THE HYDROGEOLOGY OF A KAROO BASALT/SANDSTONE CONTACT AQUIFER MORETELE II DISTRICT REPUBLIC OF BOPHUTHATSWANA SOUTHERN AFRICA

THESIS

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ABSTRACT

As part of a development programme in the Moretele II District, the Government of the Republic of Bophuthatswana, commissioned in 1983 the building of a dry system coal-fired power station. The lack of local surface water to cool the power station resulted in a decision to investigate the potential of the ground water resources. The resources will be required to supply an anticipated 30 year water demand.

Because of the high capital investment and the importance of establishing an accurate assessement of the ground water potential there was a need for a comprehensive and detailed hydrogeological study. The specific aim of the investigation is to assess and quantify the long term reliability of the ground water resources. The very limited data for the area necessitated a particularly thorough and detailed investigation.

This thesis describes the hydrogeological investigation carried out to define the ground water resource potential of this area. The main objectives of the study are to identify, recognize and evaluate the hydrogeological processes operating on this previously ill-defined Karoo aquifer.

To achieve the research objectives the hydrogeological investigation was formulated to make use of various traditional geological, hydrogeological, geophysical and hydrochemical techniques in a logical framework. More specifically, the work involved a hydrocensus, a geophysical survey, the drilling of exploratory boreholes, aquifer tests to determine the intrinsic hydraulic parameters, water level measurements and the collection and analysis of water samples.

The combined results of these various techniques provided data to quantify, evaluate and then propose management strategies for the identified resources. The study provided an understanding of the local hydrogeological conditions and has allowed for a conceptual model of the aquifer system to be derived.

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Lastly I must thank my wife, Sarah, for her patience and encouragment throughout the writing of this Thesis.

To Anna, Alexandra and Lucy
who will become of age
at the end of this Millenium.
By that stage it is hoped that
the conservation of the Natural Resources
will form an integral part of your lives.

1. INTRODUCTION

1.1. Area and Location

The choice of the power station site was not selected on the basis of available water but was sited in close proximity to a proposed coal mine. The area around the power station therefore became the target of the hydrogeological study.

The area is located in the northern portion of the Moretele II District, Republic of Bophuthatswana (Fig. 1). Pretoria is situated 90 kilometers to the south-west and Warmbaths is 40 kilometers to the north-west of the study area. Settlers, situated 15 kilometers to the west is the area´s major agricultural centre.

The area investigated covers a surface of approximately 170 square kilometers. The hydrogeological investigation was carried out in the period between mid 1984 to mid 1985.

1.2. General Physiography and Relief

The Moretele II District is situated in the transition zone between the Highveld and the Bushveld topographic regions (Tyson, 1986). It lies in the southern portion of a very flat regional feature known as the Springbok Flats (Fig. 1). In the area investigated the maximum elevation is 1036 meters above sea level and falls gently to 1006 meters above sea level over a distance of 10 Km (1:333) from the north west to the south east. This flat topography is the result of the pedeplanation process associated with African and post-African pedeplanation cycles (King, 1963).

1.3. Rainfall and Temperature

Rainfall data were obtained from Tuinplaas (Computer print out Weather Bureau, 1986). Temperature and evaporation data are from Towoomba meterological station near Warmbaths. As a result of the flat topography there are no major climatic differences between Warmbaths and the area under study. The temperature and evaporation data are therefore considered to be representative of the prevailing conditions of the Moretele II District. The

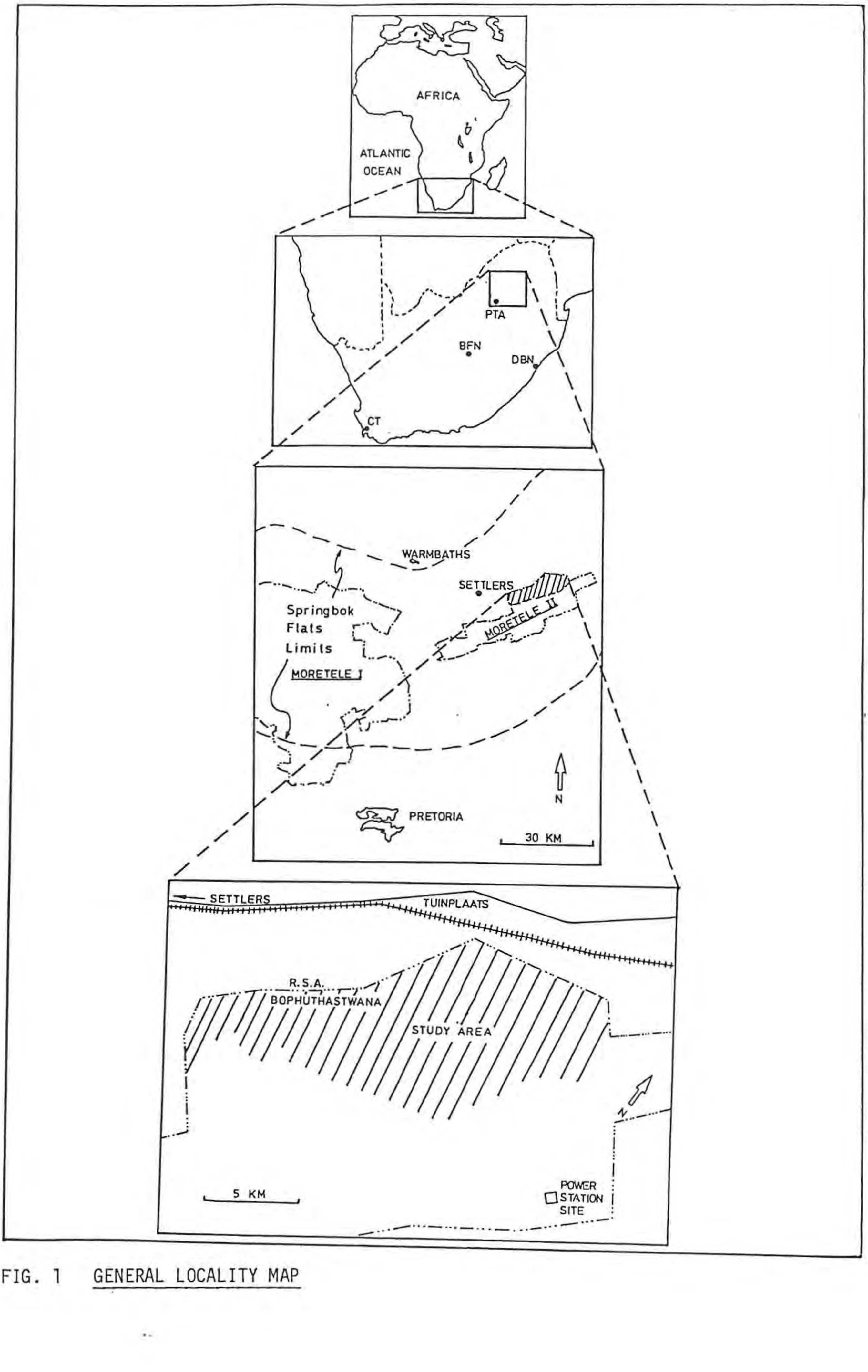


FIG. 1 GENERAL LOCALITY MAP

region is sub-arid and falls within the summer rainfall region (Tyson, 1986). The annual precipitation averages 630 mm for the period 1964 to 1986 (Computer print out Weather Bureau, 1986). Rainfall is characteristically of the convectional type with showers of high intensity. From June to August the area normally receives no rainfall.

The mean annual potential evaporation (A Pan) measured for the Springbok Flats is 2260 mm. per year for the period between 1964 and 1984 (Computer print out Weather Bureau, 1986). The yearly maximum daily temperature is 26,7°C. while the yearly minimum daily temperature is reported to be 11,2°C (Weather Bureau, 1954).

1.4. Surface Drainage

The Moretele II District falls within the surface water catchment of the Elands River system. This river has a broad, flat floored valley amid the surrounding low relief (King, 1963). The erosive potential of the river is reduced by the high absorbing properties of the sandy and clayey soils. Frommurze (1937) comments that the surface "run-off is small". In the area under study there are no pronounced or well defined drainage lines.

1.5. Soils and Vegetation

The in situ weathering of the various lithologies present give rise to distinct soil types. The residual soils found on the mudstones are reddish, slightly clayey and exhibit expansive characteristics (Brink, 1983) and belong to the Hutton form. These soils support a natural vegetation consisting of sparse thorny bushes and grass.

The sandstone is ubiquitously covered by lightly coloured loose sandy soils also of the Hutton form. These soils are spread over a larger area than the sandstone outcrop due to wind redistribution (Taylor, 1980). They sustain a vegetation consisting of grass, silver leaved Terminalia sericea and sparsely distributed Acacia trees.

The basalt mainly weathers to the characteristic "black-turf" soils of the Arcadia form. These soils possess a high clay content (+- 45%) and display the development of vertical cracks in the dry state. They are known to shrink and swell in response to slight moisture changes (Macvicar et al. 1977). These highly rich clayey soils are extensively cultivated. Red clayey soils of the

Shortland form are found in smaller areas. The vegetation comprises grass, thorny bushes and sparsely distributed Acacia trees.

2. GENERAL GEOLOGY

2.1. Structural History

Moretele II District occupies the southern edge of an outlier of the main Karoo basin which underlies the regional feature known as the Springbok Flats (Du Toit, 1959). This main Karoo basin extends as far as northern Zimbabwe (Fig. 2). The basal Karoo formations were deposited on an irregular basement topography (Taylor, 1980).

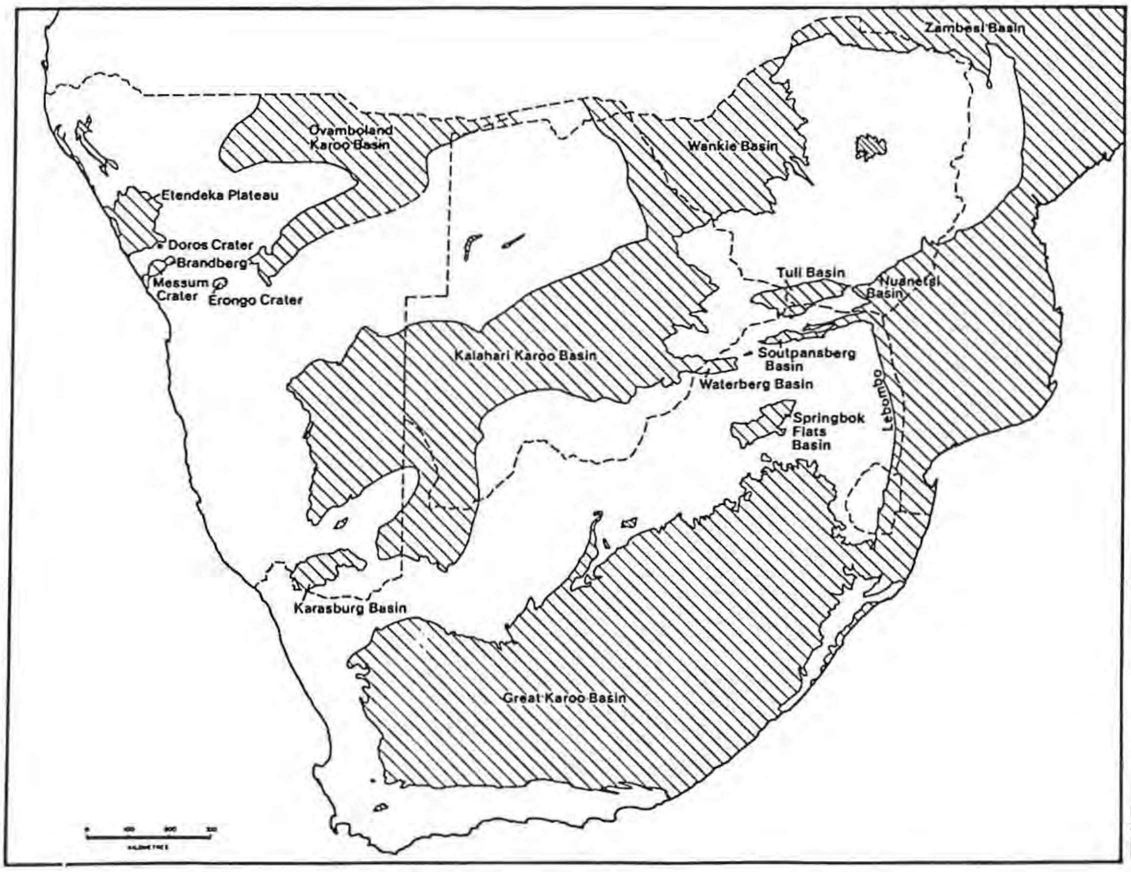


FIG. 2 : EXTENT OF THE VARIOUS KAROO BASINS IN SOUTHERN AFRICA (from BRINK, 1983)

Post-Karoo warping and faulting (<150 m.y.) was responsible for the development of the relatively shallow, elongated synclinal basin to trend in an east-north-easterly direction (Du Toit, 1959). In the area under study the strata dip gently in a north-easterly direction (Fig. 3). It is reported that the area under study is structureless with no evidence of major faults, fracture zones or dyke intrusions (L. Nel, personal communication, 1984).

2.2. Geological Units

The geological sequence comprises three lithological units. These are, from top to bottom, the Letaba Formation, the Clarens Sandstone Formation and the Irrigasie Formation (SACS, 1980). The lithological succession of the these units are presented in Table 1.

Lithology	Formation	Group	Supergroup/sequence
Amygdaloidal Basalt	Letaba	Drakensberg	
Fine grained Sandstone	Clarens		Karoo
Silstone and Mudstone	Irrigasie	Stormberg	

TABLE 1 : GENERALIZED GEOLOGICAL SEQUENCE IN THE MORETELE II DISTRICT (after SACS, 1980)

The areal distribution of the various lithologies is shown in the generalized geological map (Fig. 3). The broad structural relationship between the various lithologies is depicted in the idealized cross section through the area (Fig. 3).

Several general regional studies of a geological nature (Du Toit, 1959; Truswell, 1977; Brink, 1983) are available. However the most detailed desciption of the lithologies nearest to the study area are contained in Taylor´s report (Taylor, 1980).

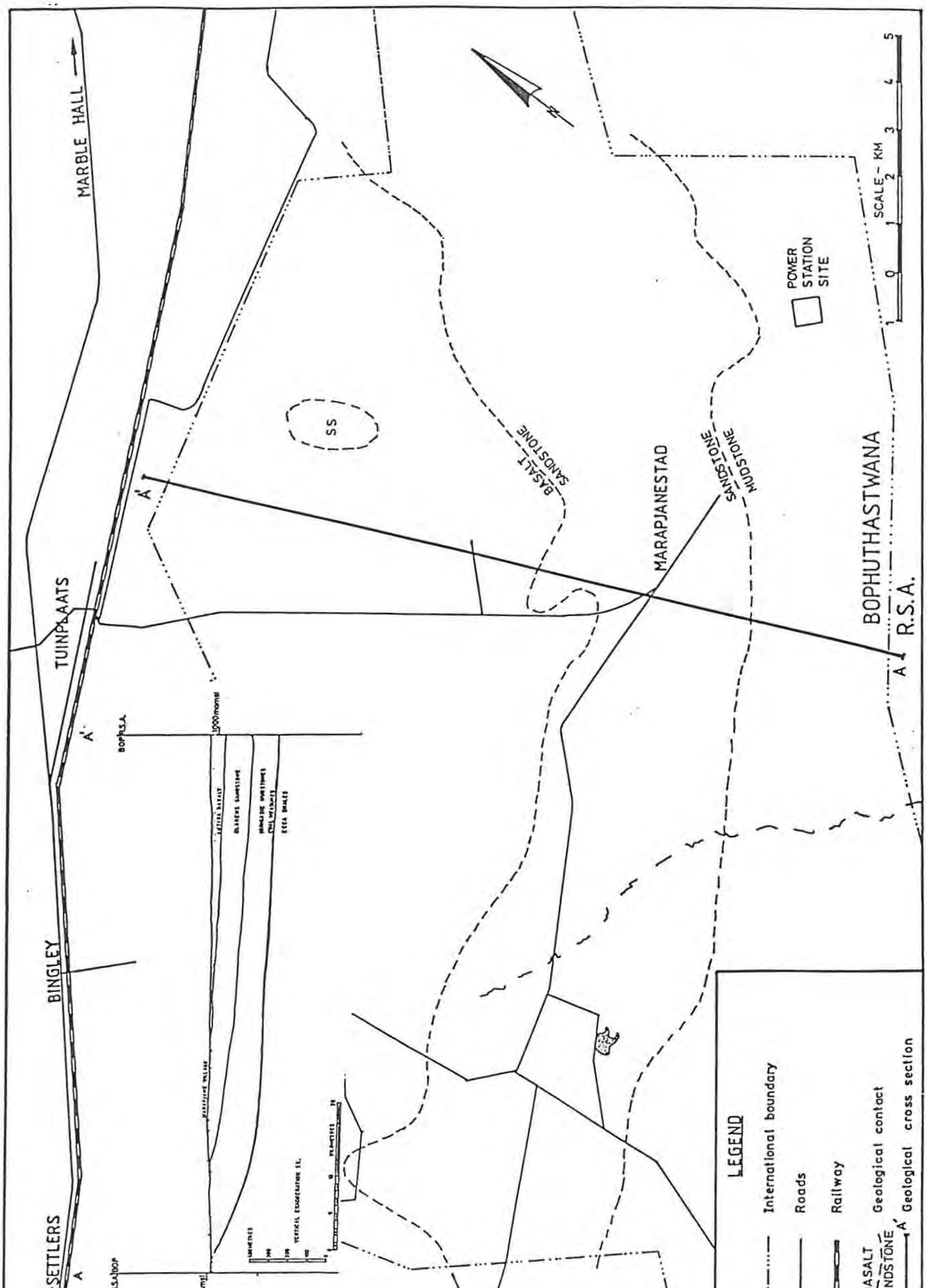


FIG. 3 GENERALIZED GEOLOGICAL MAP WITH CROSS SECTION A-A' (AFTER GEOLOGICAL SURVEY OPEN FILE SHEETS 2428 DC & DD)

2.2.1. Letaba Basalt Formation

The bulk of the basalt formation is composed of several lava flows. Truswell (1977) suggests that these basalts were extruded in quick succession. This was inferred by the lack of weathering between individual flows from observations elsewhere. The lava is a fine to medium crystalline mesotype basalt with a strong amygdaloidal character.

In the northen part of the basin Taylor (1980) describes the contact with the underlying sandstone as a parallel unconformity. In the middle of the basin the basalts are reported to reach a thickness of over 500 m. (Truswell, 1977). The rock is reported to be heavily jointed up to a depth below 50 m. (Taylor, 1980). The extensive surface weathering of the basalt and the development of black-turf soils restricts the exposure of fresh unweathered surfaces.

2.2.2. Clarens Sandstone Formation

The Letaba Formation is underlain by a medium to fine grained sandstone. The sandstone is reported to grade locally into siltstone (Taylor, 1980). The degree of cementation of the sandstone is variable. Less than 5% of the rock is composed of other minerals, mainly feldspar. The remainder is made up of well rounded and well sorted quartz grains.

It is generally accepted that the uniform and extensive nature of this formation elsewhere is indicative of an aeolian origin (Du Toit, 1959). However, Truswell (1977) comments on the lack of diagnostic features to relate the origin of these sandstones to any particular genetic environment.

Taylor (1980) reports that the sandstone mainly consists of massive units with bedded units also present particularly in the lower part of the formation. Small outcrops are seen in the area under study and these confirm the massive nature of these sandstones. The sandy soils cover the remainder of the area. In the northen part of the basin the sandstone is reported to reach a thickness of 140 m. (Taylor, 1980).

2.2.3. Irrigasie Mudstone Formation

The name Irrigasie Mudstone is applied by the South African Code of Stratigraphy to describe this largely argillaceous sequence (SACS, 1980). In the northen part of the basin this unit is reported to consist of a lower mudstone sequence overlain by a layer of sandstone and grit (Taylor, 1980).

A siltstone layer with light grey-green reduction spots represents the uppermost member of this formation. The lower contact of the Irrigasie Formation is taken to be the base of the mudstone that overlies the coal zone or topmost carbonaceous mudstone of the lowerlying Ecca Formation. Joints are sparsely developed.

2.3. General Hydraulic Properties of the Various Strata

Aquifers within basalts and mudstones are generally classified as possessing secondary porosity permeability features (Brown et al., 1972; Driscoll, 1986). This contrasts Custodio's (1975) discussion on volcanic terrains, where he states that porosity and permeability are primary features. He does however state that " soon after its formation, the volcanic materials suffer a continued process of mechanical, physical and chemical alteration which modify the primary porosity and permeability." The sandstones are characterized by water bearing horizons with either primary and/or secondary porosity features (Brown et al., 1972).

Brown et al. (1980) also state that the most difficult task for a hydrogeologist is to understand the hydrogeological regime of fractured and fissured rocks. This is related to the occurrence, movement and storage of ground water within rocks possessing secondary porosity and permeability features (Brown et al, 1972). An assessment of the physical development and distribution of the hydraulic properties (porosity and permeability) within the media in question is therefore important.

Another intrinsic property of the rock formations which is closely related to the orientation and development of secondary porosity features, is the extent and orientation of anisotropy. Aquifer anisotropy may be briefly defined as the occurence of preferential zones of permeability present within a water bearing horizon (Custodio and Llamas, 1976). This often leads to variation in yields, even over short distances (Davies and De Wiest, 1966).

The hydrogeological significance of the lithologies and formations in the area of investigation is discussed below:

2.3.1. The Letaba Basalt

In the northen portion of the basin ground water within the Letaba Basalt is reported to be found mainly within weathered zones (Martinelli and Hubert, 1980). An increase in permeability was noted to occur at the contact between lava flows (J.Blume, personal communication, 1985). This seems to be in contrast with Truswell's suggestion that there is a lack of weathering between lava flows (Sub-section 2.2.1).

Within the northern part of the basin successful boreholes have been drilled along the faulted basalt/sandstone contact (Martinelli and Hubert, 1980). Taylor (1980) report yields betwen 6 and 20 l/s at the contact with the underlying sandstone. In both instances the precise position of the water strikes is not known. These high yields, at the contact boundary, can be related to the process of differential cooling between the lava and the sandstone. This is known to result in a decrease in the volume of the cooling lava which develops joints parallel and perpendicular to the cooling surfaces (Brown et al., 1972).

The occurrence, movement and storage of ground water within this rock type is therefore mainly associated with descrete features of secondary porosity which manifest themselves as weathering zones within the basalt. There is an uncertainty on whether the basalt or the sandstone are water bearing at the contact. In Chapter 8 this ambiguity will be clarified. The presence of the weathering zones and joints impart an anisotropic nature to the basalt.

2.3.2. The Clarens Sandstone

Within the basin the Clarens Sandstone has been reported by Frommurze (1937) to display primary porosity characteristics. An average porosity of 20% has been measured (Frommurze, 1937). Similar primary characteristics were recognized by Martinelli (1980) in the Serowe area, Botswana. In this area the Clarens Formation displays a porosity of 8-16,5% which is consistent with the fine grained nature of this sandstone.

The increase in yield of exploratory boreholes within the sandstone outcrop (E. Martinelli and Associates, 1985) was noted to be progressive and not associated to specific water strikes. This further supports the evidence of a primary porosity aquifer. The isotropic nature of the sandstone is further interpretd by the small variation in yields over the sandstone outcrop (E. Martinelli and Associates, 1985).

Locally, however, this primary aquifer is intersected by secondary features i.e. joints, fissures and dolerite contacts, which have been reported by Frommurze (1937) within the Sprinbok Flats. Martinelli and Hubert (1980) further confirm the presence of dolerite sills intruding the sandstone.

2.3.3. The Irrigasie Mudstone

Frommurze (1937) reports on the lack of secondary porosity features within this Formation. These are not well developed because of the clayey nature of the mudstone and the absence of dyke intrusions. The lack of permeability, the clayey nature and the excessive depth at which it is encountered, highlights the limited hydrogeological significance of this Formation towards the study and will not be further discussed.

2.4. Summary

Chapters 1 and 2 have described the area in terms of the general climatic, geological and hydrogeological settings.

The major points pertaining to the study are summarized below:

- three rock types are present in the area namely: Letaba Basalt, Clarens Sandstone and the Irrigasie Mudstone
- the basalt is characterized by prevalent secondary permeability features and an anisotropic nature
- the sandstone displays mainly primary porosity characteristics. Secondary features are locally developed. The aquifer developed within the sandstone is isotropic.
- the Irrigasie formation is insignificant in hydrogeological terms to the study.

3. AIMS OF THE STUDY

The aims and objectives of the investigation are summarized below:

- to define the aquifer(s) present in terms of their geometry, areal extent and potential for ground water development
- to quantify the resources present by evaluating the aquifer(s) hydraulic characteristics
- to identify the prevalent recharge mechanism
- to assess the ground water quality for human and industrial use
- to predict the long term reliability of the identified resources
- to arrive at the formulation of optimum management procedures

4. STUDY HYPOTHESES

The above aims and objectives provide a basis for a theoretical approach to the problem. The hypotheses set out below are intended to provide a working (practical) framework. Around this framework the various investigation stages and exploration techniques used are conducted. These hypotheses are formulated from both the limited literature available for the area, from practical experience and theoretical knowledge. In Chapter 13 these hypotheses will be discussed and either proven or rejected according to the findings.

The general hypotheses are:

4.1. Complex aquifer hydraulic conditions occurr within the basalt because of lithological anisotropy

4.2. Relatively simple aquifer hydraulic conditions are present within the Clarens Sandstone because of the primary characteristics and isotropic nature of the Formation

4.3. There is hydraulic interconnection between the basalt and sandstone rock units

4.4. Water from each of the major aquifer types can be distinguished by their hydrochemical properties

4.5. There is active aquifer recharge via direct infiltration of rainfall which is in excess of the expected abstraction volume

Hypothesis 4.1. was formulated from references to previous work done around the area (E. Martinelli and Associates, 1976, 1977 and 1978; Martinelli and Hubert, 1980; Taylor, 1980) and from field investigations carried out in Guatemala (Velasquez, 1983), in the Canary Islands (Custodio, 1975) and in Java (Lloyd et al, 1985). Hypothesis 4.2. was postulated with reference to local work done by E. Martinelli and Associates (1983 (a) and (b)) and elsewhere (Martinelli, 1980; Wright et al, 1982). The postulation of hypothesis 4.3. was substantiated by work done in the vicinity of the study area by Taylor (1980). The existence of an hydraulic connection between two aquifers elsewhere, not necessarily between the same rock types discussed in this dissertation, has been documented (Walton, 1970; Bucsi Szabo and Szlaboczky, 1976; Herrero Ducloux, 1983). The fomulation of hypothesis 4.4. relied on the work done by Taylor (1980). The basic principle of distinguishing different aquifer types by their chemical composition is refered in the literature and in case histories elsewhere (Custodio and Llamas, 1976; Griolet, 1976; Bakiewicz et al, 1982; Lloyd et al, 1985). The assumption that recharge takes place via direct rainfall infiltration is exposed in hypothesis 4.5. which specifically relied on the work by Taylor (1980). The principle of assessing direct recharge from rainfall is well documented in text books (Walton, 1965; Castany, 1968) and field investigations throughout the world (Dowgiallo, 1976; Lebedeva, 1976; Burdon, 1977; Burdon, 1982; Powell, 1983).

5. APPROACH TO THE HYDROGEOLOGICAL INVESTIGATION

The formulation of the study hypotheses has provided the basis for the choice of the exploratory stages and techniques to be adopted during the investigation. The proposed investigation stages, as listed below, have been formulated with the purpose of fulfilling the study aims as set out in Chapter 3 and to test the validity of the hypotheses of Chapter 4.

During the investigation the results of each stage provide the input for the subsequent one. This makes the investigation dynamic and allows for the correct choice of field techniques as the work progresses. Kulinov and Yazvin (1983) report that this approach, which they term "the principle of successive approximations", has been implemented successfully in various hydrogeological investigations in the U.S.S.R. The application of this principle has resulted in the successful completion of the work and an increase of the economic efficiency of the projects.

The sequence of the various phases as listed below constitute the order in which the actual investigation stages have been carried out. A detailed discussion of each phase is presented in Chapters 6, 7, 8, 9, 10, 11 and 12.

The investigation phases are:-

. Desk study

. Photogeological study and hydrocensus

. Ground Geophysical Survey

. Drilling of Exploratory Test Boreholes

. Test Pumping programme

. Water level measurements

. Water Quality

The above Chapters 1,2,3 and 4 have given an introduction to the study area, described the general climatic and geological setting and have delineated the study aims and hypotheses. The following Chapter intruduces the first phase of the actual field investigation.

6. THE HYDROGEOLOGICAL INVESTIGATION

The purpose of a hydrogeological investigation is to gather knowledge of the hydrogeological processes within an area as reliably and economically as possible (Davies and De Wiest, 1966). To this end, hydrogeology, as an interdisciplinery science, makes use of various methods and techniques to achieve the desired objectives (Custodio and Llamas, 1976).

This hydrogeological investigation, as detailed below, was formulated to satisfy the study hypotheses and to determine the local hydrogeological conditions. The ensuing sections are a detailed exposition of the various investigation phases as carried out during the actual hydrogeological investigation. The findings and results of these phases will be tested against the working hypotheses and will be discussed in Chapter 13.

6.1. Desk Study

The preliminary phase of a regional hydrogeological investigation is the collection, synthesis and interpretation of all existing data, reports and maps (Brown et al., 1972). These provide general information regarding the geology, hydrogeology and groundwater development potential of the area prior to the commencement of the actual field work (Walton, 1970; Brown et al., 1972; Custodio and Llamas, 1976). Several reports dealing with the geology/hydrogeology of adjacent areas of comparable conditions were studied (Fig. 4) and the relevant conclusions are summarized below:

Messrs E. Martinelli and Associates (1976 and 1977) carried out a groundwater development programme on a Tweefontein approximately 30 Km. to the N-W of the study area. The findings were published by Martinelli and Hubert (1980). Tweefontein is situated on the northern edge of the basin (Fig. 4). Following a geophysical survey, several boreholes were drilled and the aquifer test pumped. Two aquifers were developed. Within the basalt yields were found to be high but the aquifer limited in places by hydraulic barrier boundary conditions (Fig 5 (a) and (b)). Recharge boundaries were found along basalt/sandstone faulted contacts (Fig. 5 (c) and (d)). The aquifer associated with the sandstone is areally extensive and within secondary permeability features moderate yields were encountered. The general hydraulic conditions found in the area are shown in figure 5 (Martinelli and Hubert, 1980).

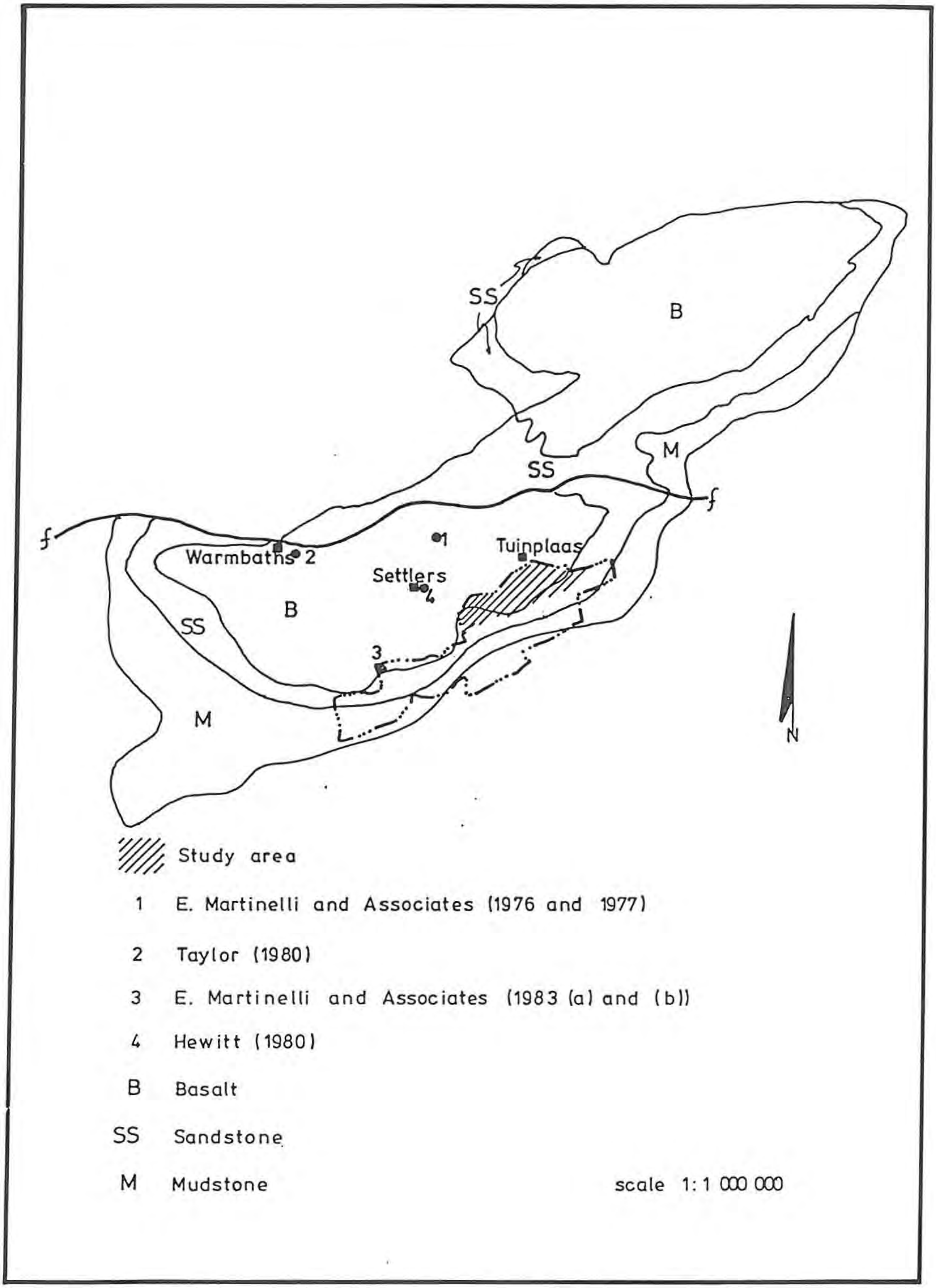
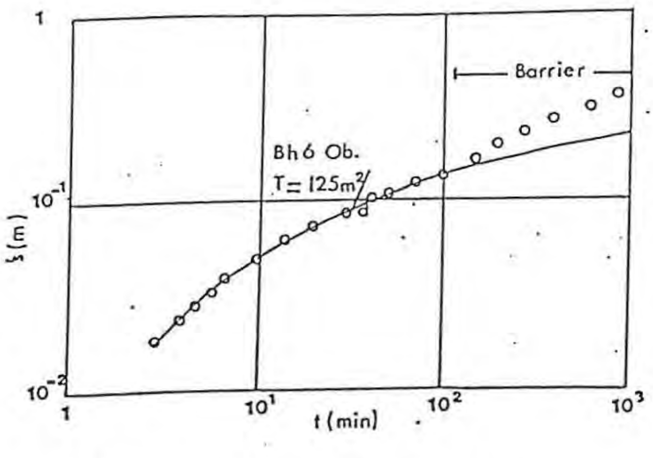
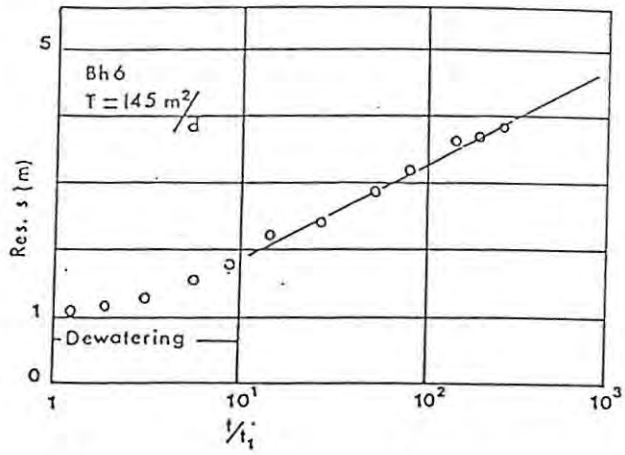


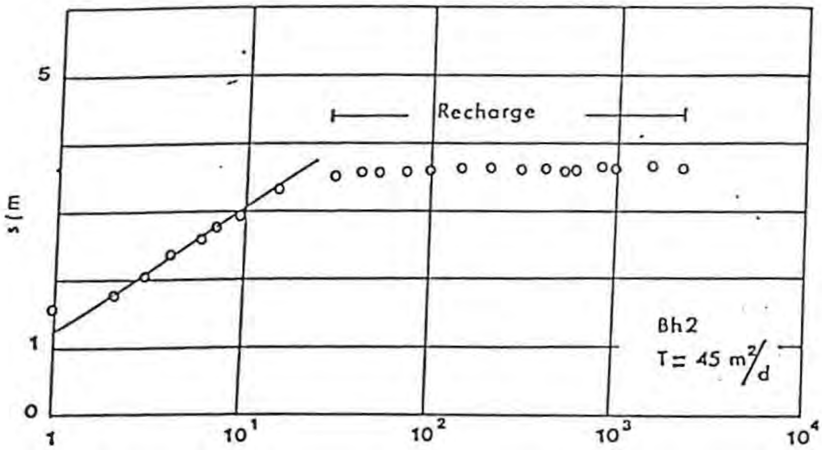
FIG. 4 POSITIONS OF PREVIOUS INVESTIGATIONS WITHIN THE KAROO BASIN



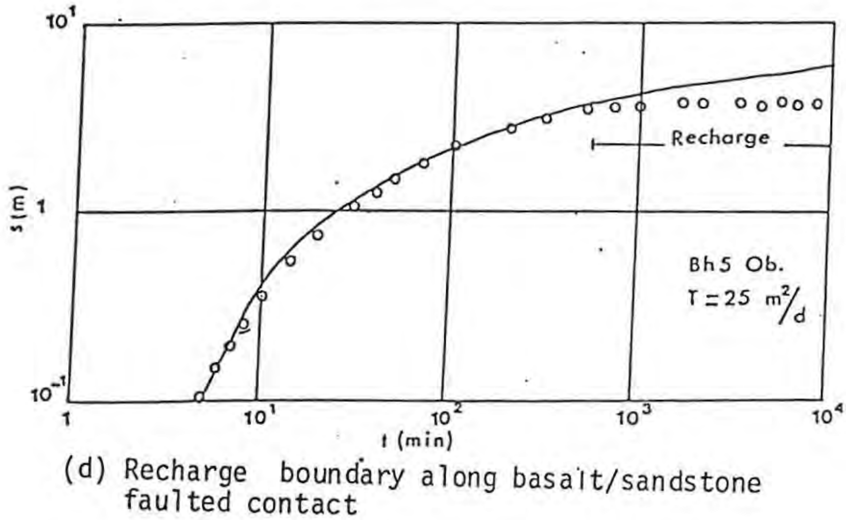
(a) Hydraulic barrier boundary within basalt



(b) Hydraulic barrier boundary with dewatering within basalt



(c) Recharge boundary along basalt/sandstone faulted contact



(d) Recharge boundary along basalt/sandstone faulted contact

FIG. 5 GENERAL HYDRAULIC CONDITIONS FOUND WITHIN THE FARM TWEEFONTEIN (AFTER MARTINELLI AND HUBERT, 1980)

Taylor (1980) conducted a regional groundwater investigation on behalf of the Department of Water Affairs in an area around and east of Warmbaths (Fig. 4). He reports both low and substantial yields both within the basalt and at the contact with the sandstone. Poor yields were recorded within the sandstone. The main recommendations included the development of the aquifer associated with the basalt which has a surfcae area of 7 km^2 and a calculated storage of approximately 3 x 10^5 m^3. The isopiestic map compiled by Taylor (1980) shows a regional ground water flow pattern direction from the north west to the south east.

A study of a small area of sandstone and basalt some 30 Km west of the area of interest (Fig. 4) was underataken by E. Martinelli and Associates (1983 (a) and (b)). Three boreholes were drilled at sites selected on the basis of the interpretation of geophysical surveys. The basalt had a maximum thickness of 25 m. No yields were intersected either within the basalt itself or on contact. The sandstone was, however, found to be water bearing with yields of 0,8 to 2 l/s.

Hewitt (1980) investigated the possibility of improving yields and the quality of the ground water below the sandstone/mudstone contact. This was as a result of poor quality water (5 mg/l of flouride) abstracted from a borehole supplying a school. The existing borehole, near Settlers (Fig. 4), drilled through the basalt and partially penetrating the sandstone, was deepened. The sandstone sequence was fully penetreted and the mudstone was penetrated by 16 m. There was no increase in the original yield (1 l/s) neither within the sandstone nor at the contact with the mudstone. The quality of the groundwater remained the same.

In conclusion the desk study indicated the large variability of the ground water development potential between the various lithologies. In particular the high development potentail associated with the basalt.

6.2. Photogeological Study and Hydrocensus

6.2.1. Photogeology

The photogeological study of black and white stereo photographs of the area was carried out prior to the field census. Aerial photographs are interpreted to obtain geological and hydrogeological information of an area such as:

- the areal distribution of the lithologies
- the presence of zones of weathering, dyke intrusions, faults and fracture zones which influence the porosity and permeability of the rocks (Brown et al., 1972).

There was a close association in the distribution of the geologies between the photogological interpretation and the geological map of figure 3. This latter map will therefore be used for future reference. In addition the interpretation of the photographs indicated that the area is devoid of any weathering zones, areas of fractures and joints, dyke intrusions etc. This supports the reported lack of these features by Nel (personal communication, 1984).

6.2.2. Hydrocensus

The field phase of the hydrocensus was preceeded by the retrieval of data on all of the existing boreholes in the area. These were available from the archives of the Bophuthatswana Water Corporation.

Custodio and Llamas (1976) observe that the field inventory of existing boreholes provides useful information on the general characteristics of the aquifers present. Important data to gather include geology, yield, borehole depth, depth of static water level and depth of water strike. However, for boreholes in the present study area, the information available in the archives was limited to yields and borehole depths.

Borehole positions are shown in figure 6. A total of fourteen boreholes fall within the basalt outcrop area. It is not known whether some of them intersect the sandstone below. The reported yields vary from 0,3 to 11 l/s. Eight boreholes are situated on the sandstone outcrop. The reported yields vary from 0,2 to 3 l/sec. Only one borehole is located on the mudstone outcrop with a reported yield of 1 l/s.

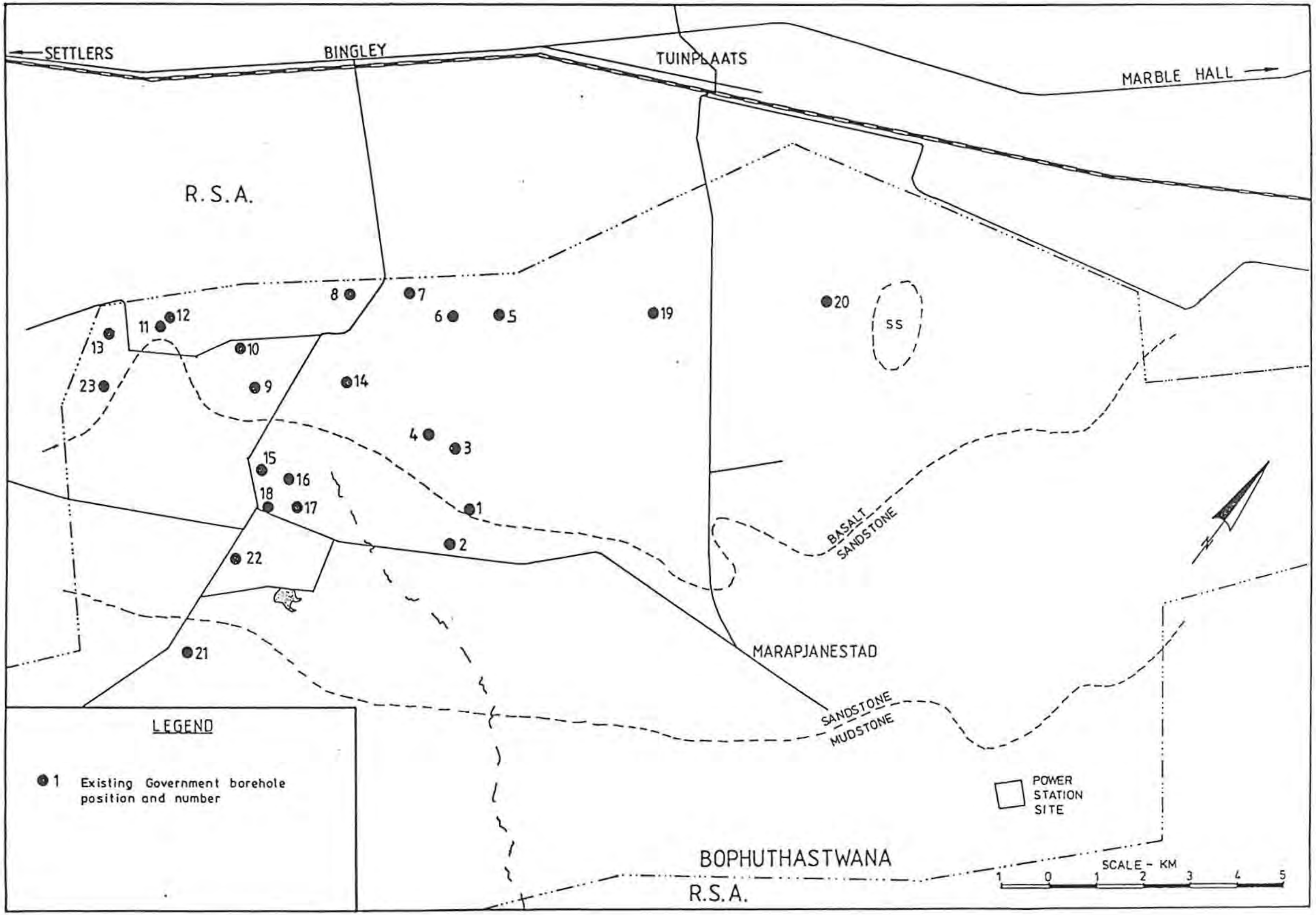


FIG. 6 POSITION OF EXISTING BOREHOLES SURVEYED DURING HYDROCENSUS

Tables 2 (a), (b) and (c) give for each geology the number of boreholes for arbitrary yield ranges. The following comments apply;

1) The basalt supports the highest yields.

2) Boreholes within the basalt area display a greater variation in reported yields.

3) Low and moderate yields are exploited from the sandstone. The narrow variation in yields is noted.

4) The mudstone is the least exploited rock unit .

Yield ℓ/s	<0,49	0,5-0,99	1-4,9	5-9,9	>10
No. Boreholes	3	3	2	3	1

(a) Basalt

Yield ℓ/s	<0,49	0,5-0,99	1-4,9	5-9,9	>10
No. Boreholes	1	-	5	-	-

(b) Sandstone

Yield ℓ/s	<0,49	0,5-0,99	1-4,9	5-9,9	>10
No. Boreholes	-	-	1	-	-

(c) Mudstone

TABLE 2 : YIELD RANGES OF THE VARIOUS GEOLOGIES

The existing boreholes are mainly used for livestock. An attempt was made to visit private boreholes. Basic information given, such as yield and depth, were vague and often unknown. The majority of the private boreholes are situated around areas of sandstone outcrop. A great number of them are equipped with handpumps. It is implied that the sandstone is able to support small reliable yields and that it is ubiquitously saturated.

6.3. Conclusion

The data gathered and analysed during the desk study and the hydrocensus showed that the potential of the Letaba Basalt Formation for ground water development is the highest. The lower potential of the Clarens Sandstone is also noted. The photogeological study provided no information of an hydrogeological nature. The geophysical investigation (Chapter 7) subsequently carried out is intended to support the findings of these earlier study phases.

7. SURFACE GEOPHYSICAL SURVEY

7.1. General Introduction

Geophysics has been applied to ground water exploration to locate weathering and fractured zones, determine the vertical and horizontal distribution of formations, evaluate total porosity and volume of water stored in an aquifer and estimate the depth to bedrock of an aquifer (Ogilvy, 1969; Astier, 1971; Brown et al., 1972).

The most common geophysical methods which are at the disposal of the geophysicists are (after Custodio and Llamas, 1976):

- the magnetic method
- the electromagnetic method
- the gravimetric method
- the seismic refraction method and
- the electrical resistivity method

The choice of the correct method applied in this investigation was made after comparing each method in turn, as discussed below:

- The magnetic profiling method is used in measuring the magnetic field around a body which contains magnetic minerals. Dykes and other intrusive bodies are known to possess these magnetic properties (Le Roux, 1980). At the contact between these intrusives and the country rock, secondary porosity zones are usually enhanced. The lack of dykes and other intrusives as seen by the photogeological study has precluded the use of this technique in the area of interest.

- Electromagnetic traverses and soundings are used to locate conductive zones at depth (Van Zijl and Kostlin, 1985). Field investigations on volcano-sedimentary terrains in Upper Volta have associated these conductive zones with areas of weathering/fracture development (Palacky, Ritsema and De Jong, 1981). However a serious drawback is the applicability of this method over a conductive cover (Van Zijl and Kostlin, 1985). The presence of the thick clayey soils associated with the basalt precluded the use of this method in the study area.

- The gravimetric method relies on the determination of the earth's gravity or its variations (Astier, 1971). The results obtained are subject to various corrections. The final output is generally a regional map depicting the Bouguer anomalies that is qualitatively interpreted (Astier, 1971). This method is relatively cheap and rapid, but has a very low resolution (Van Zijl, 1977). Davies and De Wiest (1966) state that the use of this method is limited in its application to ground water exploration and development due to the difficulty of detecting small geological changes.

- The seismic refraction method measure the reaction of the rocks to artificially induced vibrations. It is recognized to be one of the most accurate and useful methods in geophysics (Davies and De Wiest, 1966). Van Zijl (1977) states that this method bears many similarities (speed of execution, degree of resolution) to the electrical resistivity method. However, Davies and De Wiest (1966) report that the use of specialized equipment and personnel makes this method the most expensive of all geophysical methods. Slow field operations are also a limiting factor to the use of this method.

- The electrical resistivity method is based on the measurements of the distribution of electrical resistivity with depth (Van Zijl, 1977). A major limitation of this method is related to its inability to define individual geoelectrical horizons when they become deeply buried. When there is a lack in resistivity contrast between the different horizons this limitation is further enhanced. However, Van Zijl (1977) states when compared with the siesmic method for the same depth of investigation the resistivity method becomes cheaper, faster and more flexible in its application.

The resistivity method was therefore chosen for its applicability to the particular geophysical environment. This is not to say only one technique should be implemented. The most suitable prospecting procedure would have been the conjunctive use of two or more of the above mentioned methods (Van Zijl, 1977). However the electrical resistivity method was applied for technical and economic reasons.

The resistivity technique has limitations when applied to basaltic terrains (Davies and De Wiest, 1966; Brown et al., 1972; Custodio and Llamas, 1976). Exceptions are found where the rock underlying the basalt has a different geoelectrical response. During this study this resisitivity contrast is afforded by the underlying sandstone. The electrical resistivity method has been used on volcanic terrains in South Africa (Martinelli, 1978; E. Martinelli and Associates, 1982) and elsewhere (Astier, 1971) in order to:

- delineate the vertical and horizontal distribution of the various lithologies present
- quantify any weathering/fracturing development and the depth to bedrock
- select suitable borehole sites to avoid costly direct exploratory drilling.

7.2. The Electrical Resistivity Method - Schlumberger Electrical Sounding

The electrical resistivity method can be divided into two separate techniques (Bhattacharya and Patra, 1968). The first, known as resistivity or geoelectric profiling, gives an idea of the lateral distribution of resistivities. The depth of investigation remains relatively constant. In the second technique, known as the Vertical Electrical Sounding (V.E.S.), the resistivity values measured at surface are a reflection of the vertical resistivity distribution with depth. It is the latter technique that will be discussed in this Chapter. The electrode configuration used to carry out the V.E.S. is the Schlumberger array (Fig. 7 (a)). This particular array has been chosen over the Wenner configuration (Fig. 7 (b)) because of the limited distortion that takes place in the sounding curves over heterogeneous terrains (Fig. 7 (c) and (d)). Furthermore a theoretical study by Deppermann (1954), as reported by Frohlich (1974), indicates that Wenner soundings are more influenced by near surface lateral inhomogeneities than Schumberger soundings. The above mentioned distortion is sometimes attributed to a depth effect rather than a surface effect which often leads to erroneous interpretations of the Wenner curve (Van Zijl, 1977).

