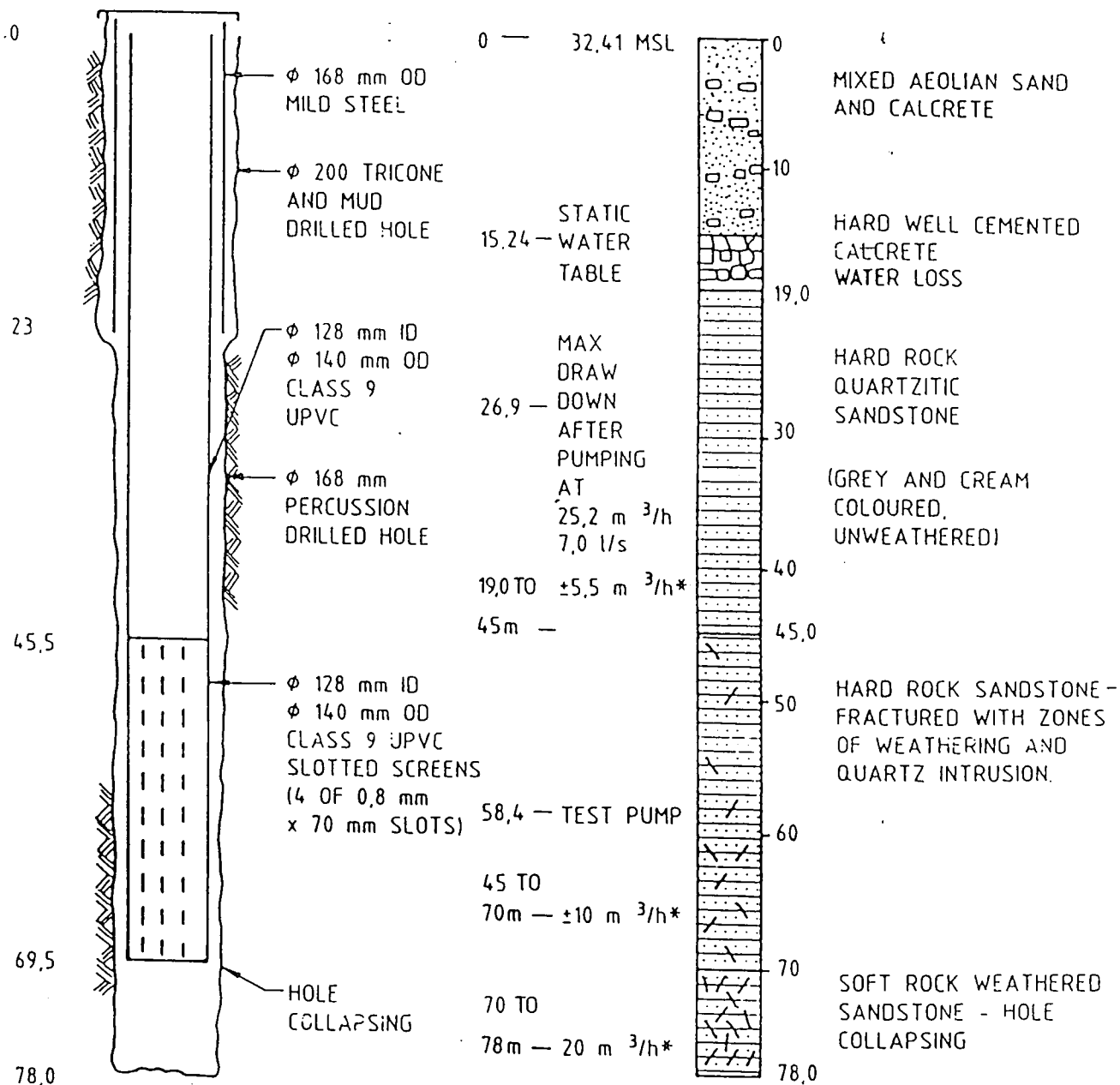
SUMMARY OF PRODUCTION BOREHOLE DATA

BOREHOLE		P1		P2	
LOCATION	Y:	90 735,35		91 034,82	
LOCATION	X:	51 886,96		51 904,96	
ELEVATION		32,41		40,52	
		DEPTH Below Surface (m)	ELEVATION (MSL)	DEPTH Below Surface (m)	ELEVATION (MSL)
Bredasdorp Formation:		19,00	13,41	28,50	12,20
Borehole base:		78,00	-45,59	100,00	-59,48
Water inflow:		45 to 70,00	-13 to -38,00	70 to 100,00	-29 to -59
Static water level:		13,10	19,30	23,07	17,52
Test pump location:		58,40	-25,99	66,86	-26,34
Constant delivery:					
Test yield:	(m ³ /hr)	25,20m ³ /hr		46m ³ /hr	
Max drawdown after 72 hours:		24,82	7,59	44,46	-3,94
Hole diameter	(OD)	168mm		200mm	
Casing diameter	(OD)	140mm		-	
	(ID)	128mm		-	
Type		UPVC class 9		-	
Screens		UPVC class 9 0,8mm slots		-	
Conductivity (mS/m)		97,8		98,4	
TDS (mg/l)		636		639	

BOREHOLE CONSTRUCTION

WATER ENCOUNTERED

PROFILE



* ESTIMATED FLOWS

DATE DRILLED : 20 - 25 MAY 1990

DATE TESTED : 5 - 8 JUNE 1990

CO-ORDINATES

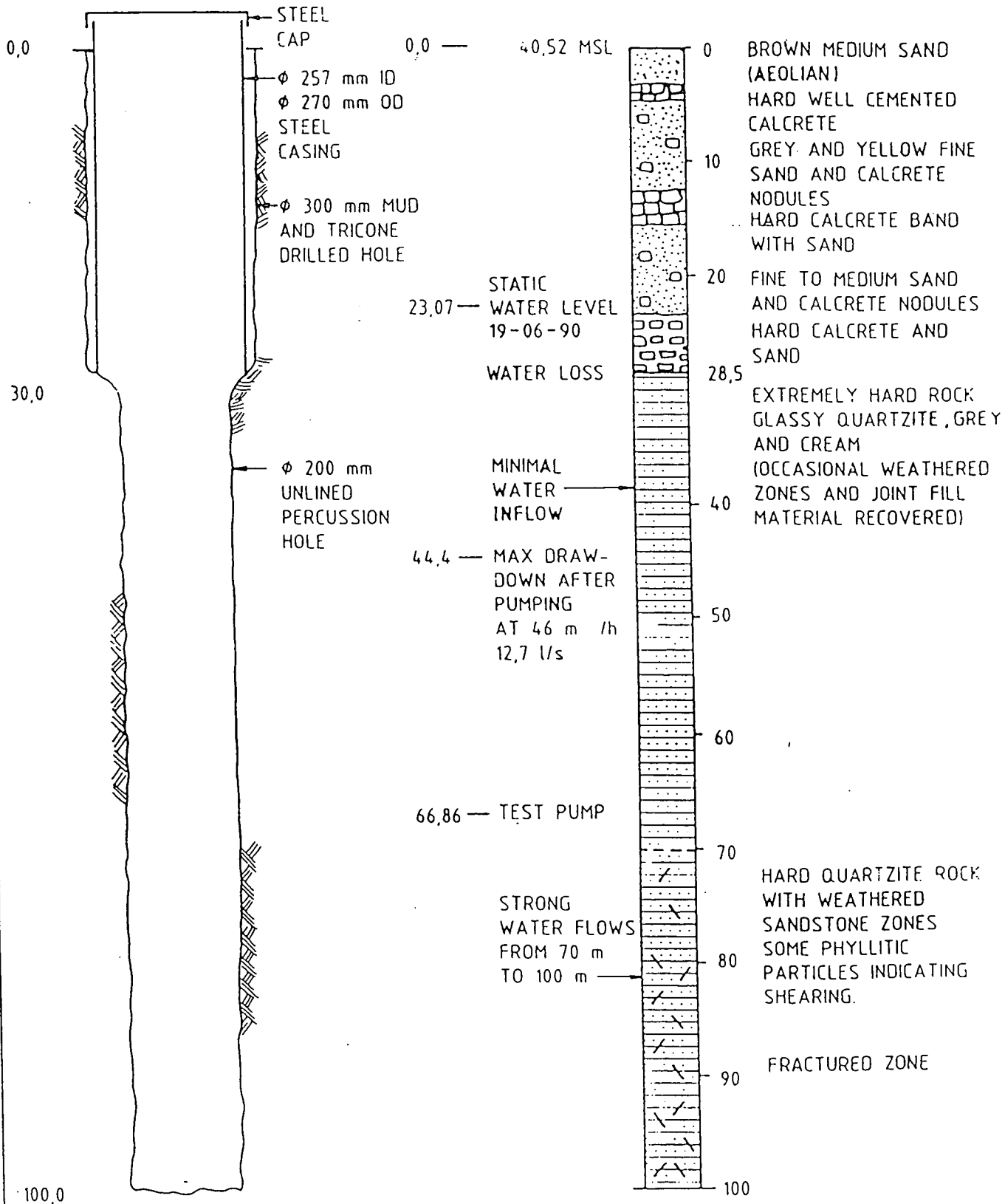
X : 51 886,96

Y : 90 753,35

BOREHOLE CONSTRUCTION

WATER ENCOUNTERED

PROFILE

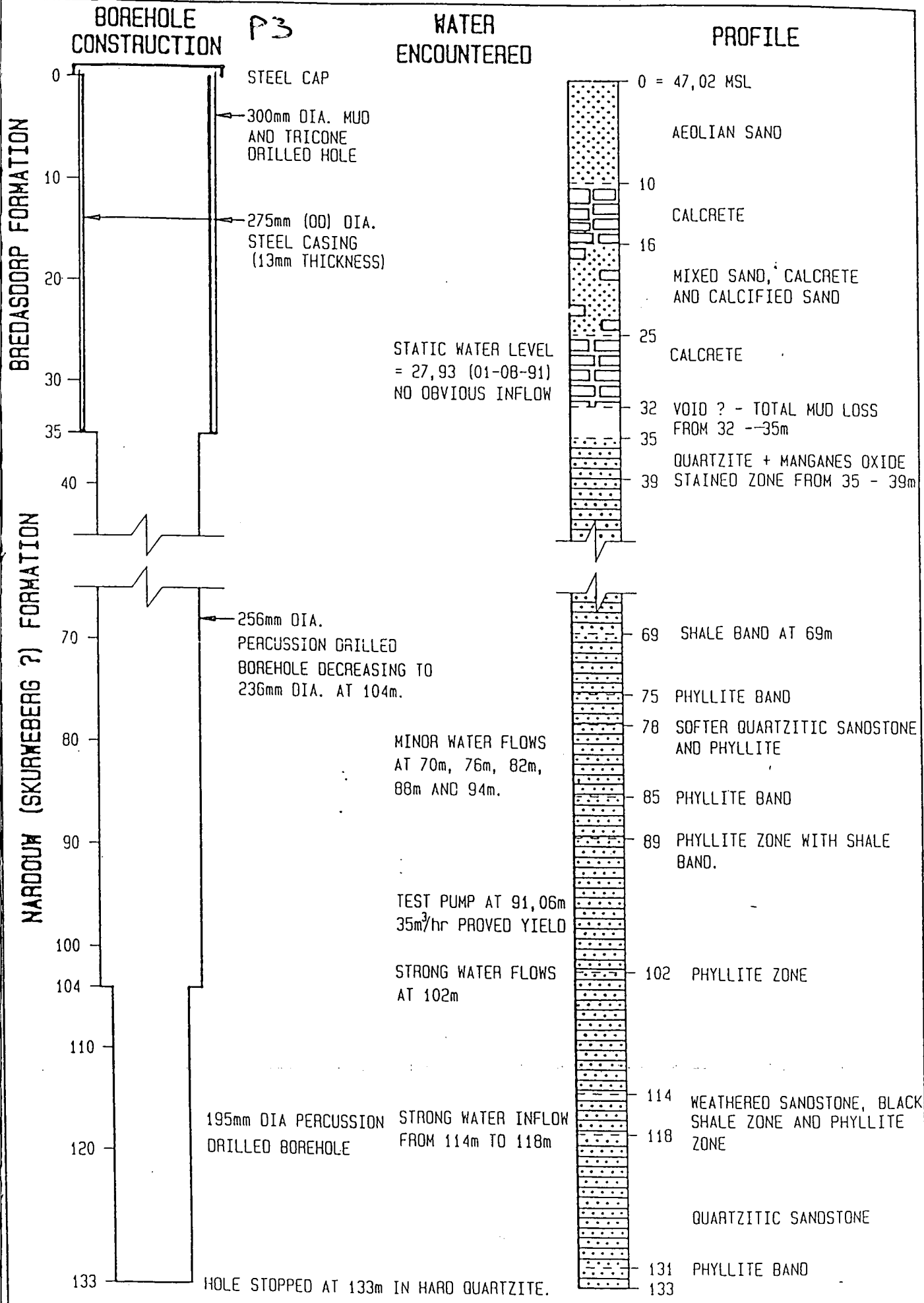


DATE DRILLED : 6 - 13 JUNE 1990

CO-ORDINATES

X : 51 904,96

Y : 01 071,87



BOREHOLE LOG

BOREHOLE No.: T1
SHEET: 1 OF 2

DRILL METHOD	SIZE	DEPTH
ROTARY TRICONE	100mm	18,3

MACHINE:
DRILLING CONTRACTOR: Myburgh Bros

DRILLER: G Myburgh

CLIENT: ESP
PROJECT: STRUISBAAI
SITE: STRUISBAAI - ERF 920
ORIENTATION: VERTICAL ELEVATION: 28,77
CO-ORDINATES: Y 90 773,14 X 51 823,93
DATE STARTED: 09/05/90 DATE COMPLETED: 09/05/90
DEPTH TO WATER TABLE: 11,86 LOGGED BY: RKM

DEPTH (m)	REC	DRILL METHOD	RQD %	REMARKS	PROFILE	MATERIAL DESCRIPTION	DEPTH (m)
0				Initial Water Level = 5,46		Light grey, subrounded fine grained to medium grained SAND. Scattered broken shell particles.	
1				Blow out test after one hour = 0,15l/s (0,54 m ³ /hr)			
2				Final water level = 11,86			
3				7/3/93 wl = 12,52 Depth = 18,63 below collar			
4						Fine grained SAND.	4,00
5							
6							6,00
7						Light grey and yellow medium grained SAND with calcareous nodules.	
8							8,00
9						Grey and yellow medium grained calcareous SAND.	
							9,10
						Hard, well cemented CALCRETE, orange and yellow with some weaker bands	

BOREHOLE LOG

BOREHOLE No.: T1
SHEET: 2 OF 2

DRILL METHOD	SIZE	DEPTH
ROTARY TRICONE	100mm	18,3

MACHINE:
DRILLING CONTRACTOR: Myburgh Bros

DRILLER: G Myburgh

CLIENT: ESP
PROJECT: STRUISBAAI
SITE: STRUISBAAI - ERF 920
ORIENTATION: VERTICAL ELEVATION: 28,77
CO-ORDINATES: Y 90 773,14 X 51 823,93
DATE STARTED: 09/05/90 DATE COMPLETED: 09/05/90
DEPTH TO WATER TABLE: 11,86 LOGGED BY: RKM

DEPTH (m)	REC	DRILL METHOD	RQD %	REMARKS	PROFILE	MATERIAL DESCRIPTION	DEPTH (m)
						Hard, calcrete continued	
						Soft calcareous SAND	10,40
11						Very hard, well cemented CALCRETE band	11,10 11,20
12						Soft calcareous gravel and silty SAND.	
13							
14							
15							15,00
16						SAND with first signs of broken shell particles. Medium grained with some calcareous particles and zones of calcrete.	
17							
						WATER LOSS ZONE. Quartz pebbles and white clay zone.	17,50 17,90
						Very hard rock, grey quartzite particles. Table Mountain Group. Peninsula formation ?	18,30

DRILL METHOD	SIZE	DEPTH
ROTARY TRICONE	100mm	0 - 12,5

CLIENT : *ESP*
 PROJECT : *STRUISBAAI*
 SITE : *STRUISBAAI - ERF 920*
 ORIENTATION : *VERTICAL* ELEVATION : *24,3*
 CO-ORDINATES : *Y 91 137,17 X 51 719,67*
 DATE STARTED : *10/05/90* DATE COMPLETED : *10/05/90*
 DEPTH TO WATER TABLE : *4,3* LOGGED BY : *RKM*

MACHINE :
 DRILLER : *G Myburgh*
 DRILLING CONTRACTOR : *Myburgh Bros*

DEPTH (m)	REC	DRILL METHOD	ROD %	REMARKS	PROFILE	MATERIAL DESCRIPTION	DEPTH (m)
0				Initial Water Level = 5,15 m.			
1				Blow out test after 1 hour = 0,085l/s (0,306 m ³ /hr).			
2				Final Water Level = 10,05 m.			
3				Recovery to 5,0m in 14 minutes.		Fine to medium grained, subrounded SAND with fine grained shell particles.	
4							
5						Zone of harder CALCRETE	4,50
6						Fine grained SAND with scattered calcareous zones	5,00
7						Layers of soft CALCRETE & CALCAREOUS SILT ± 100 to 200mm thick with harder well cemented CALCRETE.	6,00
8						As above but yellow calcareous material from 7,5m.	7,50
9						Hard to medium hard rock CALCRETE.	8,00
10							

VAN NIEKERK, KLEYN & EDWARDS

FIGURE NO: 1 J

BOREHOLE LOG

BOREHOLE No.: T 2
 SHEET: 2 OF 2

DRILL METHOD	SIZE	DEPTH
ROTARY TRICONE	100mm	0 - 12,5

CLIENT : *ESP*
 PROJECT : *STRUISBAAI*
 SITE : *STRUISBAAI - ERF 920*
 ORIENTATION : *VERTICAL* ELEVATION : *29,0*
 CO-ORDINATES : *Y 91 137,17 X 51 719,67*
 DATE STARTED : *10/05/90* DATE COMPLETED : *10/05/90*
 DEPTH TO WATER TABLE : LOGGED BY : *RKM*

MACHINE :
 DRILLER : *G Myburgh*
 DRILLING CONTRACTOR : *Myburgh Bros*

DEPTH (m)	REC	DRILL METHOD	ROD %	REMARKS	PROFILE	MATERIAL DESCRIPTION	DEPTH (m)
11						Hard to medium hard rock CALCRETE.	
12				Water loss from this zone.		Some shelly gravel	
13						Hard quartzitic sandstone. Table Mountain Group.	11,5
14							
15							12,5
16							
17							
18							
19							

BOREHOLE LOG

BOREHOLE No.: **TJ**
SHEET: **1** OF **2**

DRILL METHOD	SIZE	DEPTH
ROTARY TRICONE	100mm	0 - 18,3

MACHINE: _____ DRILLER: *G Myburgh*
DRILLING CONTRACTOR: *Myburgh Bros*

CLIENT: *ESP*
PROJECT: *STRUISBAAI*
SITE: *STRUISBAAI - ERF 920*
ORIENTATION: *VERTICAL* ELEVATION: *26,12*
CO-ORDINATES: *Y 91 422,97 X 51 676,60*
DATE STARTED: *11/05/90* DATE COMPLETED: *11/05/90*
DEPTH TO WATER TABLE: *6,65* LOGGED BY: *RKM*

DEPTH (m)	REC	DRILL METHOD	ROD %	REMARKS	PROFILE	MATERIAL DESCRIPTION	DEPTH (m)
0				Initial Water Level = 6,65			
1				Blow out test after 1 hour = 0,11/s (0,36 m ³ /hr)			
2				Final Water Level = 12,9			
3				Full recovery after 15 minutes		Fine SAND - slightly silty but grey with CALCRETE nodules.	
4							
5							5,00
6							
7						Fine SAND - slightly silty but grey with CALCRETE nodules.	
8							
9							
10							

BOREHOLE LOG

BOREHOLE No.: **TJ**
SHEET: **2** OF **2**

DRILL METHOD	SIZE	DEPTH
ROTARY TRICONE	100mm	0 - 18,3

MACHINE: _____ DRILLER: *G Myburgh*
DRILLING CONTRACTOR: *Myburgh Bros*

CLIENT: *ESP*
PROJECT: *STRUISBAAI*
SITE: *STRUISBAAI - ERF 920*
ORIENTATION: *VERTICAL* ELEVATION: *26,12*
CO-ORDINATES: *Y 91 422,97 X 51 676,60*
DATE STARTED: *11/05/90* DATE COMPLETED: *11/05/90*
DEPTH TO WATER TABLE: *11,86* LOGGED BY: *RKM*

DEPTH (m)	REC	DRILL METHOD	ROD %	REMARKS	PROFILE	MATERIAL DESCRIPTION	DEPTH (m)
11						CALCRETE and yellow brown silty calcareous SAND.	
12						Hard calcareous SAND - drill water becomes whiter.	
13							
14							
15							
16						Grey CLAY with residual calcrete particles	
17				Virtually no water loss at contact.		Some shelly gravel.	17,00
18						Quartzitic sandstone Table Mountain Group.	18,30
19							

Appendix 2

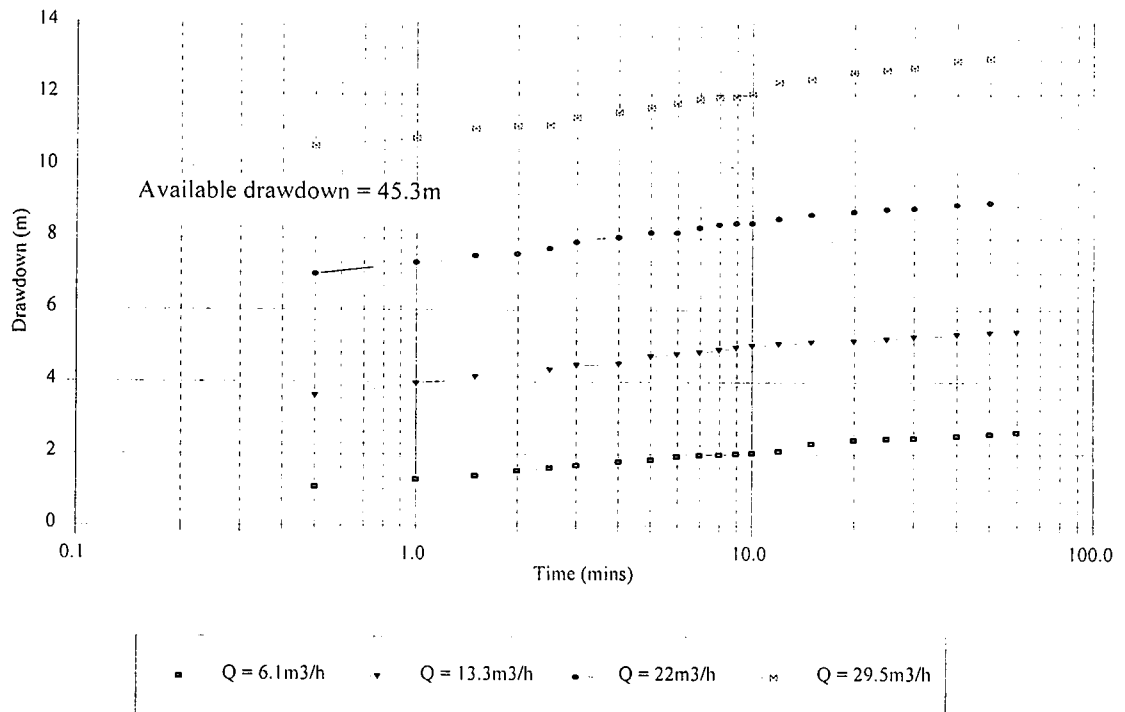
Test-Pumping Data

- Test-Pumping Graphs
- Boreholes P1, P2, P3 at Struisbaai

Data from McClea (1990 and 1991)