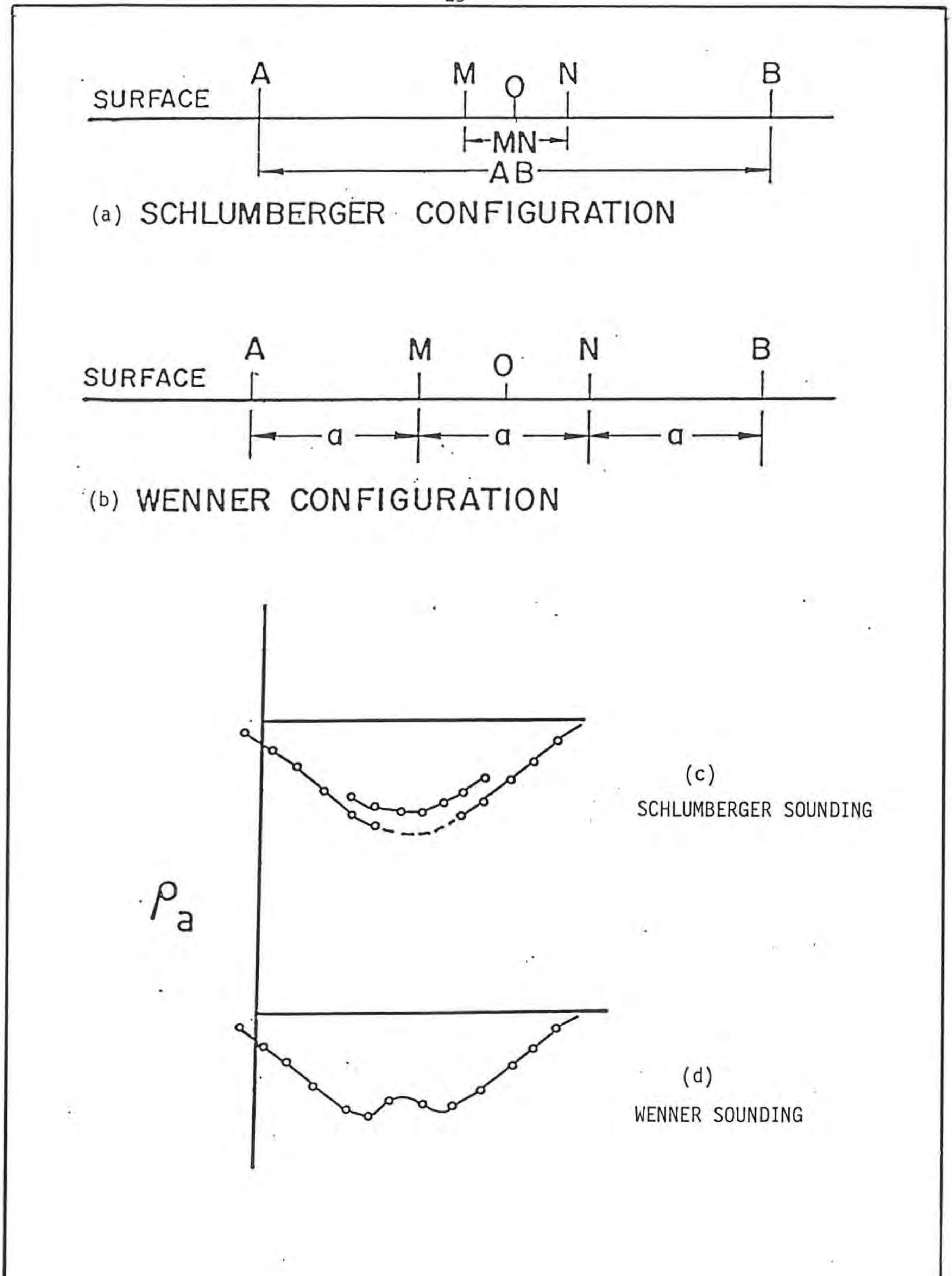


FIG. 7 SCHLUMBERGER AND WENNER ELECTRODE CONFIGURATIONS. COMPARISON OF THE DISTORTION OF SOUNDING CURVES WHEN USING SCHLUMBERGER AND WENNER SOUNDINGS (AFTER VAN ZIJL, 1977)

The field curves thus obtained are interpreted for:

a) the geophysical parameters of resistivity and thickness of each of the layers present and

b) to relate the interpreted geophysical parameters to the geology.

Under favourable conditions it is possible to arrive at a quantitative and reliable interpretetation of the above parameters. However various factors may complicate the interpretation proceedure. These include the difficulty to identify the thicknesses and resistivities of beds when they are deeply buried, the anisotropic behaviour of the medium, beds dipping at more than 15^{o}, large lateral variations in resistivity and facies changes within key formations. The interpretations of the V.E.S. curves were carried out with these limitations in mind.

7.3. Discussion of the Results

The geoelectrical survey was carried out in a pattern as shown in figure 8 prior to the drilling programme. The majority of the soundings (111) were run over the basalt outcrop because of its importance to the study (see Sections 6.1. and 6.2.). Eight soundings were carried out over the sandstone and only one over the mudstone outcrop. This is equal to approximately one sounding per square kilometer. A maximum electrode spacing of AB/2=250 m. was used. This electrode spacing allowed the sampling of the full basalt/sandstone sequence. A total of fifteen V.E.S. were run at existing boreholes investigated during the field inventory (Fig. 8).

Van Zijl (1977) suggests that the interpretation of the sounding curves is first carried out by inspecting common characteristics or progressive changes of their shapes. This interpretation thus allows for the definition of resistivity ranges for the various geoelectrical units when there is a lack of control data which is afforded from the geological logs of the surveyed boreholes. Thus it is not possible to calibrate the calculated thicknesses and resistivities obtained for the curves elsewhere. The above limitation was however overcome once the thicknesses from the drilling programme were obtained.

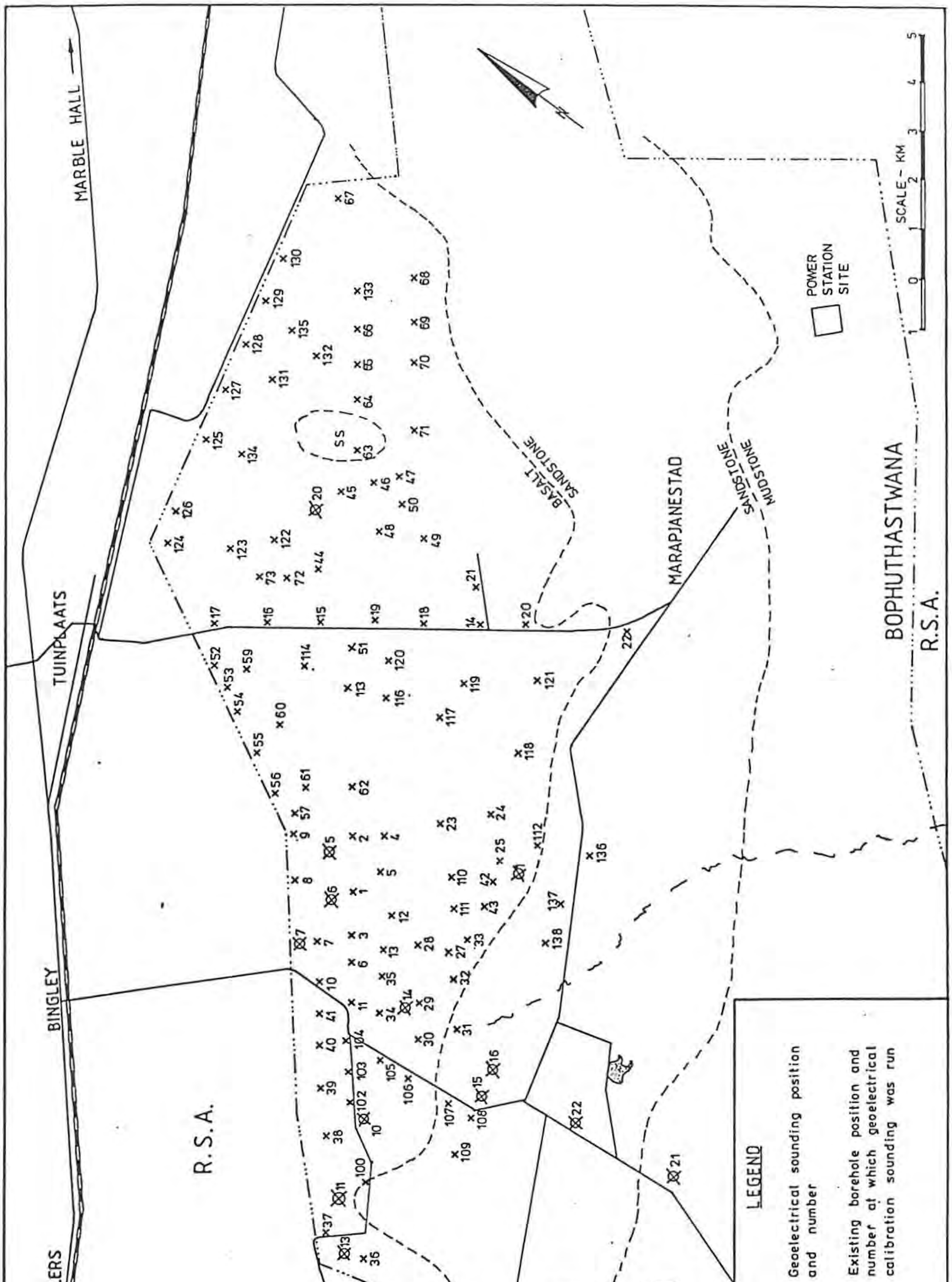


FIG. 8 <u>POSITIONS OF GEOELECTRICAL SOUNDINGS</u>

Subsequently, for each curve, the thicknesses and resistivities of the various layers are calculated. Their determination is carried out using standard graphical analytical methods of curve matching (Orellana and Mooney, 1966; Joubert, 1977). These are checked using a computer enhanced technique developed by the Geophysics Division of the CSIR (S. Joubert, personal communication, 1985). This programme utilizes the method of Ghosh (1971, (a) and (b)) as modified by Johansen (1975).

The geoelectrical results that follow have been quantified using the drilling results of Chapter 8. This discussion is therefore presented on a quantitative basis for ease of comparison with the drilling results.

The interpetation shows the majority of the soundings are three layer K-type curves. The remainder are three layer H and Q-type and two layer K and H-type curves. Representative type curves are given as figures 9 (a),(b),(c),(d) and (e) respectively. The distribution of these type curves is illustrated by four areas having differing geoelectrical responses (Fig. 10). Table 3 quantifies each area in terms of the thicknesses and resistivities of the interpreted geologies.

Area No.	Geology	Thickenss range (m)	Resistivity Range (ohm.m)
1	Basalt	90-160	>500
	Sandstone	∞	30-90
2	Basalt	50-140	200-500
	Sandstone	∞	20-70
3	Basalt	20-60	100-200
	sandstone	∞	20-80
4	Basalt	20-50	100-200
	Sandstone	∞	15-20

TABLE 3 : THICKNESSES AND RESISTIVITIES OF INTERPRETED GEOLOGIES

The progressive change in type curves and resistivity values is associated with a different geoelectrical environment interpreted to be a change in lithology. From the limited geological and geoelectrical knowledge (E. Martinelli and Associates, 1976 and 1977) the four

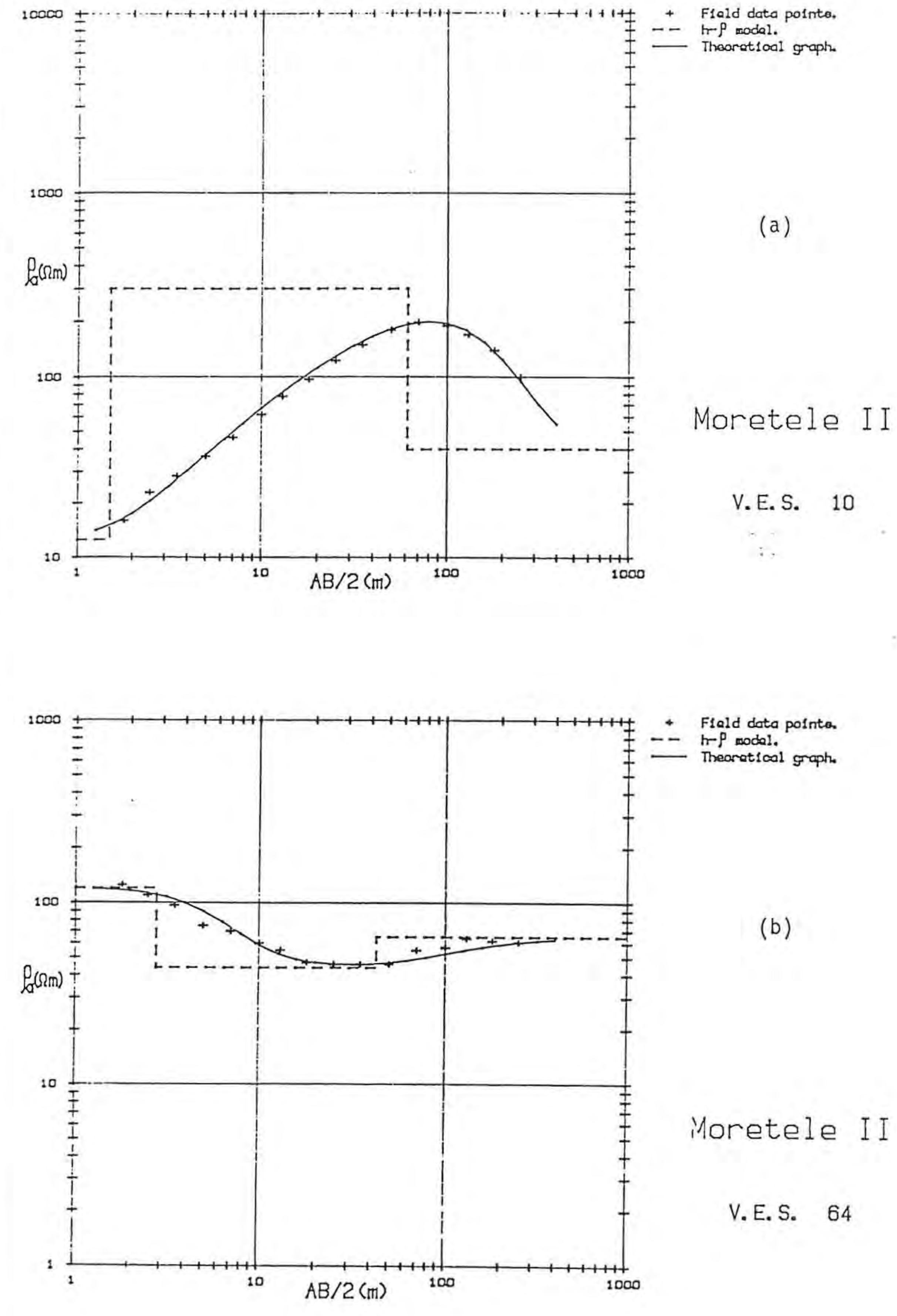
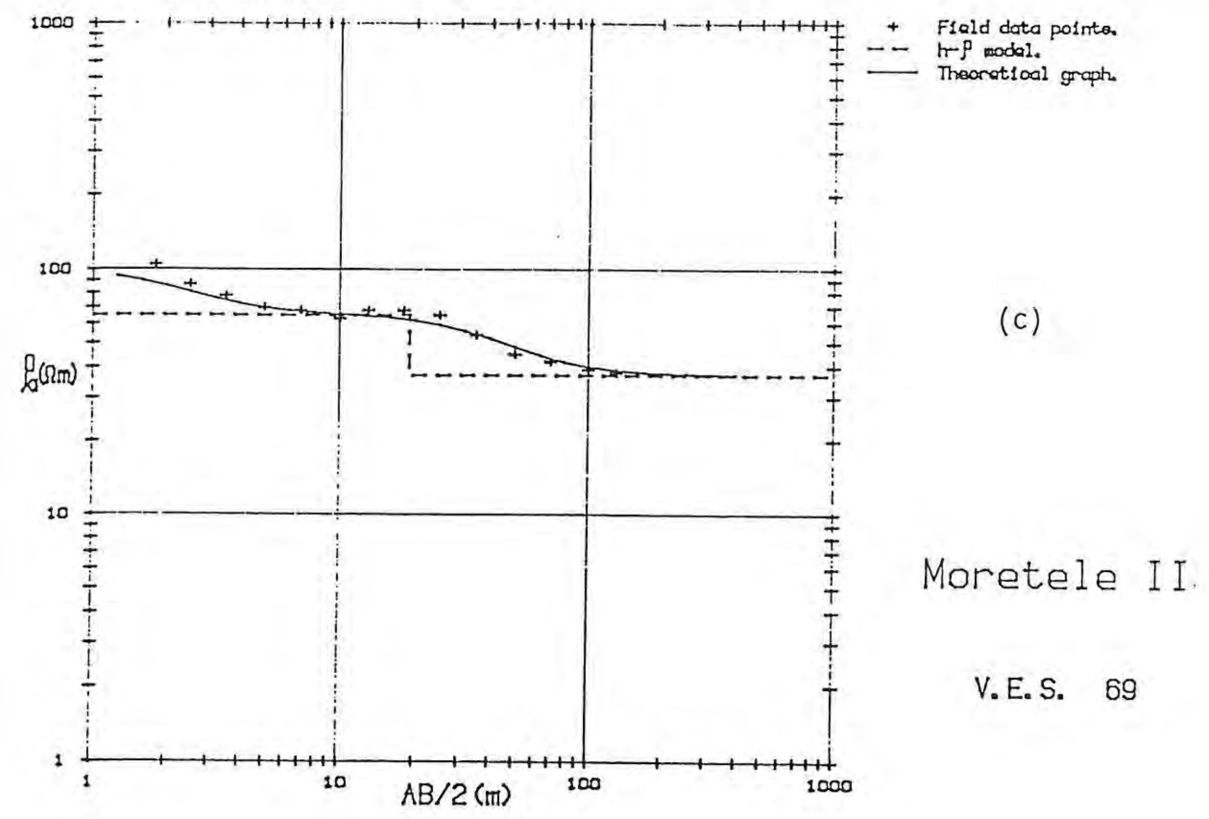


FIG. 9 EXAMPLES OF THREE-LAYER K TYPE (a) AND THREE-LAYER H TYPE (b) SOUNDING CURVES



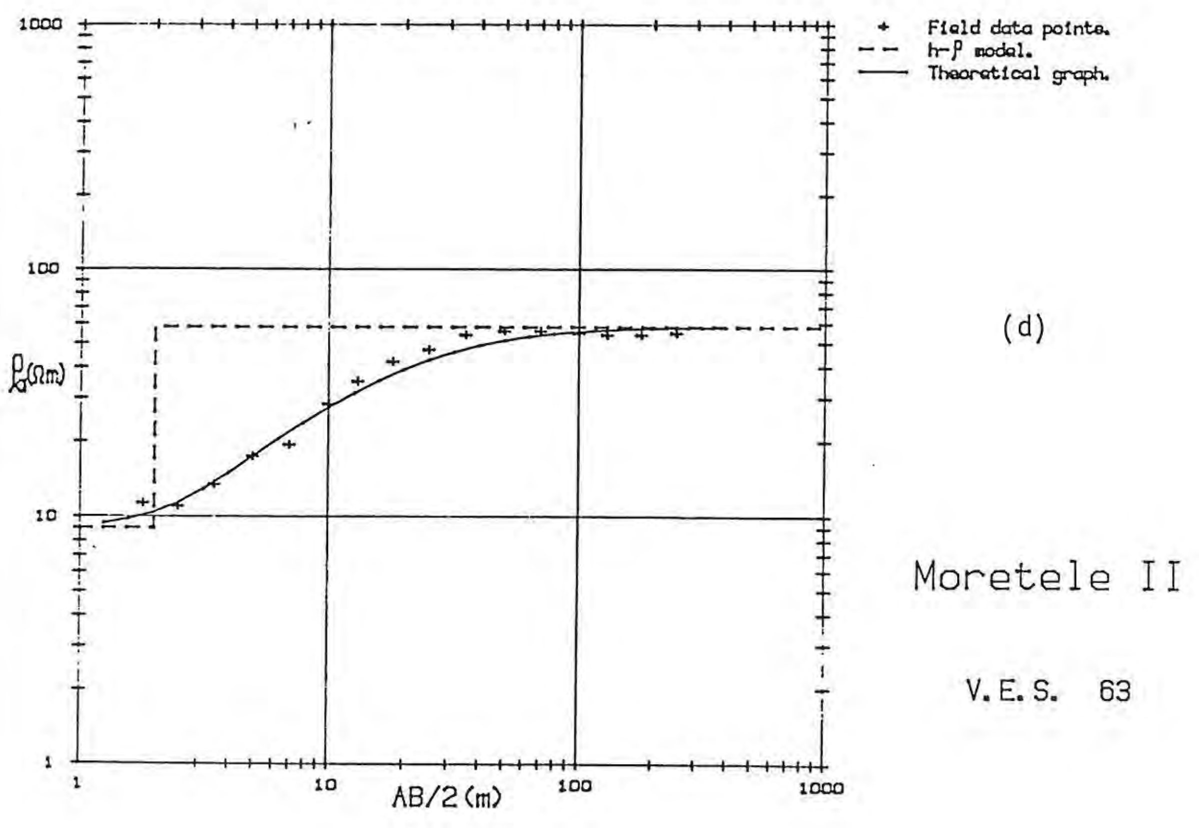


FIG. 9 EXAMPLES OF THREE-LAYER Q TYPE (c) AND TWO-LAYER K TYPE (d) SOUNDING CURVES

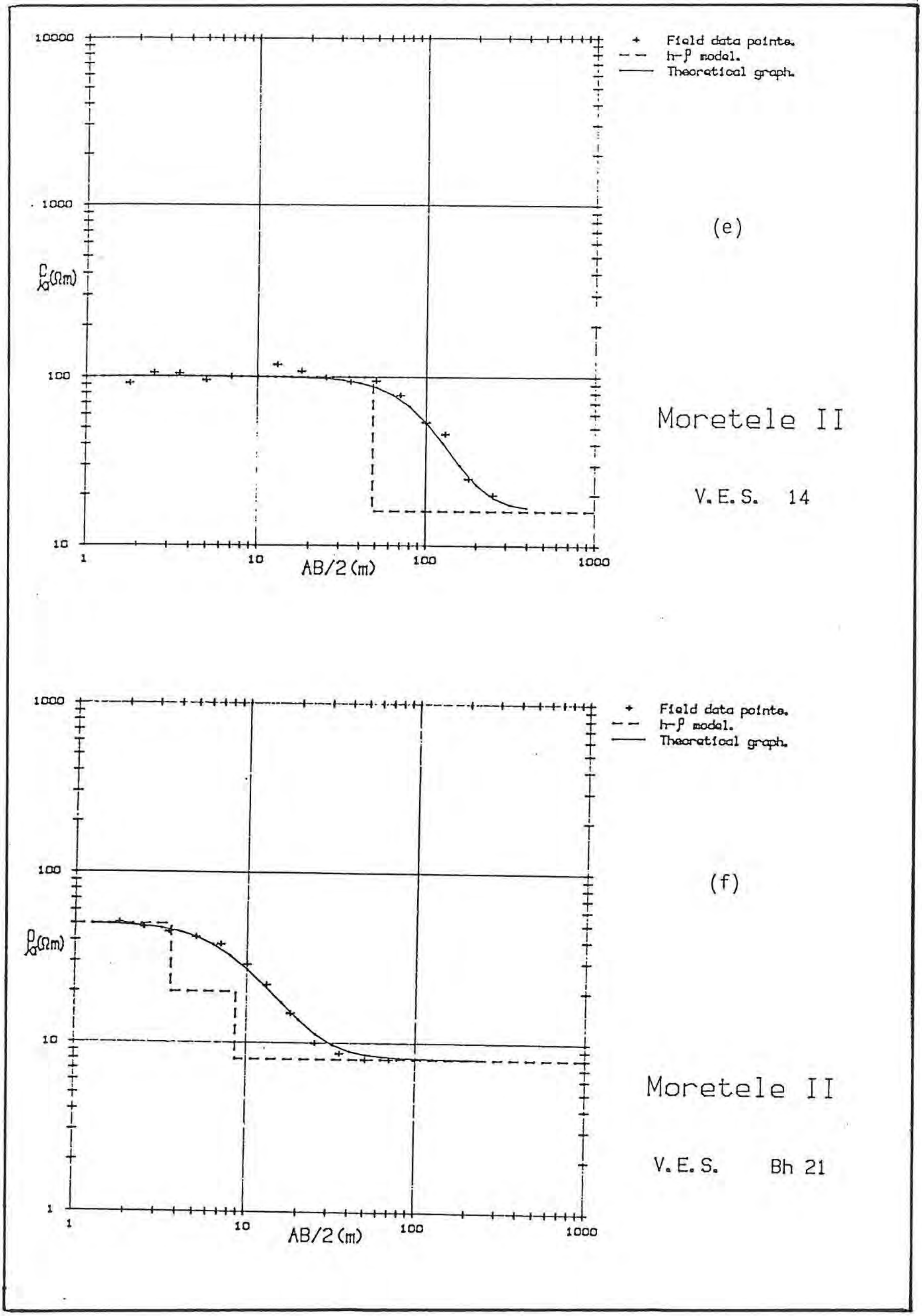


FIG. 9 EXAMPLES OF TWO-LAYER H TYPE (e) AND THREE-LAYER Q TYPE (f) SOUNDING CURVES

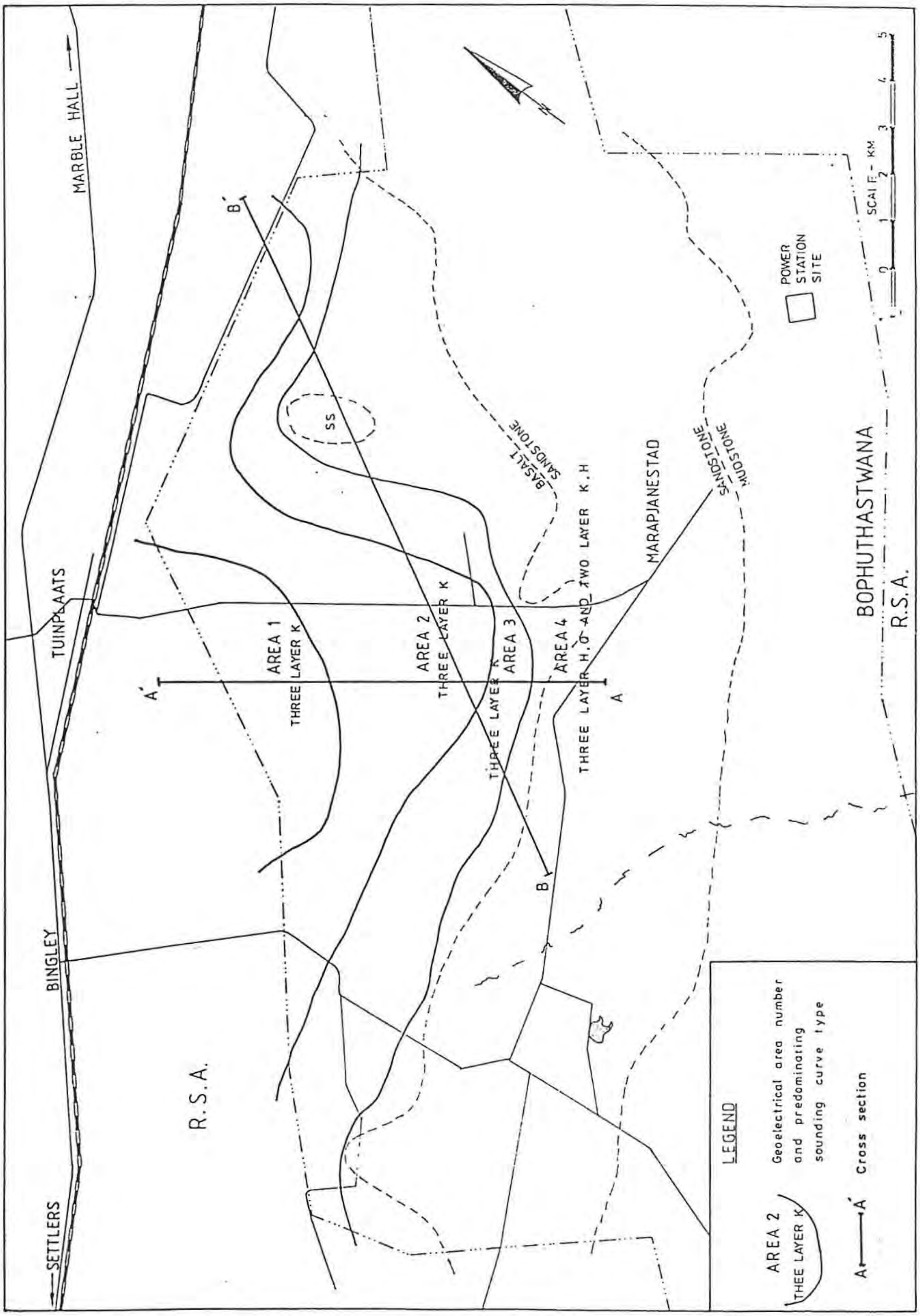


FIG. 10 DISTRIBUTION OF GEOELECTRICAL AREAS AND PREDOMINATING CURVE TYPES AND CROSS SECTION A-A' AND B-B'

geoelectrical areas of figure 10 are interpreted according to the geology.

The type curves of figure 9 (a) predominate in Areas 1,2 and 3. In all cases the basalt succession is manifested by a resistive second layer. The conductive third layer represents the underlying sandstone. The overlap between the basalt′s thickness and resistivity values (Table 3) in areas 3 and 4 can be explained by the presence of a basalt cover of variable thickness in both areas. Figures 9 (b),(c) and (d) are type curves mainly occurring in Area 4 where the sandstone is interpreted to be predominating. The second layer in figures 9 (b),(c) and (d) is attributed to a change in lithology within the sandstone. Either a decrease or increase in grain size or clay content could be responsible for the change. In Area 4, where a basalt cover of variable thickness is present, a type curve similar to figure 9 (e) is also obtained.

In all the curves, the resistivity range of the first layer varies between 3 and 200 ohm m. This variation is associated with the presence of either clay rich or mixed sandy soils respectively.

In all cases the thickness of the sandstone is interpreted to be infinite. This is due to the lack of resistivity contrast with the deeper underlying mudstone sequence which does not allow for the calculation of the sandstone thickness.

Only one sounding, at borehole 21 (Fig. 9 (f)) was carried out on the Irrigasie Formation. The curve is a three layer Q-type. The first layer, with a resistivity of 50 ohm m. is the top soil. The second conductive layer with a resistivity of 20 ohm m. is interpreted as a sandstone layer 9 m. thick. The flattening off at 8 ohm m. indicates the presence of the conductive argillacious unit of the Irrigasie Formation.

Using the calculated thicknesses and resistivity ranges and interpreted geological sequence, the vertical distribution of the basalt and sandstone is shown in figure 11 which are cross sections A-A′ and B-B′ of figure 10. Section A-A′ shows a thickening of the basalt towards the middle of the basin. Section B-B′ shows the uneven subsurface topography between the basalt and the sandstone. The sandstone is seen to suboutcrop in places.

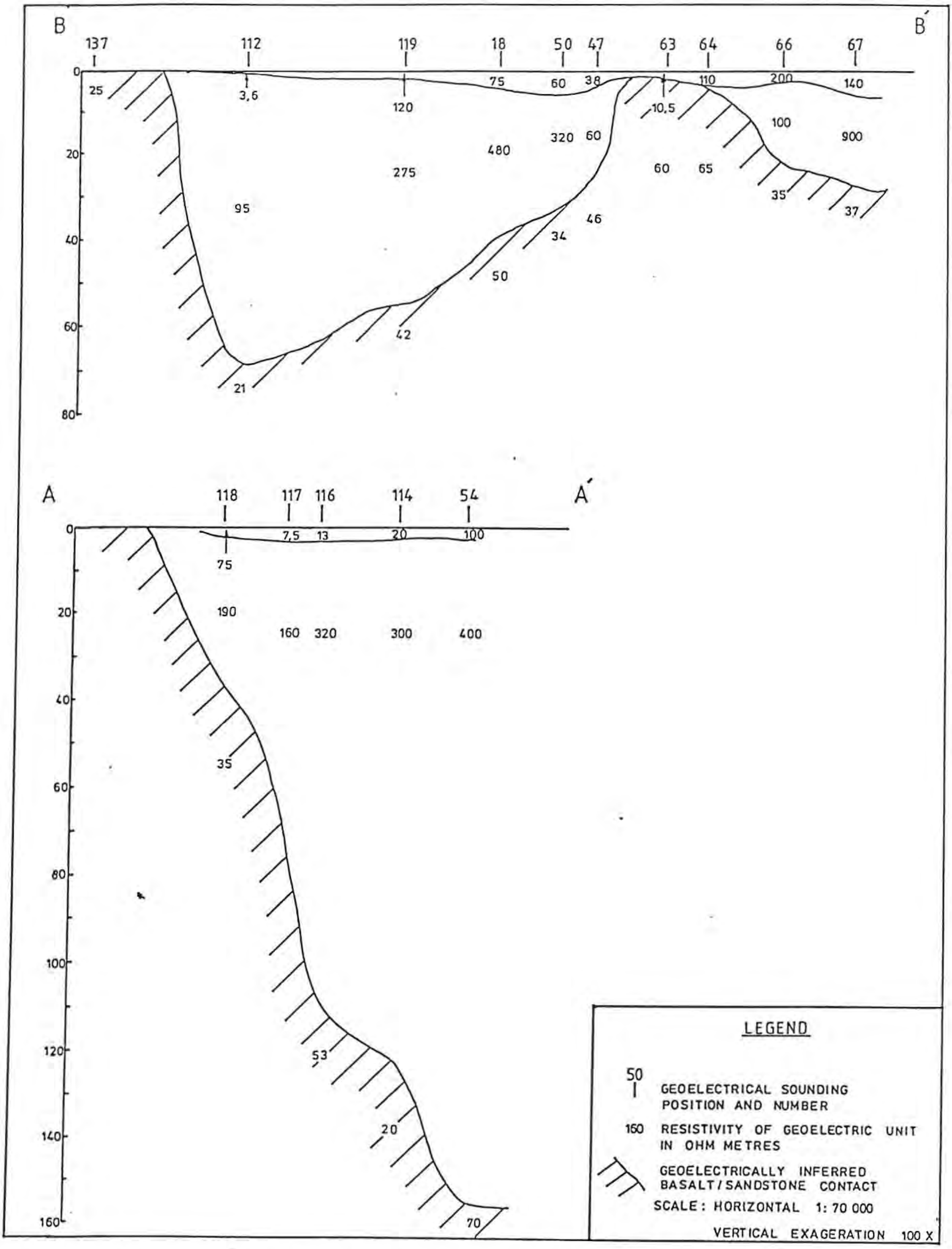


FIG. 11 GEOELECTRICAL CROSS SECTIONS A-A' AND B-B'

In general the resistivity of fresh rocks is in the order of several thousands ohm metres (Castany, 1966). A decrease in resistivity is usually associated with the chemical composition of the impregnating water, degree of saturation, the clay content and the presence of secondary features, such as porosity or fissuring (Lloyd, 1981). It is therefore possible to relate weathering and fracturing development to the resistivity of the various layers.

For this purpose Table 4 presents a simplified lithological/geoelectrical succession incorporating the interpreted geology, its weathering/fracturing development and resistivity range for each geoelectrical layer. Table 4 draws heavily upon the results of the drilling programme for the quantification of the resistivities of the various layers. Also included is the interpreted hydrogeological significance associated with the various layers using the limited geoelectrical data from E. Martinelli and Associates (1976 and 1977).

The large variation in resistivity values (25-500 ohm m.) obtained for the basalt succession, as seen in Table 4 and the four areas of figure 10, are related to variations in its weathering/fracturing development. This is indicative of the heterogeneous and anisotropic nature of this formation which is supported by the difference in the calculated thicknesses and resistivities obtained from cross soundings. Figures 12 (a) and (b) are soundings carried out next to borehole 10 in a N-S and E-W direction respectively. The effect of an heterogeneous and anisotropic medium will be the overestimation of the calculated thicknesses (Van Zijl, 1977). The position of the basalt/sandstone lower contact of figure 11 will therefore be affected (see figure 14 of Chapter 8). It should also be noted that the anisotropy of the medium also does not allow for the drawing of isopachytes for the basalt layer. In fact the thicknesses given in Table 3 are unevenly distributed throughout each area. As the main direction of anisotropy was not known, in order to minimize the effect of anisotropy and any possible lateral effect, the electrical soundings were carried out parallel to the strike of the formations, where physically possible, as suggested by Van Zijl (1977). The relatively narrow range in resistivities obtained for the sandstone succession (Table 4) is indicative of relatively more homogeneous conditions.

TABLE 4

INTERPRETED GEOELECTRICAL SUCCESSION

INTERPRETED LITHOLOGY	RESISTIVITY RANGE (ohm.m)	HYDROGEOLOGICAL SIGNIFICANCE
Top soil (genetically derived from the weathering of the basalt and/or sandstone)	3-200	Surface layer
Weathered or partly weathered/fractured basalt	25-250	Main aquifer
Poorly fractured basalt	250-500	Minor aquifer
Poorly weathered/ fractured fine grained sandstone	20-50	Minor aquifer and where infinitely thick becomes hydrogeophysical bedrock
Mudstone	3-5	Hydrogeophysical bedrock (Infinite conductor)

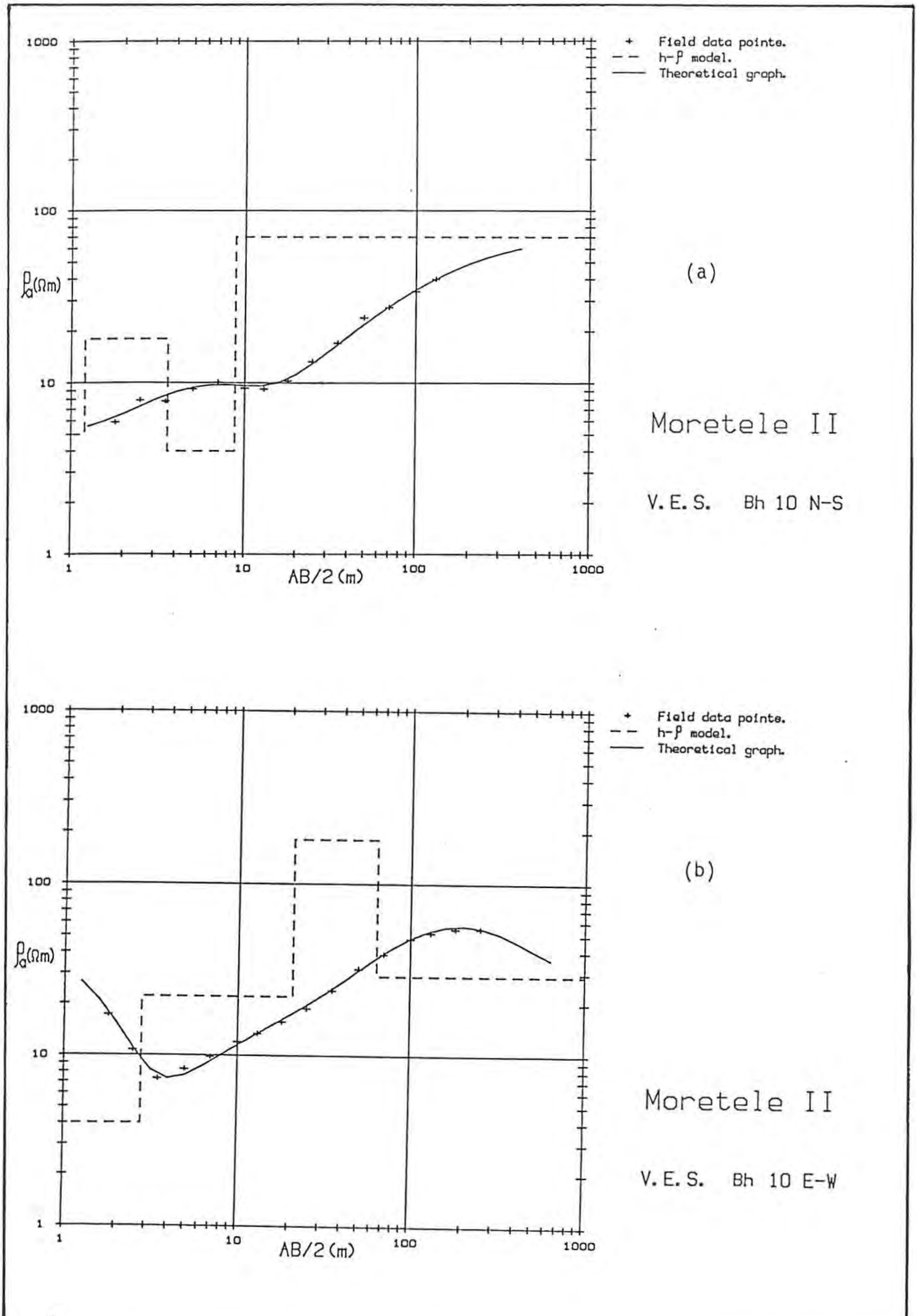


FIG. 12 CROSS SOUNDINGS AT BOREHOLE 10 IN A NORTH SOUTH (a) AND EAST WEST (b) DIRECTION SHOWING ANISOTROPIC BEHAVIOUR

7.4. Summary

The major points pertaining to the above presentation and the results of the geoelectrical survey are;

- The geoelectrical survey results, using the Schlumberger sounding method, provided a preliminary simple geological model of the area without resorting to costly drilling.
- The basalt is interpreted to be heterogeneous and anisotropic and four areas of differing geoelectrical response are recognized.
- The degree of weathering/fracturing development within the basalt is variable.
- The sandstone is interpreted to be relatively homogeneous and poorly weathered/fractured.
- The anisotropic nature of the basalt has manifested itself in the overestimation of the geoelectrically interpreted thicknesses of the basalt sequence.

To interpret quantitatively the geophysics, it is necessary to employ the drilling results. The following Chapter details the drilling programme carried out and in particular highlights these results in terms of the geoelectrical survey's interpretation and the ground water development potential of the basalt and sandstone units.

8. THE DRILLING PROGRAMME

The project involved the drilling of an aggregate depth of more than 3 Km. Brown et al. (1972) states that "each drilling method is particularly suited for drilling in some materials and not in others". The consolidated nature of the basalt and sandstone formations favoured the choice of the down-the-hole air percussion drilling method (Chiesa, 1981). The lack of circulation losses in these formations with this method results in fast and efficient drilling operations (Campbell and Lehr, 1973). With this method high quality hydrogeological information is obtained. For instance, from the drill cuttings the different lithologies are easily recognized and the lack of circulation fluid allows for the estimation of the positions and blowing yields of water strikes.

The drilling of the exploratory boreholes was carried out to:

- gather information on the subsurface distribution of the different lithologies.
- provide control information for the geophysical data
- give an indication on the types of aquifer(s) present
- provide a point from which aquifer testing can be executed.

8.1. Results of the Drilling Programme

During drilling, all pertinent geological and hydrogeological data were assessed and recorded. This included lithology, depth of water strike(s), weathering/fracturing distribution and development, estimation of the intersected yield(s) and water level(s). A summary of the drilling results is given in Table 5. Borehole positions are shown in figure 13.

No. of exploratory boreholes: 41
No. of observation boreholes: 9
Drilled in the basalt: 2174 m.
Drilled in the sandstone: 930 m.
Total meters drilled (including obs. boreholes): 3104 m.

TABLE 5 : SUMMARY OF DRILLING PROGRAMME

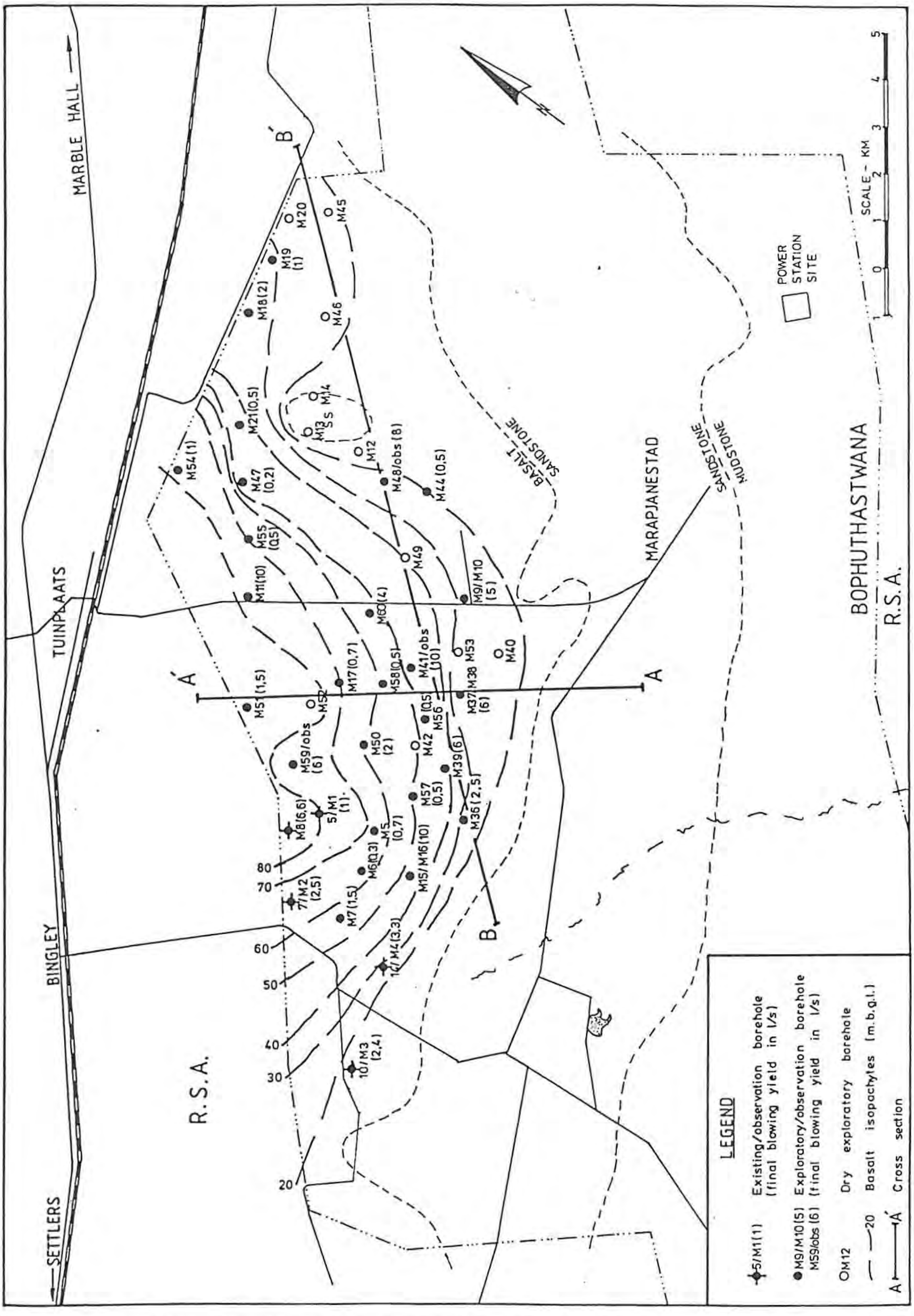


FIG. 13 POSITIONS OF EXPLORATORY BOREHOLES AND DISTRIBUTION OF BASALT ISOPACHYTES

Boreholes M1,2,3, and 4 were drilled next to high yielding existing boreholes (Fig. 13) and were used as observation boreholes. The remainder of the observation boreholes were drilled next to exploratory boreholes which intersected a blowing yield of more than 5 l/s. Each observation borehole was drilled to the same depth and 10 m away from the exploratory borehole.

During the drilling of observation boreholes M1 and M3, recorded blowing yields were far less than the reported discharges of 5 and 11 l/s for existing boreholes 5 and 10 respectively. The discrepancy in yields is due to the missing of the narrow fracture zone intersected by the existing boreholes. The presence of these discrete fracture zones are associated with the high anisotropy of the medium.

All boreholes penetrated the full basalt sequence. The sandstone was drilled to a minimum depth of 10 m. below the contact. This was to ensure the intersection of any fracture zone that could occur below the contact and to avoid boreholes only partially penetrating the aquifer.

In all cases the top collapsing overburden was cased off. Where the formation was found to be collapsing at or below the water strike, slotted casing was inserted. All boreholes have a six inch open hole final construction.

The findings of the drilling programme did not alter the surface distribution of the basalt and sandstone, based on surface data, as shown in figure 3. Instead the drilling results provided useful information for the interpretation of the geoelectrical data. The isopachytes for the basalt sequence, which due to the anisotropy of the medium, could not be drawn using the geoelectrically calculated thicknesses, are included in figure 13. The isopachytes reflect a relatively homogeneous subsurface thickening of this sequence towards the middle of the basin.

The vertical distribution of the basalt and sandstone is shown as cross sections A-A′ and B-B′ (Fig. 14). The thickening of the basalt towards the middle of the basin and the slightly irregular surface over which the basalt was deposited is noted in Section A-A′. This distribution compares well with the interpreted geophysics (cross section A-A′, Fig. 11).

In area 4 (Fig. 10) the basalt was interpreted to be less than 30 m and in places absent alltogether (Cross section B-B′, Fig. 11). The findings of boreholes M12, M13 and

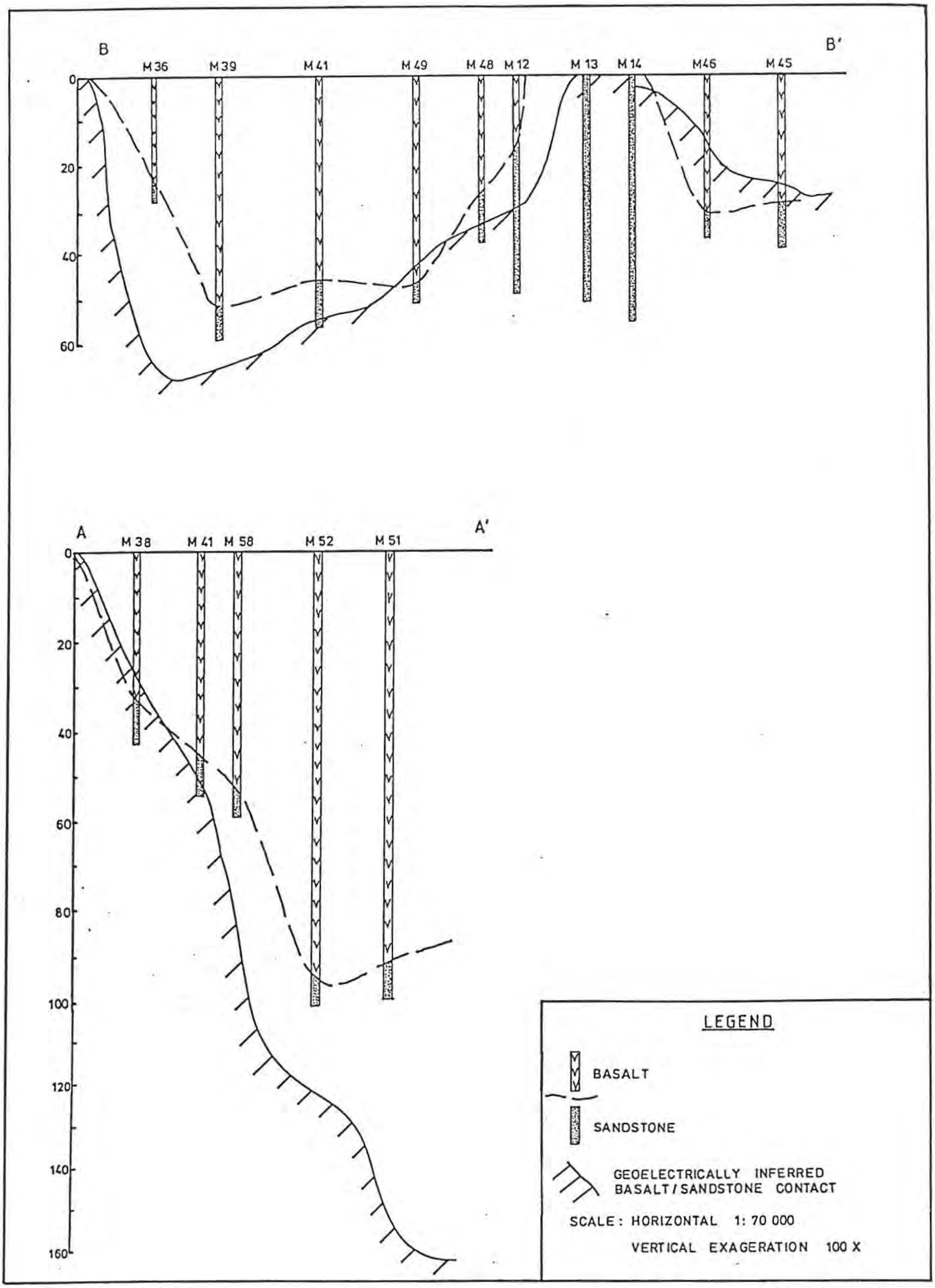


FIG. 14 CROSS SECTIONS A-A' AND B-B' SHOWING VERTICAL DISTRIBUTIONS OF THE BASALT AND SANDSTONE FORMATIONS WITH SUPER IMPOSED GEOPHYSICAL INTERPRETATION OF THE BASALT AND SANDSTONE CONTACT

M14 (Cross section B-B´, Fig. 14) confirm the predominance of the sandstone sequence.

The depths to the basalt/sandstone contact measured during drilling (Fig. 14) confirmed the presence of the strong geoelectrical anisotropy as suggested in Chapter 7 (Section 7.3). The effect of anisotropy is responsible for the difference in the position of the contact as illustrated by comparing the cross sections A-A´ of figures 11 and 14 respectively. Indeed in some boreholes the discrepancy between the measured and the geoelectrically interpreted depths of the contact was out by up to 100% in places.

The drilling results provided calibration data for the drawing up of the resistivity ranges of Table 4. The degree of weathering/fracturing development was noted. The high resistivities of areas 1 and 2 show that these areas possess a marginal ground water development potential. Poor fracturing was in fact found in boreholes M51 and M52. Throughout these two areas and area 3 the basalt sequence was found to be variably weathered and fractured. Where the basalt was interpreted to be thinly developed i.e. area 4 of figure 10, boreholes mostly penetrated the sandstone sequence. Here weathering/fracturing development was lacking. Indeed, boreholes M12, M13 and M14 (Fig. 13 and 14) were completely dry.

Blowing yields ranged from 0,2 to more than 10 l/s. This wide variation is indicative of anisotropic groundwater occurrence. A total of 11 (30%) exploratory boreholes are completely dry. The distribution of the blowing yields is illustrated in figure 13.

The main water bearing horizon was found to be associated with fracturing development within the basalt above the contact. The presence of this contact could not be geoelectrically detected. The suppression of this layer is due to its depth and relative small thickness which varied between 1 and 4 m. The presence of these narrow fracture zones is related to the process of differential cooling between the basalt and the underlying sandstone (Section 2.2.2).

Water bearing horizons only within the basalt were intersected in M5 and M6. In boreholes M3, M7 and M8 water strikes were recorded both within the basalt as well as at the contact. As weathering/fracturing is known to develop at the contact between lava flows (Brown et al., 1972), it is suggested that the presence of these strikes within the basalt in this particular area are associated with the protrusion of a lava flow. This suggestion is in contrast with Truswell´s observations of sub-section 2.2.1. but confirms Blume´s (personal communication, 1985) comment of sub-section 2.3.1. The geoelectrical method could not detect the presence of these weathered/fractured horizons due to the lack of resistivity contrast and their thin development.

The measurement of the water levels at each water strike provided useful information in determining the type of aquifers present. In all the boreholes the recorded water level rose above the strike position thus indicating that the aquifers are subject to confining pressures (Chiesa, 1981). The similarity in water levels recorded in M3, M7 and M8 after each water strike indicates a hydraulic continuity between the water bearing zone within the basalt and the lower contact aquifer.

8.2. Summary

The drilling data gathered during this phase of the study confirmed the relatively simple distribution of the lithologies as intrepreted by geoelectrical means. The variable nature of both the occurrence and yields intersected is a reflection of the anisotropy of the basalt. The main water bearing zone was found within the basalt above the contact with the sandstone. The hydrualic performance of this water bearing zone will be assessed in the following Chapter.

9. TEST PUMPING PROGRAMME AND AQUIFER HYDRAULICS

The formulation of the correct test pumping programme is done with the aim of determining the general hyrogeological characteristics from test pumping data obtained. More specifically the purpose of a test pumping programme is to determine one or more of the following.

a) the aquifer parameters transmissivity (T) and storage coefficient (S) which assist in the evaluation of the groundwater resources abd development potential of an area. These parameters determine the ability of the aquifer to transmit and store water.

b) to determine the existence of recharge/barrier boundaries which, if present, affect long term performance of the borehole.

c) to determine the long term pumping rate and associated drawdown of a particular borehole (Hazel, 1976).

In order to satisfy the above objectives a test pumping programme was formulated and carried out on both the existing and exploratory boreholes. Two types of aquifer tests were applied. These are the step drawdown and constant discharge test. Completion of each of these tests was followed by a water level recovery period. On the existing boreholes, only a constant discharge test was performed. On the successful exploratory boreholes a step drawdown test preceeded the constant discharge test.

9.1. Principles of Aquifer Test Analysis

9.1.1. Constant Discharge Tests

The determination of hydraulic parameters from constant discharge test data is restricted to those analytical techniques utilized during this particular investigation. The discussion is concerned largely with the analysis of pumping and recovery data in the non steady-state for fully penetrating boreholes under confined conditions. As these methods are largely documented (Davies and De Wiest, 1966; Walton, 1970; Kruseman and De Ridder, 1970; Custodio and

Llamas, 1976), it is sufficient to state that for boreholes where observation data are lacking, analysis is carried out by applying the Cooper-Jacob (1946) approximation to the Theis (1935) equation. This solution allows for the determination only of T values according to the following equation:

$$T= \frac{0,183\ Q}{\Delta s} \qquad ...(1)$$

where

Q=Discharge (m^3/d)
Δs=Residual drawdown per log cycle (m)

The recovery data is also analysed using the above approximation.

Where observation data are available the Theis type curve solution is applied to calculate T and S values for the drawdown and recovery phases. The equations:

$$T= \frac{Q}{4\pi s}\ W(u) \qquad ...(2)$$

$$S= \frac{4Ttu}{r^2} \qquad ...(3)$$

are solved using a graphical solution devised by Theis (1935) for curve matching.

As a check to the Theis method, T and S values were calculated using the modified Jacob straight line solution (Jacob, 1947) according to:

$$T= \frac{0,183\ Q}{\Delta s} \qquad ...(4)$$

$$S= \frac{2,25Tt}{r^2} \qquad ...(5)$$

where

$u=r^2S/4Tt$ and r=distance to the observation well (m)

The applicability of this latter method is subject to the same assumptions and conditions as the Theis method as well as the values of u must be <0,01. Custodio and Llamas (1976) consider values of u up to 0,1 to be valid.

The equations of groundwater flow mentioned above are based on the assumption that the aquifer is of infinite areal extent. However, hydraulic barrier boundary conditions are known to occur in these aquifers (E. Martinelli and Associates, 1977; Martinelli and Hubert, 1980; Page 14). The high anistropic conditions found during drilling tend to support the findings of E. Martinelli and Associates (1977) and Martinelli and Hubert (1980). In the presence of these conditions the data are analysed using equations based on the image theory.

Stallman (1963) devised a type-curve method for the solution of single boundary problems associated with confined aquifers. Parameters T and S are evaluated according to equations:

$$T=\frac{Q}{4\pi s_0} W(u_r)+W(u_i) = \frac{Q}{4\pi s_0} W(u_o) \qquad ...(6)$$

$$S=\frac{4Ttu_r}{r_r^2} = \frac{4Ttu_i}{r_i^2} \qquad ...(7)$$

where r_r is the distance from the observation borehole to the pumped well and r_i is the distance from the observatioon borehole to the image well. The position of the boundary is defined as been $(r_i+r_r)/2$ distant from the pumped well in a line which passes through the observation borhole.

9.1.2. Step Drawdown Tests

The drawdown in a pumped well comprises two components, an aquifer loss and a well loss. Aquifer loss is caused by the need to overcome the resistance to laminar flow within the formation itself. Well loss, or non-linear head loss, arises from the resistance to turbulent flow in and around the borehole, and may be assumed constant for a particular discharge rate.

Consequently, the evaluation of a single-well pumping test data using methods which assume laminar flow only will lead to an erroneous interpretation if non-linear head losses are present.

The above components are evaluated from step drawdown test data. The total drawdown during a step test is expressed as (Rorabaugh, 1953);

$$s=BQ + CQ^n \qquad ...(8)$$

where BQ is the aquifer loss, CQ^n is the well loss.

Brereton (1979) stated that there has been protracted debate over the value of n. Clark, (1977) maintains that always the value of n=2. Custodio and Llamas (1976) developed from the basic equation (8) a simplified type curve solution which is used here to calculate the above components and in particular the value of n.

The detemination of well losses is important in the determination of the efficiency of the borehole. Efficiency is defined as the percentage ratio between the theoretical and the real drawdown. During linear flow, the efficiency of the borehole is constant, but decreases as the discharge is increased and turbulent flow begins. The discharge at which turbulent flow sets in is known as critical discharge (Custodio and Llamas, 1976).

9.2. Discussion of Test Results

When analysing test pumping data the local geological and hydrogeological conditions should be known as precisely as possible. In the case of the existing boreholes the aquifer behaviour is inferred from the trends of the plot. For the newly drilled boreholes, where sound geological and hydrogeological data is available, the analysis of the test data and subsequent interpretation of aquifer behaviour was made with a higher degree of confidence.

The validity of traditional analytical methods to fractured media has been questioned by several authors (Brown et al., 1972; Custodio and Llamas, 1976). In particular the hydraulic characteristics of fractured aquifers in the vicinity of the borehole has been found to be inconsistent (Eagon and Johe, 1972). However, the general hydraulic conditions of the aquifers assume a homogeneous character when the fractures are in large numbers and well connected over a wide area (Uhl and Sharma, 1978). Furthermore, such media are considered to be homogeneous after a sufficiently long period of pumping (Gringarten and Witherspoon, 1972). According to Brown et al. (1972) a "sufficient number of tests" are needed for a reliable determination of the hydraulic parameters obtained. The data are therefore analyzed bearing in mind the above constraints of the methods applied.

9.2.1. Existing Boreholes

During the field census, ten of the boreholes with the best reported yields were selected for test pumping. The tested boreholes were chosen to sample the hydraulic behaviour of the various geologies. Early failure of borehole 13 (Table 6) necessitated the inclusion of another borehole (16). Drawdown measurements were taken only in the pumping borehole. Details of the testing programme and the calculated transmissivity values are summarized in Table 6.

Borehole No.	Test Duration (hrs) Discharge Phase	Recovery Phase	Discharge (1/s)	Transmissivity (m2/d) Discharge Phase	Recovery Phase	Average
1	100	1	1,3	50	70	60
5	100	5	4,2	600	1200	900
6	100	5	0,9	20	-	20
10	100	5	7	300	300	300
11	100	3,5	1,3	400	510	450
13	6	5	0,3	0,6	1,8	1,2
14	100	5	0,7	15	10	12
15	100	5	3	3	1	2
16	100	5	0,4	10	6	7
21	100	5	0,4	0,7	1,6	1
22	100	1,5	0,9	2	7	5

TABLE 6 : HYDRAULIC PARAMETERS-EXISTING BOREHOLES

Average T values obtained from boreholes situated on the basalt outcrop (Fig. 6) range from 1 m^2/d to 600 m^2/d. The higher values are possibly associated with boreholes intersecting the fracture zone at the contact. Lower T values are calculated for the boreholes on the sandstone outcrop. These range from 0,7 m^2/d to 17 m^2/d. Borehole 21 situated on the mudstone outcrop has an average T value of 1 m^2/d.

Examples of typical and anomalous responses to pumping of boreholes are discussed below. The remaining plots which show similar responses to the ones discussed here are included in Appendix A.

For the pumping boreholes the plots are of drawdown versus pumping time for the pumping phase and residual drawdown versus the ratio t/t' (where t=total pumping time and t'=total time since pumping ceased) for the recovery phase.

Where observation data is available the plots are drawdown versus pumping time for the pumping phase and recovery versus time since pumping ceased for the recovery phase.

A typical example of an areally extensive aquifer is shown by the early drawdown data of borehole 5 (Fig. 15). The steepening of the drawdown curve after 400 minutes would indicate the presence of an hydraulic barrier boundary. However it is suggested that a decrease in transmissivity is the result of the presence of a "pseudo" barrier. The trend of the residual drawdown curve is towards complete recovery (Fig. 15). The high transmissivity values (Table 6) reflect groundwater flow controlled by extensive fracturing. Similar aquifer behaviour is seen in boreholes 1, 10, 11, 14 and 16 (Figs. A1 to A5 of Appendix A).

The drawdown phase of borehole 6 (Fig. 16) shows an initial response of an extensive aquifer similar to borehole 5. After 1000 minutes of pumping a sudden steepening of the drawdown curve is noted. The lowering of the

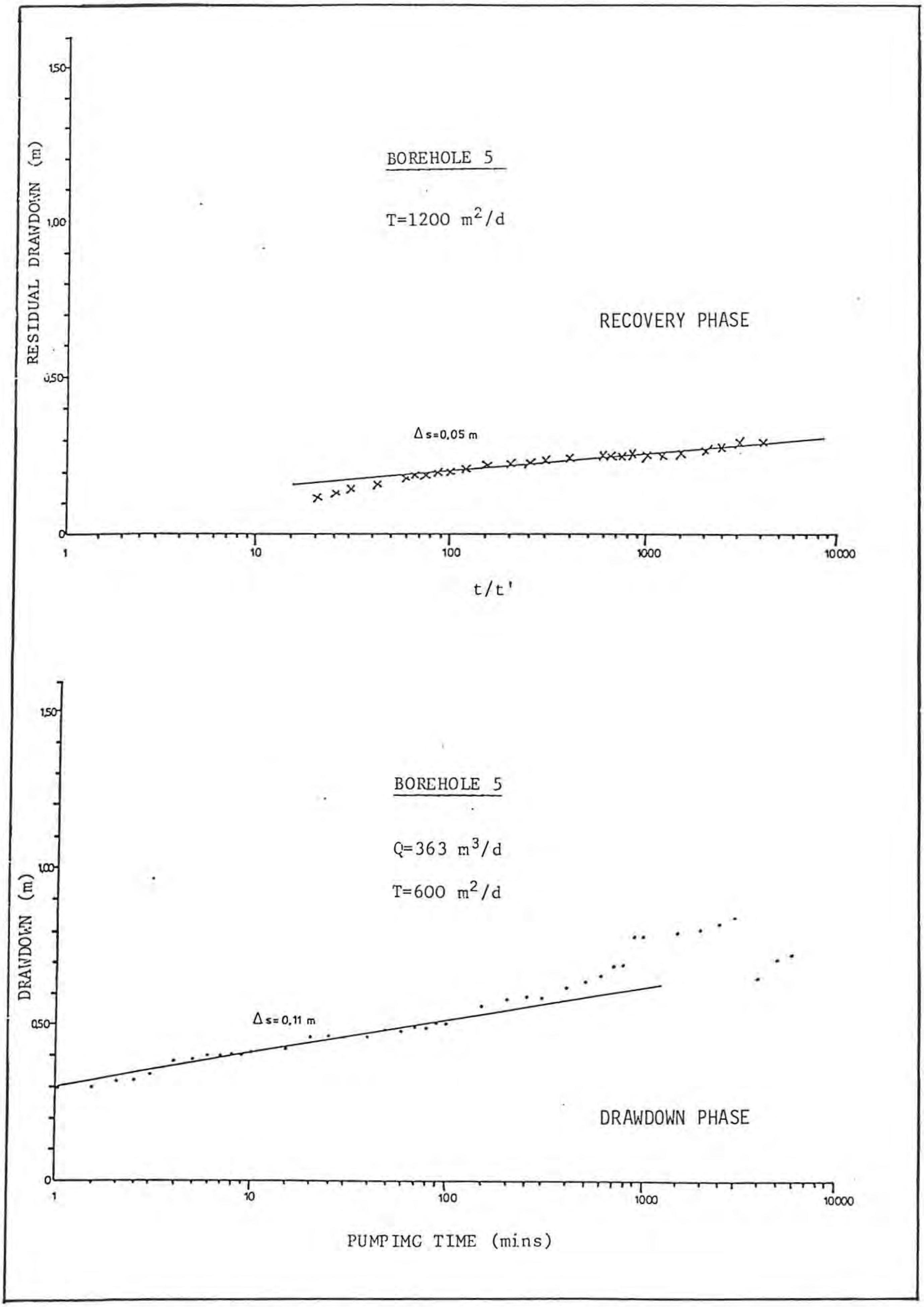


FIG. 15 DRAWDOWN AND RECOVERY DATA FOR BOREHOLE 5

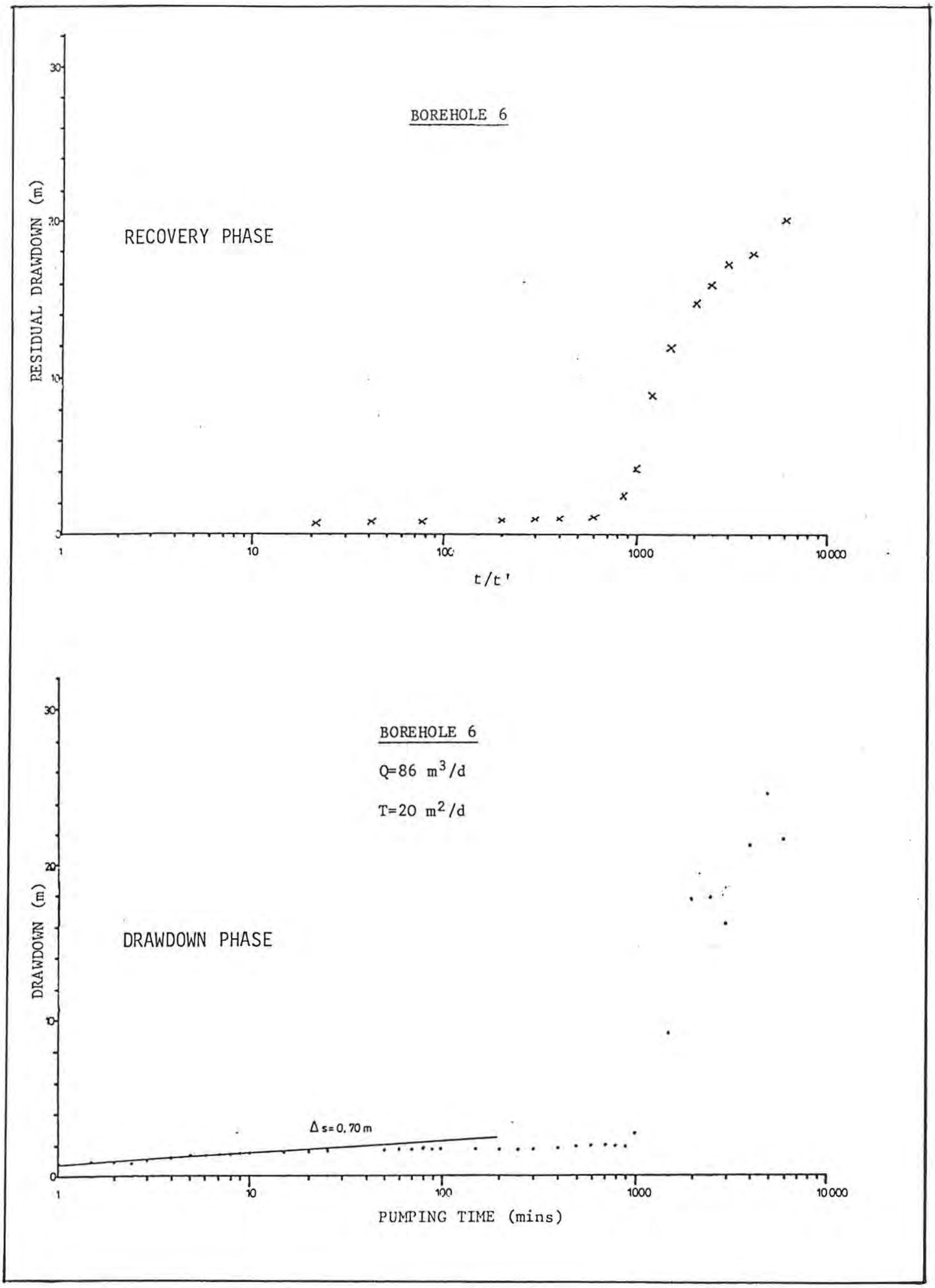


FIG. 16 DRAWDOWN AND RECOVERY DATA FOR BOREHOLE 6. STEEPENING AND SCATTERING OF DRAWDOWN DATA DUE TO DYNAMIC WATER LEVEL REACHING THE BASE OF THE WATER BEARING ZONE

dynamic water level below the base of the water bearing zone has resulted in the point scatter and steepening of the latter part of the curve. The water bearing fracture zone is approximately 2 m. wide. No dewatering of the frature has occurred as the trend of the residual drawdown curve points to complete recovery (Fig. 16). The low T value is evidence of a poorly developed fracture zone. Borehole 5 is situated only 1 km from borehole 6 (Fig. 6). The difference in their hydraulic behaviour is further evidence of anistropic groundwater flow conditions. A transmissivity value for the recovery phase could not be calculated due to the scarcity of early data points (Fig. 16).

Figure 17 is the plot of the drawdown phase from borehole 21. The drawdown points clearly shows a flattening off after 600 minutes of pumping which might indicate the presence of leakage. The jump of the drawdown curve after 1000 minutes is attributed to the dewatering of a fracture situated at about 30 m. below the static water level. The trend towards incomplete recovery (Fig. 17) suggests that the aquifer is areally limited and that dewatering has occurred. The low T values (Table 6) are representative of poorly developed transmissive properties. Other examples of areally limited aquifers possessing poor transmissing properties are illustrated in figures A6 and A7 (Appendix A).

9.2.2. Exploratory Boreholes

9.2.2.1. Without Observation Data

Each of the 20 exploratory boreholes were test pumped for a 10 day period. In addition three existing boreholes (5, 10 and 14) were also tested. This was due to the high yields obtained during the previous testing programme (Table 6) and their potential to be included in the final wellfield. Details of the testing programme where no observation data was available are summarized in Table 7. Included in Table 7 are T values calculated using the modified Cooper-Jacob solution.

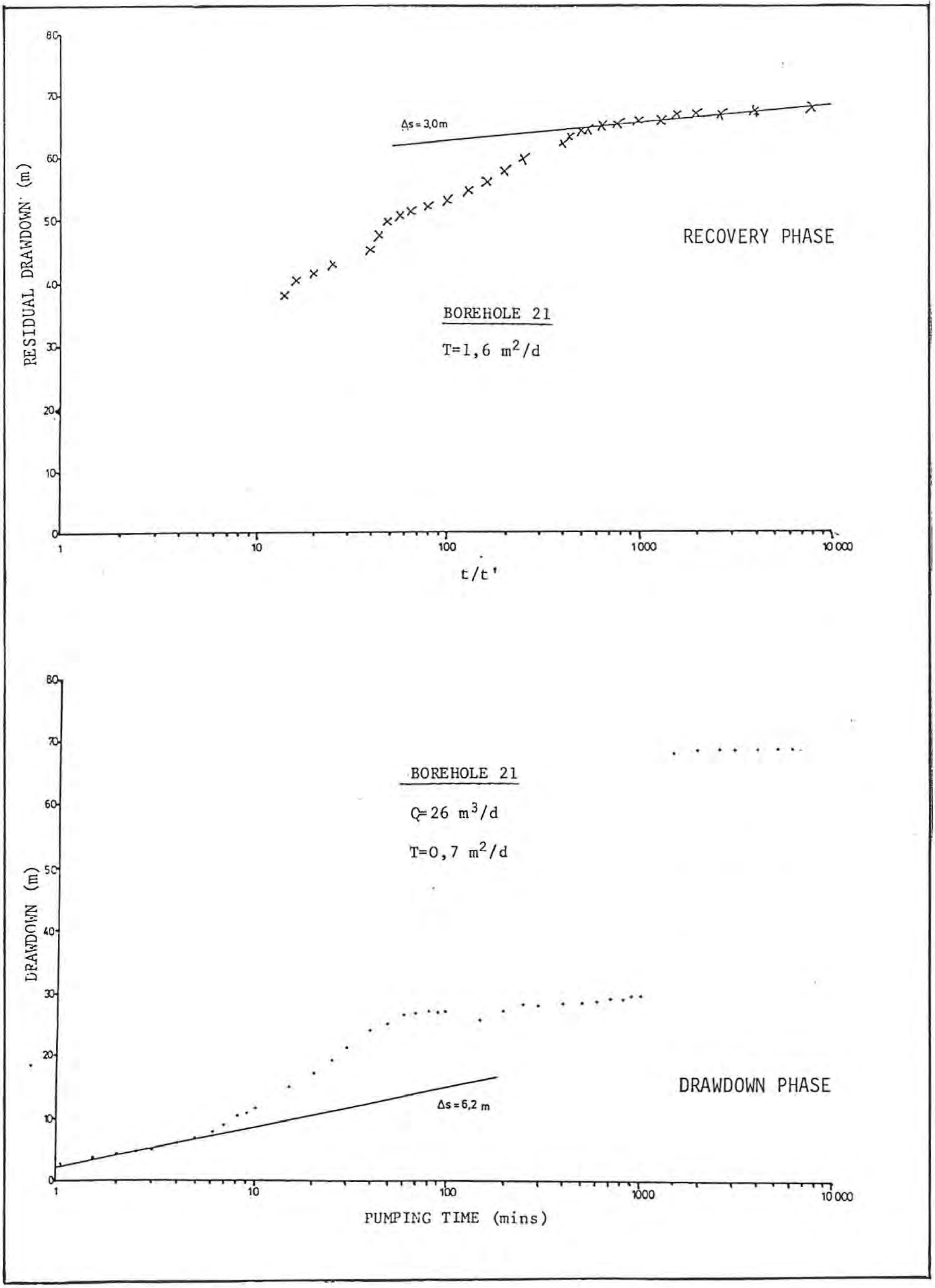


FIG. 17 DRAWDOWN AND RECOVERY DATA FOR BOREHOLE 21 SHOWING DEWATERING OF THE FRACTURE ZONE AFTER 1000 MINUTES. PUMP SUCTION WAS REACHED AFTER 1000 MINUTES

Borehole No.	Test Duration (hrs) Discharge Phase	Recovery Phase	Discharge (l/s)	Transmissivity (m^2/d) Discharge Phase	Recovery Phase	Average
M 2	240	212	1	2	2	2
M 5	240	10,7	2,5	25	-	25
M 8	240	23	7,3	75	70	73
M11	240	96	3	140	-	140
M18	240	16	0,8	3	2	3
M21	240	2	1	3	-	3
M36	240	770	5	260	100	180
M39	240	793	7	100	150	125
M44	240	25	1	50	-	50
M50	240	504	1,1	0,7	0,6	0,7
M51	240	47	1	0,8	0,8	0,8
M54	175	0,25	1,9	30	-	30
M60	240	3,3	1	3	1,5	2

TABLE 7 : HYDRAULIC PARAMETERS-EXISTING AND EXPLORATORY BOREHOLES WITHOUT OBSERVATION DATA

The average T values range from 0,7 to 180 m^2/d. All the tested boreholes are situated within the basalt outcrop (Fig. 13). The variation in T values is associated with the anisotropic conditions of the formation.

Examples of typical and anomalous responses to pumping are discussed below. The remaining plots which show similar responses to the ones discussed are included in Appendix A.

The drawdown phase for boreholes M8 is depicted in figure 18. The trend of the drawdown curve is towards an equilibrium between drawdown and time thus indicating that the aquifer around this borehole is areally extensive. During drilling two water strikes were recorded. One within the basalt (2,5 l/s) and the other at the contact (4,1 l/s). If the dynamic water level had been drawn below the first water strike, conditions would have been suitable for leakage to occur. However, this situation was not achieved. The tendency of the residual drawdown curve is towards complete recovery (Fig. 18). The relatively high T (70 m^2/d) value indicates that the degree of fracturing

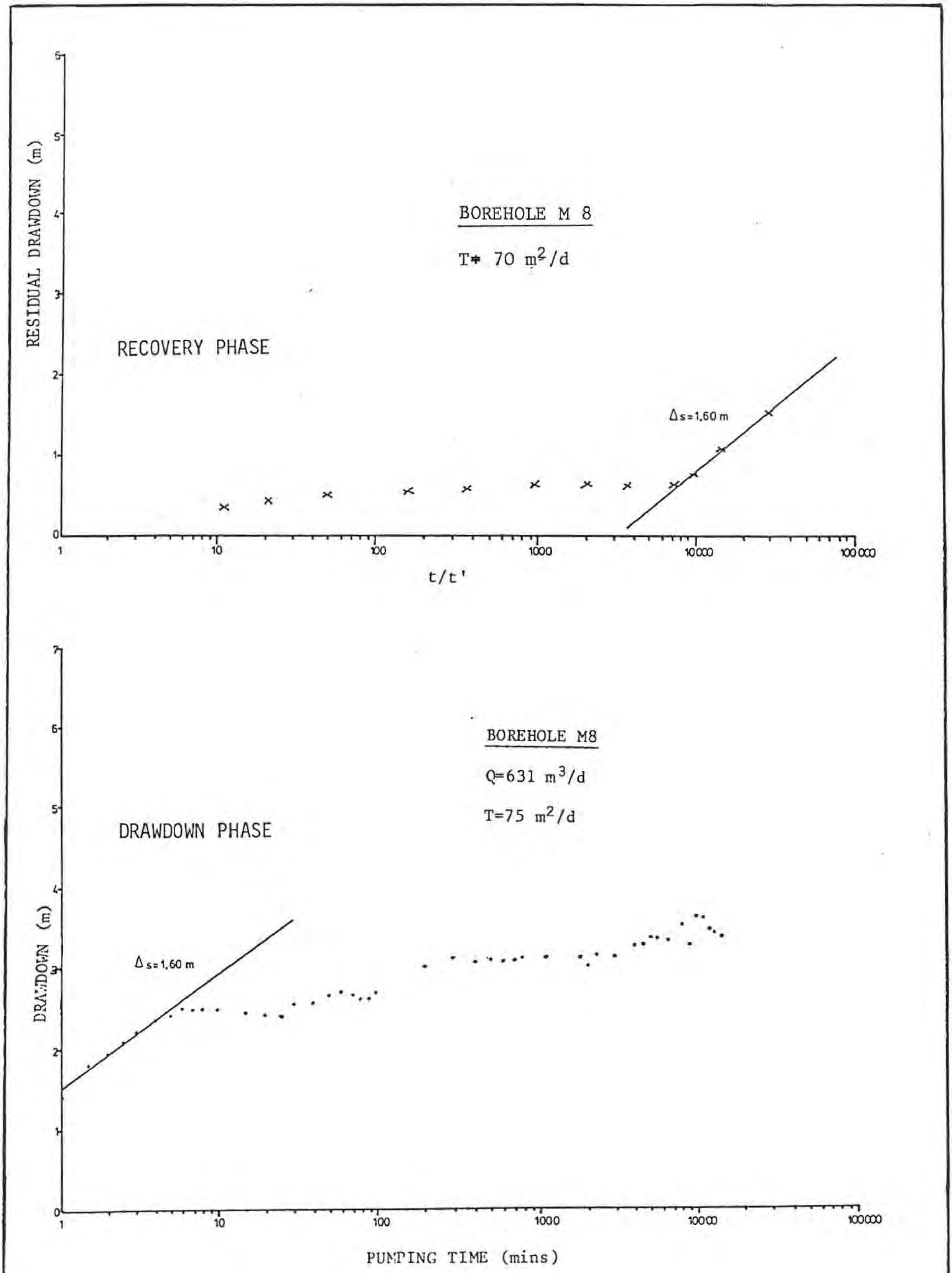


FIG. 18 DRAWDOWN AND RECOVERY DATA FOR BOREHOLE M8

is well developed. This T value could also represent the average T of the two water bearing zones.

Other responses of extensive aquifers are plotted in figures A8 to A17 (Appendix A). In some cases, however, the water level did not stabilize. A change in transmissivity related to anisotropy, which would give rise to "pseudo" barrier boundary, could be responsible for this effect. The trends of all the residual drawdown curves are towards complete recovery and indicate areally extensive aquifers.

Figure 19 (borehole M11) shows a steepening of the discharge curve after 20 minutess of pumping. The pumping rate was lowered after 2000 minutes with no effect on the drawdown trend of the curve. This linear increase in the drawdown slope is caused by the effect of true barrier boundary conditions. During the recovery phase the lack of total recovery shows that severe dewatering has occurred (Fig. 19). Drilling records show the intersection of three main water strikes. The last of these was recorded as occurring within a large cavity. The relatively high T value of 140 m^2/d is indicative of a "false" transmissivity associated with the intersected cavity. The limited areal distribution of this cavity is seen by the dewatering effect (Fig. 19). Another example of a dewatered, areally limited aquifer is plotted in figure A18 (Appendix A).

9.2.2.2. Analysis with Observation Data

The transmissivity and storage coefficient values obtained by analysing the data from observation boreholes are calculated using the Theis curve matching method and the Jacob straight line solution. Deviations from the Theis plot caused by either barrier or recharge boundaries were analysed using Stallman's method (1953). The aquifer test results are summarized in Table 8 together with the calculated T and S values.

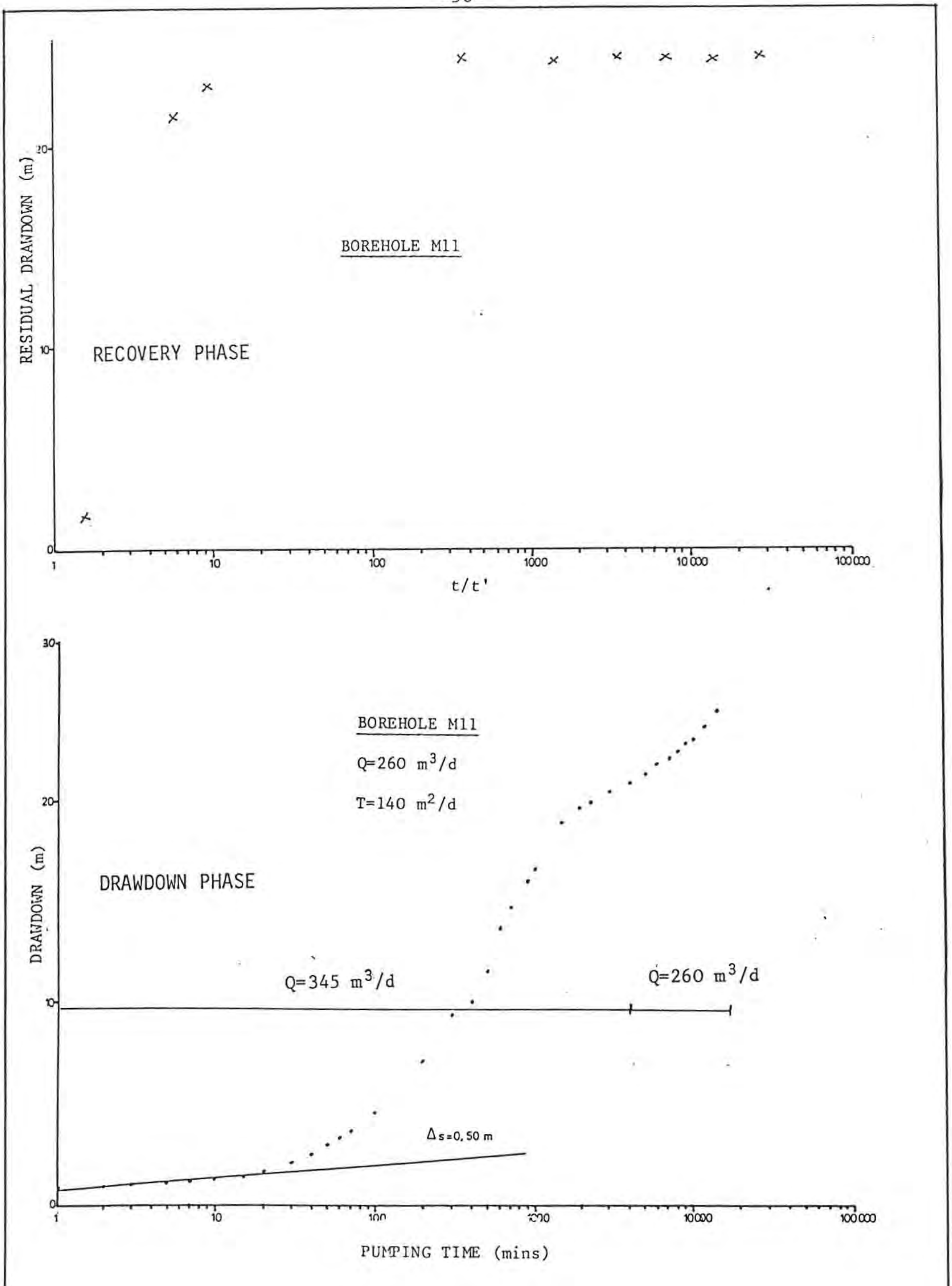


FIG. 19 DRAWDOWN AND RECOVERY DATA FOR BOREHOLE M11 SHOWING DECREASING YIELD AFTER 2000 MINUTES

TABLE 8

SUMMARY OF HYDRAULIC PARAMETERS FOR EXPLORATORY BOREHOLES USING OBSERVATION DATA

Observation Borehole No.	Theis Method				Jacob Method						Distance from * Hydraulic Boundary Effect	Aquifer Type (inferred)
	Discharge Phase		Recovery Phase		Discharge Phase			Recovery Phase				
	T (m^2/d)	S	T ** (m^2/d)	S	T (m^2/d)	S	u	T (m^2/d)	S	u		
M1	490	0,46	430	$6,4x10^{-2}$	608	0,3	0,56	500	$4,9x10^{-2}$	0,55	40m(-)	Unconfined
M3	250	$2,1x10^{-3}$	150	$2,9x10^{-2}$	220	$3,4x10^{-3}$	0,57	160	$4,8x10^{-2}$	0,58	213m(-)	Semiconfined
M4	210	$1,6x10^{-3}$	370	$1,1x10^{-5}$	370	$1,3x10^{-5}$	0,56	320	$1,5x10^{-4}$	0,56		Confined
M10	15	$1,2x10^{-3}$	2	$1,9x10^{-2}$	15	$1,0x10^{-3}$	0,57	2	$1,4x10^{-2}$	0,64		Semiconfined
M16	28	$6,2x10^{-3}$	25	$9,6x10^{-3}$	25	$9,1x10^{-3}$	0,52	20	$1,2x10^{-2}$	0,57	180m(+)	Confined
M38	135	$3,1x10^{-3}$	80	$4,8x10^{-4}$	90	$1,0x10^{-2}$	0,57	75	$1,2x10^{-2}$	0,56	80m(-)	Semiconfined
M41 Obs	195	$1,8x10^{-4}$	350	$8,6x10^{-3}$	185	$2,0x10^{-4}$	0,70	280	$1,2x10^{-5}$	0,56	156m(-)	Confined
M48 Obs	1250	$2,0x10^{-3}$	1375	$4,2x10^{-4}$	1400	$2,0x10^{-3}$	0,49	1300	$1,7x10^{-3}$	0,79	186m(-)	Confined
M59 Obs	45	$5,0x10^{-5}$	10	$5,1x10^{-3}$	55	$3,0x10^{-5}$	0,64	10	$4,7x10^{-3}$	0,57		Confined

* Distance of pumped well from an hydraulic boundary, which is the result of a decrease (-) or increase (+) in the transmissive properties of the aquifer

** Average transmissivity value is 310 m^2/d.

Figure 20 is the drawdown phase for observation borehole M3. The data shows a fairly good fit to the Theis type curve. However, the flat curvature allows more than one matching position. In this case the values of T and S will display a wide variation and should be treated with caution. The calculated T is 250 m^2/d and S is 2×10^{-3}. This later value is considered to be representative of semi confined conditions (Freeze and Cherry, 1979). The recovery does show a fairly good fit (Fig. 20).

Worthington (1978) suggests that if the data conforms only partially to the type curve, only the matching portion should be analysed using the straight line method. This comment applies to the rest of the analysed data. In this case because of the goodness of the Theis curve fit after 10 minutes, the data plotted on semi log paper gives a straight line (Fig. 21). The calculated value for T is 220 m^2/d and S is $3{,}5 \times 10^{-3}$ again indicating semi confined conditions.

The application of the Jacob straight line solution requires values of u less than or equal to 0,01 (Custodio and Llamas, 1976). In this case the value of u is 0,55 (Table 8). However it is clear from the fit that this method does give reasonable results. In fact all the calculated values of u in Table 8 are greater than 0,01. Judging by the good results obtained there is some doubt to the necessity for this value to be less than 0,01. Nevertheless the values of T and S should be treated with caution.

The data from the recovery phase are analysed using the above procedures (Figs. 20 and 21). With the Theis method T is equal to 150 m^2/d and S is 3×10^{-2}. The Jacob method yields value for T=100 m^2/d and S=5×10^{-2} (Table 8). In this case the S values are indicative of unconfined conditions. The difficult matching positions which result from the flat curvature are responsible for the difference in S value as calculated from the drawdown phase.

The presence of a barrier boundary is seen in the deviation from the Theis type curve and the change in slope of the straight line (Figs. 20

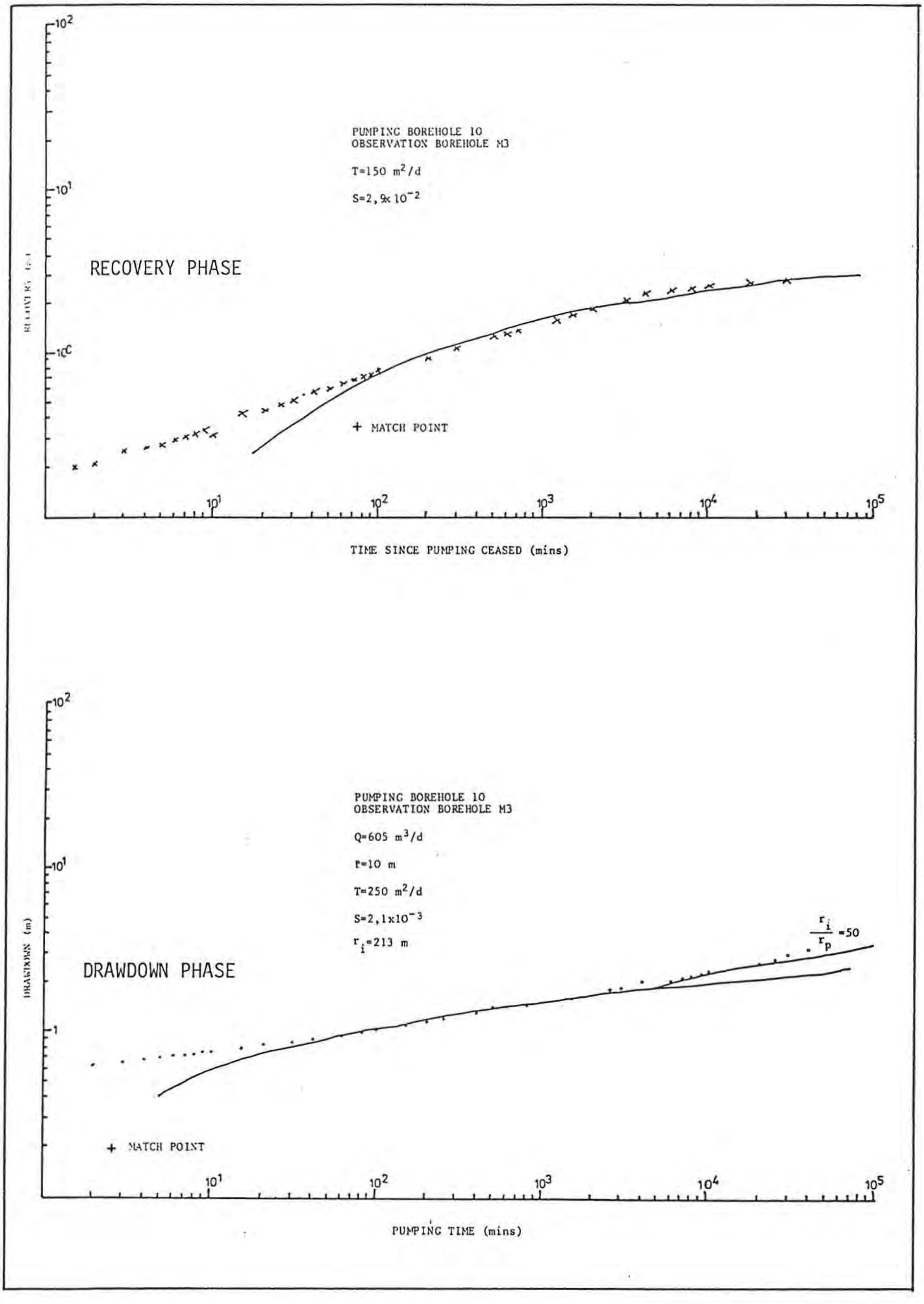


FIG. 20 DRAWDOWN AND RECOVERY DATA FROM OBSERVATION BOREHOLE M3 SHOWING "PSEUDO" BARRIER BOUNDARY CONDITIONS AFTER 6000 MINUTES USING THEIS TYPE CURVE SOLUTION

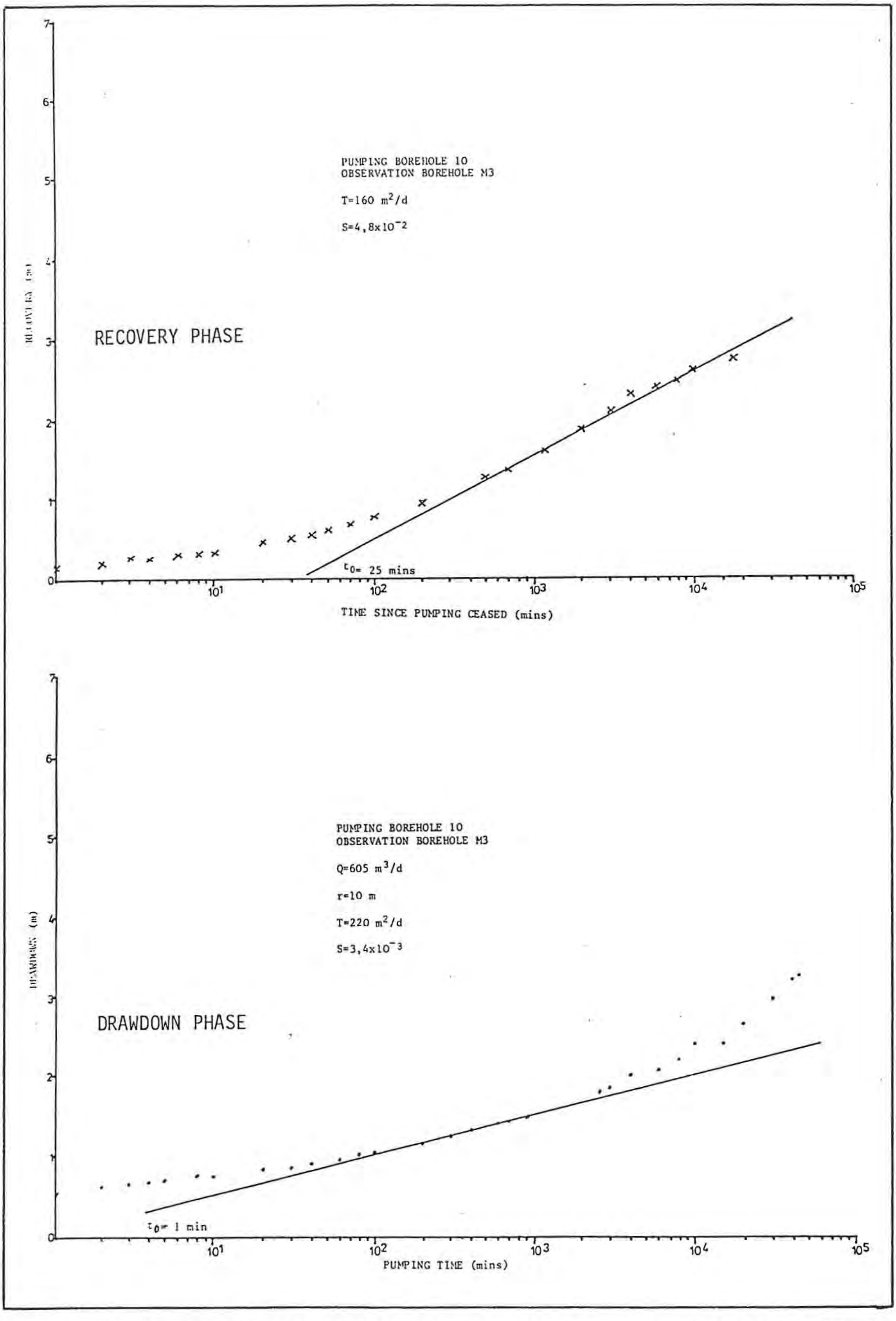


FIG. 21 DRAWDOWN AND RECOVERY DATA FROM OBSERVATION BOREHOLE M3 SHOWING "PSEUDO" BARRIER BOUNDARY CONDITIONS AFTER 3000 MINUTES USING JACOB STRAIGHT LINE SOLUTION

and 21). The distance of the boundary is calculated using the Stallman (1953) method to be 250 m. The complete recovery of the water level indicates that the aquifer is not areally limited. It is therefore suggested that the presence of this "pseudo" hydraulic barrier boundary is a result of a decrease in the transmitting properties of the medium probably due to a decrease in aquifer thickness. Similar departures from the Theis curve plot have already been found elsewhere (Page 16 ;Fig. 5).

Other test pumping resuts showing similar hydraulic behaviour i.e. the presence of a negative "pseudo" boundary, are from pumping boreholes M37, M41, M48 and M59 (Figs. A19 to A26, Appendix A). The presence of a "pseudo" barrier around borehole M59 after 40 minutes is in fact due to dewatering (Figs. A25 and A26). This is confirmed by the lack of complete recovery (Figs. A25 and A26). The initial departure and subsequent re-fit to the Theis curve of the drawdown data (Fig. A25) is the result of a change in discharge rates. The flattening of the recovery data between 3 and 60 minutes after pumping ceased is noted. Within the same period the pumped borehole had recoverd by 2,9 m. and the observation only by 0,60 m. This difference provides additional support to the occurrence of anisotropic flow conditions.

Figure 22 is the drawdown-time plot for observation borehole M16. A levelling off and a departure from the Theis type curve in the later part of the curve (10 000 minutes) indicates the intersection of either a recharge zone or a highly transmissive area. A similar departure from the Theis curve plot have been already mentioned elsewhere (Page 16; Fig. 5). The discharge outlet was at a distance of 500 m downslope, recycling of water is therefore ruled out. The data were analysed using the Theis and Jacob methods (Figs. 22 and 23). The calculated parameters of T and S are given in Table 8. The complete recovery (Fig. 22 and 23) and the presence of only one water strike at the contact indicates that a more transmissive zone has affected the drawdown data. The distance of this zone is calculated to be 180 m. (Table 8).