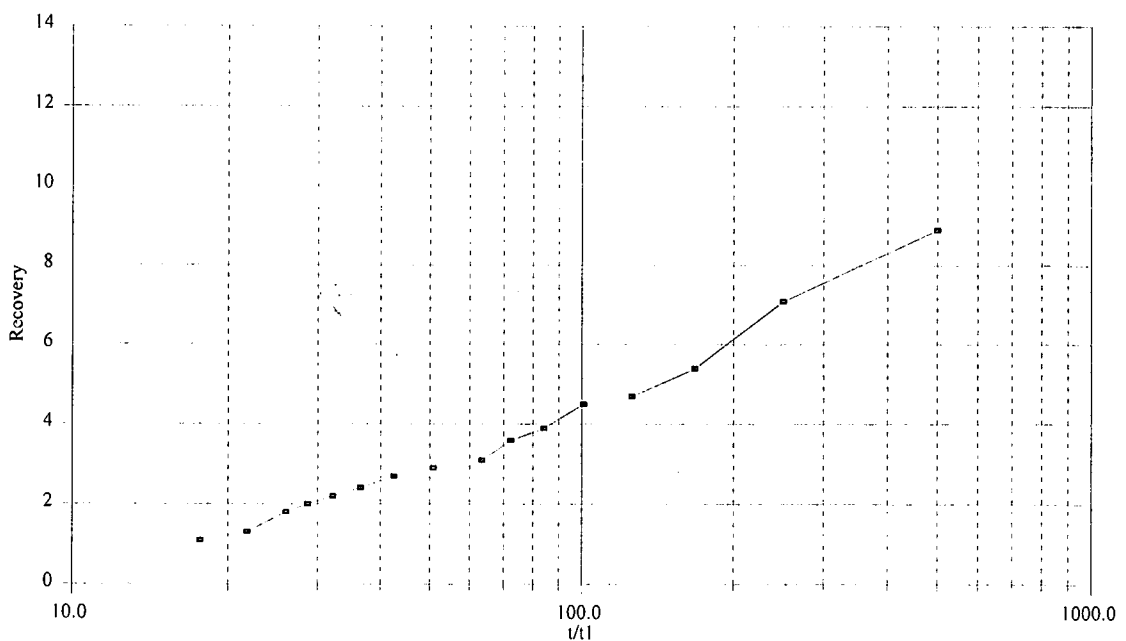
Multiple discharge rate test

BH P1



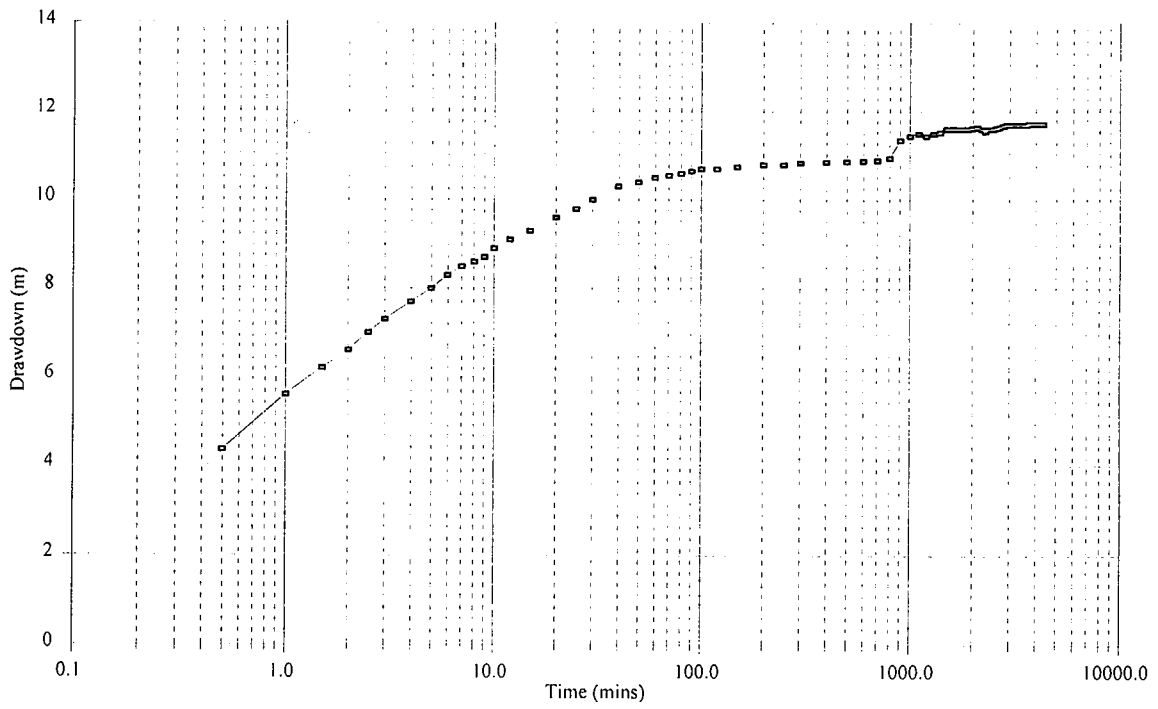
Multiple discharge rate test

BH P1 - Recovery



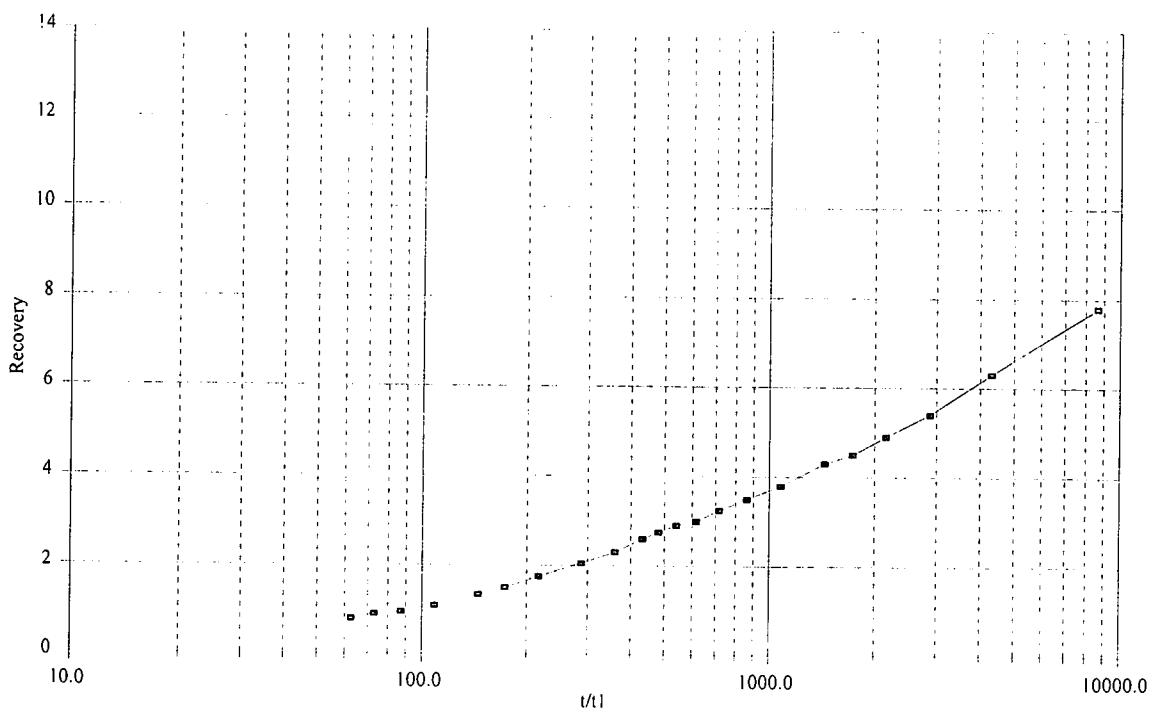
Constant discharge test: BH P1

Abstraction rate = 25.20m³/h



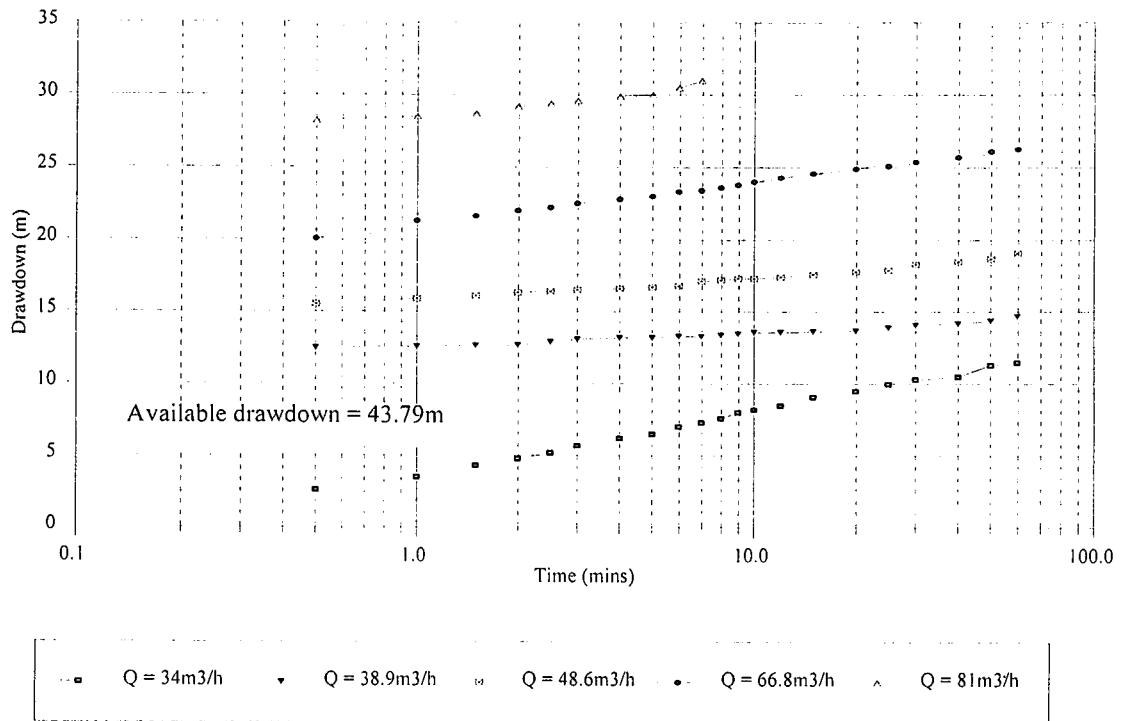
Constant discharge test

BH P1 - Recovery



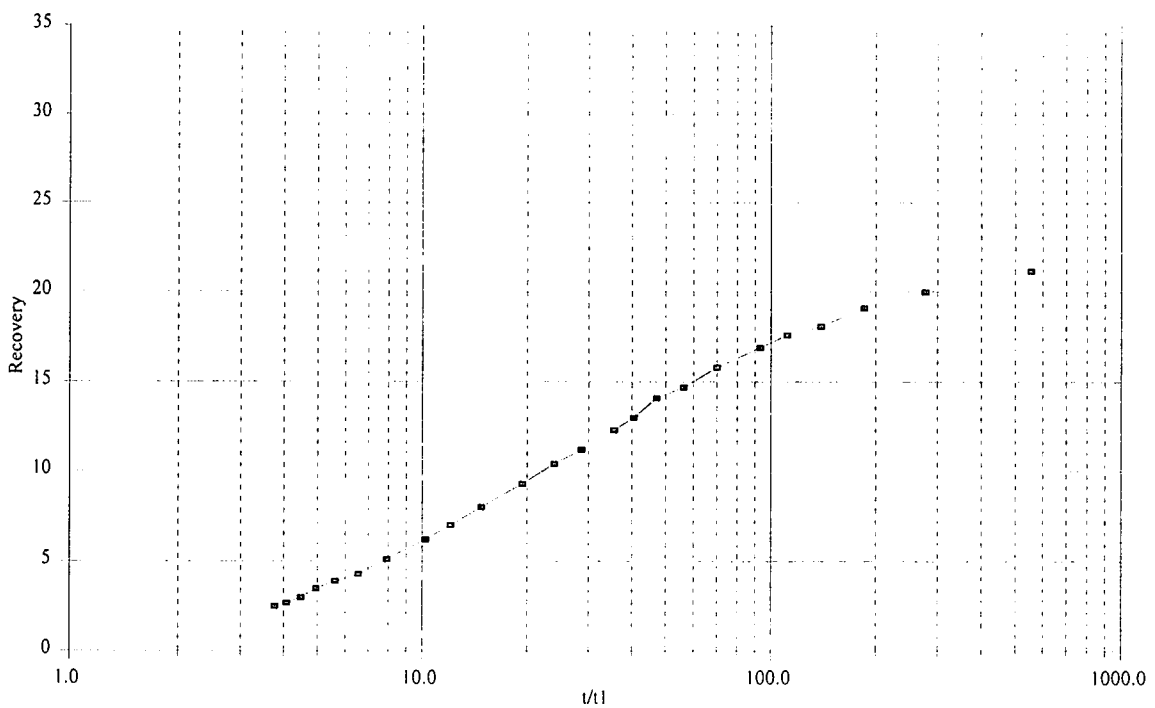
Multiple discharge rate test

BH P2



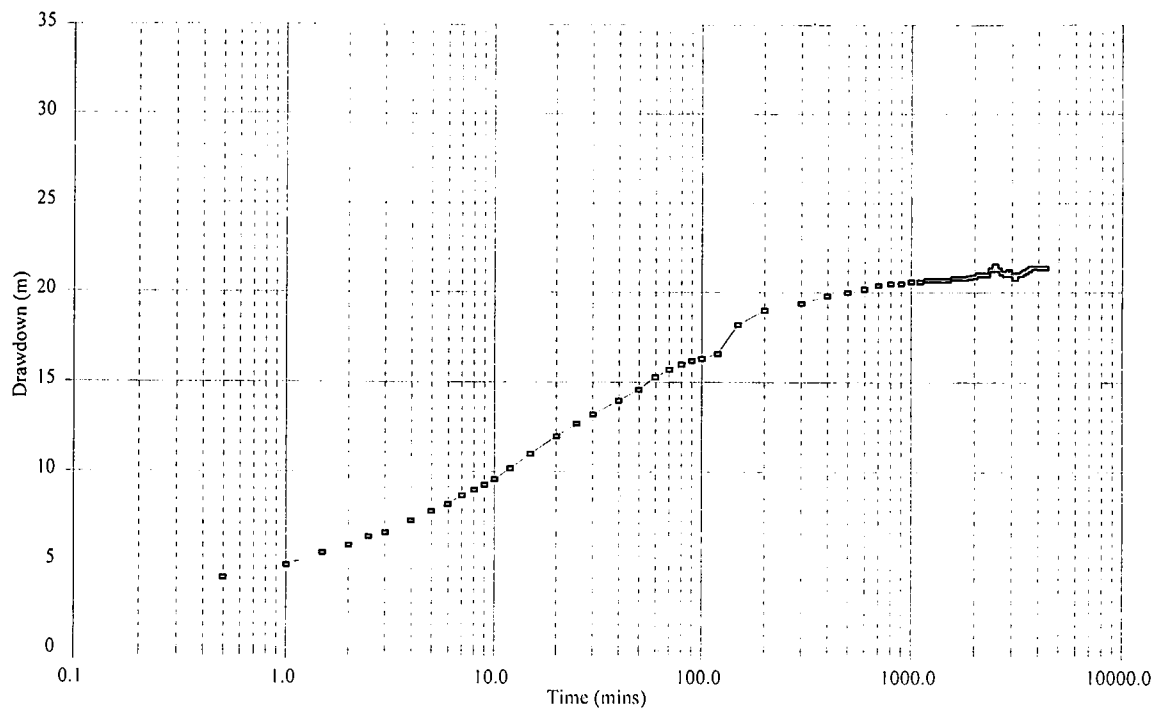
Multiple discharge rate test

BH P2 - Recovery



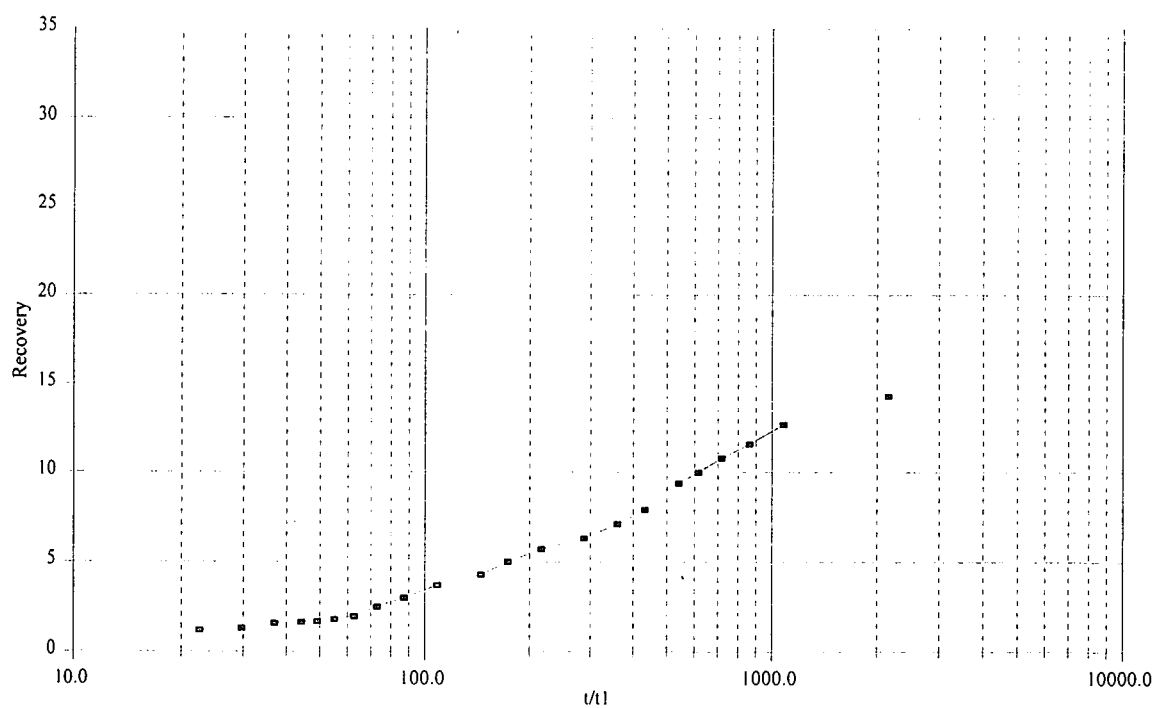
Constant discharge test: BH P2

Abstraction rate = 46.10 m³/h

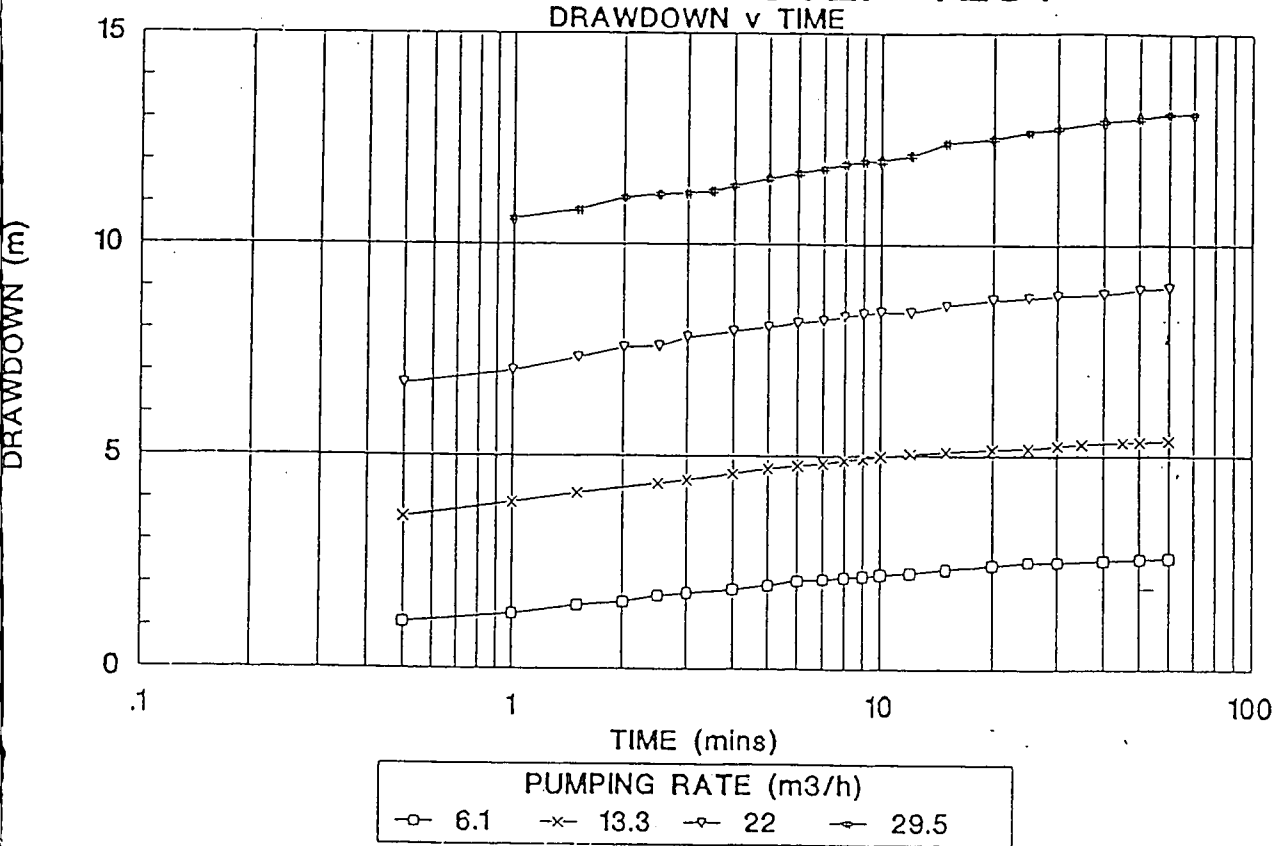


Constant discharge test

BH P2 - Recovery



STRUISBAAI WATER BOREHOLES BOREHOLE 1 - STEP TEST



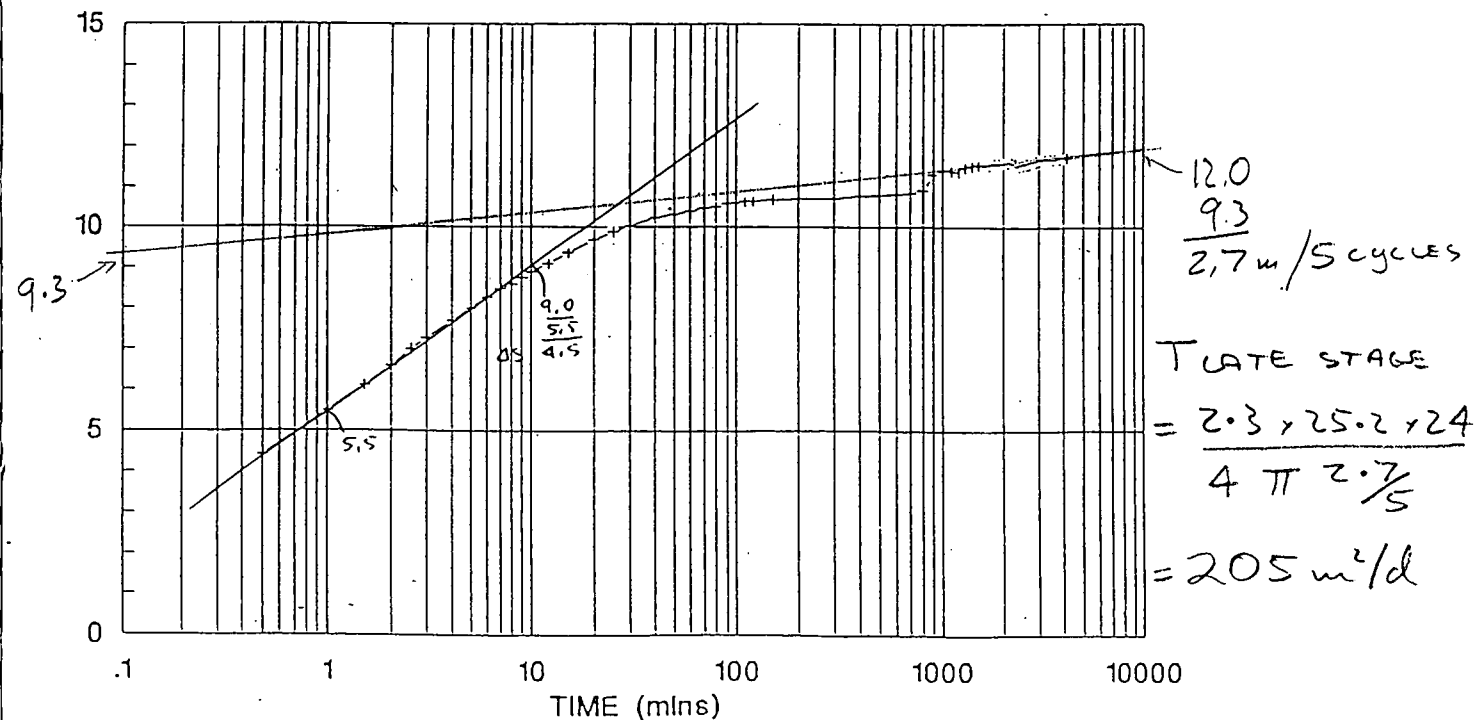
$Q = 25.2 \text{ m}^3/\text{hr}$ STRUISBAAI WATER BOREHOLES
BOREHOLE 1
72hr CONSTANT DELIVERY TEST

$$T = \frac{2.3Q}{4\pi Ds}$$

$$= 24.6 \text{ m}^2/\text{day}$$

$$= 25 \text{ m}^2/\text{day}$$

DRAWDOWN v TIME



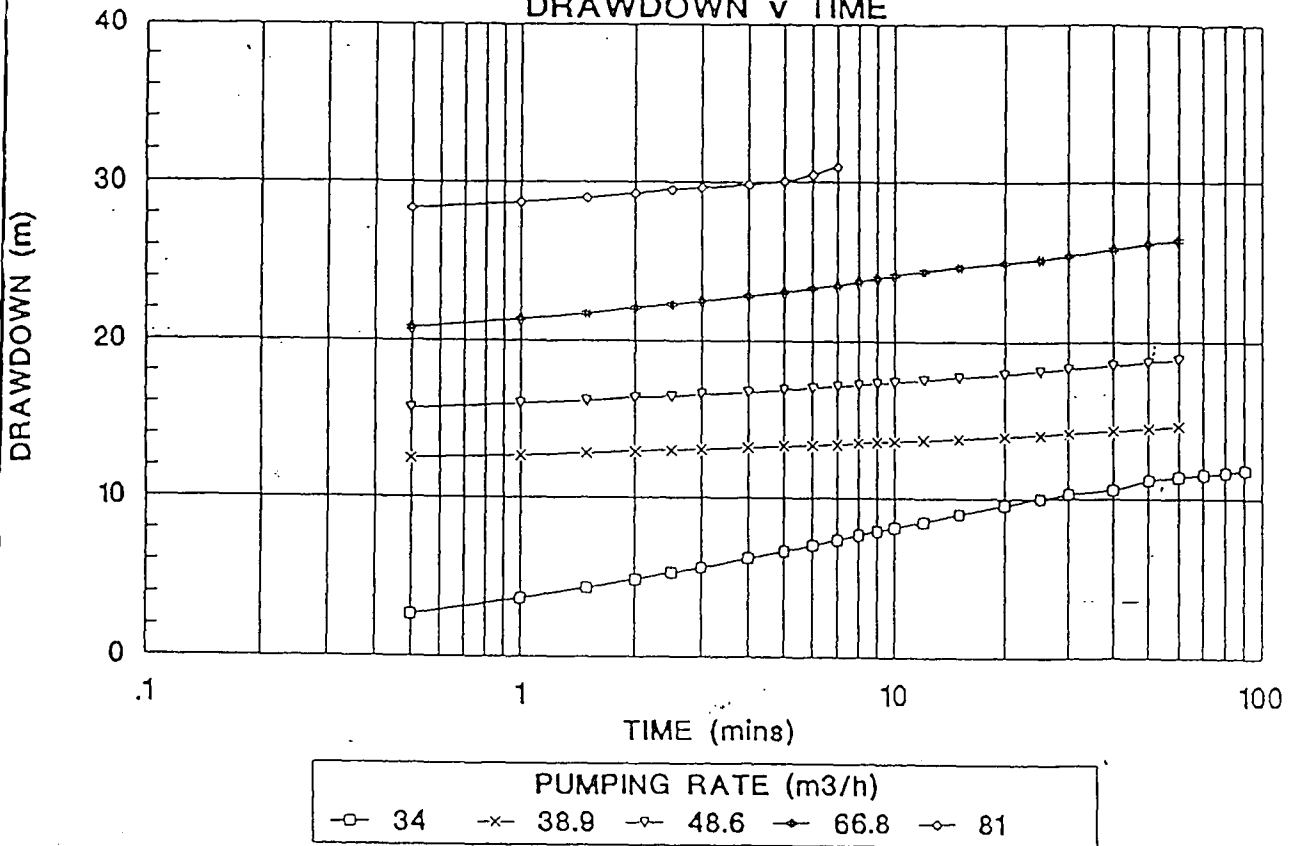
T LATE STAGE

$$= \frac{2.3 \times 25.2 \times 24}{4\pi \times 2.7}$$

$$= 205 \text{ m}^2/\text{d}$$

STRUISBAAI WATER BOREHOLES BOREHOLE 2 - STEP TEST

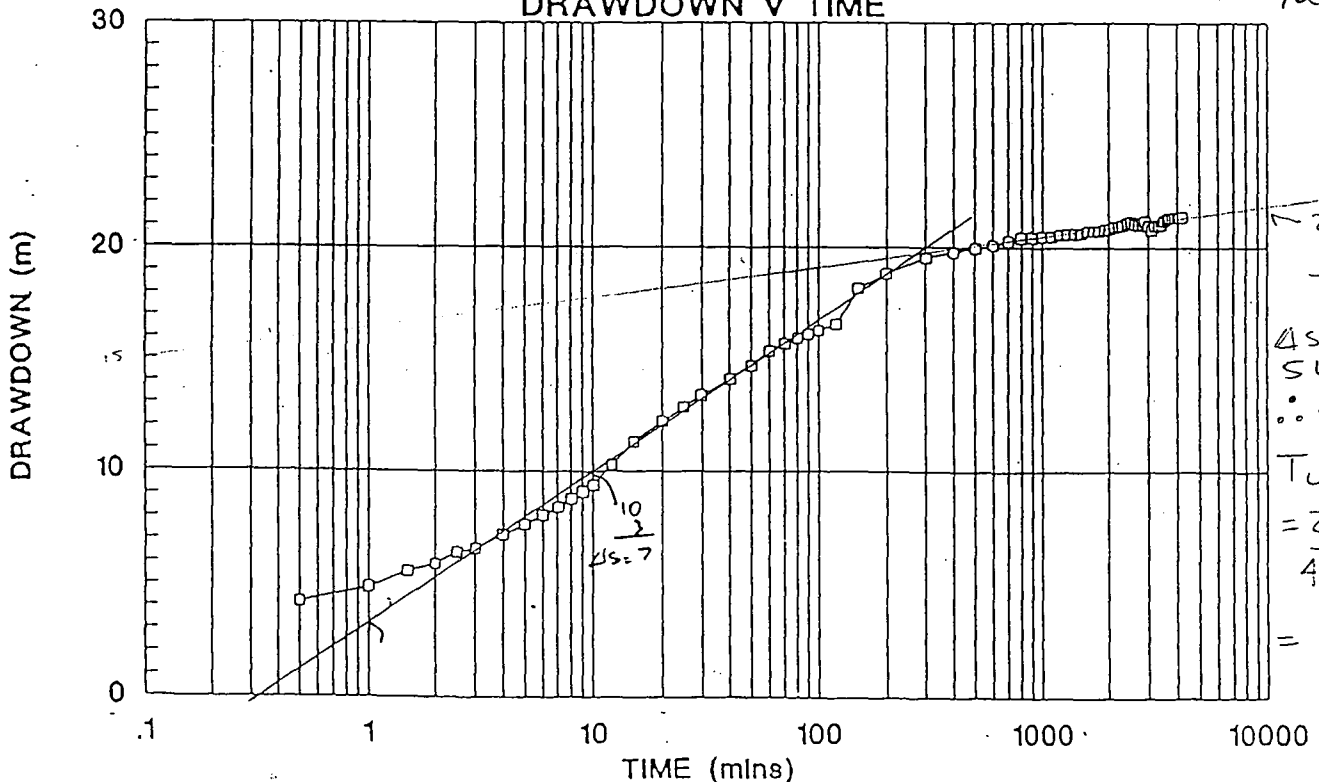
DRAWDOWN v TIME



$Q = 46.1 \text{ m}^3/\text{hr}$

STRUISBAAI WATER BOREHOLES BOREHOLE 2 72hr CONSTANT DELIVERY TEST DRAWDOWN v TIME

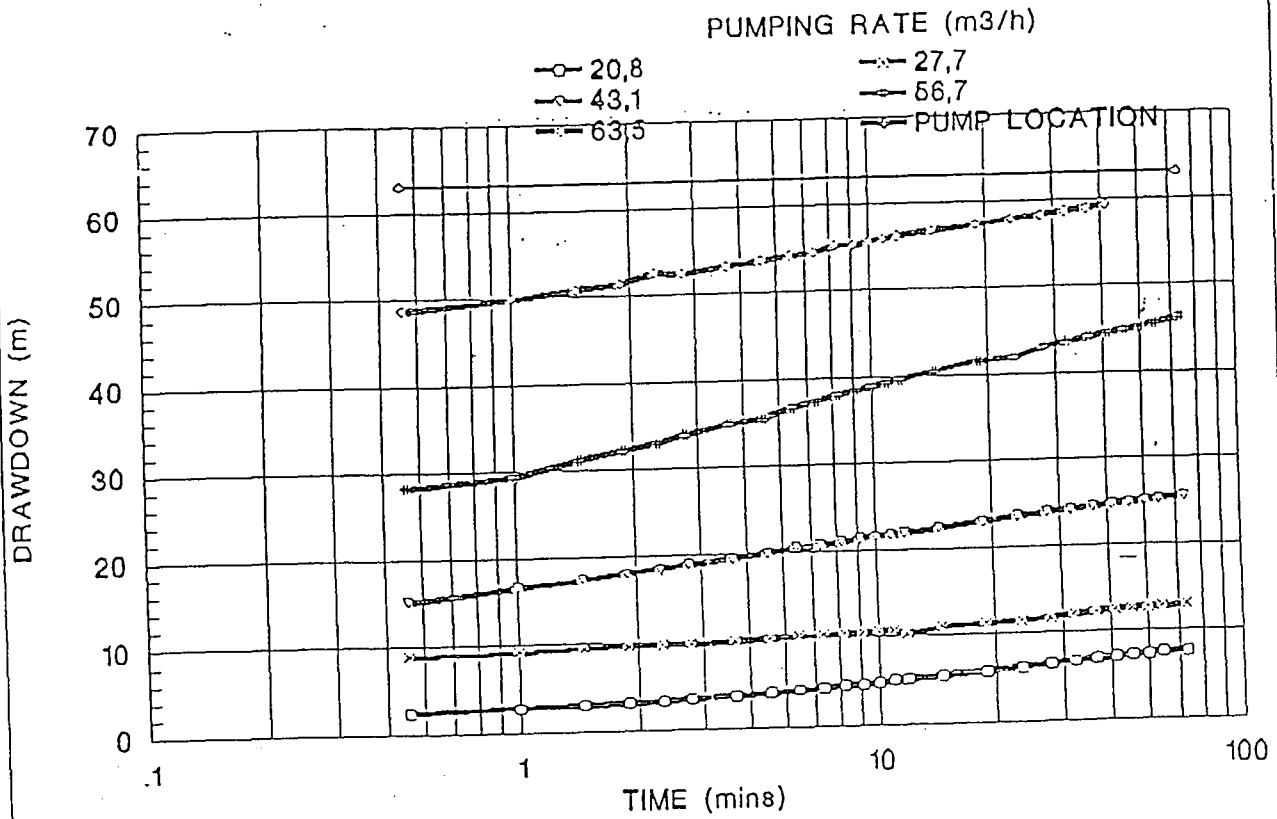
$T = \frac{2.3Q}{4\pi AS}$ EARLY STAGE
 $= 29 \text{ m}^2/d$



PUMP RATE 46.1 m³/Hr

STRUISBAAI - ERF 920 - BOREHOLE P3

STEP TEST

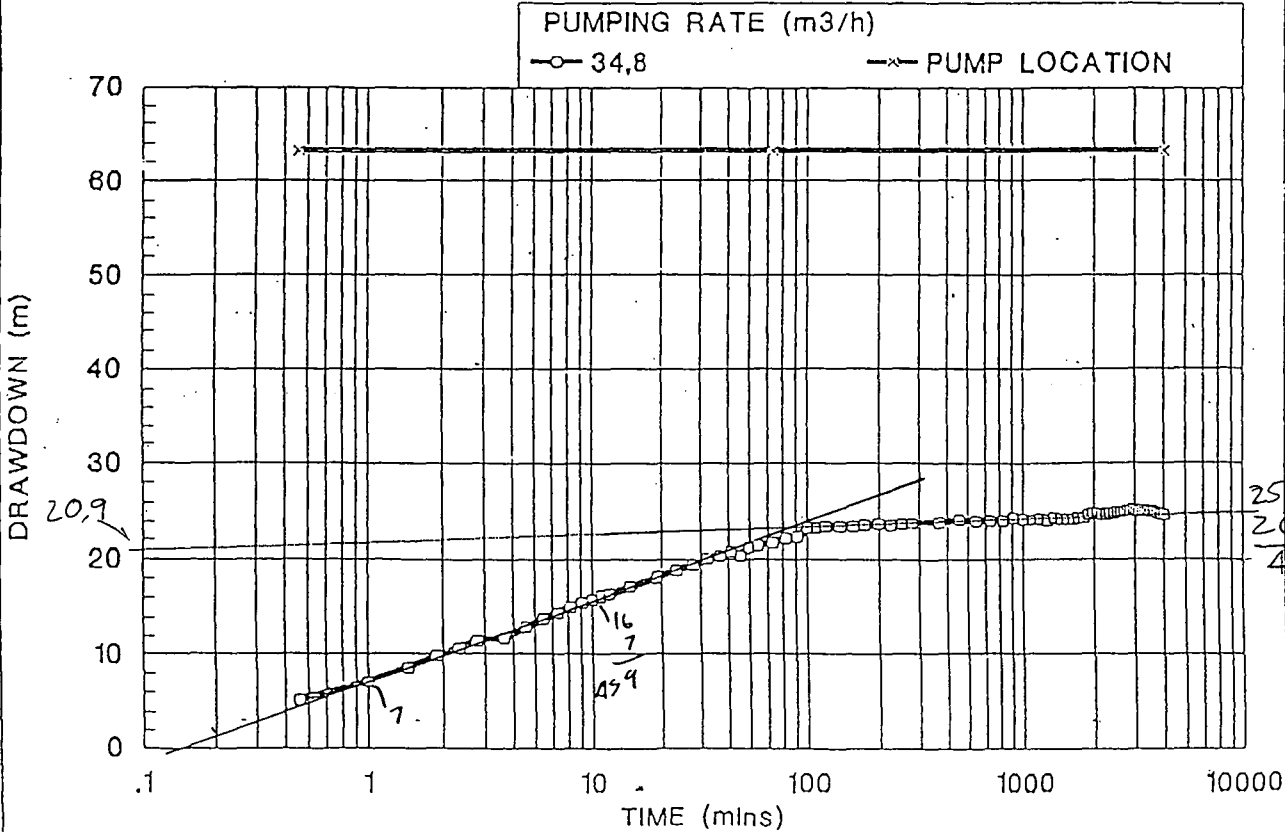


Sheet B1

STRUISBAAI - ERF 920 - BOREHOLE P3

CONSTANT DELIVERY TEST

$T = \frac{2.3Q}{4\pi AS}$ EARLY STAGE
 $= 17 \text{ m}^2/\text{day}$

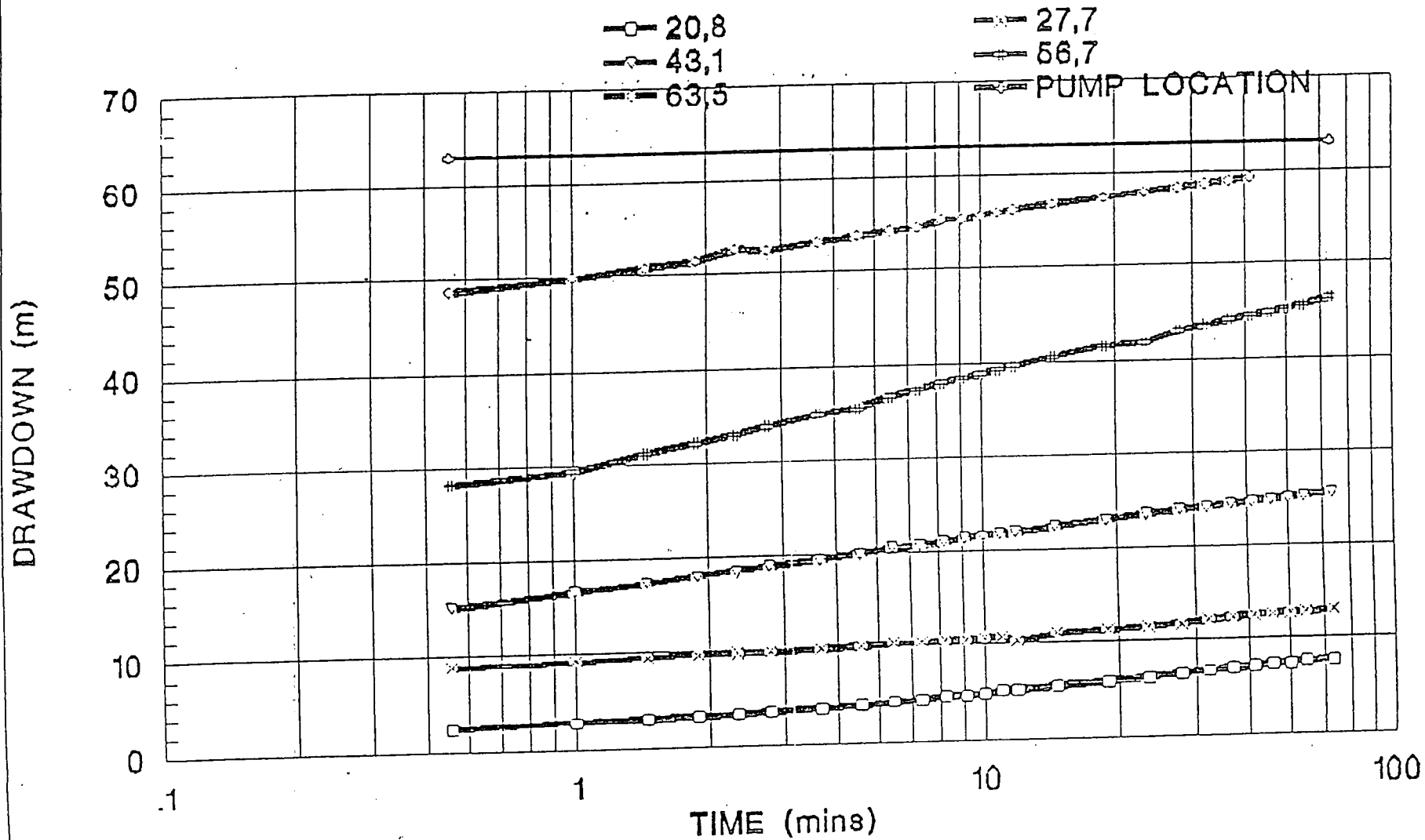


$T_{\text{LATE STAGE}} = \frac{2.3 \times 34.8 \times 2}{4\pi \times 4.2 \times 5} = 182 \text{ m}^2/\text{d}$

STRUISBAAI - ERF 920 - BOREHOLE P3

STEP TEST

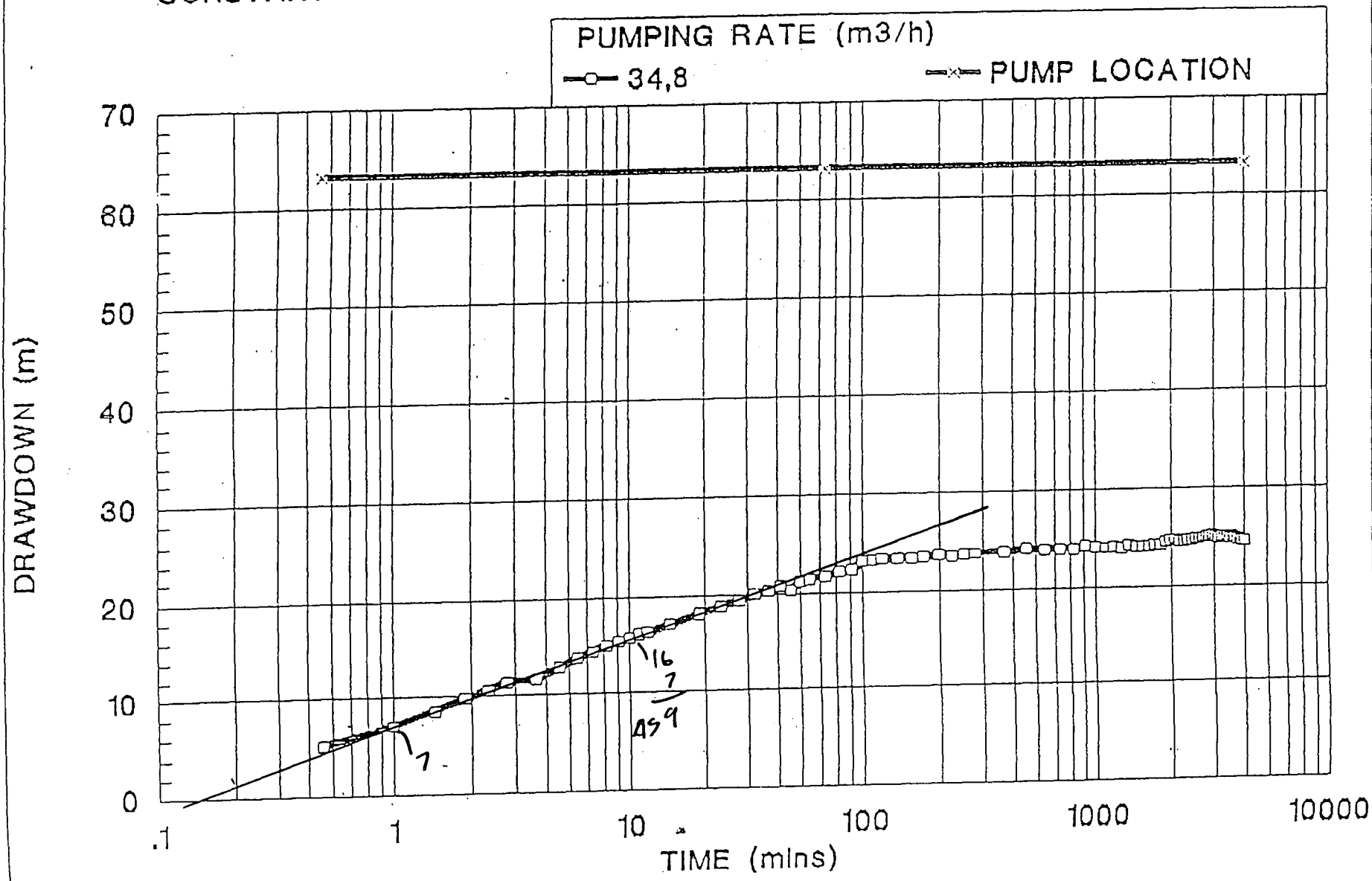
PUMPING RATE (m³/h)



STRUISBAAI - ERF 920 - BOREHOLE P3

$$T = \frac{2.3Q}{4\pi AS} = 17 \text{ m}^2/\text{dag}$$

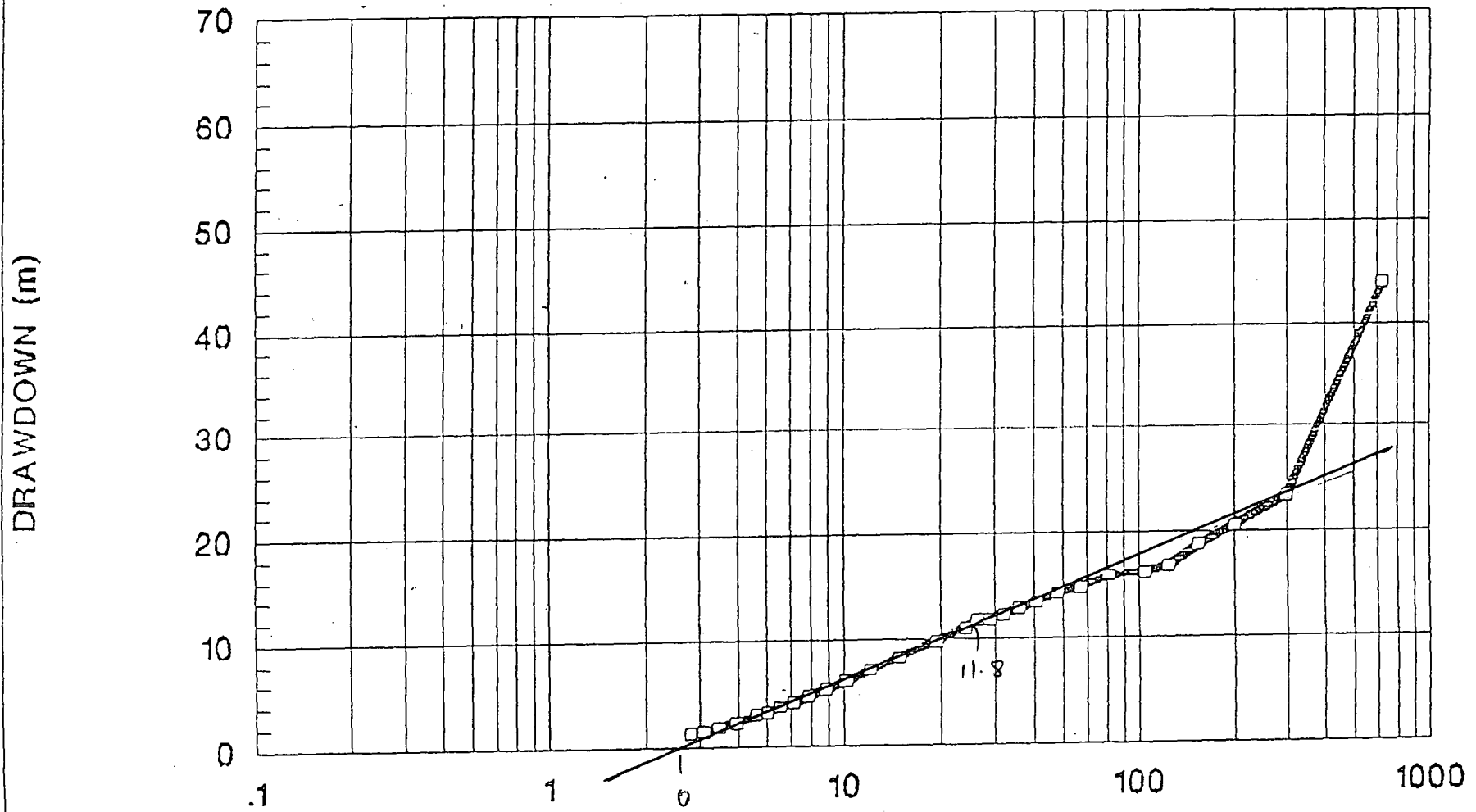
CONSTANT DELIVERY TEST



STRUISBAAI - ERF 920 - BOREHOLE P3

STEP TEST - RECOVERY
DRAWDOWN VS t/t''

STATIC WATER LEVEL
-o- -27.93



$$T_r = \frac{2.3 Q}{4\pi ds} = \frac{2.3 \times 835}{4\pi \times 11.8} = 13 \text{ m}^2/d$$

Appendix 3

Chemistry and Isotopic Data

- ▣▣▣▣ Struisbaai Groundwater Chemistry
- ▣▣▣▣ Struisbaai Groundwater Isotopic Composition
- ▣▣▣▣ Struisbaai Rainfall Chemistry
- ▣▣▣▣ CSIR Chemistry Laboratory Precision and Recovery Data

GROUNDWATER CHEMISTRY DATA

AG1

DATE	03/04/93	10/28/93	04/14/94	08/28/94	12/07/94
K (mg/L)	6.4	6.0	6.4	5.6	5.9
Na (mg/L)	195	206	210	213	209
Ca (mg/L)	91	93	94	89	88
Mg (mg/L)	24	25	26	25	25
NH4 (mg/L N)	<0.05	<0.05	<0.1	<0.1	<0.1
SO4 (mg/L)	52	56	50	53	52
Cl (mg/L)	347	359	356	364	367
Alk (mg/L CaCO3)	215	228	216	217	212
NOx (mg/L N)	2.40	4.70	3.10	2.30	2.30
P (mg/L)	<0.05	<0.05	<0.1	<0.1	<0.1
Si (mg/L)	4.4	3.8	3.8	3.9	3.9
Cu (mg/L)	<0.02	<0.02	<0.03	<0.03	<0.03
Fe (mg/L)	<0.02	<0.02	<0.03	<0.05	<0.05
Mn (mg/L)	<0.02	<0.02	<0.03	<0.05	<0.05
Zn (mg/L)	<0.01	<0.02	<0.03	<0.03	<0.03
Sr (mg/L)	1.14	1.17	1.0	1.17	1.09
Rb (mg/L)	-	-	-	<0.03	<0.03
Ba (mg/L)	-	-	-	<0.25	<0.25
Li (mg/L)	0.008	0.006	0.010	0.008	0.009
DOC (mg/L C)	4.4	6.9	3.0	1.4	0.8
EC - field (mS/m)	-	168	-	-	-
EC - lab (mS/m)	155	170	165	160	160
pH - field	-	6.5	-	7.3	-
pH - lab	7.7	7.7	7.2	7.7	-
Cations (meq/l)	15.16	15.81	16.08	15.88	15.63
Anions (meq/l)	15.33	16.19	15.63	15.86	15.83
% balance	1.07	2.42	2.91	0.13	1.32
Carbon-13 (‰ PDB)	-10.6	-10.6	-10.5	-10.6	-10.5
TIC (mmol/L)	4.4	4.6	4.4	4.4	4.4
Carbon-1 pMC	45.5	46.3	45.1	45.3	44.7
Oxygen-18 (‰ SMOW)	-4.8	-4.7	-4.7	-	-5.0
87-Sr/86-Sr	0.709196	0.709224	0.709156	0.709203	0.709145

ICP-MS Microchemistry Data (concentrations in ppb)

Borehole AG1

Date	03/04/93	04/14/94	Date	03/04/93	04/14/94
Li	23.700	30.723	I	-	8.731
Be	0.070	0.327	Te	-	-
B	-	371.849	Cs	-	-
Al	-	17.393	Ba	6.060	5.186
Sc	7.570	6.139	La	-	1.758
Ti	-	159.200	Ce	-	-
V	5.810	43.388	Pr	-	0.776
Cr	10.300	3.378	Nd	-	-
Mn	-	-	Sm	-	0.057
Fe	1657.000	956.167	Eu	-	1.515
Co	0.390	0.344	Gd	-	-
Ni	2.170	2.093	Tb	-	0.013
Cu	3.020	2.522	Dy	-	-
Zn	2.890	4.223	Ho	-	-
Ga	0.250	0.775	Er	-	-
Ge	-	-	Tm	-	0.019
As	-	0.594	Yb	-	-
Se	15.200	5.008	Lu	-	-
Br	-	1410.216	Hf	-	-
Rb	3.680	3.905	Ta	-	0.003
Sr	1503.000	1638.937	W	0.180	-
Y	-	0.022	Re	-	0.065
Zr	-	0.005	Os	-	-
Nb	-	0.742	Ir	-	0.009
Mo	0.300	-	Pt	-	-
Ru	-	-	Au	-	-
Rh	-	0.028	Hg	-	-
Pd	-	0.088	Tl	-	-
Ag	-	-	Pb	-	-
Cd	-	0.053	Bi	-	-
In	-	-	Th	-	0.020
Sn	2.850	1.887	U	0.350	2.512
Sb	0.060	0.029			

GROUNDWATER CHEMISTRY DATA

BH10

DATE	03/03/93	10/28/93	04/15/94	08/26/94	12/06/94
K (mg/L)	7.0	5.9	6.2	5.6	6.0
Na (mg/L)	291	274	269	250	280
Ca (mg/L)	143	120	123	111	126
Mg (mg/L)	37	33	34	29	35
NH4 (mg/L N)	<0.05	<0.05	0.12	<0.1	<0.1
SO4 (mg/L)	81	67	65	55	71
Cl (mg/L)	616	508	506	455	575
Alk (mg/L CaCO3)	217	241	236	238	228
NOx (mg/L N)	1.1	1.4	2.3	1.3	1.1
P (mg/L)	<0.05	<0.05	<0.1	<0.1	<0.1
Si (mg/L)	4.7	3.9	4.1	4.2	4.2
Cu (mg/L)	<0.02	<0.02	<0.03	<0.03	<0.03
Fe (mg/L)	0.05	0.06	0.11	<0.05	<0.05
Mn (mg/L)	<0.02	<0.02	<0.03	<0.05	<0.05
Zn (mg/L)	0.05	<0.02	<0.03	<0.03	<0.03
Sr (mg/L)	1.35	1.16	1.07	0.93	1.12
Rb (mg/L)	-	-	-	<0.25	<0.03
Ba (mg/L)	-	-	-	<0.03	<0.25
Li (mg/L)	0.011	0.008	0.010	0.009	0.011
DOC (mg/L C)	4.5	9.6	3.3	4.0	0.8
EC - field (mS/m)	-	-	-	-	-
EC - lab (mS/m)	230	220	215	190	225
pH - field	-	6.2	-	6.9	-
pH - lab	7.4	7.8	6.8	7.5	-
Cations (meq/l)	23.03	20.80	20.80	18.88	21.52
Anions (meq/l)	23.48	20.64	20.50	18.83	22.34
% balance	1.96	0.79	1.50	0.28	3.85
Carbon-13 (‰ PDB)	-12.0	-13.2	-12.8	-13.0	-12.5
TIC (mmol/L)	4.7	5.1	4.9	5.1	5.0
Carbon-14 (pmc)	78.9	87.9	86.2	86.6	84.0
Oxygen-18 (‰ SMOW)	-4.9	-4.7	-4.7	-	-5.0
87-Sr/86-Sr	0.709246	0.709272	0.709200	0.709245	-