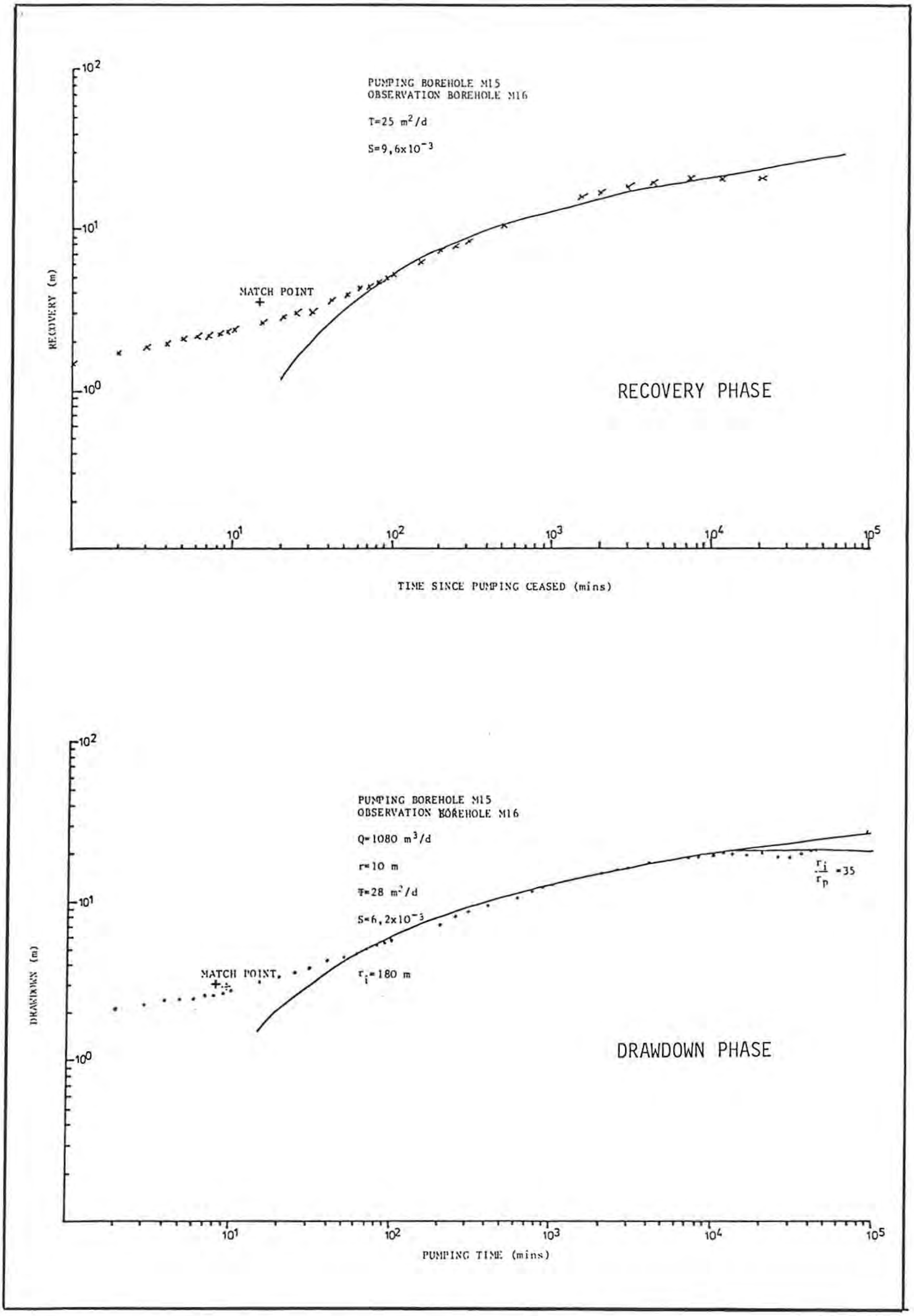


FIG. 22 DRAWDOWN AND RECOVERY DATA FOR OBSERVATION BOREHOLE M16 SHOWING "PSEUDO" RECHARGE BOUNDARY CONDITIONS AFTER 10 000 MINUTES USING THEIS TYPE CURVE SOLUTION

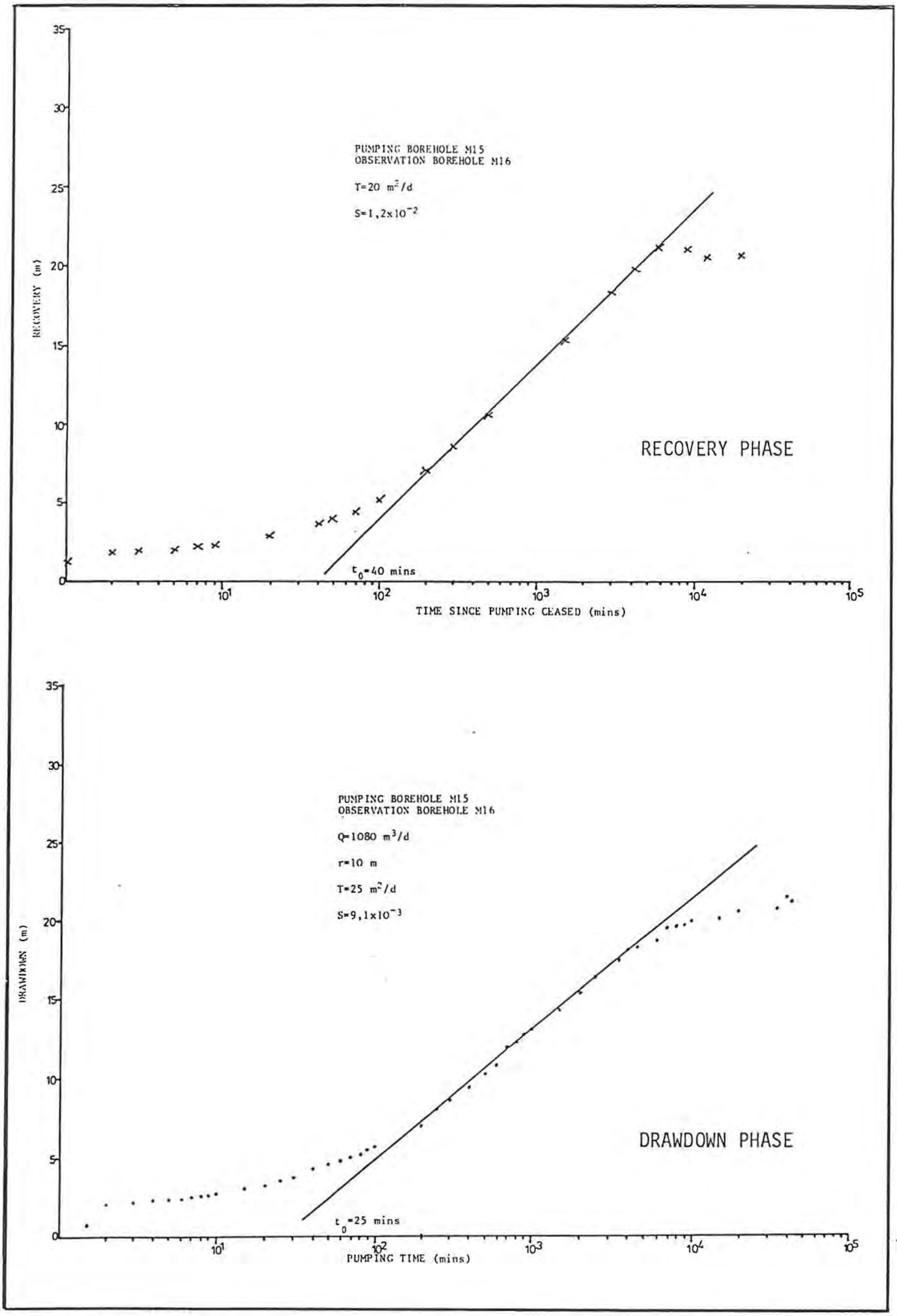


FIG. 23 RECOVERY AND DRAWDOWN DATA FOR OBSERVATION BOREHOLE M16 SHOWING "PSEUDO" RECHARGE BOUNDARY CONDITIONS AFTER 7000 MINUTES USING JACOB STRAIGHT LINE SOLUTION

The log-log drawdown plot for observation borehole M10 (Fig. A27, Appendix A) also shows a flattening of the latter part of the curve. This is however due to a drastic reduction of the discharge. The T values (Table 8) are indicative of poorly developed secondary porosity. The partial recovery of the water level shows severe dewatering (Fig. A27). During the first 60 minutes of the recovery phase the pumped borehole had recovered by 0,70 m. In the same peiod the observation borehole recovered only 0,002 m. This difference is explained by the high anisotropy of the medium in the vicinity of this borehole.

Only two sets of test pumping results were not affected by either apparent recharge or barrier boundaries. These are seen in Fig. 24 and 25 (observation borehole M4) and figures A29 and A30 of Appendix A. Both end portions of the curves depart from the Theis curve due to uncontrolled yield changes. However the latter trend of the curve closely matches the rest of the data only slightly shifted. The T and S values obtained are given in Table 8.

As a general comment to Table 8 similar values of either T or S are obtained for the Theis and Jacob methods for the discharge or recovery phases. This is the result of the data which have been analysed using only the matching portions. More emphasis in placed on the results obtained for T and S during the recovery phase due to the lack of discharge variations (Worthington, 1978; Driscoll, 1986). The values of S are one and simetimes two orders of magnitude different from the discharge and recovery phases as calculated from the Theis and Jacob methods (Eg. M59, Table 8). An average value of T=310 m^2/d for the basalt, as seen from the recovery phase data of Table 8, should be treated with caution because of the great variations in T resulting from anisotropic conditions. Transmissivity values are plotted in figure 26 to show the areal distribution and variation of this parameter.

From the values of S, aquifers conditions vary from unconfined (M1) to totally confined (M4). An average S value of 1×10^{-3} is considered

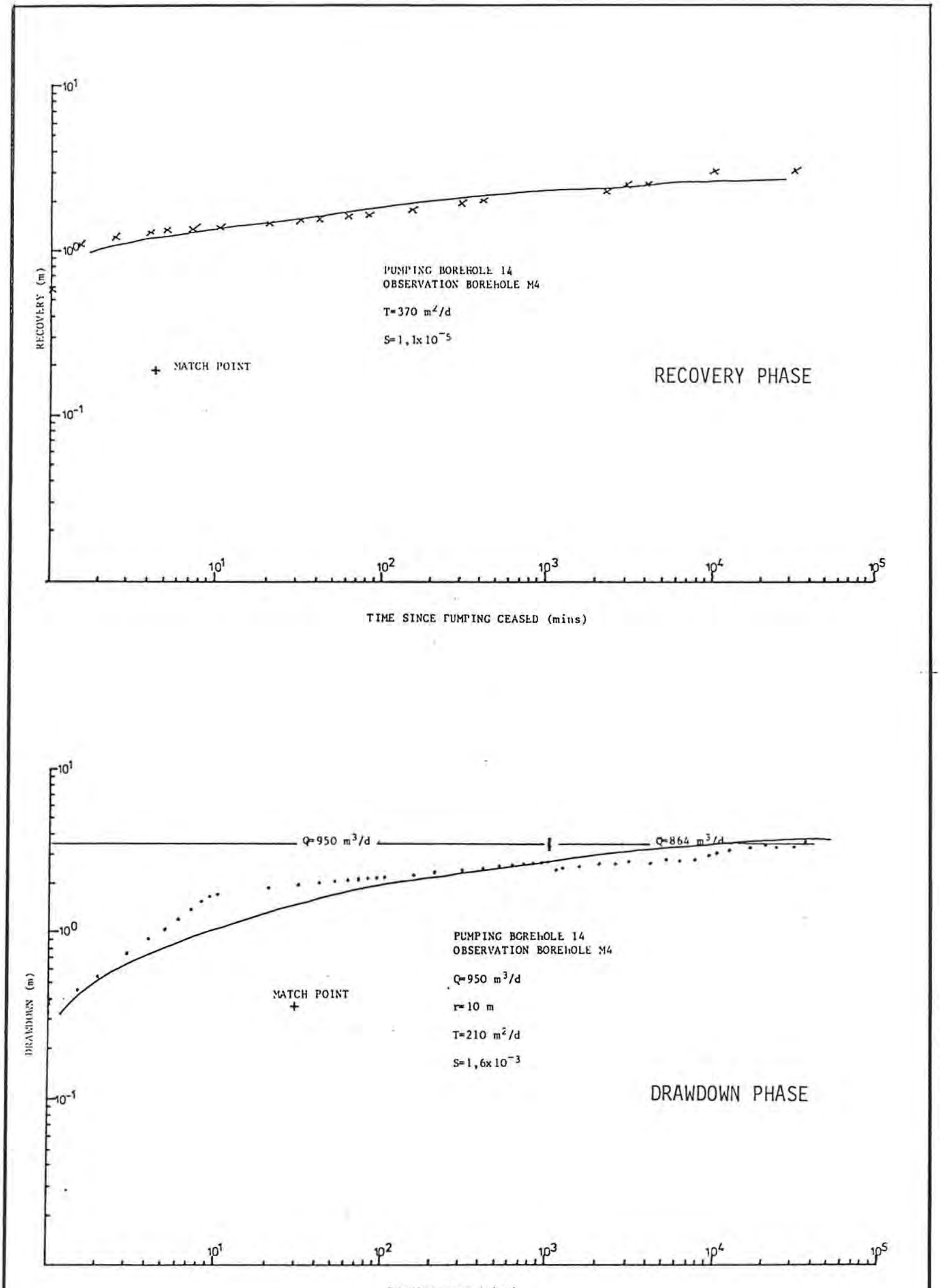


FIG. 24 RECOVERY AND DRAWDOWN DATA FOR OBSERVATION BOREHOLE M4 USING THEIS TYPE CURVE SOLUTION

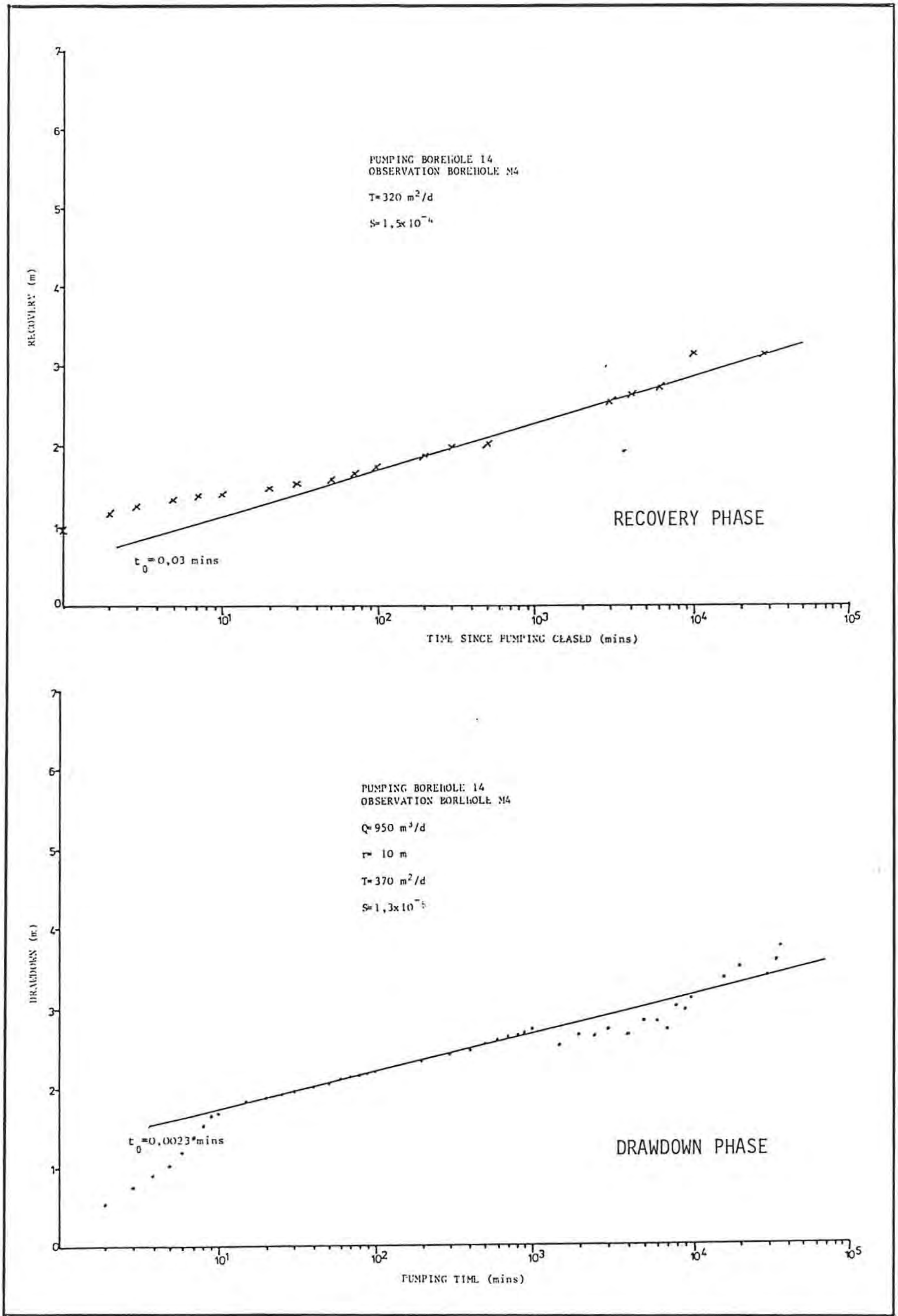


FIG. 25 RECOVERY AND DRAWDOWN DATA FOR OBSERVATION BOREHOLE M4 USING JACOB STRAIGHT LINE SOLUTION

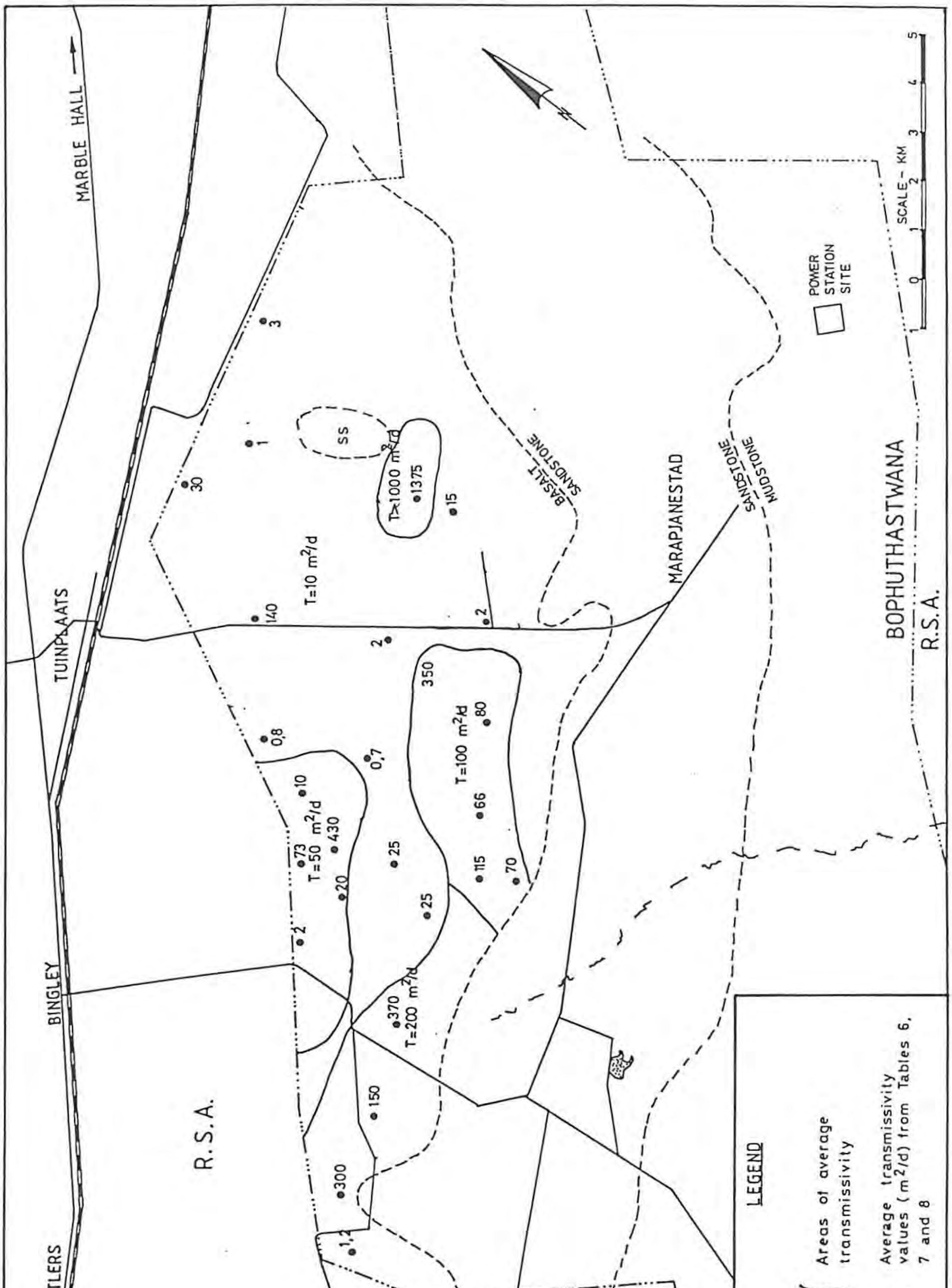


FIG. 26 DISTRIBUTION OF AVERAGE TRANSMISSIVITY VALUES

to be representative of the average hydraulic conditions. However such an average value should be applied with care and is later used for the quantitative estimation of recharge in Chapter 12. The aquifer types as summarized in Table 8 are defined according to the S values obtained for the Theis method. The reliance of the Theis values stems from the fact that the Jacob method is applicable only to data which conforms to the Theis plot, hence the former should be considered as supplementing rather than superseeding the Theis method.

9.3. Boreholes Hydraulic Characteristics

The step drawdown data were analyzed for aquifer and well loss components using the curve matching technique developed by Custodio and Llamas (1976). A total of 16 boreholes were step tested. Table 9 (a) is a summary of the test data which could be analysed. Analysis were not carried out on three boreholes due to small variations in yield which afforded no graphycal solution. The value of n in this case is taken to be equal to 1 and according to equation (8) the drawdowns are proportional to the yield. However this situation does not preclude the presence of well losses (Custodio and Llamas, 1976). Seven boreholes were not tested as a result of the water level reaching pump suction before obtaining four steps. The minimum of four steps is required for a meaningful interpretation of the results (Clark, 1977). Each step had a duration of one hour.

Table 9 (b) details the coefficients B, C and n. The characteristic equations are also included. With the exception of M8, all boreholes have values of n equal to or less than 2 indicating that turbulent flow conditions have not set in at the pumped rates (Custodio and Llamas, 1976). The high n value and associated low value of C for borehole M8 indicate the presence of well losses (Custodio and Llamas, 1976). This is seen in Table 9 (c) were aquifer losses, BQ, well losses, CQ^n, and efficiencies are tabulated.

TABLE 9(a)

SUMMARY OF STEP DRAWDOWN TEST DATA

Borehole No.	Stage	Q (m^3/d)	s (m)	s/Q (d/m^2)
14	1	233	0,92	$3,95x10^{-3}$
	2	330	1,21	$3,67x10^{-3}$
	3	432	1,68	$3,89x10^{-3}$
	4	605	2,43	$4,02x10^{-3}$
M8	1	320	1,26	$3,94x10^{-3}$
	2	483	1,90	$3,93x10^{-3}$
	3	674	3,00	$4,45x10^{-3}$
	4	950	6,24	$6,57x10^{-3}$
M15	1	700	3,15	$4,50x10^{-3}$
	2	1300	5,98	$4,60x10^{-3}$
	3	1730	8,78	$5,08x10^{-3}$
	4	2000	9,31	$4,66x10^{-3}$
M37	1	363	0,74	$2,04x10^{-3}$
	2	613	1,49	$2,43x10^{-3}$
	3	1000	2,94	$2,96x10^{-3}$
	4	1470	5,01	$3,41x10^{-3}$
M39	1	233	1,65	$7,08x10^{-3}$
	2	460	5,32	$1,15x10^{-2}$
	3	786	16,97	$2,16x10^{-2}$
	4	950	24,80	$2,6x10^{-2}$
M41	1	260	0,50	$1,92x10^{-3}$
	2	475	1,14	$2,40x10^{-3}$
	3	1055	3,60	$3,40x10^{-3}$
	4	1356	5,45	$4,02x10^{-3}$

Borehole No.	n	B (d/m^2)	C (d^3/m)	Characteristic Equations
14	1,8	$3,22x10^{-3}$	$1,83x10^{-4}$	$s=3,22x10^{-3}Q+1,83x10^{-4}Q^{1,8}$
M8	3	$2,85x10^{-3}$	$1,14x10^{-2}$	$s=2,85x10^{-3}Q+1,14x10^{-2}Q^{3}$
M15	1,5	$3,97x10^{-3}$	$8,82x10^{-8}$	$s=3,97x10^{-3}Q+8,8,2x10^{-8}Q^{1,5}$
M37	1,6	$8,00x10^{-4}$	$3,38x10^{-5}$	$s=8,00x10^{-4}Q+3,38x10^{-5}Q^{1,6}$
M39	2,1	$1,33x10^{-3}$	$1,47x10^{-5}$	$s=1,33x10^{-3}Q+1,47x10^{-5}Q^{2,1}$
M41	1,6	$7,50x10^{-4}$	$4,04x10^{-5}$	$s=7,50x10^{-4}Q+4,04x10^{-5}Q^{1,6}$

TABLE 9 (b) : SUMMARY OF VALUES OF B, C AND n AND CHARACTERISTICS EQUATIONS

The well efficiencies are calculated according to:

$$E= \frac{BQ}{BQ+CQ^n} 100 \qquad \text{....(9)}$$

where

BQ=Aquifer losses and $BQ+CQ^n$=Total losses

All the boreholes have an open hole construction and this results in a maximum effective open area and noted high efficiencies. With the exception of M8 all losses are attributed to the formation. Custodio and Llamas (1976) cite anisotropy, heterogeneties in the medium and barrier boundaries as responsible for the occurrence of aquifer losses.Usually well losses are associated to the presence of well screens and gravel pack (Brereton, 1979). Since an open hole construction was adopted for all the boreholes (Section 8.1; Page41) the poor performance of M8 can be associated to the two following causes:

. losses between the pump inlet and the borehole or

. the aquifer is yielding water from a few fractures (Custodio and Llamas, 1976).

TABLE 9 (c)

SUMMARY OF AQUIFER LOSSES, WELL LOSSES AND EFFICIENCIES

Borehole No	Q (m^3/d)	Aquifer Losses BQ (m)	Well Losses CQ^n (m)	Efficiency
14	233	0,75	0,04	95%
	330	1,06	0,06	95%
	432	1,39	0,08	95%
	605	1,95	0,10	95%
M8	320	0,91	3,65	20%
	483	1,38	5,51	20%
	674	1,92	7,68	20%
	950	2,71	10,83	20%
M15	700	2,78	-	100%
	1300	5,16	-	100%
	1730	6,87	-	100%
	2000	7,94	-	100%
M37	363	0,29	0,01	97%
	613	0,47	0,02	96%
	1000	0,80	0,03	96%
	1470	1,18	0,05	96%
M39	233	0,31	0,00	100%
	460	0,61	0,01	98%
	786	1,05	0,01	98%
	950	1,26	0,01	98%
M41	260	0,20	0,01	95%
	475	0,36	0,02	95%
	1055	0,79	0,04	95%
	1356	1,02	0,05	95%

The second cause cannot be the explained by the relatively high T value obtained during the testing of this borehole which does not indicate the present of a limited number of water brearing zones (Table 7; Page 55).

A graphical method of visualising the relationship between aquifer (BQ) and well losses (CQ^n) of Table 9 (c) is a graph of drawdown versus yield for each step. An example where the well losses of M8 are significant is illustrated in figure 27 (a). The remainder of the boreholes are characterized by very small or neglegible well losses and their characteristic curves are all straight lines (Fig. 27 (b),(c) and (d)).

9.4. Borehole Specific Capacities and Yield Distribution

The specific capacity (Qs) of a borehole is defined as the yield obtained per unit of drawdown. It is therefore another paramenter that measures the performance of the borehole in terms of its potential for ground water abstraction.

There exists a relationship between Qs and Transmissivity which is given from the Theim (1906) formula:

$$s = \frac{Q}{2\pi T} \ln \frac{R}{r} \quad \text{....(10)}$$

The specific capacity is therefore:

$$Q/s = Qs = \frac{2\pi TS}{\ln \frac{R}{r}} \quad \text{....(11)}$$

In accordance with the above formula Qs is independent of the borehole discharge and depends only upon the hydraulic characteristics of the aquifer. Taking into consideration that the radius of all the boreholes tested during the investigation is approximately 0,075 m. and that R usually varies from 10 m. to 500 m. for unconfined aquifers and from 200 m. to 10 000 m. for confined aquifers, then the plotted straight line relationship

$$Qs = \frac{2\pi}{\ln \frac{R}{r}} \quad \text{....(12)}$$

varies between 0,71 and 1,28 for unconfined situations and between 0,53 and 0,80 for confined aquifers. These values

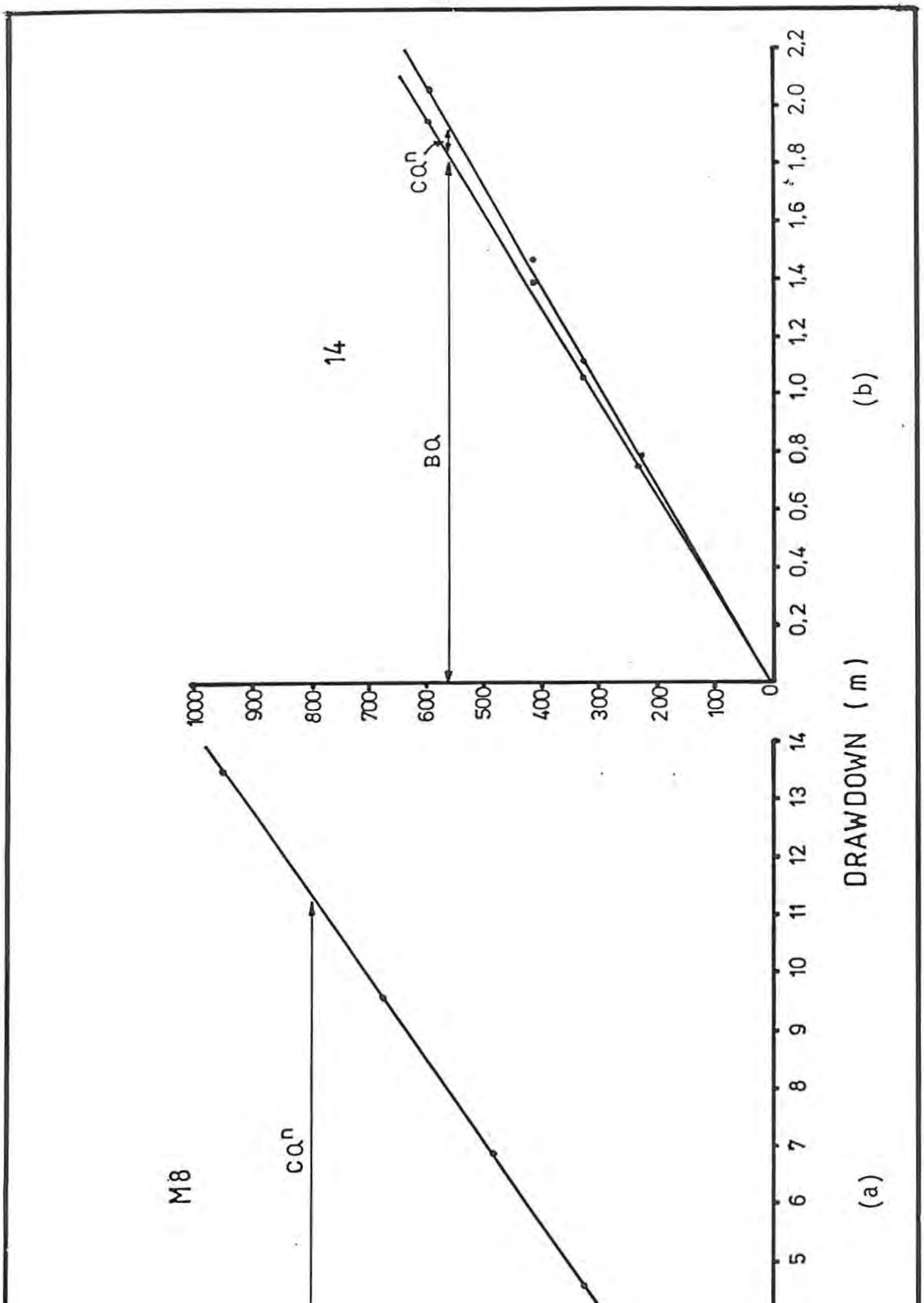


FIG. 27 GRAPHICAL RELATIONSHIP BETWEEN AQUIFER (BQ) AND WELL LOSSES (CQ^n) FOR BOREHOLE M8 (a) AND 14 (b)

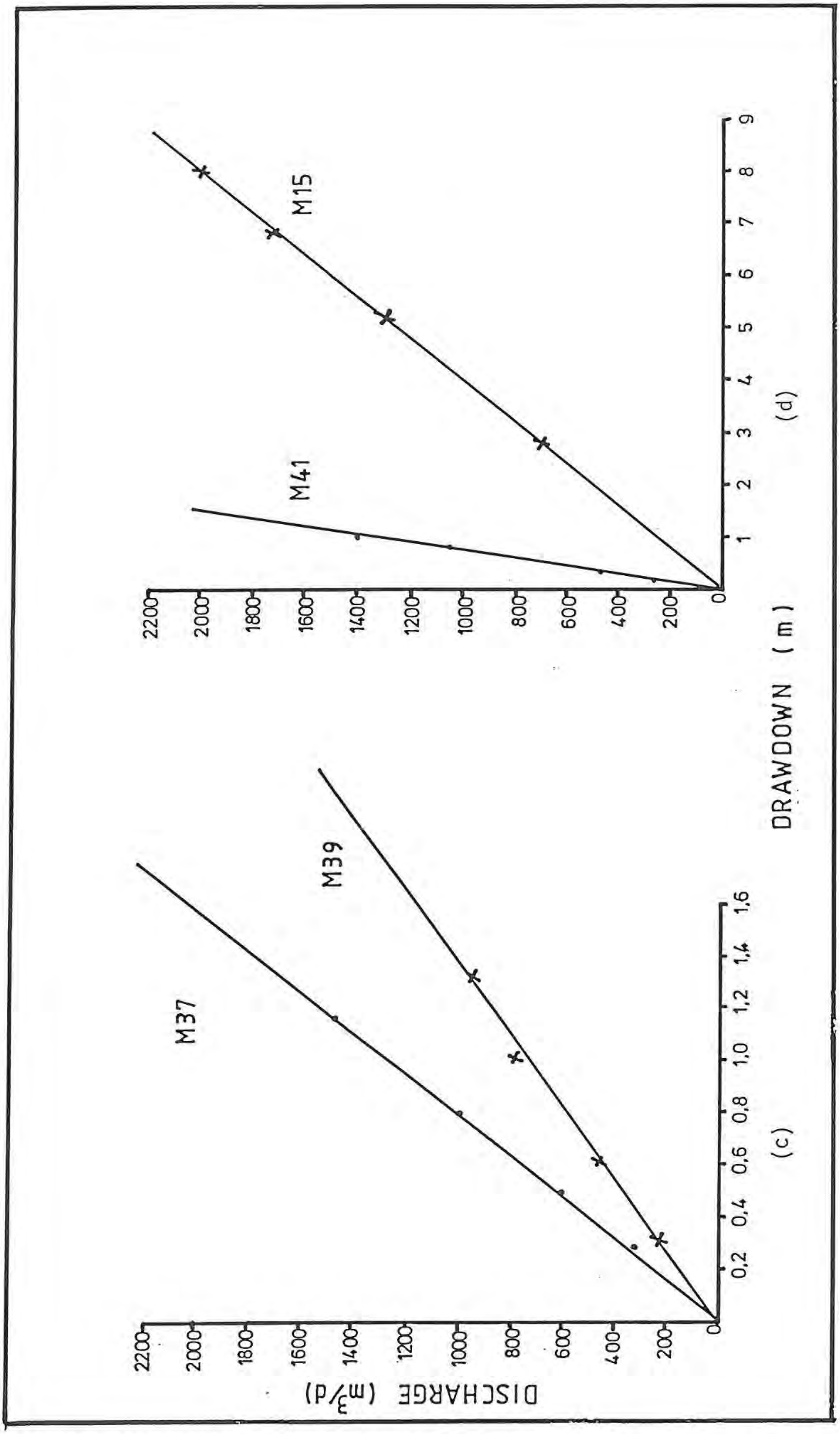


FIG. 27 GRAPHICAL RELATIONSHIP BETWEEN AQUIFER (BQ) AND WELL LOSSES (CQ^n) FOR BOREHOLES M37, M39 (c) AND M15, M41 (d)

are, of course, theoretical and assume that the borehole is unaffected by well losses.

The above numerical relationship calculated for steady-state conditions is also applicable to an unsteady-state condition after a few hours of pumping (Custodio and Llamas, 1976). The specific capacities used for this discussion have been calculated after 500 minutes of pumping.

A diagram of the relationship between transmissivity and specific capacity has been prepared for the basalt/sandstone unit (Fig. 28). Additional data from five other boreholes elsewhere in the district (E. Martinelli and Associates, 1986) have been added to allow for a representative plot. Deviations from the theoretical straight line plot involve point scattering and/or a change in the slope of the line of best fit. This may result in a T versus Qs ratio outside the limits of the theoretical range that can be attributed to either the prevaling flow mechanism, borehole construction or adoption of incorrect test pumping procedures.

The Qs versus T plot is illustrated in figure 28. The empirical relationship between the two parameters is Qs=0,6 T which falls well inside the range of confined aquifers. The regression equation characterising the line of best fit is Y=1,01+0,72X. A correlation coefficient of r=0,90 has been calculated. The relatively narrow point scatter is indicative of low well losses during testing and the correct application of testing procedures. The anisotropy of the aquifer is again evidenced by the wide spread of T values.

Figure 29 is a specific capacity frequency plot. The relatively high specific capacities and therefore available yields are illustrated by this diagram with 60% of the boreholes having Qs values in excess of 20 m^3/d/m of drawdown and 30% of the boreholes displaying a Qs in excess of 100 m^3/d/m. The severe anisotropy of the aquifer is further illustrated by the wide range of specific capacities.

A meaningful appreciation of the average sustainable borehole yield that can be expected from the basalt/sandstone contact aquifer is obtained by relating the yield to the available drawdown. Where the average relationship between transmissivity and specific capacity are available, the application of the Theis non-equlibrium formula (1933) allows expected borehole yields to be calculated assuming simplified hydraulic conditions. By assuming that the Theis formula is applicable, using a

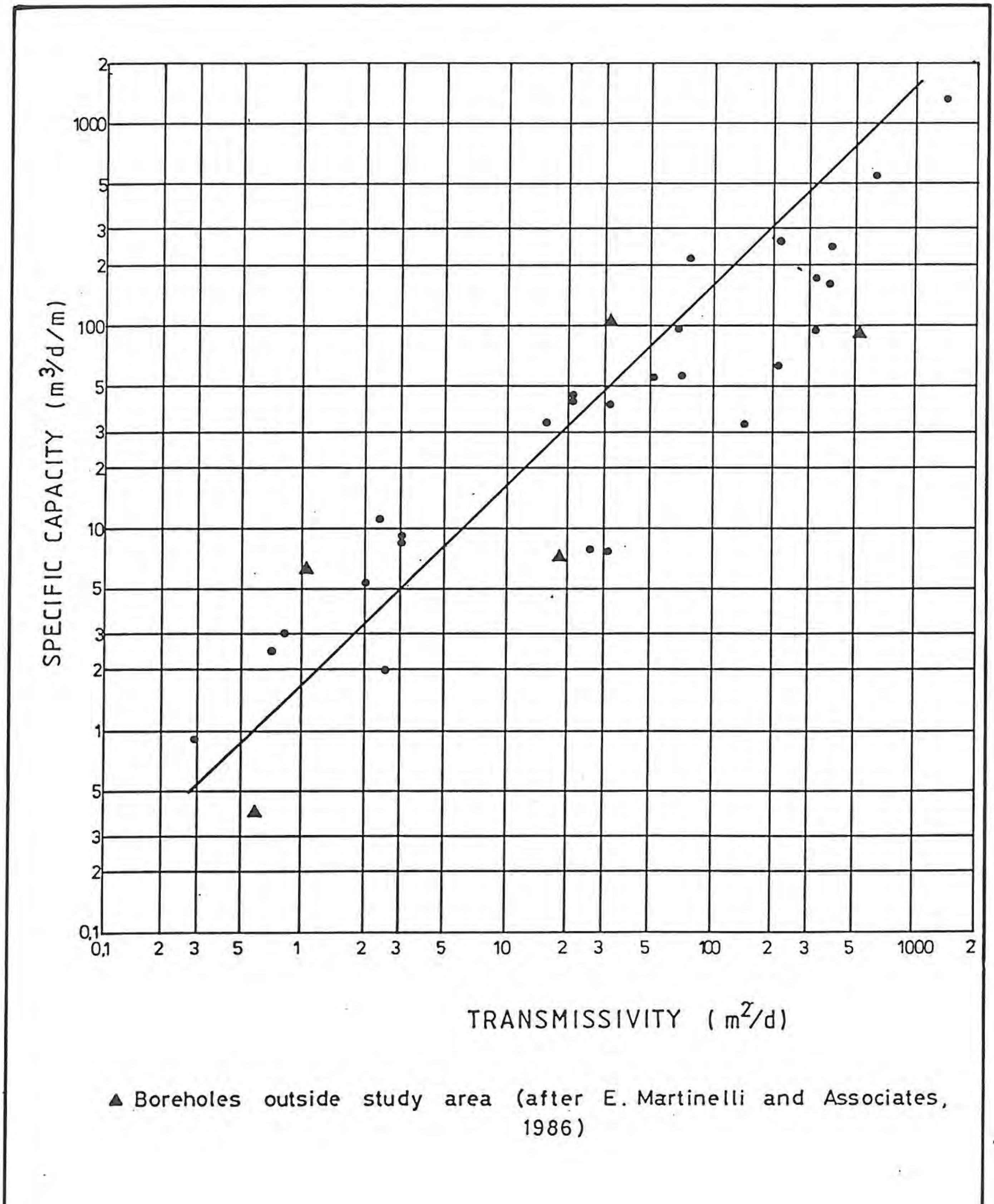


FIG. 28 GRAPHICAL RELATIONSHIP BETWEEN TRANSMISSIVITY AND SPECIFIC CAPACITY

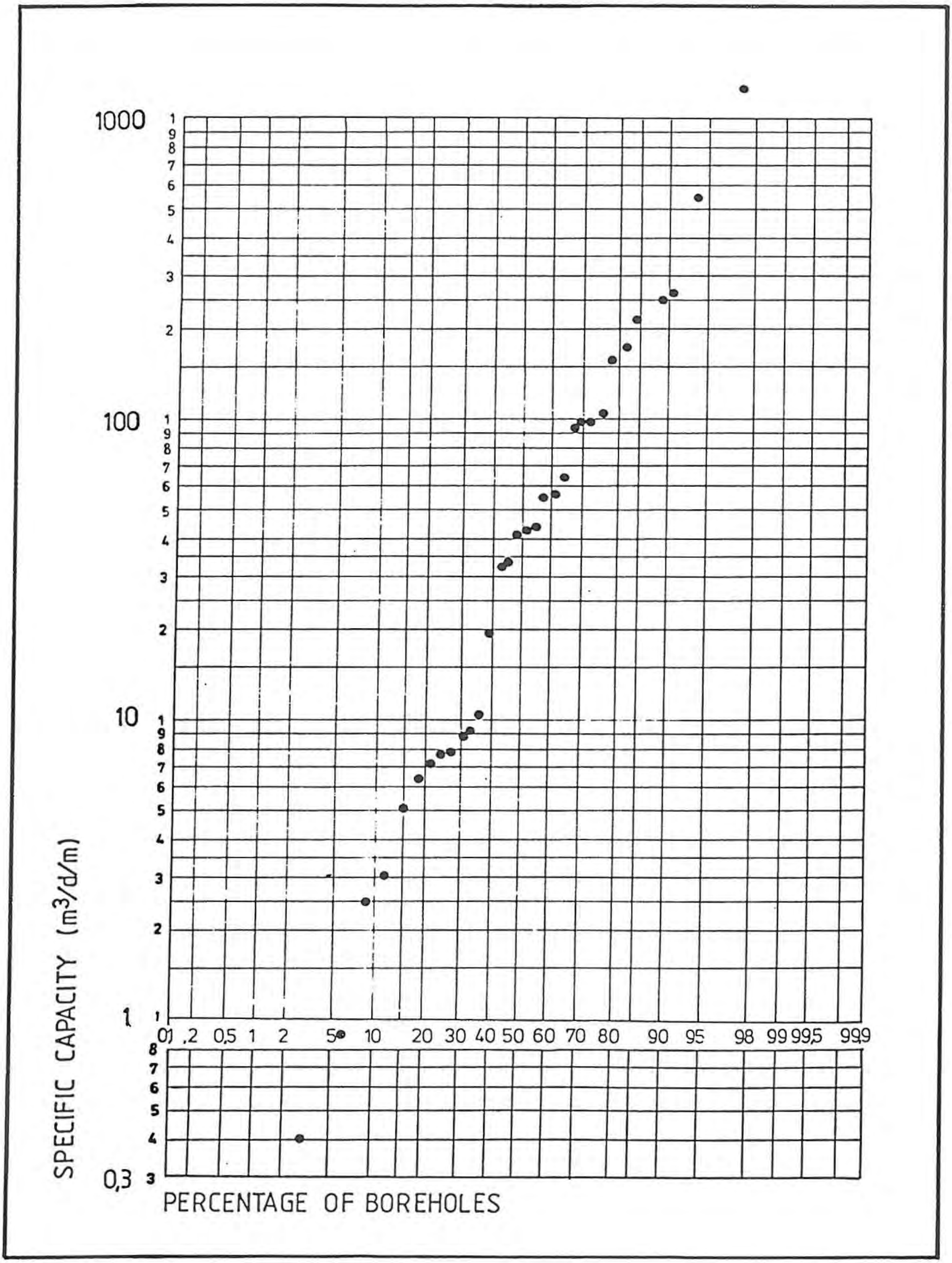


FIG. 29 SPECIFIC CAPACITY FREQUENCY PLOT

Coefficient of Storativity of 1 x 10^{-3}, a standard borehole radius of 0,075 m. and a pumping time of 180 days, a nomogram (Fig. 30) has been constructed showing a theoretical range of expected yields and drawdowns for the calculated range of transmissivity and specific capacity. The lower part illustrates the empirical relationship between T and Qs. The upper part illustrates the range of borehole yield values that can be obtained for different values of the controlling hydraulic parameters.

This plot obviously assumes that the aquifer is homogeneous and isotropic and the hydraulic conditions allow for the applicability of the Theis equation. As the nature of this aquifer has been confirmed to be, in general, strongly anisotropic, departures from the calculated yields and drawdowns should be expected. In particular around boreholes where changes in transmissivity are seen to occur (Sub-section 9.2.2.2.).

9.5. Summary

In this Chapter the methods used for the analysis of the test pumping data were briefly described. The hydraulic paramaters of Transmissivity and the global Storage Coefficient were calculated. These results will be later used in the formulation of the management recommendations (Chapter 12). The following Chapter describes the theory of development of the piezometric surface and the general ground water movement within the area under study.

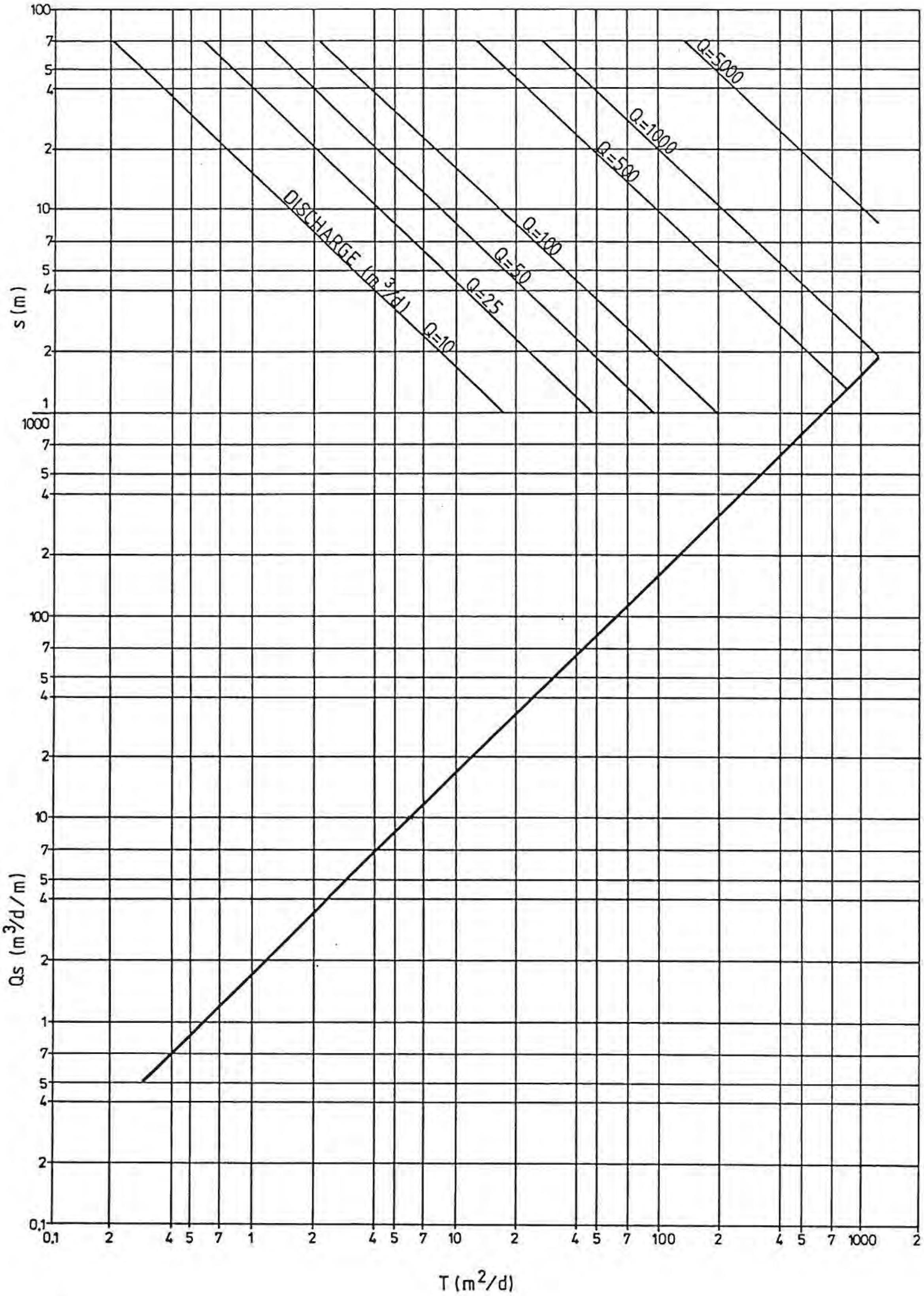


FIG. 30 THEORETICAL YIELD NOMOGRAM BASED ON ASSUMED VALUES OF STORATIVITY AND BOREHOLE RADIUS BY APPLYING THE THEIM FORMULA

10. PIEZOMETRY AND GROUNDWATER RECHARGE

10.1. Groundwater Levels

The information gathered during the field investigation on ground water level fluctuations is scarce and limited. The Department of Water Affairs has installed a water level recorder in Tuinplaats. Records are available from 1976 to mid 1986 (Fig. 31). In the area under study, measurements of water level variation are available from the exploratory boreholes for the period June 1984 to August 1985 (Fig. 32).

10.1.1. Water Level Fluctuations

Water level trends in hydrograph PL 85 bear some comparison to rainfall from 1976 up to the end of 1984 (Fig. 31). During this period the levels are seen to rise after each rainfall event with the peak showing a time lag ranging from 3 to 4 months. This is clearly seen in the years 1979-84 (Fig. 31). Each peak is followed by the natural regression of the water level during the dry winter months. However the period mid 1976-78 is characterized by a high rainfall pattern which is not reflected by individual peaks. The general trend is towards a replenishment of the aquifer. In general the fluctuations over the period 1976-84 have been very small i.e. a variation of 2 m. for this period, which suggests that the aquifer is behaving under natural conditions. Fluctuations of about 0,30 m. in water levels are noted after each rainfall event.