ICP-MS Microchemistry Data (concentrations in ppb)

Borehole BH10

Date	03/03/93	04/15/94	Date	03/03/93	04/15/94
Li	26.400	-	I	-	0.930
Be	0.120	-	Te	-	0.065
B	-	39.056	Cs	-	11.033
Al	-	-	Ba	10.200	14.463
Sc	8.320	318.592	La	-	0.001
Ti	-	318.592	Ce	-	6.892
V	9.460	20.897	Pr	-	-
Cr	10.400	234.306	Nd	-	0.727
Mn	17.300	46.244	Sm	-	-
Fe	2601.000	3.099	Eu	-	9.614
Co	0.640	19.933	Gd	-	2.721
Ni	2.870	1179.641	Tb	-	0.026
Cu	2.680	0.474	Dy	-	-
Zn	96.500	3.028	Ho	-	0.012
Ga	0.290	3.476	Er	-	0.123
Ge	-	0.837	Tm	-	0.007
As	0.240	0.218	Yb	-	0.036
Se	23.600	0.229	Lu	-	0.012
Br	-	1.153	Hf	-	-
Rb	4.480	37.077	Ta	-	0.026
Sr	1718.000	1573.786	W	0.280	-
Y	-	4.352	Re	-	-
Zr	-	1600.103	Os	-	-
Nb	-	1.719	Ir	-	0.010
Mo	0.440	-	Pt	-	2.335
Ru	-	2.720	Au	-	0.041
Rh	-	-	Hg	-	-
Pd	-	-	Tl	-	-
Ag	-	1.692	Pb	0.590	10.737
Cd	-	0.054	Bi	-	0.008
In	-	5.419	Th	-	-
Sn	0.370	13.345	U	0.430	-
Sb	0.190	-			

GROUNDWATER CHEMISTRY DATA

	BH6		BH8	
DATE	10/29/93	04/15/94	12/07/94	03/03/93
K (mg/L)	5.3	4.8	5.1	10.9
Na (mg/L)	213	200	209	604
Ca (mg/L)	107	105	103	240
Mg (mg/L)	28	26	26	78
NH4 (mg/L N)	<0.05	<0.1	<0.1	<0.05
SO4 (mg/L)	54	49	49	196
Cl (mg/L)	384	365	392	1333
Alk (mg/L CaCO3)	237	229	227	205
NOx (mg/L N)	1.4	1.1	0.9	1.2
P (mg/L)	<0.05	<0.1	<0.1	<0.05
Si (mg/L)	3.9	4.0	4.2	4.6
Cu (mg/L)	<0.02	<0.03	<0.03	<0.02
Fe (mg/L)	1.67	0.12	<0.05	0.08
Mn (mg/L)	<0.02	<0.03	<0.05	<0.02
Zn (mg/L)	0.13	<0.03	<0.03	<0.01
Sr (mg/L)	1.03	1.03	0.95	2.35
Rb (mg/L)	-	-	-	-
Ba (mg/L)	-	-	-	-
Li (mg/L)	0.007	0.011	0.009	0.016
DOC (mg/L C)	9.1	2.8	0.8	4.5
EC - field (mS/m)	174	-	-	-
EC - lab (mS/m)	180	167	170	420
pH - field	6.4	-	-	-
pH - lab	7.6	7.2	-	7.3
Cations (meq/l)	16.99	16.18	16.51	44.94
Anions (meq/l)	16.81	15.97	16.66	45.89
% balance	1.07	1.26	0.95	2.10
Carbon-13 (‰ PDB)	-12.1	-12.4	-12.4	-12.5
TIC (mmol/L)	4.8	4.8	4.9	4.5
Carbon-14 (pmc)	83.2	80.8	81.6	81.0
Oxygen-18 (‰ SMOW)	-4.7	-4.9	-5.1	-4.6
87-Sr/86-Sr	0.709299	0.709177	0.709226	0.709260

ICP-MS Microchemistry Data (concentrations in ppb)

	BH6		BH8		
Date	04/15/94	03/03/93	Date	15/04/94	03/03/93
Li	31.351	39.200	I	7.184	-
Be	18.199	0.130	Te	5.016	-
B	296.518	-	Cs	-	-
Al	-	-	Ba	5.633	21.100
Sc	6.511	7.120	La	-	-
Ti	184.606	-	Ce	6.318	-
V	34.682	12.900	Pr	0.042	-
Cr	3.602	8.700	Nd	26.851	-
Mn	25.589	3.400	Sm	36.91	-
Fe	956.894	3592.000	Eu	-	-
Co	0.232	0.820	Gd	23.15	-
Ni	2.825	5.170	Tb	0.019	-
Cu	1.468	4.470	Dy	-	-
Zn	10.053	9.780	Ho	-	-
Ga	0.332	0.430	Er	30.378	-
Ge	-	-	Tm	-	-
As	0.730	2.710	Yb	-	-
Se	3.974	55.500	Lu	0.012	-
Br	1458.955	-	Hf	19.089	-
Rb	3.382	6.160	Ta	-	-
Sr	1448.368	2647.000	W	4.039	0.160
Y	5.700	-	Re	0.031	-
Zr	-	-	Os	15.972	-
Nb	3.689	-	Ir	0.061	-
Mo	-	0.370	Pt	-	-
Ru	-	-	Au	-	-
Rh	2.659	-	Hg	2.845	-
Pd	0.232	-	Tl	-	-
Ag	15.426	-	Pb	-	0.260
Cd	13.231	-	Bi	-	-
In	-	-	Th	2.232	-
Sn	0.989	0.350	U	0.034	0.450
Sb	-	0.090			

GROUNDWATER CHEMISTRY DATA

G33427

DATE	10/29/93	04/18/94	08/29/94	12/08/94
K (mg/L)	13.4	13.8	13.0	13.4
Na (mg/L)	446	430	447	448
Ca (mg/L)	122	123	114	124
Mg (mg/L)	53	54	54	54
NH4 (mg/L N)	<0.05	0.20	<0.1	<0.1
SO4 (mg/L)	92	93	88	88
Cl (mg/L)	777	751	757	831
Alk (mg/L CaCO3)	303	285	284	282
NOx (mg/L N)	1.5	4.3	1.2	1.2
P (mg/L)	<0.05	<0.1	<0.1	<0.1
Si (mg/L)	3.9	4.1	4.2	4.2
Cu (mg/L)	<0.02	<0.03	<0.03	<0.03
Fe (mg/L)	<0.02	<0.03	<0.05	<0.05
Mn (mg/L)	<0.02	<0.03	<0.05	<0.05
Zn (mg/L)	<0.02	<0.03	<0.03	<0.03
Sr (mg/L)	0.93	0.81	0.77	0.94
Rb (mg/L)	-	-	<0.03	<0.03
Ba (mg/L)	-	-	<0.25	<0.25
Li (mg/L)	0.009	0.012	0.009	0.011
DOC (mg/L C)	-	4.1	2.7	0.9
EC - field (mS/m)	272	-	-	-
EC - lab (mS/m)	315	295	295	305
pH - field	6.9	-	7.1	-
pH - lab	7.7	7.0	7.6	-999.0
Cations (meq/l)	30.22	29.60	29.90	30.44
Anions (meq/l)	30.00	29.10	28.95	31.00
% balance	0.76	1.71	3.29	1.83
Carbon-13 (‰ PDB)	-12.4	-12.3	-12.3	-12.2
TIC (mmol/L)	6.2	5.9	5.9	6.0
Carbon-14 (pmc)	66.8	67.0	68.3	69.8
Oxygen-18 (‰ SMOW)	-4.7	-4.9	-	-4.9
87-Sr/86-Sr	0.709466	0.709209	0.709257	0.709211

ICP-MS Microchemistry Data (concentrations in ppb)

Borehole G33427

Date	04/18/94	Date	04/18/94
Li	-	Li	13.813
Be	20.677	Te	-
B	353.574	Cs	0.794
Al	287.707	Ba	8.888
Sc	4.010	La	-
Ti	286.701	Ce	0.106
V	134.415	Pr	2.974
Cr	1.306	Nd	0.135
Mn	2.018	Sm	0.139
Fe	1330.011	Eu	-
Co	1.105	Gd	-
Ni	3.467	Tb	-
Cu	2.659	Dy	-
Zn	20.424	Ho	-
Ga	1.071	Er	-
Ge	0.914	Tm	-
As	3.179	Yb	0.139
Se	13.442	Lu	1.007
Br	2702.593	Hf	0.082
Rb	9.595	Ta	1.011
Sr	1564.195	W	0.003
Y	0.123	Re	0.004
Zr	5.864	Os	0.021
Nb	0.086	Ir	3.496
Mo	16.403	Pt	6.386
Ru	9.280	Au	-
Rh	0.073	Hg	-
Pd	0.065	Tl	0.012
Ag	0.039	Pb	-
Cd	0.214	Bi	0.004
In	-	Th	0.008
Sn	0.404	U	0.031
Sb	0.020		

GROUNDWATER CHEMISTRY DATA

G39940

DATE	10/28/93	04/15/94	08/19/94	12/08/94
K (mg/L)	41	36	40	40
Na (mg/L)	892	876	874	901
Ca (mg/L)	144	144	141	139
Mg (mg/L)	99	98	91	99
NH4 (mg/L N)	0.2	0.6	0.1	<0.1
SO4 (mg/L)	229	229	227	232
Cl (mg/L)	1479	1422	1486	1482
Alk (mg/L CaCO3)	452	418	418	415
NOx (mg/L N)	<0.05	0.4	<0.1	<0.1
P (mg/L)	<0.05	<0.1	<0.1	<0.1
Si (mg/L)	5.3	5.7	6.0	5.9
Cu (mg/L)	<0.02	<0.03	<0.03	<0.03
Fe (mg/L)	0.29	0.75	0.45	0.24
Mn (mg/L)	<0.02	<0.03	<0.05	<0.05
Zn (mg/L)	<0.02	<0.03	<0.03	0.03
Sr (mg/L)	3.41	2.48	2.15	2.44
Rb (mg/L)	-	-	0.03	0.04
Ba (mg/L)	-	-	<0.25	<0.25
Li (mg/L)	0.020	0.026	0.020	0.027
DOC (mg/L C)	-	-	-	7.1
EC - field (mS/m)	499	-	-	-
EC - lab (mS/m)	550	540	520	540
pH - field	6.5	-	7.0	-
pH - lab	7.8	7.2	7.6	-
Cations (meq/l)	55.17	54.29	43.54	55.31
Anions (meq/l)	55.52	53.25	55.01	54.94
% balance	0.64	1.94	2.75	0.67
Carbon-13 (‰ PDB)	-11.6	-11.5	-11.4	-11.2
TIC (mmol/L)	9.2	8.7	8.6	8.7
Carbon-14 (pmc)	87.6	84.6	86.4	85.8
Oxygen-18 (‰ SMOW)	-4.1	-4.2	-	-4.4
87-Sr/86-Sr	0.709301	0.709341	0.709270	0.709279

ICP-MS Microchemistry Data (concentrations in ppb)

Borehole G39940

Date	04/15/94	Date	04/15/94
Li	46.232	I	226.471
Be	-	Te	-
B	617.781	Cs	-
Al	-	Ba	15.177
Sc	-	La	4.224
Ti	149.912	Ce	19.155
V	107.819	Pr	-
Cr	-	Nd	-
Mn	21.184	Sm	21.530
Fe	1623.368	Eu	-
Co	12.139	Gd	-
Ni	-	Tb	-
Cu	42.936	Dy	-
Zn	1.54	Ho	0.040
Ga	96.397	Er	120.518
Ge	-	Tm	-
As	12.944	Yb	-
Se	-	Lu	0.082
Br	5104.244	Hf	-
Rb	13.011	Ta	-
Sr	2737.036	W	-
Y	23.171	Re	-
Zr	-	Os	0.114
Nb	-	Ir	18.404
Mo	-	Pt	0.355
Ru	-	Au	-
Rh	0.1	Hg	188.505
Pd	-	Tl	-
Ag	-	Pb	-
Cd	36.009	Bi	0.040
In	-	Th	0.073
Sn	-	U	60.307
Sb	28.337		

GROUNDWATER CHEMISTRY DATA

G39941

DATE	10/28/93	04/15/94	08/30/94	01/12/95
K (mg/L)	6.5	5.4	5.5	5.5
Na (mg/L)	265	184	202	172
Ca (mg/L)	101	90	87	89
Mg (mg/L)	34	28	30	26
NH4 (mg/L N)	<0.05	<0.1	<0.1	<0.1
SO4 (mg/L)	89	69	62	61
Cl (mg/L)	458	320	362	292
Alk (mg/L CaCO3)	236	214	218	212
NOx (mg/L N)	0.7	0.4	0.6	0.8
P (mg/L)	<0.05	<0.1	<0.1	<0.1
Si (mg/L)	4.0	4.0	4.2	3.7
Cu (mg/L)	<0.02	<0.03	<0.03	<0.03
Fe (mg/L)	<0.02	<0.03	<0.05	<0.05
Mn (mg/L)	<0.02	<0.03	<0.05	<0.05
Zn (mg/L)	<0.02	<0.03	0.04	0.07
Sr (mg/L)	0.98	0.67	0.69	0.68
Rb (mg/L)	-	-	<0.03	<0.03
Ba (mg/L)	-	-	<0.25	<0.25
Li (mg/L)	0.007	0.008	0.007	0.008
DOC (mg/L C)	7.9	3.1	1.1	1.9
EC - field (mS/m)	199	-	-	-
EC - lab (mS/m)	205	150	160	143
pH - field	6.4	-	7.3	7.2
pH - lab	7.8	7.3	7.7	7.4
Cations (meq/l)	19.54	14.94	15.66	14.20
Anions (meq/l)	19.53	14.78	15.91	13.71
% balance	0.02	1.12	1.54	3.57
Carbon-13 (‰ PDB)	-11.2	-11.6	-11.4	-11.3
TIC (mmol/L)	4.4	4.3	4.5	3.9
Carbon-14 (pmc)	67.6	67.7	61.8	63.6
Oxygen-18 (‰ SMOW)	-4.7	-4.8	-	-5.1
87-Sr/86-Sr	0.709262	0.709134	0.709240	0.709260

ICP-MS Microchemistry Data (concentrations in ppb)

Borehole G39941

Date	04/15/94	Date	04/15/94
Li	30.049	I	12.663
Be	16.047	Te	-
B	282.863	Cs	-
Al	18.253	Ba	12.403
Sc	5.398	La	0.162
Ti	223.362	Ce	-
V	25.170	Pr	0.016
Cr	3.317	Nd	-
Mn	7.327	Sm	-
Fe	1095.103	Eu	0.102
Co	0.553	Gd	-
Ni	16.388	Tb	0.022
Cu	0.798	Dy	3.447
Zn	3.430	Ho	-
Ga	1.098	Er	0.021
Ge	0.108	Tm	-
As	0.459	Yb	-
Se	2.803	Lu	0.015
Br	1514.323	Hf	-
Rb	4.819	Ta	3.343
Sr	1475.115	W	-
Y	0.058	Re	-
Zr	0.048	Os	-
Nb	0.008	Ir	0.011
Mo	-	Pt	10.400
Ru	-	Au	-
Rh	0.025	Hg	-
Pd	-	Tl	1.402
Ag	-	Pb	-
Cd	0.614	Bi	-
In	-	Th	-
Sn	2.375	U	-
Sb	3.301		

GROUNDWATER CHEMISTRY DATA

G39942

DATE	10/29/93	04/18/94	08/29/94	12/08/94
K (mg/L)	11.2	3.4	2.9	3.0
Na (mg/L)	83	78	79	81
Ca (mg/L)	56.8	73.6	78.1	78.5
Mg (mg/L)	1.7	11.2	11.1	11.3
NH4 (mg/L N)	<0.05	<0.1	<0.1	<0.1
SO4 (mg/L)	61	21	18	20
Cl (mg/L)	150	146	146	145
Alk (mg/L CaCO3)	72	172	185	188
NOx (mg/L N)	0.6	0.5	0.5	0.3
P (mg/L)	<0.05	<0.1	<0.1	<0.1
Si (mg/L)	4.0	4.3	4.3	4.0
Cu (mg/L)	<0.02	<0.03	<0.03	<0.03
Fe (mg/L)	<0.02	<0.03	<0.05	<0.05
Mn (mg/L)	<0.02	<0.03	<0.05	<0.05
Zn (mg/L)	<0.02	<0.03	<0.03	<0.03
Sr (mg/L)	1.82	0.84	0.77	0.82
Rb (mg/L)	-	-	<0.03	<0.03
Ba (mg/L)	-	-	<0.25	<0.25
Li (mg/L)	0.011	0.010	0.008	0.009
DOC (mg/L C)	4.2	2.7	1.3	0.9
EC - field (mS/m)	68	-	-	-
EC - lab (mS/m)	91	83	84	86
pH - field	9.3	-	7.6	-
pH - lab	10.9	7.5	7.9	-
Cations (meq/l)	6.85	8.09	8.34	8.47
Anions (meq/l)	6.99	8.03	8.23	8.28
% balance	2.00	0.76	1.30	2.26
Carbon-13 (‰ PDB)	-11.1	-11.4	-11.2	-11.0
TIC (mmol/L)	1.5	3.4	3.6	3.7
Carbon-14 (pmc)	90.9	90.6	90.4	89.6
Oxygen-18 (‰ SMOW)	-4.7	-4.9	-	-5.0
87-Sr/86-Sr	0.709393	0.709397	0.709227	0.709192

ICP-MS Microchemistry Data (concentrations in ppb)

Borehole G39942

Date	04/18/94	Date	04/18/94
Li	237.855	I	2.851
Be	-	Te	-
B	141.112	Cs	0.690
Al	1264.250	Ba	12.776
Sc	5.126	La	0.338
Ti	56.347	Ce	-
V	34.419	Pr	0.020
Cr	6.137	Nd	-
Mn	14.311	Sm	6.109
Fe	648.807	Eu	-
Co	0.551	Gd	-
Ni	3.593	Tb	-
Cu	2.361	Dy	0.035
Zn	2.234	Ho	-
Ga	1.894	Er	2.178
Ge	-	Tm	0.004
As	0.925	Yb	-
Se	3.433	Lu	0.017
Br	679.340	Hf	-
Rb	45.933	Ta	0.741
Sr	1387.553	W	-
Y	1.602	Re	0.059
Zr	-	Os	-
Nb	-	Ir	0.007
Mo	-	Pt	-
Ru	-	Au	-
Rh	1.577	Hg	0.023
Pd	-	Tl	0.024
Ag	3.155	Pb	-
Cd	0.041	Bi	0.880
In	-	Th	-
Sn	0.598	U	0.025
Sb	1.128		

GROUNDWATER CHEMISTRY DATA

G39943

DATE	10/29/93	04/18/94	08/29/94	12/08/94
K (mg/L)	6.5	4.1	3.5	3.3
Na (mg/L)	74	72	71	72
Ca (mg/L)	15.7	48.2	56.8	62.8
Mg (mg/L)	7.4	8.3	8.7	10.6
NH4 (mg/L N)	<0.05	0.2	1.2	0.7
SO4 (mg/L)	23	20	17	18
Cl (mg/L)	125	123	126	128
Alk (mg/L CaCO3)	36	120	148	162
NOx (mg/L N)	0.6	0.3	0.3	0.2
P (mg/L)	<0.05	<0.1	<0.1	<0.1
Si (mg/L)	4.1	3.3	6.3	5.8
Cu (mg/L)	<0.02	<0.03	<0.03	<0.03
Fe (mg/L)	<0.02	<0.03	<0.05	<0.05
Mn (mg/L)	<0.02	<0.03	<0.05	<0.05
Zn (mg/L)	<0.02	<0.03	<0.03	<0.03
Sr (mg/L)	1.20	0.97	0.94	0.95
Rb (mg/L)	-	-	<0.03	<0.03
Ba (mg/L)	-	-	<0.25	<0.25
Li (mg/L)	0.005	0.009	0.007	0.009
DOC (mg/L C)	5.4	4.0	1.2	0.8
EC - field (mS/m)	74	-	-	-
EC - lab (mS/m)	57	67	74	76
pH - field	10.0	-	8.2	-
pH - lab	9.5	9.0	8.3	-
Cations (meq/l)	4.78	6.35	6.83	7.27
Anions (meq/l)	4.79	6.30	6.89	7.24
% balance	0.32	0.77	0.93	0.46
Carbon-13 (‰ PDB)	-11.9	-11.5	-11.4	-11.0
TIC (mmol/L)	0.9	2.7	3.1	2.7
Carbon-14 (pmc)	-999.0	89.0	90.8	88.0
Oxygen-18 (‰ SMOW)	-4.7	-4.8	-	-5.0
87-Sr/86-Sr	0.709373	0.709665	0.709290	0.709281

ICP-MS Microchemistry Data (concentrations in ppb)

Borehole G39943

Date	04/18/94	Date	04/18/94
Li	41.328	I	13.919
Be	-	Te	-
B	168.545	Cs	0.073
Al	170.898	Ba	13.535
Sc	3.821	La	0.198
Ti	155.566	Ce	-
V	44.421	Pr	1.883
Cr	0.867	Nd	-
Mn	17.228	Sm	-
Fe	1010.857	Eu	0.042
Co	0.262	Gd	-
Ni	1.235	Tb	3.041
Cu	2.249	Dy	21.211
Zn	5.590	Ho	0.802
Ga	2.111	Er	0.019
Ge	0.771	Tm	3.111
As	1.717	Yb	-
Se	6.110	Lu	0.006
Br	664.294	Hf	-
Rb	8.906	Ta	2.026
Sr	1632.456	W	-
Y	0.034	Re	0.011
Zr	5.040	Os	-
Nb	0.025	Ir	5.426
Mo	-	Pt	13.582
Ru	-	Au	3.360
Rh	0.013	Hg	-
Pd	0.125	Tl	-
Ag	-	Pb	-
Cd	22.526	Bi	1.171
In	-	Th	-
Sn	18.248	U	0.014
Sb	0.104		

GROUNDWATER CHEMISTRY DATA

P2

DATE	03/04/93	10/27/93	04/14/94	08/28/94	12/06/94
K (mg/L)	3.0	2.6	2.6	2.4	1.3
Na (mg/L)	88	87	84	85	86
Ca (mg/L)	95	89	89	88	81
Mg (mg/L)	11.3	12.7	12.2	11.6	7.7
NH4 (mg/L N)	<0.05	0.1	0.1	<0.1	<0.1
SO4 (mg/L)	29	28	25	23	24
Cl (mg/L)	153	150	149	144	142
Alk (mg/L CaCO3)	222	230	213	213	211
NOx (mg/L N)	0.1	0.3	<0.1	0.3	<0.1
P (mg/L)	<0.05	<0.05	<0.1	<0.1	<0.1
Si (mg/L)	4.3	4.1	4.1	4.2	4.2
Cu (mg/L)	<0.02	<0.02	<0.03	<0.03	<0.03
Fe (mg/L)	0.13	0.08	0.09	0.07	<0.05
Mn (mg/L)	<0.02	<0.02	<0.03	<0.05	<0.05
Zn (mg/L)	<0.01	<0.02	<0.03	0.03	<0.03
Sr (mg/L)	1.13	0.98	0.89	0.98	0.92
Rb (mg/L)	-	-	-	<0.03	<0.03
Ba (mg/L)	-	-	-	<0.25	<0.25
Li (mg/L)	0.007	0.005	0.008	0.007	0.008
DOC (mg/L C)	4.7	7.0	2.9	1.6	0.8
EC - field (mS/m)	-	91	-	-	-
EC - lab (mS/m)	96	98	92	91	92
pH - field	-	6.4	-	-	-
pH - lab	7.6	7.7	7.4	7.2	-
Cations (meq/l)	9.54	9.34	9.19	9.14	8.46
Anions (meq/l)	9.37	9.43	9.00	8.84	8.72
% balance	1.91	0.91	2.12	3.50	3.09
Carbon-13 (‰ PDB)	-11.2	-11.3	-11.2	-11.1	-11.0
TIC (mmol/L)	4.6	4.6	4.4	4.4	4.4
Carbon-14 (pmc)	80.6	79.6	81.7	80.5	81.6
Oxygen-18 (‰ SMOW)	-4.8	-5.0	-4.9	-999.0	-5.1
87-Sr/86-Sr	0.709233	0.709244	0.709170	0.709215	-

ICP-MS Microchemistry Data (concentrations in ppb)

Borehole P2

Date	03/04/93	04/14/94	Date	03/04/93	04/14/94
Li	15.100	13.276	I	-	6.817
Be	0.010	0.090	Te	-	3.203
B	-	100.980	Cs	-	0.110
Al	-	-	Ba	3.450	3.203
Sc	7.970	4.758	La	-	0.110
Ti	-	204.365	Ce	-	-
V	268.000	19.583	Pr	-	-
Cr	9.650	3.195	Nd	-	28.094
Mn	0.690	1.725	Sm	-	-
Fe	1826.000	921.277	Eu	-	0.063
Co	0.490	0.465	Gd	-	-
Ni	2.230	2.930	Tb	-	2.166
Cu	1.850	6.543	Dy	-	-
Zn	24.100	1.633	Ho	-	-
Ga	0.130	-	Er	-	0.024
Ge	-	0.044	Tm	-	-
As	1.300	0.371	Yb	-	-
Se	4.820	44.721	Lu	-	-
Br	-	723.471	Hf	-	14.322
Rb	2.310	2.552	Ta	-	0.961
Sr	1357.000	1805.872	W	0.380	-
Y	-	0.033	Re	-	0.013
Zr	-	0.272	Os	-	-
Nb	-	0.032	Ir	-	-
Mo	0.710	-	Pt	-	3.007
Ru	-	-	Au	-	-
Rh	-	0.030	Hg	-	-
Pd	-	7.733	Tl	-	-
Ag	-	1.668	Pb	0.480	-
Cd	-	0.295	Bi	-	1.444
In	-	-	Th	-	-
Sn	0.660	13.282	U	0.210	0.017
Sb	0.300	0.268			

GROUNDWATER CHEMISTRY DATA

P3

DATE	03/04/93	10/27/93	04/15/94	08/28/94	12/06/94
K (mg/L)	2.8	2.4	2.6	2.3	2.6
Na (mg/L)	79	80	79	82	83
Ca (mg/L)	83	83	85	84	84
Mg (mg/L)	11.1	11.8	11.7	12.1	11.5
NH4 (mg/L N)	<0.05	0.1	0.1	<0.1	<0.1
SO4 (mg/L)	23	24	24	24	24
Cl (mg/L)	139	142	138	140	147
Alk (mg/L CaCO3)	208	220	209	238	208
NOx (mg/L N)	0.1	0.1	<0.1	0.1	<0.1
P (mg/L)	<0.05	<0.05	<0.1	<0.1	<0.1
Si (mg/L)	4.8	4.1	4.3	4.4	4.2
Cu (mg/L)	<0.02	<0.02	<0.03	<0.03	<0.03
Fe (mg/L)	0.03	0.04	0.06	<0.05	<0.05
Mn (mg/L)	<0.02	<0.02	<0.03	<0.05	<0.05
Zn (mg/L)	0.04	0.03	0.13	0.07	<0.03
Sr (mg/L)	0.89	0.97	0.83	0.86	0.85
Rb (mg/L)	-	-	-	<0.03	<0.03
Ba (mg/L)	-	-	-	<0.25	<0.25
Li (mg/L)	0.006	0.005	0.008	0.007	0.007
DOC (mg/L C)	4.1	7.2	2.9	1.4	0.8
EC - field (mS/m)	-999	85	-	-	-
EC - lab (mS/m)	88	90	88	87	88
pH - field	-	6.3	-	7.2	-
pH - lab	7.6	7.7	7.4	7.6	-
Cations (meq/l)	8.54	8.66	8.71	9.14	8.81
Anions (meq/l)	8.57	8.89	8.57	8.84	8.80
% balance	0.41	2.63	1.65	3.50	0.04
Carbon-13 (‰ PDB)	-11.1	-11.4	-11.3	-11.3	-11.1
TIC (mmol/L)	4.3	4.5	4.2	4.3	4.3
Carbon-14 (pmc)	84.1	83.2	82.6	84.1	82.3
Oxygen-18 (‰ SMOW)	-4.9	-4.8	-4.0	-	-5.1
87-Sr/86-Sr	0.709200	0.709291	0.709141	0.709202	0.709185

ICP-MS Microchemistry Data (concentrations in ppb)

Borehole P3

Date	03/04/93	04/15/94	Date	03/04/93	04/15/94
Li	12.900	10.389	I	-	5.576
Be	0.030	-	Te	-	-
B	-	124.045	Cs	-	-
Al	-	117.268	Ba	3.290	2.942
Sc	7.470	6.155	La	-	0.031
Ti	-	196.666	Ce	-	5.195
V	2.560	20.652	Pr	-	-
Cr	10.000	3.201	Nd	-	-
Mn	5.630	26.036	Sm	-	25.506
Fe	1613.000	830.848	Eu	-	0.015
Co	1.070	2.829	Gd	-	23.868
Ni	2.490	3.090	Tb	-	0.015
Cu	2.320	1.898	Dy	-	-
Zn	62.600	139.589	Ho	-	-
Ga	0.140	0.339	Er	-	24.685
Ge	-	11.389	Tm	-	0.038
As	3.550	1.092	Yb	-	-
Se	5.800	2.165	Lu	-	0.023
Br	-	596.697	Hf	-	-
Rb	2.440	2.329	Ta	-	-
Sr	1203.000	1628.538	W	0.660	-
Y	-	0.009	Re	-	0.024
Zr	-	3.262	Os	-	15.972
Nb	-	0.040	Ir	-	0.049
Mo	0.510	4.695	Pt	-	-
Ru	-	-	Au	-	-
Rh	-	-	Hg	-	0.075
Pd	-	0.069	Tl	-	-
Ag	-	0.052	Pb	-	-
Cd	-	0.140	Bi	-	-
In	-	-	Th	-	4.289
Sn	0.750	0.954	U	0.190	0.075
Sb	0.390	1.099			

RAINWATER CHEMISTRY DATA

	SBR1				SBR2			SBR3			
DATE	10/29/93	11/23/93	04/16/94	08/30/94	10/29/93	11/23/93	04/16/94	08/28/94	08/28/94	01/12/95	
K (mg/L)	3.7	3.5	1.6	0.6	5.0	5.1	4.1	0.8	3.3	13.0	
Na (mg/L)	67	74	51	11	46	38	23	7.7	11.2	15	
Ca (mg/L)	20.3	17.8	14.6	1.3	26.1	19.8	14.4	4.2	3.1	7.5	
Mg (mg/L)	8.6	9.1	7.0	1.2	5.9	4.9	3.4	0.9	1.4	1.8	
NH4 (mg/L N)	0.3	<0.1	<0.1	<0.1	0.1	1.0	<0.1	<0.1	<0.1	18	
SO4 (mg/L)	27	26	17	3	21	18	9	2	3	5	
Cl (mg/L)	122	143	109	19	86	72	59	17	21	23	
Alk (mg/L CaCO3)	34	12	8	1	49	41	16	5	8	24	
NOx (mg/L N)	0.8	0.8	<0.1	<0.1	0.3	<0.1	<0.1	<0.1	<0.1	19.9	
P (mg/L)	<0.05	<0.1	<0.1	<0.1	<0.05	<0.1	<0.1	<0.1	<0.1	2.33	
Si (mg/L)	0.4	<0.5	<0.5	-	0.2	<0.5	<0.5	-	-	-	
Cu (mg/L)	0.04	<0.03	<0.03	-	<0.02	<0.03	<0.03	-	-	-	
Fe (mg/L)	0.06	<0.03	0.03	-	0.05	0.04	<0.03	-	-	-	
Mn (mg/L)	<0.02	<0.03	<0.03	-	<0.02	<0.03	<0.03	-	-	-	
Zn (mg/L)	0.07	0.51	0.13	-	0.03	0.03	0.03	-	-	-	
Sr (mg/L)	0.14	0.09	0.05	-	0.14	0.08	<0.05	-	-	-	
Rb (mg/L)	-	-	-	-	-	-	-	-	-	-	
Ba (mg/L)	-	-	-	-	-	-	-	-	-	-	
Li (mg/L)	<0.005	<0.005	<0.005	-	<0.005	<0.005	<0.005	-	-	-	
DOC (mg/L C)	11	2.1	3.2	0.5	16	4.7	2.7	1.9	7.2	14	
EC - field (mS/m)	-	-	-	-	-	-	-	-	-	-	
EC - lab (mS/m)	56	59	34	9	45	37	24	8	-10	34	
pH - field	-	-	-	-	-	-	-	-	-	-	
pH - lab	7.7	6.5	7.0	5.9	7.8	6.8	7.2	6.6	6.9	6.9	
Cations (meq/l)	4.77	4.92	3.56	0.64	3.90	3.23	2.13	0.64	0.84	2.77	
Anions (meq/l)	4.73	4.87	3.58	0.62	3.88	3.22	2.15	0.62	0.81	2.88	
% balance	0.68	1.00	0.55	3.66	0.55	0.20	0.85	2.65	3.33	3.94	

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ANALYTICAL SERVICES (STELLENBOSCH LABORATORY)
PRECISION AND RECOVERY DATA

	n	Avg mg/L	Addn. mg/L	Std dev.	CV %	Rec %	n	Avg mg/L	Addn. mg/L	Std dev.	CV %	Rec %
Potassium as K mg/L	10	1.7	1.5	0.02	0.9	95	10	5.4	4.5	0.03	0.6	101
Sodium as Na mg/L	10	23.6	5	0.22	0.9	105	10	69.6	15	0.32	0.5	98
Calcium as Ca mg/L	10	12.5	5	0.21	1.7	102	10	37.2	15	0.75	2.0	100
Magnesium as Mg mg/L	10	3.6	1.5	0.04	1.1	108	10	10.7	4.5	0.12	1.1	104
Ammonia as N mg/L	10	1.0	0.25	0.01	1.3	100	10	4.6	1.5	0.09	1.9	105
Sulphate as SO ₄ mg/L	10	17.1	5	0.74	4.3	114	10	228	200	3.68	1.6	103
Chloride as Cl mg/L	10	53.6	10	1.51	2.8	115	10	488	400	7.32	1.5	101
Alkalinity as CaCO ₃ mg/L	10	25.1	5	0.44	1.8	101	10	250	50	0.82	0.3	97
Nitrate as N mg/L	10	1.0	0.25	0.04	3.6	90	10	4.6	1.5	0.05	1.1	109
Phosphate as P mg/L	10	1.0	0.25	0.01	1.0	109	10	4.5	1.5	0.02	0.0	96
Conductivity mS/m	10	-	-	-	-	-	10	88.3	-	0.75	0.9	-
Dissolved Organic Carbon as C mg/L	10	-	-	-	-	-	10	10.2	2.5	0.24	2.4	97
Fluoride as F mg/L	10	0.50	0.25	0.03	5.2	98	10	2.0	0.5	0.07	3.4	100
Aluminium as Al mg/L	10	0.35	0.25	0.02	4.8	102	10	1.25	0.25	0.02	1.8	90
Copper as Cu mg/L	10	0.35	0.25	0.01	3.0	100	10	1.25	0.25	0.01	0.7	98
Iron as Fe mg/L	10	0.35	0.25	0.01	2.5	101	10	1.25	0.25	0.01	1.1	95
Manganese as mn mg/L	10	0.35	0.25	0.01	2.7	104	10	1.25	0.25	0.01	1.0	95
Zinc as Zn mg/L	10	0.35	0.25	0.01	4.0	98	10	1.25	0.25	0.01	1.1	93
Chemical Oxygen Demand mg/L	10	75	25	1.8	2.4	100	10	525	25	6.5	1.2	102

Appendix 4

Down Hole Geophysics

Boreholes

- ▣▣▣▣ G33427 - 79 m
- ▣▣▣▣ G39940 - 12 m
- ▣▣▣▣ G39941 - 69 m
- ▣▣▣▣ G39942 - 50 m
- ▣▣▣▣ G39943 - 35 m
- ▣▣▣▣ BH 7 - 49 m

APPENDIX 4

STRUISBAAI: DOWN-THE-HOLE GEOPHYSICAL LOGGING

(References Repsold, 1989 and Jorgensen, 1989)

1 INTRODUCTION

The logging was carried out by Mr Barry Venter of DWA&F. The probes used were:

Gamma-Ray Log (γ): Gamma-Ray measures the relative absence of presence of clay minerals. It is thus used to determine lithological boundaries and differentiation of shaly (clayey) and non-shaly rocks. Measurement is in counts per second with high clay registering high c.p.s.

Formation Resistivity Log (ρ and $\omega\rho$): This records the resistivity profile of the layers in Ω -metres. There are always two logs namely the short-spaced and long-spaced where the short-spaced has a shallow depth of rock measurement and the long-spaced a deeper rock measurement but a poorer layer resolution.

Neutron-neutron Log (N-n): The neutron probe is used to determine the rock density. Measurement is in counts per second.

Water Resistivity Log (R): This records the resistivity of the water in the borehole and is used to detect salinity layering.

Self-Potential Log (SP): This is recorded simultaneously with the resistivity log. This is a reflection of the salinity of the pore water in porous rock, recorded in Ω -m.

Temperature Log (T): This records the temperatures of the water in the borehole.

Note: For the Struisbaai boreholes the Caliper log was not available.

2 INTERPRETATION OF THE LOGS

The logs are attached. Each borehole log was interpreted as follows:

BH7: The self-potential log is very erratic and is probably due to the heavy corrosion of the casing, i.e. the log is "seeing" through the hole in the casing. No anomalies are seen below the end of the casing. No geological log is available for this borehole.

G33427: At 57 m there is a drop in Formation Resistivity with a corresponding increase in Gamma indicating porous (fractured) rock. At 64 m is also a fracture although the Gamma log has a lower reaction than the 57 m fracture. At both 57 m and 64 m the water resistivity and formation resistivity (short) approach each other which indicates a large cavity with minimal influence of rock material on the formation resistivity log. At both 57 m and 64 m the Neutron-neutron log moves to the left, i.e. this is where the neutrons are "captured" by the water in the cavity. Below the 64 m fracture the temperature of the water increases and the formation resistivity (long) increases, both

indicating solid rock. No geological log is available for this borehole.

G39940: No anomalies are observed. However, note the position of the Neutron-neutron probe which is far to the left which shows this rock has a higher porosity than for any of the other boreholes. The geological log shows this is drilled in Enon Formation which confirms that this rock is more porous. Note too the low water resistivity, this borehole has the highest salinity water.

G39941: At 62.5 m there is a good cavity response by the Gamma and the Neutron-neutron probe moving in opposite directions. The drill log records a water strike at 63 m. A water strike at 53.2 m does not reflect in the geophysical log. At 48 m there is a sharp right spike of the Neutron-neutron. This could be some clay material which has deposited in the cavity at the calcrete-quartzite contact.

G39942: At 49 m is a cavity indicated by the Gamma log moving sharply to right with the Neutron-neutron moving to left. The geological log confirms a water strike at 49 to 51 m.

G39943: Fractures at 20 m at 23 m, at 26 m and at 33 m are indicated by the Neutron-neutron log moving left. The Gamma log only confirms the 20 m and 33 m fractures by moving right. The geological log does not record a water strike at 20 m, but does record water strikes at 23.2 m, at 27.2 m and at 33 m. The geophysical log shows a 35 m borehole, but the drill log shows the borehole was drilled to 42 m, but collapsing. The Gamma log shows an anomaly at 16 m to 18 m, however, the lack of response by the Neutron-neutron probe shows this is not a cavity.

In general the on-site geological logging of the boreholes and the geophysical logs show good agreement.