The steady decline in the water level after 1984 is clear (Fig. 31). This continual decline of the regional water levels is commonly attributed to discharge exceeding recharge (Ward, 1967) resulting from either a decrease in rainfall and/or an increase in pumping. Around Tuinplaas there has been an increase in pumping for irrigation since 1984 (E. Martinelli and Associates, 1985). The effect of a decrease in rainfall during 1984 could not have resulted in a decline of regional water levels as evidenced in the relatively dry periods 1978-79 and 1981-82 (Fig. 31) which did not cause any drop in ground

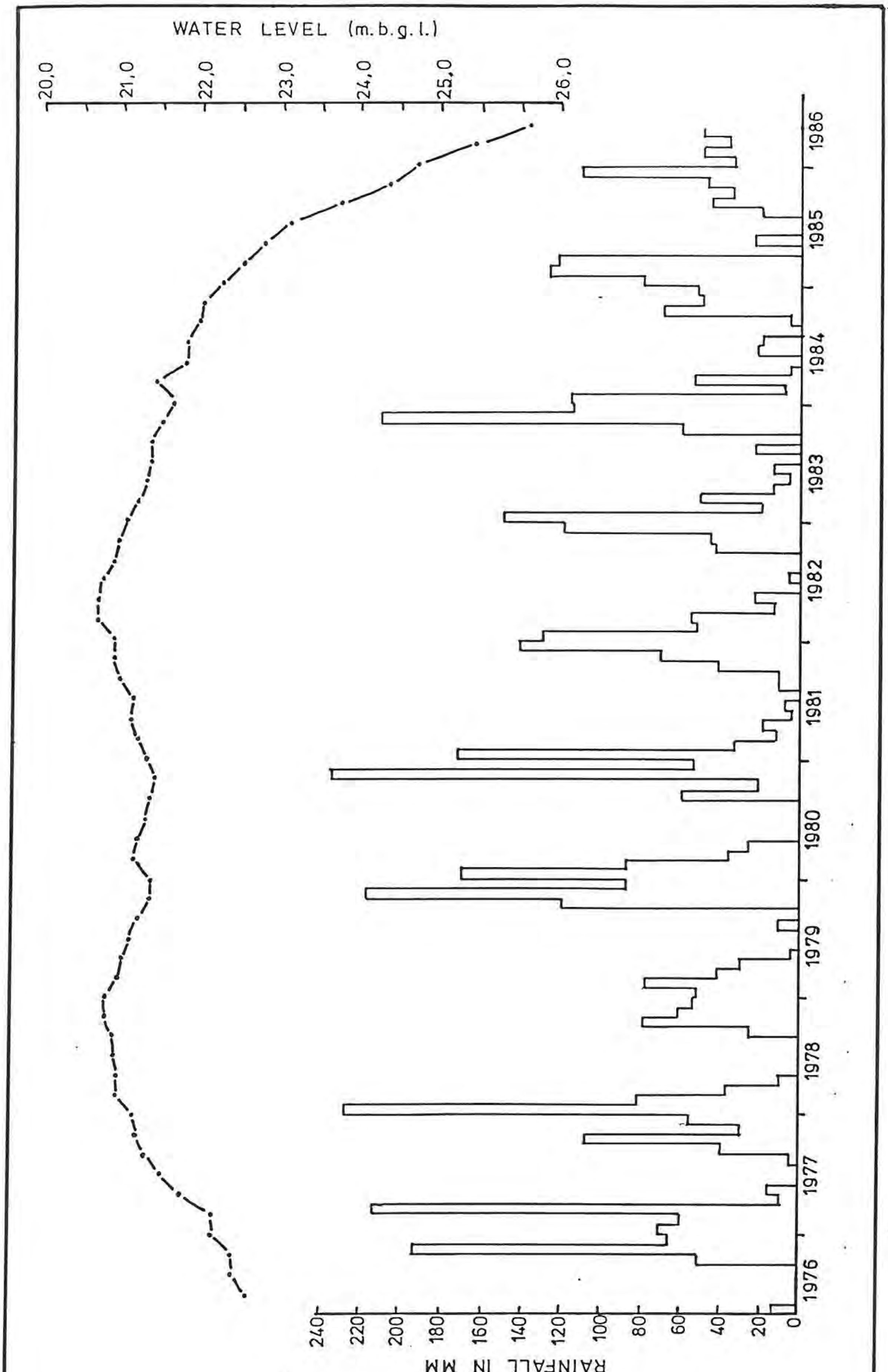


FIG. 31 <u>WATER LEVEL FLUCTUATIONS FROM HYDROGRAPH PL85 AND RAINFALL DISTRIBUTION</u>

water levels. It is suggested that the lower rainfall recorded during 1984 is not the cause for the noted decline. During 1985 an inventory of abstraction points within a radius of 10 km from Tuinplaas was carried out. It was reported that an increase of 24% in the number of irrigation boreholes had taken place within 1984-85. The steeper decline in levels is therefore likely to be due to the increase in the number of abstraction boreholes and corresponding ground water withdrawal.

It is possible to compare this latter decline with the trends of the well hydrographs from the exploratory boreholes (Fig. 32). During the period 1984-85 the water level in PL 85 dropped 2,5 m. whereas the average decline in the exploratory boreholes was 0,70 m. The smaller decline can be related to the greater distance to the area of pumping near Tuinplaas. Only two boreholes are seen to register a noticeable increase in piezometric level i.e. M18 and M19. The response of the water level to the rainy period is seen after a time lag of 3 months (Fig. 32) in these two boreholes. Smaller increases are seen to occur in boreholes 14 and M6. The rise in water level ranges from 0,60 m. in borehole M19 to 0,20 m. in borehole M6 (Fig. 32).

From the above comments it is clear that the presence of the abstraction points around the borehole (well hydrograph (PL 85)) has an effect not only on the steep decline after 1984 but also in dampening the water level fluctuations before 1984. This is evidenced by Meizer's statement in Ward (1967) that "the water level in a well is sensitive to every force that acts upon the water body with which the well communicates". This is particularly true of confined aquifers where it is necessary to know the effect of outside factors in order to distinguish their influence on the changes in water level (Ward, 1967).

10.2. Piezometric Surface

The water level data have been used to construct two isopiestic maps. The sparseness of the information available limits the interpretation of these maps. The map of figure 33 was drawn up using the water level data for August 1984. Figure 34 depicts the isopiestic map for

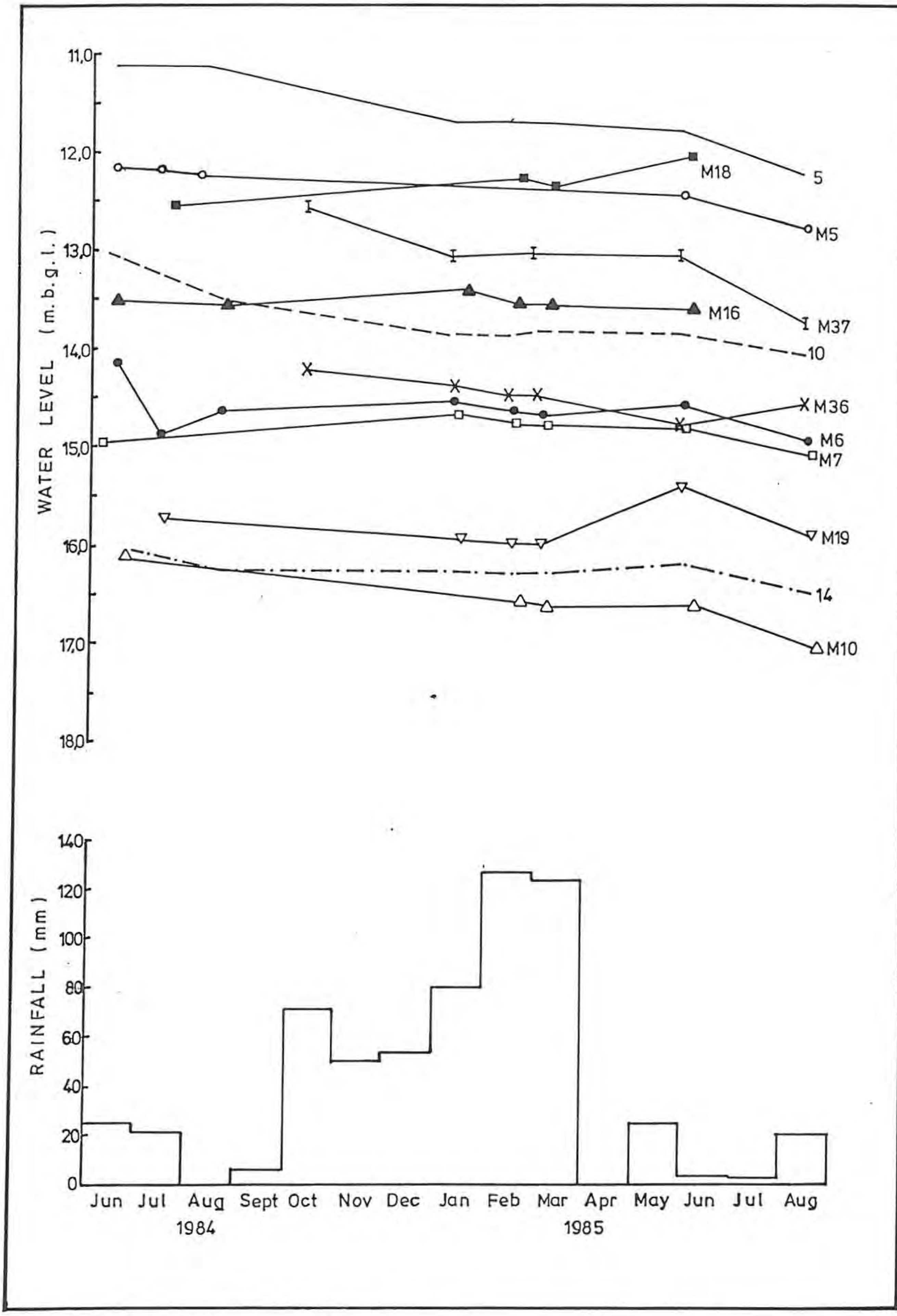


FIG. 32 WATER LEVEL FLUCTUATIONS FROM EXPLORATORY BOREHOLES AND RAINFALL DISTRIBUTION

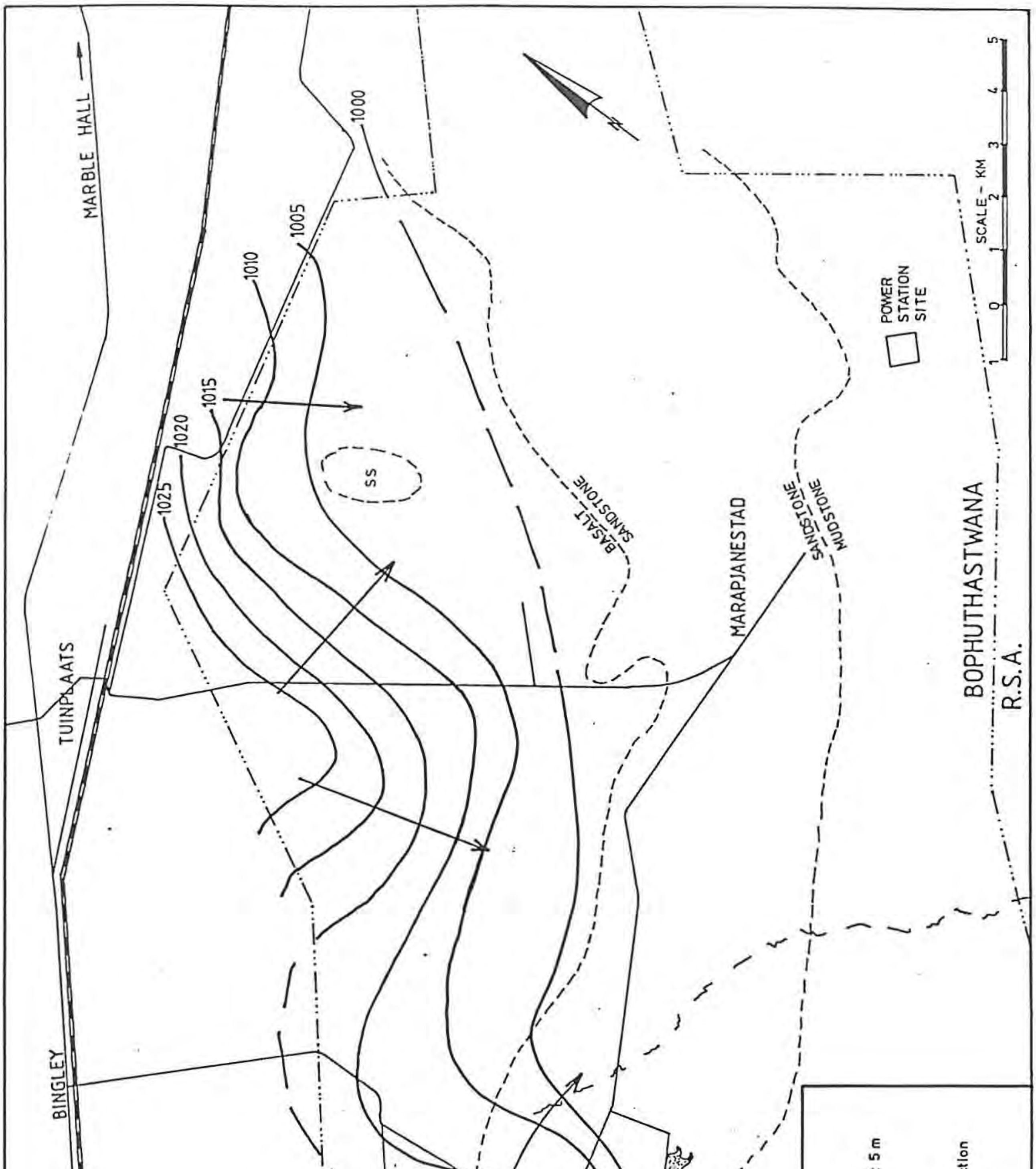


FIG. 33 <u>ISOPIESTIC CONTOURS - AUGUST 1984</u>

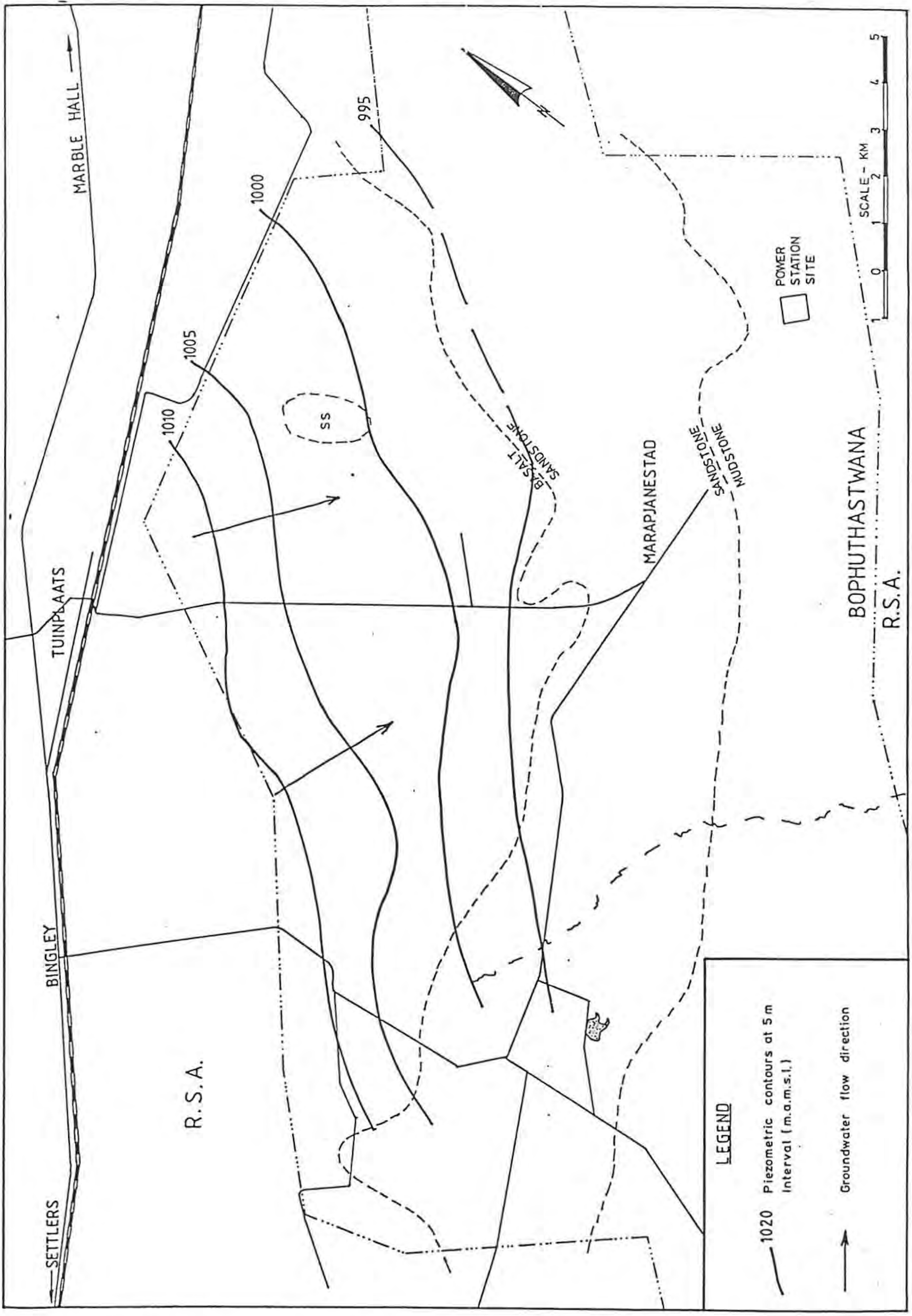


FIG. 34 ISOPIESTIC CONTOURS - SEPTEMBER 1985

data collected in September 1985. The different patterns seen in both maps are discussed below.

10.2.1. Isopiestic Map- August 1984

The isopiestic configuration (Fig. 33) fairly closely reflects the topographic gradient (See Section 1.1.). The flow direction seems also to be controlled by the topographic gradient. The direction of groundwater flow is from north west to south east. The general flow direction is in accordance with Taylor´s (1980) findings which are depicted on the piezometric map (Taylor, 1980; Enclosure 2). In brief his study showed that there was a ground water divide (which coincided with a surface water divide) just to the north of Warmbath striking, approximately, in a east west direction. To the south of this divide the ground water flowed "in a southerly direction".

In the study area the hydraulic gradients range from 6×10^{-2} (1:166) in the eastern part to 4×10^{-4} (1:2500)in the western part of the area. The lower gradients are associated with the zone of higher transmissivities (Fig. 26). Conversely the higher gradients are associated with the areas of lower transmissivity (Figs. 26 and 33). The continuity of the isopiestic network from the basalt into the sandstone indicates that these two geologies are hydraulically interconnected.

10.2.2. Isopiestic Map-September 1985

A comparison of figure 33 and 34 shows a change in the pattern of groundwater flow between 1984 and 1985. There has been both a shift of the isopiestic network towards the north west and a decline in hydraulic gradients. These now range from 3×10^{-3} (1:333) in the western part of the area to 2×10^{-4} (1:5000) in the eastern part of the area. This change can be compared to the decline in the water level recorded in hydrograph PL 85 (Fig. 31) for this period.

From the existence of a ground water flow as seen by the sloping piezometric surface (Figs. 33 and 34) it can be inferred that active recharge, as ground water through flow, is occurring as found elsewhere (Burdon, 1977). The direction of flow indicates that the zone of recharge is outside and to the north west of the area under study. The conceptual model of flow here proposed is supported by the findings of Taylor (1980) (Section 6.1) and of this study. The model suggests that recharge takes place within the Warmbath area and ground water which flows south of the divide, circulates within the basalt, sandstone and mudstone formations towards and through the area under study. The hydraulic continuity between the basalt and the sandstone was described in Section 8 (Page 44). The continuity between the sandstone and the mudstone is inferred by the absence of spring emergences that would otherwise manifest themselves against the surface contact of the lower permeability mudstones. The portion of the investigated area is therefore part of a regional groundwater flow system within the Karoo basin.

10.3. Summary

The measurements of the water levels and the compilation of the isopiestic maps has given an insight to the general ground water movement within the study area. The following Chapter will be an exposition of the chemical composition of the ground waters. An attempt to establish the possible origin of the ground water and its movements will be undretaken through the study of the chemical character.

11. HYDROCHEMISTRY

11.1. General Introduction

The importance of determining the chemical attributes of groundwater is illustrated by Walton's (1970) statement "In groundwater resource evaluation, the quality of groundwater is of nearly equal importance to quantity". During this investigation samples were collected from existing and newly drilled boreholes. During the long term testing of the exploratory boreholes, samples were taken at different time intervals to determine any temporal chemical changes. The samples were analyzed for their chemical, physical, bacteriological and isotopic characteristics.

Several authors (Chebotarev, 1955; Schoeller, 1959; Back and Hanshaw, 1965) have suggested procedures for assessing ground water movement by refering to the regional variations in hydrochemical properties of ground water.

These propositions are;

1. The bicarbonate content is high in recharge areas and low in discharge areas.

2. Recharge areas are characterized by ground waters with a low Total Dissolved Solids (TDS) content.

3. The ratio of the chloride concentration to that of bicarbonate increases with the age of the ground waters in a given environmnent.

In general there is an increase in the mineralization of the water as it moves from a zone of local circulation to one of regional circulation. Custodio and Llamas (1976) have suggested a simple evolution of the predominant anions as the water moves from a local to regional circulation flow pattern:

$HCO_3 \rightarrow SO_4 \rightarrow Cl$

The following sequence applys to the evolution of the cationic character of the water

$Ca \rightarrow Mg \rightarrow Na$

Hence waters which have been subject to short circulation and duration of contact will display a Ca and/or Mg $(HCO_3)_2$ character. Within a regional circulation system, where the time of contact is longer, the salinity of the water increases displaying either a strong Na or Cl character. However exceptions to the above sequences are known.

11.2. Discusion of the Chemical Results

11.2.1. Existing Boreholes

The analytical results of samples collected from existing boreholes are summarized in Table B1 of Appendix B. The ionic concentrations of the cations and anions have been converted into percentage milli-equivalents per litre and are plotted on the Piper diagram of figure 35.

Attention is drawn to the results of Table B1 (Appendix B) where the Ca ion concentration is at times less than that of Mg (Samples borehole 1,5,6,10,11 and 14). These samples were analyzed one month after collection. It is possible that the Ca ion precipitated out as $CaCO_3$ as a result of changes either to the pH or to the partial pressure of CO_2 with time. The reliability of these results is therefore in doubt.

It can be seen from figure 35 that the boreholes plot in three hydrochemical zones. The majority of the ground waters are classified as Ca/Mg + HCO_3 type. It is noted that the position of some boreholes plotted in the anion triangle is affected by the presence of the NO_3 ion (Table B1). Two samples (Boreholes 16 and 22) fall within the Na + HCO_3 type plot. The Na, Cl + SO_4 nature of the sample situated within the mudstone outcrop is clearly seen (Fig. 35). The position of borehole 21 is solely related to its chloride character.

The circulation pattern of the different waters can be identified from the above plots. None of the ground waters plot in the extreme left-hand area of the diamond field which, according to Worthington (1978), is generally indicative of recent recharge waters. However according to proposition 1 (Section 11.1.) and Johnson (1975) the Ca, Mg + HCO_3 character of most of the waters are indicative of recent recharge and local dynamic ground flow conditions. Johnson (1975)

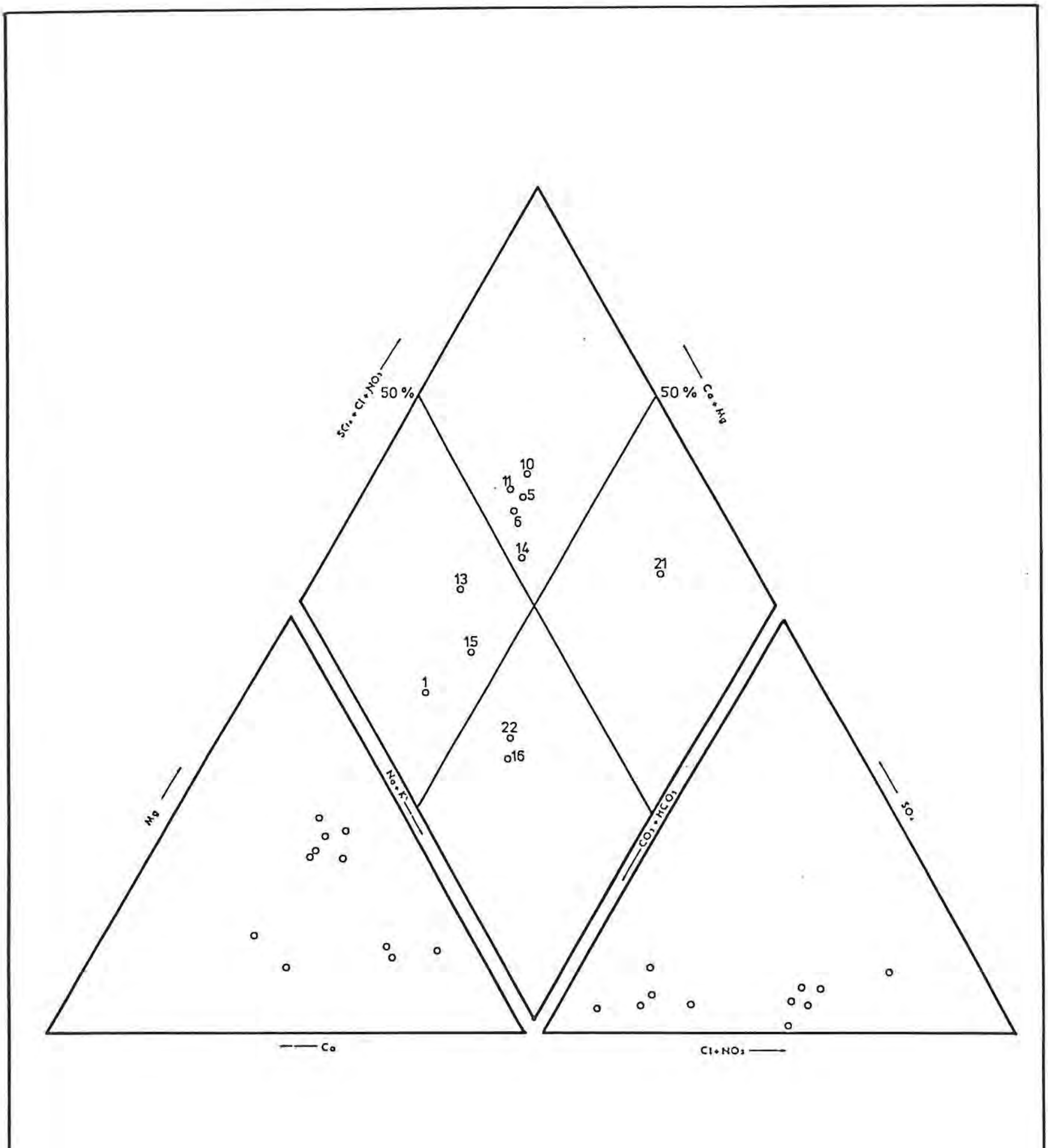


FIG. 35 PIPER PLOT OF EXISTING BOREHOLES

would describe the Na + HCO_3 nature of ground water, such as from boreholes 16 and 22 (Table B1), to be affected by a base exchange mechanism and is incorporated into a "dymanic underflow" system which is maintained as long as the T and the hydraulic gradient are high. This latter conclusion is not supported by the low T values (Table 6) and the low hydraulic gradients (Chapter 10). The possible presence of a clay fraction within the sandstone could be responsible for a change from a calcium/magnesium bicarbonate character to a sodium bicarbonate nature through base exchange. The saline nature of the water within the mudstone is indicative of stagnant waters associated with the very low permeation properties (longer contact time) characterizing this formation.

The list of TDS values in figure 36 (a) shows two plotting positions with higher figures associated with boreholes 1 to 14. Lower TDS values ($<$ 150 mg/l) which characterize recent recharge waters (proposition 2) are found in boreholes 15,16,21 and 22. The anomalously low TDS value of sample 21 is in contrast with the stagnant nature of this water through a longer time of contact associated with the low permeability of the mudstone as mentioned above. This result puts in question the validity of proposition 2.

A more realistic evaluation of the antecedent movement of ground waters is afforded by the ratio $(Cl)/(HCO_3)$ (Custodio and Llamas, 1976). These plots are illustrated in figure 36 (b). The majority of the boreholes appear to be tapping relatively recent recharge waters. In particular boreholes 1, 15, 16 and 22. In the remainder (5, 6, 10, 11, 13 and 14) the precipitation of $CaCO_3$ will have an effect of slightly increasing the value of the $(Cl)/(HCO_3)$ ratio. The strong chloride character of sample 21 is clearly illustrated.

11.2.2. Exploratory Boreholes

Plots of the percentage milli equivalents per litre for samples collected from the exploratory boreholes are illustrated as a Piper diagram in figure 37. The results of the analyses are summarized in Table B2 in Appendix B. Where more

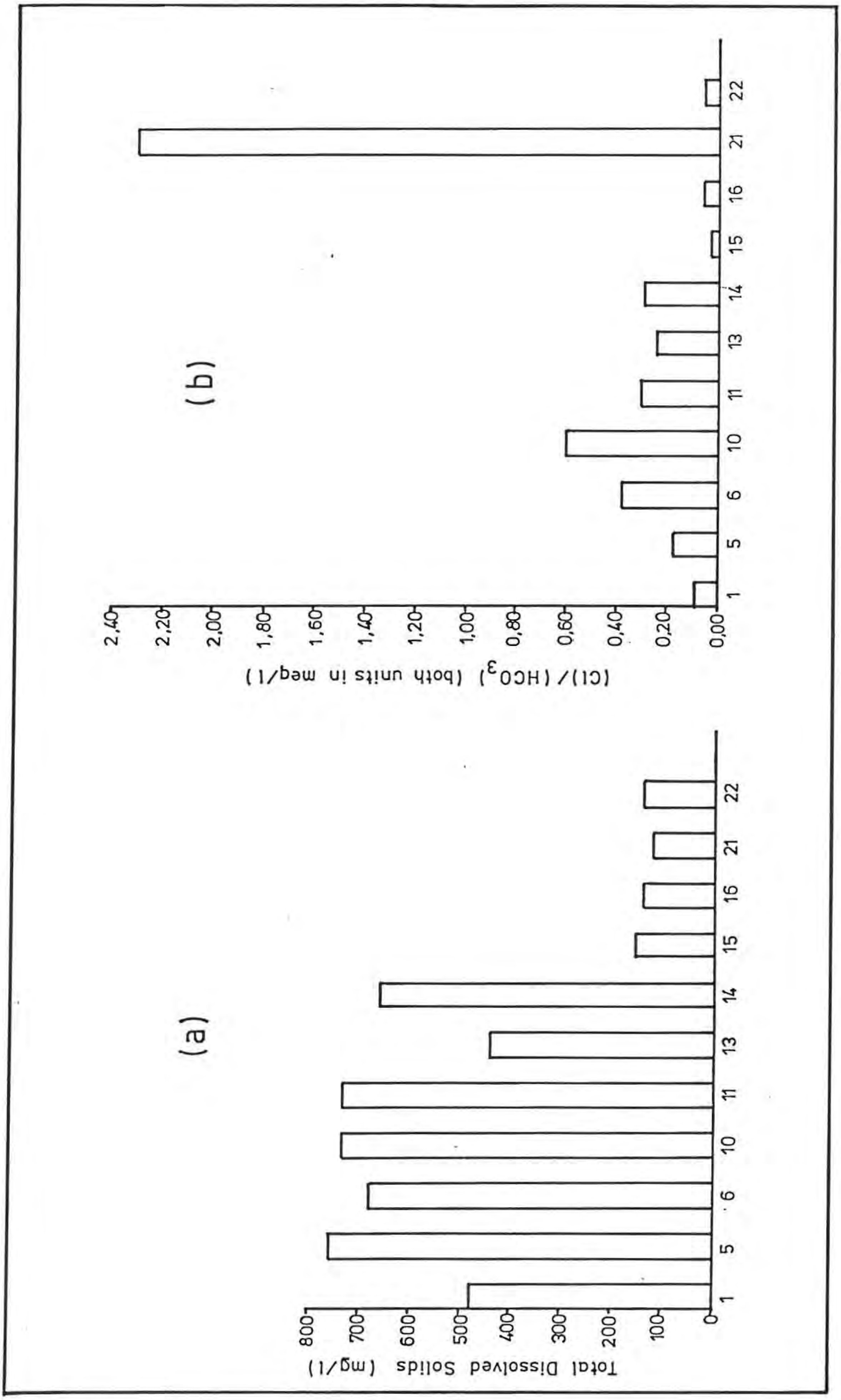


FIG. 36 HISTOGRAMS OF CHEMICAL CHARACTERISTICS - EXISTING BOREHOLES

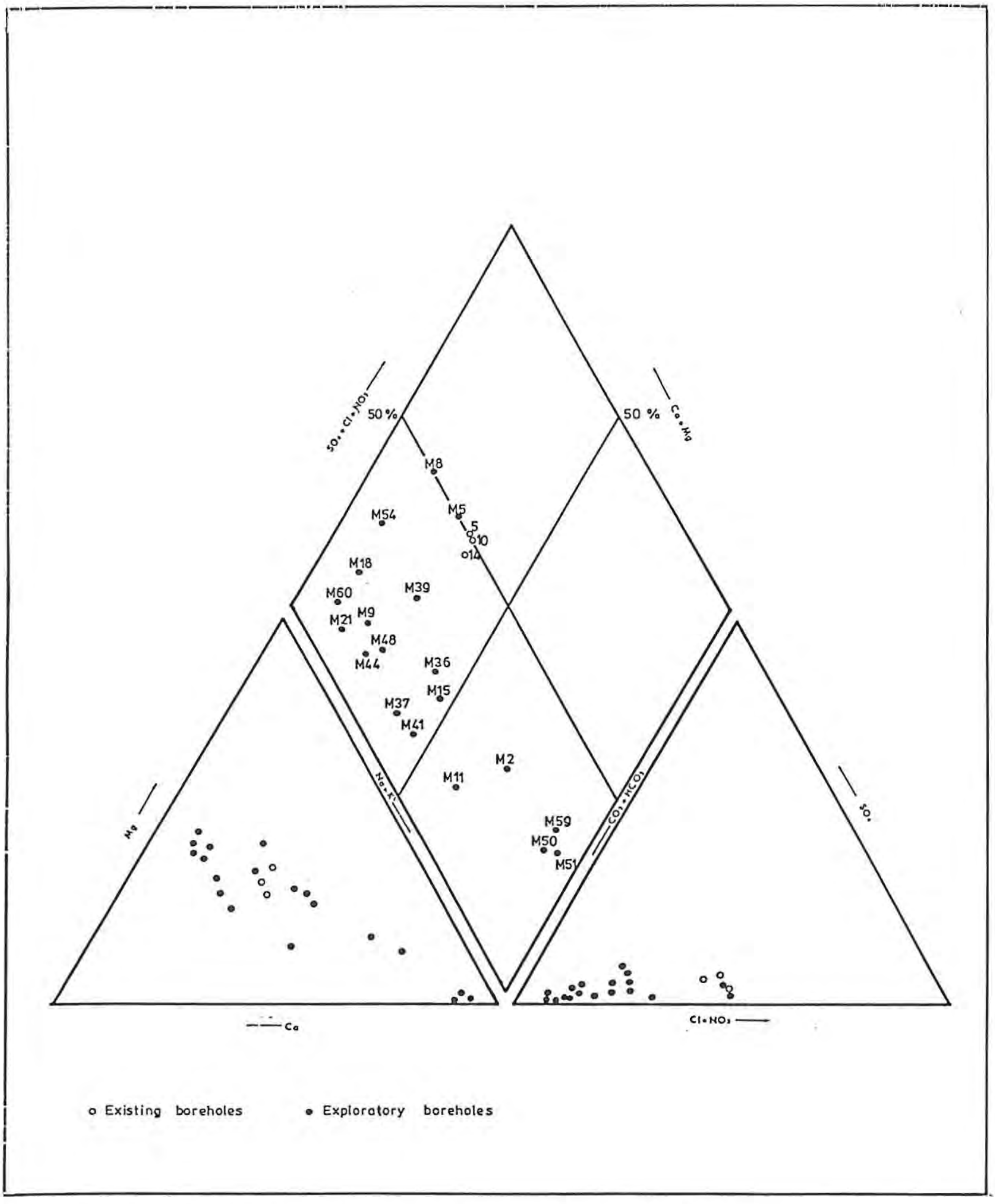


FIG. 37 PIPER PLOT OF EXISTING AND EXPLORATORY BOREHOLES

than one sample was collected during testing, the last one is chosen for the Piper plot.

The majority of the waters plot within the diamond field of the Ca, Mg + HCO_3 type. In particular samples M9, M21 and M60 plot in the area representing recent recharge waters. The positions of boreholes 5,10,14,M5 and M8 in the anion triangle are again affected by the high concentrations of the NO_3 ion (Table B2). Samples from boreholes M2,M11,M50,M51 and M59 fall within the Na + HCO_3 field with the latter three showing a more sodic character.

The calcium/magnesium bicarbonate waters are representative of recent recharge with local, dynamic ground water flow conditions. The waters grouped within the sodium bicarbonate field (Fig. 37) and especially M50,M51 and M59 would indicate the effects of a base exchange of calcium and magnesium ions for sodium, as a result of an increase in clay content within the aquifer. This conclusion is supported by the limited fracturing found at M50 and M51 during drilling and the poor hyraulic behaviour (T=0,7 and 0,8 m^2/d respectively) of these boreholes (Table 7).

The TDS values of figure 38 (a) range between 300 and 870 mg/l and show no distinct pattern. Figure 38 (b) is the plot of the (Cl)/(HCO_3) ratio shows the general recent recharge character of the waters.

The small variation in the chemical character of the waters with time of selected boreholes is seen from Tables B1 and B2. The lack of pronounced temporal changes is a reflection of the uniformity of the ground water quality and the areally extensive nature of the ground water body. From the Piper diagrams of Figures 35 and 36 the similar plotting positions of waters from the sandstone eg. 16 and 22 (Fig. 35) and from the rest of the boreholes (Fig. 37) is further evidence of the hydraulic continuity between these two formations.

11.3. Groundwater Quality

For human consumption the use of ground water is controlled by its chemical and bacteriological quality.

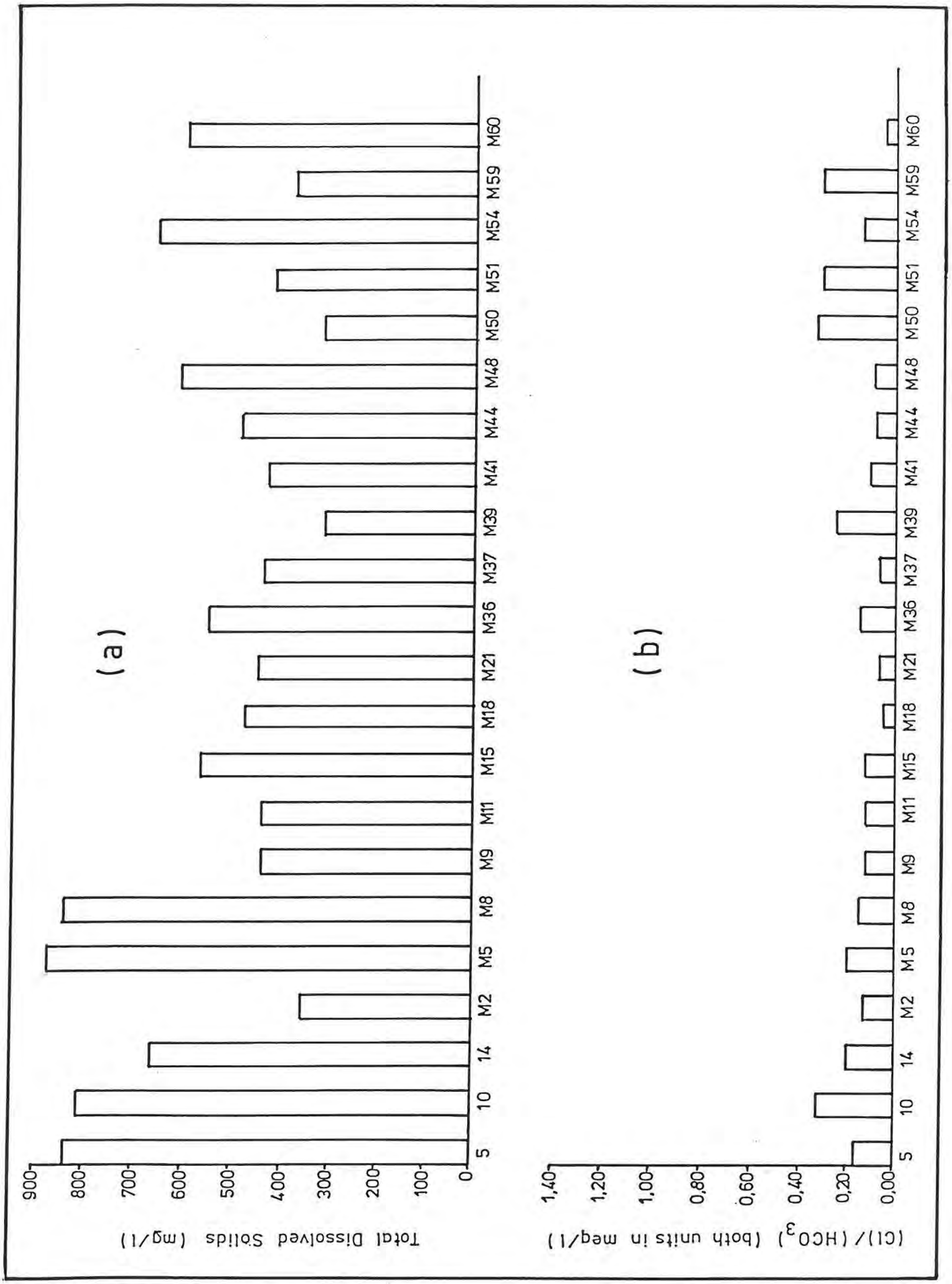


FIG. 38 HISTOGRAMS OF CHEMICAL CHARACTERISTICS - EXISTING BOREHOLES AND EXPLORATORY BOREHOLES

For industrial usage only the chemical character is of importance.

11.3.1. Quality for Human Consumption

Tables 10 and 11 summarise the number of samples falling within recommended and maximum permissible levels as specified by the South African Bureau of Standards (1971) and the World Health Organization (1962) for various constituents. From Tables 10 and 11 it is clear that the quality of the ground waters is generally acceptable for human consumption. Exceptions occur in some samples where the NO_3 and F contents are above the maximum limits. The presence of these high values is discussed in detail below.

In general the waters tend to be slightly hard. Scale formation is therefore likely to occurr. The low Cl and SO_4 values render these water non-corrosive. Physical properties such as turbidity, colour and unpleasant tastes and smells were not present. The suspended solids content in all cases is less than 1 mg/l which is considered acceptable (Custodio and Llamas, 1976).

11.3.2. Nitrates in Groundwater

Two specific diseases have been linked to water containing nitrate concentrations higher than 45 mg/l. One is methaemoglobinaemia or infantile cyanosis and the other is carcinogenesis. The former has been linked to relatively few reported cases. For the latter, information is too limited for allowing any conclusions (Lewis, Foster and Drasar, 1980). Nevertheless the potential health hazard of nitrate pollution cannot be overlooked.

The presence and cause of nitrate contamination in groundwaters in various areas of the world has been reported by several authors (Kreitler and Jones, 1975; Gormly and Spalding, 1979; Robertson, 1979). In particular in the ground waters of the Springbok Flats its presence has been reported by Verhoef (1973), Porszasz (1976)

TABLE 10

SUMMARY OF CHEMICAL DATA SHOWING THE RELATIONSHIP BETWEEN THE VARIOUS CONSTITUENTS TO WHO/SABS STANDARDS - EXISTING BOREHOLES

CONSTITUENTS	RECOMMENDED AND MAXIMUM PERMISSIBLE WHO/SABS STANDARDS	STANDARDS RANGE		
pH	6,5-8,5	<6,5	6,5-8,5	>8,5
		-	11	-
TDS (mg/l)	500-1500	<500	500-1500	>1500
		6	5	
Ca (mg/l)	7-200	<200	>200	
		11	-	
Mg (mg/l)	100-150	<150	>150	
		11	-	
Fe (mg/l)	0,3-1	<0,3	0,3-1	>1
		11	-	-
Mn (mg/l)	0,1-0,5	<0,1	0,1-0,5	>0,5
		-	-	-
Total Hardness as $CaCo_3$ (mg/l)	200-1000	<200	200-1000	>1000
		9	2	-
Cl (mg/l)	200-600	<200	200-600	>600
		11	-	-
SO_4 (mg/l)	200-400	<200	200-400	>400
		11	-	-
NO_3 as N (mg/l)	10	<10	>10	
		6	5	
F (mg/l)	1,5	<1,5	>1,5	
		11	-	

TOTAL NUMBER OF SAMPLES = 11

TABLE 11

SUMMARY OF CHEMICAL DATA SHOWING THE RELATIONSHIP BETWEEN THE VARIOUS CONSTITUENTS TO WHO/SABS STANDARDS - EXPLORATORY BOREHOLES

CONSTITUENTS	RECOMMENDED AND MAXIMUM PERMISSIBLE WHO/SABS STANDARDS	STANDARDS RANGE		
pH	6,5-8,5	<6,5	6,5-8,5	>8,5
		-	22	-
TDS (mg/l)	500-1500	<500	500-1500	>1500
		13	9	-
Ca (mg/l)	7-200	<200	>200	
		22	-	
Mg (mg/l)	100-150	<150	>150	
		22	-	
Fe (mg/l)	0,3-1	<0,3	0,3-1	>1
		21	1	
Mn (mg/l)	0,1-0,5	<0,1	0,1-0,5	>0,5
		22	-	-
Total Hardness as $CaCo_3$ (mg/l)	200-1000	<200	200-1000	>1000
		8	14	-
Cl (mg/l)	200-600	<200	200-600	>600
		22	-	-
SO_4 (mg/l)	200-400	<200	200-400	>400
		17	-	-
NO_3 as N (mg/l)	10	<10	>10	
		13	9	
F (mg/l)	1,5	<1,5	>1,5	
		18	4	

TOTAL NUMBER OF SAMPLES = 22

and Hewitt (1980). Of interest is a study by Heaton (1985) who suggested that the process of nitrification is responsible for the high concentations of NO_3 in this area. This process is associated with an increase in the conversion of virgin areas into arable lands. In addition this process is continued by the cultivated soils left fallow between crops and contributing to an increase in nitrate with time.

The above conclusion was reached after comparing the isotopic composition (δ 15 N values) of ground water nitrate with the δ 15 N values of potential sources of nitrate i.e. rainwater, fertilizer, animal waste and "black turf" soils. The results indicated that the isotopic composition of the groundwater nitrate is identical to that of the soil nitrate and distinctly different from the compositions of the other sources (Fig. 39). However Lindau and Spalding (1984) note that the δ 15 N values are influenced by the volumes of extracting solution used. This leads to misinterpretation of the sources of nitrate. In addition Heaton (1985), from ^{14} C data, suggests that the leaching of the soil nitrate into the "shallower portions of the aquifer" has taken place during the last 30 years.

Intrepretation of land use from aerial photographs shows that approximately 84% of the basalt outcrop is and/or has been placed under cultivation. The point distribution map of NO_3 values (Fig. 40) shows two distinct areas of NO_3 values above the maximum recommended limit of 45 mg/l. If nitrification is the main source then the distibution of these values should have been more homogeneous.

Samples analysed for isotopic dating using tritium (^3H) and carbon (^{14}C) falling within the larger high nitrate area are also plotted on figure 40. The Tritium values are mostly representative of waters more than 30 years old (Table 13). Exceptions are the values at boreholes 6,11 and M8 which are interpreted to include a small percentage of younger waters (Table 13). Of interest are the ^{14}C values (boreholes 10 and 5) which show contrasting ages of less that 30 years (Table 13; Fig. 40). In the smaller area of high nitrates, there is no information on the isotopic age of the waters.

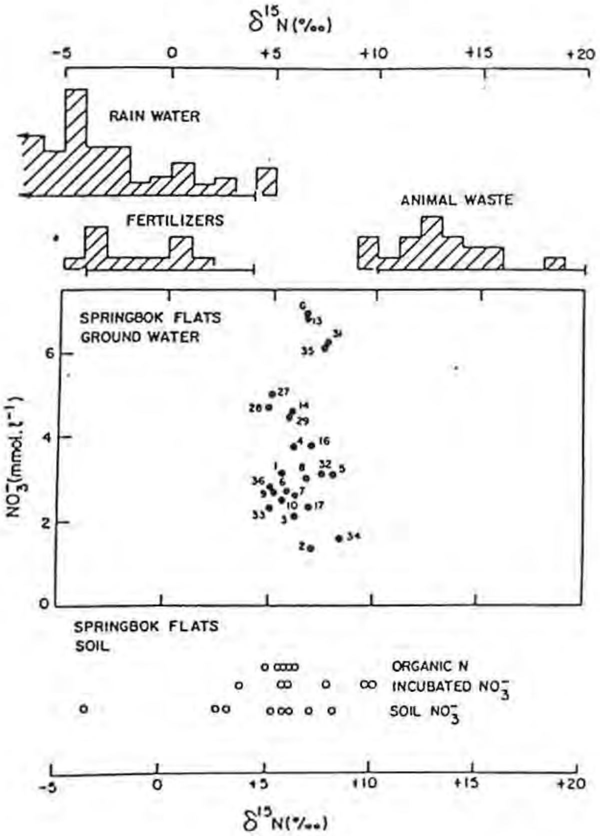


FIG. 39: ISOTOPIC COMPOSITION OF GROUND WATER IN THE SPRINGBOK FLATS COMPARED OTHER SOURCES OF NITRATE (After HEATON, 1985)

The only isotopic value which includes some recent waters (less than 30 years) is found in M8. The presence of shallow water strikes within the basalt encountered in this borehole during drilling would tend to support Heaton's conclusion that the nitrate leaching has taken place along the shallower portions of the aquifer within the last 30 years. However the data are too scanty to comfirm this conclusion.

The derivation of the nitrates from the basalt itself was discounted by Verhof (1973). Heaton (1985) states that "under special environments nitrate rich horizons may occur in rock formations, but in all cases the nitrate is accompanied by higher concentrations of the other soluble anions eg. SO_4 and Cl". Figure 41 is a plot of the nitrate concentrations versus the concentrations of the other anions (less nitrate). This

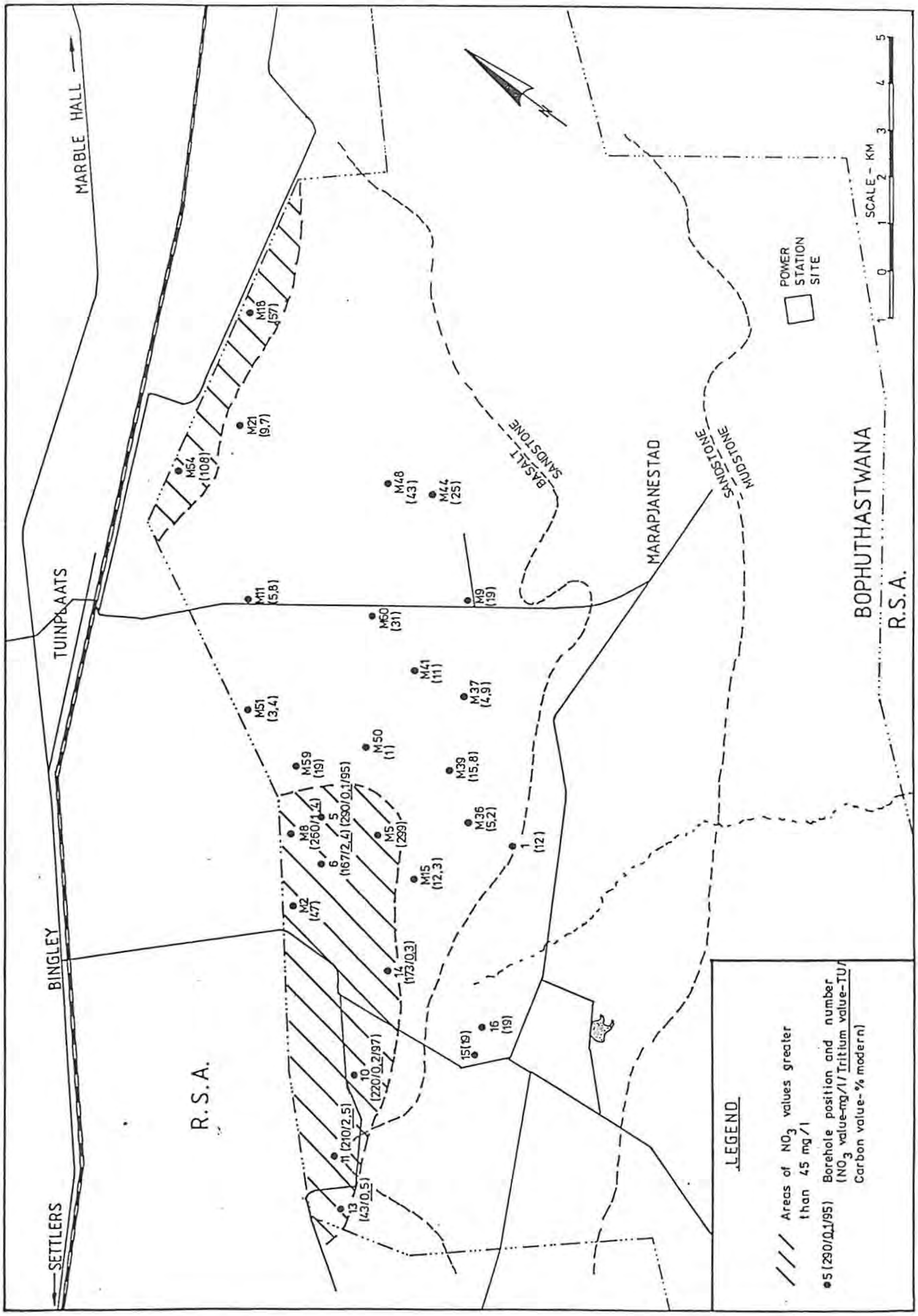


FIG. 40 <u>POINT DISTRIBUTION OF NITRATE CONCENTRATIONS AS WELL AS TRITIUM AND CARBON ISOTOPIC DETERMINATIONS</u>

plot illustrates that an increase in nitrates is followed only by a small increase in the other anions. The low correlation coefficient (r) of 0,37 is further evidence that the source from which the nitrate is derived is different from that which supplies the other anions.