BH 7
St. Louis
49m

BH 7

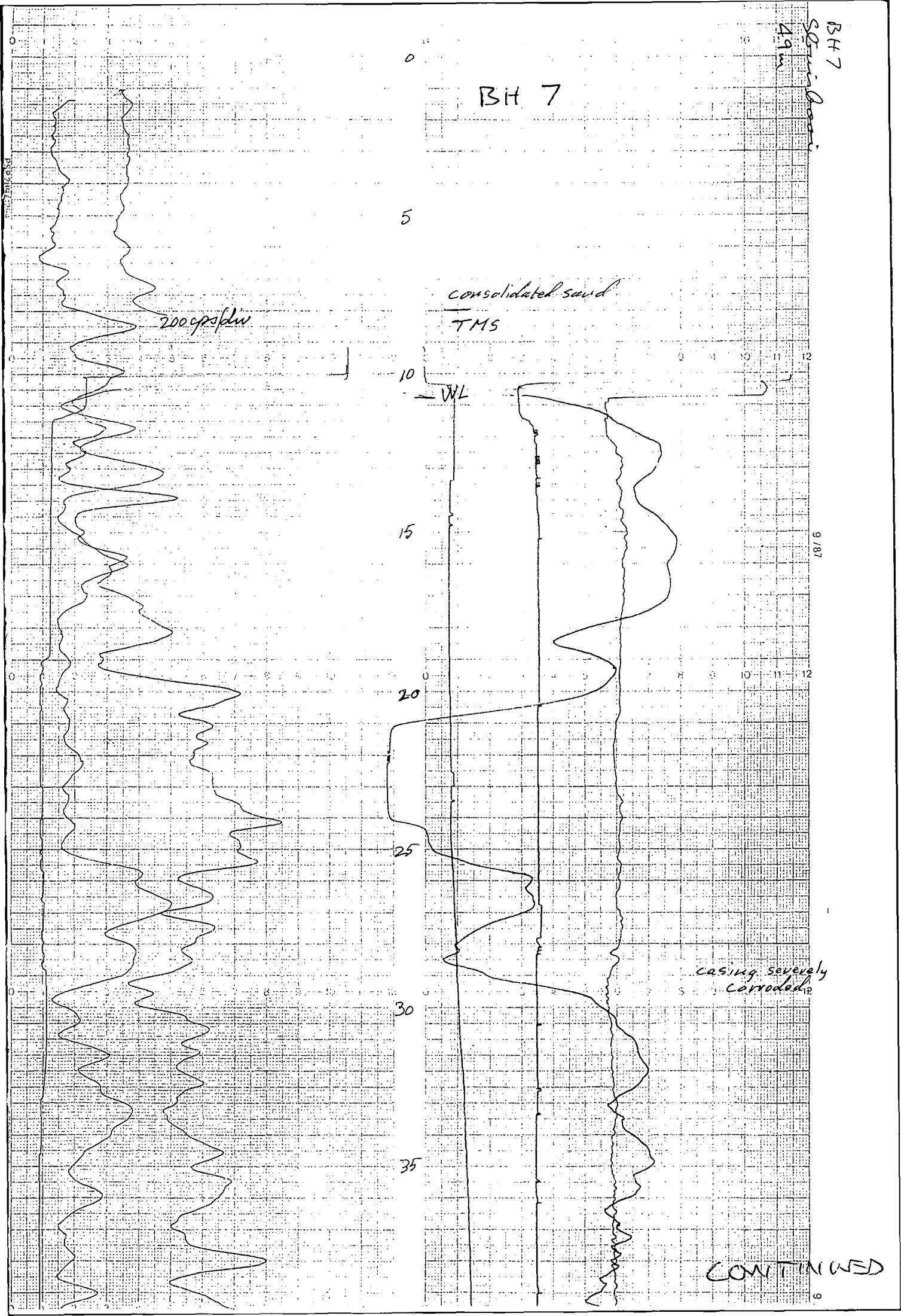
200 cps/dw

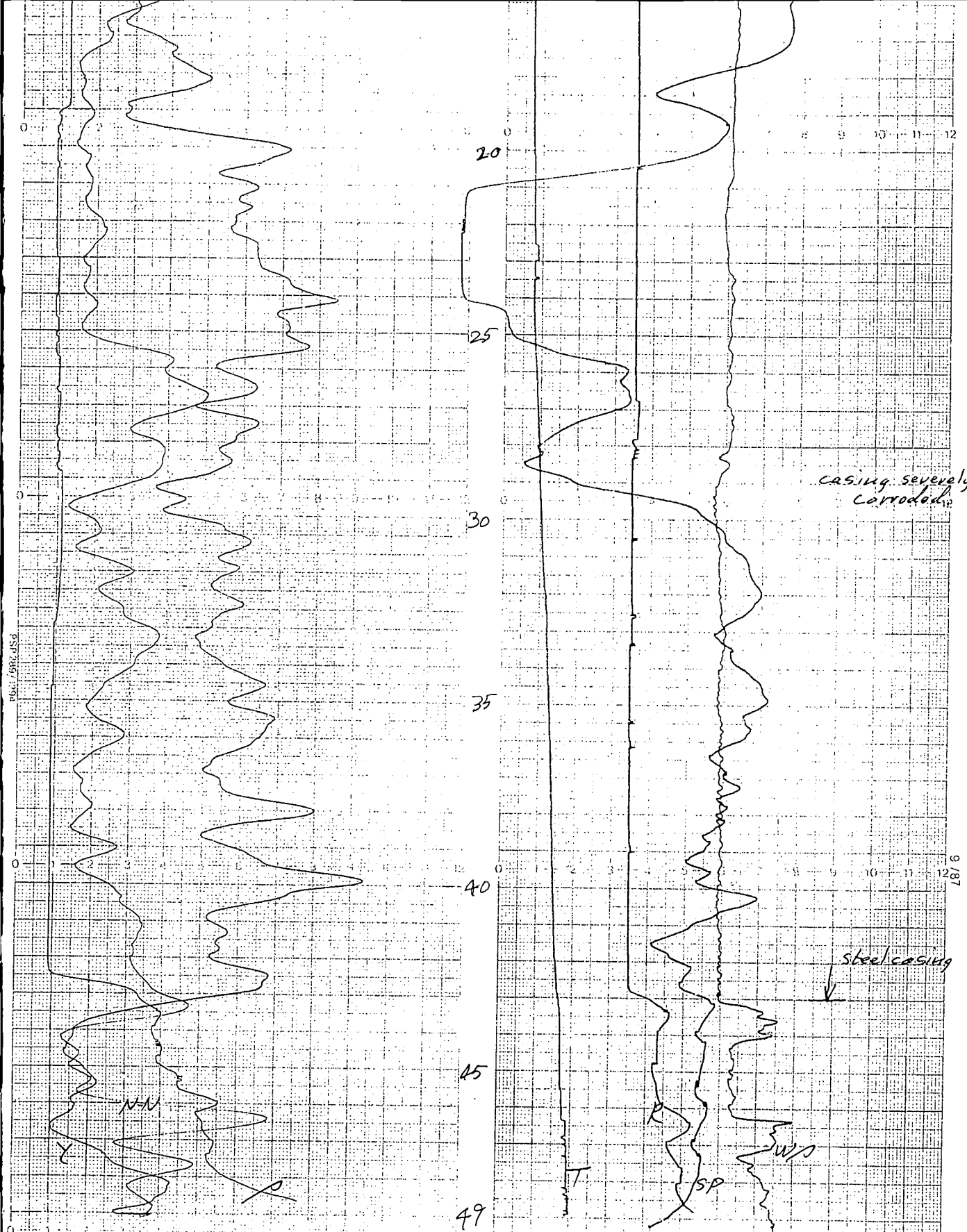
consolidated sand
TMS

WL

Casing severely
Corroded

CONTINUED





casing severely Corroded

steel casing

N-N

R

SP

W/S

T

20cps/div Tc 1/2 sec disp 0	50Ωm/div	N-N 100 cps/div Tc 1/2 sec disp 0
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50Ω/div disp 100	SP 20mV/div bias +450	W/S 1.5cm/div	T 0.2°C/div 0 = 18°C
---------------------	-----------------------------	------------------	----------------------------

(2118)

Struisbaai

Ou Pomgab 87

9370-12

G 33427

10

15 consolidated sand

TMS

20

-WL

25

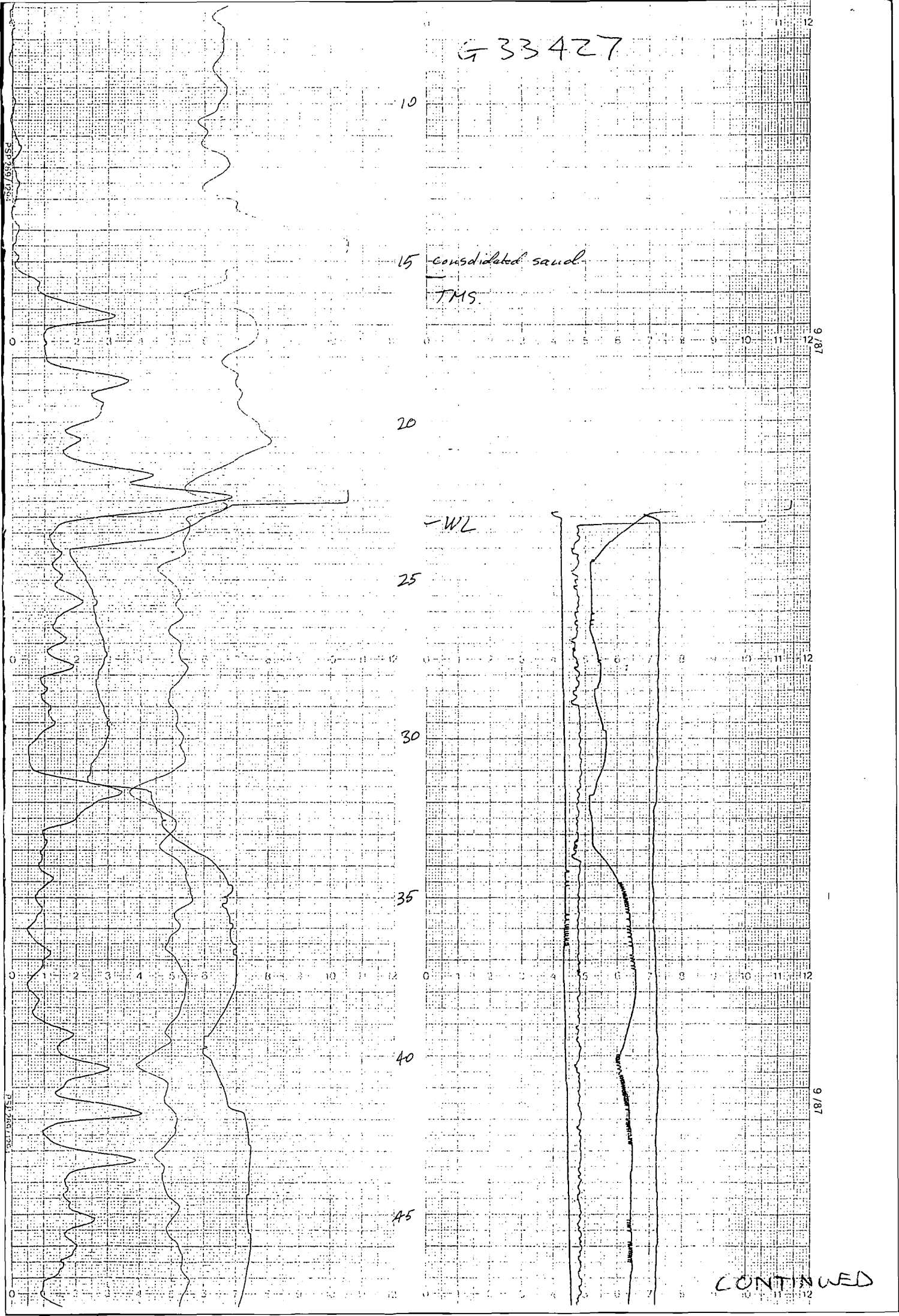
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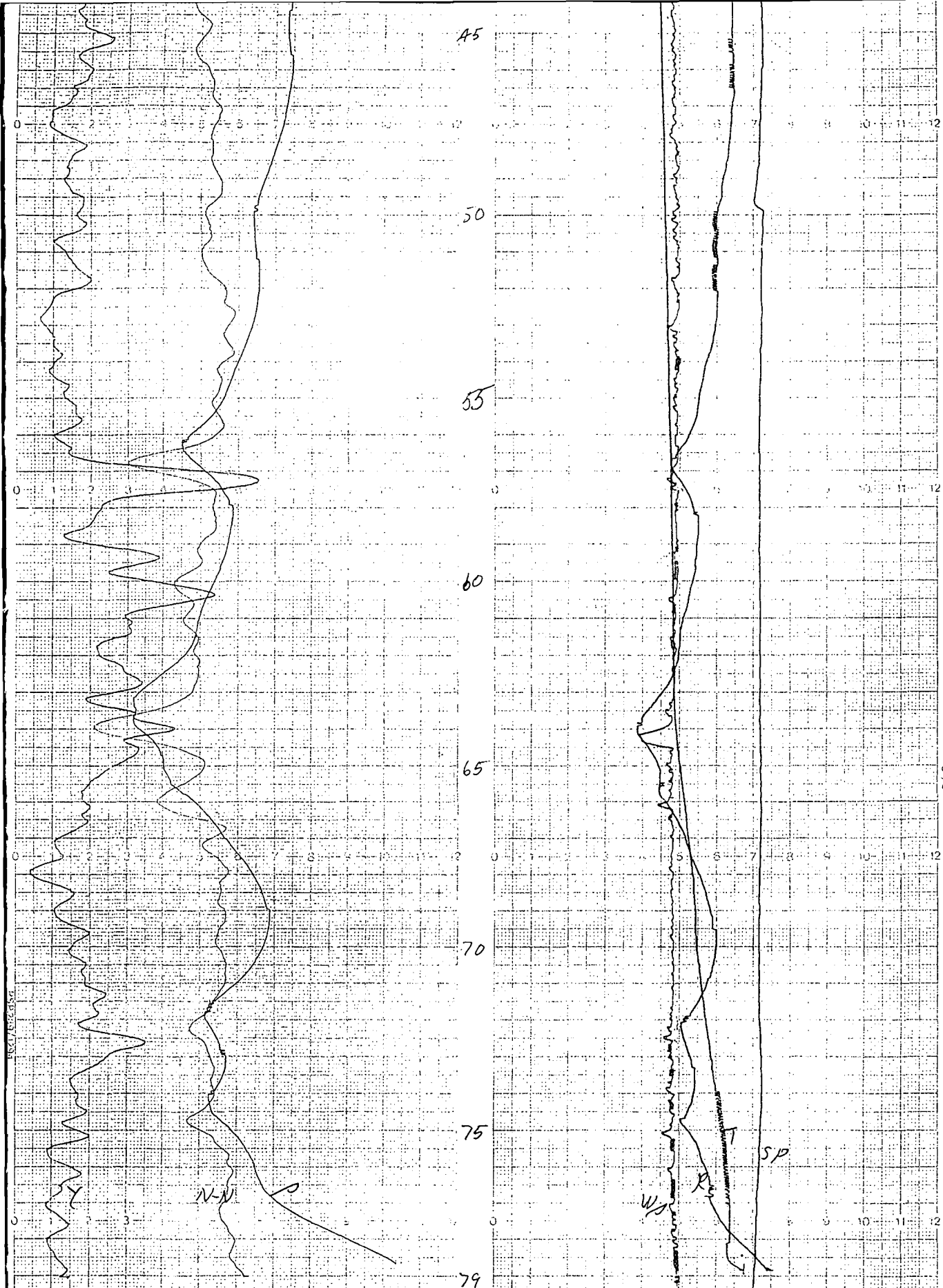
35

40

45

CONTINUED





9/87

2000m/div T ₀ sec disp 0	S 2000m/div	N-N 2000m/div T ₀ sec disp 0
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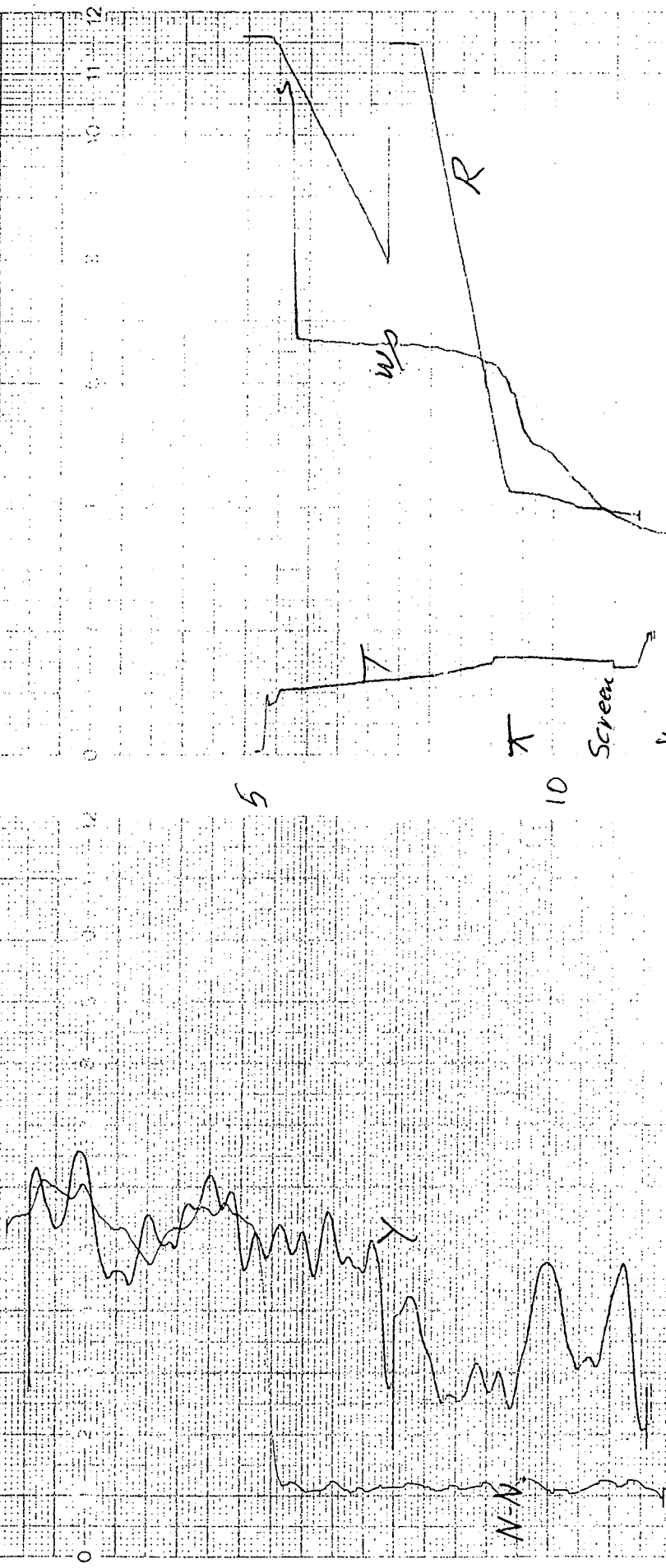
R 2000m/div disp 0	SP 2000m/div bias 0	W 2000m/div	T 0.2°C/div 0-18°C
--------------------------	---------------------------	----------------	--------------------------

2116

Sbruiskaa

G33A21

93-10-12



N-N

T

Screen

12 V

5 cps/div
 100 cps/div
 100 cps/div
 100 cps/div
 100 cps/div

N-N
 100 cps/div
 100 cps/div
 100 cps/div
 100 cps/div

R
 200 cps/div
 200 cps/div

W/D
 0.5 cm/div
 0.2°C/div
 0 = 18°C

(2113)

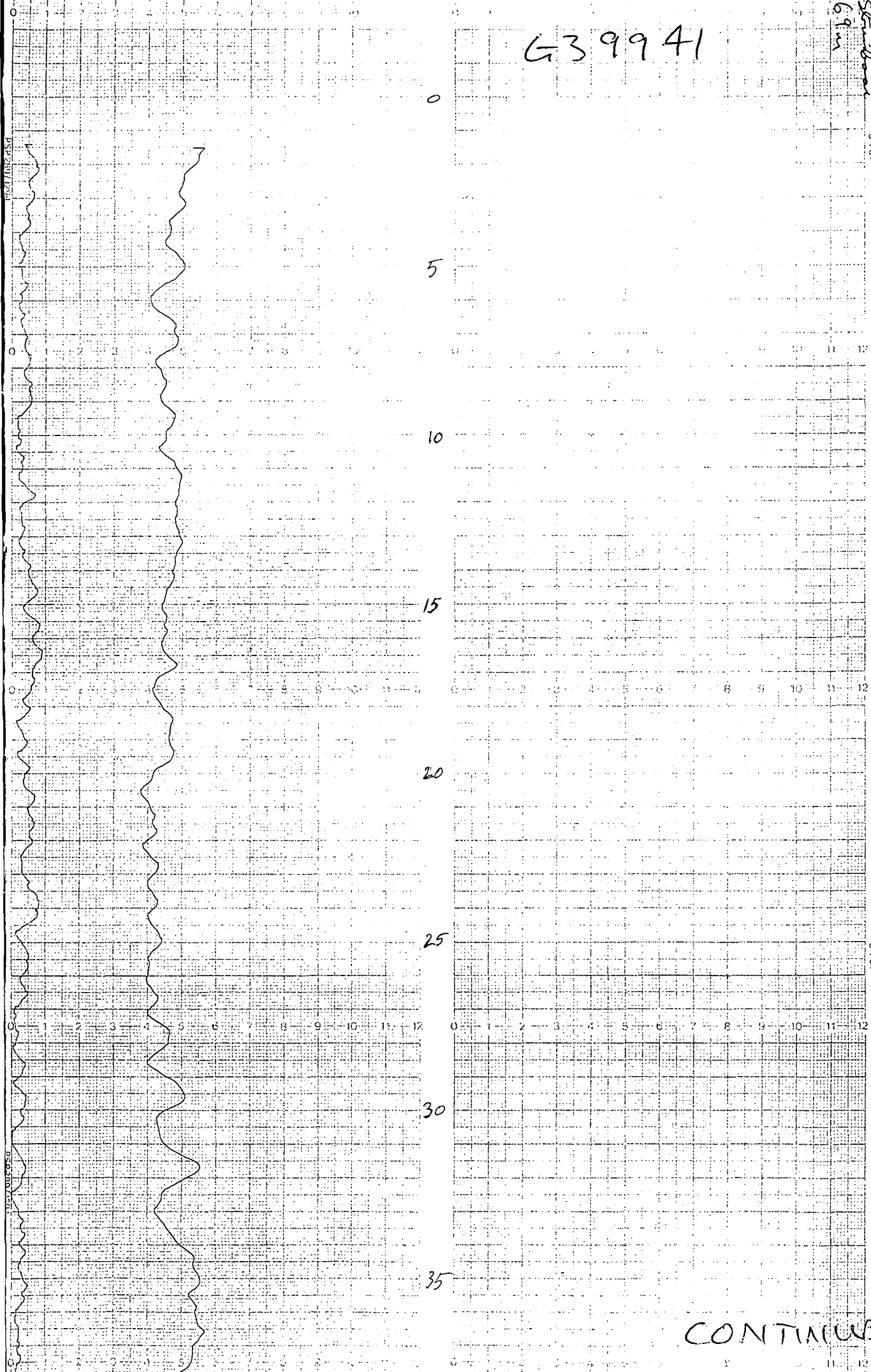
Streisbaai

639940

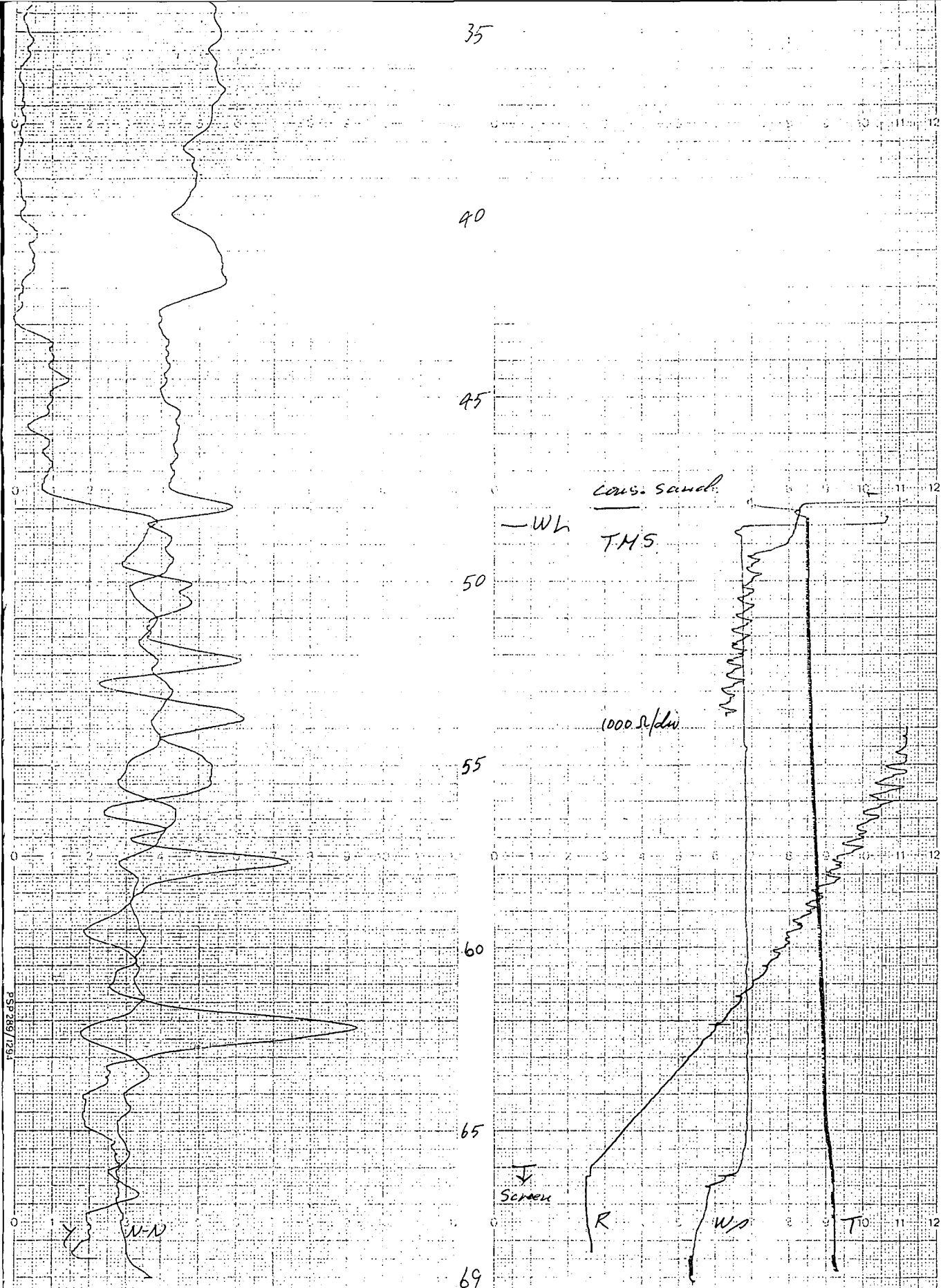
93-10-12

G39941

G39941
Stratigraphic
69m
9.87



CONTINUED



9/87

9/87

X
1000 R/dw
T_{cc} sec
disp. 0

N-N
1000 R/dw
T_{cc} sec
disp. 0

R
500 R/dw
disp. 0

Wp
1500 R/dw

T_{cc}/div
0 = 18°C

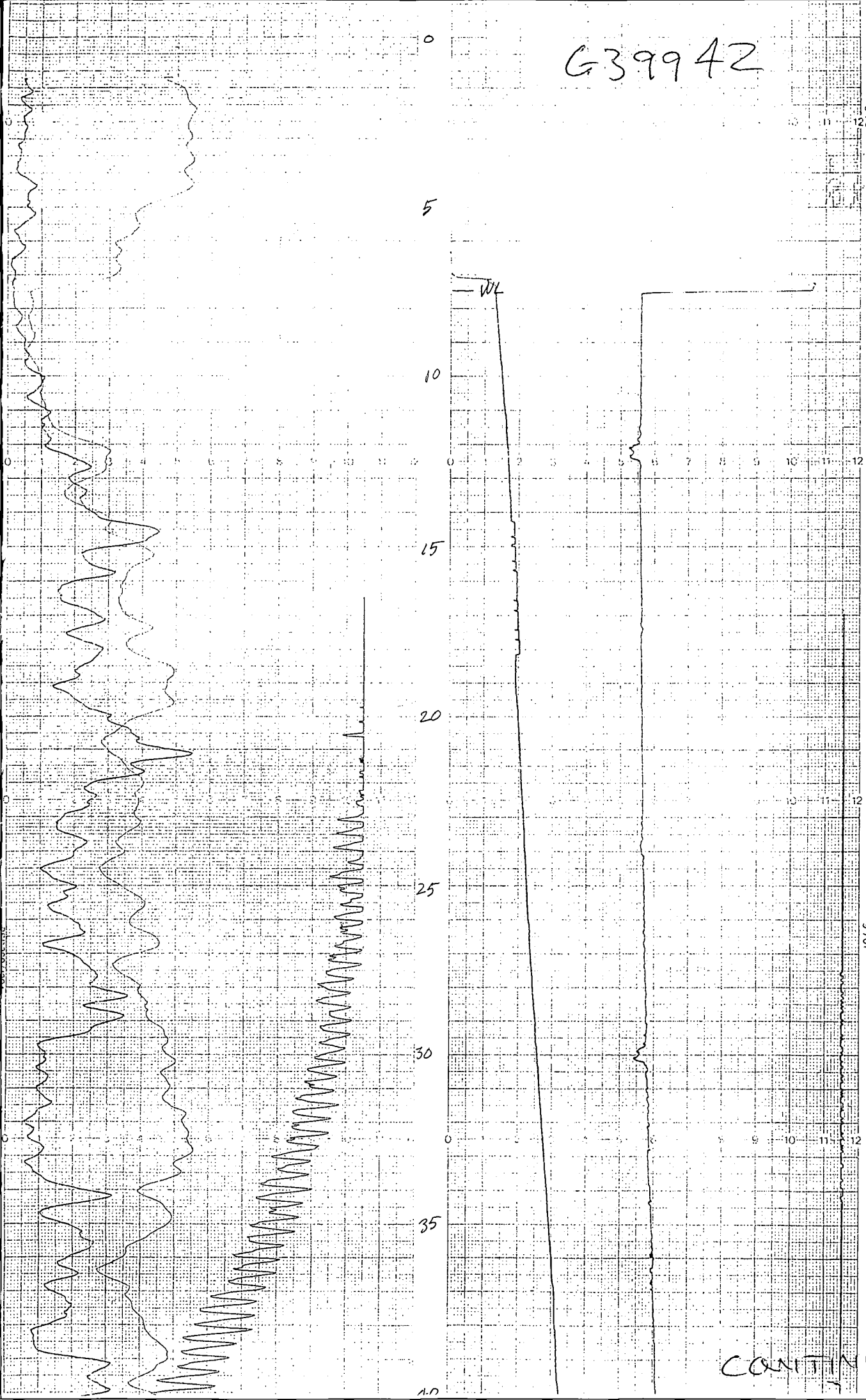
(2117)

Struisbaai

639941

93-10-12

G39942



0

5

10

15

20

25

30

35

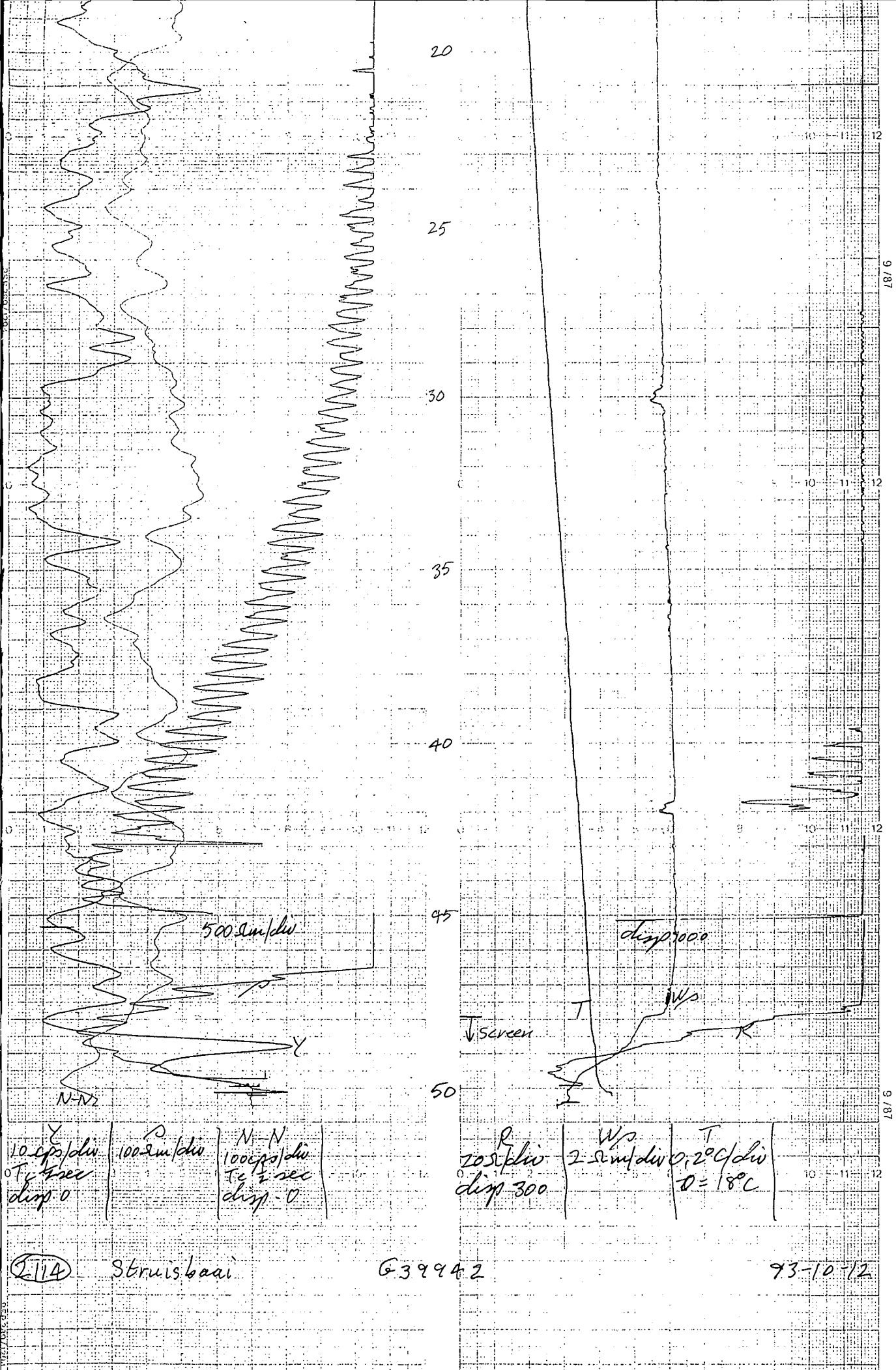
40

WL

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9/87

CONTINUED

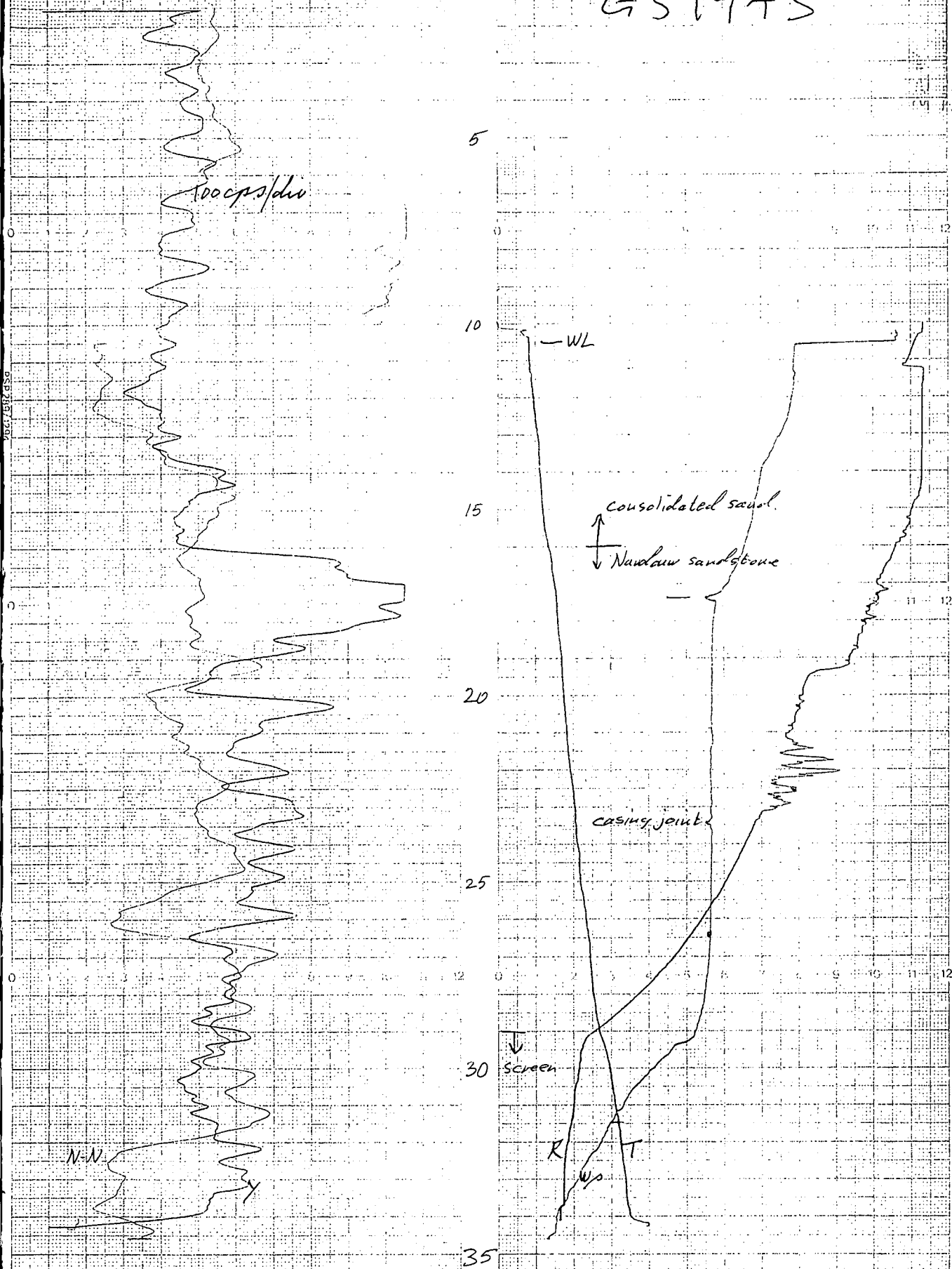


X 10 cps/div Tc 1/2 sec disp 0	P 100 cm/div	N-N 100 cps/div Tc 1/2 sec disp 0
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R 200 cps/div disp 300	Ws 2 cm/div	T 2°C/div D=18°C
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②114 Struisbaai G39942 93-10-12

G39943



9/87

<p>100 cps/div</p> <p>10 sec</p> <p>div 0</p>	<p>N-W</p> <p>50 cps/div</p> <p>10 sec</p> <p>div 0</p>	<p>R</p> <p>500 cps/div</p> <p>div 0</p>	<p>W/S</p> <p>2 simplio</p>	<p>T</p> <p>0.2° C/div</p> <p>0 = 15°C</p>
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(2115)

Struisbaai

G39943

93-10-12

Appendix 5

Recommendations for Future Groundwater Management

Appendix 5

Recommendations for Future Groundwater Management

The decision to replace the old wellfield with the new wellfield has been a fortuitous decision. By doing so two positive effects have occurred. Firstly the wellfield is now in an area where local recharge is slightly less saline due to it being further away from the sea and thus receiving less sea-spray. Secondly the possibility of over-pumping and inducing seawater intrusion is much reduced.

The current practice of satisfying summer peak demand by obtaining the extra water from the old wellfield is acceptable.

The danger with the current water-supply set-up is that complacency may set in with the belief that the water-supply and water-quality problems have been solved for now and also for the future. There is at present no scientifically calculated wellfield yield and wellfield management plan. The only calculation that has been carried out is individual borehole yield calculations. The potential danger is that as the demand for water increases, both from population increase and by increased use of the better quality water for gardening, this demand will be supplied by increasing the yield from the three production boreholes. When the maximum yield of the individual boreholes is increased beyond their capacity then additional boreholes will be drilled close by, the effect of which will be to further increase the local drawdown. This may induce seawater intrusion.

The modelling exercise that has been carried out is only the first step in developing a wellfield management and control plan. The hydraulic information available for this modelling exercise was minimal as the focus of this thesis was not the hydraulics of the system but the water quality. Pump-testing of the old boreholes and water level monitoring to obtain summer and winter regression curves is important additional information. The very big advantage that Struisbaai has compared to most other wellfields is that there is no apparent limit to inland development of the wellfield. As more water is needed so the wellfield can be extended inland. The important factor is to know at what stage must this inland extension occur.

The recommendations for future groundwater management are thus as follows:

- Carry out an investigation to obtain additional hydraulic information.
- Refine the groundwater model.
- Develop a series of water-demand scenarios and apply these to the model to determine the effect on water-levels.
- Determine the maximum water that can be obtained from the existing wellfield.
- Develop population growth and water demand forecasts to determine when the water demand and existing water yield are equal. This will ensure that wellfield expansion plans can be put into place before the need for additional water arises, thus preventing "emergency" overexploitation.
- Identify where the future wellfield expansion areas are and ensure that these are protected and reserved for groundwater abstraction.

★★★