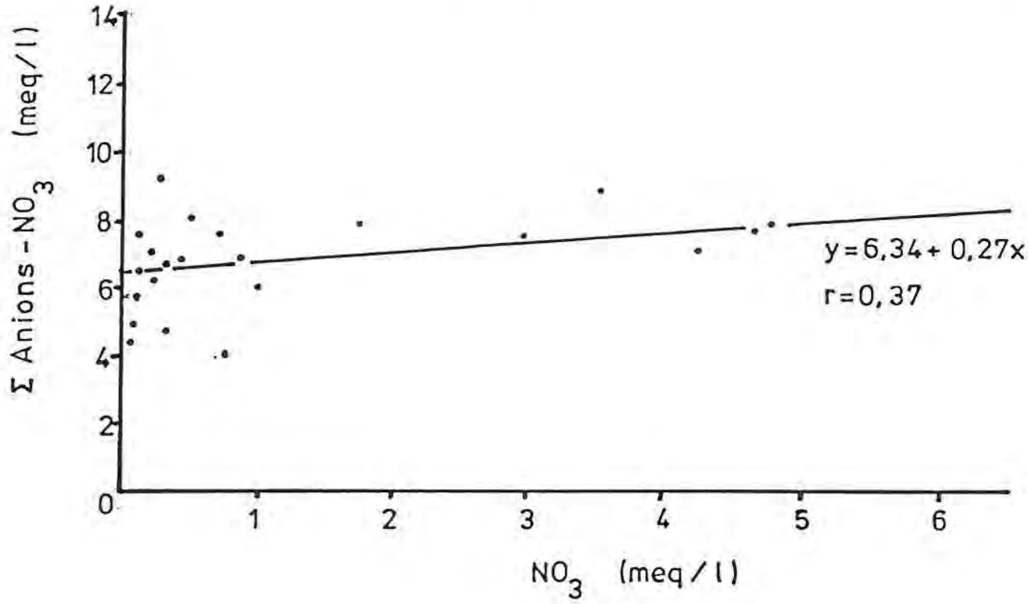


FIG. 41 : PLOT OF NITRATE COMNCENTRATIONS VS ALL OTHER ANIONS

From the above discussion it appears that the presence of high nitrates in the area under study cannot be explained as a local phenomenon associated with cultivation practices. By considering the isopiestic network of figure 33 it is interesting to note that the path of the contaminated front moves in the same direction as the ground water. It is therefore suggested that contamination takes place somewhere north of the area and migrates south under natural hydraulic conditions. Furthermore the greater advancement of the western front is seen to be associated with the zones of high T (Fig. 26).

11.3.3. Fluorides in Ground Water

Fluoride is an important constituent in the formation of human teeth. Although it is not toxic, concentrations in excess of 1 mg/l are the cause of dental fluorosis (mottled enamel) (Bond, 1946). In this area the presence of fluoride in excess of 1 mg/l is particularly associated with ground waters having a sodium bicarbonate character (Figs. 35 and 37). The plots of boreholes 16 and 22 in the Na + HCO_3 field (Fig. 35) have fluoride values below 1 mg/l. The chemical results for the exploratory boreholes are in accordance with Davies and De Wiest (1966) who note that F is less than 1 mg/l where calcium is present in high amounts (Table B2). Bond (1946) reports that various geologies are possible sources of fluoride. In this case there is not enough data to correlate geology with the presence of fluoride. However the distribution of these high values seems to be associated with boreholes tapping relatively deep waters eg. 11, M50, M51 and M59. Hewitt (1980) reported a Fluoride content of 5 mg/l in a borehole which intersected the basalt sandstone contact at 208 m. Talma (personal communication, 1985) measured the age of this water to be more than 1000 years. Comparing the ages from waters of boreholes 11 and M59 these are found to be more than 30 and 15 000 years respectively (Table 13).

11.4. Bacteriological Quality

Pathogenic organisms are rarely found in groundwater (Walton, 1970). These organisms, when transmitted through contaminated water, are responsible for various intestinal diseases (Lewis, Foster and Draser, 1980). Since the coliform group of bacteria is common to the faeces of all warm-blooded animals it has been selected as an indicator organism (Lewis, Foster and Draser, 1980). The determination of faecal coliforms (E. Coli) are therefore used as indicators of faecal pollution.

In total 28 samples were collected and analysed for bacterial content. The results are summarized in Table 12 (a). These results are compared to the S.A.B.S. (1971) drinking water standards for bacteriological requirements Table 12 (b).

It is seen from Table 12 (a) that the total coliform and the faecal coliform counts are within the maximum allowable S.A.B.S. limits. The waters are therefore bacteriologically acceptable. An exception is the sample from M36 where the abnormally high value is an indication of human pollution. There is no field evidence eg. pit latrine or livestock enclosure, for such a high value. Its presence is ascribed to either operator, sampling or laboratory error.

TABLE 12 (a)

SUMMARY OF BACTERIOLOGICAL RESULTS

BOREHOLE NO.	TOTAL COLIFORM BACTERIAL COUNT per 100ml	FAECAL COLIFORM BACTERIAL COUNT per 100ml	STANDARD PLATE COUNT per ml
1	1	0	+ 37
5	0	0	+ 1000
6	0	0	+ 1000
10	0	0	+ 18
15	0	0	347
16	0	0	155
22	0	0	52
5	0	0	+ 1000
10	0	0	18
14	33	0	-
M 2	19	0	-
M 8	25	0	+ 1000
M 9	1	0	+ 1000
M 11	14	0	300
M 16	0	0	+ 1000
M 18	1	0	305
M 21	0	0	290
M 5	24	0	386
M 41	2	0	81
M 44	20	0	223
M 48	30	0	+ 1000
M 51	34	0	+ 1000
M 54	20	0	510
M 59	>1000	0	404
M 60	134	0	+ 1000
M 38	87	0	+ 1000
M 36	53	45	550
M 39	0	0	144

+ Sign = more than

TABLE 12 (b)

S.A.B.S. DRINKING WATER STANDARDS FOR

BACTERIOLOGICAL QUALITY

ORGANISM	*RECOMMENDED LIMIT*	*MAXIMUM ALLOWABLE LIMIT*
Total Coliform bacterial count per 100 ml	*	10
Feacal Coliform bacterial count per 100 ml	ml	Nil
Standard Plate count per 100ml	100	NOT SPECIFIED

* a) If any coliform organisms are found in a sample, a second sample shall be taken immediately after the tests on the first sample have been completed and shall be free from coliform organisms, and

b) not more than 5 per cent of the total number of water samples (from any one reticulation system) tested per year may contain coliform organisms.

11.5. Industrial Use

The quality requirement for industrial processes varies according to the specific application (Hem, 1970). The corrosive and scaling nature of the water is of prime importance when passing through the boiler and condenser units of a power station (Bond, 1946). Since the raw water from the boreholes will be passed through a demineralization plant its original characteristics will be changed to suit the operating conditions.

11.6. Environmental Isotopes in Groundwater

The main uses of environmental isotopes in hydrogeological studies are associated with the dating and tracing of groundwater movement (Davies and De Wiest, 1966). Being a new technique, isotopic dating was firstly found useful but limited in scope (Lloyd, 1981). Lloyd (1981) further states that many external factors affect their concentrations in groundwaters. This limits their use to qualitative interpretation. They are usually utilized when dealing with regional hydrogeological studies (Custodio and Llamas, 1976). The most commonly used isotopes are tritium (^{3}H) and carbon (^{14}C) and these were used in the present study. Their results are summarized in Table 13 and their distribution is illustrated in figure 42.

The limited tritium data available indicates that the majority of the waters are older than 30 years. According to Brown et al (1972) such low values usually occur within confined aquifers. The lack of variation in ^{3}H values with time (Table 13) indicated that there has been no lateral mixing of waters of different ages. Exception is the value of borehole 6. As seen from figure 42 the distribution of values above 1 tritium unit (TU) are mainly concentrated around the area of high transmissivities (Fig. 26) and where more than one water strike was encountered (Chapter 8). Vertical mixing with a very small portion of recent recharge waters from the upper water bearing horizons could have occurred. The general decrease in tritium values from the South African border towards the basalt/sandstone contact zone is in accordance with the noted regional groundwater flow pattern. The difference in tritium values over short distances suggests anisotropic recharge conditions.

Samples with a content of more than 85% of ^{14}C are considered to be of 'modern' (less than 30 years) age (Brown et al., 1972). Such values are only found in boreholes 5, 10 and M48 (Table 13). The lower amount of Carbon values show that there is a decrease in ^{14}C content

TABLE 13

SUMMARY OF THE ISOTOPIC DETERMINATIONS FOR TRITIUM (^3H) AND CARBON (^{14}C) AND INTERPRETED AGE MODEL

Borehole No.	^3H (TU)	Age Model (Years)	^{14}C (%)	Age Model (Years)	Pumping Time (Mins)
1	0,1 ±0,2	>30	–	–	6000
5	0,2 ±0,2	>30	–	–	2700
	0,3 ±0,2	>30	–	–	6000
6	0,4 ±0,2	>30	–	–	3000
	2,4 ±0,5	Mix with younger water(?)	–	–	6000
10	0,2 ±0,2	>30	–	–	2650
	0,0 ±0,2	>30	–	–	6000
11	2,2 ±0,5	Mix with younger water(?)	–	–	3000
	2,7 ±0,5		–	–	6000
14	0,3 ±0,2	>30	–	–	3215
	0,3 ±0,2	>30	–	–	6000
15	0,0 ±0,2	>30	–	–	6000
21	0,9 ±0,2	>30	–	–	6000
22	0,2 ±0,2	>30	–	–	3210
	0,2 ±0,2	>30	–	–	6000
5	0,1 ±0,2	>30	95,3 ±0,6	<25	43200
10	–	–	97,1 ±0,5	<25	43200
14	0,3 ±0,2	>30	–	–	43200
M8	1,4 ±0,4	Mix with younger water(?)	–	–	14400
M9	0,2 ±0,2	>30	76,0 ±0,5	630	14400
M11	0,2 ±0,2	>30	–	–	14400
M15	0,1 ±0,2	>30	79,3 ±0,5	560	43200
M21	1,4 ±0,3	Mix with younger water(?)	–	–	14400
M36	0,3 ±0,2	>30	–	–	43200
M38	0,2 ±0,2	>30	65,0 ±0,7	2160	14400
M41	–	–	70,5 ±0,8	>1510	44500
M48	–	–	96,5 ±0,8	<25	43200
M59	–	–	13,7 ±0,4	>15000	14400

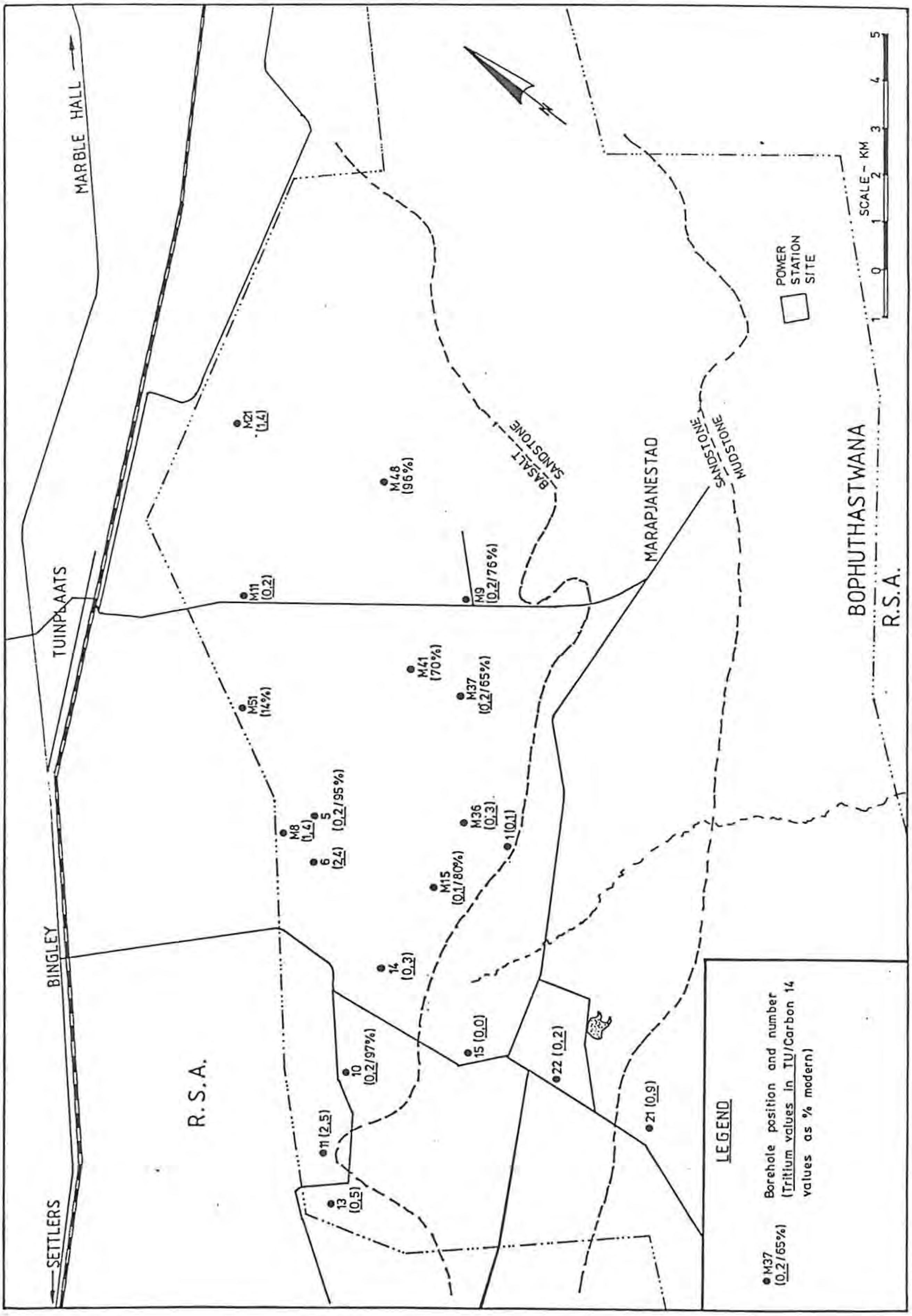


FIG. 42 POINT DISTRIBUTION OF TRITIUM AND CARBON ISOTOPIC VALUES

towards the sandstone surface outcrop (Fig. 42). The exceptionally low value found at M51 is associated with the pocket of high fluoride waters. Similar low values have been recorded in the deeper parts of the basin (Talma, personal communication, 1985). The variation of Carbon values over distance again represents anisotropic recharge and/or flow rate conditions.

When comparing isotopic values from the same boreholes they are in accordance with each other eg. M9, M16 and M38 (Table 13). Exceptions are the values from boreholes 10 and 5. As an overall comment the limited data available shows that ground water movement is seen to be sluggish and recharge to the area is areally limited. This is contrast to the hydrochemical data of Chapter 10 where the general character of the waters indicates recent recharge and local, dynamic circulation.

11.7. Summary

The ground waters sampled in the area under study from the basalt and sandstone formations display similar chemical characteristics. The only sample collected from the predominantly argillaceous sequence of the Irrigasie Formation exhibits a marked chemical change in character when compared to the other formations.

The majority of the ground waters within the basalt and sandstone have a Calcium/Magnesium bicarbonate character thus reflecting local recharge and a dynamic circulation pattern. The Na, Cl + SO_4 character of the sample from the mudstone reflects that the chemical evolution of the ground water has been influenced by the very low permeation properties of this rock.

The influence of man's activities is seen by the presence of higher than normal nitrate values in parts of the area. The source of these nitrates is thought to be related to the process of nitrification (Sub-section 11.3.2). This conclusion however could not be confirmed with the limited data available for the area of study.

The results of the isotopic measurements provide limited support to the conclusions reached by the analyses of the chemical character of the ground waters. In instances even the values of ^{3}H and ^{14}C determinations from the same boreholes do not coincide. In general the ground waters are older than 30 years, according to Tritium values. The distribution of high values of either ^{3}H or ^{14}C represent anisotropic recharge conditions.

The ground waters are generally suitable for human use. Exceptions arise where boreholes encounter high nitrate or flouride waters.

The collection of water samples is the end of the field investigation phases. Chapter 12 is an attempt to quantify the amount of ground water recharge and storage in the area of interest. Management recommendations are formulated in the light of the results obtained. In Chapter 13 the study hypotheses are tested against the results of the completed investigation. Chapter 14 delineates the overall conclusions of the study.

12. GROUNDWATER RESOURCES

12.1. Groundwater Recharge

Direct recharge usually takes place via infiltration of rainwater. In the area under study this is thought to be the prevalent mechanism. The difficulty in estimating recharge is associated with the various factors which influence this compoment eg. the amount of effective infiltration, which itsself is related to the duration and intensity of precipitation, evapotraspiration, runoff, type of soil and vegetal cover. This Chapter therefore attempts to quantify recharge to the area of interest using all available information.

Recharge can be estimated by assuming that the rise in water level after a rainfall event is related to a change in volume (storage) in the aquifer (Custodio, 1981). There is a limited amount of water level fluctuations data in the area under study (Fig. 32). The water level data prior to 1984 of figure 31 are used in the following relationship

$$R=S.A.h \quad \text{....(13)}$$

where S= storage coefficient, A= surface area of the aquifer (170 Km^2) and delta h is the average rise in the water level (0,30 m.) as seen during the years 1977-78, 1979-80, 1980-81, 1981-82 and 1983-84 (Fig. 31). By using a figure of $S=1 \times 10^{-3}$ recharge to the aquifer is equal to 51 000 m^3 per annum. The average rainfall over this area is 630 mm. This amounts to 107×10^6 m^3 over the surface area of 170 Km^2 hence the recharge calculated with the above method is equivalent to 0,05% of the precipitation. This figure seems unrealistically low due the small water level change of 0,30 m. This noted small change is related to the influence of the abstraction for irrigation around this borehole (Sub-section 10.1.1). The amount of pumping in the vicinity of this borehole is not known. Hence from the fluctuations in water level the effect of pumping and the amount of natural infiltration cannot be separated. The figure thus calculated cannot be used towards the quantification of recharge. In addition, according to Boonstra and de Ridder (1981) the above relationship should not be used for confined conditions.

From the hydrographs of the area under study, where the influence of pumping is, to an extent lessened, values for recharge ranges from 1,02 x 10^5 m3 for borehole M19 and 3,40 x 10^4 m^3 for borehole M6 (Page 85). The information is limited by the amount of data available to be considered representative of recharge in the area.

The decline of the water levels during 1984-85 within PL 85 (Fig. 31) amounts to a loss in volume of 4,3 x 10^5 m^3 for this period. For the same period (1984-85) using the water level data of figure 32, the decline in volume is calculated to be 1,2 x 10^5 m^3.

Water also enters the area via ground water through flow. Applying Darcy's law:

$$Q=i.T.L \qquad ...(14)$$

where i is the piezometric gradient and T is the transmissivity for the various zones of differing transmissivity values (Fig. 26) and L is the average width of the aquifer at each transmissivity zone. By giving to the hydaulic gradient a value of 6 x 10^{-2} for the eastern part and 4 x 10^{-4} to the western area (Page 88) the total computed flow across the area is 2,27 x 10^6 m^3/annum or 72 l/s. This value is equivalent to 2% of the average precipitation over a phreatic catchment area of 1700 Km^2. A figure of 3% of rainfall was assumed for effective recharge in a computer model by Hodgson (1985) for the water levels in the area under study to stabilize. However the true amount of through flow is disguised by the decline in water levels from the end of 1984 onwards. Recalculating using gradients of 3 x 10^{-3} for the western and 2 x 10^{-4} in the eastern areas the amount of through flow is reduced to 2,6 x 10^5 m^3 or 8 l/s for the 1984-85 period.

The calculated amounts of through flow are also beset by the same inherent errors which characterize the recharge values using the water level rise method. These values should thus be considered with extreme caution.

With the potential evaporation data available it was attempted to calculate the possible recharge from the soil moisture balance proposed by Custodio and Llamas (1976). The results obtained with this method indicate that there are no surpluses within the unsaturated zone to allow for an effective infiltration of rainwater. This is an unrealistic situation. Custodio and Llamas (1976) suggest that when applying this method rainfall should be uniformly distributed throughout each month or important variations in the results are obtained. As rainfall patterns in this area are characterized by rain storms of a very short duration the applicability of this method is therefore inhibited. Furthermore the main soil types ie. "black turf" and the red soils, are thought to display differing absorbing properties. According to Fischer (1962) the swelling and shrinking properties of the "black turf" and the rapid disintegration of the peds essentially impede infiltration after the first few raindrops. Conversely the red soils which possess a good pedal structure are thought to improve rainwater infiltration (Fischer, 1962). The differing infiltration exhibited by these two soils cannot obviously be simulated within the soil water balance. It is more likely that recharge takes place locally around small depressions, such a model would be in accordance with the scattered isotopic values reported in Section 11.6 (Page 108).

12.2. Groundwater Storage

The amount of temporary storage has been already calculated with the water level rise method to vary between 51000 m^3 and 1,2 x 10^5 m^3 (See above Section). An estimation of the amount of ground water available from permanent or "dead" storage of the contact aquifer is given by multiplying the saturated thickness of the aquifer, an average of 30 m, by the area (170 Km^2) and its storage coefficient (1 x 10^{-3}). A figure of 5 x 10^6 m^3 is thus obtained. Due to the anisotropy of the aquifer the above figure is regarded as an order of magnitude of ground water in storage. By assuming that the noted decrease in water level after 1984 will continue, a decrease in storage will result. It therefore seems that even without abstraction taking place in the area of interest, limited depletion from "dead" storage is already taking place. This will influence the way in which the water resources of the area is managed.

It would therefore appear that a reliable figure for recharge to the area cannot be calculated using the available data. From literature recharge figures, in particular for basaltic terrains elsewhere, range from 10% to a high of 25% of the annual rainfall (Brown et al., 1972). Custodio and Saenz-Oiza (1972) estimated a long term recharge in the Canary Islands, where rainfall is less than 200 mm/year, to be not more than 10-15 mm/year (5-7,5%). It is therefore unlikely that recharge in this area would be less than the figures given above. Especially when the flat topography and an average rainfall of 630 mm/year characterize this area.

12.3. Management Recommendations

The aquifer management recommendations are formulated to satisfy the 30 year requirement of 2440 m^3/d. The recommedations take into account the variable ground water development potential, the anisotropic nature, the changeable hydraulic properties and related borehole outputs over short distances which characterise this aquifer. The influence of the abstractions from the north (Sections 12.1 and 12.2) has also been taken into consideration.

Lower borehole discharges and spacings chosen to minimize aquifer drawdowns and interference effects are given in Table 14. The positions of the selected production boreholes can be seen in figure 13.

Borehole No.	Depth of Pump Inlet (m)	Static Water Level (m.b.g.l.)	Maximum Yield (l/s)	Abstraction (m^3/d)	Remarks
5	50	12,3	4	345	
M3	25	14,1	4	345	STANDBY
M4	23	16,5	4	345	
M5	50	13,8	2,5	215	STANDBY
M8	50	12,9	4	345	
M15	50	14,7	4	345	
M36	22	14,6	2,5	215	
M37	31	13,8	2,5	215	
M39	46	15,0	2,5	215	
M41	41	18,1	3	260	
M48	26	16,0	3	260	
		Total	29,5	2550	

TABLE 14 : SUMMARY OF MANAGEMENT RECOMMENDATIONS

The proposed management recommendations as detailed in Table 14 rely on the results of the test pumping programme, where the complete recoveries indicate long term reliability of the supply (Sub-sections 9.2.1. and 9.2.2.), and a sensitivity analysis using a finite element computer model by Hodgson (1985). The simulation takes into account the large scale abstractions (34000 m^3/d) occurring to the north of the study area as well as the wellfield's demand. An assumed figure of 3% effective recharge sustained the combined irrigation and wellfield demands at the present abstractions for the anticipated 30 years demand. This value would therefore seem to be realistic for the area.

Unfortunately due to financial constraints the completion of the power station has been temporarily shelved. Water level measurements in the area under study are only available up to 1985 (Fig. 32). Should constuction be resumed a quantified assessment of the amount of effective recharge to the aquifer is imperative. As the pumpage to the north will effect the amount of ground water through flow, the installation of a monitoring system within the wellfield is crucial in following the evolution of the water level trends and to build up aquifer history. The resumption of the recording of the water level and an estimation of recharge by using environmental isotopes are suggested. The latter technique has been used succefully by Bredenkamp (1978). However it is proposed that from the results obtained during the test pumping programme and the computer model´s analysis, the yields recommended in Table 14 will satisfy the water requirements of the power station.

12.4 Summary

The quantitative assessment of ground water recharge is a problem that invariably besets the ground water analyst. To a large extent recharge remains an indeterminate variable. Unfortunately this has proven to be the case. The attempts to calculate recharge by means of the data available yielded either to be unrealitic or no solution was possible. The formulation of the management recommendations therefore relied on a computer model were the major controls to the aquifer behaviour were the irrigation abstractions and the value assigned to recharge. The assumed value of 3% used in the computer model would seem to be valid for the quantification of recharge within this area. In the next Chapter the study hypotheses as postulated in Chapter 4 will be tested against the results obtained during the field investigation.

13. HYPOTHESIS TESTING

Hypothesis 1 : Complex aquifer hydraulic conditions occurr within the basalt because of lithological anisotropy

From previous investigations (E. Martinelli and Associates, 1976, 1977; Martinelli, 1980; Martinelli and Hubert, 1980; Taylor, 1980; E. Martinelli and Associates, 1983) consulted during the desk study (Section 6.1.) an indication of the high potential for ground water exploitation of the basalt was gathered.

The variability in yields reported during the desk study (Page 17) and the data collected during the hydrocensus (Page 18) indicate the anisotropic nature of the basalt. The general anisotropy of the basalt was further illustrated by the results of the geoelectrical survey (Section 7.2.). During drilling a few water strikes were found within the basalt rockmass (boreholes M3, M5, M6, M7 and M8). The majority of the water strikes were however encountered above the contact with the underlying sandstone (Section 8.1). The variation of yields over short distances is evidence of strong anisotropic ground water flow conditions (Davies and De Wiest, 1966). Indeed the difference in blowing yields between observation borehole M3 and the reported yield of existing borehole 10 confirms this conclusion. The presence of anisotropy is also reflected in the hydraulic behaviour of the of the basalt contact aquifer. The presence of ´pseudo´ barrier boundary conditions in some boreholes and difference in water level between pumping and observation boreholes M9/M10 is the result of the anisotropy of the medium.

From the test pumping results storage coefficients varied from 0,46 and 1×10^{-5}. This indicates that the hydraulic characteristics of this aquifer vary from unconfined to totally confined hence they are a reflection of the anisotropic nature of this aquifer. The transmissivity values varied between 15 and 1250 m^2/d. This large variation in T values is further confirmation of the anisotropic nature of this aquifer with the higher values associated with areally extensive fracturing development. This hypothesis is therefore accepted.

Hypothesis 2 : Relatively simple aquifer hydraulic conditions are present within the Clarens sandstone because of the primary characteristics and isotropic nature of the Formation

The primary porosity nature of this formation is reported in Sub-section 2.3.2. (Martinelli, 1980). During the desk study, for the Clarens Sandstone Formation, the discharges were reported to vary between 0,8 and 2 l/s (E. Martinelli and Associates 1983 (a) and (b)). The narrow variation of reported low yields, gathered during the hydrocensus, is evidence that the aquifer is homogeneous and ubiquitously saturated (Page 20). The geoelectrical survey results indicated that the sandstone is relatively homogeneous in character (Page 35). During drilling operations in boreholes where the sandstone was intersected at 30 m or less below the contact, yields were found to be minimal eg.M18 (2 l/s), M19 (1 l/s). Where only the sandstone was intersected eg. M12, M13 and M14, yields recorded were all less than 0,1 l/s (Section 8.1). The hydraulic parameter of Transmissivity of boreholes situated on the sandstone outcrop (Fig. 6) range from 0,7 m^2/d to 17 m^2/d (Table 6). This narrow range in T values is representative of uniform hydraulic conditions. This hypothesis is accepted.

Hypothesis 3 : There is hydraulic interconnection between the basalt and sandstone rock units

Where water strikes occured only in the basalt (boreholes M5 and M6) and in the basalt as well as the contact (boreholes M3, M7 and M8) the water levels were found to be the same. This is evidence of an hydraulic continuity between the basalt and basalt/sandstone contact aquifers (Page 44). The uninterrupted isopiestic network extending itsself into the sandstone formation (Page 89) points to an hydraulic continuity between the basalt and sandstone aquifers. The hypothesis is accepted.

Hypothesis 4 : Water from each of the major aquifer types can be distinguished by their hydrochemical properties

The comparison of plots of the ionic concentrations on Piper diagrams (Figs. 35 and 37) shows a uniformity in the chemical character of the waters from the basalt and sandstone aquifers. The different hydrochemical composition of the borehole sited on the mudstone is clearly seen in figure 35. Where the nitrate concentration is above than normal, waters could be classified as coming from the basalt. The presence of this anion must not be, however, considered as diagnostic. From the bacteriological analyses, ground waters cannot be used to distinguish the various geologies. The hypothesis is, therefore, partly accepted.

Hypothesis 5 : There is active aquifer recharge via direct infiltration of rainfall which is in excess of the expected abstraction volume

The isopiestic network shows that the area is part of a regional ground water circulation system. The conceptual model suggests that recharge takes place around the Warmbath area and ground water flows from the north west to the south eastern part of the basin as through flow (Page 89).

An attempt to calculate recharge from rainfall using the water level fluctuations, Darcy's law and a soil moisture balance yields inconclusive results (Section 12.1.). Variable recharge conditions are, however, suggested by the presence of differing soil types with unequal infiltration capacities. The distribution of ^{3}H and ^{14}C values of figure 41 (Section 11.6.) would tend to support the evidence.

The results of the test pumping programme have indicated that the aquifer is areally extensive and bound by "pseudo" hydraulic barrier boundaries. Nevertherless the recovery trends show that it is able to support sizeable yields in the long term. However, by having lower yielding widely spaced boreholes, as put forward in the management recommendations of Section 12.3, the water requirement of 2440 m^3/d (8,9 x 105 m^3/year) will be satisfied by exploiting the identified ground water resources. These recommendations rely on a sensitivity analysis by Hodgson (1985) which assumes a 3% effective recharge. Continuous water level monitoring will help in refining the evolution of the water levels and in gathering long term aquifer history. Any adverse effects on the aquifer will be detected and management recommendations changed accordingly. Such a situation would arise if the present irrigation abstractions continues. By not been able to quantify the amount of recharge to the area this hypothesis is rejected.

14. CONCLUSIONS

The main conclusions relating to the findings of this investigation are presented and discussed here against the study aims as set out in Chapter 3.

. Aquifer(s) Definition.

The systematic approach afforded by the various investigation phases has confirmed the potential for exploitation of the aquifer at the basalt/sandstone contact. The results of the hydrocensus, the geoelectrical survey and the drilling were particularly useful in the delineation and quantification of the contact aquifer (Sub-section 6.2.2; Sections 7.3. and 8.1.). However the importance of the contact aquifer will diminish as drilling is undertaken further into the basin. This is the result of an increase in costly drilling depths and in pumping lifts.

. Aquifer Hydraulic Characteristics

The rise of the water level above the water strike was recorded during the drilling of the exploratory boreholes. It showed that the ground waters are under confined conditions. The majority of the test pumping results yielded values for the storage coefficient ranging from 0,5 to 1×10^{-5}. These values are representative of semi-confined to totally confined conditions respectively.

Transmissivity values ranged from 0,3 to 1250 m^2/d. The higher T figures are indicative of areally extensive fracture development and are found in the area of a suggested lava flow protrusion (Section 8.1.). The areal variation of T and the varied aquifer responses are evidence of anisotropic conditions.

In the portion of the aquifer where more than one water strike was encountered, leakage from the overlying basalt could not be assessed. However the similarity in the static water level with the underlying contact aquifer suggest that these aquifers are in hydraulic continuity.

. Recharge Mechanism

Recharge to the area is thought to take place via the conjunctive interaction of rainfall and ground water through flow (Sections 10.2. and 12.1.). However there has been a recent decline in both rainfall and the volume of through flow as seen in the water level trends (Section 10.1.). Long term monitoring is essential to pinpoint any changes to the recharge as reflected by changes in the water level trends.

. Ground Water Quality

Except where isolated pockets of fossil water (Sub-section 11.3.3.) are encountered, the quality of the ground waters is good. Encroachment of nitrate rich waters could be slowed down and even reversed by the lowering of the piezometric gradient caused by excessive pumping from South Africa. The reversal in piezometric levels will obviously have a detrimental effect on resource management assuming that irrigation abstractions will continue at the present level.

. Ground Water Resources Management

According to Walton (1970) optimum development and management of the resources is achieved when replenishment is balanced by discharge. In order to formulate optimal management procedures the concept of safe yield must be defined. As reported in Custodio and Llamas (1976) this concept was defined by Meinzer (1920) as "the practicable rate of withdrawing water from it (i.e. the ground water reservoir) perennially for human use." In the above definition the specified usage can include industrial and agricultural applications. The determination of a safe yield relies on six factors (Custodio and Llamas, 1976) namely; available water supply, economics, water quality, legal, agricultural and geotechnical aspects. Of interest to this study are the first four factors.

The decline in the ground water levels over the last two years around Tuinplaas is evidence that recharge in this area is exceeded and that overexploitation of the resources is taking place. In this case water held in storage is ´mined´ thus the safe yield can only be exploited from storage causing the permanent depletion of the reserves. This situation is further exagerated by the declining rainfall which is counteracted by the farmers by an increased dependence on groundwater for irrigation. In the area under study the influence of these abstractions is not fully understood. Long term monitoring of the water level trends will allow for an understanding of the effect of these abstractions on the area under study.

The ecomomic implications of the decline of water levels is governed by increasing borehole depths, lowering of pump intakes and the installation of bigger pumps. These steps are associated with an important overall increase in abstraction costs, which according to Stramel (1965), are usually overlooked. If water levels continue to decline there is a limit to how deep boreholes, in the area under study, can be drilled. This is related to the maximum available drawdown taken to be the base of the contact zone. Deepening of boreholes would only result in the abstraction of lower yields and higher pumping costs from the low porosity sandstone. It is envisaged that in the area where irrigation abstraction is taking place, the decrease in yields, usually accompanying declining water levels below which the irrigation systems cannot economically operate, will allow a part of through flow into the study area. In fact, some of the farmers are reported to have shut down their irrigation systems because of decrease in yields.

Even under the present hydraulic conditions ground water quality in parts of the area under study has already exceeded the definition of safe yield. By introducing even further abstractions, this will have an increased effect on the encroachment of the contaminated water due to head differentials. This comment applies mainly to the nitrate rich waters which are seen to travel through the shallower high T zone. Intrusion of the high Fluoride waters is checked by the low T properties of the aquifer (Sub-section 9.2.2.).

The declining water levels and amount of through flow would have legal implication of an international nature. To declare the present abstraction area within South Africa a ground water control area will only maintain the present status quo. In order to avoid international disputes, stricter management of the present resources should be implemented. The monitoring of abstractions around the area under study, and in some cases the curtailing of pumping by farmers who have excess ground water, could help in restoring the aquifer to its natural conditions.

In conclusion the results of the various investigation stages discussed in this dissertation have provided an insight into the general hydrogeological conditions of the study area and to the external factors influencing the ground water regime. By using the integrated results of the hydrogeological investigation a wellfield to satisfy the water demand of the power station has been designed. Strict management procedures have been formulated to take into account the noted depletion of the ground water resources to the north. These include widely spaced production boreholes and long term discharges significantly lower than their tested short term potential (Table 14). Continous monitoring of the aquifer´s hydraulic behaviour must be carried out.

The choice of the various investigation stages has contributed to a satisfactory completion of the work. The methods and techniques adopted during this investigation are expected to have a fairly general application to ground water resources evaluation throughout the remainder of the basin and elsewhere.

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APPENDIX A

PLOTS OF TEST PUMPING DATA

FOR THE REMAINING EXISTING AND EXPLORATORY BOREHOLES

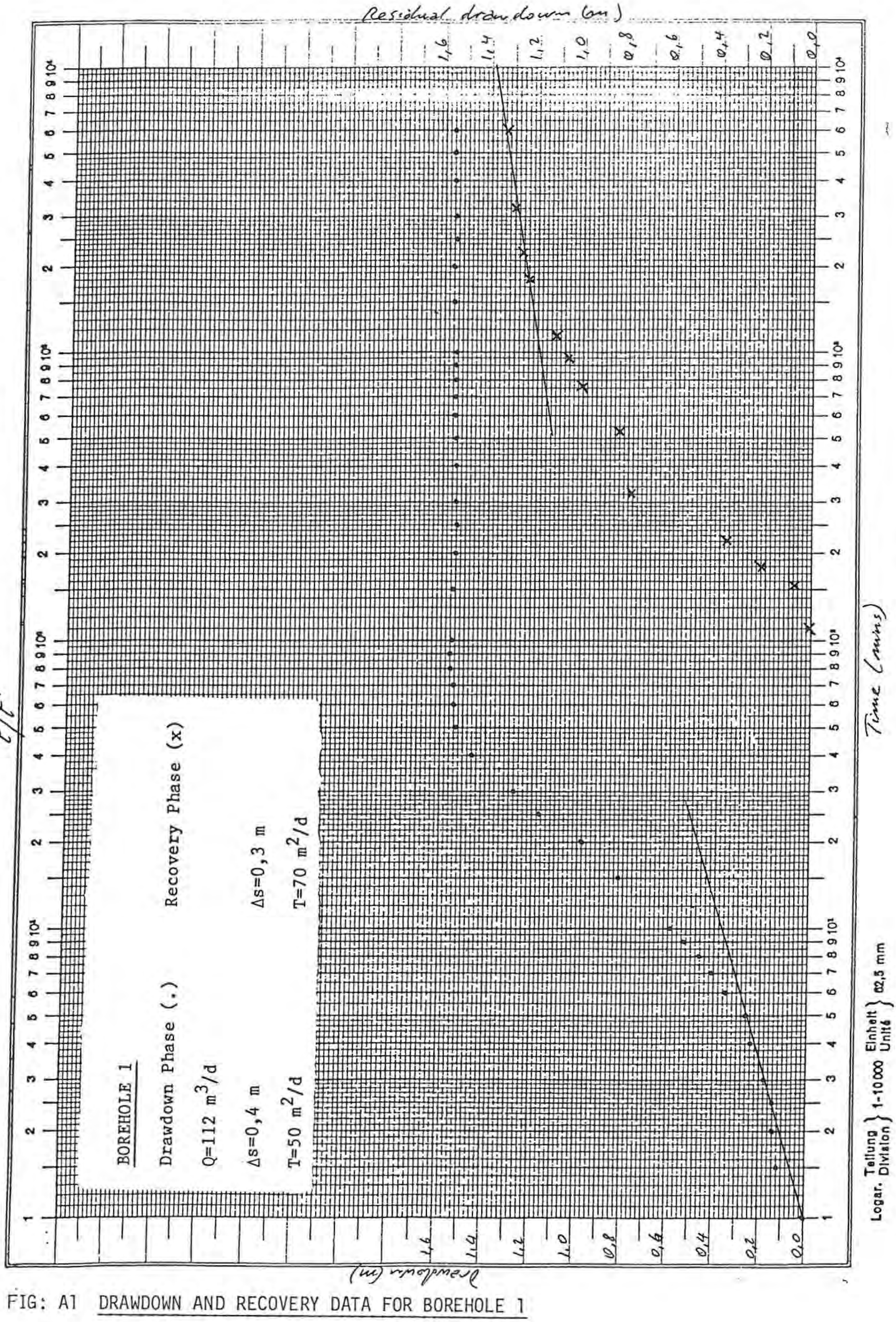

FIG: A1 DRAWDOWN AND RECOVERY DATA FOR BOREHOLE 1

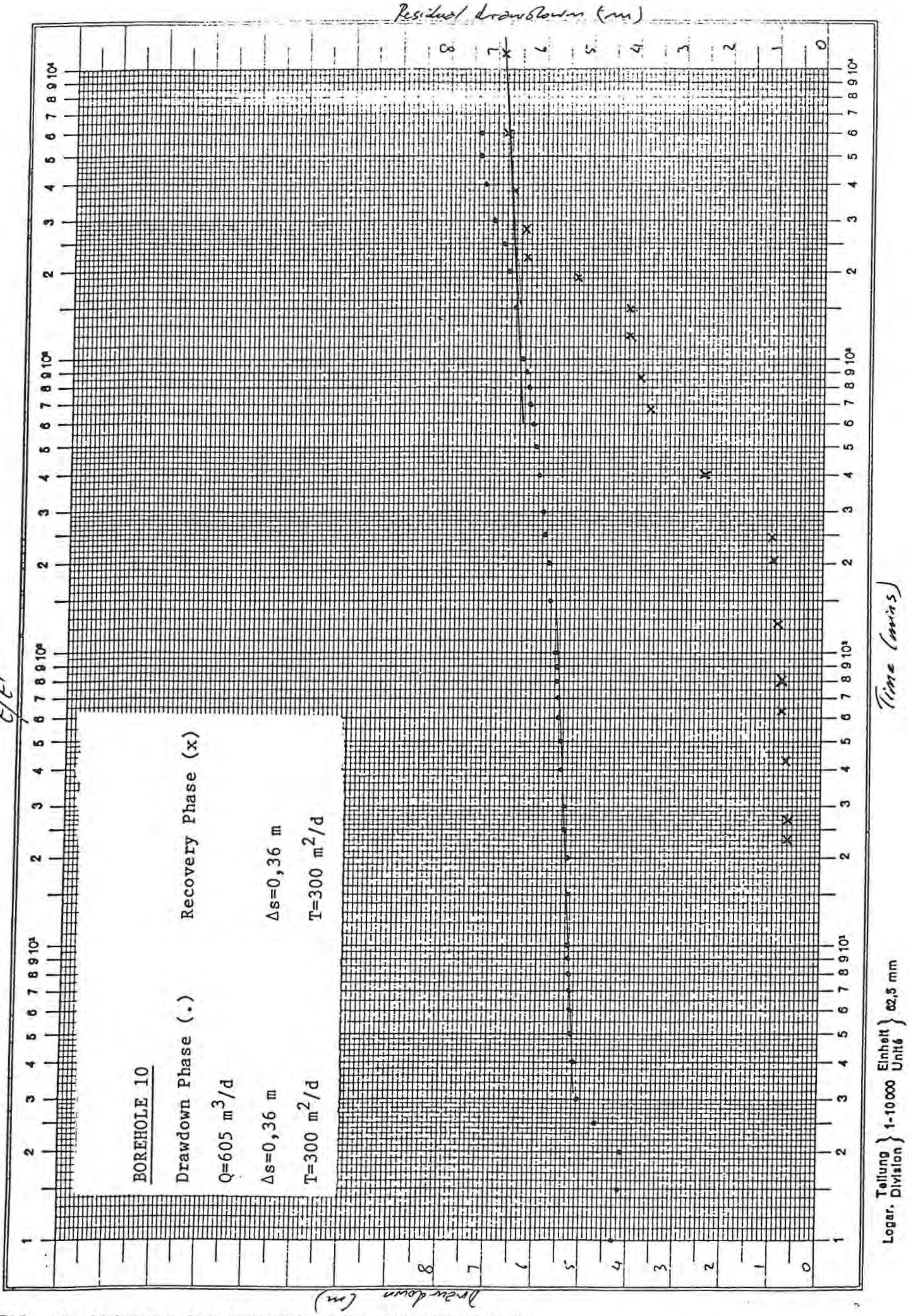

FIG. A2 DRAWDOWN AND RECOVERY DATA FOR BOREHOLE 10

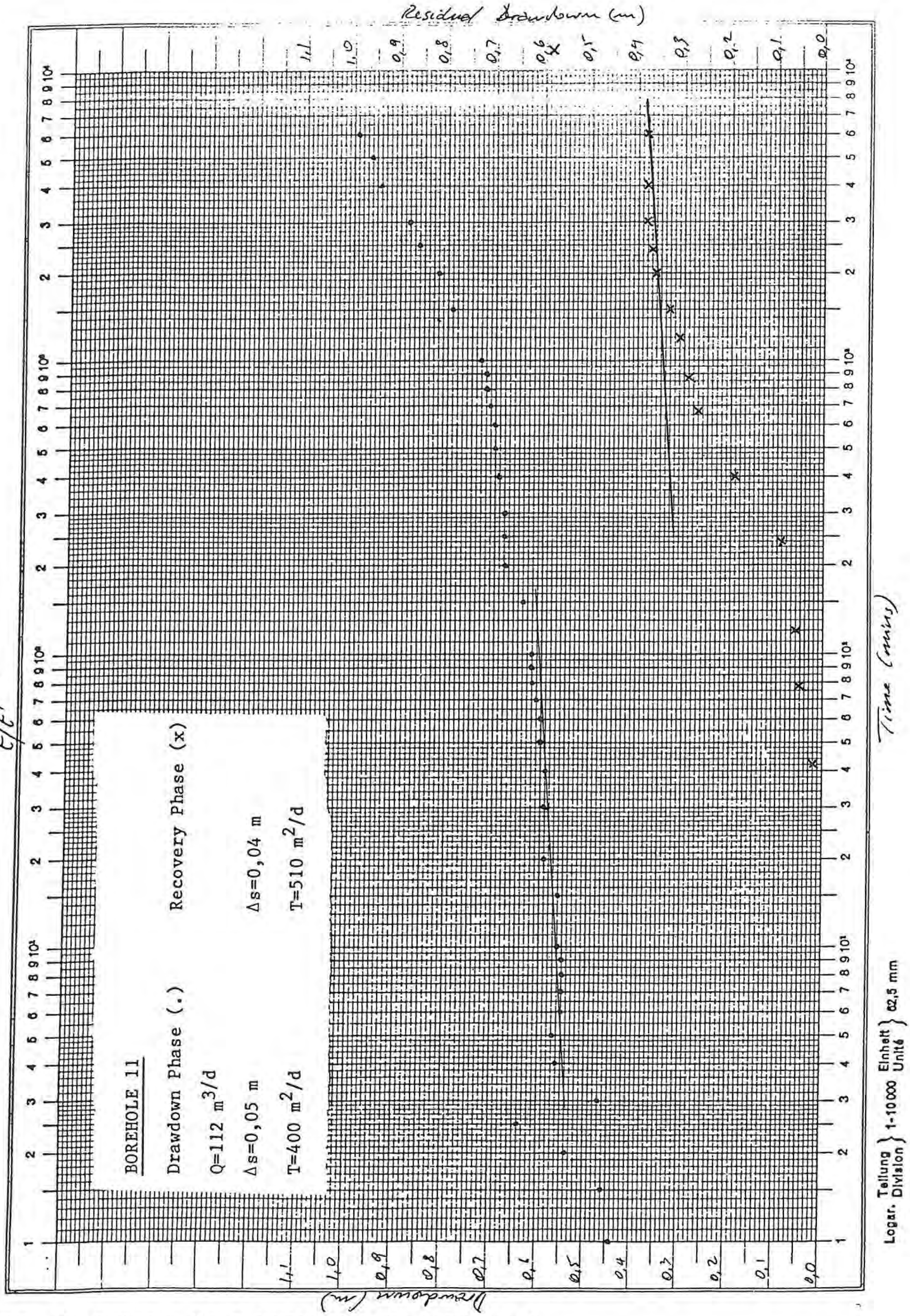

FIG. A3 DRAWDOWN AND RECOVERY DATA FOR BOREHOLE 11

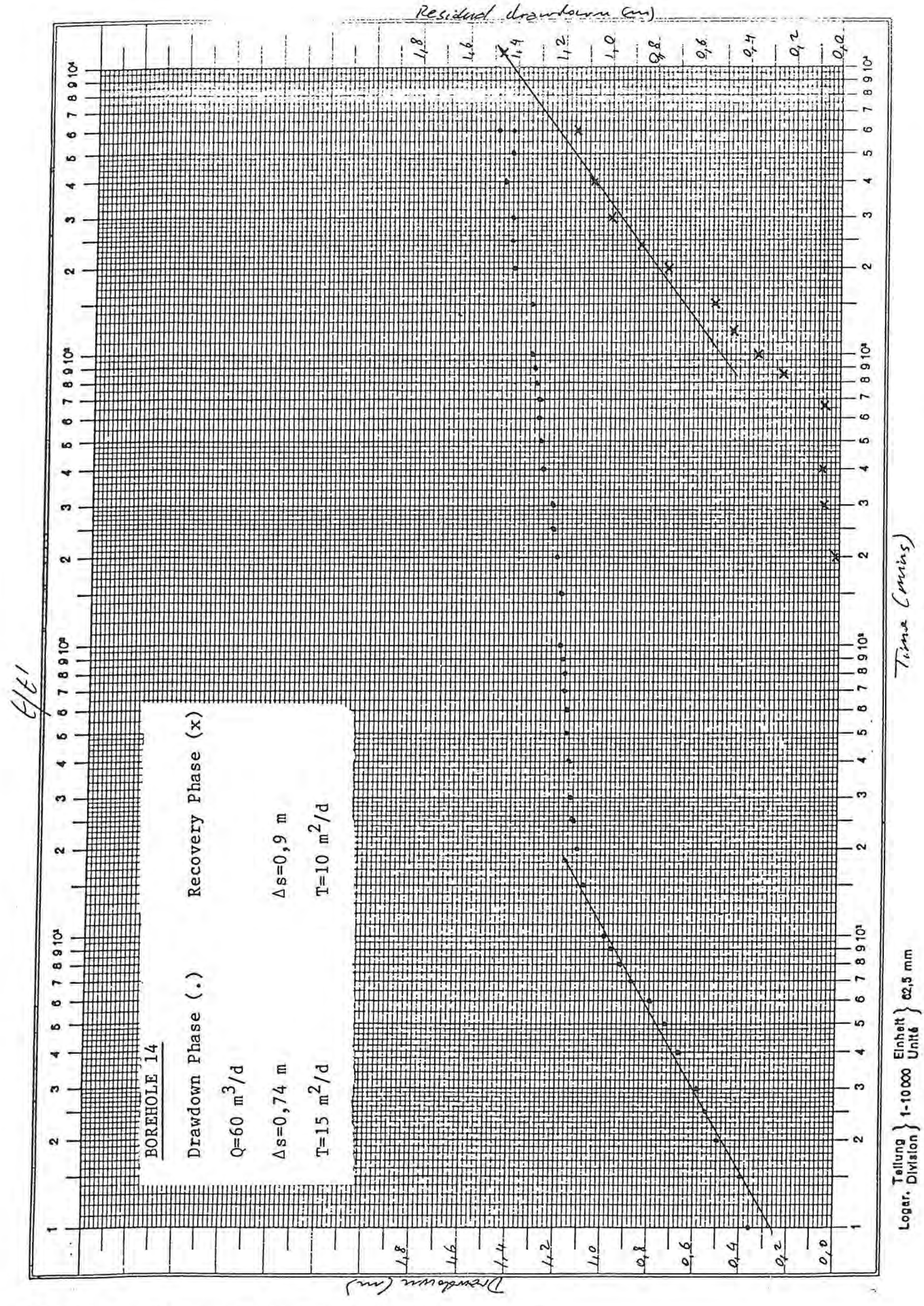

FIG. A4 DRAWDOWN AND RECOVERY DATA FOR BOREHOLE 14

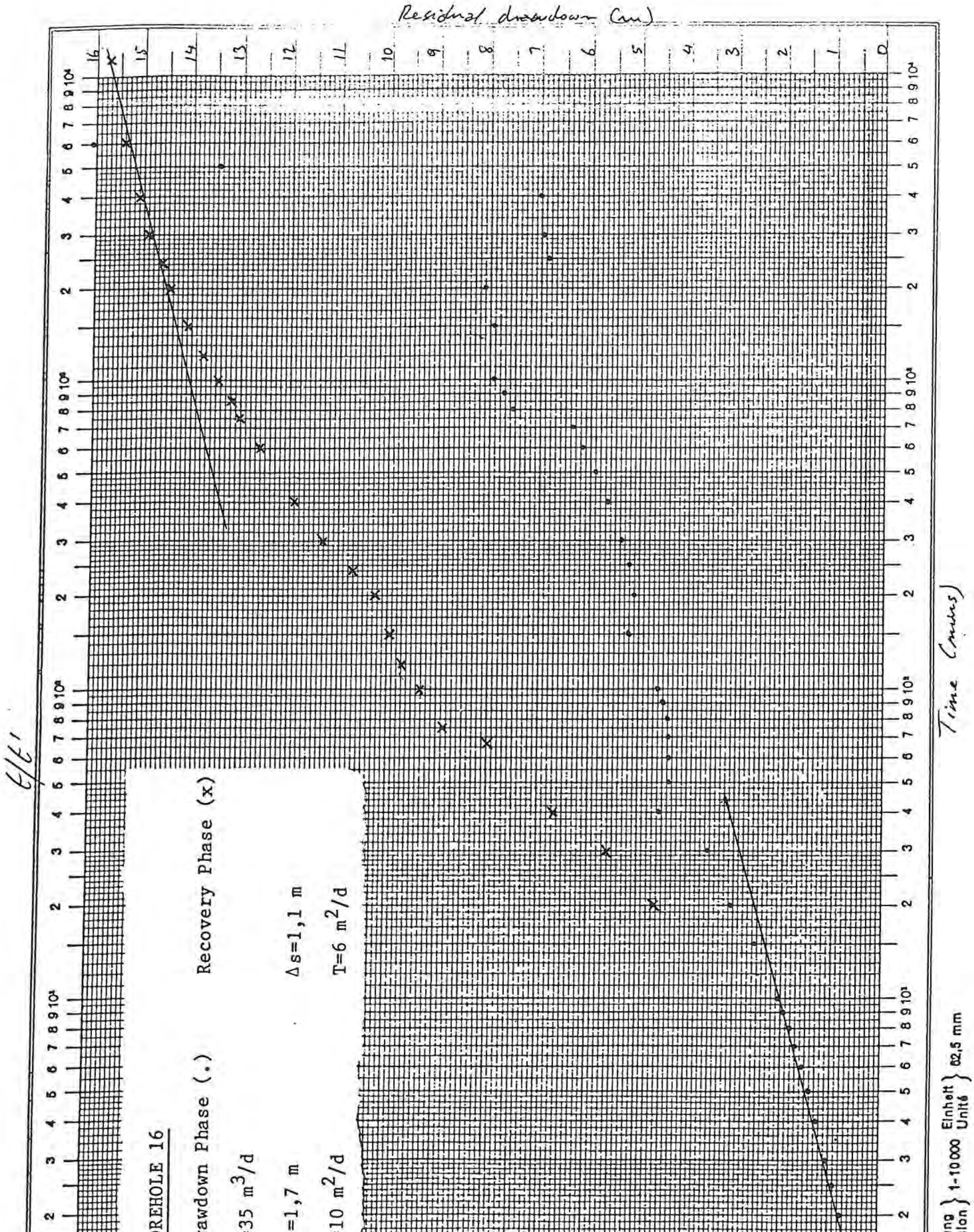

FIG. A5 DRAWDOWN AND RECOVERY DATA FOR BOREHOLE 16

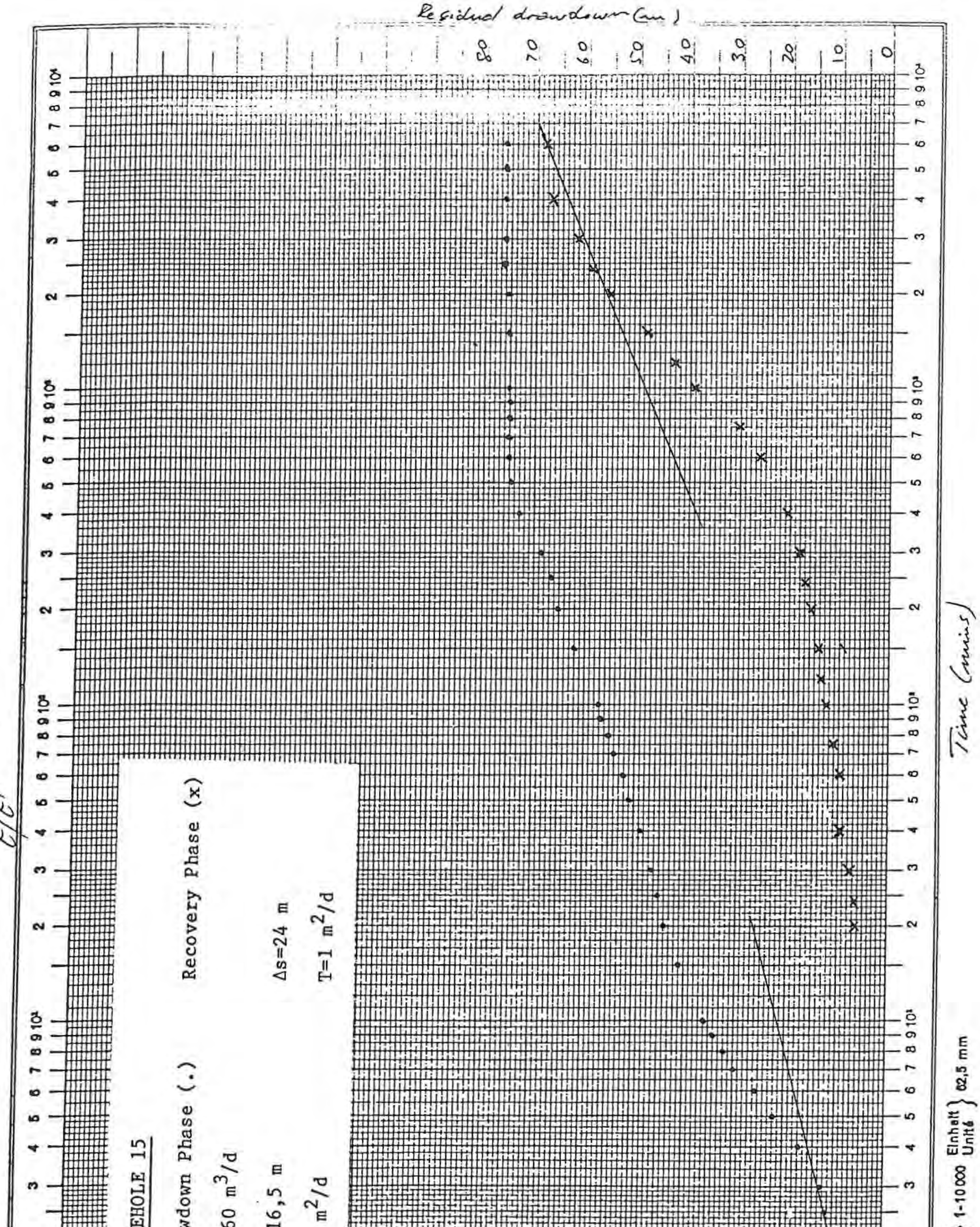

FIG. A6 DRAWDOWN AND RECOVERY DATA FOR BOREHOLE 15

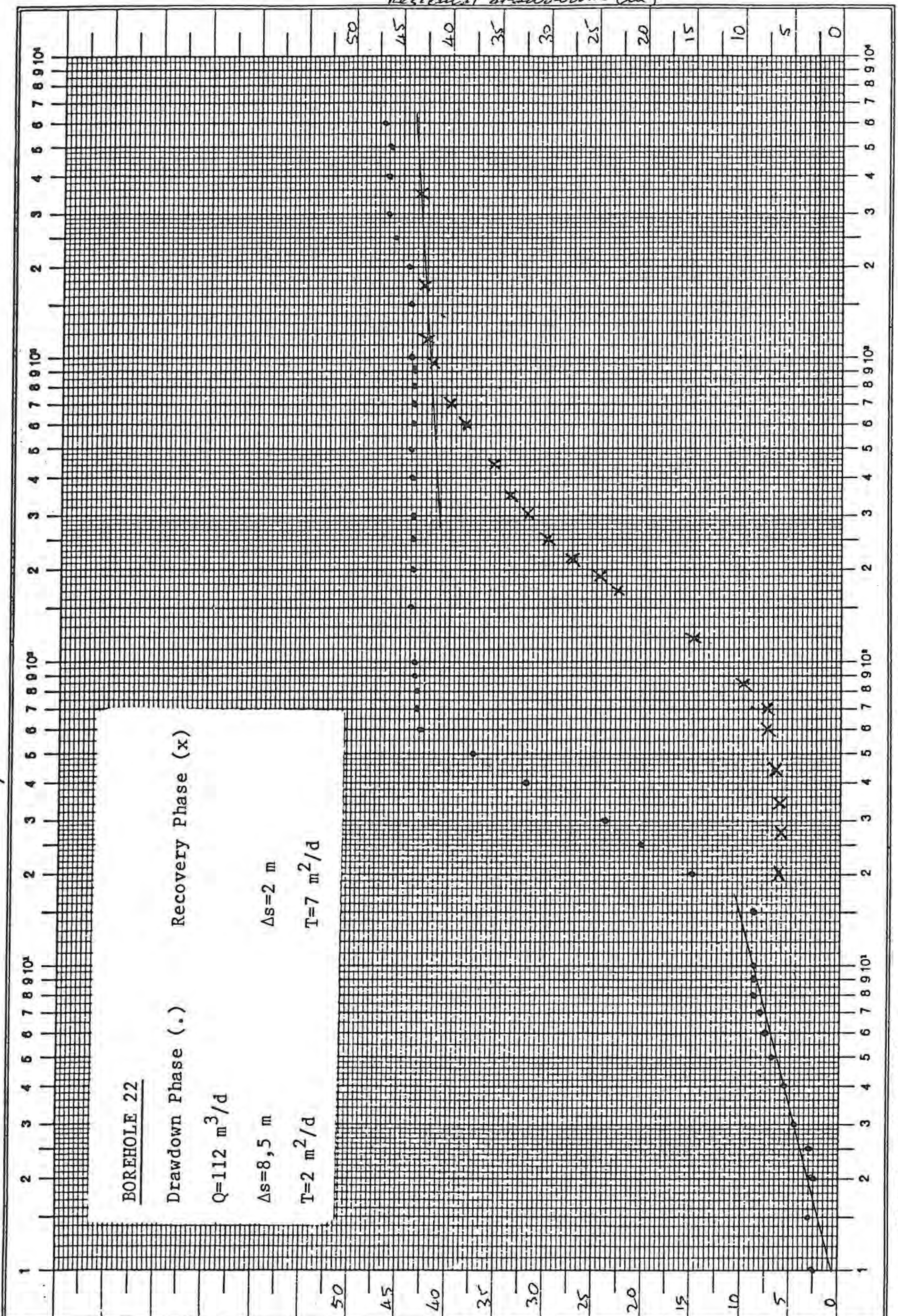

FIG. A7 DRAWDOWN AND RECOVERY DATA FOR BOREHOLE 22

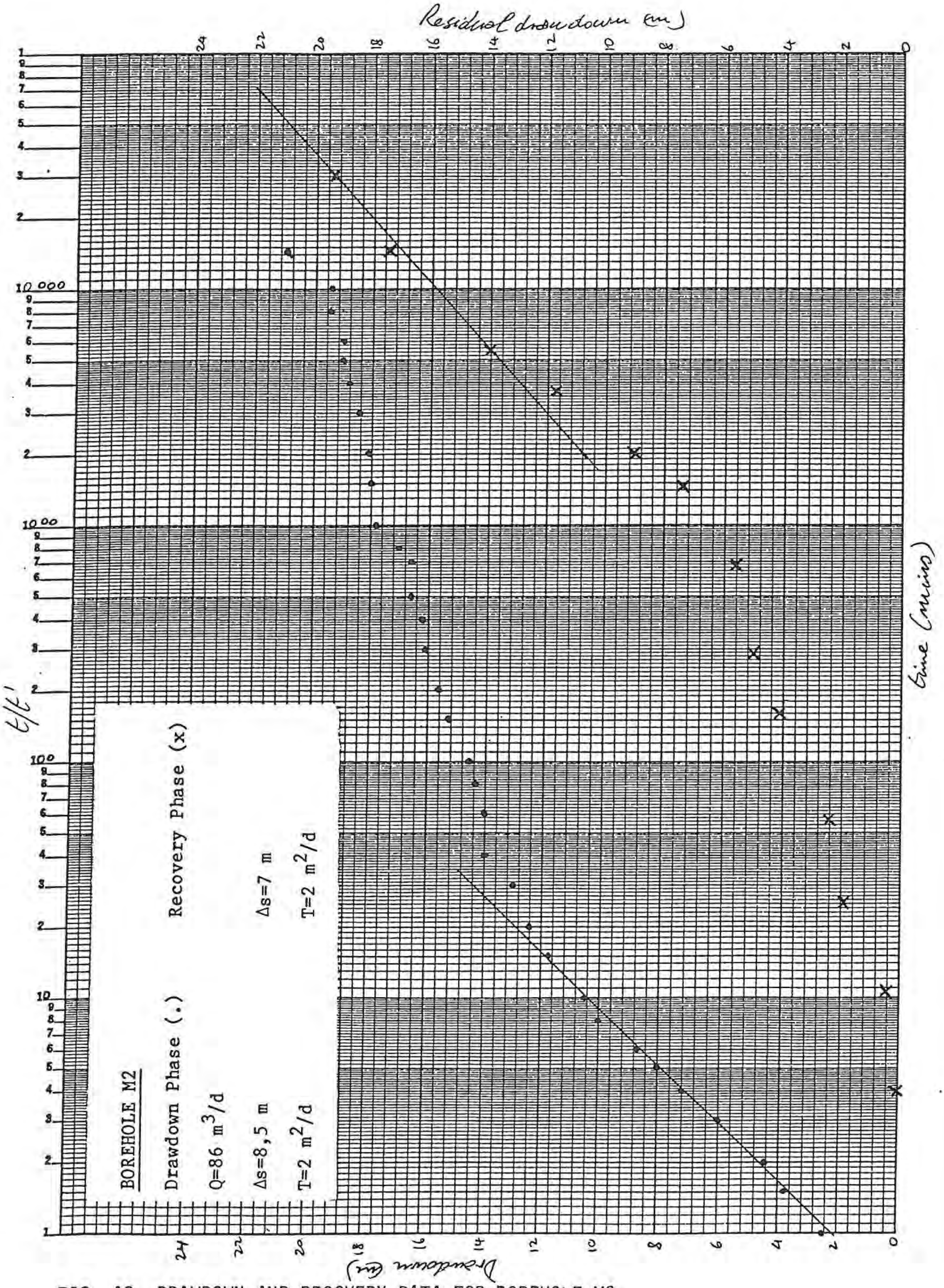

FIG. A8 DRAWDOWN AND RECOVERY DATA FOR BOREHOLE M2

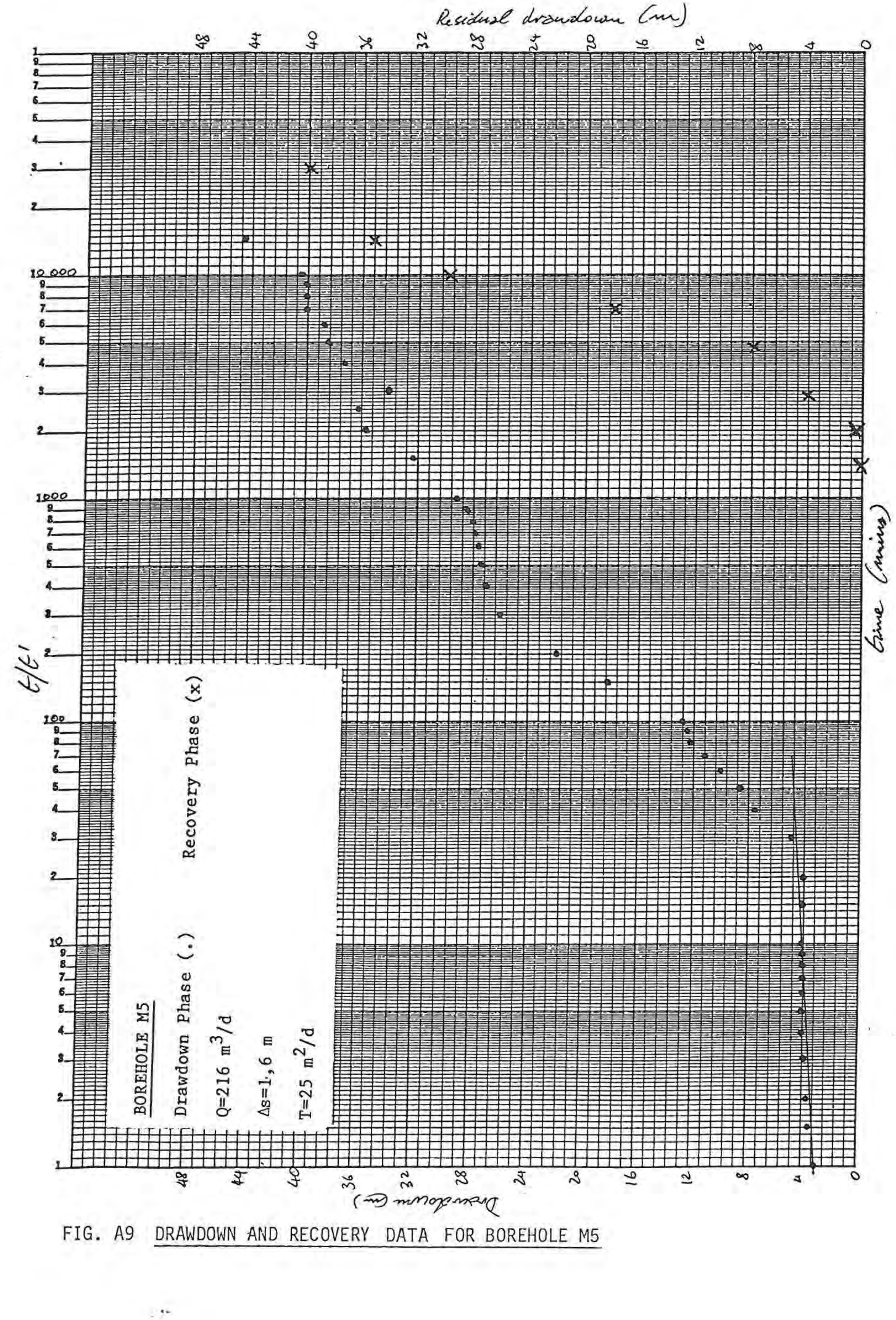

FIG. A9 DRAWDOWN AND RECOVERY DATA FOR BOREHOLE M5

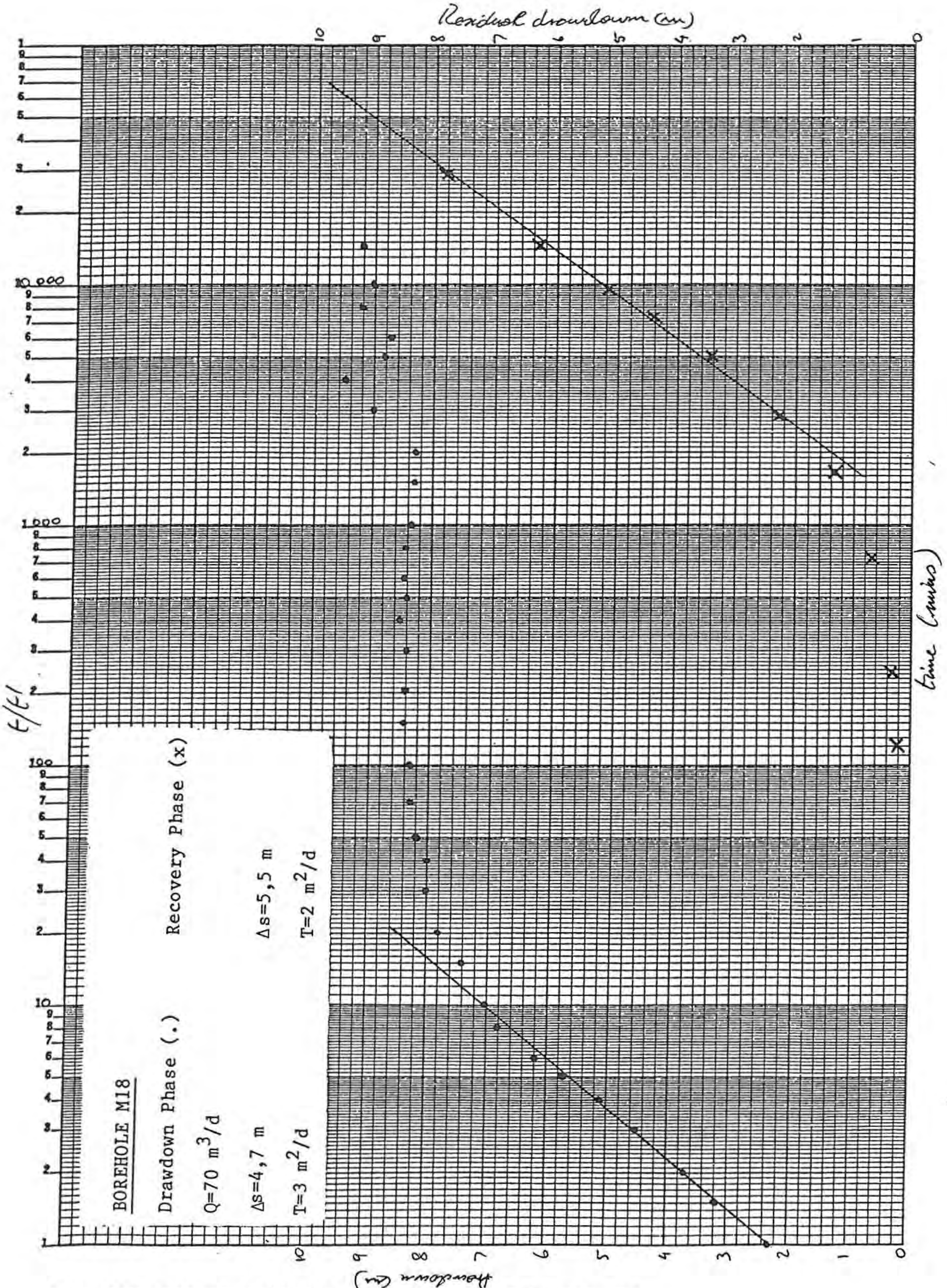

FIG. A10 DRAWDOWN AND RECOVERY DATA FOR BOREHOLE M18

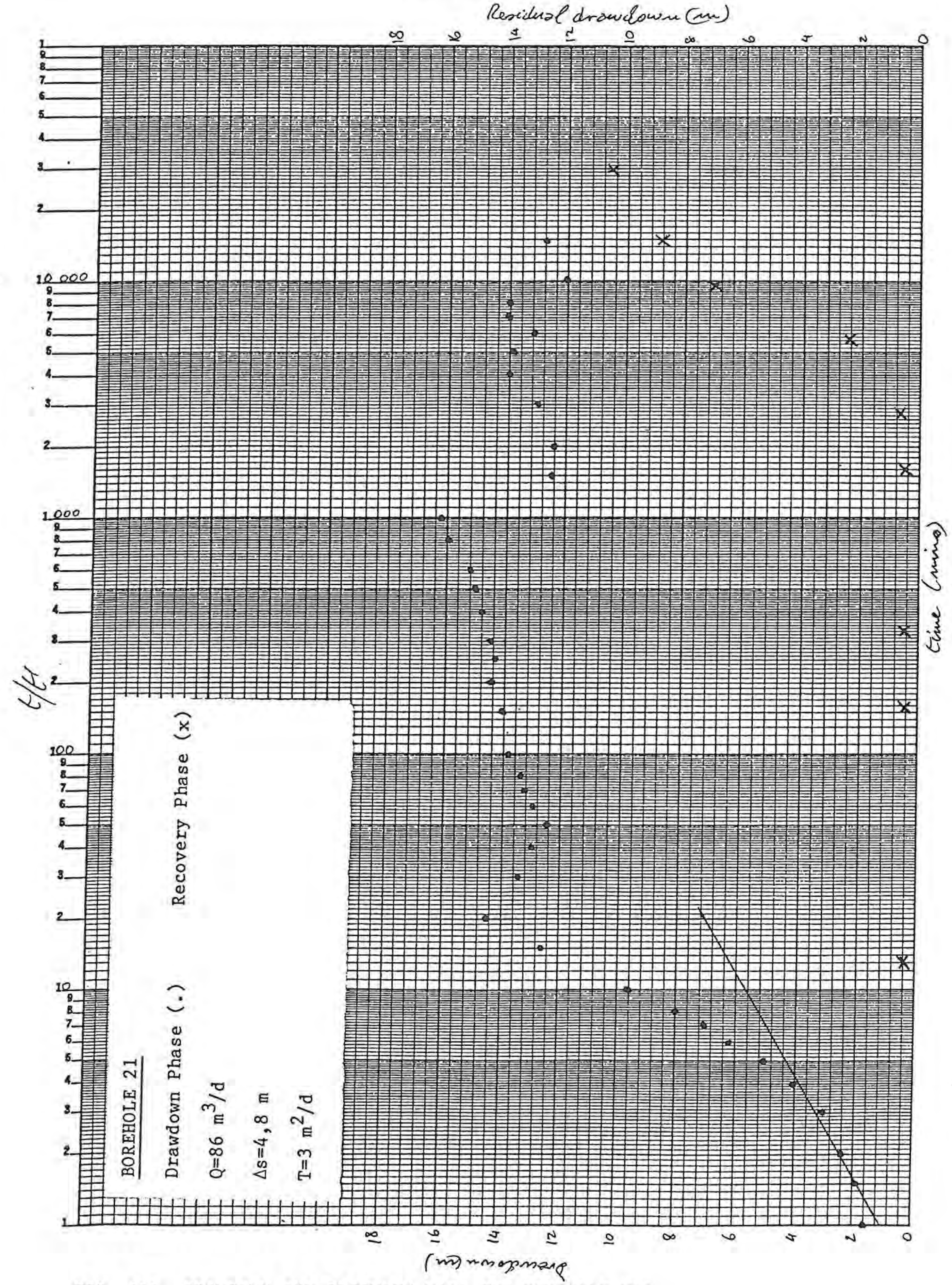

FIG. A11 DRAWDOWN AND RECOVERY DATA FOR BOREHOLE M21

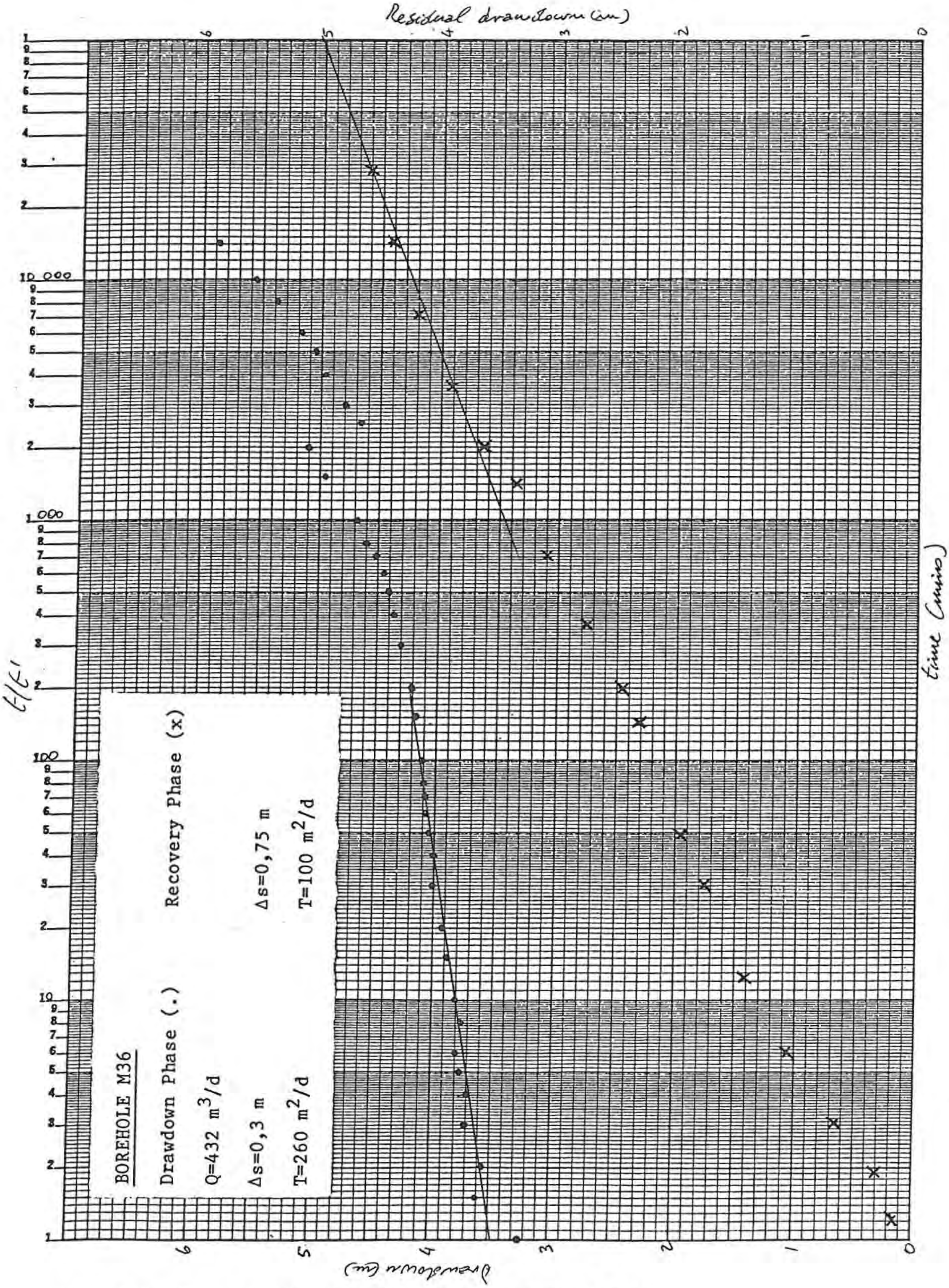

FIG. A12 DRAWDOWN AND RECOVERY DATA FOR BOREHOLE M36

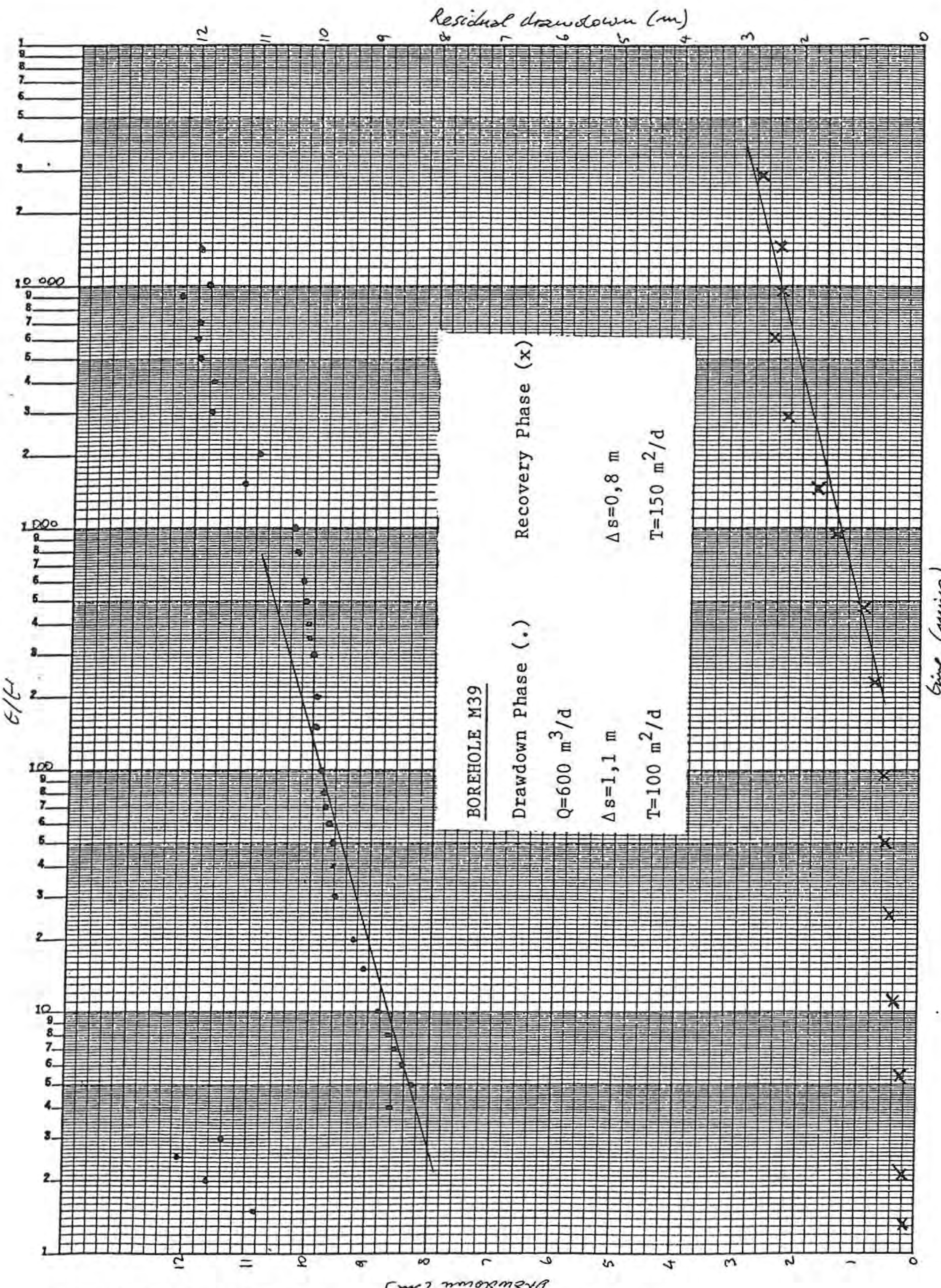

FIG. A13 DRAWDOWN AND RECOVERY DATA FOR BOREHOLE M39

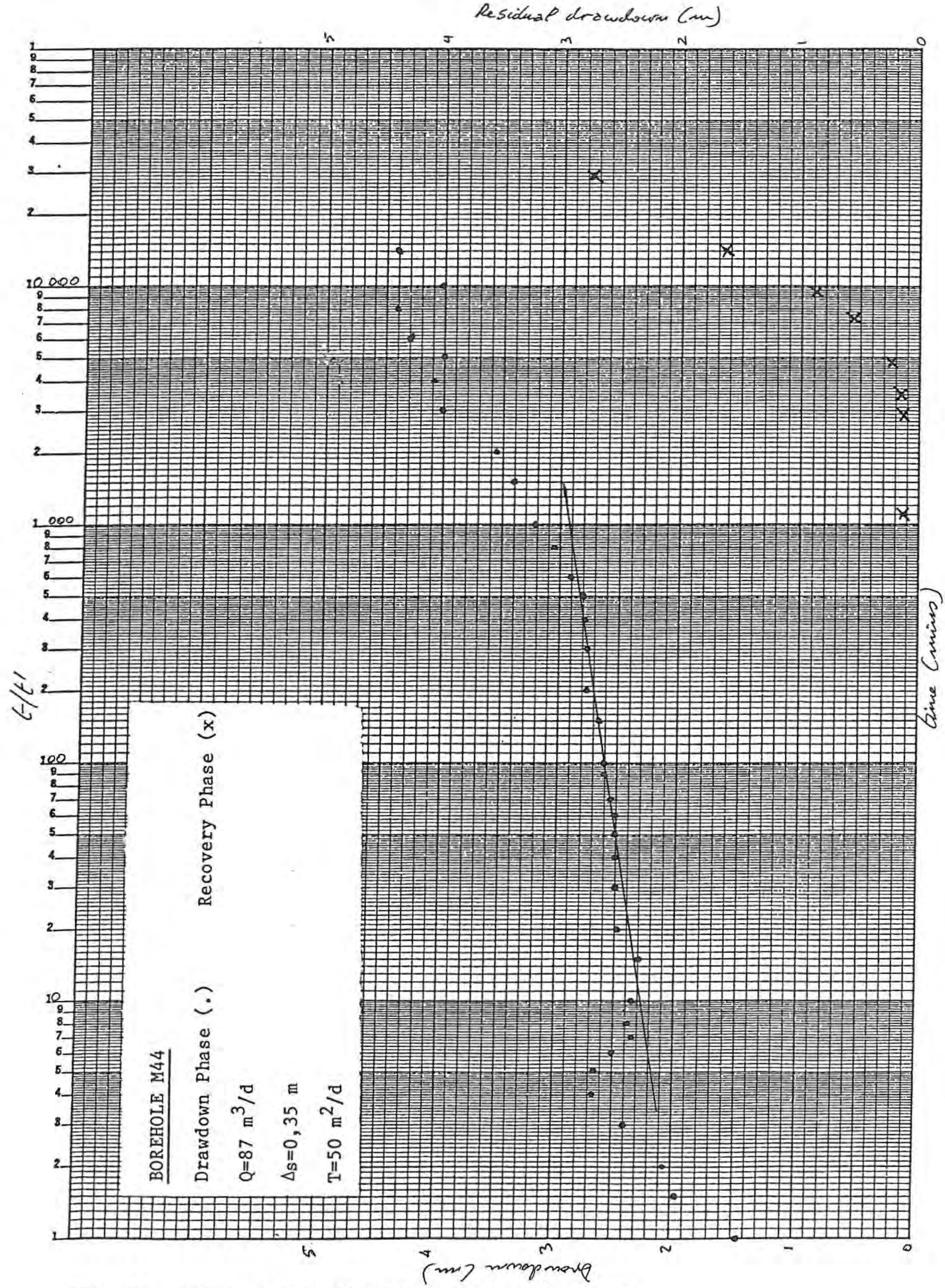

FIG. A14 DRAWDOWN AND RECOVERY DATA FOR BOREHOLE M44

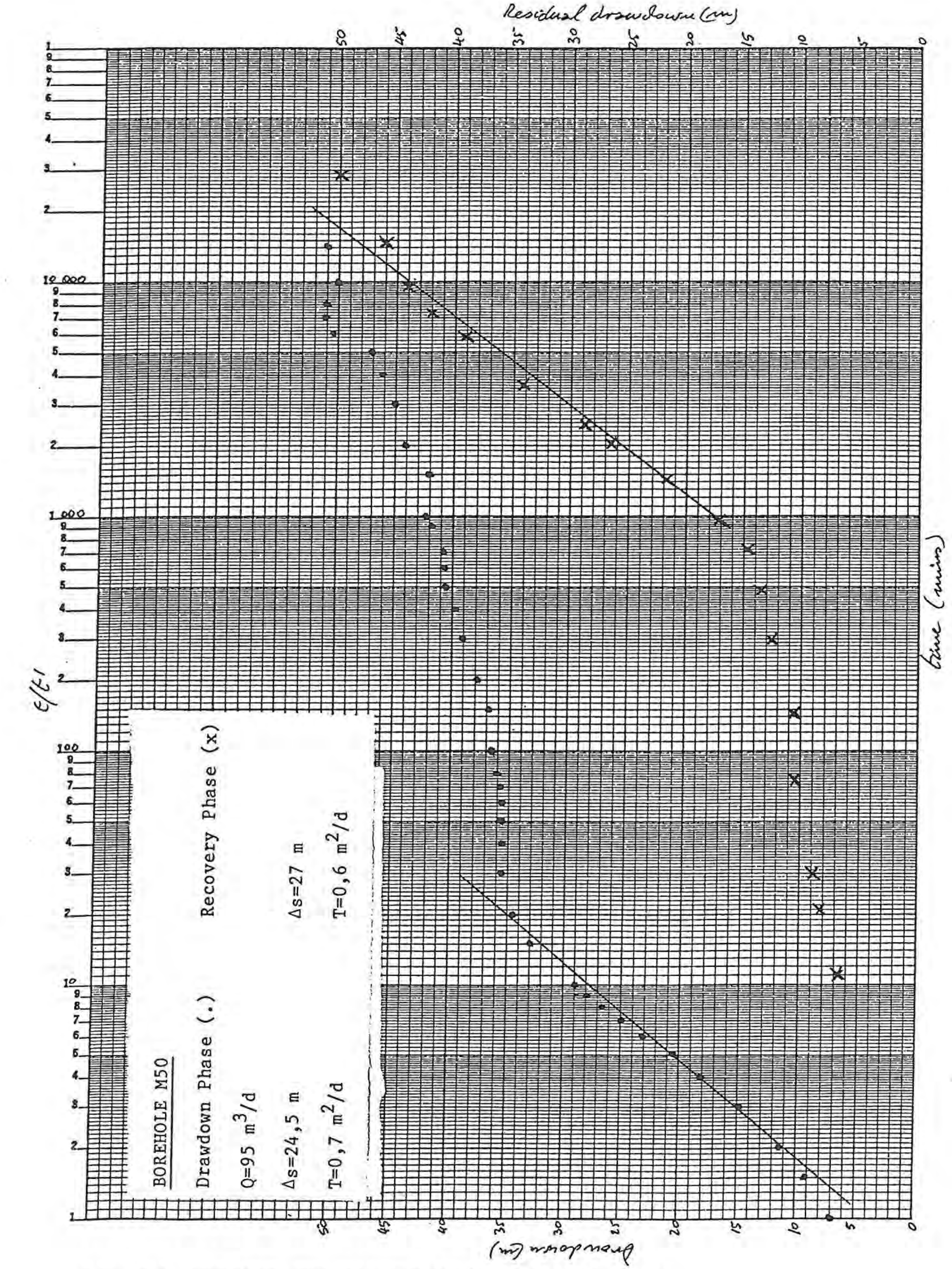

FIG. A15 DRAWDOWN AND RECOVERY DATA FOR BOREHOLE M50

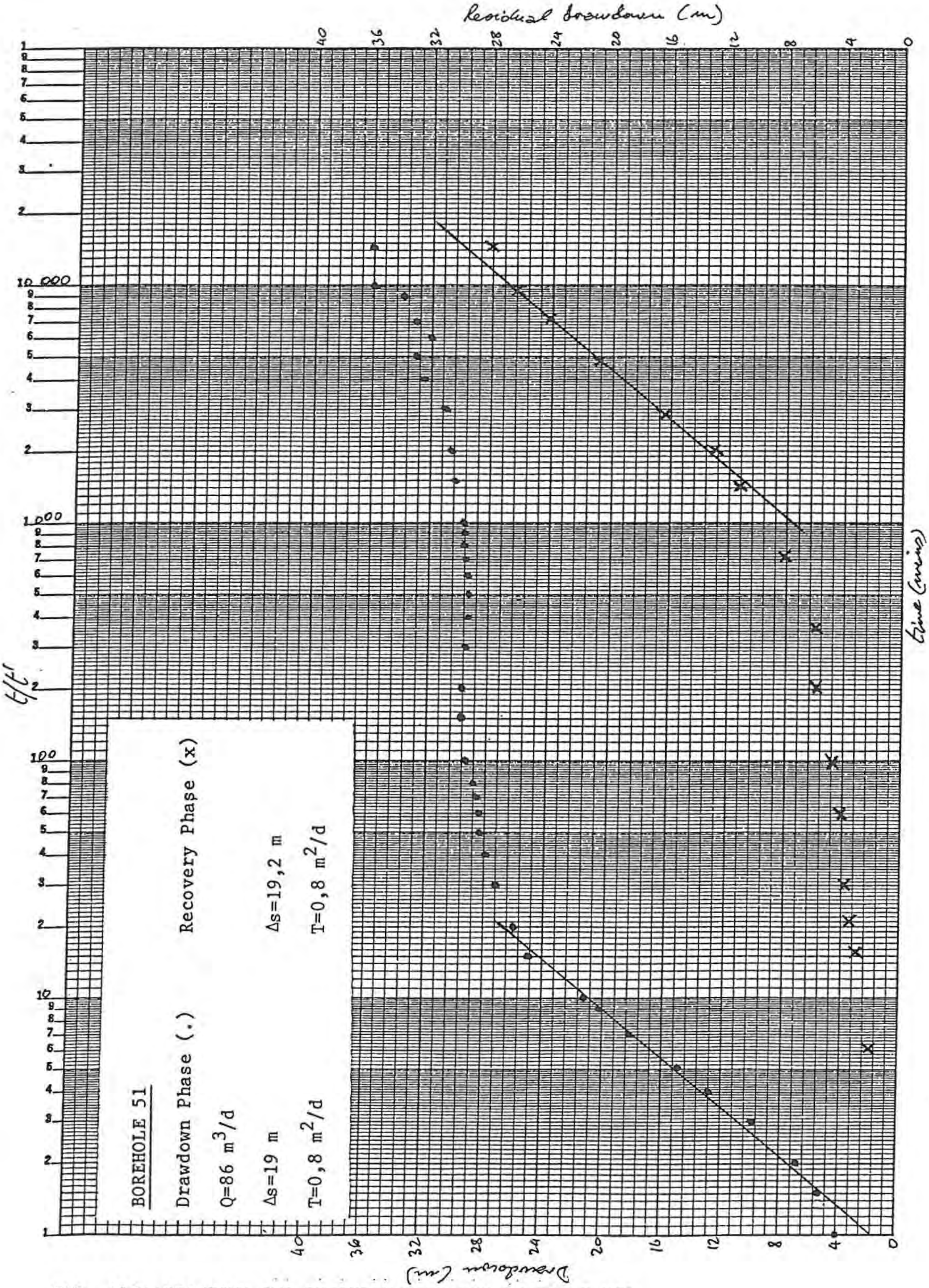

FIG. A16 DRAWDOWN AND RECOVERY DATA FOR BOREHOLE M51

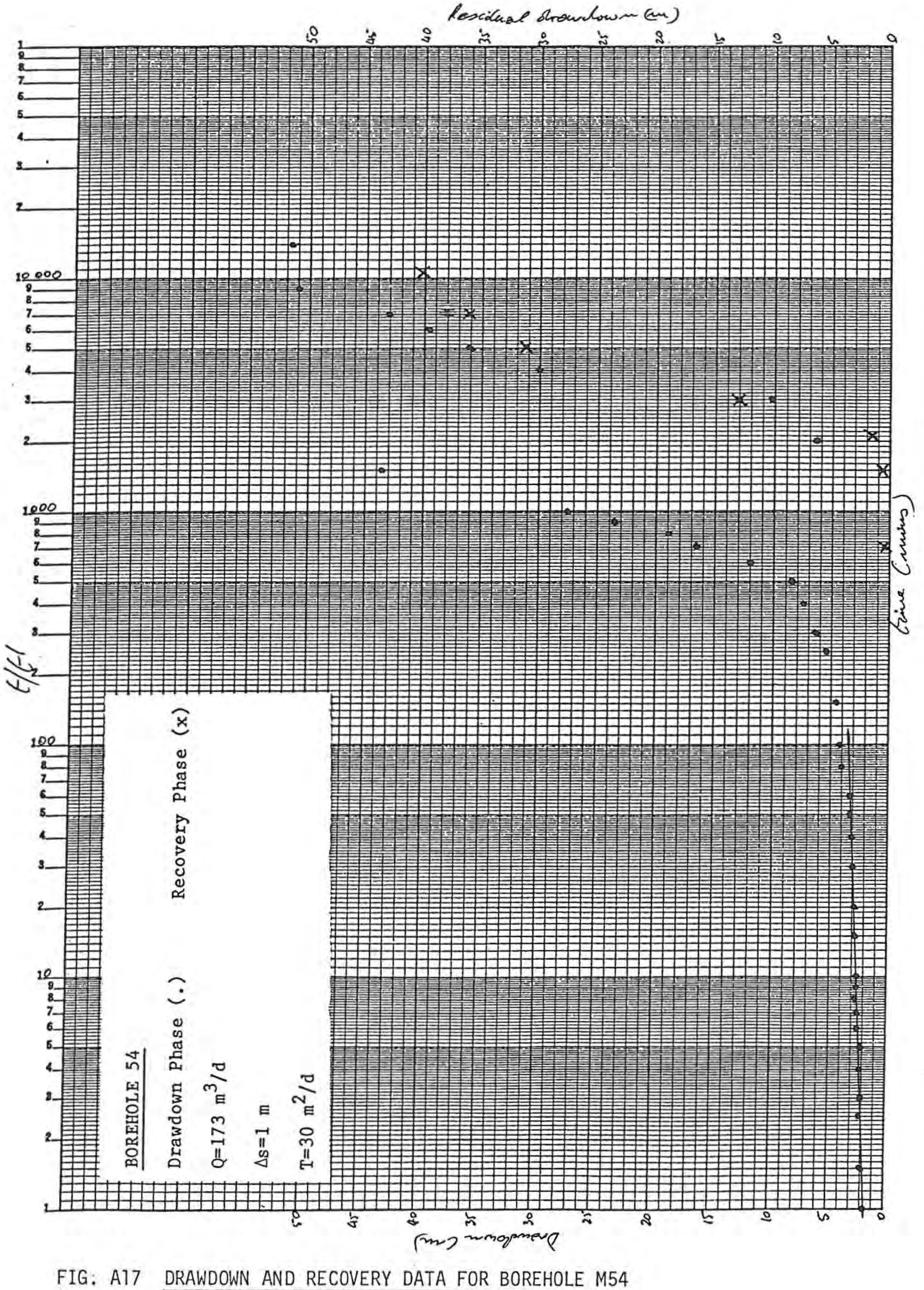

FIG: A17 DRAWDOWN AND RECOVERY DATA FOR BOREHOLE M54

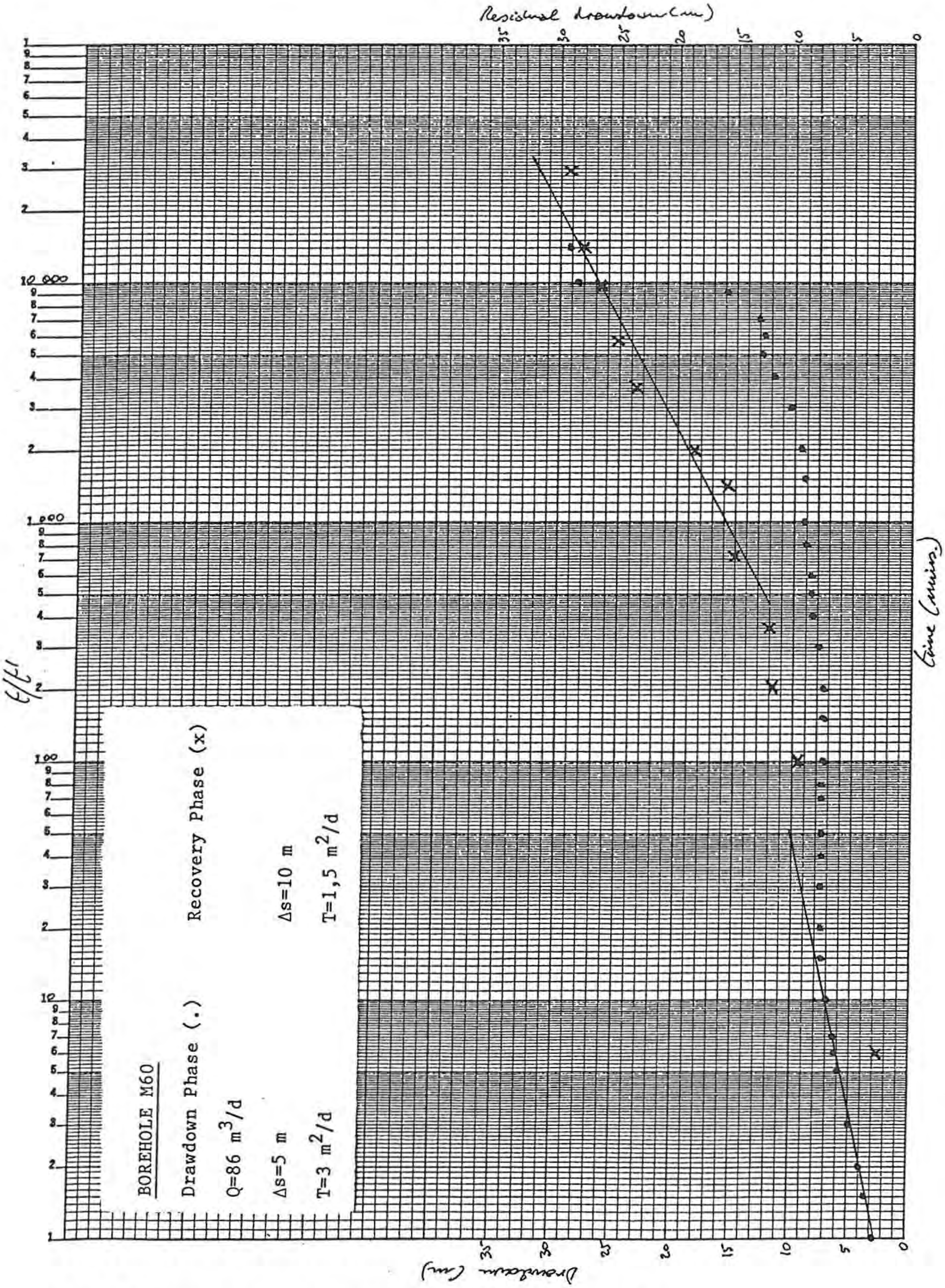

FIG. A18 DRAWDOWN AND RECOVERY DATA FOR BOREHOLE M60

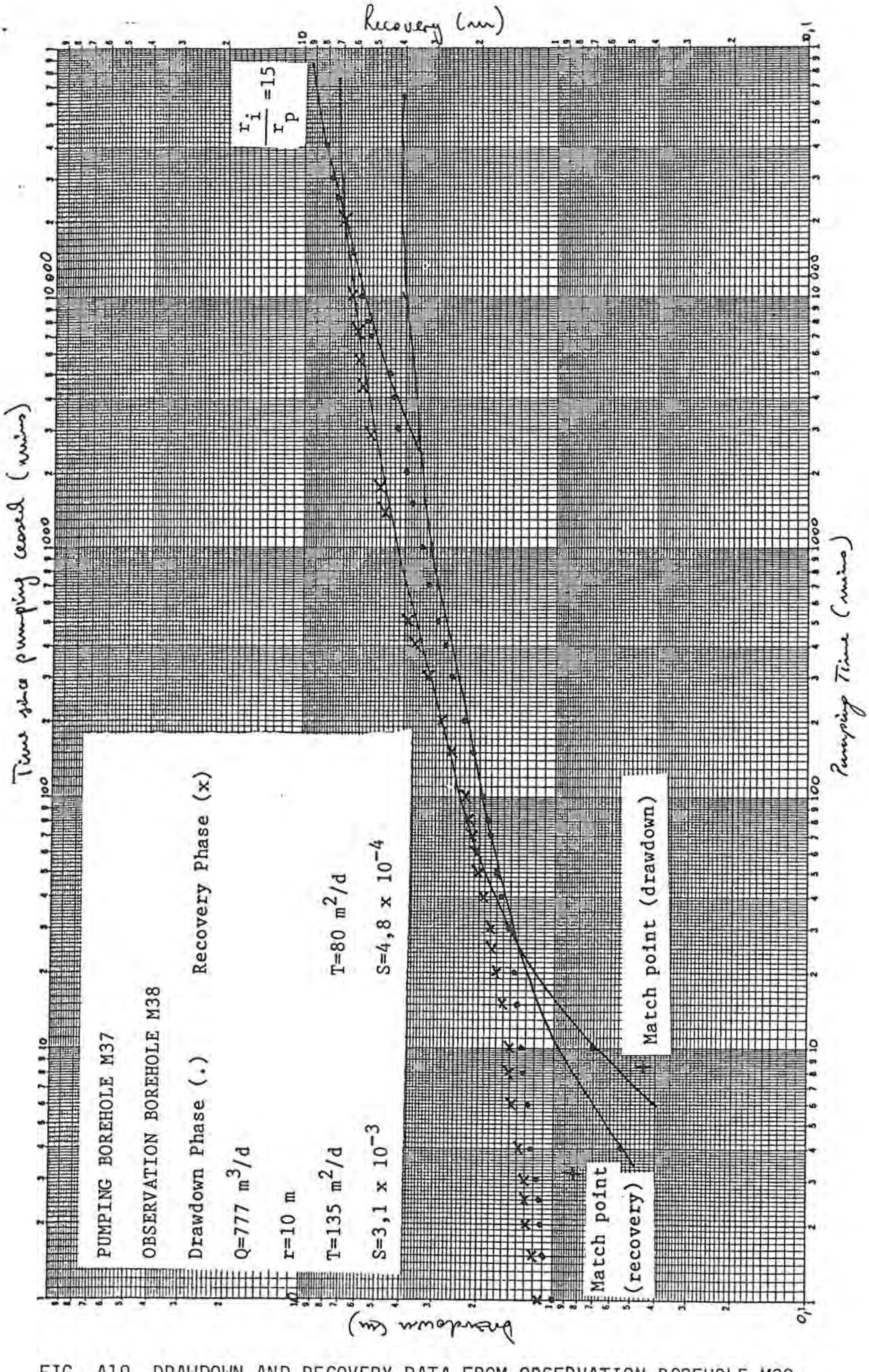

FIG. A19 DRAWDOWN AND RECOVERY DATA FROM OBSERVATION BOREHOLE M38 USING THEIS TYPE CURVE SOLUTION

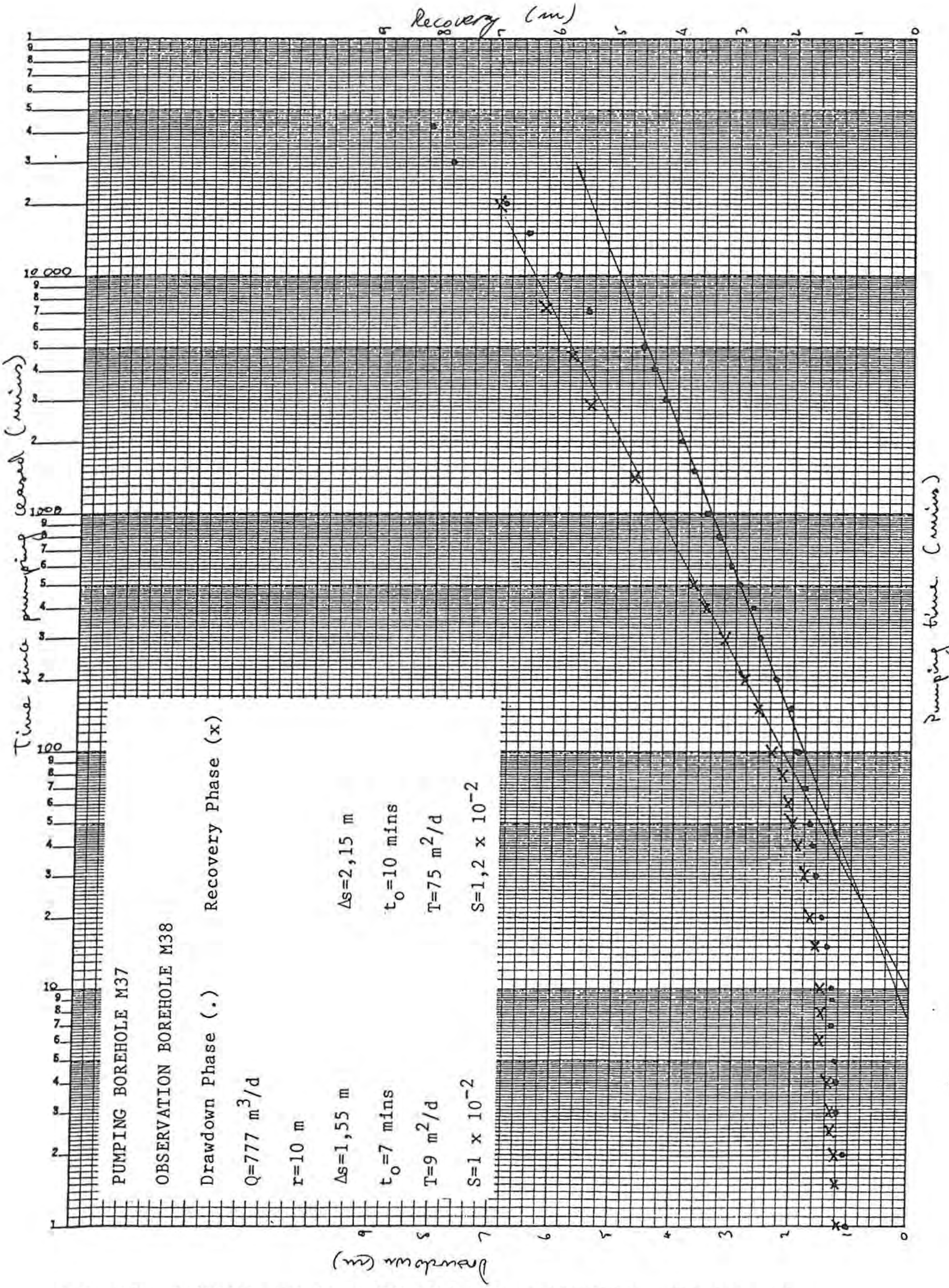

FIG. A20 DRAWDOWN AND RECOVERY DATA FROM OBSERVATION BOREHOLE M38 USING JACOB STRAIGHT LINE SOLUTION

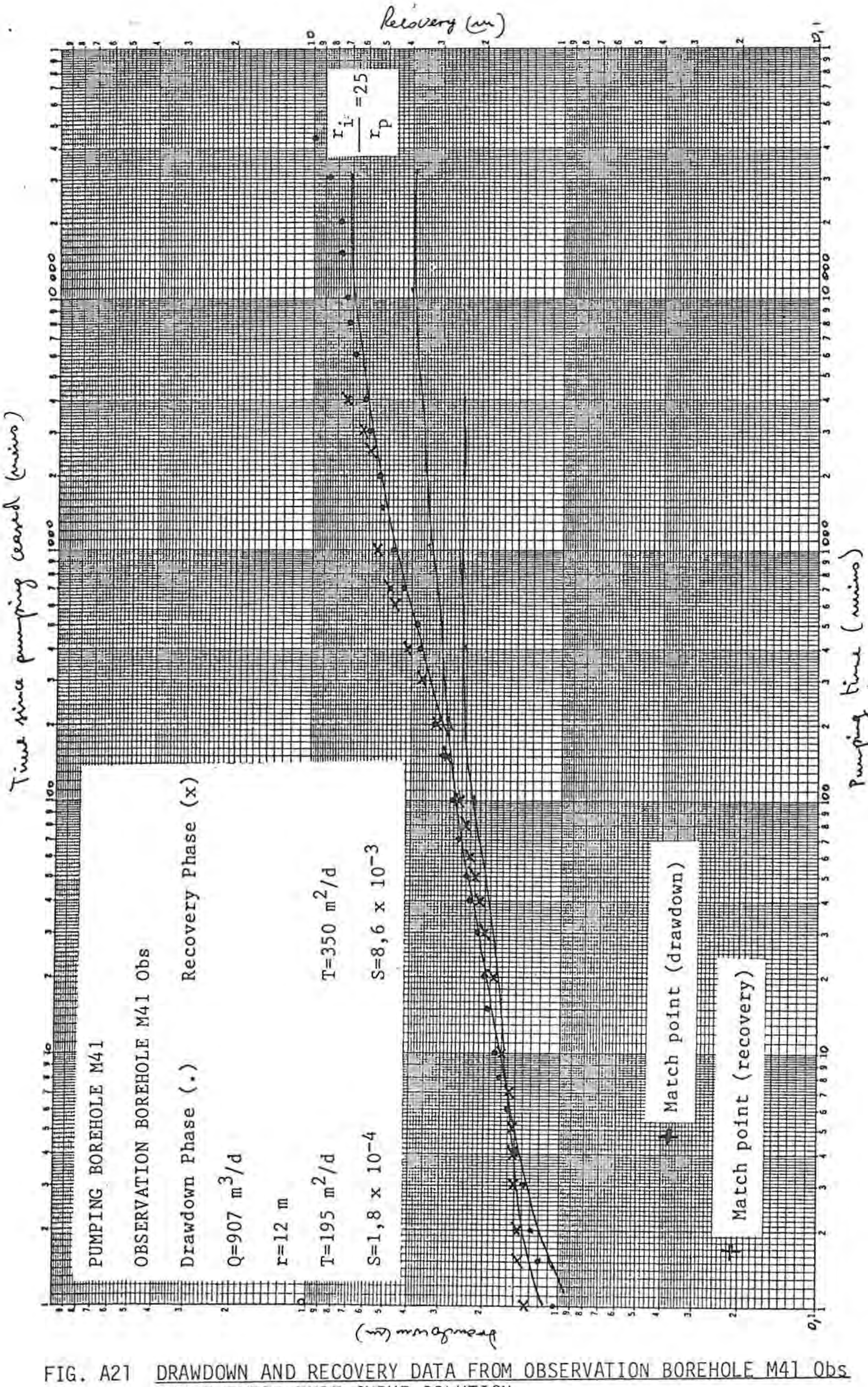

FIG. A21 DRAWDOWN AND RECOVERY DATA FROM OBSERVATION BOREHOLE M41 Obs USING THEIS TYPE CURVE SOLUTION

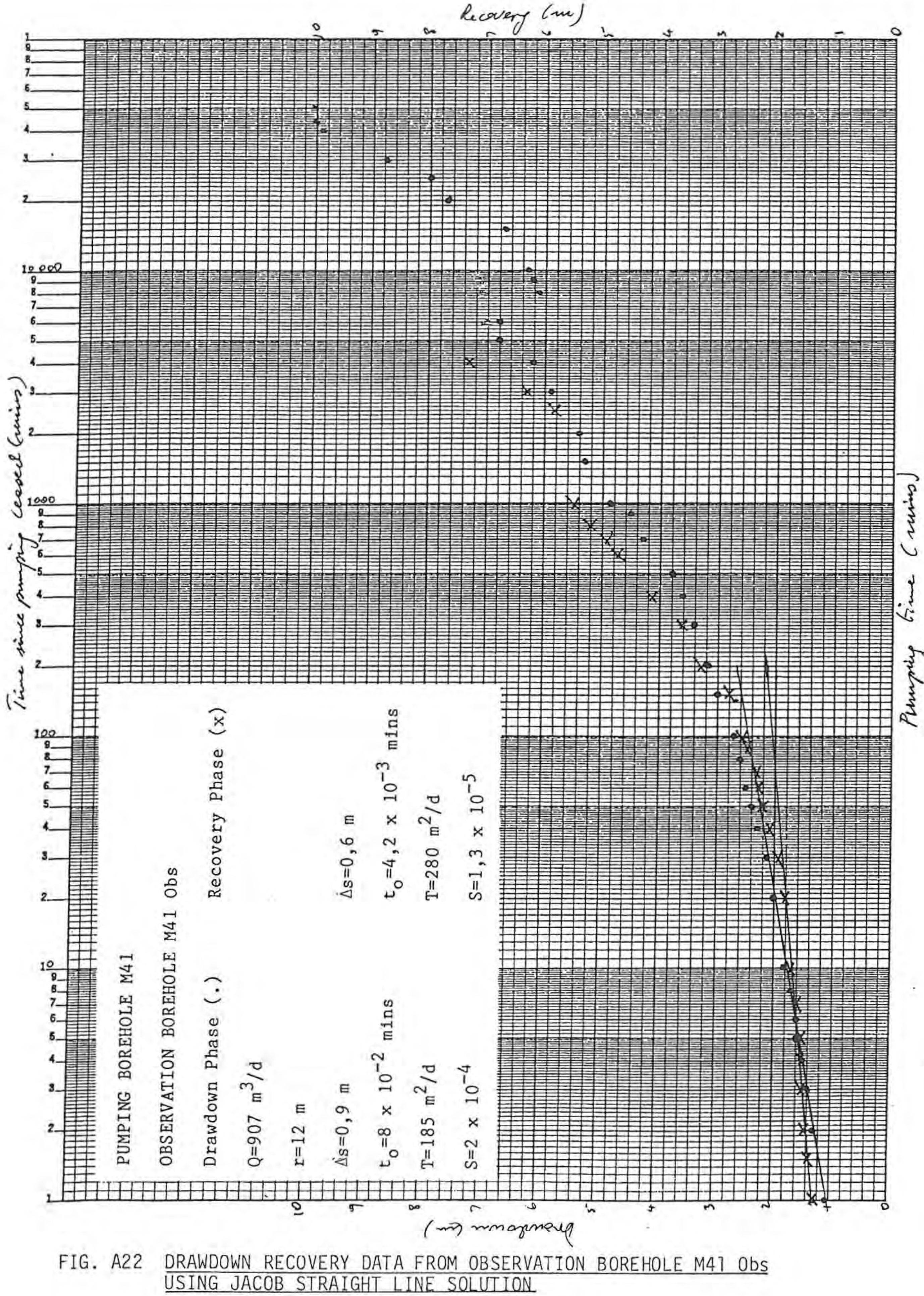

FIG. A22 DRAWDOWN RECOVERY DATA FROM OBSERVATION BOREHOLE M41 Obs USING JACOB STRAIGHT LINE SOLUTION

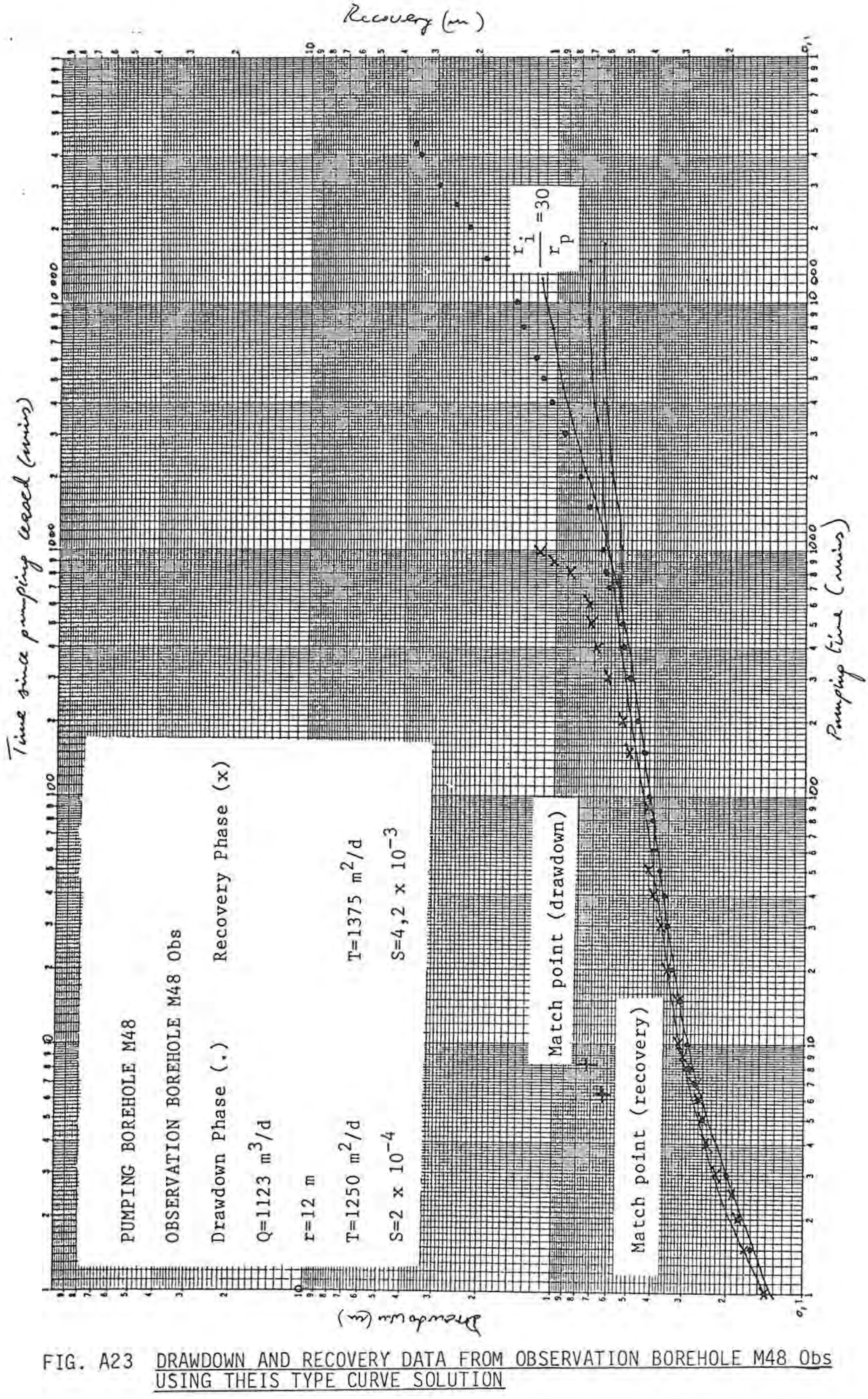

FIG. A23 DRAWDOWN AND RECOVERY DATA FROM OBSERVATION BOREHOLE M48 Obs USING THEIS TYPE CURVE SOLUTION

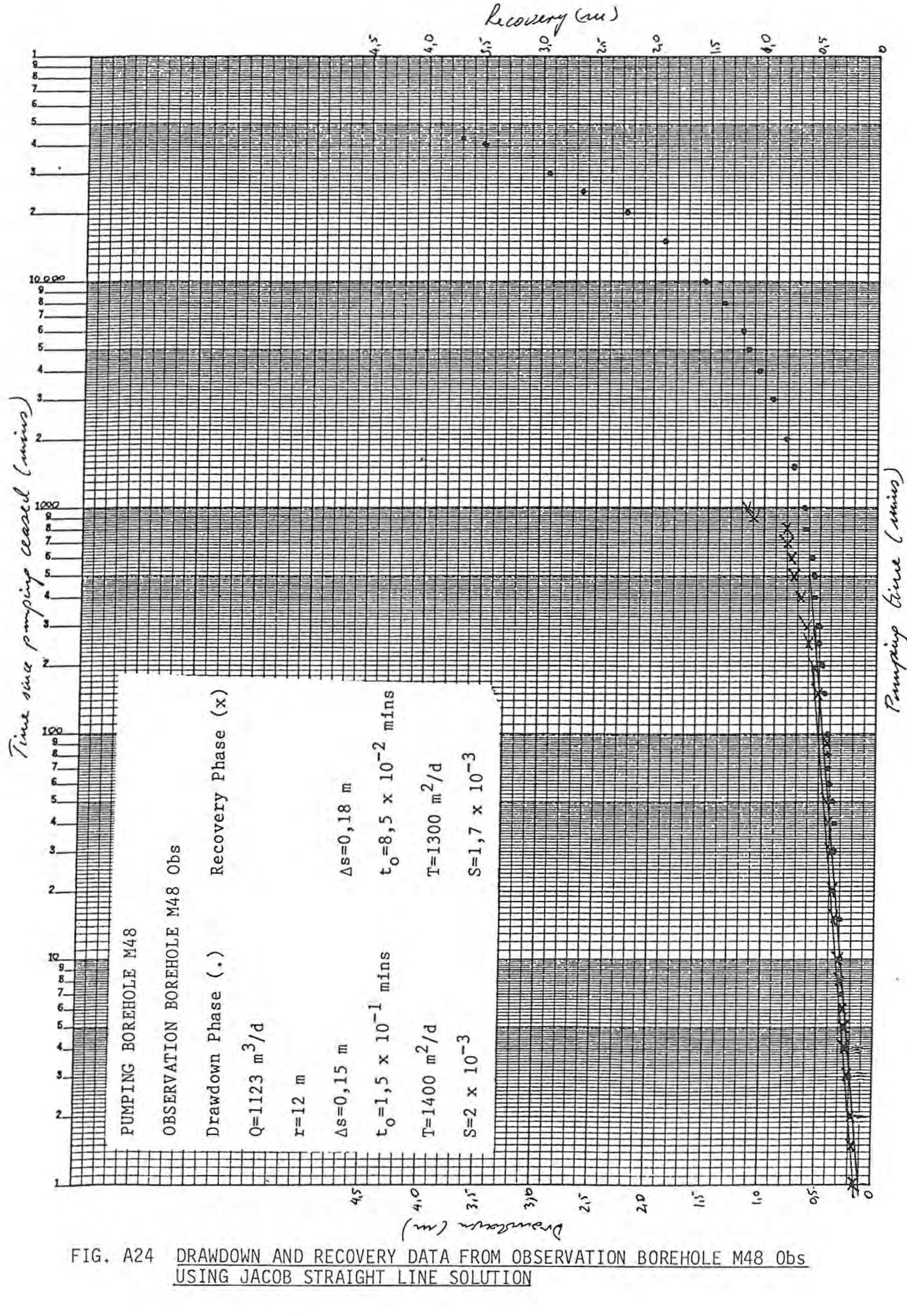

FIG. A24 DRAWDOWN AND RECOVERY DATA FROM OBSERVATION BOREHOLE M48 Obs USING JACOB STRAIGHT LINE SOLUTION

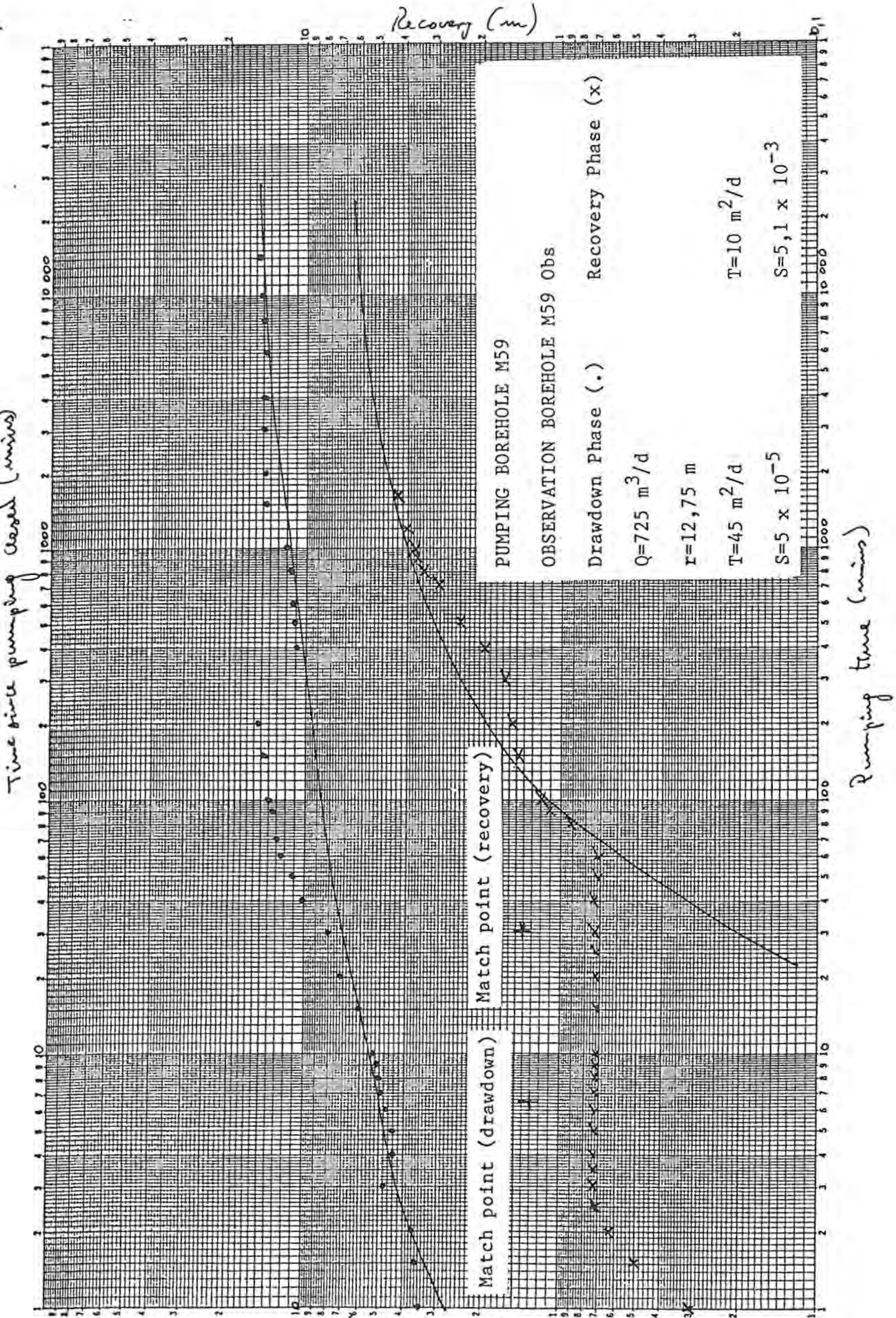

FIG. A25 DRAWDOWN AND RECOVERY DATA FROM OBSERVATION BOREHOLE M59 Obs USING THEIS TYPE CURVE SOLUTION

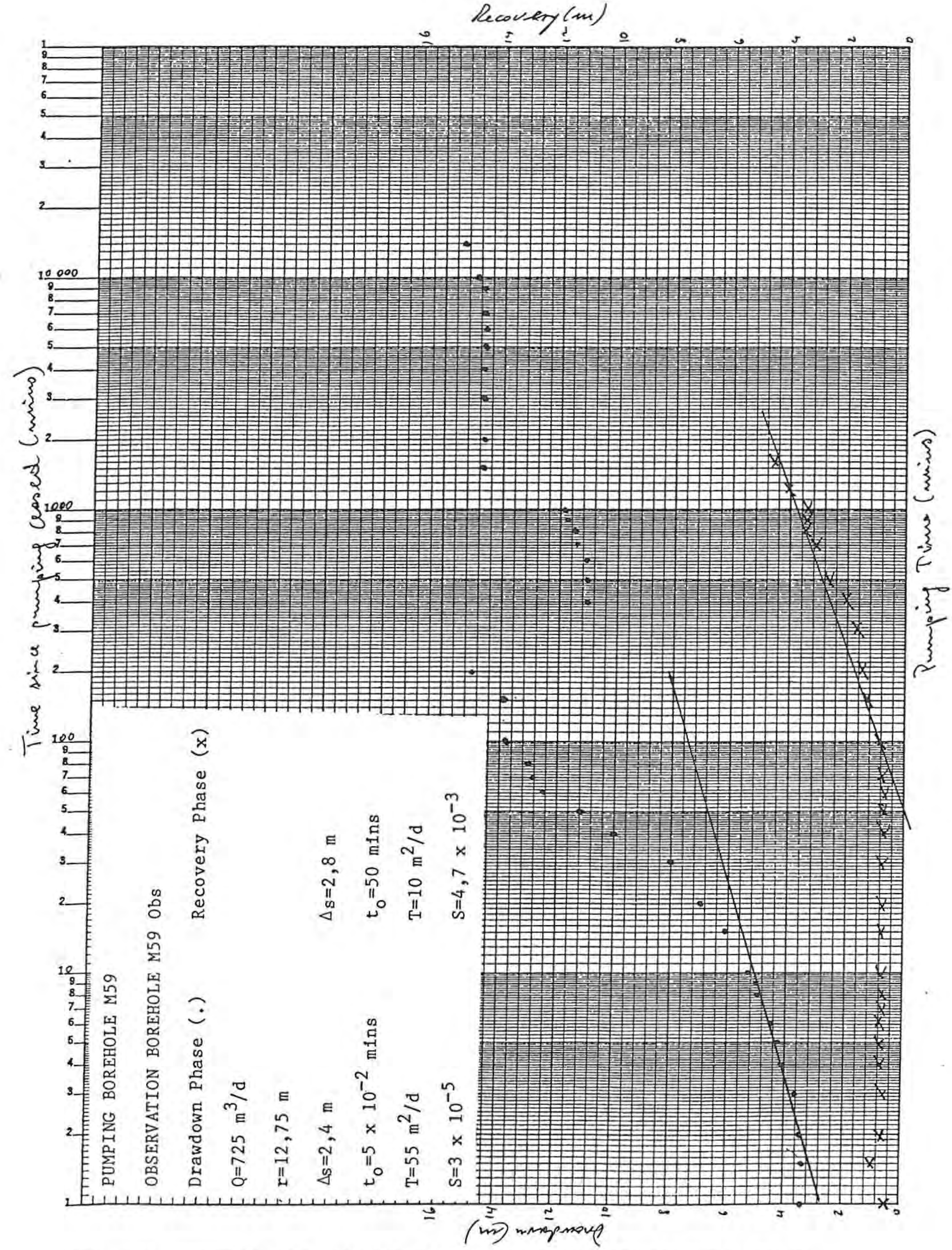

FIG. A26 DRAWDOWN AND RECOVERY DATA FROM OBSERVATION BOREHOLE M59 Obs USING JACOB STRAIGHT LINE SOLUTION

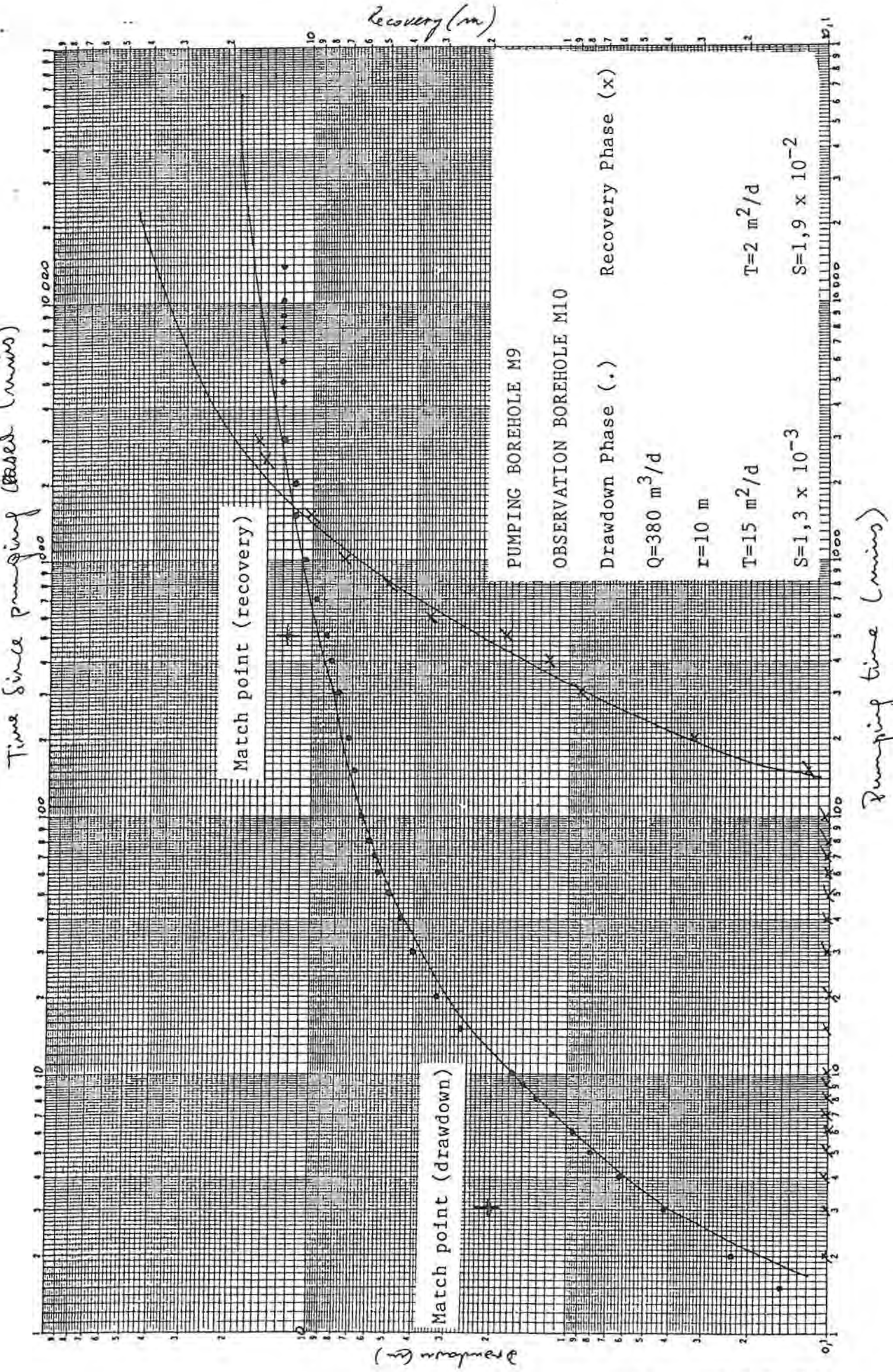

FIG. A27 DRAWDOWN AND RECOVERY DATA FROM OBSERVATION BOREHOLE M10 USING THEIS TYPE CURVE SOLUTION

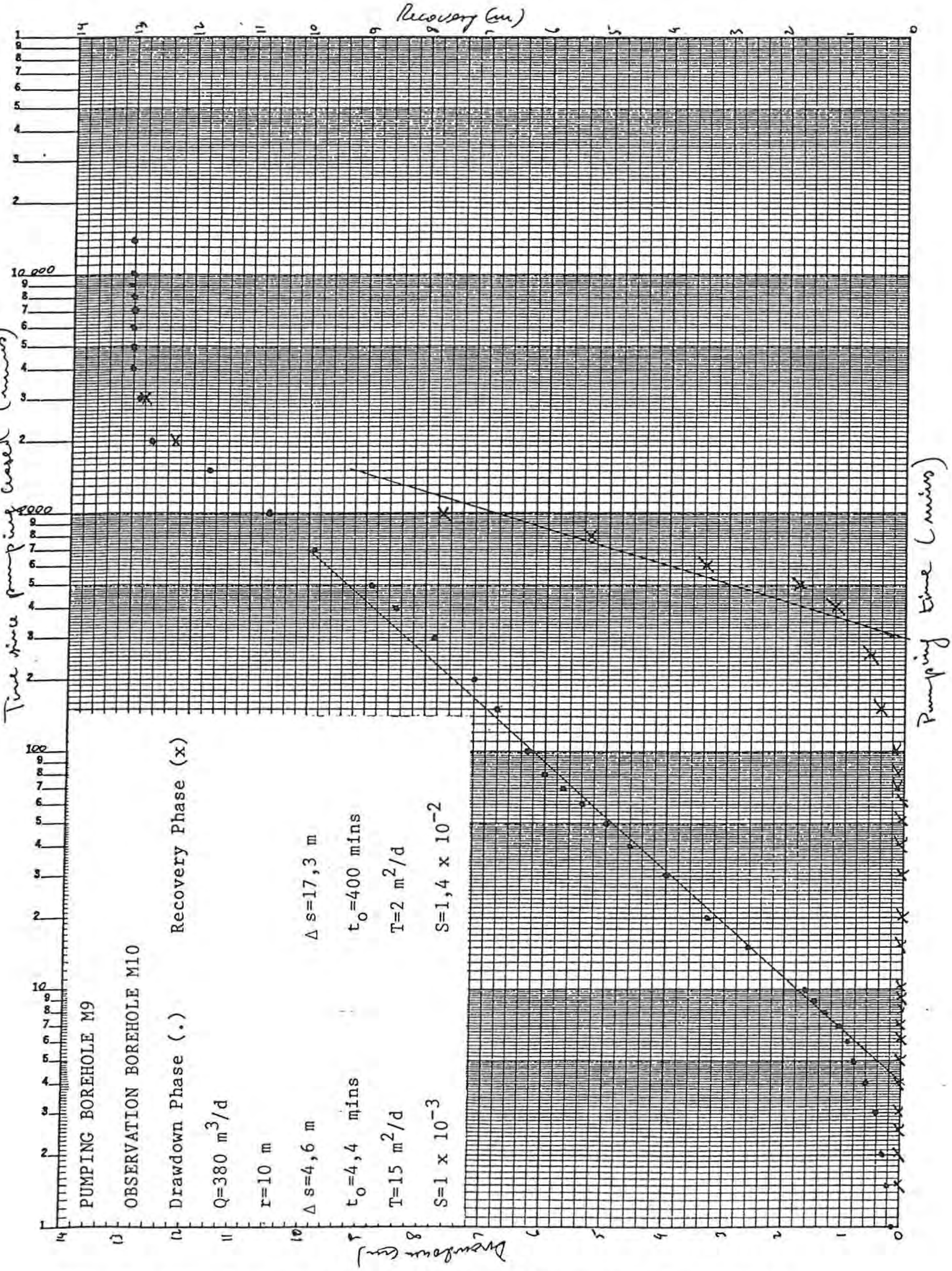

FIG. A28 DRAWDOWN AND RECOVERY DATA FROM OBSERVATION BOREHOLE M10 USING JACOB STRAIGHT LINE SOLUTION

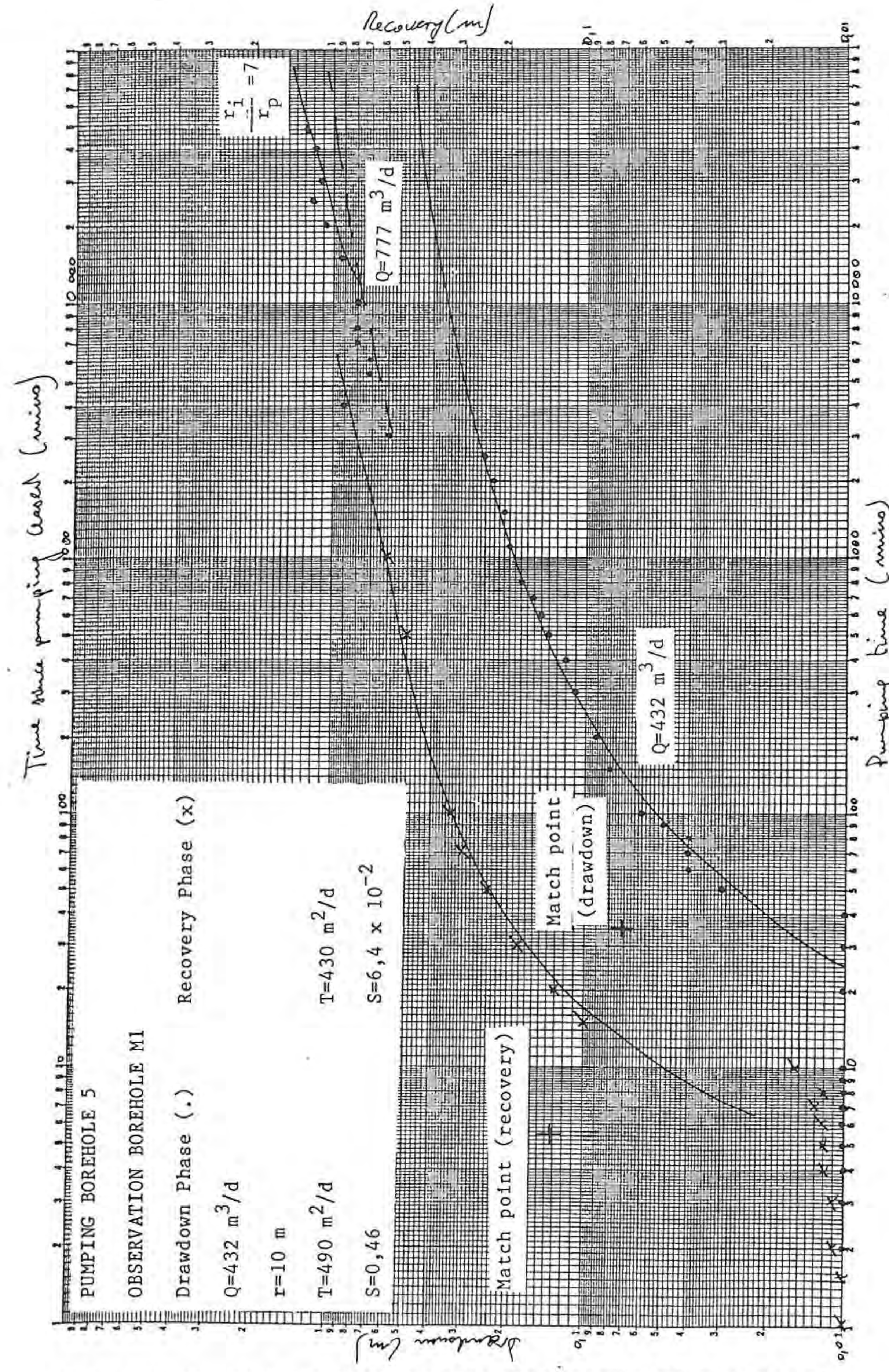

FIG. A29 DRAWDOWN AND RECOVERY DATA FROM OBSERVATION BOREHOLE M1 USING THEIS TYPE CURVE SOLUTION

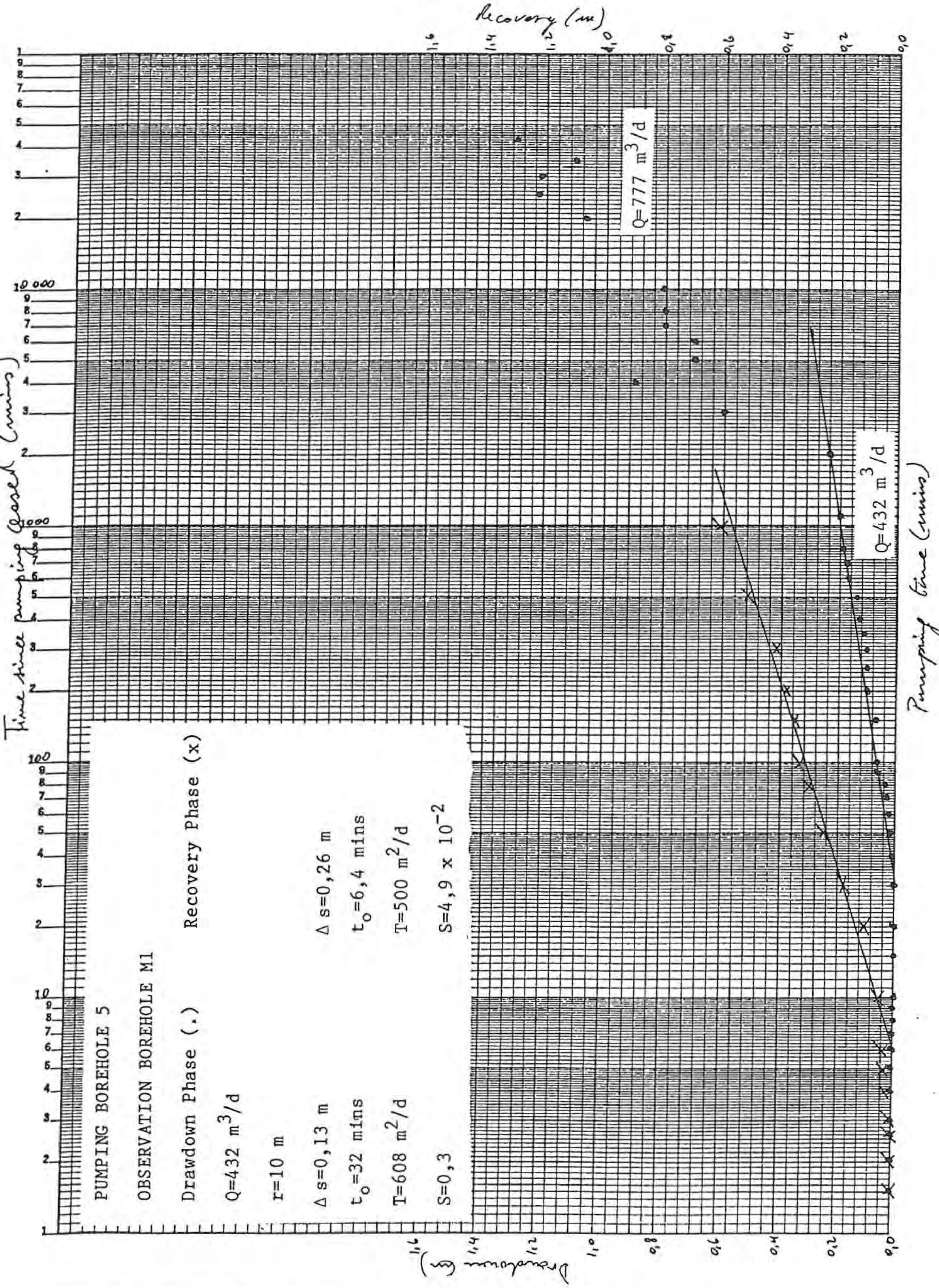

FIG. A30 DRAWDOWN AND RECOVERY DATA FROM OBSERVATION BOREHOLE M1 USING JACOB STRAIGHT LINE SOLUTION

APPENDIX B

SUMMARY OF THE ANALYTICAL RESULTS FOR THE EXISTING AND EXPLORATORY BOREHOLES

TABLE B1

SUMMARY OF ANALYTICAL RESULTS FROM EXISTING BOREHOLES

Borehole No.	CONSTITUENTS (meq/ℓ)									TOTAL	
	Na	Ca	Mg	K	Cl	SO_4	HCO_3	NO_3	F	Cations	Anions
1	2,83	1,00	3,63	0,08	0,34	0,48	6,64	0,19	0,03	7,54	5,66
5	3,92	2,05	5,12	0,12	0,71	0,92	4,00	4,03	0,01	11,21	9,66
6	3,31	2,05	4,13	0,07	1,34	0,64	3,44	2,69	0,01	9,56	8,07
10	3,52	2,40	4,30	0,05	1,89	0,29	3,20	2,69	0,01	10,27	8,57
11	3,05	1,90	5,12	0,22	1,02	0,44	3,43	3,38	0,02	10,29	8,27
13	2,96	2,20	1,40	0,03	0,79	0,44	3,35	0,69	0,01	6,59	5,27
14	3,65	1,55	3,72	0,05	1,02	0,21	3,53	2,79	0,02	8,97	7,55
15	1,04	1,00	0,38	0,01	0,05	0,42	1,67	0,31	0,01	2,43	2,45
16	1,35	0,40	0,37	0,02	0,10	0,16	1,75	0,31	0,01	2,14	2,32
21	1,35	0,16	0,32	0,04	0,90	0,31	0,39	0,45	0,01	1,87	2,05
22	1,04	0,30	0,37	0,02	0,10	0,21	1,59	0,31	0,01	1,73	2,21

TABLE B2

SUMMARY OF ANALYTICAL RESULTS FROM EXISTING AND EXPOLORATORY BOREHOLES

	CONSTITUENTS (meq/ℓ)									TOTAL	
Borehole No	Na	Ca	Mg	K	Cl	SO_4	HCO_3	NO_3	F	Cations	Anions
5	3,26	4,15	4,71	0,16	1,02	0,31	6,00	5,31	0,06	12,28	12,64
10	3,26	4,50	3,97	0,07	1,86	0,52	5,76	3,14	0,02	11,80	11,28
14	3,61	4,20	3,96	0,08	1,16	0,62	5,87	2,98	0,03	10,98	10,43
M2	3,57	0,80	0,67	0,07	0,45	0,17	3,43	0,76	0,06	5,11	4,81
M5	3,05	4,35	4,63	0,15	1,18	0,37	6,25	4,81	0,02	12,17	12,62
M8	1,65	5,25	4,30	0,11	0,82	0,54	5,64	4,27	0,02	11,21	11,27
M9	1,26	3,35	2,40	0,14	0,73	0,06	5,92	0,30	0,03	7,15	7,01
M11	3,87	1,30	0,93	0,01	0,59	0,21	4,92	0,09	0,09	6,11	5,81
M15	3,35	2,20	2,07	0,03	0,77	0,19	5,95	0,84	0,05	7,64	7,75
M18	0,67	3,30	2,56	0,12	0,28	0,08	5,56	1,00	0,02	6,65	6,92
M21	1,00	3,50	2,64	0,19	0,45	0,04	6,56	0,17	0,02	7,33	7,22
M36	3,05	2,20	2,15	0,12	1,47	0,36	5,81	0,08	0,05	7,51	7,71
M37-(3100)*	2,65	1,50	1,40	0,08	0,52	0,42	5,48	0,05	0,05	5,63	6,47
M37-(26300)*	2,44	1,68	1,46	0,08	0,46	0,12	5,71	0,06	0,04	5,66	6,35
M37-(43200)	2,39	2,04	1,50	0,09	0,41	0,15	5,81	0,08	0,04	6,38	6,44
M39	2,44	3,60	3,22	0,14	1,64	0,96	6,53	0,25	0,04	9,40	9,37
M41-(1000)*	1,74	2,45	1,82	0,10	0,39	0,13	5,53	0,16	0,04	6,11	6,21
M41-(6000)*	2,31	2,20	1,46	0,06	0,45	0,15	5,40	0,12	0,04	6,03	6,12
M41-(14400)*	2,31	2,30	1,55	0,09	0,42	0,13	5,48	0,14	0,03	6,25	6,17
M41-(43200)*	2,09	2,40	1,64	0,07	0,59	0,04	5,48	0,8	0,02	6,20	6,29
M44	0,81	3,55	2,81	0,20	0,51	0,06	6,25	0,40	0,02	7,36	7,22
M48-(14400)*	1,48	3,65	3,14	0,15	0,56	0,15	6,95	0,64	0,02	8,42	8,30
M48-(28800)*	1,39	3,70	3,14	0,15	0,56	0,21	6,89	0,64	0,02	8,38	8,30
M48-(43200)*	1,22	3,85	3,06	0,18	0,59	0,08	6,89	0,69	0,02	8,30	8,26
M50-(1000)*	4,39	0,23	0,01	<0,01	0,90	0,31	3,12	0,02	0,13	4,63	4,35
M50-(6000)*	4,00	0,18	0,01	0,05	0,96	0,19	3,12	0,02	0,13	4,24	4,29
M50-(14400)*	3,92	0,38	0,02	0,04	1,02	0,17	3,12	0,02	0,13	4,35	4,31
M51-(1000)*	6,09	1,25	0,17	<0,01	0,73	0,17	5,20	0,89	0,04	4,36	4,33
M51-(6000)*	5,00	0,40	0,02	<0,01	1,07	0,35	3,39	0,04	0,14	5,42	4,85
M51-(14400)*	4,79	0,35	0,02	<0,01	1,07	0,37	3,44	0,05	0,13	5,16	4,93
M54-(1000)*	0,58	4,85	4,13	0,18	1,02	0,44	6,56	1,79	0,03	9,74	9,81
M54-(10080)*	0,64	4,35	3,88	0,16	0,90	0,44	6,56	1,74	0,02	9,03	9,64
M59-(1000)*	4,39	0,41	0,02	<0,01	1,41	0,29	3,03	0,24	0,09	4,82	4,97
M59-(14400)*	4,48	0,49	0,01	<0,01	1,07	0,23	3,44	0,30	0,12	4,98	5,05
M60-(1000)*	0,71	4,60	4,79	0,11	0,28	0,10	9,04	0,48	0,02	10,21	9,90
M60-(6000)*	0,67	3,90	3,80	0,09	0,34	0,06	7,45	0,43	0,02	8,46	8,28
M60-(14400)*	0,72	3,85	3,80	0,09	0,37	0,08	7,53	0,50	0,02	8,46	8,48

* Elapsed pumping time of sampling in minutes